

Ash resistivity profiling and effect of a high frequency power supply on electrostatic precipitator efficiency

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Executive summary

Particulate emissions of coal-fired power stations are governed by the air quality legislation as stipulated by the Department of Environmental Affairs. The legislation stipulates the amount of particulate emission a coal-fired power station is licenced to emit during operation at full load. Failure to comply with the set-out emission limits results in none compliance, which can result in a stiff fine or jail sentence for the responsible personnel. Alternatively, a power station or production unit that fails to comply with and operate within the set-out emission limits may be required to de-load, i.e. reduce production until the point where emissions are low and within legislation compliance.

Air quality legislation requires existing power plants to operate with a particulate emission limit of 100 mg/Nm^3 daily average per unit for the station in which tests are conducted. The Department of Environmental Affairs is set to further reduce the emission limit for existing plants to be 50 mg/Nm^3 by 2020. At present, many of Eskom's power stations are having difficulties in maintaining particulate emissions to the required emission levels and as a result, these power stations consistently operate with load losses in order to reduce their emissions and to be within the legal specifications. Eskom power stations mainly make use of electrostatic precipitators (ESPs) for particulate emissions. In recent years, the ESPs have found it difficult to maintain emission levels and within the required limits. The reason for the power stations' ESPs' inability to maintain low emissions is due to a variety of factors, such as coal quality deterioration, aging plants and outdated power supply technology.

This project investigates ash resistivity testing and profiling in order to determine whether the resistivity profile of the collected ash is still within the required ESP operating spectrum. The deterioration of coal quality over the years may have resulted in a high resistivity ash mean captured by the ESP, which is not ideal to maintain low particulate emissions. This project is also aimed at investigating new power supply technology for the ESPs and to compare that system's performance with the existing power supply system. An industrial project was implemented, testing the ESP performance for existing power supply technology as well as with a new power supply system, in order to quantify the reduction in emissions within the Eskom environment.

Keywords: Electrostatic precipitator, particulate emissions, fly ash resistivity, high frequency power supply, transformer rectifier

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CHAPTER 1: INTRODUCTION

The purpose of this chapter is to provide background of the work presented in this dissertation. A literature background is discussed, describing the problem statement and context thereof and objectives of the study in order familiarise the reader with the concepts. The problem statement will form the basis from which the rest of the study will stem. Research aims and objectives are also discussed in this section. The dissertation overview is also discussed.

1.1 Introduction and content

South Africa generates the majority of its electricity supply by means of fossil fuel power stations. The burning of coal has a negative impact on the environment as the by-products gases of the combustion process extracted and released into the atmosphere contain chemical substances and particulate matter that are harmful to the environment and living organisms. This is influenced by the combustion process, the grade of coal combusted and implemented filtration process.

South African power stations are designed to burn low-grade coal, with high ash content, resulting in a great environmental impact. The majority of the power stations are designed to operate until 2040 and research has shown that a further deterioration in coal quality is to be expected as mines are running out of reserves [1].

Coal quality is determined by the amount of volatile/combustible matter present as compared to the coal's ash content. At present, there are power stations that burn low quality coal, with volatile matter as low as 14 MJ/kg and ash content (non-combustible matter) as high as 38.3%. The consequence of combusting such low-grade coal is that the boiler is required to fire more in order to achieve the desired Megawatts, resulting in high emissions as the electrostatic precipitator (ESP) needs to handle a larger quantity of fly ash due to the increased firing. A boiler at full load (in this instance 618 MW) typically produces up to 850 tons of coarse ash and 3 400 tons of fly ash per day, meaning that 20% of the ash content is in a form of coarse ash, while the remaining 80% are made up of fly ash/particulate matter [2]. These 3 400 tons of particulate matter are what need to be captured and collected by the ESPs.

Particulate emissions (fly ash) from industrial process have recently come under scrutiny in the driver to ensure a green future and minimising air pollution. Studies have shown that fossil-fired power stations contribute the majority in terms of dust particulate emissions [7, 9]

compared to other industrial process. Conferences such as COP17 highlighted the need to reduce these particulate emissions drastically, with Eskom also pledging to contribute to the reduction of its emissions. Eskom, being the largest power generating company in Africa, produces the majority of its power by means of coal-fired power stations. Therefore, they have come under scrutiny to reduce their emission levels in order to comply with stringent air quality legislation.

1.1.1 ESP basic operation

The main systems typically implemented in industry for particulate emission filtration are electrostatic precipitators (ESPs) and fabric filter plants/bags (FFPs). Power stations normally experience dust particulates with diameters of less than or equal to $10\text{ }\mu\text{m}$ (PM_{10}) [13]. These systems have proven effective in limiting particulate emissions and can achieve collection efficiencies of up to 99% under ideal operating conditions [5, 10]. Fabric filter bags' principle operation is similar to that of a vacuum cleaner and their drawback is that they cannot effectively capture fine particles (PM_{10}). Whereas, ESPs are capable of collecting these fine particles, their principle operation is slightly more complex as it incorporates three specialised fields of expertise (electrical, chemical and mechanical engineering) to collect particulate emissions. Figure 1 illustrates the dust particulate filtration process for a typical power station that makes use of an ESP.

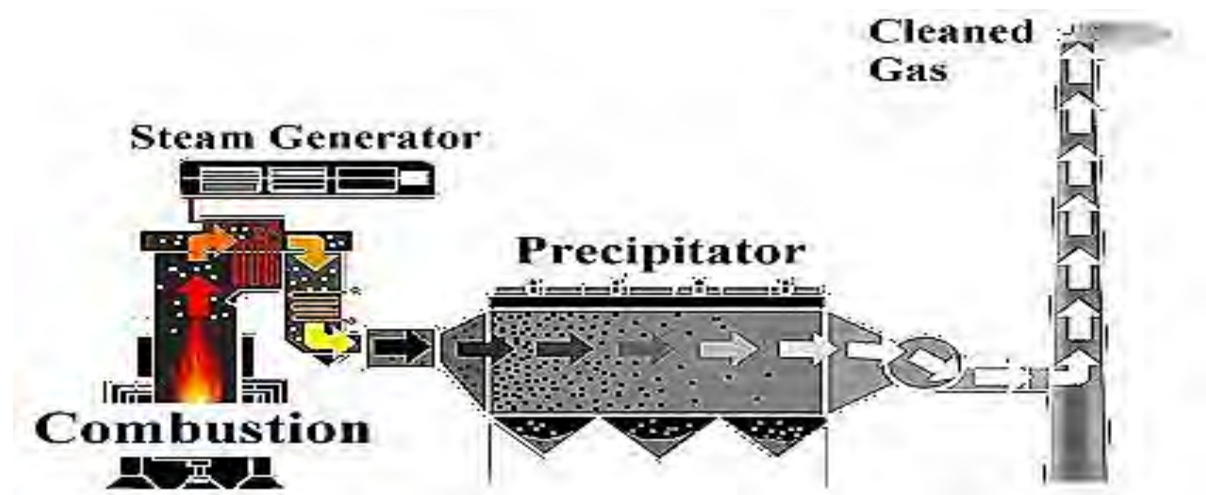


Figure 1-1: Schematic illustration of ESP [11]

Electrostatic precipitators (ESPs) make use of electrical forces in order to collect suspended dust particles from the flue gas stream extracted from the boiler. Electric forces are established between a discharge and collector plate arrangement; a pathway for the flue gas stream, also known as a field. The power station to be investigated for the purpose of this

project makes use of a single-stage, dry-type, parallel plate arrangement ESP and each unit has four parallel casings, each with seven fields in a row – therefore 28 fields per unit. A single stage ESP design is one whose arrangement allows for the charging and collection of dust particles to occur in the same region/field [5, 10]. Each field in an ESP arrangement consists of a discharge wire/active electrode and two collector plates/electrodes on either side of the discharge electrode forming horizontal ducts. Figure 1-2 illustrates the electrode arrangement.

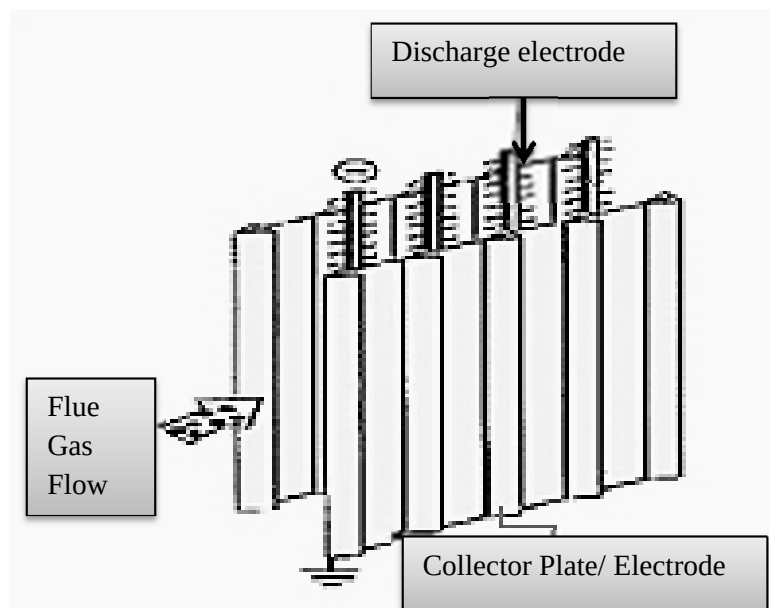


Figure 1-2: ESP field arrangement (modified) [57]

Suspended dust particles are extracted inside the boiler/combustion chamber from the boiler by means of an induction fan and enter the ESP fields. These discharge electrodes are connected to a high voltage DC supply in order to produce the corona needed for ionisation. There are six fundamental principles involved inside the ESP to achieve dust particulate collection [5, 10]:

- Ionisation: Charging of particles
- Migration: Transporting the charged particles to the collecting surfaces
- Collection: Precipitation of the charged particles onto the collecting surfaces
- Charge dissipation: Neutralising the charged particles on the collecting surfaces
- Particle dislodging: Removing the particles from the collecting surface to the hopper
- Particle removal: Conveying the particles from the hopper to a disposal point

Flue gas enters the ionisation region, resulting in dust particles attaining a charge (negative), and through the applied electric field, the charged dust particles migrate to the collector plate and subsequently lose their charge and are removed through the rapping process. Figure 1-3 illustrates how dust collection is achieved by means of the above-mentioned collection process [15].

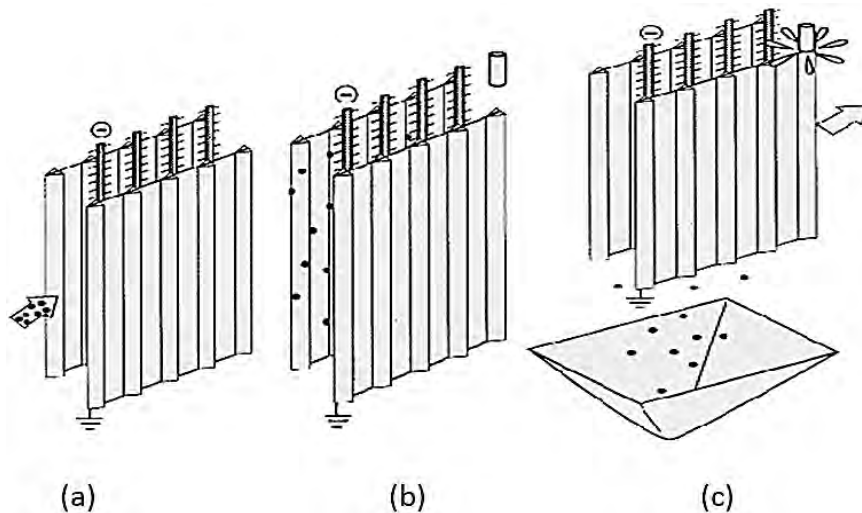


Figure 1-3: ESP dust collection, principle operation [57]

The ionisation process takes place when electrons within the vicinity of the corona discharge are excited/energised. The electron excitation results in electron collision, which causes an electron avalanche and these electrons attach themselves to the suspended dust particle passing through the ionised inter-electrode space. The flue gas stream flows through the ionised chamber such that the suspended dust particles acquire a charge, i.e. particle separation. The particles attain a negative charge and are deflected out of the flue gas stream due to the presence of the electric field established by the presence of high voltage DC. The charged particles deflect and migrate to the positively charged collector plate under the influence of the electric field for collection. The collected dust burden is retained on the collector plate and subsequently dislodged periodically by a rapping process. The rapping process makes use of a hammering system that strikes the collector plate, dislodging the dust burden into ash hoppers to be collected and transported to the ash dump. This process removes more than 98% of solid dust particles [5, 10, 15, 57].

1.1.2 Particulate emissions' legal requirements

The majority of Eskom's coal-fired power stations make use of electrostatic precipitators (ESPs) to capture particulate emissions. ESPs have therefore proven to be an effective way of particulate emission collection; however, due to plant deterioration, deteriorating coal quality

and stringent air quality legislation, their performance has come under scrutiny and the means of optimising their performances need to be investigated.

Changes in air quality legislation to stringent requirements require existing power plants to meet particulate emissions below 100 mg/Nm^3 per stack monthly average (to be changed to daily average in 2016), whereas newly built power plants are required to emit 50 mg/Nm^3 . The Department of Environmental Affairs is set to reduce the emission limit for existing plants to be the same as that of those newly built by 2020. This has resulted in the need to optimise the collection efficiency of the ESPs in order to comply with the set legislation [2, 9].

Eskom's operations fall under the jurisdiction of independent regulator Chief Air Pollution Control Officer (CAPCO) appointed by the Department of Environmental Affairs and Tourism. The emission limit has been set at 100 mg/Nm^3 per stack monthly average, with continuous hourly opacity measurements. Failure to operate within the set limits is taken as non-compliance and the operating licence stipulates that failure to operate within the set limit requires the respective unit/boiler to reduce load/production until the unit is within the required emission limits. The loss in revenue due to load losses because of high emissions is in the range of millions of rands, as the unit is unable to produce electricity as contracted for with national control. Presently, electrostatic precipitators are unable to successfully and continuously achieve the 100 mg/Nm^3 set limit with opacity measurements averaging well above 100 mg/Nm^3 [2, 9]. South Africa currently has power shortages, as there is no spare capacity. The reduction of production due to high emission levels further aggravates this issue and results in load shedding in order not to violate the set regulation.

1.1.3 ESP electrical supply

The existing power supply systems for the ESPs within the Eskom environment are what are termed conventional rectifier transformer sets. Rectifier transformers make use of 50 Hz main frequency and are thyristor controlled to deliver the required corona power into the ESP fields. Due to the deterioration in plant and process conditions, the rectifier transformers have proven ineffective, as they are unable to supply and maintain the required corona power to effectively collect the dust particulates and ensure compliance to particulate emissions regulations.

The transformer set delivers a high DC voltage that is coupled with an AC ripple. The generated ripple has a 50 Hz main frequency and the amplitude (peak-to-peak) of this ripple

has been found to be in the range of 30 to 40% of the output DC voltage [24]. This significantly reduces the average DC output voltage and limits ESP performance. The operating ESP voltage is primarily limited by sparking, and a spark typically occurs on the peak of the AC ripple voltage [5, 10]. The control system is designed in such a way that when a spark is detected the control reduces a certain percentage of the voltage. A high-percentage ripple voltage effect results in significant voltage reduction when sparking occurs and a subsequent reduction in corona power. The reduced average voltage results in a reduction in the effective electric field intensity that is required to repel the charged particulates for collection. This results in ineffective charging and collection of the dust particulate. The delivered corona power needs to be optimised in order to improve the ESP collection efficiency. Figure 1-4 illustrates the electrical circuitry representation of a conventional rectifier transformer connection to an ESP field.

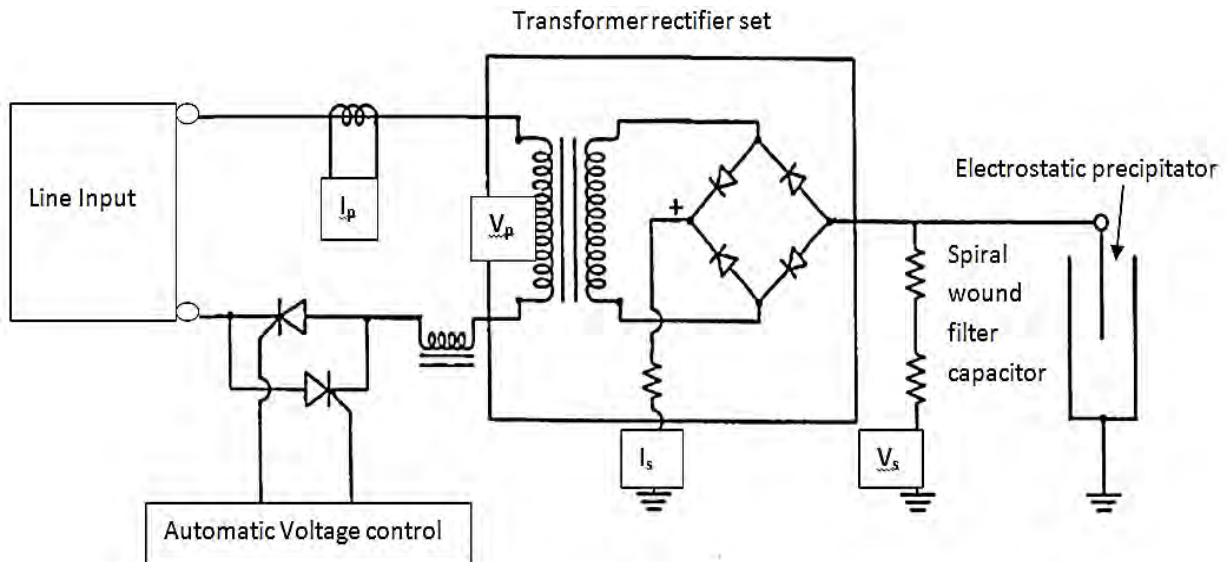


Figure 1-4: Electrical circuitry configuration of an ESP field (modified) [25]

Increasing the voltage and maintaining corona power in the field can improve the field performance, and therefore the effectiveness in the collection of dust particles as the ESP collection efficiency is influenced by the generated electric field as stipulated by Deutsch's efficiency formula [5, 10].

1.1.4 Fly ash resistivity

Fly ash resistivity is the primary parameter in the operation of ESP performance, and there is an optimum operating resistivity range and any deviation outside this set range results in undesired effects, affecting the performance of ESPs. Resistivity influences the ability of the

dust particles to attain the required charge in order for them to be collected. Fly ash particles have an associated conductivity that is influenced by temperature, moisture, particle size and chemical composition of the dust burden. Resistivity above the defined range is classified as high resistivity ash and is mainly due to combusted low-grade coal with low sulphur content, whereas low resistivity ash is due to unburnt carbon. The consequence of an ESP operating with high or low resistivity ash is reduced collection efficiency [4, 5, 10].

High resistivity ash causes the undesired effect of back-corona within the ESP. Low ash resistivity, on the other hand, results in particles easily attaining a charge, but cannot be retained long enough to be collected, thereby resulting in particles not being collected due to particle re-entrainment. Based on the coal quality that is utilised by South African power plants, it can be deduced that the installed ESP operates with high resistivity ash. Quantifying the resistivity range that locally installed ESPs are exposed to may assist in better understanding the extent to which resistivity affects ESP performance.

There is currently no research that is being conducted locally in terms of the fly ash resistivity. Eskom has in the past years been sending ash samples to India to be tested at the India Institute of Technology. This is a time-consuming and costly exercise and the results can be affected due to various changes in conditions. The resistivity profile is required and needs to be associated with frequent operating condition changes, such as coal quality and back-end temperatures in order to optimise ESP operation properly. Due to the large quantities of fly ash produced during combustion, the ash can act as heat sink. Operating gas temperatures have been measured to be in the range of 160 to 180°C, which is 18 to 28% above the design criteria. This will severely affect the resistivity of the dust burden.

1.2 Problem statement

High particulate emissions in Eskom power stations are a major concern, as the inability to operate the plant below the stipulated emission limits results in non-compliance to legislation and as a result, the unit needs to de-load in order to operate within the required emission limits. The loss in revenue because of de-loading units is extremely significant and, more so, the consequences of de-loading units further put a strain on a power grid that is already overloaded. This action to de-load the unit also contributes heavily to load shedding currently experienced in South Africa.

High particulate emissions occur due to poor ESP performance as well as an inability to provide sufficient and consistent corona power required to collect particulate dust effectively. The resistivity range of the fly ash being captured further affects this. However, at present, this range is unknown, due to the deterioration of the coal quality being combusted. Knowing the resistivity profile of the ash captured can assist in optimising the performance of the ESP fields. Additionally, as has been established, conventional rectifier transformers are unable to supply the required corona power. A new power supply technology, referred to as HFPS, is to be tested, which will increase the power input into the ESP fields and quantify the effect that this will have on particulate emissions in order to ensure they are consistently below the legislative limits.

1.3 Project objectives

Electrostatic precipitators incorporate three fields of expertise for effective particulate collection, i.e. chemical, mechanical and electrical engineering. Therefore, the effective optimisation of the system as a whole requires a combined understanding of all fields. This project will investigate the electrical optimisation of ESPs by investigating different ESP power supplies and the effects of fly ash resistivity to the electrical operating conditions. Figure 1-5 illustrates the steps to be followed in order to ensure that the main objective of optimising and ultimately reducing particulate emissions is achieved.

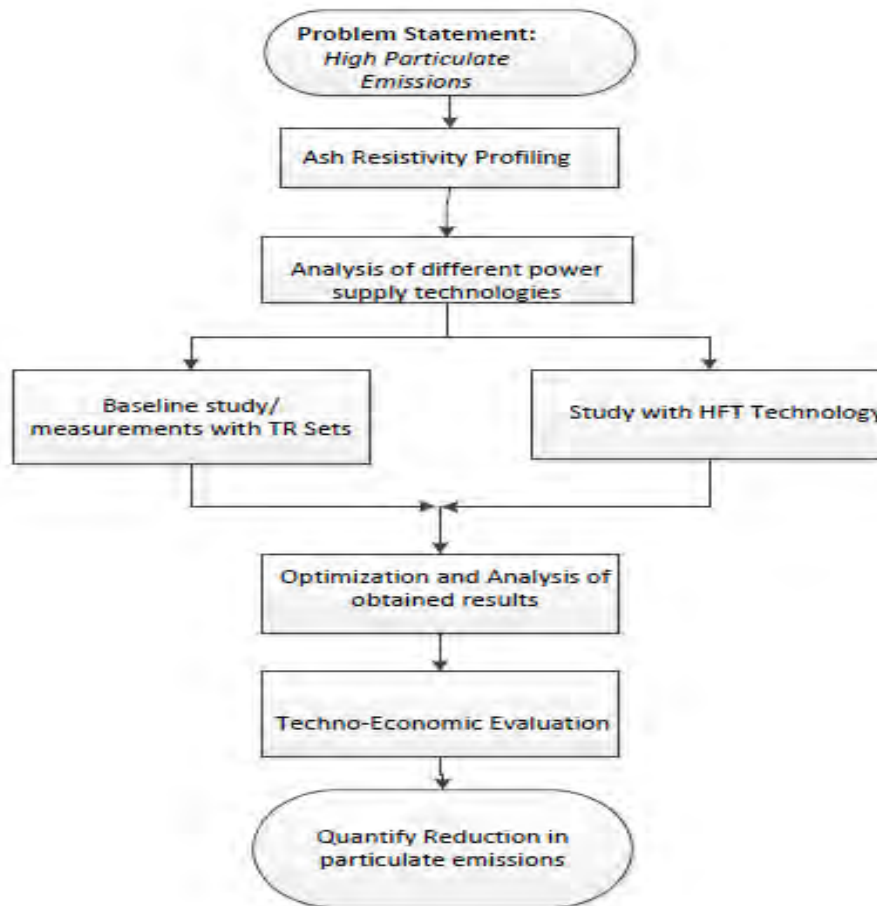


Figure 1-5: Project steps to be followed to achieve project objectives

1.3.1 Fly ash resistivity profiling

Fly ash resistivity is the primary parameter in the operation of ESP performance, and there is an optimum operating resistivity range and any deviation outside this set range results in undesired effects, affecting the performance of ESPs. Resistivity influences the ability of the dust particles to attain the required charge in order for them to be collected. Presently, the resistivity profile of the captured ash is unknown due to the deterioration of the coal quality. Obtaining a resistivity profile for the selected power station will assist in understanding at what range in the resistivity spectrum the power station's ESP is operating and therefore assist in analysing the behaviour of the ESP and its performance in order to optimise the electrical performance.

1.3.2 ESP power supply technologies

Technological assessment for different ESP power supply in industrial application, mainly conventional thyristor-driven rectifier transformers will be evaluated in comparison to IGBT-driven high frequency power sets. The emphasis will be on the ripple effect of the different

power supplies and will be investigated by running simulations and conducting practical measurements from the operating system. The simulation will be based on design criteria parameters to get an understanding of what the system's operating parameters ideally need to look like. A range of comparative tests shall be conducted for both technologies. The influence of ash resistivity will also be investigated to understand its influence on the voltage and current characteristics of the different power supplies. Experimental work will be conducted to determine the resistivity profile of the ash samples obtained from the selected power station. The respective particulate emissions will be monitored and recorded for various operations to get an understanding of how the system's operation is influenced by resistivity and voltage ripple.

1.3.3 Techno-economic evaluation

The system's energy consumption will be, evaluated based on practically measured to be conducted during plant operation. A techno-economic evaluation shall be, conducted based on the different technologies deviation in energy consumptions.

1.4 Project scope

This project is a pilot study and industrial application of a new technology to evaluate its effectiveness in quantifying the emission reduction in comparison to existing technology. The theoretical analysis of the circuitry configurations of the different technologies will be simulated and analysed. The key parameter that the two technologies have is the operational frequency that has a direct influence on the ripple voltage that is supplied to the ESP field.

Tests will be conducted on the ESP system for both technologies, i.e. the ESP efficiency test and electrical measurements taken to determine the electrical characteristics of each technology during operation. Test measurements and calculations will be conducted on both technologies to determine:

- precipitator efficiency tests
- corona power produced
- techno-economic evaluation

In addition, laboratory experiments will be conducted to determine the resistivity profile of the fly ash samples collected from the selected power station.

1.5 Methodology overview

The project methodology to be followed will comprise seven chapters, each chapter evaluating an aspect of the project. The process flowchart of the project is highlighted by Figure 1-6. The starting point is defining the problem statement, as discussed in this chapter.

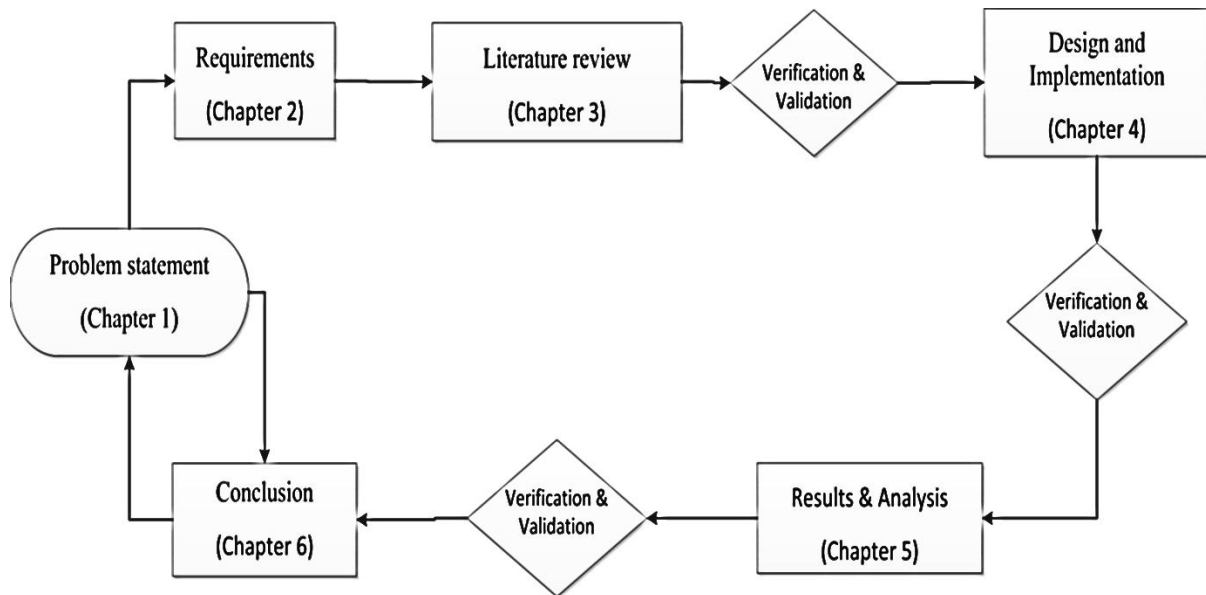


Figure 1-6: Project workflow

Chapter 2 evaluates the project constraints, discussing technical, social and financial issues and the impact they may have on the outcome of the project. The validation and verification requirements to be used for the literature, design and obtained results are discussed in this chapter.

Chapter 3 discusses a literature review on conducting and determining fly ash resistivity, as well as a study of the technologies to be evaluated during this project. The literature review provides a better understanding of how much work has been done thus far in industry and publications.

Chapter 4 discusses the design and implementation phase of the project, which include systematic descriptions of tests conducted to obtain results as well as calculations of primary parameter as would have been identified in the literature review. This also includes software simulations, laboratory experiments and industrial operating measurements.

Chapter 5 deals with the analysis of the data obtained in Chapter 4 of the project and discusses the obtained simulation and practical measurement results as defined in the project scope discussed in Chapter 1. A techno-economic evaluation of the project ensues to

determine the financial benefits of selecting one technology above another. The electrical efficiency of both systems will also be evaluated based on the obtained results in order to conduct a techno-economic evaluation. The techno-economic evaluation will determine the return on investment of both systems. This will also include cost savings for both systems in terms of unit performance versus emission levels.

Chapter 6 is the conclusion chapter, whereby all the obtained and analysed data are summarised to conclude the findings of the project based on the stipulated project objectives.

1.6 Deliverables

The following deliverables have been completed and submitted as part of the dissertation submission in order to meet the objectives set out in this dissertation.

- The project deliverables will be an equivalent circuit simulation, depicting the operations of both the conventional rectifier and high frequency transformer set operation.
- Fly ash resistivity profile.
- Discussions of the influence of the voltage ripple on the effective output DC voltage.
- Electrical operating efficiency of the transformer sets.
- Techno-economic evaluation for both transformer sets.
- South African universities' power engineering conference article: A conference article was written and presented during SAUPEC 2013 conference.
- Journal article to be published on the findings and results of the project

1.7 Beneficiaries

The stakeholders for this project are the power station, Eskom as a whole and the general population. The power station stands to gain valuable insight into the operating resistivity they experience at the station. The value of this knowledge will assist in optimising the ESP's collection efficiency by ensuring that the dust particles to be collected are within the required/specified resistivity range. If not, then the necessary steps can be taken to ensure that the dust particles are within an accurate resistivity range.

Eskom as a whole will also benefit from the project if it is proven that the ESP's collection efficiency can be improved by ensuring that the dust particles are within the required resistivity range for collection. This will ensure that Eskom will reduce its carbon footprint and particulate emissions as was stipulated in the COP17 conference and as stipulated by the

World Bank. All Eskom power stations, old and newly built, must conform to particulate emissions of 50 mg/Nm³ by the year 2020. Therefore, a drastic ESP collection improvement is needed and the results of this project can assist in improving the collection efficiency.

There have been public complaints against Eskom in terms of air pollution, and if Eskom can prove they have improved the ESP collection efficiency then their complaints can be resolved. Therefore, the public as a whole will benefit as this project aims to reduce particulate air pollution and airborne contaminants harmful to the health of the general population [7].

1.8 Publications

The research presented in this dissertation has been documented and published in a number of journal publications. The published papers together with the relevant abstracts are as follows:

- G. Chauke and R. Gouws, “Fly ash resistivity profiling for coal fired power stations to optimize electrostatic precipitator” *Proceedings of the Southern African Universities Power Engineering Conference (SAUPEC 2013)*, January 2013, pp 275-269, ISBN 978-186822-631-3.

Article abstract

Electrostatic precipitators (ESP) are, used in coal-fired power plants for the removal of particulate emissions. Fly ash resistivity is a primary parameter in the collection of particulate emissions. ESP systems operating with high or low resistivity ash find it difficult to effectively and efficiently collect fly ash, as high resistivity ash results in back-corona discharge, whilst low resistivity results in particle re-entrainment into the flue gas stream. The purpose of this paper is to investigate and obtain a fly ash resistivity profile for existing power plants in South Africa. Ash samples obtained from power plants are, tested making use of an, ash resistivity test oven in accordance with IEEE standard 548-1984. This paper discusses the preliminary experimental results, to determine the resistivity profile in which power plant ESP's are operating. The electrical efficiency of the ESP system is, evaluated based on the obtained resistivity profiles.

- G. Chauke and R. Gouws, “Fly Ash resistivity Profiling for South African Coal Fired Power Stations” *Journal of Energy and Power Engineering*, Volume 7, December 2013, pp 2306 -2311, ISSN 1934-8983

Article abstract

Particulate emission is a major problem in industrial processes, mainly power plants that make use of coal as a primary source of energy. Stringent emissions limits, set by government organisations requires industries to conform to these limits to ensure that air quality is, sustained and with minimum pollutant present. Electrostatic precipitators are, typically used to filter and collect these particulate emissions. Fly ash resistivity is a primary parameter in the collection of particulate emissions, and there is a resistivity range at which electrostatic precipitator collection is most efficient and anything outside this range limits, their operation. High resistivity ash results in back-corona discharge, whilst low resistivity results in particle re-entrainment into the flue gas stream. The purpose of this paper is to investigate and obtain a fly ash resistivity profile for existing power plants in South Africa. Ash samples obtained from power plants are, tested making use of an ash-resistivity test oven, in accordance with IEEE Standard 548-1984. This paper discusses obtained experimental results, to determine the resistivity profile at which South African power plant electrostatic precipitators operate. The electrical efficiency of the electrostatic precipitator system is evaluated based on the obtained resistivity profiles.

- G. Chauke and R. Gouws, “Effect of high frequency power supply on electrostatic precipitator collection efficiency”. “, SAIEE Africa Research Journal, ISSN: 1991-1696, submitted: 13 November 2015.

Article abstract:

Particulate emission is a major problem in industrial processes, mainly power plants that make use of coal as a primary source of energy. Stringent emissions limits, set by government organisations requires industries to conform to these limits to ensure that air quality is, sustained and with minimum pollutant present. Electrostatic precipitators are, implemented as the main form of dust burden collection. In recent years, Eskom power stations have struggled to maintain particulate emissions below legislation limits, resulting power stations having to de-load and reduce power generation production. A pilot project was initiated to investigate the effects of a high frequency power supply will have on electrostatic precipitator collection efficiency.

This journal paper presents the results obtained from the implemented pilot project, whereby 16 HFPS were installed in a 28 field electrostatic precipitator plant.

(Complete version of paper available in Appendix D)

1.9 Summary

Particulate emissions are a major concern for the global community, especially for coal-fired power stations. The negative impact that this has on the environment, electricity supply and Eskom's image has resulted in the initiation of this project in order to investigate means to minimise particulate emissions. This project investigates new technologies that may assist in limiting particulate emissions and ensuring a safe, pollution-free environment.

The project entails two subsections that are to be implemented in order to reduce particulate emissions. The first part of the project entails the quantification of the ash resistivity profile of the collected ash from the power station's ESP. The resistivity profile testing was conducted by means of an ash-resistivity test oven, built and commissioned by Eskom. Determining the resistivity profile of the ash gives an indication as to whether the ESP is operating within the desired resistivity range. It is highly possible that due to the deterioration of the coal quality over the years, that the ash resistivity has significantly increased and may result in effective dust burden collection.

The second part of the project involves practical testing to be conducted in the power station, testing two types of power supply technologies. ESP testing is conducted for conventional main frequency power supply and for high frequency power supply (HFPS). This testing is aimed at quantifying the reduction in emissions because of the different power supply technologies within a practical context in the Eskom environment. A techno-economic evaluation of the project is also conducted, determining the financial benefits of the project objectives.

The project requirements are discussed in the upcoming chapter (Chapter 2), inclusive of the methodologies implemented in conducting testing, with reference to relevant standards.

CHAPTER 2: REQUIREMENT ANALYSIS

The purpose of this chapter is to provide the requirements analysis of the work presented in this dissertation. This chapter discusses the project constraints, standards to be adhered to in conducting this project during implementation, obtaining data results, and the analysis thereof in order to obtain accurate results. A verification and validation sub-section of the dissertation discusses the manner in which respective results of the project are to be obtained and analysed with regard to the respective standards in order to meet the project objectives. The social and environmental impact of the project is discussed in this chapter, as the project addresses an existing industrial problem.

2.1 Introduction

This chapter discusses the anticipated constraints, standards, verification and validation of the project results associated with project through the project cycle from inception, implementation, testing, result analysis and close out.

2.2 User requirement specification

This research project is an industrial project implemented at an Eskom power station to test a new ESP power supply technology in comparison with the existing technology and therefore quantifies the benefits thereof primarily through the quantification of the reduction in particulate emissions. The specifications of the transformer on which the quantification of particulate emission reduction is conducted are in Table 2-1:

Table 2-1: Transformer specifications

Power supply type	Transformer rectifier set	High frequency power supply
Power rating	113 kVA	120 kVA
Supply voltage	380 V (single phase)	400 V (3Phase)
Supply current	297 A	196 A
Output voltage (RMS)	46.5 kV	70 kV
Output voltage (peak)	70 kV	70 kV
Output current (mean)	1700 mA	1700 mA
Oil quantity	520 litres	90 litres

The selected production unit is to be on an outage, whereby maintenance work is conducted in order to repair identified defects on the ESP system. The unit was scheduled to be on an outage from 28 January 2014 until 27 April 2014. Upon the unit's return to service with main frequency transformer rectifiers, a settling period for the unit was agreed upon to obtain stable load conditions for the unit. A baseline ESP efficiency test (as per EPA Method 17)

[31] was conducted; the base-line performance tests were conducted at maximum continuous rating (MCR).

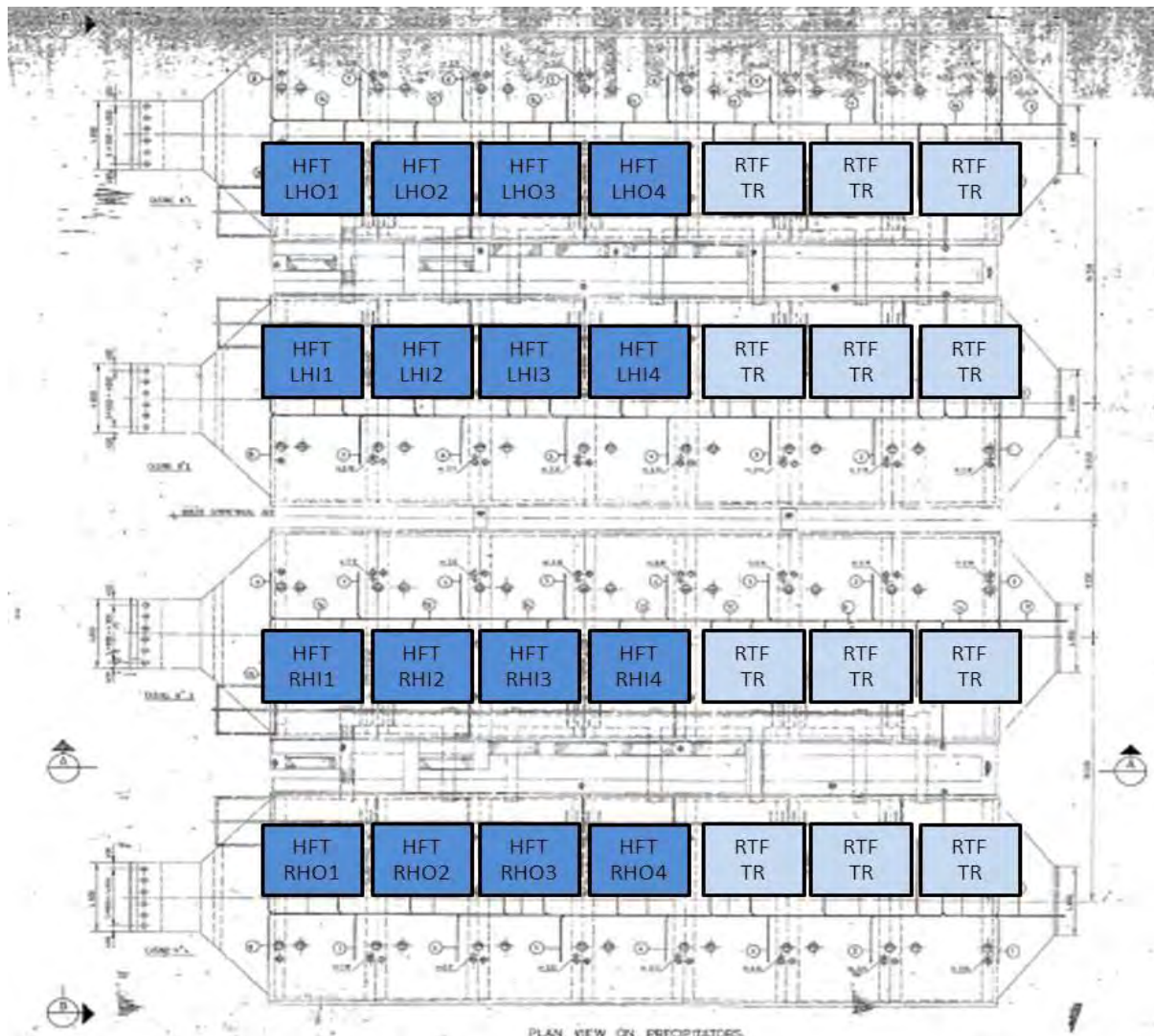


Figure 2-1: ESP HFT power supply arrangement

The installation of 16 HFTs across the first four fields in each of the four casings commenced after the baseline ESP efficiency tests were concluded. The installation and commissions processes were conducted while the unit was on load; Figure 2-1 illustrates the ESP and power supply transformer arrangement. The 16 HFTs were installed on the front four fields of all the casings, as the front field captures the majority of particulate matter [5, 10]. Upon completion of the installation of the 16 HFTs, a settling period was allocated and optimisation was conducted in terms of the rapping process and the second ESP efficiency tests were conducted.

2.3 Identified issues, constraints and impact

This research project is directly linked to an industrial project and therefore faces a number of constraints in its implementation and is subject to Eskom's internal project processes. The technical, financial and legal constraints of the project are discussed below.

2.3.1 Technical

This is an industrial pilot project to assess a new technology in comparison to the currently implemented system in order to optimise and reduce particulate emissions of an ESP. Consequently, the required tests to be conducted on the two systems will need to be carried out at a live plant. The safety standards are stringent when it comes to working at a live plant and only a trained and authorised person is allowed to work on a live plant.

The power supply operates with high voltages and therefore will require specialised equipment to conduct test measurements as stipulated in the project scope (section 1.4). This will also be limited by the system design, i.e. is any test point allocated to accommodate online testing?

2.3.2 Ash resistivity testing

In 1995, Eskom built and commissioned a resistivity measurement apparatus in order to conduct resistivity measurements in-house. There are a number of designs of resistivity measurement apparatus, many being designed for use in-house by ESP manufacturers, but the IEEE Standard 548-1984 for the measurement of dust resistivity is a repeatable standard used by independent laboratories [6]. Consequently, Eskom built their resistivity apparatus according to IEEE Standard 548-1984. However, this capability was lost over the years and has since been re-established.

The resistivity-testing oven was re-commissioned and recalibrated in 2011 in order to re-establish Eskom's ability to conduct its own in-house measurements. The test oven was mainly designed for in-house resistivity profiling for all of Eskom's power plants; however, the test facility was never intended to publish the obtained results.



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SANAS ACCREDITED CALIBRATION LABORATORY No 306

TEMPERATURE METROLOGY

CERTIFICATE OF CALIBRATION

Date of issue : 18/02/2012

Certificate No : 1202T3972-1

Technical Signatory

M Mathieson.

Page 1 of 2 pages.

The results of all measurements are traceable to the national measuring standards.

The values in this certificate are correct at the time of calibration. Subsequently the accuracy will depend on such factors as the care executed in handling and use of the device, and the frequency of use. Recalibration should be performed after the period so chosen to ensure that the instrument's accuracy remains within the desired limits.

This certificate is issued in accordance with the conditions of the accreditation granted by the South African National Accreditation System (SANAS). It is a correct record of the measurements made. This certificate may not be reproduced other than in full except with prior written approval of the issuing laboratory. Legal liability shall be limited to the cost of recalibration and or certification, but the applicant indemnifies Unique Metrology (Pty) Ltd against any consequential or other loss.

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Figure 2-2: Ash resistivity test oven calibration certificate (page 1)



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CERTIFICATE OF CALIBRATION

Page 2 of 2 pages.

Certificate Number : 1202T3972-1
Calibration of a : Oven
Manufacturer & Type : Scientific, Circulated air.
Serial Number : TG7723311
Calibrated for : Eskom Holdings SOC limited, Rosherville.
Procedure Number : 53-176-02
Date of Calibration : 04/02/2012
Date of Issue : 18/02/2012
Laboratory Environment : 28.3°C.
Reference Standards : DT 600 Datalogger with 4 type K thermocouples,
serial numbers UM5, UM6, UM7 and UM8

Set Point	Error at			
	Position 1	Position 2	Position 3	Position 4
90	-1.7	-2.6	-1.2	-1.7
140	-1.6	-4.6	-0.4	-2.0
190	-0.9	-6.1	1.0	-1.4
240	-0.6	-7.8	1.6	0.1
290	-0.4	-6.5	2.7	2.4
340	1.3	-4.7	5.9	5.5

The uncertainty of measurement is $\pm 5.0^\circ\text{C}$

The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of $k=2$, which unless specifically stated otherwise, provides a confidence level of 95%, in accordance with the Guide to the Uncertainty in Measurement, first edition, 1993.

Comments: The oven was calibrated on site in the Resistivity Laboratory, in the ERIC building at Rosherville.
The circulating oven was on during the calibration, and access to the heated volume was through the door. The positions indicated are in the same sequence as those indicated on the sample holders.

Calibrated by : M Mathieson


Technical Signatory

Figure 2-3: Ash resistivity test oven calibration certificate (page 2)

2.3.3 Plant design and operating conditions

The power plant is designed to operate at a specific range, based on the coal quality, i.e. a coal analysis that determines the ESP loading. The tables below stipulate the design data for the power station.

Table 2-2: ESP design data

Design data	1 to 6
Boiler rating (at 97% MCR)	618 MW
Efficiency (at 97% MCR) for all fields in service	99.88%
Parallel casings	4
Plate height	14.8 m
Plate length	5 m
Lanes per filter casing	46
Pitch between lanes	300 mm
Fields in series per pass	7
Plate area (total)	190624 m ²
Flow area	817 m ²
Specific collecting area	191.6 s/m
Number of TR sets	28
Aspect ratio	2.4

The operating design base for the ESP at 97% maximum continuous rating is presented in Table 2-3. These parameters are evaluated when conducting the ESP efficiency test in order to determine the process operating conditions of the boiler unit in comparison to the design base. Any deviation from the design base can affect the ESP collection efficiency negatively.

Table 2-3: Operating design data (at 97% MCR)

Parameter	Value
Gas volume flow rate	995 Am ³ /s
Gas temperature	130 deg C
Dust burden	30 g/Am ³
Treatment time	28.7 s
Migration velocity (Deutsch)	35.1 mm/s
Migration velocity (modified Deutsch, k=0.5)	236.1 mm/s
Gas velocity at electrodes	1.2 m/s

The design base coal specification is listed in Table 2-4. Coal samples were taken during ESP efficiency testing. The obtained coal analysis results were analysed and compared to the specified design base. The coal quality is expected to have deteriorated from when the power station was commissioned and therefore emissions may be high due to the poor quality coal.

Table 2-4: Design coal specification

COAL SPECIFICATION (original design coal specification)		
Moisture free values for:		
Volatile content	21.7%	
Ash content	35%	
Fixed carbon	43%	
As received values:		
Surface moisture	4.5%	
Inherent moisture	6%	
Sulphur	1.0%	
Nett C.V		16.8 MJ/kg

The design base ash elementary analysis is as follows:

Table 2-5: Ash elementary analysis

ASH SPECIFICATION	AVERAGE
Silicon (as SiO ₂)	49.1 %
Aluminium (as Al ₂ O ₃)	4.9 %
Iron (as Fe ₂ O ₃)	31.5 %
Titanium (as TiO ₂)	1.7 %
Phosphorus (as P ₂ O ₅)	5.1 %
Calcium (as CaO)	1.3 %
Magnesium (as MgO)	0.3 %
Sodium (as Na ₂ O)	0.2 %
Potassium (as K ₂ O)	0.3 %
Sulphur (as SO ₃)	3.9%
Loss on ignition	1.7%

2.3.4 Academic

The project is an industrial pilot project to investigate two types of technologies in order to quantify whether an emission reduction can be achieved by implementing new technology to the existing ESP system. Therefore, the project is not a purely academic research project; however, the necessary academic criteria will be fulfilled by conducting a literature review on the industrial system and studying the engineering governing fundamental equations to merge the industrial aspects of the project as well as academic requirements.

2.4 Verification and validation

The verification and validation of the work presented in this dissertation are to be conducted in the following manner.

2.4.1 Ash resistivity profiling

Laboratory experiments shall be conducted to quantify the fly ash resistivity profile from samples obtained from the selected power station. An ash resistivity test oven will be used to conduct ash resistivity measurements. This test oven was built in accordance with IEEE testing standard (Std. 548-1984) [6]. The test procedure is outlined in IEEE Standard 548-1984, which provides a detailed and comprehensive guideline for the measurement and reporting of fly ash resistivity.

Prior to testing, each respective sample is sent out for analysis, elementary analysis and particle size distribution. The tests conducted are accredited by SANAS, but there are also some that are not accredited, but recognised by Eskom. Refer to Table 2-7:

Table 2-6: Ash analysis test procedures

Elements	Standard	Accreditation
Analytical moisture	Eskom method no. 103 Rev 2	Accredited
Ash	Eskom method no. 101 Rev 1	Accredited
Volatile	Eskom method no. 102 Rev 1	Accredited
Fixed carbon	Eskom method no. 128 Rev 1	Accredited
Carbon, nitrogen, hydrogen	Eskom method no. 118 Rev 1	Not accredited
Carbonate	Eskom method no. 100	Not accredited
Total sulphur	Eskom method no. 104 Rev 1	Accredited
Oxygen (difference)	Eskom method no. 132 Rev 1	Not accredited
Gross calorific value	Eskom method no. 105 Rev 1	Accredited
Element analysis	Eskom method no. 121	Not accredited

Additionally, a particle size distribution analysis is conducted along with ash elementary analysis. Moreover, a common sample from a different power plant is utilized throughout the testing period in order to ensure repeatability of results. These results are to be validated by further comparing them with those obtained from samples sent for testing to the Southern Research Institute (SRI) and results/data received from earlier tests conducted for the respective power station.

2.4.2 Plant measurements

Practical measurements shall be conducted to evaluate the electrical operating parameters of the two technologies in question. The tests will be conducted for similar operating conditions in terms boiler load, gas volume flow rate and back-end temperatures. The measurements to be conducted are defined in the project scope (section 1.4).

Tests will need to be conducted on a live plant and in accordance with the safety standards of the Occupational Health and Safety Act no. 85 of 1993 [28]. Work conducted on high voltage will be conducted in accordance with the operating regulations for high voltage systems.

Plant measurements are conducted in accordance with the following metering standards: Eskom Metering Strategy; 240-48907866 and Metering and Measurement Systems for Power Stations in Generation Standard; 240-56359083 [26, 27]. These standards are implemented in the capturing of the data to be utilised for the analysis of the plant performance of the ESP system for this project.

Extensive measurements are conducted when conducting the ESP efficiency tests. The efficiency tests are conducted by an independent, accredited contractor and these tests are performed in accordance with the following stack emissions standards:

- Particulate emission measurements were carried out employing procedures and equipment that comply with the requirements of EN 13284-1 [29, 30]. The VDI correlation procedure was followed in the determination of the linear regression of the correlation spot check [31, 32].
- Manual stack emission monitoring performance standard for organisations, Environment Agency November 2011 Version 7.2 [33]

On-load particulate emissions monitoring and reporting are conducted in accordance with the following standards:

- Standard for emissions monitoring and reporting: 474-187 [34]
- Particulate emissions are regulated by Department of Environmental Affairs (DEA) to the *Employer's* Power Stations (Air Quality Act, 2004 [Act 39/2004], [2])

The obtained data is submitted to Eskom, and the analysis and interpretation of the data remain Eskom's responsibility.

2.5 Assumptions and exclusions

This project is an industrial pilot study of the industrial application of a new technology to evaluate its effectiveness and to quantify the emission reduction in comparison to the existing technology. Therefore, the project will not be conducted in a controlled environment, but rather at a live operational plant. Results obtained will be primarily dependent on the

operating process and condition of the plant that will vary; however, regardless of how the process conditions may vary, the particulate emissions must not exceed the set CAPCO limit.

The plant processes will not be explicitly analysed – only those that have a direct influence on the performance of the ESP. Plant parameters include the ESP inlet temperature, boiler load, rapping philosophy and SO₃ conditioning plant performance, as well as dosing rate of 18 ppm into the flue gas stream. All 28 ESP fields are to be in operation for the duration of the testing period. In cases where certain fields experience faults, the plant will off-load in other fields to repair whatever fault may be present.

2.6. Social and environmental impact

South Africa is presently experiencing an energy crisis in terms of electricity supply, as there are no reserves. This has resulted in systematic load shedding in the past in order not to overload the supply grid. This has a negative effect on the general population and industrial business.

Power plant operations fall under the jurisdiction of the independent regulator Chief Air Pollution Control Officer (CAPCO) appointed by the Department of Environmental Affairs and Tourism. The emission limit has been set at 100 mg/Nm³ per stack monthly limit, with continuous hourly opacity measurements. Failure to operate within the set limits is taken as non-compliance and results in incurred load losses, as well as de-loading of a boiler resulting in a reduced power output to reduce the emission levels [1, 2].

The project might have a negative impact on society as the installation of the HFPS technology requires the unit to reduce load; 118 MW for a period of five weeks. This can further put strain on the power supply grid, resulting in load shedding. However, the success of this project has significant social benefits, as it results in a reduction in particulate emissions into the atmosphere. The success and sustainability of this project –, running units continuously at full load with stack emissions below regulation limits – can see other power plants implementing similar technologies to improve and enhance ESP performance and reduce particulate emissions. Additionally, power plants would limit the amount of load losses as a result of high stack emissions and will thereby improve the availability of the power plant to produce the required load.

2.7. Summary

The work presented in this dissertation involves laboratory testing of collected ash samples from a power station as well as the industrial testing of two power supply technologies on an existing ESP plant. The technical and academic constraints of the project were identified and discussed in this chapter, ensuring that the work presented meets both industrial and academic requirements.

The relevant standards and procedures implemented in the execution of the project were also discussed in this chapter. The referencing of the standards for the project is done in order to ensure that the obtained results are validated by approved standards. These processes and standards must be adhered to in conducting resistivity testing as well as ESP efficiency testing for the two power supply technologies in order to ensure that the obtained results are accurate. This will assist in ensuring that the set-out project objectives are met, as the collected data is in accordance with approved standards.

The social and environmental impact of the project was discussed, i.e. the project has significant and practical outcomes for an existing industrial problem. Particulate emissions have a great impact on social and environmental issues in society as Eskom strives to produce electricity while complying with the air quality particulate emission limits. This project aims at ensuring that Eskom meets its commitment to limiting gaseous emissions.

CHAPTER 3: LITERATURE STUDY

The purpose of this chapter is to provide a literature review of published work that relate to electrostatic precipitators. The literature review focuses on fly ash resistivity and ESP fundamental operations and the influence of different power supply technologies. The most recent publications are reviewed in order to ensure that there is no duplication of work in this dissertation.

3.1 Introduction

This section discusses the fundamentals of fly ash resistivity testing and profiling and the operating principles of an electrostatic precipitators. The importance and influence of resistivity on the ESP operation are discussed. The process of conducting ash resistivity testing is described with reference to the respective IEEE guidelines and the manner in which they are quantified.

The fundamental operating principles of electrostatic precipitators are reviewed, with an emphasis of on Deutch's [5] efficiency formula and the influence of power input into the ESP on Deutch's equation. The electrical circuitry of the different power supply technologies is also discussed to evaluate the differences in operating principles.

3.2 Overview

The main, focus of this chapter is to research the principles of ash resistivity profiling and operations of ESPs. The research is mainly focused on the influence of ash resistivity and the influence of power supply on the collection efficiency of ESPs. The overview of the literature study is illustrated in Figure 3-1. The figure illustrates the process flow of the project, with two legs, i.e. resistivity testing and ESP testing. Resistivity profiling is conducted by means of laboratory testing and the obtained results link into the ESP operation and collections efficiency with regard to the ability of the dust particles to attain charge for effective collection. The second leg of the project deals with the fundamental operation of an ESP plant, and the influence electrical power has on the operation and collection efficiency of the system. This operation is influenced by the resistivity of the fly ash being collected in other process conditions. These factors are discussed in detail; Figure 3-1 only highlights the key points of discussion that are covered by the chapter.

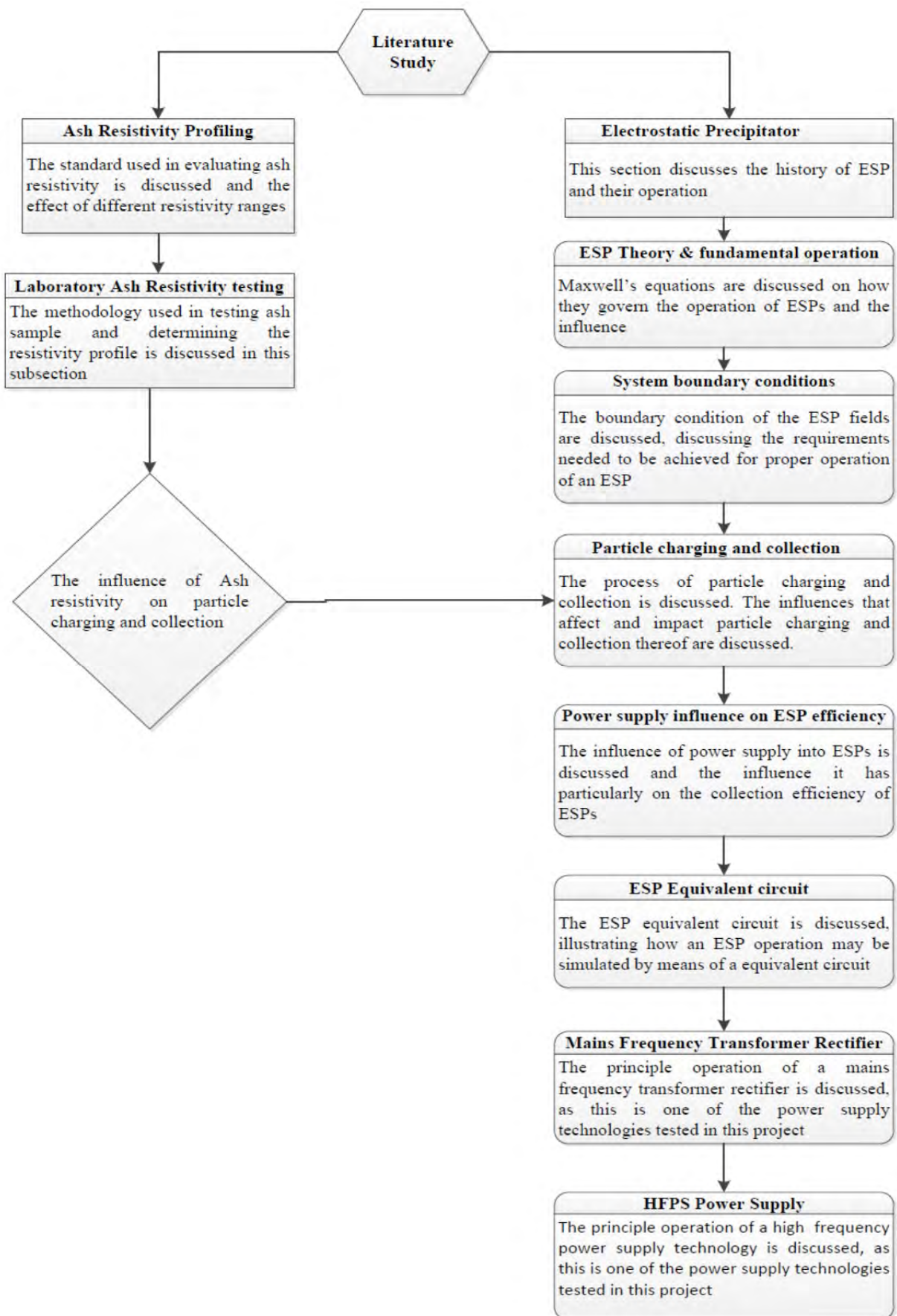


Figure 3-1: Literature study overview

3.3 Ash resistivity profiling

Fly ash resistivity is one of primary parameters in the operation of electrostatic precipitators, and is measured as a function of temperature. It influences the charging and collection of fly ash particles, the ability for ash particulates to acquire and retain charge, until the particulate is effectively collected. Resistivity is defined as the electrical resistance of a 1cm cube of material, expressed in ohm-cm and it is dependent on a wide range of factors [6, 18]. The Southern Research Institute [3, 4] is at the forefront in conducting research on the measuring of ash resistivity. IEEE Standard 548-1984 [6] was published as a guideline on conducting ash resistivity measurements on ash in a controlled laboratory environment.

As discussed in section 1.1.1 of this dissertation, the dust particles to be captured need to acquire charge and retain this charge long enough for the dust particles to be deflected on to the collector plate. Fly ash resistivity influences this vital process of collection, inside the ESP. There is a range of factors that influence resistivity, ranging from temperature, particle size, conditioning of the dust particles, as well as elementary composition, among other factors. These factors are influenced by the type/quality of coal and the operating conditions of the ESP.

Fly ash resistivity can be effectively categorised into three ranges when it comes to the operation of electrostatic precipitators. The respective ranges in which fly ash resistivity may fall under are low, optimum and high resistivity ranges. The different resistivity ranges have different influences on the performance of an ESP. Ideally, ESP must operate with fly ash resistivity that falls within the optimum range; however, this is not always the case. Precipitators are designed to operate within a certain range of resistivity for optimum dust collection, i.e. 1×10^8 to 1×10^{11} Ω -cm [5, 10, 57]; therefore, any resistivity outside this range results in ineffective collection. In this range, the dust is conductive enough that charge does not build-up in the collected dust layer and insulates the collecting plate, and therefore collected with high efficiency.

Low resistivity ash has a resistivity value that is below 1×10^8 Ω -cm. Low resistivity ash is difficult to precipitate and collect in an ESP. The main reason for the difficulty in the collection of low resistivity ash is the dust particle having to retain charge and stay ionised long enough to be collected. The dust particles easily attain charge from the ionised area between the inter-electrode spacing; however, once the charge is attained, it rapidly and easily loses the charge before it can be collected. The charged particles need to retain a

charge long enough to migrate to the collector plate and the loss of charge results in particle re-entrainment. When the particle loses its charge, it is repelled and re-enters the flue gas stream; this is called re-entrainment. This process occurs several times, and as a result, the dust particles end up not being captured. Therefore, these particles will exit the precipitator into the atmosphere. The main reason for low resistivity ash has been found to be due to the presence of metallic particles and un-burnt carbon in ash. Particle re-entrainment occurs when particles re-enter the flue gas stream and are not collected, exiting into the atmosphere [3-5, 10, 63].

High resistivity ash has resistivity values above $1 \times 10^{11} \Omega\text{-cm}$ and similarly has a negative impact on ESP performance. High resistivity ash is as a result of low-grade coal that has reduced-sulphur content. This property makes it difficult for the ash particle to attain charge in the ionisation region, making it difficult to collect and reduces the collection efficiency of ESP significantly. The performance of the ESP is further affected by high resistivity ash, as it results in high spark rates with the ESPs. High spark rates within an ESP are undesired, as this leads to a reduction in the power input into to ESP fields – more specifically if the control system is on continuous. Pulsing; which is the intermediate energising of the field with pulses, has proven to be the most effective way of collecting high resistivity ash. However, the most common and effective way of treating high resistivity ash is by means of SO_3 conditioning. SO_3 conditioning refers to the injection SO_3 into the flue gas stream; the SO_3 covers the surface with the dust particles and as a result reduces the surface resistivity of the particles [3-5, 10, 62].

Fly ash resistivity testing was developed in early 1970 by the Southern Research Institute [3]. The Southern Research Institute's work mainly focused on quantifying the fly ash resistivity of different industries. The research also investigated the relationship between resistivity and the associated chemical composition of the dust burden, as well as different particle sizes of dust burden, and temperature effects [3, 4, 62, 63]. The majority of authors on electrostatic precipitator make reference the Southern Research Institute's findings.

Resistivity is measured as a function of temperature and therefore boiler back-end temperatures will influence the measured resistivity. High temperatures result in an increase in the migration velocity of the charged dust particles [3, 4]. As stipulated in Chapter 2, section 2.3.3, ESPs are designed to operate within a range of certain of parameters, which includes temperature, which influences the migration velocity.

3.3.1 Laboratory ash resistivity testing

IEEE Standard 548-1981 was published as a guideline on conducting ash resistivity measurements on ash [6]. A resistivity test oven was built as specified by the above-mentioned standard. Figure 3-2 illustrates an ash resistivity test, set-up.

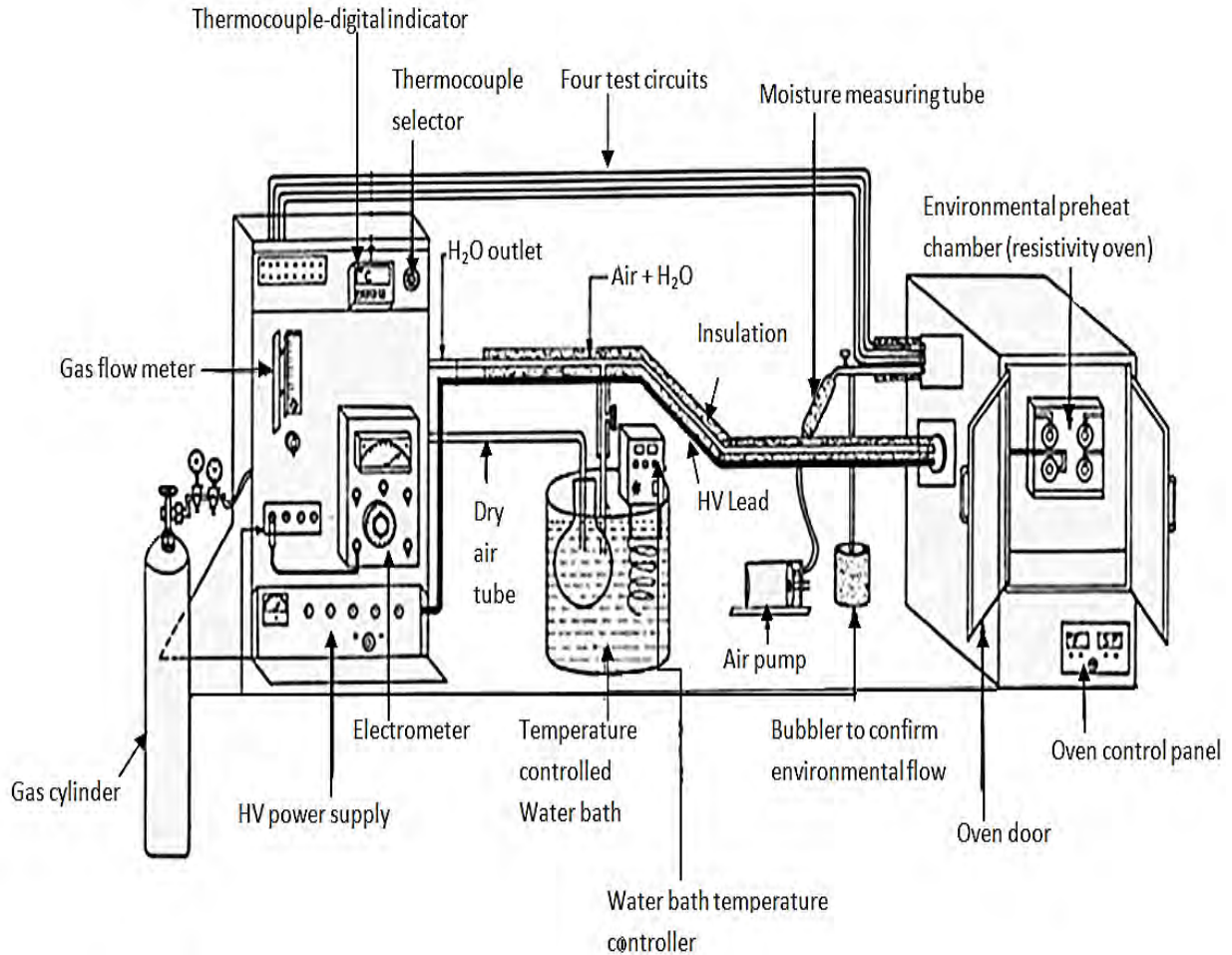


Figure 3-2: Fly ash resistivity test set-up apparatus [59]

The resistivity oven is designed to function in temperature ranges of 50 to 350°C. Resistivity measurements can be conducted by making use of two techniques, i.e. ascending temperature or descending temperature. For the purpose of this project, only the descending method is utilised, as ESP dust particles are most likely to experience descending temperatures during operation. The test oven is also set up and consists of a gas cylinder, which introduces the respective gases found inside an ESP. The four gases are carbon dioxide (CO₂), oxygen (O₂), nitrogen (N₂) and sulphur dioxide (SO₂). Trace heating on the gas lines is also implemented, in order to prevent moisture from forming inside the piping. Moisture is introduced into the test oven to condition the ash sample being tested [3, 4, 6, 59].

Testing is conducted by making use of a disc-to-disc electrode arrangement, with the discharge disc being the same size as the collector disc. The ash sample is evenly placed on the collecting disc of the test instrument and subsequently placed in an ash resistivity oven. The ash resistivity oven is constructed such that operating conditions are simulated in terms of moisture, nitrogen, oxygen and temperature conditions that the ash is exposed to during normal operating conditions during plant operations. Figure 3-3 illustrates the test cell arrangement inside the test oven.

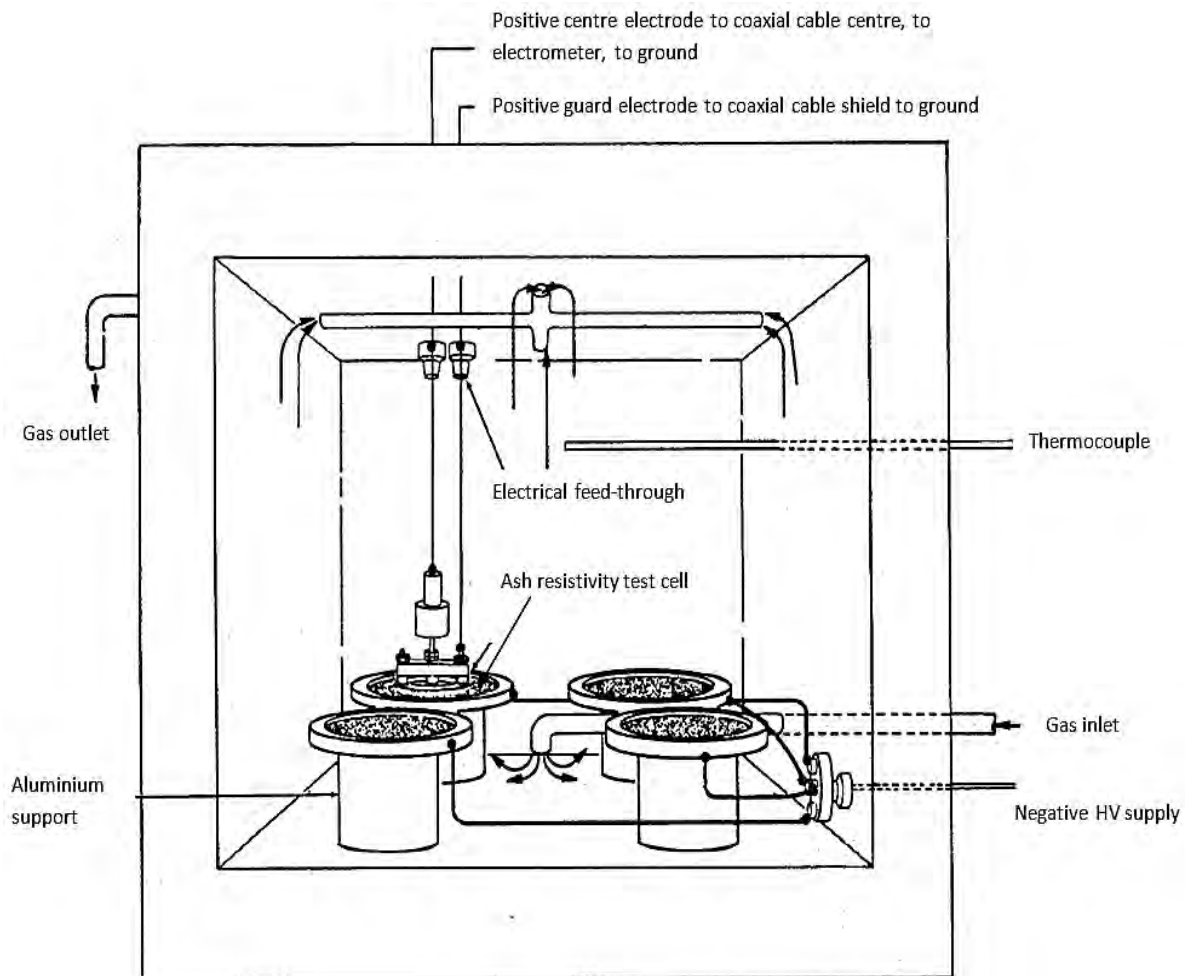


Figure 3-3: Illustration test electrode arrangement inside the oven chamber [6]

The analysed ash sample is evenly distributed on the collector electrode and placed inside the resistivity oven. The test oven makes use of four test electrodes and are used to conduct simultaneous resistivity measurements of one ash sample as shown in Figure 8. In testing the ash resistivity, current and voltage measurements will be measured from the disc-to-disc test instrument. A voltage supply is connected to the test instrument, while the collector plate of the system is earthed. Two measurement techniques are implemented to determine the

resistivity of an ash sample, i.e. constant voltage and mixed voltage measurements. A constant voltage measurement is conducted for voltages of 2 kV and 4 kV with a variation of temperature (descending). Current readings are recorded for every temperature set point for the respective voltages at a defined moisture content. Mixed voltage measurements are conducted at a constant temperature and moisture content, and the applied voltage is incremented until the electrical breakdown point of the dust layer is reached (spark-over). Current readings are recorded for every voltage increment [6, 62].

The recorded voltages and current measurements are used to determine the resistivity profile of the ash sample. In the mixed voltage/mixed-kV method, the measured voltage prior to spark-over is used to determine the ash resistivity as it represents the breakdown voltage of the dust layer. The formula used to determine the resistivity of a dust layer is expressed as follows:

$$\rho_{ash} = \frac{R \cdot A}{l} \quad (3 - 1)$$

Whereby; (ρ_{ash}) is the resistivity of the dust layer that will be measured in *ohm-cm*, and is expressed as a function of the resistance (R) obtained by making use of Ohm's law ($R = \frac{V}{I}$), the area (A) of the collector plate/disc and the accumulated dust layer thickness (l). Substituting Ohm's law for resistance into equation 2 gives the following expression:

$$\rho_{ash} = \frac{(\frac{\Delta V}{i}) \cdot A}{l} = \frac{\Delta V \cdot A}{i \cdot l} \quad (3 - 2)$$

Therefore, the dust layer resistivity can be expressed as a function of the voltage drop (ΔV) across the dust layer and the measured current through the dust layer. The voltage drop is obtained by means of interpolation between the V-I curve of a clean disc-to-disc characterisation and that of a system with dust burden. It is noted that in cases of high or low resistivity it can happen that the voltage drop obtained through interpolating the V-I curves can be a negative value. In such cases, the V-I curve procedure may be used to calculate the resistivity. These principals of determining ash resistivity by analysing the V-I curves of the ESP system can be adapted and applied to a live operation plant. As previously stated, no work has ever been published in South Africa indicating the resistivity profile of South African fly ash. However, the profile of the resistivity graph as a shape is well documented, as illustrated in Figure 3-4:

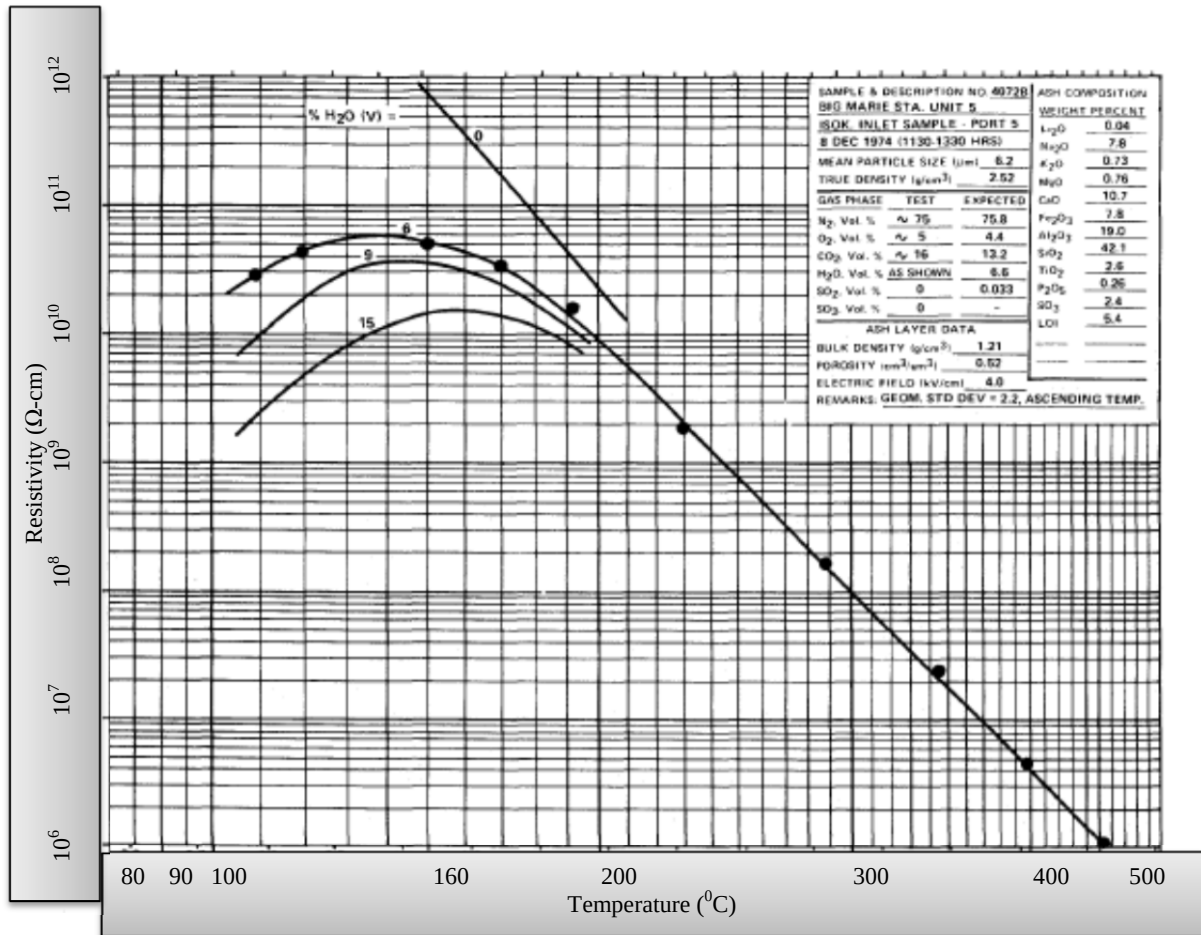


Figure 3-4: Resistivity vs. temperature standard profile (x & y axis edited) [6]

Theoretical ash resistivity predictive models were also derived by the Southern Research Institute, in particular by Dr Roy Bickelhaupt in the early 1970s [63]. Extensive research was conducted through laboratory experiments in order to characterise the resistivity of ash. This led to the development of predictive ash resistivity models based on the chemical composition of the ash. Four models were developed, each building on the previous model based on changes in the ash conditioning. Extensive laboratory experiments were conducted that correlated the ash resistivity to the gas composition of the ash samples. It was found that the resistivity is primarily dependent on the molecular concentration of lithium, sodium, magnesium, calcium and iron present in the ash, and therefore Li, Na, Fe, Ca and Mg are the atomic concentrations of the respective elements in ash. Ultimate and ash mineral analysis is used to determine the fly ash constituent concentration [22, 63]. However, the model is based on American coal and ash, and is not covered in this project.

3.4 Electrostatic precipitators

Electrostatic precipitation is a widely used technology for effective dust or fume collection from industrial furnaces. Dust collection is achieved by making use of electric forces to

collect suspended dust particles in the flue gas streams. This collection process is achieved through a three-step process: i.) The first stage of the process involves the charging of the suspended dust particle; ii.) the second stage of the process is the collection of the charged particles; and iii.) the third and final stage involves the removal of the collected/precipitated material for disposal or other use. This technology has been in existence as early as 1906, with research conducted by Dr Frederick G Cottrell and WA Schmidt. Dr FG Cottrell was an American born professor in chemistry and is credited as being the inventor of the first electrostatic precipitator [5, 10, 57].

Cottrell's method was to apply electric forces for dust collection. This process proved more effective compared to the conventional mechanical process. By applying an electric field to a dust stream, the separation forces from the electric field act on the dust particles and therefore separation occurs on even the finest of particles in a range of submicron in size for effective collection [5, 10]. The only challenge that hampered the development of ESPs for industrial application at the time was that of the electrical power supply for the ESP fields. The strength of the electric field/forces exerted on the particles to ensure particle separation is dependent on the power supply to the ESP. At the time when Cottrell developed the ESP concept the only power supply available to produce the required corona was spark coils. Cottrell subsequently invented a pubescent electrode, which was made from semiconducting fibrous material providing a small discharge point, thereby creating a corona field. This provided a relatively uniform corona discharge covering the surfaces of the entire electrode, given the limited power supply of the spark coils [5, 10, 57].

The development of synchronous mechanical rectifiers and high-voltage AC transformers at the time (1906) that could achieve voltages as high as 15 kV assisted Cottrell, as these could supply a high enough voltage, ensuring that electrodes could produce a stronger and sustained corona field. His experiments/work also proved that negative corona were more effective compared to positive corona when implemented in dust particle collection, as the breakdown voltage required to induce corona is far less than of a positive corona. The success of Cottrell's experiments allowed for industrial application.

The first ESP plant was built and installed in a smelter plant for the removal of sulphuric acid fumes. The project was deemed an exceptional success. Figure 3-5 illustrates Cottrell's first industrial ESP design making use of a high-voltage transformer and a synchronous rectifier.

Cottrell's ESP design was further improved by one of his former students, a chemical engineer named Mr Walter A Schmidt.

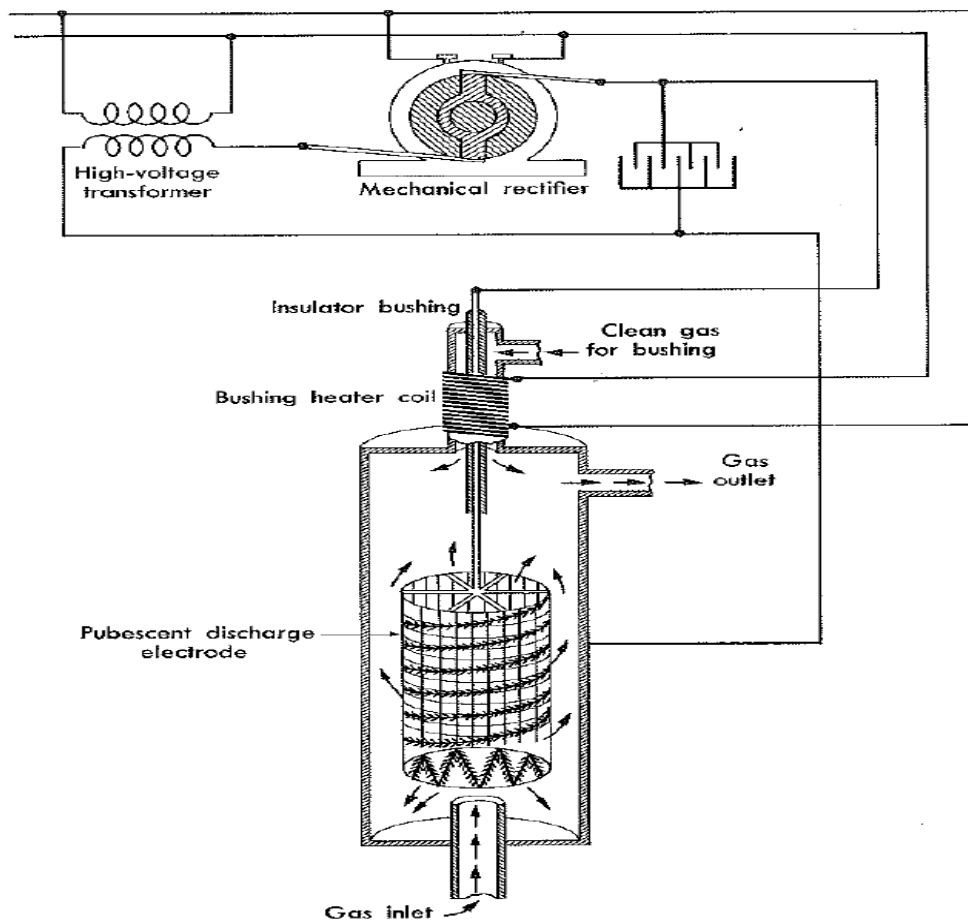


Figure 3-5: Cottrell's electrostatic precipitator (patent 895,729 (1908)) [5]

ESPs were mainly installed in smelter plants; however, air-pollution laws were not only limited to the smelting industry. There was a need to expand this technology into different industries such as cement manufacturers. The cement manufacturing industry also needed to reduce their air pollutants and therefore had to implement ESPs. However, unlike smelters, which produce sulphuric acid fumes, cement manufacturers mainly emitted lime and clay dust particles. This posed a new challenge in implementing ESPs in this industry, as the emitted particles had varying range particle sizes in large quantities and at different temperatures [5, 10].

Walter Schmidt in 1910 undertook the challenge to modify Cottrell's original ESP design to accommodate the conditions found in the cement industry for effective dust collection. Schmidt effectively redesigned Cottrell's pubescent electrode and implemented a fine-wire corona discharge electrode. The fine-wire electrode produced stronger corona discharge,

capable of charging the wide range of sized particles for collection. His work also included research on collecting electrodes, different methods of supplying high potential currents, the effects of sectionalising precipitators and methods of controlling the re-entrainment of collected dust. Schmidt's work allowed ESPs to be successfully implemented in a wide range of industries with particulate emission problems. The growth of coal-fired power utilities also resulted in ESPs being installed in the early 1920s and has since been the preferred gas cleaning process by the majority of power utilities [5, 10, 57, 64].

In the 1950s and 1960s, electricity demand grew, and consequently resulted in the construction of coal-fired power stations with bigger boilers to meet demand. The increase in boiler sizes stimulated a technological growth of electrostatic precipitators in order to accommodate the quantity of ash produced. Therefore, bigger and more efficient ESPs were required with collection efficiency in the range of 94 to 98%. The dust burdened is extracted from the furnace by means of a suction action achieved by a motor, such that the dust burden exits the boiler furnace, passing through the electrostatic precipitator, and is finally exhausted out into the atmosphere through a chimney (also known as a smoke stack) open to the atmosphere at a high altitude. Dr Harry White [5] through his research institute pioneered the technological advancement required to achieve high collection efficiency for ESP performance installed in power utilities. Figure 14 illustrates the combustion process for a typical coal-fired power utility making use of ESPs to clean the dust burden.

Dr H White's work resulted in a number of changes from the earlier designs by Cottrell and Schmidt, due to the availability of advanced technologies at the time. The power supply was modified thereby changing the mechanical synchronous rectifier with solid-state rectifiers. This modification made it possible to house the rectifier and the high-voltage transformer in the same oil-filled tank. The different coal qualities posed another challenge as poor quality coal with high ash content/low sulphur characteristics resulted in high ash resistivity, making it difficult for collection. Other effects that influenced the performance of the ESPs were boiler back-end temperatures. The temperature in which the dust burden exits the boiler/furnace is the same as when it enters the electrostatic precipitators. It was observed that low back-end temperatures resulted in a major reduction of the ash resistivity, thereby affecting the collection efficiency of the ESPs. Further advancements that were made in order to improve the collection efficiency of ESPs included the scattering of collecting fields thereby introducing further challenges of gas flow distribution and temperature patterns at the

inlet of the ESPs. These conditions are still present today and still affect the collection efficiency of the currently installed ESPs.

This highlights the complexity of electrostatic precipitators and their efficiency being dependent on a number of factors ranging from the electrical aspect to the mechanical fluid dynamic aspect and chemical composition of the collected dust burden. This project focuses on the power supply aspect of ESP and how it can further improve ESP performance.

3.4.1 ESP theory and fundamental operation

Electrostatic precipitators make use of high voltage DC to ionise and collect dust particles by means of a corona discharge. Industrial ESPs mainly make use of negative corona as the breakdown voltage required to induce ionisation is far less than of a positive corona. A corona discharge is established within the vicinity of the discharge electrode, creating an ionisation region within the inter-electrode space through which a flue gas stream has to pass [35]. Figure 3-6 illustrates the electrical circuitry representation of an ESP field.

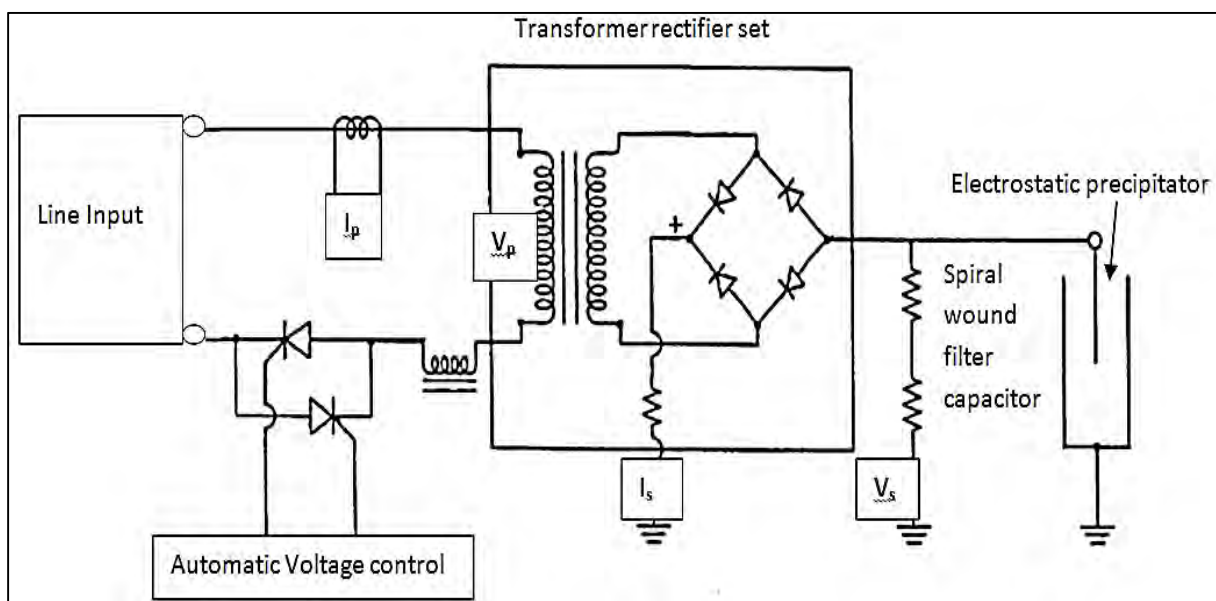


Figure 3-6: Electrical circuitry configuration of an ESP field (modified) [25]

The collector plates/electrode of the ESP are effectively grounded, while the discharge electrode is connected to the power supply output. When energised, the discharge electrode becomes the point source of corona ionisation and an electric field is established as illustrated in the figure below (Figure 3-7).

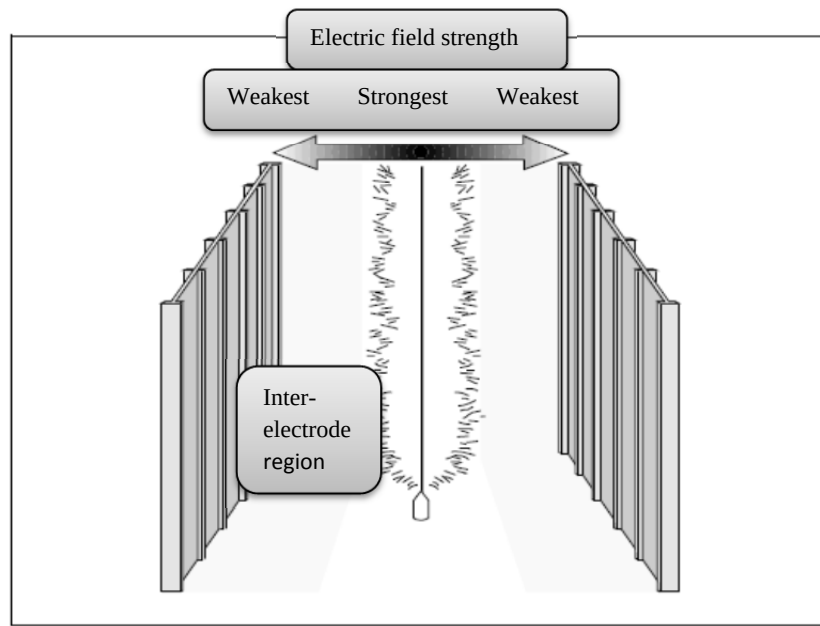


Figure 3-7: ESP Electric field graphical representation [57]

Figure 3-7 illustrates a graphic representation of an electric field formed on the surface of an ESP discharge electrode. The formed electric field and its distribution can be expressed by Maxwell's equations. Maxwell's equations can be used to express and evaluate the formation of corona and electric field distribution in an ESP. The solution to these fundamental equations determines the operating electrical parameters of an ESP [18, 38-40]. A corona current discharge establishes an ionised region within the vicinity of the discharge electrode. In addition, the applied high DC voltage establishes an electric field within the inter-electrode spacing arrangement, repelling the charged particles for capture.

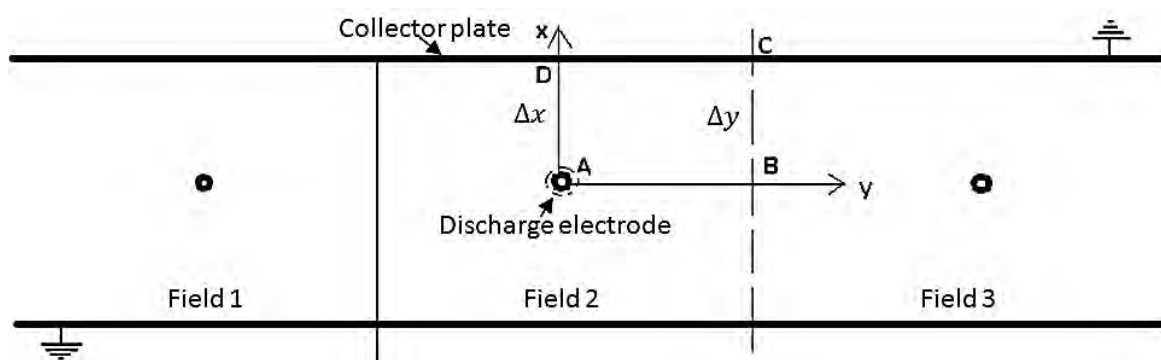


Figure 3-8: ESP field illustration

Figure 3-8 illustrates a conventional duct-type field electrode arrangement comprising a number of discharge electrodes hanging vertically between collector electrodes. An industrial ESP can have a number of fields in series and in parallel with one another – all fields have their own independent power supplies. This arrangement ensures efficient and effective

particulate collection. Industrial plants make use of multiple field arrangements as it results in a higher average electric field throughout the entire casing near the collector plates as compared to one field system [43]. The presence of electric fields near the collector plates is imperative for effective dust burden collection.

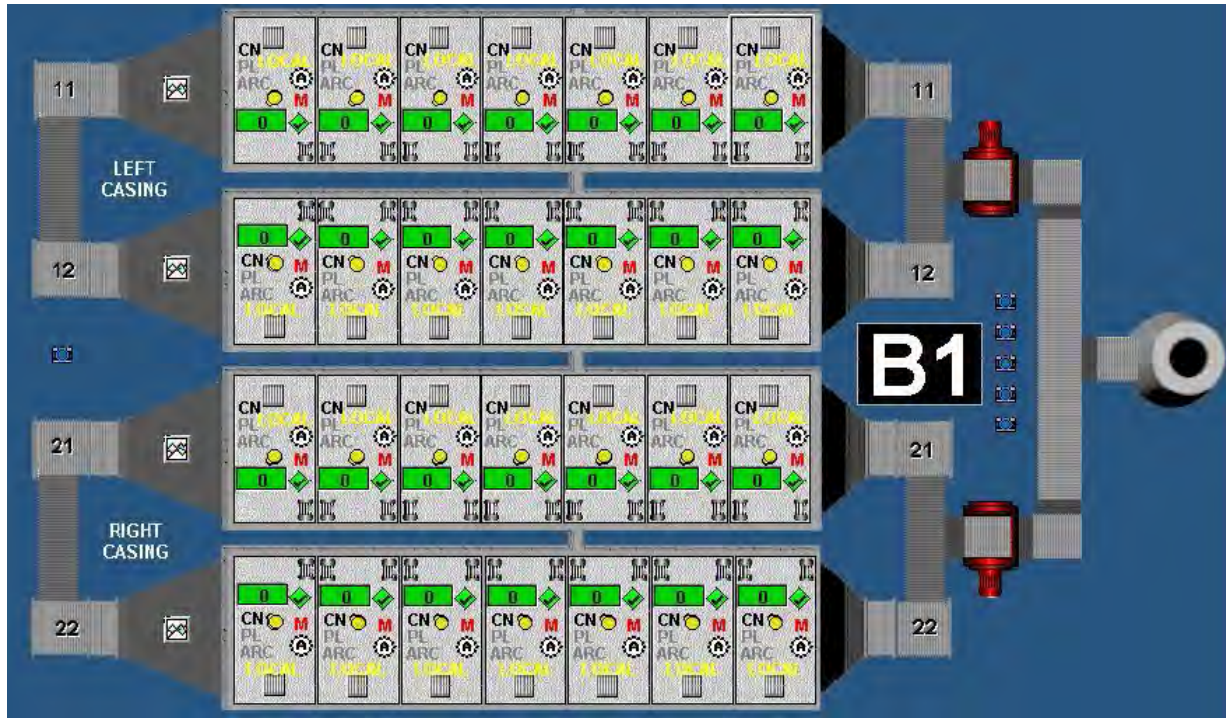


Figure 3-9: ESP field and casing arrangement

The larger the number of fields in series, the more effective the collect of particulates, as each field has a certain and optimum collection efficiency, with the front fields known to collect most of the dust burden and the back-end field collecting the finer particles. In the case of the selected power station, it has six production units (boilers) with a production capacity of 618 MW each. Each unit is equipped with its own ESP plant, with four parallel gas passes (referred to as casing in this report) and each casing has seven (7) fields in a row. Figures 3 to 9 are print screens of the control system for the ESP plant, illustrating the field arrangement of a unit.

The applied high DC voltage sets up an electric field in the space surrounding the discharge electrode. The resultant electric field strength acts as a force that deflects charged particles toward the collector plate. The direction of the electric field at any point is the direction of the force exerted on a charged body within the vicinity of the electric field [35]. The established electric field by the discharge electrode results in a surface charge on the discharge electrode. The surface charge builds up with an increase in the applied voltage and eventually fills the

inter-electrode space. The charge in the inter-electrode spacing, known as space charge density, relates to the electric field as formulated by Gauss's law [15-16, 18-20, 41]. Gauss's law, equation (1), formulates the electric field in point form as a function of the space charge density.

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad (3 - 3)$$

Where, ρ is the charge density (Cm^{-3}) and ϵ_0 is dielectric constant and is valid for most of the gases found in the operation of precipitators. The solution for a wire-to-plate arrangement is somewhat complex but is simplified by assuming that the current is small.

Townsend theorised that when a uniform electric field is applied, ionisation takes place such that it results in the growth of the electron current as a function of the distance covered by the electric field [40]. An electrostatic precipitator is similar to a Townsend discharge chamber, which induces avalanche ionisation by means of a uniform electric field in a gas-filled chamber. Therefore, the electric field is expressed as a function of the displacement within the inter-electrode spacing. Equation 3 is a point form representation of the electric field distribution as a function of displacement across the inter-electrode spacing. This implies that the space charge density will also vary with displacement, as it is dependent on the varying electric field. Figure 3-10 illustrates a top view of a single field arrangement with the discharge electrode located in the centre of the collector plates.

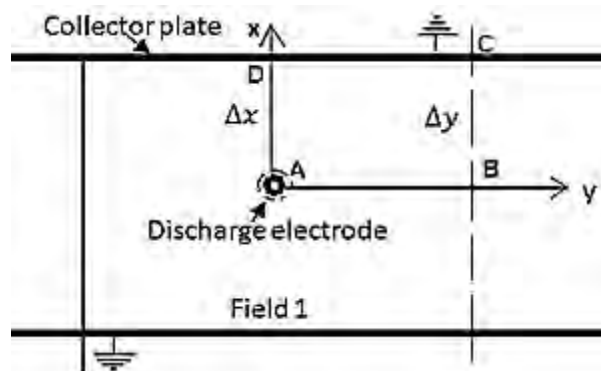


Figure 3-10: Representation of a single field ESP electrode arrangement

The ionisation process is initiated by a corona discharge in the inter-electrode spacing from the active electrode, ionising the immediate vicinity closest to the discharge. The ionisation region is characterised by the product of the electric field strength and the resultant space charge density. The resultant current density due to the presence of the electric field and its

resultant space charge for an isotropic conducting system can be expressed in point form of Ohm's law.

Consequently, the current density is expressed as follows:

$$\vec{J} = \rho e(\mu \vec{E} + u) \cong \rho e \mu \vec{E} \quad (3 - 4)$$

The current density is expressed as a function of the displacement varying electric field, the space charge density (ρ), ion mobility μ , the transport gas velocity (u) and e being the electrical charge unit. The transport gas velocity is found to be two orders lower in magnitude than the ion mobility and therefore is neglected from the equation. Ion mobility is approximately $1.82 \times 10^{-4} \text{ m}^2/\text{Vs}$, as experimentally measured by Lawless and Spark [47] in a flue gas condition simulation.

The steady state current continuity expression, describing how the space charge density varies with a change in time, is defined as follows:

$$\frac{\partial \rho}{\partial t} + \frac{1}{e} \vec{\nabla} \cdot \vec{J} = 0 \quad (3 - 5)$$

Maxwell's governing equation (combination of Gauss's law equation 3-3, current continuity equation 4 and current density equations equation 3-5) for the electric field due to charge density in relation to Poisson's in point form can be used to describe an ESP's operation. This is true under steady-state conditions and in the absence of magnetic effects.

Substituting equation 3-4 into 3-5 gives the expression for the change in charge density along the electric field line:

$$\left(\frac{d\rho}{dt} \right)_{field\ line} = \frac{\partial \rho}{\partial t} + \mu \vec{E} \cdot \vec{\nabla} \rho \quad (3 - 6)$$

Applying Poisson, the equation is simplified under steady state conditions such that it is expressed as:

$$(d\rho)_{field\ line} = - \frac{\rho^2}{\epsilon_0 \vec{E}} dx \quad (3 - 7)$$

x is the curvilinear co-ordinate that is along the electric field line and therefore it is noted that under steady state, the charge density is independent of ion mobility μ . Integrating this displacement results in the following representation:

$$\frac{1}{\rho(x)} - \frac{1}{\rho(x_0)} = \frac{1}{\varepsilon_0} \int_{x_0}^x \frac{1}{E(x)} dx \quad (3 - 8)$$

The above equation is known as the ‘unipolar charge drift formula’, describing the variation in the charge density along displacement x_0 to x within the inter-electrode spacing. $\rho(x_0)$ is the charge density boundary condition; ideally, the boundary charge density is within the border of the drift and ionisation region. Nevertheless, it is typically assumed in ESP geometry that the ionisation region’s thickness is small and therefore the boundary condition will be associated with the surface of the discharge electrode [15-16, 18-20, 43].

Fundamentally, Maxwell’s equations define the governing equation for the electrical properties that characterise the operation of ESPs. In the practical sense, the electric field is established by the applied high DC voltage on the discharge electrode and is expressed as:

$$\vec{E} = -\vec{\nabla}V \quad (3 - 9)$$

Substituting eq. 3-7 into equations 3-1 and 3-2, gives expressions that relate the space charge and current density to the applied voltage:

$$\vec{\nabla}^2 V = - \frac{\rho}{\varepsilon_0} \quad (3 - 10)$$

$$\vec{J} = \rho\mu\vec{E} = -\rho\mu\vec{\nabla}V \quad (3 - 11)$$

When the high DC potential is applied, the established electric field reaches a threshold value initiating the ionisation of the gas molecules by means of electron collision resulting in an electron avalanche. The primary electron avalanche develops along the direction of the maximum electric field away from the discharge electrode. The above stated Maxwell’s equations are solved by iterative processes by making use of a finite element method based on the boundary operating condition of the ESP. Firstly, the corona onset voltage must be determined. Therefore, in defining the boundary conditions of the system to solve the fundamental Maxwell’s equation, the initiation voltage and electric field are extremely important. The governing equation can be analysed by either making use of a finite difference method (FDM) or a finite element method (FEM) [42, 46-49]. These analytical techniques have given accurate results in papers presented by the likes of E Lami *et al.* [16].

3.4.2 System boundary condition

Boundary conditions of ESPS are discussed in order to understand the system operating limits in terms of electrical parameters based on the design and operating conditions. These boundary parameters vary from the minimum and maximum required input parameters to simulate the effective operation of the system.

The electrical energy level required for effective dust particle separation from the flue gas stream must first be determined, in order to ensure that the above established electrical properties will achieve the required energy for particle separation. In the design of electrostatic precipitators, Whites [5] states that the following fundamental principles necessary for effectively determine the required electrical energy to displace dust particles. He states that Stokes' law for frictional resistance (D) of a spherical particle, which is dependent on the viscous drag of the gas (η), radius of the particle (r_p) to be ionized and the electrode drift velocity is v_d should be applied.

$$D = 6\pi\eta r_p v_d \quad (3 - 12)$$

Stokes' law for frictional resistance is evaluated to establish the minimum energy or work in joules required to move a spherical particle through distance x . Distance x is the distance the particle is required to travel to the collecting plate.

$$W = Dx \quad (3 - 13)$$

The above expression is only valid to move one dust particle and therefore the number of dust particles present in a flue gas stream for 1m^3 must be determined. The number of particles present in a flue gas stream is determined by the expression below (equation 12), which is a function of the duct particle loading C (mg/m^3) and the subsequent particle density (σ).

$$N_0 = \frac{C}{\frac{4}{3}\pi r_p^3 \sigma} \quad (3 - 14)$$

In addition, work or energy required to remove the particles present for a 1m^3 in a flue gas duct will be:

$$W_0 = WN_0 \quad (3 - 15)$$

The minimum energy required for electrical stress build-up that will result in the excitation of free electrons within the vicinity of the discharge electrode will be obtained by solving

equation 3-13. Industrial ESPs mainly make use of negative corona as the breakdown voltage required to induce ionisation is far less than of a positive corona.

There are three boundary conditions that must to be known prior to solving the governing equations, i.e. 3-1) the corona onset voltage, 3-2) the potential of the passive electrode (collector electrode), 3-3) and the resultant electric field due to the onset corona voltage. Extensive experimental work has been conducted in order obtain practical representation of these fundamental expressions for design purposes. Corona need to be induced in order to charge/ionise dust particles for collection and this is achieved by establishing an electric field. Kaptzov's [50] assumption is applied, which assumes that the corona discharge on the surface of the discharge wire is uniformly distributed. The required electric field required to produce a corona discharge sufficient to ionise the dust particles for a round wire was experimentally obtained [18], and is expressed as follows:

$$E_c = 31.02 \times 10^5 \alpha \cdot \delta \left(1 + \frac{0.0308}{\sqrt{r_w \cdot \delta}} \right) \quad (3 - 16)$$

Whereby, the electric field is expressed as a function of the wire electrode radius r_w in meters, the dimensionless surface roughness of the discharge electrode α (for a smooth wire $\alpha = 1$), δ is the relative density of air, and expressed as a function of the temperature and pressure as follows.

$$\delta = \frac{293}{(273 + T)} \cdot \frac{P}{(101325)} \quad (3 - 17)$$

The undesired consequence of having a large electric field in the inter-electrode spacing is that it may result in spark discharge. Upon applying the corona onset voltage, ionising currents will start flowing between the inter-electrode spacing ionising this vicinity such that an increase in supply voltage results in an increase in corona discharge current. However, the increase in voltage also has undesired consequences, whereby the electric field strength becomes too strong within the inter-electrode space due to increased voltage. The electric field at which sparking is observed is estimated as a function of the gas pressure (atmospheric) and the absolute temperature (kelvin), and is expressed as:

$$E_s = 6.3 \times 10^5 \left(\frac{273}{T} P \right)^{1.65} \quad (3 - 18)$$

The electrical energy required for a corona discharge breakdown is inversely proportional to the temperature within the precipitator chamber. As a result, the electric field will be limited as defined by the above expression for efficient ESP operation.

Evaluating the integral of the electric field from the active electrode to the collector plate gives an expression for the minimum required corona onset voltage (V_c). The voltage expression has a logarithmic dependence on the dimensions of the electrode and expressed below [18]:

$$V_c = E_c r_w \ln \left(\frac{d}{r_w} \right) \quad (3 - 19)$$

d is taken as inter-electrode spacing; distance from active electrode to collector plate (BC on Figure 3-10). The obtained corona onset voltage can therefore be substituted into equation 3-5 and accordingly the current density produced due to the corona onset voltage can be determined. The corona voltage and electric field parameters are strongly influenced by the inter-electrode displacement; the corona voltage and electric field will be strongest at a point where $d \cong r_w$. The ionisation process is primarily dependent on the radius of operation, i.e. displacement from the discharge electrode toward the collector plate [15, 16, 46]. The onset ionisation radius was analytically expressed by Cobine [47] as follows:

$$d = r_w + 0.3\sqrt{r_w} \quad (3 - 20)$$

It is noted that point nearest the to the discharge electrode, the electric field and corona voltage will be at their highest. The obtained potential can be, substituted into equation 3-15 to obtain the current density at the point of corona onset.

$$j = \mu \epsilon_0 \left(\frac{V^2}{L^3} \right) \quad (3 - 21)$$

The maximum current density that can be achieved is given as a function of the applied voltage (V), ion mobility ($\mu \dots m^2/volt \ sec.$) and the shortest distance (L) from discharge electrode to collecting plate. The obtained current density is subsequently substituted into equation 3-9 to obtain a new potential V , for every potential and space charge density obtained.

The boundary conditions of the precipitators system can be taken for sub-areas (fields) in a multi-wire configuration. Dirichlet and Neumann boundary conditions will be applied to the

system boundary [42, 44]. For the applied voltage, Dirichlet's boundary condition is applied such that point A in Figure 6 represents the electric potential at the discharge electrode, and therefore $V = V_0$ (Corona voltage) and $V = 0$, at the collector plate at DC as illustrated in Figure 3-11. Neumann's boundary condition is applied along the system boundary AB, BC and AD such that the applied voltage at these points will be as follows:

$$\left. \frac{\partial V}{\partial x} \right|_{AB} = \left. \frac{\partial V}{\partial y} \right|_{BC} = \left. \frac{\partial V}{\partial y} \right|_{AD} = 0 \quad (3 - 22)$$

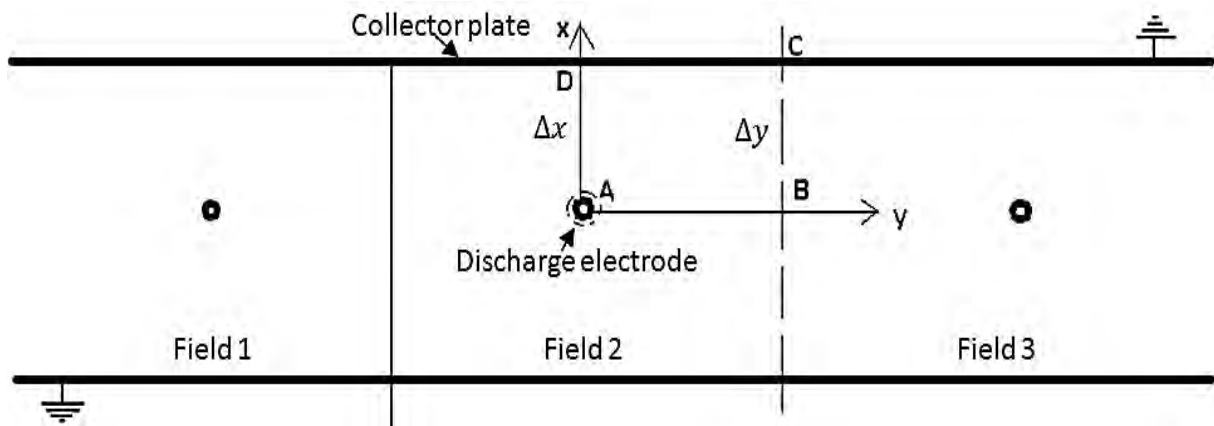


Figure 3-11: System boundary for a single field

3.4.3 Particle charging and collection

This subsection provides a brief summary of the particle charging process and discusses the importance and influence of the electrical parameters on the charging process. The electric field is an important parameter as it provides the force required to repel charged particles for collection.

Particle charging occurs in the area between the active plasma region and the passive electrode surface. In this region, there is high a concentration of free electrons, as well as negative and neutral ions that move toward the passive/collecting electrode due to the electric field force. Charging occurs because of ions attaching themselves to the surface of a particle and there are two principal phenomena that occur, i.e. diffusion- and field charging. Diffusion charging occurs due to randomly moving gas ions, described by the kinetic theory of gas, better known as Brownian motion. Diffusion charging mainly occurs on particles with a diameter less than $0.5\mu\text{m}$ and is due to thermal kinetic energy of the ions that overcome the repulsion of the ions already existing in the particle. Field charging is due to the presence of the electric field and occurs when ions follow the electric field line that is still the point of

termination on the particle; for particles greater than 2 μm [10, 18]. Intermediately sized particles acquire their charge through both charging mechanisms.

The ultraviolet radiation due to the negative corona, in what is termed the plasma region, releases electrons. The electrons are rapidly repelled from the emitting electrode (negative polarity) to produce ion pairs on impact with flue gas molecules. The particle charge is analytically expressed as follows:

$$q_p = \pi d_p^2 E \epsilon_0 \left(\frac{3\epsilon}{2 + \epsilon} \right) \quad (3 - 23)$$

The above expression can be used to determine the charge valid for particles whose diameter (d_p) by the applied electric field (E). ϵ is the dielectric constant of the particle; experimentally determined to be approximately 3.7[5, 20].

The negatively charged molecules migrate to the earthed passive electrode due to the applied electric field strength on the emitter electrode for collection. Coulomb's law states that the force acting on a particle is proportional to the product of the charge of the particle and the electric field acting on it. Therefore, the driving force that migrates the charged particles is essentially expressed as the product of the applied the electric field and the particle charge [18, 36].

$$F_E = q_p E \quad (3 - 24)$$

This driving force needs firstly to overcome the particles of which the drag force is, defined as:

$$F_d = \frac{3\pi\mu_f d_p v_e}{C_c} \quad (3 - 25)$$

For the particle to migrate to the collecting plate, $F_E \geq F_d$, such that the required particle migration/particle velocity, as a result of the electric field acting on a particle, can be expressed as a function of the electric field, the charge on the particle, and the gas viscosity ($\mu_f = 1.85 \times 10^{-5} \text{ kg/m.s}$). According to Stokes' law, equating the electric field force and the drag force component due to the electric field acting on the particle [18, 20], the particle velocity with respect to still air is expressed as:

$$v_e = \frac{C_c q_p E}{3\pi\mu_f d_p} \quad (3 - 26)$$

It is noted that the larger the electric field, the faster a particle will migrate to the collecting plate and therefore it is essential to maintain a high electric field at all times. In the expression (eq. 3-23), C_c is the Cunningham slip factor, a correction to Stokes' law, and is dimensionless. This factor is a function of the particles diameter, λ_g is the ionic mean free path and increases with an increase in particle radius [20, 41].

$$C_c = 1 + \frac{\lambda_g}{d_p} \left[2.51 + 0.80 \exp \left(\frac{0.55 d_p}{\lambda_g} \right) \right] \quad (3 - 27)$$

However, flue gas flow is turbulent within the ESP, which results in instantaneous gas velocities of the same magnitude as the particle velocities (in random directions) [18]. Therefore, the motion of particles toward the collecting plate is a statistical process and is expressed in the collection equation as:

$$N(r) = N_0(r) \exp \left(\frac{-v(r)}{v_0} \right) \quad (3 - 28)$$

The expression is a function of $N(r)$; the particle concentration of size r at the collecting zone (No./m^3), $N_0(r)$; the particle concentration of size r at the entry zone, $v(r)$; particle velocity dependent on the particle size and v_0 ; is the characteristic velocity at which the ESP has been designed for. The above collection equation needs to be averaged out for the particle size ranges that the ESP operates.

The ESP characteristic velocity is defined as a function of the volumetric gas flow rate (Q (m^3/s)) over the collection zone/plate area (A (m^2)). SCA is the specific collection area in s/m

$$v_0 = \frac{Q}{A} = \frac{1}{SCA} \quad (3 - 29)$$

Upon collection, the negatively charged molecules subsequently lose their charge on the earthed passive electrode. The collected fly ash is dislodged through a rapping process, whereby a motor-driven hammering system strikes the collector plate dislodging the collected dust depositing it into dust hoppers. The ESP collection efficiency can be expressed as a function of particle penetration, which is a fraction of particles that escape [18]. Therefore, the collection efficiency is expressed as:

$$Eff(\%) = 100(1 - p) = 100 \left(1 - \frac{\text{outlet load}}{\text{inlet load}} \right) \quad (3 - 30)$$

Where, p is the penetration and can be expressed as an exponential function of the effective migration velocity for particle ensemble and the specific collection area.

$$p = \exp(-v_e \cdot SCA) \quad (3 - 31)$$

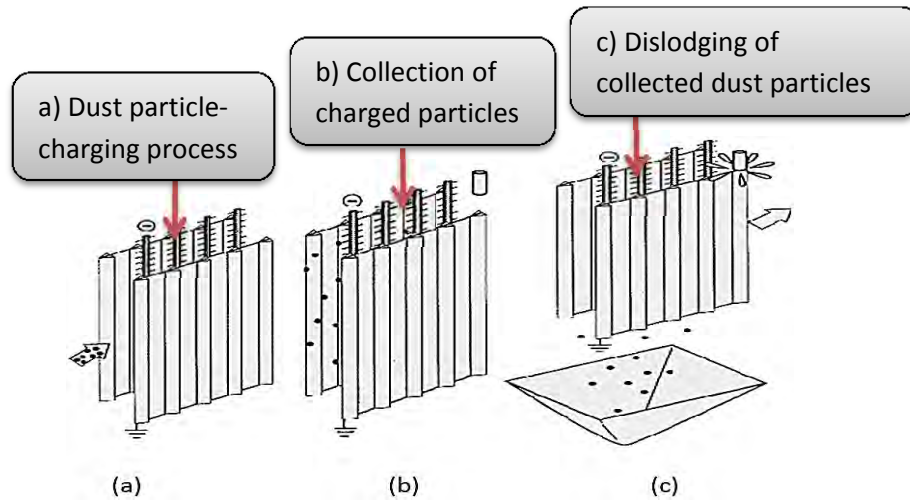


Figure 3-12: ESP fly ash collection process, (a), (b) and (c) [15].

Figure 3-12 illustrates the collection process, from flue gas entry, to charging, collection and cleaned gas exit. Typical collection efficiency as described in equation (34) takes into account the amount of flue gas entering the ESP duct as compared to that exiting.

3.4.4 Power supply influence on ESP efficiency

Deutsch's [5, 10] efficiency formula is primarily used in determining ESP collection efficiency; the efficiency is defined as a function of the migration velocity (ω), effective collection area (A) and the volumetric gas flow (Q), $e = 2.7182828$

$$\eta = 1 - e^{(-\omega \cdot (A/Q))} \quad (3 - 32)$$

Where:

$\ln$ = natural log – (base e)

Q = volumetric gas flow – (m^3/s)

A = total projected collecting electrode area – (m^2)

ω = effective particle migration velocity – (m/s)

The effective collection area of the ESP is fixed and is given by collector plate area, and therefore a redesign would be required if it were to be used to influence the efficiency. An increased volumetric flow will reduce the overall efficiency; and consequently, the particle

migration velocity is one aspect that can be evaluated to optimise the collection efficiency. The migration velocity is defined as dependent on the displacement electric field and is defined as:

$$\omega = K.E_0.E_C.a^2 \quad (3 - 33)$$

Whereby, E_0 is the charging electric field and E_C is the collection electric field, K is a constant and a is the particle radius. Eskom makes use of single stage ESPs and for these ESPs the charging and collection occurs simultaneously, therefore:

$$E_0 = E_C \quad (3 - 34)$$

Consequently, the particle migration velocity can be expressed as:

$$\omega = K.E^2.a^2 \quad (3 - 35)$$

The relationship between the electric field and the migration velocity highlights the fact that the removal and retention of the dust burden is directly dependent on the corona ionisation and the electric field strength. The velocity of a charged particle moving through an electric field is proportional to the applied voltage. Therefore, high levels of electrical energisation need to be maintained in order to improve the collection efficiency of the system.

White [5] also states that the migration velocity can be defined as a function of the corona current and the kV input with the superimposed ripple voltage, thereby further highlighting the importance of the voltage ripple effect on the collection efficiency:

$$\omega = (I_{DC}).(kV_{peak}).(kV_{DC}) \quad (3 - 36)$$

Increasing the particle migration velocity can only be achieved by increasing the electric field and this is achieved by increasing the kV input into the ESP fields. The particle size is a quantity that is process dependent and cannot be varied at will. Therefore, the migration velocity of a charged particle moving through an electric field will be proportional to the square of the applied voltage.

The operating ESP voltage level is limited by the occurrence of flashovers, and as such, the voltage is required to be high enough that some sparking occurs. Sparking results in loss of power, thereby reducing the corona input required for ionisation.

ESPs make use of DC voltage to produce corona required for particle collection, but the output voltage is not necessarily a pure DC voltage as it contains an AC component that is superimposed on the DC voltage. The AC component is produced as a result of the switching circuit utilised in the control circuit. Therefore, the output DC voltage is influenced by the produced voltage ripple. A large ripple effectively decreases the DC voltage output and the converse is also true. The removal and retention of dust particles are directly proportional to the ionisation and electric field strength. Therefore, high levels of electrical energisation need to be established and maintained within the ESP fields.

The operating DC voltage is typically limited by the sparking that occurs during operation; sparking occurs at the peak of the voltage ripple. However, the collection efficiency is at its highest when the voltage is closest to the spark inception voltage, i.e. peak voltage of the ripple. Sparking results in loss of power and as a result less power is used for the corona. Reducing the ripple to be near the spark over voltage will increase the effective DC input voltage. Increasing the DC input voltage results in an increased intensity of the effective collection electric field present in the inter-electrode spacing. The electric field repels the charged particles and the strength of the electric field will influence the particle migration velocity. Migration velocity is the velocity at which the charged particle is drawn toward the collector plate; a high migration velocity is desired for effective particle collection.

The ripple effects play a vital role in increased kV input into the ESP fields and high frequency switching appears to provide the capability to increase the kV supply to the ESP fields. The voltage ripple is inversely proportional to the switching frequency and the load capacitance. The corona current does not vary significantly in ESP operation and is a function of the change in charge with time.

$$i = \frac{dq}{dt} \quad (3 - 37)$$

Charge can be expressed as a function of capacitance and potential difference; the potential difference refers to the voltage ripple's peak-to-peak quantities as they represent the time constant for voltage decay within the capacitor.

$$q = C\Delta V \quad (3 - 38)$$

Substituting the charge function into current gives the following expression for voltage ripple:

$$i = \frac{dq}{dt} = C \frac{dV}{dt} = C \frac{\Delta V}{\Delta t} \quad (3 - 39)$$

$$\Delta V = \frac{\Delta t \cdot i}{C} \quad (3 - 40)$$

Δt is the conduction/switching time of a semiconductor and this determines the voltage ripple frequency.

$$\Delta t = \frac{1}{f} \quad (3 - 41)$$

Hence:

$$\Delta V = \frac{i}{f \cdot C} \quad (3 - 42)$$

ESPs operating with convention 50 Hz transformers will obviously have a higher voltage ripple compared to transformer sets operating at high frequency range. As previously stated, the quantity of the ripple influences the overall average DC output voltage, which is dependent on the resonance capacitance. The influence of the produce ripple can be expressed as follows:

$$V_{avg} = \sqrt{(V_{DC})^2 \pm (V_{DC} \times \%V_{ripple})^2} \quad (3 - 43)$$

Therefore, the ripple affects the ionisation and collection process as a whole.

The corona power is significantly increased by effectively reducing the voltage ripple and increasing the ESP input DC voltage. White defines the corona power as a product of the input voltage and the corona current flow.

$$W = (I_{DC}) \cdot (KV_{DC}) = (I_{DC}) \cdot \left(\frac{KV_{max-peak} + KV_{min-peak}}{2} \right) \quad (3 - 44)$$

KV_{DC} is the average DC system voltage input.

The higher the average power supply into the ESP fields, the stronger and more intense the electrostatic field will be. This means that the time needed to treat a particle can be much shorter compared to conventional transformers. This, in turn, results in more effective particle charging. The higher the electrical field strength, the faster the migration velocity (the

velocity at which the charged particle is drawn towards the collector electrode) will be. The ESP efficiency is calculated using the Deutsch formula and it is a function of the migration velocity as indicated in equation 3-35.

3.4.5 ESP equivalent circuit

The equivalent circuit of an ESP can be represented as shown in Figure 3-13. An ESP has a highly capacitive load due to the electrode arrangement, with a capacitance of between 10 nF and 200 nF, dependent on the inter-electrode spacing and volume of gas (acts as a dielectric) passing through the fields. A Zener diode is connected in parallel to the capacitor and the Zener voltage represents the corona-onset voltage required for the corona current to flow from the discharge electrode towards the collecting electrode. The corona flow V/I relationship is governed by a flat non-linear characteristics and is represented by a non-linear resistor. This relationship implies that an increase in voltage (corona voltage) will result in an increase in the corona current, although disproportionately so [66-68].

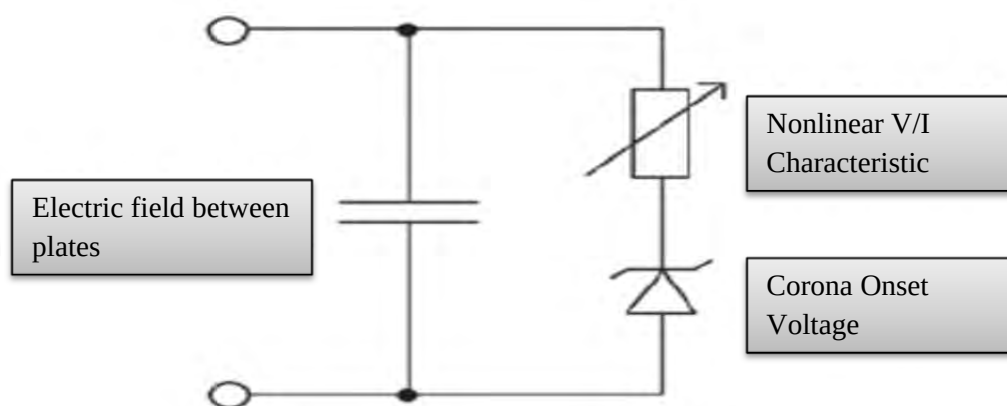


Figure 3-13: ESP electrical equivalent circuit [66]

The above equivalent circuit can be reduced to a simple RC parallel circuit for the purpose of a single operating point of an ESP power supply. The value of the resistor subsequently determines the corona current input into the ESP field and therefore, for a given output voltage, determines the power input into the field [68, 69]. The resistivity profile, as determined in this paper, can be used to represent, the non-linear resistance of the ESP fields.

3.4.6 Mains frequency transformer rectifier power supply:

A TR makes use of a single-phase supply and makes use of an anti-parallel phase angle controlled thyristor set, connected to the primary of the transformer. Each thyristor conducts for each half cycle of the supply waveform. The drawback of thyristor control is that the

maximum half cycle cannot be utilised. Thyristors can only be turned on for conduction when the voltage and current are in the same phase position, and therefore only 60% of each cycle can be utilised to conduct. A typical thyristor control transformer set will consequently only have a maximum of 6 ms of conduction time per half-cycle for a 50 Hz mains supply. Voltage distortions can be produced due to the continuous partial utilisation of the half cycles and be fed back into the mains and may damage sensitive equipment. These controls are achieved by implementing an automatic voltage controller and therefore ensures that the output of the power supply matches that of the operating condition of the ESP [5, 10, 69].

The TR set produces a high DC voltage for the power station in question, i.e. 70 kV peak, generated by the full-bridge diode rectifier connected at the output end of the set. As described, this output voltage is controlled by varying the firing angle of the anti-parallel thyristors. Figure 22 is an equivalent circuit representation of a TR set. The set has a series inductor connected to the primary also known as a choke, and the main purpose of having the choke is to limit current surges that may occur as a result of spark-over in the fields that would damage the transformer windings [5, 10, 25].

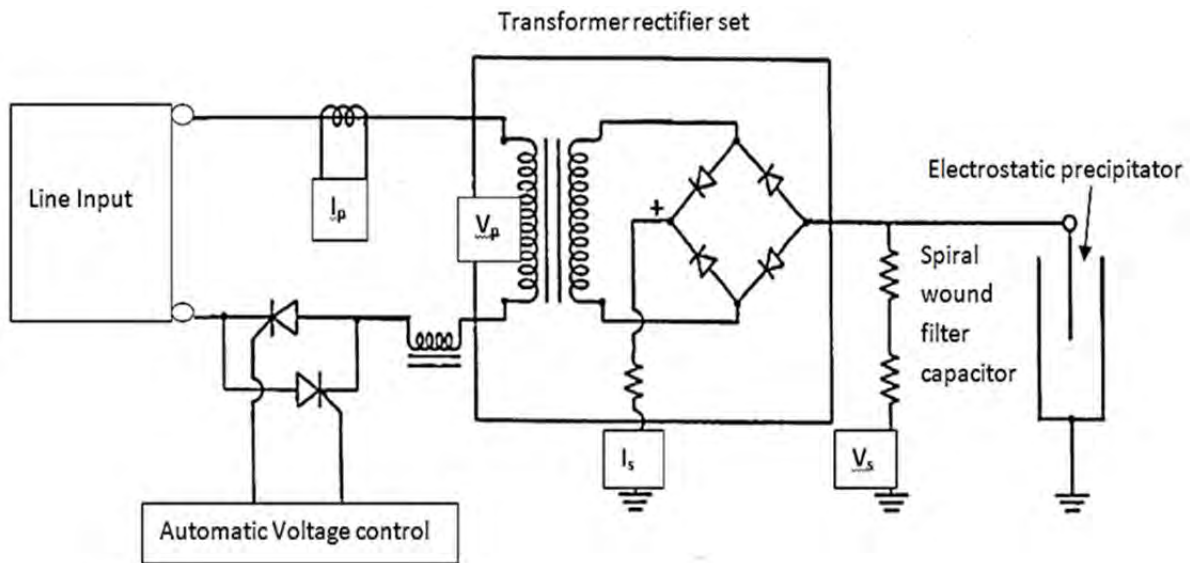


Figure 3-14: Electrical circuitry configuration of an ESP field (modified) [25]

The pulse parameters used in thyristor control is dependent on the mains frequency (50 Hz), and therefore limited in terms of optimising the switching. The limitation of the conduction cycles also limits the produced output ESP voltage. The slow switching characteristics of thyristors result in a large ripple voltage component imposed on the output voltage. The ripple is dominated by a component with twice the main's frequency. The produced current

waveform also contains a large ripple. The produced ripple has been estimated to be in the region of 30 to 40%, peak-to-peak, of the average DC voltage [5, 10, 25]. This large ripple results in a reduction in the mean operating voltage input into the ESP fields. The TR set output voltage is limited by the spark-over voltage. The peak of the ripple voltage reaches the spark-over point of the field, resulting, in a reduction in the corona current and subsequently the electric field strength of the field, affecting the collection efficiency of the field. Figure 3-15 illustrates the ripple voltage waveform of an open circuit test conducted on a main TR set.

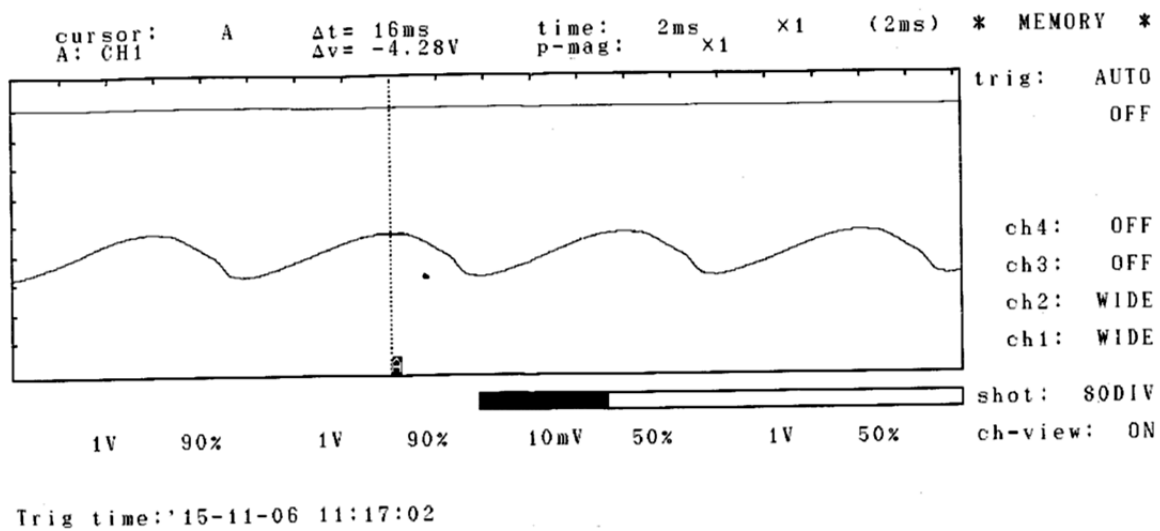


Figure 3-15: Voltage ripple waveform of a TR set open circuit test [scanned].

This above waveform is analysed in Chapter 5 of this dissertation to determine the exact ripple percentage of the TR set. The second drawback of a thyristor-controlled system is the slow response to abnormal conditions that may occur inside the ESP, namely spark-over. Excessive sparking/flashover is undesired inside an ESP; a spark rate of 50 sparks per minute can be deemed as excessive sparking; however, the spark rate is also dependent on the ESP field positions. Typically, the front fields of an ESP are, expected to spark significantly as compared to those at the back end of the ESP. Excessive sparking is undesirable as it results in the ESP's instantaneous voltage remaining low for a significant period. Excessive sparking can also lead to an arc if not extinguished adequately.

Due to the electrode configuration and dielectric strength of the flue gas, all ESPs have a certain flashover point. The spark-over point of an ESP limits the maximum operating voltage of an ESP. The operating ESP voltage needs to be as high as possible, and needs to operate without triggering a spark-over/flashover. Spark-over/flashover is the breakdown of the dielectric strength of the flue gas, resulting in a short circuit condition inside the ESP.

This interrupts the precipitation process. Whenever a spark-over occurs, it requires the ESP to reduce the power input in order to quench the spark. The slow response in the control system to quenching of the sparking is as a result of the control system's dependence on the main's frequency; the philosophy is to delay the firing of the thyristor for the subsequent half after a spark-over is detected. The average time taken to de-ionise and extinguish the spark and recover the voltage for ionisation is in the range on milliseconds. This time is considered to be too long, within the context of ESP operations, as it results in large quantities of dust particles passing through the ESP without being captured.

3.4.7 High frequency transformer power supply:

A high frequency ESP power supply makes use of a three-phase supply, which ensures a balanced load and consists of three stages in its operation. The fundamental stages of operation are an input rectification of the three-phase supply that feeds the DC link of the transformer, the rectified DC voltage is fed through a high frequency inverter/IGBT converting the DC voltage into high frequency AC, feeding the primary of the transformer, the output is a high voltage at a high frequency [10, 69]. Figure 3-16 illustrates a block diagram of the described stages of operation of a typical HFPS system.

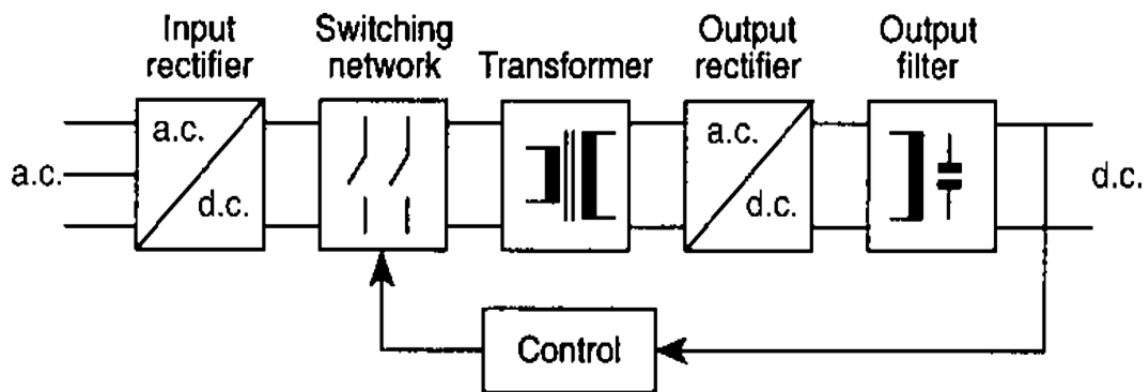


Figure 3-16: Block diagram of a HFPS system [10]

Resonant converters (LCC resonant converters) are the preferred topology when it comes to the control and switching of HFPS, as they have the ability to operate in a variety of ranges. The resonant network has the effect of filtering high harmonic voltages, resulting in a near sinusoidal current appearing at the input of the resonant network [71]. This makes it possible to enable the soft switching of the IGBTs, whereby a PWM is employed to trigger the IGBTs for either zero current crossing (ZCS) or zero voltage crossing (ZVS), reducing switching losses. The reduction in the switching losses by implementing the ZCS or ZVS switching modes results in higher switching frequencies and as a result reduces the size of the passive

components, i.e. the high voltage transformer. A series-parallel resonant converter operating above resonant is used in the operation of HFPSs, as it results in high power density and low component stresses [69 -72]. Figure 25 illustrates an electrical circuit presentation of an LCC resonant converter for an HFPS.

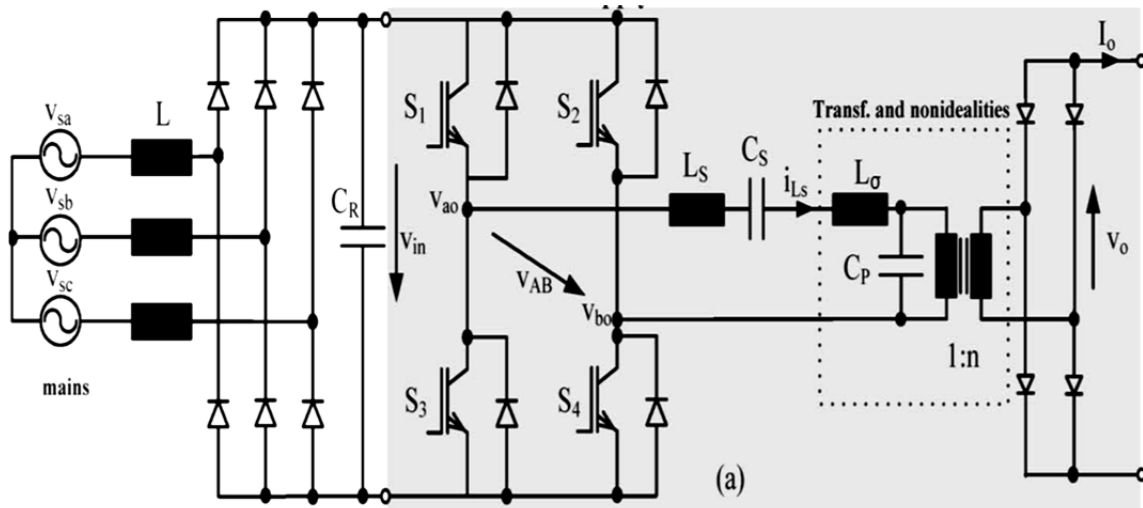


Figure 3-17: HFPS based on a LCC resonant converter [72]

The operating frequency is determined by the switching frequency IGBTs. In the case of ESP application, the switching frequency is selected to be above the resonant tank of the LCC converter. The reasons, as presented in [72], are that operating above resonance reduces the losses as the generated continuous current makes it possible to implement soft switching. Operating above resonance makes the circuit inductive and therefore the generated continuous current will lag the applied resonant tank voltage. This makes it possible to enable soft switching at turn-on; however, losses are generated at turn-off and these losses are reduced by connecting snubber capacitors across the IGBTs. Typically, the switching frequency of the HFPS inverter is above 20 kHz [10].

Due to the applied switching topology, the produced output voltage has a significantly small ripple effect imposed on it. The peak-to-peak ripple is reported to be in the range of less than 5% [5], and as a result, the operating mean voltage fed into the ESP is significantly higher than that of a conventional TR set. The capacitance of the ESP serves as a filter capacitance, filtering the ripple voltage from the transformer and smoothing out the voltage ripple. The filtering, as a result of the capacitance of the ESP fields, ensures that the precipitator voltage is a near constant DC voltage; pure DC voltage goes into the ESP fields. The power delivered into the ESP is significantly higher compared to that of a conventional mains frequency TR

set, due to the reduced voltage ripple effect, allowing the HFPS to achieve a higher voltage input into the ESP. This increased power input into the ESP can improve the collection efficiency of the ESP [5, 10, 25, 69 - 71].

The fast control topology system employed in the switching of the converter circuit enables a fast system response to any abnormal condition that may arise inside the ESP. Sparking/spark-over in an ESP is a major problem, as it requires fields to de-ionise in order to extinguish the spark. The control system allows for short de-ionisation time (spark quenching) and fast voltage recovery and therefore significantly reduces the average time in which fields are not in operation. Due to the high frequency switching, the response/recovery time of sparking is placed in the range of microseconds, whereas for conventional TR sets it is dependent on the main's frequency and can be in the range of milliseconds.

3.5 Summary

Electrostatic precipitators are complex in that their operation incorporates chemical, electrical and mechanical principles to accomplish flue dust filtration. The literature review on fly ash resistivity profiling and testing is reviewed in order to determine what work has been done and is currently being done with regard to resistivity profile and the latest findings. The testing process utilised to conduct ash resistivity profiling measurements as well as the impact of various resistivity profiles on the performance and particularly collection efficiency are discussed. This will assist in analysing the obtained data from laboratory tests and plant performance for the purpose of this project.

The history and fundamental equations of an ESP are also discussed; this gives a background and further insight into the functioning of ESP technology. Maxwell's equations that govern the operation of the ESP are discussed. The influence of ESP power supply is discussed, and provides further insight into the influence this has on the ESP and collection efficiency (Deutch's efficiency formula). The influence of power supply into ESP affects the charging of dust particles and migration velocity of charged particles. The different power supplies for ESPs are discussed along with the operational philosophies, drawbacks and advantages of each technology. These are the technologies being evaluated for the purpose of achieving the set objectives for this project.

CHAPTER 4: DESIGN

The purpose of this chapter is to provide the design process undertaken to obtain the set-out project objectives. The apparatus and process followed in conducting the measurement of the ash resistivity profiling are discussed. The process of testing of the two power supply technologies on the effect on emissions is also discussed in this chapter.

4.1 Introduction

The following chapter details the process followed in obtaining results for this project in order to achieve the set-out objectives as stipulated in Chapter 1. The design chapter is essentially sub-divided into two sub-sections, i.e. ash resistivity profiling and power supply technology application in ESPs.

4.2 Overview

Figure 5-1 illustrates the chapter overview in terms of the content discussed in this chapter. The figure shows the two legs of the project, resistivity testing and ESP power supply analysis. The process and procedure used in conducting the ash resistivity testing and data capturing are discussed – from the sampling process, ash elementary analysis to the testing of the ash samples. The procedure for conducting the testing is discussed, as well as the validation and verification process of the obtained results.

The power supply analysis of the ESP is discussed by firstly outlining the mechanical scope of work executed on the ESP and the SO₃ during an outage on the unit in which tests were conducted. The project timeline is discussed, giving a clear schedule as to when activities were planned for the execution of the project. Plant performance monitoring and testing for each power supply technology is discussed, as well as the validation and verification process implemented to ensure that the obtained results are accurate.

A conclusion section combines and discusses the two legs of the project as discussed in the chapter. The conclusion also discusses the outcome of the project as a whole, with the installation of the HFPS on the unit as pilot project.

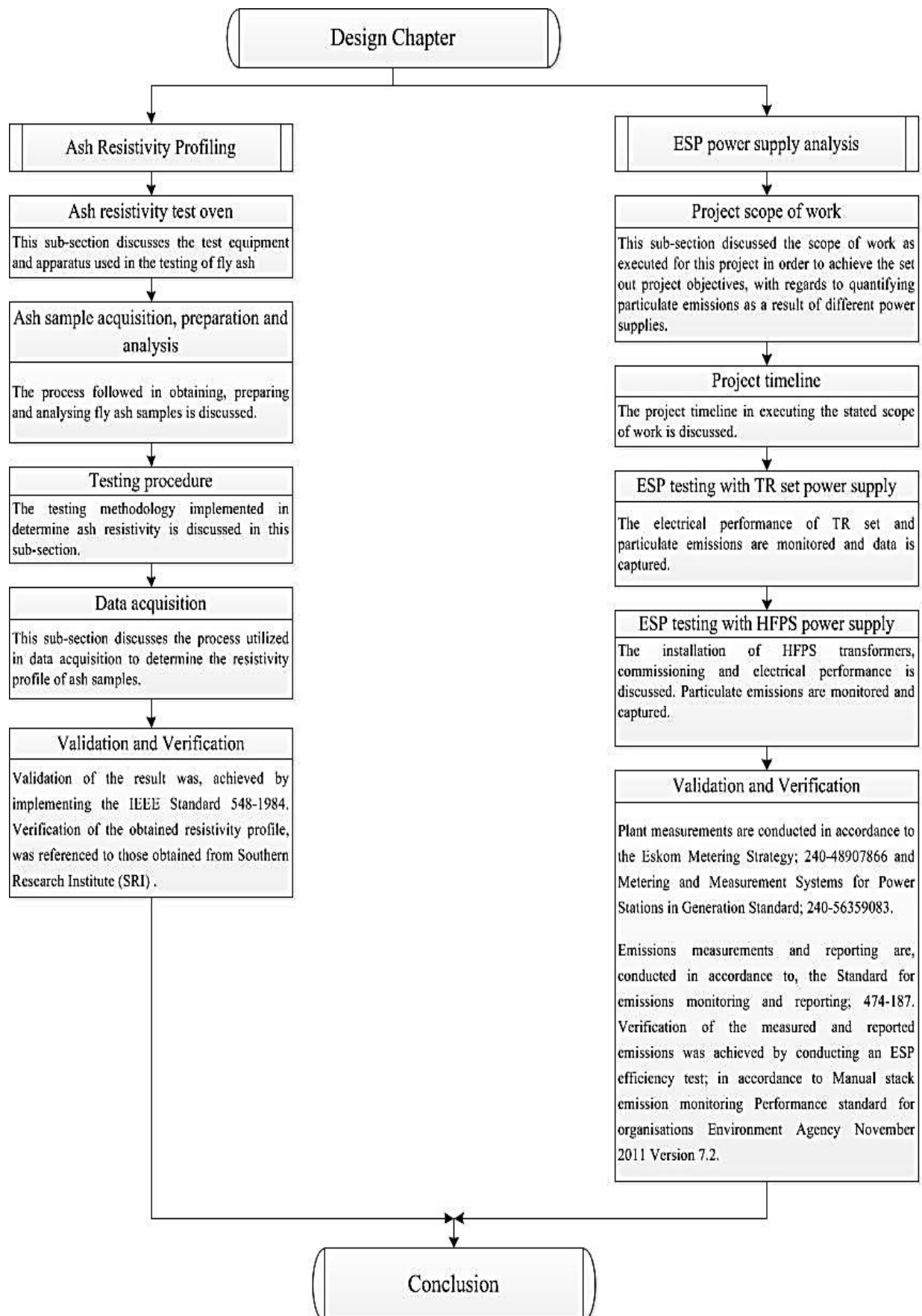


Figure 4-1: Chapter 4 overview

4.3 Ash resistivity profiling

Ash resistivity testing was conducted at Eskom's research, test and development (R,T&D) facilities located in Germiston. As previously stated in Chapter 2 of this dissertation, Eskom has built and commissioned an ash resistivity test oven. The test oven was built in accordance with the IEEE Standard 548-1984.

Ash samples were taken from a power plant, whose coal is solely supplied from an open cast mine. The equipment and process implemented in determining ash resistivity profile are discussed in this sub-section of the chapter.

4.3.1 Ash resistivity test oven

The ash resistivity test oven utilised to conduct ash resistivity measurements and profiling is shown in Figure 4-2. The resistivity oven comprises a test oven with test electrodes connected to the control panel and gas line piping.

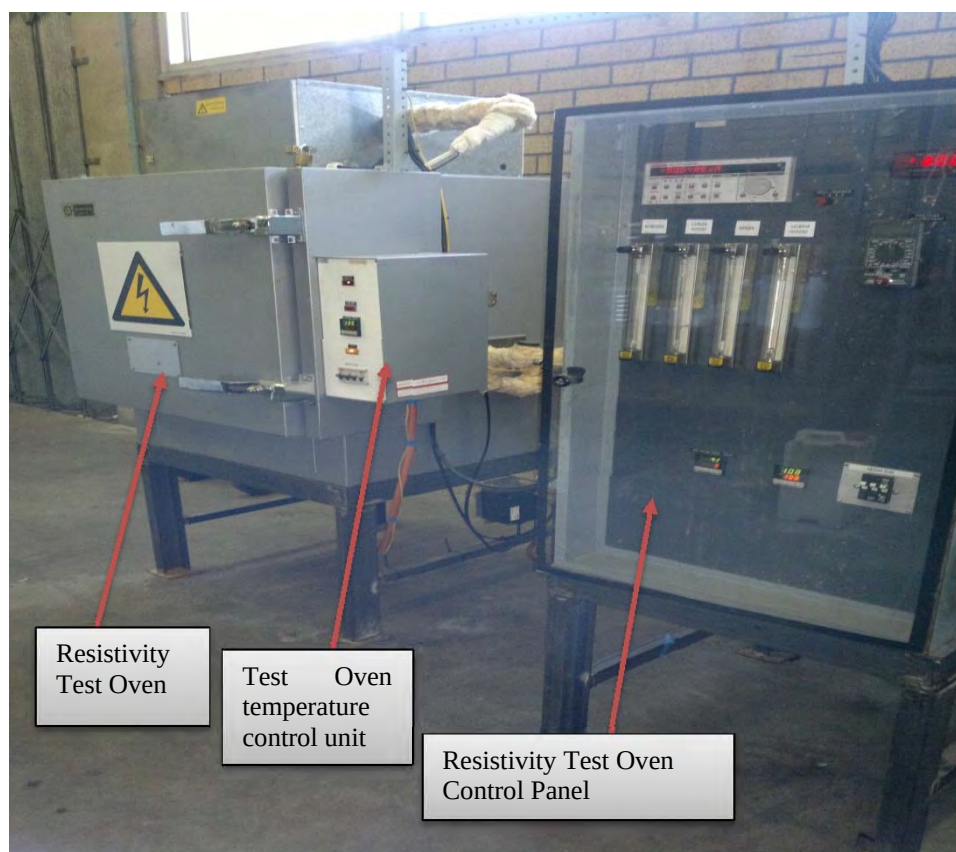


Figure 4-2: Ash resistivity test oven system

The test oven houses test electrodes utilised in conducting resistivity testing along with gas inlet piping and an extraction fan. The test oven has an adjustable temperature control system, making it possible to conduct resistivity measurement for either temperature increments or

decrements. ESPs typically experience a temperature drop across the fields; from the boiler inlet to the smoke stack and, therefore, for this project, the resistivity profile is conducted making use of the temperature decrement methodology. Figure 4-3 shows the internals of a resistivity test oven used in conducting resistivity testing for this project.

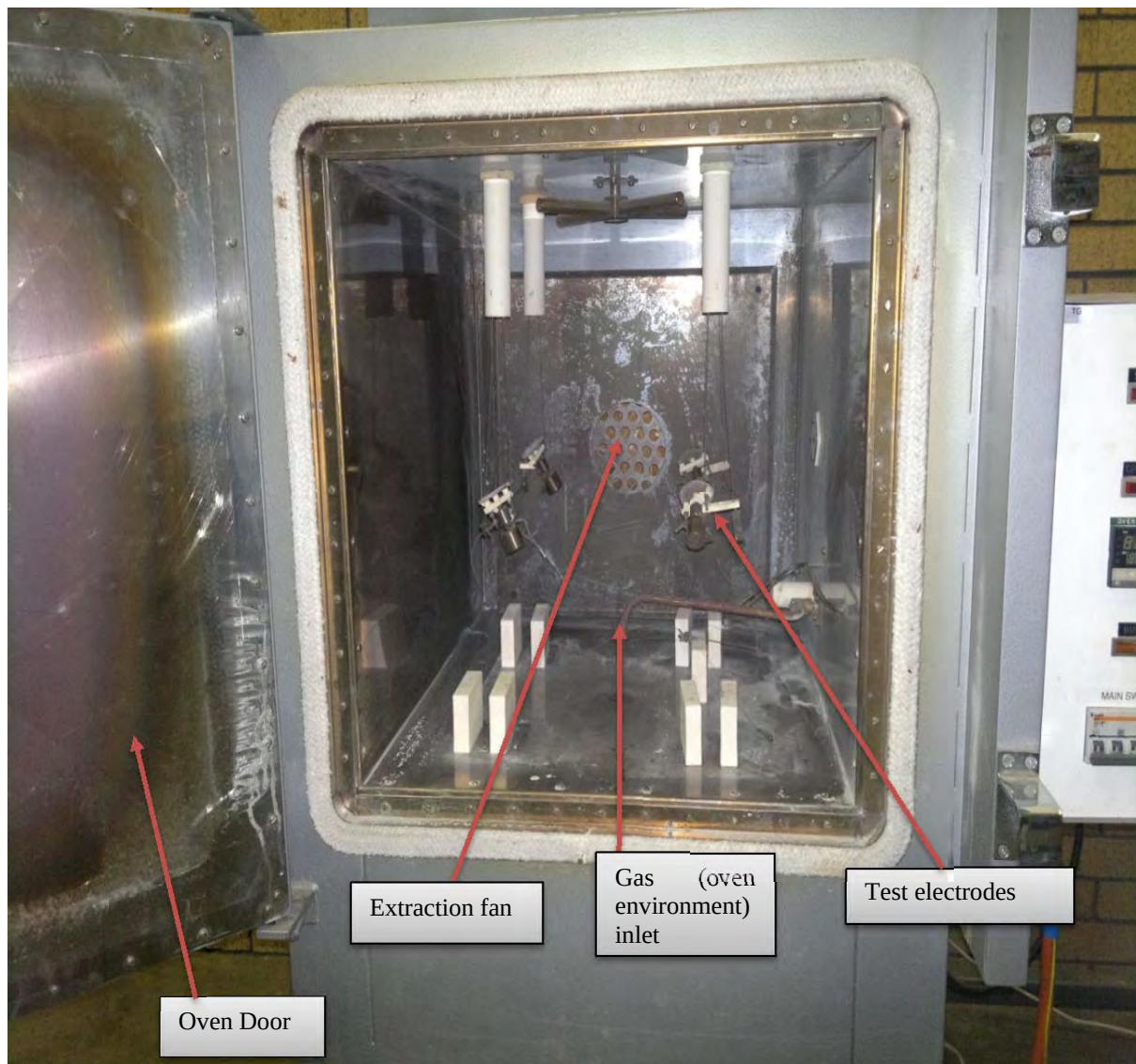


Figure 4-3: Resistivity test oven internal

The test cells are prepared and placed inside the test oven as seen in Figure 4-3. The test cells consist of two plates (electrodes); the bottom plate holds the ash sample and is connected to ground and the top plate is placed on top of the ash sample and has voltage applied to it. This testing configuration is similar to the operation of an ESP, where one collector electrode is grounded and voltage is applied to a discharged electrode across a flue gas flow.

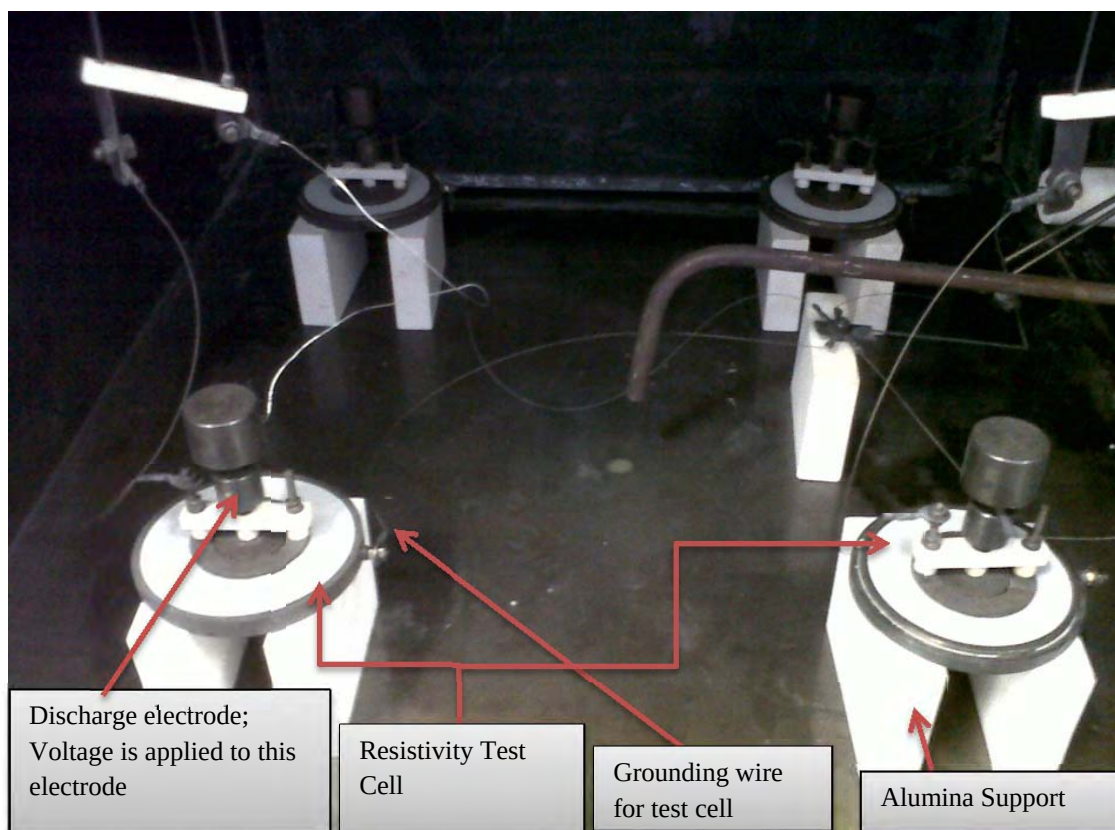


Figure 4-4: Resistivity testing cells arrangement

The resistivity test oven is constructed to mimic industrial ESP operations, and most important are the gas composition and respective flow rates. The four gases utilised in testing are nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), and sulphur dioxide (SO_2). The following gases and flow rates are used for testing conditions:

Table 4-1: Oven parameters for gases and heat tracer tests

Gas Constituent	Oven (test) environment
N_2	8.7 ml/min, dry basis
O_2	4.6 ml/min, dry basis
CO_2	13.8 ml/min, dry basis
H_2O	Based on respective P/S
Heat Tracer	On - 100°C

The moisture in gas content in the oven gas environment has a significant influence on the ash resistivity, more so than the gas components. Because some of the gas components are electropositive and others electronegative, the flue gas environment is replicated as closely as reasonably practical in the resistivity oven environment. However, no tests have been conducted to determine the sensitivities of changes to the gas compositions.

The IEEE Standard 548-1984 recommends moisture contents of 0%, 6%, 9% and 15%. Eskom's measured moistures in flue gases ranged from 3.4 to 9.1%, with an average of 6.5%. Generally, the typical moistures ranged from 6 to 8%. For this reason, the ranges of moistures for Eskom's ash resistivity measurements are conducted at 0%, 3%, 7% and 13%. The three moistures would allow for more complete measurement in line with the intentions of the IEEE Standard 548-1984 and interpolation of moistures either side of 7%.



Figure 4-5: Gas cylinder and piping into the test oven

Figures 4-6 shows the trace heating system installed on the gas lines and to the oven. Trace heating was installed according to the specifications shown in Table 4-1. Trace heating is implemented and controlled at approximately 100°C to ensure that the moisturised gases do not condense, forming moisture inside the gas pipes.

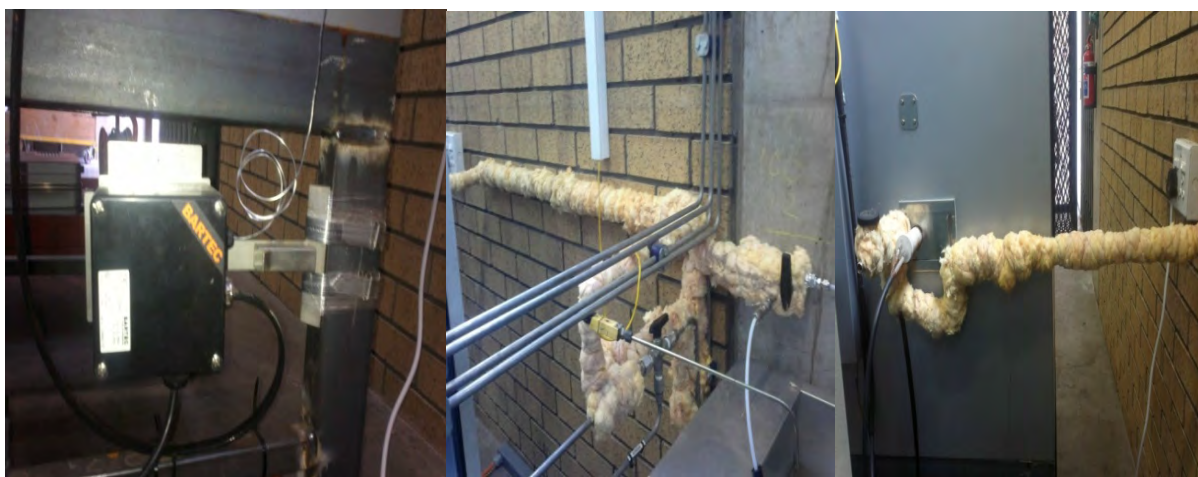


Figure 4-6: Trace heating system

The trace heating specifications are given in Table 4-1:

Table 4-2: Trace heating system specification

1) TECHNICAL SPECIFICATION

ITEM	TECHNICAL SPECIFICATION	CIRCUIT 1
1,1	PIPE DIAMETER (inch)	3/8
1,2	TOTAL LENGTH OF PIPE (m)	7
1,3	No. OF PUMPS	NA
1,4	No. OF VALVES	Na
1,5	THERMAL INSULATION THICKNESS (mm)	25
1,6	THERMAL INSULATION TYPE	Fibre Glass wool
1,7	THERMAL INSULATION K FACTOR (W/m°C)	0.038
1,9	MAINTAIN TEMPERATURE	± 100 °C
1,10	MINIMUM AMBIENT TEMPERATURE (°C)	2 °C
1,11	VOLTAGE (Volts)	230
1,12	LOAD (Watts per meter	± 98 watts @ 0°C
1,13	ELEMENT LENGTH (m)	± 8
1,14	ELEMENT SHEATH	Fluoropolymer
1,17	NUMBER OF ELEMENT RUNS ON PIPEWORK	1:1
1,18	CONTROL	Thermostat
1,19	ELEMENT RESISTANCE (Ohms)	See Test Sheets

4.3.2 Sample preparation

Grab samples of fly ash were taken from the power station from ESP dust hoppers. The bulk fly ash sample is then mixed and subdivided with a rotary sample splitter to obtain smaller representative samples for the different analyses, such as chemical, particle size distribution, and particle density analyses. The ash sample was subsequently sieved using a 180 µm sieve. This is done in order to remove any foreign matter that may be present in the ash samples. This was conducted as per IEEE Standard 548-1984; the un-sieved ash was used for the chemical, particle size distribution, and particle density analyses.

4.3.3 Ash elementary analysis

The ash elemental composition was determined by x-ray fluorescence (XRF) spectroscopy. With elemental analyses, the elements are reported as stable oxides, which do not necessarily reflect the actual compounds that do occur. For example, sulphur is reported as SO₃ (a gas), but occurs as a sulphate or organic.

Note: XRF is not suitable for sodium (Na) and lithium (Li), and therefore atomic absorption (AA) or induction coupled plasma mass spectrometer (ICP-MS) spectroscopy is used for these two elements.

4.3.4 Test cell preparation

Figure 4-8 shows what the test cell dish looks like; this dish is the one that holds the ash samples during the testing phase.

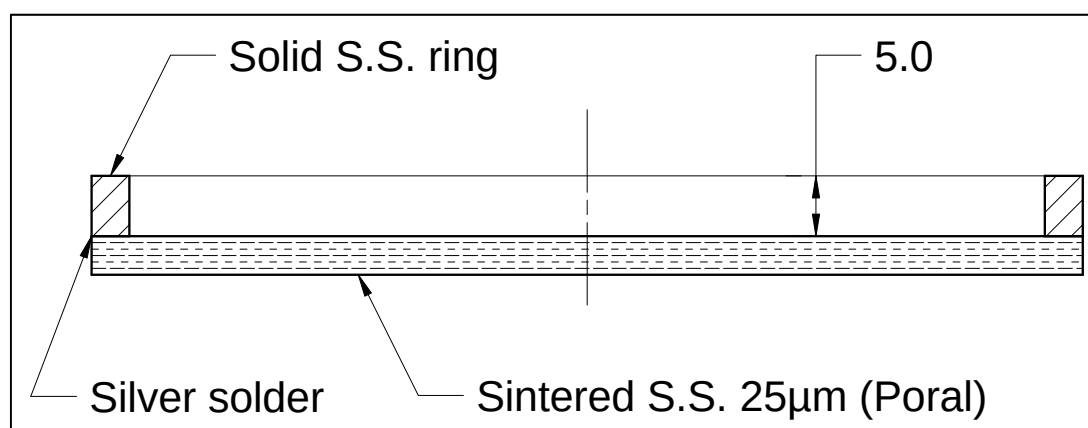


Figure 4-7: Test cell dish

Prior to filling the test cell with ash for testing, the test cells are cleaned making use of an ultrasonic water bath and dried using compressed air. This is done in order to remove any deposits on the test cells that might affect resistivity measurements. The dimensions of the test cells are as follows:

Table 4-3: Test cell depth measurements

Dish	Centre	Side point 1	Side point 2	Side point 3	Side point 4	Average
	mm	mm	mm	mm	mm	mm
1	4.85	4.82	4.82	4.82	4.85	4.83
2	4.80	4.86	4.84	4.80	4.75	4.81
3	4.98	5.02	4.92	4.95	4.85	4.94
4	5.14	4.89	5.16	4.94	5.14	5.05

Note: The side points are four points equally spaced along the perimeter of a 25.4mm circle.

The test cells are subsequently numbered and weighed with no ash loaded on them. The sieved ash samples are then loaded onto the test cells, filling all the spaces ensuring that there are no voids and are levelled using a straight metal edge ruler vertically across the top of the

cells. The loaded test cells are weighed and the mass recorded. The weight difference between the loaded and empty cell is used to determine the packing density of the samples. Figure 4-9 shows the prepared test cells.

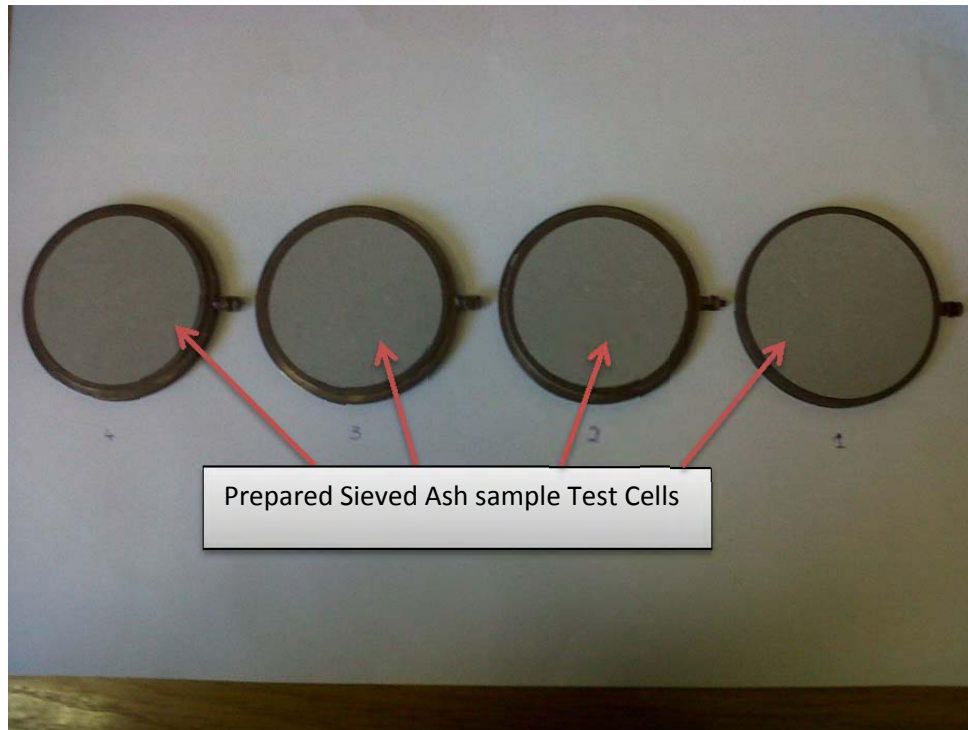


Figure 4-8: Ash cell prepared for the commissioning tests

The prepared test cell subsequently placed inside the test oven, the testing procedure is discussed in section 4.2.6.

4.3.5 Testing procedure

Except for the details given below, the procedures are as outlined in IEEE Standard 548-1984 [6], which is a detailed and comprehensive guideline and standard for the measurement of resistivity.

- For the determination of the resistivity of coal fly ash to be collected in a cold side ESP, the descending temperature method, as outlined in IEEE Standard 548-1984, is used.
- For the determination of the resistivity of coal fly ash to be collected in a cold side ESP, the temperature range is 215 to 95°C, in decrements of 30 °C.
- Clean fly ash samples obtained from an operating ESP, or sampled from the flue gas stream, are not sieved as described in IEEE Standard 548-1984. If foreign objects are detected in the samples then the ash is passed through a 180µm sieve to remove the contamination.

- The resistivity test facility control system makes use of a Keithley Model 486 Picoammeter.

- ***Overnight set-up (~16h before commencement of measurements)***

The ash-filled cell dishes were carefully transferred into an oven chamber and connected to the high voltage supply. The upper disc electrode was gently lowered onto the ash surface, taking care not to disturb the ash. The oven was then sealed and the power switched on and the temperature was ramped from 50 to 350°C.

- Establish N₂ flow.
- Open gas supply valve on N₂ cylinder or tank.
- Adjust N₂ pressure-regulator to 400 kPa (in panel next to gas rack outside).
- Ensure that N₂ flow bypasses moisturizer (two-way valve handle pointing up).
- Adjust N₂ gas flow to 3.2 (rotameter).
- Check regulator pressure. Readjust if necessary.
- Check N₂ gas flow.

The oven was, left on for approximately 16 hours (overnight) at 350°C.

- ***Control panel***

- Power up panel (circuit breaker at bottom right of panel).
- Switch on Keithley 486 Picoammeter (power button).
- Ensure high voltage power supply is off (toggle switch at top right of panel).
- Adjust moisturiser water bath temperature control (SV) to the required temperature depending on the test to be conducted.
- Ensure that gas lines and manifold trace heaters are set to 100 °C (dial on Bartec controller attached to the oven frame).

- ***Oven temperature***

- Adjust oven temperature control (SV) to 215°C.

- ***Resistivity measurement preparations***

- Open CO₂ and O₂ cylinders.
- Adjust CO₂ and O₂ pressure-regulators to 400 kPa.
- Adjust N₂, CO₂ and O₂ gas flows (~5 gas changes per hour).
- Check N₂, CO₂ and O₂ pressure-regulators. Readjust if necessary.
- Check N₂, CO₂ and O₂ gas flows. Readjust if necessary.

- Repeat 2.1.4 & 2.1.5 if necessary.
- If moisture is required, divert the N₂ flow through the moisturizer (two-way valve handle pointing to the wall).
- Allow system to stabilize for at least 60 minutes before commencing measurements.
- ***Resistivity measurement (215 to 95°C descending)***
 - Check that oven temperature is at 215°C.
 - Check that pre-heater controller is set to 95°C.
 - Check that gas lines trace heater is set to 100°C.
 - Check that gas-flows and pressure-regulator settings are correct.
- ***Measure leakage or induced current (background) readings***
 - Zero picoammeter.
 - Set measurement cell selector (cell 1, 2, 3 or 4).
 - Measure leakage or induced current for each cell at a time
- ***Data store***
 - Press and release menu (once) until the following message is displayed:
data store no
 - Use the rotary knob or the ◀ and ▶ keys until the following message is displayed:
data store yes
 - Press menu to arm the data store. The following message should appear on the large display: buffer size 012 rdgs
 - If the buffer size is not at 012 rdgs, then use the rotary knob or the ◀ and ▶ keys to display the desired number of readings on the small display.
 - Press menu when the desired buffer size value displayed. The instrument will exit the menu and waits for a trigger to start the storage process as shown in the following example: —.— — — — μA *
 - The * (star) indicates that the data store is armed and the flashing trigger indicator light denotes that the instrument is waiting for a trigger.
 - Press trigger to start the current measurement. When the * (star) disappears from the display the measurement is complete and the data can be recalled.
- ***Data recall***
 - Press and release menu (twice) until the following message is displayed:
data recl no

- Use the rotary knob or the ◀ and ▶ keys to display the following message:
data recl yes
- Press menu. The stored reading at memory location 001 will be displayed. For example if the stored reading is -1.00000nA , the following will be displayed:
- -1.00000nA loc001
- Record the reading, complete with sign (+ or –) and units (nA, μA or mA) on the log sheet.
- Use the rotary knob to display the next reading at loc002.
- Record the reading, complete with sign (+ or –) and units (nA, μA or mA) on the log sheet.
- Repeat until all 12 readings have been taken.
- Exit from the menu by pressing shift and then exit. The instrument will return to normal operation.
- Set measurement cell selector (top centre of panel) to 2.
- Measure leakage or induced current for cell 2.
- Repeat for cells 3 and 4.

▪ ***Record gas flows and temperatures***

- Note the flow tube (rotameter) settings for N_2 , CO_2 and N_2 and record on log sheet.
- Note the line temperature settings (in front of the panel) and record on log sheet. This needs to be done every time when taking readings.
- Note the moisturiser and oven temperatures (PV) and record on log sheet.

▪ ***Measure current flow (with voltage applied) at 215°C***

- Adjust voltage supply to 2.00 kV
- Select cell 1.
- Zero stopwatch.
- Switch on high voltage power supply (toggle switch to ON). Start stopwatch simultaneously.
- Set range on picoammeter. To ensure that the instrument is not out of range, ensure that there is a least one zero at the beginning of the display. For example $-012.456\ \mu\text{A}$
- Prepare picoammeter as described in data store below.

Data store

- Press and release menu (once) until the following message is displayed:
data store no
- Use the rotary knob or the ◀ and ▶ keys until the following message is displayed:
data store yes
- Press menu to arm the data store. The following message should appear on the large display: buffer size 012 rdgs
- If the buffer size is not at 012 rdgs, then use the rotary knob or the ◀ and ▶ keys to display the desired number of readings on the small display.
- Press menu when the desired buffer size value displayed. The instrument will exit the menu and waits for a trigger to start the storage process as shown in the following example:— . — — — — μA *
- The * (star) indicates that the data store is armed and the flashing trigger indicator light denotes that the instrument is waiting for a trigger.
- After 60 seconds, press trigger on picoammeter.
- After the * (star) disappears from the display, press the button on the small voltmeter, note the reading and switch off the high voltage power supply (toggle switch to OFF).
- Record the reading from the small voltmeter on the log sheet.
- Read and record the current readings as described in data recall below.

▪ ***Data recall***

- Press and release menu (twice) until the following message is displayed:
data recl no
- Use the rotary knob or the ◀ and ▶ keys to display the following message:
data recl yes
- Press menu. The stored reading at memory location 001 will be displayed. For example if the stored reading is -1.00000nA , the following will be displayed:
- -1.00000nA loc001
- Record the reading, complete with sign (+ or –) and units (nA, μA or mA) on the log sheet.
- Use the rotary knob to display the next reading at loc002.
- Record the reading, complete with sign (+ or –) and units (nA, μA or mA) on the log sheet.

- Repeat until all 12 readings have been recorded.
- Exit from the menu by pressing shift and then exit. The instrument will return to normal operation.
- Select cell 2 and repeat procedure.
- Repeat for cells 3 and 4.

▪ ***Prepare for next temperature measurement (30°C decrements)***

- Adjust oven temperature (SV) to 185 °C (215 °C minus 30 °C decrement).
- Check gas flows and pressure-regulator settings. Readjust if necessary.
- When the temperature has reached 185 °C, ensure that it remains steady for approximately 15 minutes to ensure that ash in the cells is at the required temperature.

▪ ***Measure current flows at 185°C***

- Measure leakage or induced currents as above.
- Measure current flow (with voltage applied) as above.

▪ ***Next temperature decrement***

- Repeat at 30°C decrements down to and including 95 °C. (215 °C, 185 °C, 155 °C, 125 °C & 95 °C)

4.3.6 Data acquisition

Data was acquired as per IEEE Standard 548-1984, IEEE Standard Criteria and Guidelines for the Laboratory Measurement and Reporting of Fly Ash Resistivity. The descending temperature measurements are taken at a 2 kV voltage supply, which equates to an electric field of approximately 4 kV/cm. Twelve (12) current measurements are recorded for each test cell, for every temperature measurement point and averaged out. Making use of equation 2, the dust layer resistivity is determined with respect to the oven temperature. The measurement of the leakage current was not conducted as it was found that the leakage current affects the total average current by a factor less than 2%.

Mixed kV measurements were conducted at set temperatures and moisture content as specified by the respective power stations. Voltage is incremented from 2 kV with 2 kV

increments until spark-over occurs; 12 current measurements are taken for each supply voltage.

4.3.7 Resistivity profiling verification and validation

The obtained results were verified and validated. Validation of the results was achieved by following the IEEE Standard 548-1984 on testing the sampled ash. The process followed in testing and analysing the sampled ash is an accredited process and therefore validates the obtained results as accurate.

Verification of the obtained resistivity profile of the tested ash samples was achieved by means of comparison. Ash samples were sent to the Southern Research Institute (SRI) to be tested. The same testing standard applied by Eskom in conducting the resistivity tests was utilised by the Southern Research Institute in conducting their testing. The results obtained by the Southern Research Institute were used as a basis of comparison.

4.4 ESP power supply analysis

A production unit was selected in which the scope of work is to be executed in order to quantify the reduction in particulate emissions on an electrostatic precipitator by implementing two different types of power supply technologies. However, prior to commencing with the evaluation of the two technologies, the ESP was refurbished. The mechanical refurbishment was to restore the ESP to a sound mechanical condition. In doing so, the emission reduction after the outage is attributed to the mechanical repairs as well as the conventional transformer rectifier sets, and this is taken as a baseline on how the ESP performs with conventional TR sets.

The ESP power supply transformers for both technologies are as follows:

Table 4-4: ESP supply transformer specifications

Power supply type	Transformer rectifier set	High frequency power supply
Power rating	113 kVA	120 kVA
Supply voltage	380 V (single phase)	400 V (3Phase)
Supply current	297 A	196 A
Output voltage (RMS)	46.5 kV	70 kV
Output voltage (peak)	70 kV	70 kV
Output current (mean)	1700 mA	1700 mA
Oil quantity	520 litres	90 litres

The ESP power supply transformers have the same electrical output rating, and therefore any reduction in emissions in comparison to the two technologies will be due to the transformer's control system, i.e. the ability of the control system to deliver more power into the fields, spark quenching and recovery as compared to the other.

4.4.1 Project timeline

Table 4-5 gives the high-level project timeline/schedule of the project. The project execution began in 2014/01/21 and was completed in 2014/09/24.

Table 4-5: HFPS pilot project execution schedule

Task Name	Start	Finish
Eskom power station – HFPS pilot project	14/01/21	14/09/24
Unit 3 Outage	14/01/21	14/04/11
Mechanical refurbishment of the ESP	14/01/21	14/04/11
Procurement, fabrication and delivery phase	13/11/20	14/04/27
HFPS	13/11/20	14/04/07
Procure raw material	13/11/20	14/01/09
Manufacturing	13/12/20	14/02/13
FAT	14/02/14	14/02/20
Delivery to South Africa (via sea freight)	14/02/21	14/04/03
Offloading and storage	14/04/04	14/04/07
Ducting	14/02/15	14/04/27
Procure raw material	14/02/15	14/02/20
Mechanical assembly	14/02/21	14/04/11
Assembly of HFPS onto wagon	14/04/14	14/04/25
Delivery to site	14/04/26	14/04/27
Electrical cables & components	14/02/15	14/03/12
Procurement	14/02/15	14/03/12
Delivery to site	14/03/01	14/03/12
C&I cables and hardware	14/02/15	14/02/26
Procurement	14/02/15	14/02/24
Delivery to site	14/02/25	14/02/26
Delivery complete, construction start	14/05/02	14/05/02
Installation phase during Unit 3 outage	14/01/27	14/05/05
Cable installation (electrical sub-station work)	14/03/10	14/03/30
380 V board modification to supply 3-phase	14/03/10	14/03/30

380 V board modification to supply 3-phase	14/03/10	14/03/30
Cable installation (electrical and C&I)	14/03/22	14/05/05
Pull in and secure earth cables	14/03/22	14/04/02
Site establish sky jacks	14/04/02	14/04/09
Install winch on ESP roof	14/04/09	14/04/10
Install cable rack on horizontal section	14/04/10	14/04/14
Skyjack training to MJW	14/04/14	14/04/17
Install new cable rack on vertical section	14/04/17	14/04/21
Install 3 core cables and secure	14/04/21	14/05/05
Install and test Ethernet cables (CAT6 & fibre)	14/04/21	14/04/25
Testing of electrical cable installation	14/05/03	14/05/05
C&I work	14/04/02	14/06/15
PROMO FAT	14/04/02	14/04/02
C&I offline software programming	14/04/07	14/04/25
PROMO & network installation	14/04/25	14/05/02
Hardware installation (relay)	14/05/08	14/06/14
C&I testing	14/05/08	14/06/15
First ESP performance testing phase	14/04/11	14/05/02
Settling of precipitator requires 2 weeks before performance testing	14/04/11	14/04/25
Pre-installation ESP efficiency measurement	14/04/25	14/05/02
Installation of HFPS phase	14/05/04	14/06/15
Fields 1 to 4 on all casings		
Isolate transformers & casing and obtain permits to work		
C&I		
Install IP 65 network junction box		
Terminate Ethernet cable from SIR4 in network junction box		
Terminate Ethernet cables onto new switches in Sub A		
Connect & test new relay/existing signal cable in MCC panel to HFPS		
Integrate new software signals into PLC, make available on HMI		
Mechanical		
Cut & weld the existing vertical ducting to required		

length (Estimate 294 mm)		
Rig out old transformers to ground floor		
Rig up HFPS transformers along with wagon assembly		
Align existing with new ducting and tack weld		
Perform final ducting installation		
Electrical		
Cable installation check		
Modify power supply cables in MCC and precipitator panel as defined in electrical URS		
Install IP 65 junction box next to HFPS		
Cut & terminate 400 V power & earth cables onto SIR4 & junction box		
Install protective earth		
Install return earth		
HV conductor work (extend 22 mm HV conductor to SIR4 output)		
Cut out about 294 mm from HV conductor to accommodate lowered duct		
HV insulator installation (inside horizontal section of duct)		
Completion, commissioning and take-over phase		
Tap-up main supply transformer to supply 400 Vac		
Site acceptance testing		
Clear permit & client hand-over to switch field back on line		
Allow for stable operation		
Post-commissioning	14/06/16	14/09/24
2 weeks' settling period	14/06/16	14/06/21
Proving period	14/06/21	14/09/01
Optimisation (tuning)	14/09/01	14/09/24
Optimise control & rapping philosophy	14/09/02	14/09/15
Optimisation complete	14/09/15	14/09/15
Post installation performance & acceptance testing	14/09/17	14/09/24
Completion certificate issued	14/09/24	14/09/24

The project was successfully completed on 24 September 2014.

4.4.2 ESP outage scope of work

The project scope executed during an outage is to mechanically refurbish an electrostatic precipitator plant. The mechanical scope of the work was executed in order to address defects that occur while the plant is running on the ESP, SO₃ plant and ducting. The executed mechanical scope of work on the ESPs and SO₃ plant are as follows:

➤ ESP mechanical scope:

Field 1-7:

DISCHARGE SYSTEM

- Clean support insulators with a clean dry rag and inspect for damage (cracks, chips); damaged insulators must be replaced.
- Clean torque insulator with a clean dry rag and inspect for damage (cracks, chips); damaged torque insulators must be replaced.
- Clean, inspect for excessive wear and repack all self-aligning (top steady) bearings with high temperature grease, type 'Omega 71'
- Replace all universal joints.
- Replace both rapper worm drives.
- Replace all L- shaped DE hammer assemblies with new specification hammer assemblies (including hammer bracket); all bolts to be tag welded.
- Replace all DE hammer inner bushes.
- Replace all DE hammer liner bushes that have worn oval.
- Replace all worn V-pads on shaft bearing assemblies (>50%, if thickness of V-pad is <10 mm).
- Replace all worn bearing hardened bushes (>3 mm worn away).
- Replace all damaged DE anvils; ensure all anvils are rigid and all bolts are tag welded.
- Ensure DE anvils are aligned so that the hammer hits the anvil in the centre (vertically & horizontally).
- Replace all bolts on flanged couplings; bolts to be tag welded.

COLLECTING SYSTEM

- Scaffolding to be built on all seven fields per casing
- Both CE drive gearboxes to be removed, dirty oil drained, filled with clean oil, and refitted.
- Open, clean and inspect for excessive wear on both outboard bearings (between gearbox and casing inside plumber block).
- Condition:
- Poor (worn out): Replace bearing and grease bearing.
- Good: Re-grease
- Replace all CE hammers with their liner bushes worn oval; hammers not to be scrapped must be refurbished; will only be scrapped with system engineer's consent.
- All CE hammer inner bushes to be replaced.
- Replace all worn V-pads on shaft bearing assemblies (>50%, if thickness of V-pad is <10mm).
- Replace all worn bearing hardened bushes (> 3 mm worn away).
- Replace all rapper bar bolts and replace cylindrical bushes with conical bushes on fields specified after inspection (old conical bushes to be reused). All bolts to be tightened by torque wrench (specs to be, found below). All bolts to be tag welded.

Rapper bar bolt specs:

- M20 bolts: Material grade: 8.8; Tightening torque: 370 Nm.
- M16 bolts: Material grade: 8.8; Tightening torque: 200 Nm
- Rapper bars to be inspected for any damage on fields specified after inspection (cracked, broken, shows excessive wear) and be replaced if damaged; with rapper bars appropriate to field. Refer drawing (0.63/5894).
- All new anvils to be welded on to rapper bar assembly as per welding specifications in drawing (063/5894).
- All cracked anvils to be re-welded as per welding specifications in drawing (0.63/5894).
- Ensure shaft and hammer alignment to rapper bars to be aligned (Vertically) 150 mm above the grating, horizontal alignment determined by guide bars
- Ensure all guide bars are perpendicular to grating.
- Rectify any damage to electrodes (plates) at connecting point at top and bottom.

SO₃ plant

Inspection and repairs on SO₃ burner, process air supply, SO₂ cooler, converter, lances and skid. Replacements will be conducted on the inspect 2nd stage cooling air valve, turbulator expansion joint, blower expansion joint vertical, blower expansion joint horizontal, both Mixing chamber valves and gaskets, blower, blower coupling, motor blower, discharge safety valve, SO₃ isolating valves, all burner thermocouples and pockets, turbulator cooling fan, SO₃ lances, sight glass gasket, replace all gaskets (combustion air valve line; mixing air valves lines; air lines; SO₂/SO₃ lines).

Flue gas ducting

Work to be executed on the following areas: ESP inlet distribution screens, ESP inlet ducting, secondary air-heater outlet duct, primary air-heater outlet duct, economiser outlet duct, ESP outlet to stack base and dampers

4.4.3 ESP operation with conventional TR sets

ESP performance is evaluated with TR sets in operation after the production unit has returned to service and after a settling period of approximately one month. In the settling period, rapping optimisation is conducted to reduce the emissions and minimising rapping emission spikes. A precipitator efficiency test is conducted to determine the exact particulate emission when the ESP is in good mechanical condition with conventional main frequency TR sets power supply implemented. The results obtained are taken as a baseline, when the HFPS is implemented, to determine whether there will be an improvement in emissions.



Figure 4-9: TR sets installed on an ESP field

Figure 4-10 shows a conventional transformer rectifier set connected to an ESP. The operation and control of the TR sets are achieved by an automatic voltage controller (AVC). The electrical performance of the ESP fields is monitored and recorded during performance testing. Additionally, voltage-current curves are plotted for each field to better analyse the internal condition of the fields. Plotting of V-I curves gives an indication of how the field is performing, as one is able to observe and determine the corona onset voltage and spark-over points of individual fields, which assists in the optimisation of the fields.

The AVC controls the TR set ensuring that they operate optimally, ensuring maximum possible power output to be supplied to the fields, with minimum disturbances. Settings that are input into the AVC are:

- Spark rate settings: the number of disturbances that may occur causing a depression of the discharge electrode voltage for not more than one-half cycle of the supply.
- Step: amount by which the conduction angle is reduced following the detection of a spark.
- Step: rate at which the conduction angle of the thyristors will increase from the step setting after a spark has occurred (4.5 kV/sec).
- De-ionisation time: time setting ensures that no ionised gas remains in the vicinity of the initial spark.
- Recovery: rate at which the voltage returns to the STEP level following a de-ion time, ensuring stable recovery – minimises follow spark situation.
- Is limit, Vs limit, and Ip limit.
- Protection settings such as under-voltage settings and over-current setting to trip out the TR when faults occur within the ESP fields

The above settings ensure that the fields operate optimally, and whatever faults may occur inside the fields are dealt with and power is swiftly re-established into the fields. As previously stated in Chapter 3 of this dissertation, the control system is primarily dependent on the mains supply frequency and this limits the speed at which the controller reacts to faults.

The precipitator plant management system (PPMS) is used to monitor and control the ESP fields. Figure 4-11 illustrates a PPMS print screen for an ESP plant that is in operation. The voltage, current, spark rates and so forth that are measured by the AVC are sent to the PPMS, which gives a graphical representation of the plant while in operation. Voltage and current

trends of each individual field are accessible for analysis along with historical trends. The unit's combustion process parameters that particularly have an influence on emissions are also monitored via this system. Process parameters include O₂, mill loading/configuration, ESP inlet and outlet temperatures and unit load.

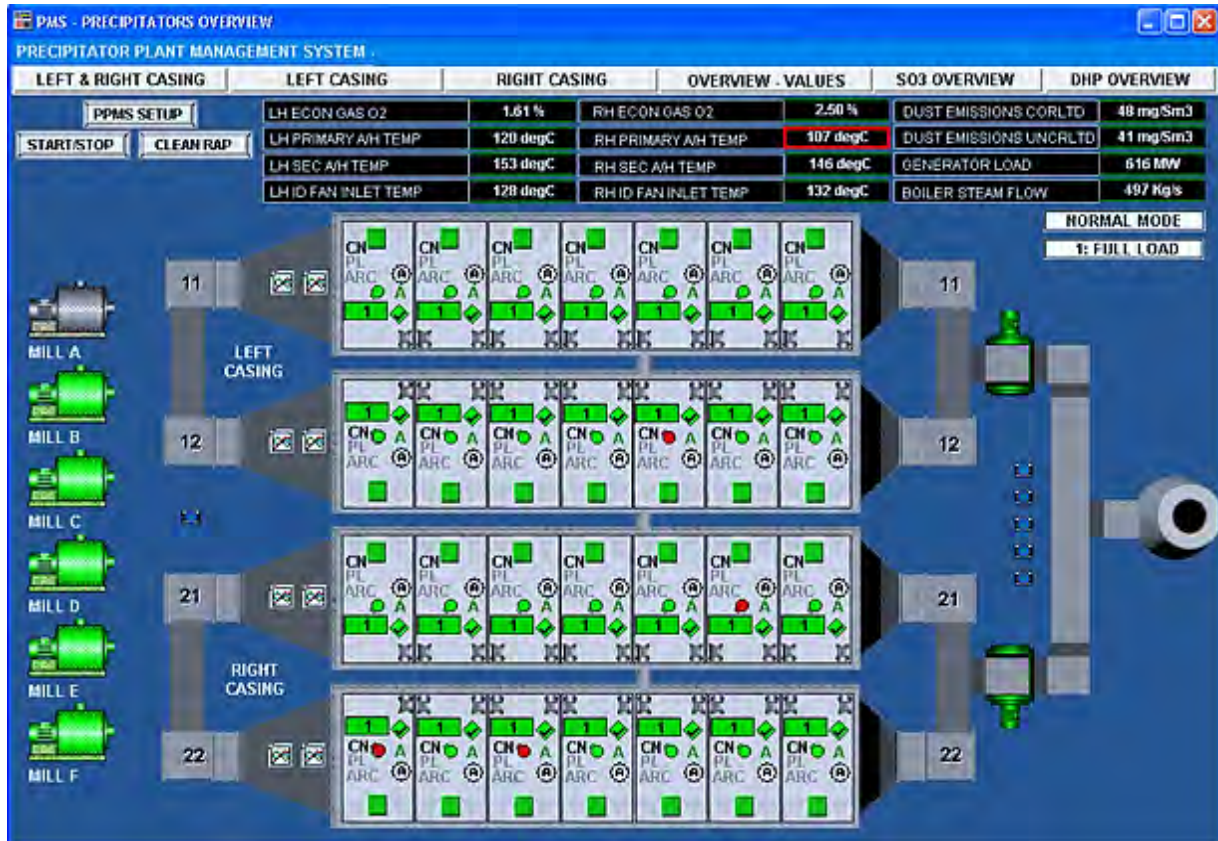


Figure 4-10: PPMS print screen of an ESP plant

The rapping done on the ESP is also controlled by the AVC controllers, along with the precipitator plant management system (PPMS). Rapper settings are set on the controllers, i.e. duration and interval for different operating programmes. The rapping philosophy is discussed in detail in section 4.3.5.

4.4.4 Plant modification for HFPS

The baseline electrical design of the ESP system makes use of a single-phase supply for the conventional TR sets. The HFPS requires three-phase supply, and therefore the baseline electrical system design needs to be modified. The work required was cabling, tapping up of the main supply transformer to supply 400 Vac, installation of the control and instrumentation equipment to be integrated into the existing monitoring system (PPMS).

- **Electrical modification**

Two substations supply power to ESP transformers, with each substation supplying the LH or RH casing respectively. Inside the substation, the 380 V supply from the 380 V precipitator board is connected to the precipitator control cabinets (also referred to as the high tension panel or HT panel) of each transformer; 14 control panels per substation. From the HT panels, cables are routed to the precipitator roof, where the precipitator transformer-rectifiers are located.

The electrical system was configured to supply single phase 380 Vac, as the conventional TR requires single-phase power. The installation of the HFPS requires a three-phase supply and therefore the plant had to be modified such that it supplies three phases. Work carried out required the modification of the supply boards, as well as installing new cabling from the bus-section to the control cubicle and all the way to the precipitator roof.



a)

b)

Figure 4-11: (a) HFPS transformer installation, (b) Commissioned HFPS

The installation and commissioning of the HFPS transformers were conducted while the unit was online. The online installation and commissioning was done on a casing-by-casing basis; the first four TR sets were isolated and decommissioned. Installation started on the fourth field, moving upstream, from fourth field to the first field. The reason for

implementing this installation methodology was for safety reasons. The upstream fields have to be isolated in order to avoid charge carry-over that can discharge fields worked on and possibly create an unsafe working environment. Upon completion of the HFPS transformers, a settling and proving period was observed for a period of about two to three weeks, while monitoring the performance of the ESP.

Optimisation of the rapping was conducted for the new installation after the proving period. The conducted optimisation is further discussed in section 4.3.5.

- ***Control and instrumentation modification***

The signals from the HFPS controllers had to be interfaced with the existing precipitator plant management system (PPMS). The PPMS consists of a PLC (Sixnet) as an automatic control system and a SCADA (Citect) using communications interfaces of Modbus (CANbus) and Ethernet [73]. The rapping on all seven fields is managed and controlled by the existing PPMS. The electrical parameters on the newly installed HFPS on the first four fields are controlled by the HFPS controllers and the last three fields will still be controlled by the existing PPMS. The HFPS controllers are interfaced to the SCADA via the existing PLC. The PLC was expanded/programmed to accommodate the new HFPS controllers. Figure 4-12 illustrates the configuration of the control and instrumentation integrated into the existing control and monitoring system.

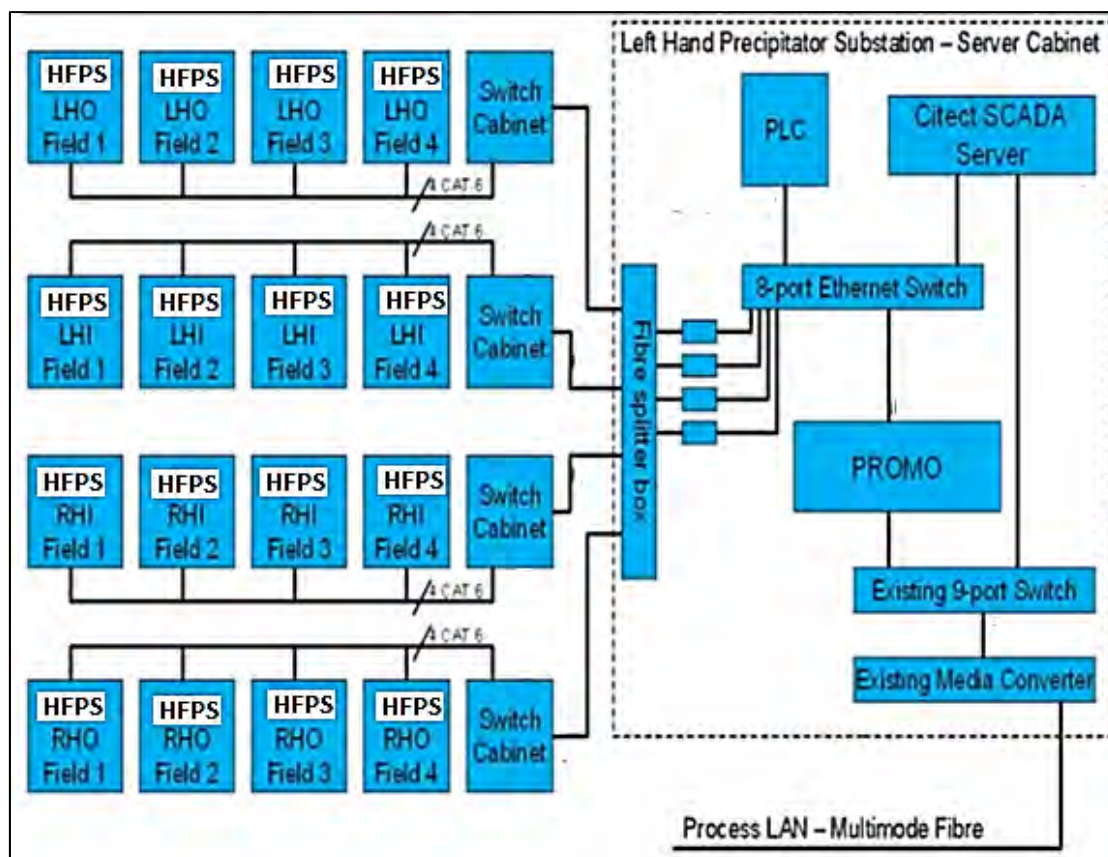


Figure 4-12: HFPS control system configuration

The control system of the HFPS provides the following information to the PPMS, for monitoring purposes.

- Primary current
- Primary voltage
- Secondary current
- Secondary voltage
- Sparking and arc rate
- Power output
- Fault indication

The control thereof of the HFPS is achieved with the ProMo system; this is to optimise the HFPS by changing settings, as and when required. Figure 4-13 shows a print screen of the HFPS transformer's control and monitoring system (ProMo).

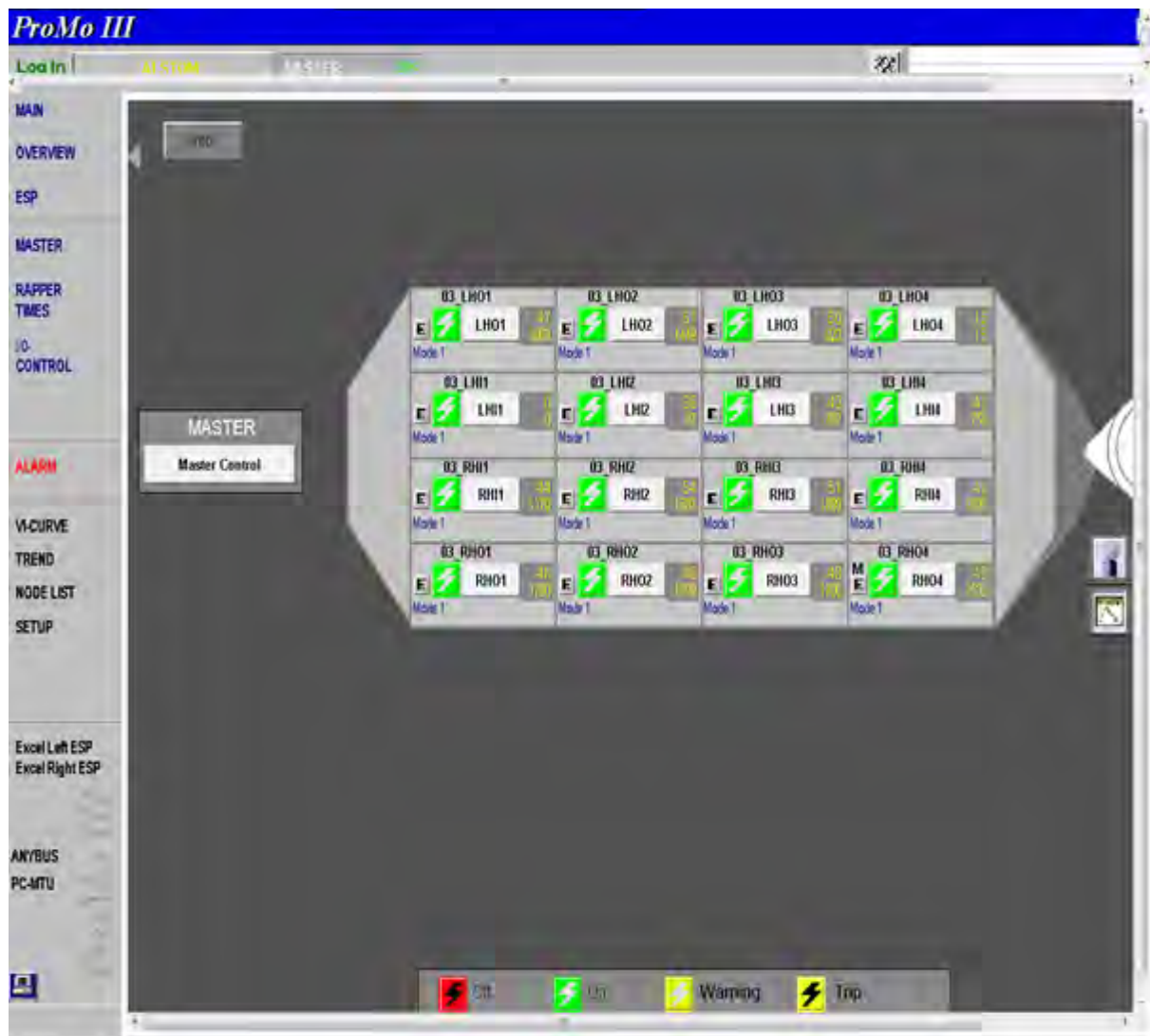


Figure 4-13: HFPS ProMo print screen

The ProMo system was integrated into the PPMS as it can only control the HFPS transformer, whereas the fifth, sixth and seventh fields still made use of the PPMS. This system has the capability to plot V-I curves in order to analyse the status and conditions of the fields with HFPS. Similar to the PPPMS, different modes of operations can be selected; continuous or pulsing mode, depending on the operating conditions. Pulsing mode is typically implemented whenever the ESP is receiving high resistivity ash in instances when the SO₃ plant is not available to condition the flue gas. For the purpose of this project, the pulsing mode operation and effectiveness thereof was not evaluated.

4.4.5 Rapping control and philosophy

The rapping philosophy implemented in the station is a queuing rapping philosophy. Queuing refers to the sequence in which rapping is triggered for the fields; this philosophy is to ensure that two fields in the same casing never rap during the same time interval and therefore

reduces emission rapping spikes. The front fields (Fields 1, 2 and 3) collected most of the flue gas, and therefore have to be rapped more frequently compared to the rear fields. The queuing process gives priority to the front fields, meaning that if ever there is a scenario where the sixth field is triggered to start rapping at the same time as field 2, field 7's rapping will be delayed allowing field 2 to rap first and field 7 will only rap once field 2 has completed its rapping. This rapping process is controlled by the PPMS based on the timer setting input on the AVC for each field.

The PPMS has several programmes loaded on it and these programmes control the performance of the ESP fields, particularly for rapping. Programmes 1, 2, and 5 are utilised during normal operation on the unit and each programme has specific rapper timer settings, intervals and duration. The implemented operating programmes utilised are as follows:

- ***Running unit (programme 1):***

Programme 1 is active during normal operating conditions of the unit in the period 01:00-00:00. This programme mode is active during normal running conditions of a unit, and manages the rapping process, without creating large emission spikes. The rapping intervals and durations thereof are set in the AVCs for each field. This rapping occurs while the fields are energised. The rapper settings for this programme are as follows:

Table 4-6: Programme 1 rapper settings

Field	Interval (minutes)	Duration (seconds)	Mode	Vs Lim	Rap enabled
1	10	35	Group coordinated	0	Rap 1
2	18	35	Group coordinated	0	Rap 1
3	30	35	Group coordinated	0	Rap 1
4	55	35	Group coordinated	0	Rap 1
5	95	35	Group coordinated	0	Rap 1
6	170	35	Group coordinated	0	Rap 1
7	1440	1	Group coordinated	0	Rap 1

- ***Power down rapping (programme 2)***

Programme 2 is a power down rapping programme; the programme sends a signal to the AVC to switch off the respective field's transformer for the period of rapping. This

programme activates cyclically; it activates after a set periodical cycle of normal rapping. Normal rapping refers to the rapping of a field while the field is energised. This process has proven to be an effective manner of cleaning both the collector and discharge electrodes during the course of a production day. The rapper settings for this programme are as follows:

Table 4-7: Programme 2 rapper settings

Field	Interval (minutes)	Duration (seconds)	Mode	Vs Lim	Rap enabled
1	10	35	Group coordinated/VsLim	0	Rap 1
2	18	35	Group coordinated/VsLim	0	Rap 1
3	30	35	Group coordinated/VsLim	0	Rap 1
4	55	35	Group coordinated/VsLim	0	Rap 1
5	95	35	Group coordinated/VsLim	0	Rap 1
6	170	35	Group coordinated/VsLim	0	Rap 1
7	1440	1	Group coordinated/VsLim	0	Rap 1

▪ ***Clean rapping (programme 5)***

Programme 5 is set to activate automatically at 00:00 and is active until 01:00, after which the PPMS switches back to programme 1. Programme 5 is used to conduct clean rapping or de-ionised rapping, whereby all the ESP fields are switched off and continuous rapping is conducted. This form of rapping is an effective way of cleaning the collector plates, as it dislodges all the collected dust that was not dislodged during the course of the day that normal rapping was not able to dislodge. The rapper settings for this programme are as follows:

Table 4-8: Programme 5 rapper settings

Field	Interval (seconds)	Duration (minutes)	Mode	Vs Lim	Rap enabled
1	1	60	Uncoordinated/VsLim	0	Rap 1
2	1	60	Uncoordinated/VsLim	0	Rap 1
3	1	60	Uncoordinated/VsLim	0	Rap 1
4	1	60	Uncoordinated/VsLim	0	Rap 1
5	1	60	Uncoordinated/VsLim	0	Rap 1
6	1	60	Uncoordinated/VsLim	0	Rap 1
7	1	60	Uncoordinated/VsLim	0	Rap 1

4.4.6 ESP efficiency testing

ESP efficiency tests were conducted by an external party, for both the conventional TR set and HFPS power supplies. An ESP efficiency test is a gravimetric test (EPA Method 17) [33] that measure the volume dust burden entering and exiting the ESP. The percentage difference of the outlet compared to the inlet is an indication of the collection efficiency of the ESP system.

A baseline ESP efficiency test was conducted with a conventional TR set power supply. A post-HFPS installation ESP efficiency test was also conducted to determine the performance of the ESP. These tests were conducted under identical loading conditions; however, they were conducted approximately four months apart and the results obtained were correlated by making use of Eskom's approved correction curves. The following procedure was conducted during the efficiency tests:

- ***Operating conditions***

All the tests were carried out at 618 MW unit load with the plant having operated steady at this load for a period of 24 hours and during the testing period. Plant parameters recorded and monitored during the testing period were:

- ESP fields in service
- Electrical condition of fields (obtained from PPMS)
- Primary current (I_p), primary voltage (V_p), secondary current (I_s), secondary voltage (V_s)
- VI curves
- Process conditions; inlet and outlet temperatures, mill configuration, O_2

- ***Coal sampling***

There are six mills installed per unit, with five out of six mills being in service during maximum continuous operation. Each mill has a dedicated coalbunker with two feeders drawing from it. Coal sampling was conducted every eight hours by installing a chute on one of the feeders on each mill; the coal sample was taken in order to conduct general and moistures analysis. The analysis is conducted to determine the boiler operating condition, i.e. is the boiler operating within its design base and are the results analysed within the context of the emissions measurements taken during the efficiency tests and determined?

The analyses were conducted in-house at Eskom's research, test and development facilities (R,T&D). The conducted tests are accredited by the South African National Accreditation System (SANAS).

- ***Moisture sample***

It was agreed that only one moisture sample would be analysed, as any time delay would cause moisture to be lost from spare samples. The moisture samples would be analysed for:

- Surface
- Inherent and
- Total moisture

- ***General analysis***

A general analysis was also conducted in order to ensure that the plant is operating within its specified design base in terms of the process and boiler combustion conditions. The following general analyses were, conducted:

- Proximate
- Ultimate
- Calorific value
- Sulphur content
- Elemental analysis

- ***Isokinetic dust sampling***

Five isokinetic tests were carried out at each duct; with each inlet duct being equipped with four sampling ports and the outlet duct having six sampling ports. Four sets of sampling equipment were used simultaneously and placed so that two casings are traversed sequentially by one set of equipment.

- Set 1 – ESP LH inlet inner and outer ducts sequentially
- Set 2 – ESP RH inlet outer and inner ducts sequentially
- Set 3 – ESP LH outlet inner and outer ducts sequentially
- Set 4 – ESP RH outlet outer and inner ducts sequentially

An effort was made to start and stop the isokinetic sampling simultaneously on all casings, more specifically the corresponding inlet and outlet positions on a specific ESP casing. A probe was inserted to the deepest point in the traverse where sampling started. The traversing started simultaneously on the RH outer and LH inner and progressed to the RH inner and LH outer. The obtained data was captured for each ducting, analysed and averaged out to

determine the combined collection efficiency of the ESP. These results will be the bases of determining and quantifying the exact reduction or lack thereof in the ESP as a result of implementing two types of power supply technologies.

4.4.7 Power supply technology analysis validation and verification

The analysis of the ESP and its subsequent performance with the two different power supply technologies is validated by the set standards in terms of measurements and reporting. Plant measurements are conducted in accordance with the following metering standards: Eskom Metering Strategy; 240-48907866 and Metering and Measurement Systems for Power Stations in Generation Standard; 240-56359083. Plant performance historical data was used as a form of verification; the historical performance data of the plant after an outage gives an indication as to where the emissions stabilise and how ESP fields perform after an outage. The measuring components were calibrated during the outage and tested for correct functionality. This ensures that the captured data is accurate for reporting purposes as required by the implemented metering standards. The captured data is then analysed in order to draw incisive conclusions about the system performance.

Emissions measurements and reporting are conducted in accordance with the Standard for Emissions Monitoring and Reporting; 474-187. Therefore, implementing the reporting standard validates the measured particulate emissions by the opacity monitors. The verification process on the reported particulate emissions is achieved by conducting the ESP efficiency tests. The efficiency test is conducted in accordance with Manual Stack Emission Monitoring Performance Standard for Organisations Environment Agency November 2011 Version 7.2. The testing process was discussed in section 4.4.6. The plant data obtained from isokinetic measurements was used to verify the obtained measurements from the historical system.

4.5 Conclusion

This chapter discussed the process to be implemented in order to obtain data to be analysed in order to achieve the set-out project objectives.

The process to be followed in conducting ash resistivity testing and profiling was discussed in detail. The resistivity oven's operating philosophy was discussed as well as the testing methodology that is to be utilised in conducting the testing. A temperature descending methodology is utilised for this project, as the ash experiences descending temperatures from

the boiler during the combustion process and to the ESP for collection. The ash sample preparation process was also discussed, which is conducted in order to remove any foreign materials that may have been collected through the sample collection process. Ash elementary analysis is conducted in order to determine the elementary composition of the ash sample; this is compared to the design base data as stipulated in Chapter 2, when the station was commissioned. The test procedure and data acquisition processes, as discussed in sections 4.3.5 and 4.3.6 respectively, are implemented in order to determine the resistivity profile of the ash sample. The validation of the obtained results is achieved by following the set IEEE standard on ash resistivity testing and reporting. Verification of the obtained results is achieved by means of comparison, whereby results obtained from the Southern Research Institute on the ash sample taken from the station were sent for testing.

The power supply technology analysis was conducted as discussed in this chapter, with the emphasis on the power input into the fields for both power supply systems. Post-outage testing and plant monitoring are to be conducted with conventional TR sets as the primary source of power supply into the ESPs. The obtained results are to be taken as baseline results to be used as bases of comparison in the operation of the two power supply technologies. The installation, commissioning and optimisation of the HFPS on the front four fields of each casing, scheduled for a period of five weeks, are to be conducted. Rapping intervals were modified to suit the new power supply system, as the HFPS had a significantly higher power input and therefore required the front field to rap more frequently. A second efficiency test was conducted to determine the reduction in particulate emissions of the ESP as a result of installing HFPS on the front four fields of the ESP.

Figure 4-14 shows a side-by-side installation of a conventional TR set and an HFPS transformer operation in the plant.



Figure 4-14: Conventional TR set and an HFPS transformer as installed in the plant

Deutch's ESP efficiency formula alludes to the factor that the efficiency of an ESP is primarily dependent on the power supplied to the ESP. Therefore, in installing HFPS and the subsequent increase in the power input to the fields, a reduction in emissions is expected.

CHAPTER 5: RESULTS AND ANALYSIS

The purpose of this chapter is to analyse and discuss the obtained test results as stipulated in the design chapter. Testing was conducted following processes, procedures and standards as discussed in Chapter 4 in order to obtain the required results. The analysis of the obtained results will be used to determine whether the project objectives are met.

5.1 Introduction

The following chapter discusses the obtained results as per implemented design as discussed in Chapter 4 of this document. Ash resistivity test results were obtained from a laboratory test set-up, and performed in accordance with the relevant standard that governs the measuring and analysing of ash resistivity. The influence of the obtained resistivity profile on the performance of the ESP and impact on emissions is also discussed.

Technological testing of power supplies to the ESP was conducted as discussed in Chapter 4 of this document. The obtained results are analysed in order to quantify the influence and impact that the different power supplies have on the emitted particulate emissions. The tests were conducted on a live plant, and tests were conducted in accordance with the relevant ESP testing standards. **Ash resistivity profiling results**

Ash resistivity profiling consists of a variety of steps in order to determine the actual resistivity of the ash. Firstly, the ash sample was analysed to determine the elementary composition of the ash; studies show that the elementary composition of ash influences the resistivity thereof. Other influences of the resistivity profile include the moisture, gases in the atmosphere in which the ash is tested, and the temperature variance in which testing is conducted.

5.2.1 Coal analysis

Ash resistivity is predominately influenced by the quality of coal burnt in the combustion process. Coal with low volatile content and high ash content is classified as poor quality coal and as such will result in high resistivity ash. The power station in which the ash was obtained for testing operates with poor quality coal. Over time, the quality of coal deteriorates, and therefore results in further increases in the ash resistivity of the collected ash. This makes it difficult to effectively and efficiently collect the ash and has low

particulate emissions. However, this deterioration of coal and resultant increase in ash resistivity are combated by the SO₃ conditioning of the flue gas, which reduces the surface resistivity of the collected ash. Tables 5-1 and 5-2 show the analysed coal quality of the power station; Table 5-1 shows the design base coal, when the station was commissioned in the late 1980s; and Table 5-2 shows the results of analysed coal as of 2012, when the resistivity tests were conducted.

Table 5-1: Baseline design coal analysis results

COAL SPECIFICATION (Original design coal specification)	
Moisture free values for:	
Volatile content	21.7%
Ash content	35%
Fixed carbon	43%
As received values:	
Sulphur	1.0%
Nett C.V	16.8 MJ/kg

When the station was commissioned, the coal quality was approximately 16.8 MJ/kg, with ash content of 35%.

Table 5-2: Coal analysis results from 2012

COAL SPECIFICATION (Original design coal specification)	
Moisture free values for:	
Volatile content	19.5%
Ash content	39.5%
Fixed carbon (by difference)	33.8%
As received values:	
Sulphur	0.73%
Nett C.V	14.9 MJ/kg

Coal samples were taken in 2012 and analysed, and the coal quality was approximately 14.9 MJ/kg, with ash content of 39.5%. The ash content has increased significantly from the design base data, as well as a reduction in the calorific value of the coal. This is an indication that the ash resistivity seen by the ESPs has also increased over the years. The deterioration of coal quality and increase in ash resistivity lead to high particulate emissions leading to the inability to operate plants at acceptable levels as stipulated by Government legislation and international law. SO₃ conditioning and the implementation of new power supply technologies can assist in reducing particulate emissions to meet stringent emission laws.

5.2.2 Ash elemental analyses

Ash elementary analysis was conducted on the ash samples to be tested; the analyses were conducted in accordance with accredited testing procedures. Tables 5-3 and 5-4 list the elemental composition of the fly ash samples.

Table 5-3: Design baseline fly ash elemental composition

Elemental	% Composition
Silicon (as SiO ₂)	49.1
Aluminium (as Al ₂ O ₃)	4.9
Iron (as Fe ₂ O ₃)	31.5
Titanium (as TiO ₂)	1.7
Phosphorus (as P ₂ O ₅)	5.1
Calcium (as CaO)	1.3
Magnesium (as MgO)	0.3
Sodium (as Na ₂ O)	0.2
Potassium (as K ₂ O)	0.3
Sulphur (as SO ₃)	3.9
Loss on ignition	1.7

Table 5-4: Fly ash elemental composition

Elemental	% Composition
Silicon (as SiO ₂)	53.4
Aluminium (as Al ₂ O ₃)	27.5
Iron (as Fe ₂ O ₃)	3.6
Titanium (as TiO ₂)	1.5
Phosphorus (as P ₂ O ₅)	0.28
Calcium (as CaO)	6.5
Magnesium (as MgO)	1.3
Sodium (as Na ₂ O)	0.3
Potassium (as K ₂ O)	0.8
Sulphur (as SO ₃)	2.6
Loss on ignition	2.2

The elemental composition of the ash is not used in the determination of the resistivity, although it is a given that the composition influences the resistivity. No accurate theoretical model is available that correlates the elementary composition to the resistivity for South African coal and ash.

The baseline design of the ESP was based on Table 5-3's ash elementary composition; the elementary composition was primarily dependent on the coal quality at the time. Table 5-4 shows the obtained results of an elementary analysis conducted on the tested ash sample; tests conducted in 2012. It is observed that the elementary composition of the ash has changed compared to the baseline data. The silicon composition of the ash has increased from 49.1 to 53.4%. The aluminium composition present in the ash had a significant increase from 4.9 to 27.5%. The huge increase in the aluminium composition of the ash was accompanied by a drastic decrease in the iron content present in the ash from 31.5 to 3.6%. These drastic changes in the ash elementary composition, as illustrated in Table 5-3, compared to that of Table 5-4, gives the impression that the ash being captured by the ESPs has a significantly higher resistivity than that in which the ESP baseline design was intended.

5.2.3 Ash resistivity profile at 2 kV

Precipitators are designed to operate within certain range of resistivity for optimum dust collection; this range being 1×10^8 to 1×10^{11} Ω -cm. The recorded voltage and current measurements are used to determine the resistivity profile of the ash sample. The formula used to determine the resistivity of a dust layer is expressed as follows:

$$\rho_{ash} = \frac{R \cdot A}{l} \quad (5 - 1)$$

Whereby; (ρ_{ash}) is the resistivity if of the dust layer will be measured in *ohm-cm*, and is expressed as a function of the resistance (R) obtained by making use of Ohm's law ($R = \frac{V}{i}$), the area (A) of the collector plate/disc and the accumulated dust layer thickness (l). Substituting Ohm's law for resistance into equation 2 gives the following expression:

$$\rho_{ash} = \frac{(\frac{\Delta V}{i}) \cdot A}{l} = \frac{\Delta V \cdot A}{i \cdot l} \quad (5 - 2)$$

Therefore, the dust layer resistivity can be expressed as a function of the voltage drop (ΔV) across the dust layer and the measured current through the dust layer. The voltage drop is obtained by means of interpolation between the V-I curve of a clean disc-to-disc

characterisation and that of a system with dust burden. It is noted that in cases of high or low resistivity, it can happen that the voltage drop obtained through interpolating the V-I curves can be a negative value. An Excel spreadsheet was developed with the abovementioned equation embedded into the spreadsheet such that the obtained current measurements during the testing period are entered into the sheet to determine the resistivity as well as plotting the resistivity curves for the various test temperature points and test voltage.

Table 5-5 illustrates the dish diameters, dust layer thickness and the respective gas flow for testing. The gas flow ranges are representative of the power station's operating conditions.

Table 5-5: Test cells data and testing operating gas flows

Gas pressure (regulators)		kPa	400	
Dish diameter	Cell 1	cm	76.2	Reference sample
	Cell 2	cm	70	Test station sample
	Cell 3	cm	70	Test station sample
	Cell 4	cm	70	Test station sample
Electrode diameter		cm	2.54	

Dust thickness	Cell 1	cm	0.483	Reference sample
	Cell 2	cm	0.481	Test station sample
	Cell 3	cm	0.494	Test station sample
	Cell 4	cm	0.505	Test station sample

GAS PHASE		
Gas	Range	Flow
N ₂	6-10	8.7
CO ₂	8-16	13.8
O ₂	4-8	4.6

Gas flows & composition		
Gas	l/min (STP)	%
N ₂	8.123	77.3
CO ₂	1.823	17.3
O ₂	0.568	5.4
Sum	10.514	100

Test preparations also involve the weighing of the ash samples in order to determine the packing density of each cell. Ash samples have different particle size distributions, which influence their respective packing densities. Table 4-2 represents the masses obtained for the sample and the subsequent packing densities of the four test cells.

Table 5-6: Test cell dimensions and mass measurements

Cell #	Dia. (mm)	Dish mass (g)	Dish + dust mass (g)	Dust mass (g)	Packing density (g/cm ³)
1	76.2	99.3	121.1	21.80	0.99
2	70	116.7	135.8	19.10	1.03
3	70	118.8	135.8	17.00	0.89
4	70	115.9	135.2	19.30	0.99
Average				19.30	0.98

Cell 1 was packed with an ash sample from a different station and was used as a reference cell, which validated the repeatability of the test experiment. The test samples were tested for four moisture set points; these moisture set points are as per operating conditions that exist during the running of the production units and as seen in the ESP. The moisture set-points for which the resistivity tests are conducted are 0%, 7%, 10% and 13% moisture.

▪ ***At 0% moisture***

The test procedure, as described in section 4.2.6 in the design chapter, was followed. Resistivity is tested for 0% moisture and Table 5-7 shows the obtained data from the resistivity test oven. At 0% moisture, the resistivity was expected to be high, as seen on the obtained results below. Cell 1 was used as a reference test cell, which proves the repeatability of the test experiment.

Table 5-7: Ash resistivity test results at 0% moisture

MOISTURISER			Zero moisture
Water temperature	°C	0	
Moisture content in N2 gas flow	% vol.	1.1	
Moisture content in total gas flow	% vol.	0.6	

**DESCENDING
TEMPERATURES**

Time			10H07	10H55	11H45	13H25	14H25
Temperature	Oven	°C	215	185	155	125	95
Voltage	Cell 1	kV	2.00	2.00	2.00	2.00	2.00
	Cell 2	kV	2.00	2.00	2.00	2.00	2.00
	Cell 3	kV	2.00	2.00	2.00	2.00	2.00
	Cell 4	kV	2.00	2.00	2.00	2.00	2.00
Current	Cell 1	A	3.95×10^{-09}	1.09×10^{-09}	4.12×10^{-10}	2.31×10^{-10}	1.38×10^{-10}
	Cell 2	A	1.37×10^{-08}	3.28×10^{-09}	8.51×10^{-10}	3.17×10^{-10}	2.22×10^{-10}
	Cell 3	A	1.70×10^{-08}	4.28×10^{-09}	1.09×10^{-09}	3.52×10^{-10}	2.43×10^{-10}
	Cell 4	A	1.44×10^{-08}	3.32×10^{-09}	8.34×10^{-10}	3.17×10^{-10}	2.00×10^{-10}
Field strength	Cell 1	kV/cm	4.1	4.1	4.1	4.1	4.1
	Cell 2	kV/cm	4.2	4.2	4.2	4.2	4.2
	Cell 3	kV/cm	4.0	4.0	4.0	4.0	4.0
	Cell 4	kV/cm	4.0	4.0	4.0	4.0	4.0
	Averages	kV/cm	4.1	4.1	4.1	4.1	4.1
Resistivity	Cell 1	ohm.cm	5.31×10^{12}	1.93×10^{13}	5.09×10^{13}	9.09×10^{13}	1.53×10^{14}
	Cell 2	ohm.cm	1.53×10^{12}	6.42×10^{12}	2.48×10^{13}	6.64×10^{13}	9.48×10^{13}
	Cell 3	ohm.cm	1.20×10^{12}	4.79×10^{12}	1.89×10^{13}	5.83×10^{13}	8.44×10^{13}
	Cell 4	ohm.cm	$1. \times 10^{12}$	6.04×10^{12}	2.41×10^{13}	6.32×10^{13}	1.00×10^{14}
	Averages	ohm.cm	2.36×10^{12}	9.13×10^{12}	2.97×10^{13}	6.97×10^{13}	1.08×10^{14}

**Graph
Data**

Temperature	°C	Oven	215	185	155	125	95
Resistivity	ohm.cm	Cell 1	5.31×10^{12}	1.93×10^{13}	5.09×10^{13}	9.09×10^{13}	1.53×10^{14}
	ohm.cm	Cell 2	1.53×10^{12}	6.42×10^{12}	2.48×10^{13}	6.64×10^{13}	9.48×10^{13}
	ohm.cm	Cell 3	1.20×10^{12}	4.79×10^{12}	1.89×10^{13}	5.83×10^{13}	8.44×10^{13}
	ohm.cm	Cell 4	1.39×10^{12}	6.04×10^{12}	2.41×10^{13}	6.32×10^{13}	1.00×10^{14}

At 0% moisture, it is seen that the resistivity of the ash sample is at values above exponent 12, which is above the optimum ESP operating range of 1×10^8 to 1×10^{11} Ω-cm. The resistivity profile for each test cell is plotted in Figure 5-1.

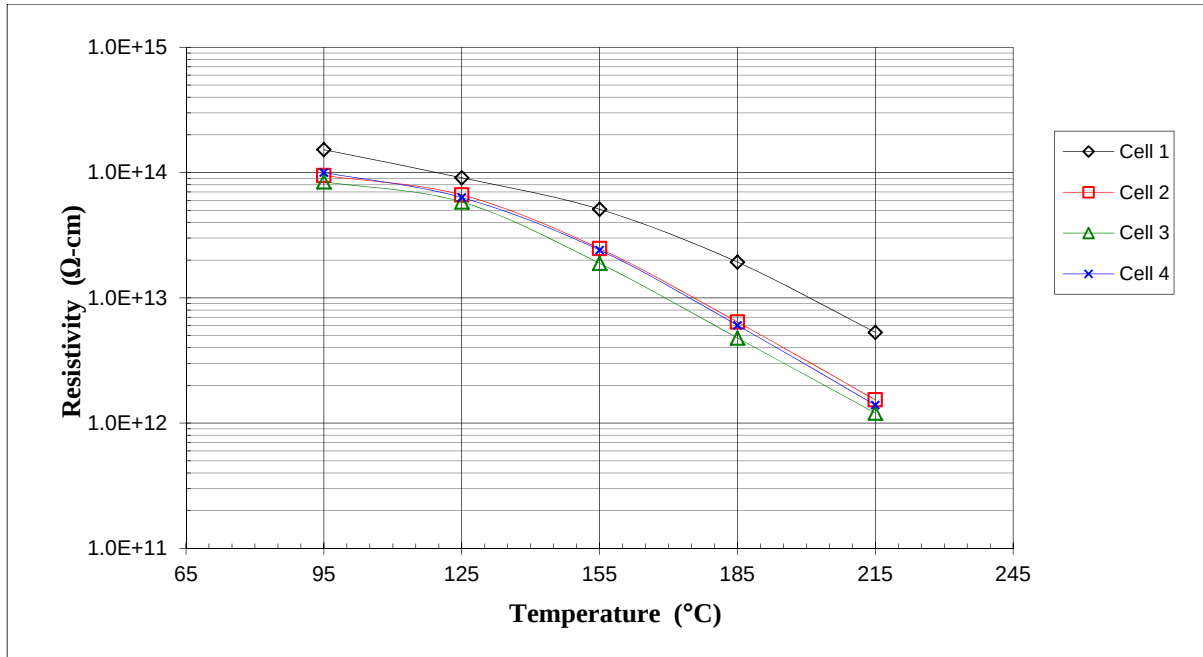


Figure 5-1: Resistivity profile at 0% moisture

Table 5-8 shows the averaged-out values for the three test cells of the test sample; the averaged-out resistivity profile has a high resistivity profile.

Table 5-8: Averaged out resistivity profile

Graph data - Cells 2-4 average

Temperature	°C	215	185	155	125	95
Resistivity	ohm.cm	1.38×10^{12}	5.75×10^{12}	2.26×10^{12}	6.26×10^{13}	9.31×10^{13}

The resistivity profile graph is plotted in Figure 5-2 for the averaged-out test cells at 0% moisture test.

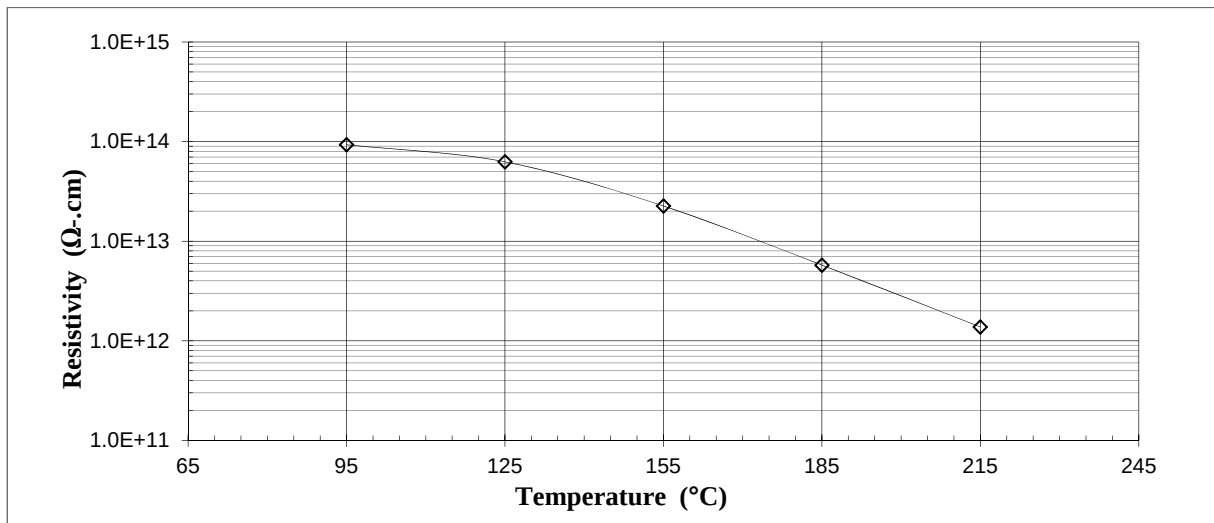


Figure 5-2: Averaged out resistivity profile at 0% moisture

The resistivity profile, as found for 0%, was excessively high. It was observed that the resistivity profile is such that at low temperature the resistivity is high, and decreases with an increase in temperature.

▪ **At 7% moisture**

Resistivity testing was conducted for 7% moisture, with an applied voltage of 2 kV; Table 5-9 illustrates the obtained results and subsequent calculated resistivity results.

Table 5-9: Resistivity test results at 7% moisture

MOISTURISER							
Water temperature	°C		55				
Moisture content in N2 gas flow	% vol.		13.3				
Moisture content in total gas flow	% vol.		10.3				

DESCENDING TEMPERATURES							
Temperature	Oven	°C	215	185	155	125	95
Voltage	Cell 1	kV	2.00	2.00	2.00	2.00	2.00
	Cell 2	kV	2.00	2.00	2.00	2.00	2.00
	Cell 3	kV	2.00	2.00	2.00	2.00	2.00
	Cell 4	kV	2.00	2.00	2.00	2.00	2.00
Current	Cell 1	A	9.69×10^{-9}	3.31×10^{-9}	1.82×10^{-9}	1.86×10^{-9}	2.34×10^{-8}
	Cell 2	A	5.27×10^{-8}	2.12×10^{-8}	1.16×10^{-8}	1.29×10^{-8}	1.10×10^{-7}
	Cell 3	A	6.15×10^{-8}	2.37×10^{-8}	1.27×10^{-8}	1.38×10^{-8}	1.13×10^{-7}
	Cell 4	A	5.53×10^{-8}	2.17×10^{-8}	1.21×10^{-8}	1.32×10^{-8}	1.18×10^{-7}
Field strength	Cell 1	kV/cm	4.1	4.1	4.1	4.1	4.1
	Cell 2	kV/cm	4.2	4.2	4.2	4.2	4.2
	Cell 3	kV/cm	4.0	4.0	4.0	4.0	4.0
	Cell 4	kV/cm	4.0	4.0	4.0	4.0	4.0
	Averages	kV/cm	4.1	4.1	4.1	4.1	4.1
Resistivity	Cell 1	ohm.cm	2.16×10^{12}	6.33×10^{12}	1.15×10^{13}	1.13×10^{13}	8.97×10^{11}
	Cell 2	ohm.cm	4.00×10^{11}	9.94×10^{11}	1.82×10^{12}	1.64×10^{12}	1.92×10^{11}
	Cell 3	ohm.cm	3.34×10^{11}	8.67×10^{11}	1.61×10^{12}	1.49×10^{12}	1.81×10^{11}
	Cell 4	ohm.cm	3.63×10^{11}	9.23×10^{11}	1.66×10^{12}	1.52×10^{12}	1.70×10^{11}
	Averages	ohm.cm	3.65×10^{11}	9.28×10^{11}	1.70×10^{12}	1.55×10^{12}	1.81×10^{11}

Graph data

Temperature	°C	Oven	215	185	155	125	95
Resistivity	ohm.cm	Cell 1	2.16×10^{12}	6.33×10^{12}	1.15×10^{13}	1.13×10^{13}	8.97×10^{11}
	ohm.cm	Cell 2	4.00×10^{11}	9.94×10^{11}	1.82×10^{12}	1.64×10^{12}	1.92×10^{11}
	ohm.cm	Cell 3	3.34×10^{11}	8.67×10^{11}	1.61×10^{12}	1.49×10^{12}	1.81×10^{11}
	ohm.cm	Cell 4	3.63×10^{11}	9.23×10^{11}	1.66×10^{12}	1.52×10^{12}	1.70×10^{11}

The obtained resistivity profile for 7% moisture is plotted in Figure 5-3. Cells 2, 3 and 4 follow the same resistivity pattern through the varying temperatures. As previously stated, test cell 1 was filled with a different ash sample, and is used to validate the repeatability of the testing procedure and obtained results.

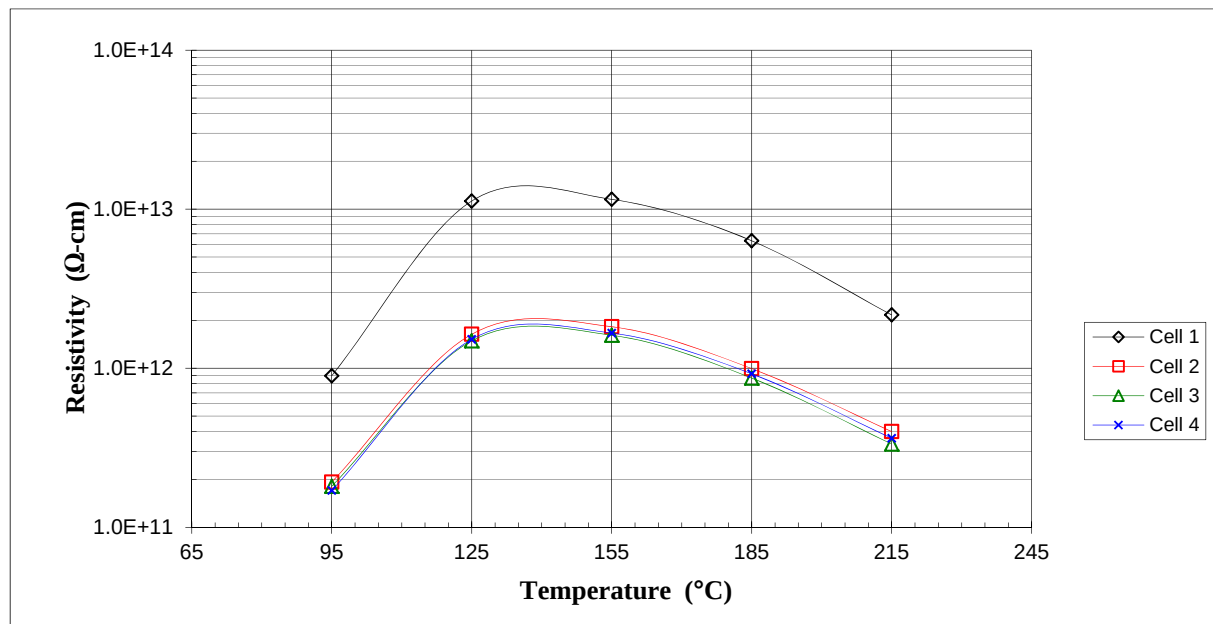


Figure 5-3: Resistivity profile plot at 7% moisture

Table 5-10 shows the averaged-out resistivity results from test cells 2, 3 and 4.

Table 5-10: Averaged out resistivity results at 7% moisture

Graph data - Cells 2-4 Average							
Temperature	°C	Oven	215	185	155	125	95
Resistivity	ohm.cm	Cell 2-4 Avg.	3.48×10^{11}	8.95×10^{11}	1.64×10^{12}	1.50×10^{12}	1.76×10^{11}

The resistivity profile for the averaged out values is plotted in Figure 5-4; the resistivity profile at 7% moisture has slightly decreased from that obtained at 0% moisture.

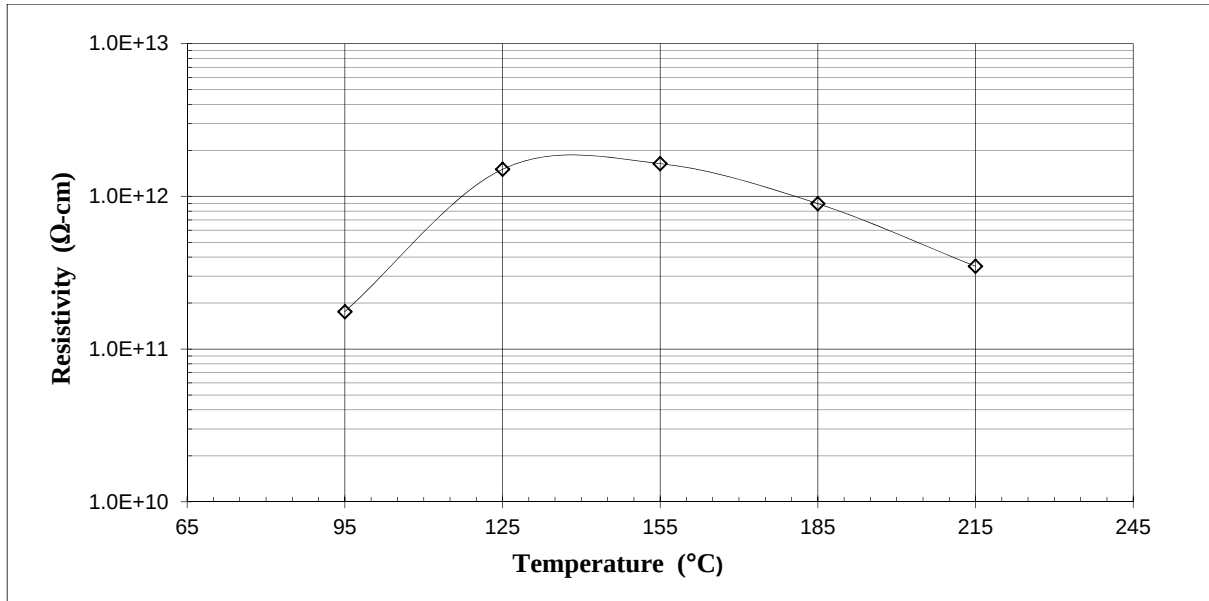


Figure 5-4: Averaged out resistivity profile at 7% moisture

The reason for the reduction in resistivity at 7% moisture compared to 0% is that the moisture in the atmosphere reduces the surface resistance of the ash sample, thereby allowing the corona current to flow easily through the ash sample.

▪ ***At 10% moisture***

Resistivity testing was conducted for 10% moisture, with an applied voltage of 2 kV; Table 5-11 illustrates the obtained results and subsequent calculated resistivity results. It is expected that the resistivity will decrease, as there is more moisture in the system and therefore reduces the surface resistance.

Table 5-11: Resistivity profile test results at 10% moisture

MOISTURISER		
Water temperature	°C	50
Moisture content in N2 gas flow	% vol.	10.7
Moisture content in total gas flow	% vol.	8.2

DESCENDING TEMPERATURES

Time			05:39	09:12	10:29	5.48E-01	6.40E-01
Temperature	Oven	°C	215	185	155	125	95
Voltage	Cell 1	kV	2.00	2.00	2.00	2.00	2.00
	Cell 2	kV	2.00	2.00	2.00	2.00	2.00
	Cell 3	kV	2.00	2.00	2.00	2.00	2.00
	Cell 4	kV	2.00	2.00	2.00	2.00	2.00
Current	Cell 1	A	1.26×10^{-8}	4.78×10^{-8}	2.80×10^{-9}	4.56×10^{-9}	8.78×10^{-8}
	Cell 2	A	6.89×10^{-8}	2.98×10^{-8}	1.81×10^{-8}	3.18×10^{-8}	4.34×10^{-7}
	Cell 3	A	8.16×10^{-8}	3.19×10^{-8}	1.94×10^{-8}	3.27×10^{-8}	5.44×10^{-7}
	Cell 4	A	7.60×10^{-8}	3.05×10^{-8}	1.87×10^{-8}	3.19×10^{-8}	6.07×10^{-7}
Field strength	Cell 1	kV/cm	4.1	4.1	4.1	4.1	4.1
	Cell 2	kV/cm	4.2	4.2	4.2	4.2	4.2
	Cell 3	kV/cm	4.0	4.0	4.0	4.0	4.0
	Cell 4	kV/cm	4.0	4.0	4.0	4.0	4.0
	Averages	kV/cm	4.1	4.1	4.1	4.1	4.1
Resistivity	Cell 1	ohm.cm	1.66×10^{12}	4.39×10^{12}	7.50×10^{12}	4.60×10^{12}	2.39×10^{11}
	Cell 2	ohm.cm	3.06×10^{11}	7.08×10^{11}	1.16×10^{12}	6.62×10^{11}	4.85×10^{10}
	Cell 3	ohm.cm	2.52×10^{11}	6.44×10^{11}	1.06×10^{12}	6.28×10^{11}	3.77×10^{10}
	Cell 4	ohm.cm	2.64×10^{11}	6.59×10^{11}	1.07×10^{12}	6.29×10^{11}	3.30×10^{10}
	Averages	ohm.cm	6.21×10^{11}	1.60×10^{12}	2.70×10^{12}	1.63×10^{12}	8.95×10^{10}

Graph Data

Temperature	°C	Oven	215	185	155	125	95
Resistivity	ohm.cm	Cell 1	1.66×10^{12}	4.39×10^{12}	7.50×10^{12}	4.60×10^{12}	2.39×10^{11}
	ohm.cm	Cell 2	3.06×10^{11}	7.08×10^{11}	1.16×10^{12}	6.62×10^{11}	4.85×10^{10}
	ohm.cm	Cell 3	2.52×10^{11}	6.44×10^{11}	1.06×10^{12}	6.28×10^{11}	3.77×10^{10}
	ohm.cm	Cell 4	2.64×10^{11}	6.59×10^{11}	1.07×10^{12}	6.29×10^{11}	3.30×10^{10}

The obtained resistivity profile for 10% moisture is plotted in Figure 5-5. Cells 2, 3 and 4 follow the same resistivity pattern through the varying temperatures. The graph shows that the resistivity is slightly below the exponent 12 mark at 125°C, which is the typical ESP operating temperature; however, this value is still above the optimum resistivity range.

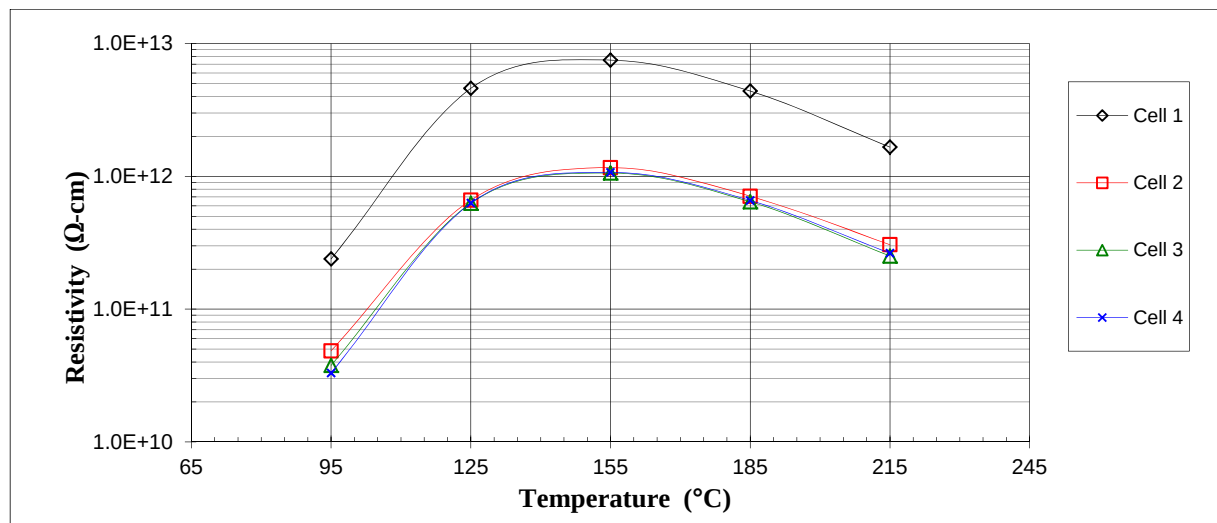


Figure 5-5: Resistivity profile at 10% moisture

Table 5-12 shows the averaged-out resistivity results from test cells 2, 3 and 4.

Table 5-12: Averaged-out resistivity at 10% moisture

Graph data - Cells 2-4 average

Temperature	°C	Oven	215	185	155	125	95
Resistivity	ohm.cm	Cell 2-4 Avg.	2.58×10^{11}	6.51×10^{11}	1.07×10^{12}	6.28×10^{11}	3.54×10^{10}

The resistivity profile for the averaged-out values is plotted in Figure 5-6; the resistivity profile at 10% moisture has slightly decreased from that obtained at 7% moisture.

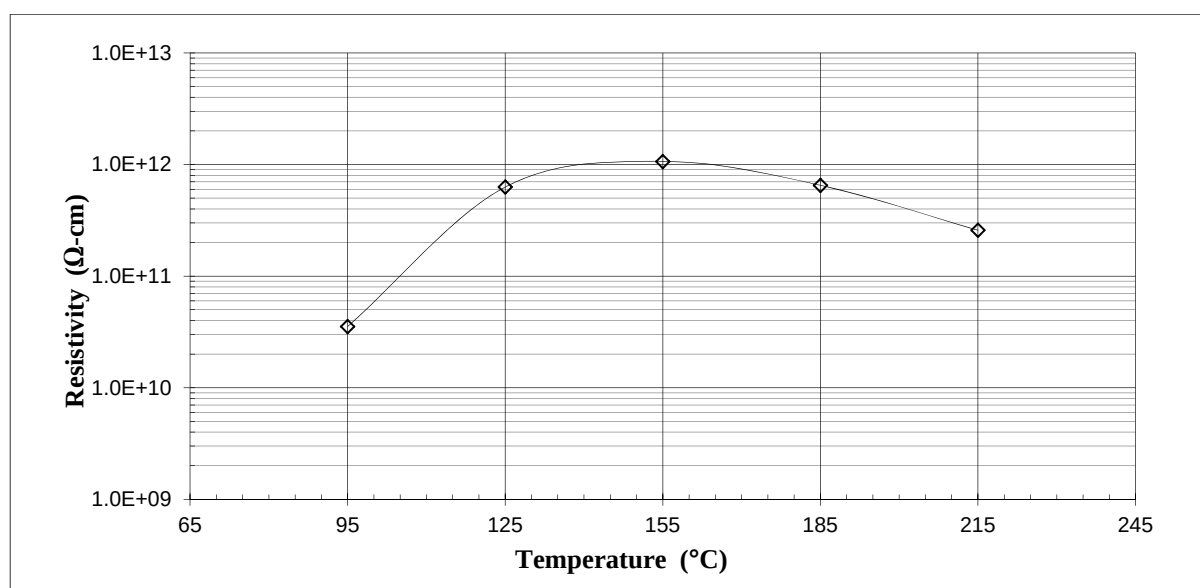


Figure 5-6: Averaged out resistivity values

▪ **At 13% moisture**

Resistivity testing was conducted for 13% moisture, with an applied voltage of 2 kV; Table 5-13 illustrates the obtained results and subsequent calculated resistivity results. It is, expected that the lowest resistivity of the ash sample will be obtained from this percentage moisture, as there is more moisture in the system to reduce the surface resistance.

Table 5-13: Ash resistivity at 13% moisture

MOISTURISER							
Water temperature			°C	61			
Moisture content in N ₂ gas flow			% vol.	17.3			
Moisture content in total gas flow			% vol.	13.4			
DESCENDING TEMPERATURES							
Temperature	Oven	°C	215	185	155	125	95
Voltage	Cell 1	kV	2.00	2.00	2.00	2.00	2.00
	Cell 2	kV	2.00	2.00	2.00	2.00	2.00
	Cell 3	kV	2.00	2.00	2.00	2.00	2.00
	Cell 4	kV	2.00	2.00	2.00	2.00	2.00
Current	Cell 1	A	1.62 x 10 ⁻⁸	5.46 x 10 ⁻⁹	5.07 x 10 ⁻⁹	1.53 x 10 ⁻⁸	1.59 x 10 ⁻⁷
	Cell 2	A	8.91 x 10 ⁻⁸	3.78 x 10 ⁻⁸	3.11 x 10 ⁻⁸	7.91 x 10 ⁻⁸	7.89 x 10 ⁻⁷
	Cell 3	A	1.04 x 10 ⁻⁷	4.01 x 10 ⁻⁸	3.24 x 10 ⁻⁸	7.88 x 10 ⁻⁸	9.31 x 10 ⁻⁷
	Cell 4	A	9.49 x 10 ⁻⁸	3.86 x 10 ⁻⁸	3.40 x 10 ⁻⁸	8.05 x 10 ⁻⁸	5.85 x 10 ⁻⁷
Field strength	Cell 1	kV/cm	4.1	4.1	4.1	4.1	4.1
	Cell 2	kV/cm	4.2	4.2	4.2	4.2	4.2
	Cell 3	kV/cm	4.0	4.0	4.0	4.0	4.0
	Cell 4	kV/cm	4.0	4.0	4.0	4.0	4.0
	Averages	kV/cm	4.1	4.1	4.1	4.1	4.1
Resistivity	Cell 1	ohm.cm	1.29 x 10 ¹²	3.84 x 10 ¹²	4.14 x 10 ¹²	1.37 x 10 ¹²	1.32 x 10 ¹¹
	Cell 2	ohm.cm	2.36 x 10 ¹¹	5.57 x 10 ¹¹	6.78 x 10 ¹¹	2.66 x 10 ¹¹	2.67 x 10 ¹⁰
	Cell 3	ohm.cm	1.97 x 10 ¹¹	5.11 x 10 ¹¹	6.33 x 10 ¹¹	2.60 x 10 ¹¹	2.20 x 10 ¹⁰
	Cell 4	ohm.cm	2.11 x 10 ¹¹	5.20 x 10 ¹¹	5.90 x 10 ¹¹	2.49 x 10 ¹¹	3.43 x 10 ¹⁰
	Averages	ohm.cm	4.84 x 10 ¹¹	1.36 x 10 ¹²	1.51 x 10 ¹²	5.36 x 10 ¹¹	5.37 x 10 ¹⁰

Graph Data

Temperature	°C	Oven	215	185	155	125	95
Resistivity	ohm.cm	Cell 1	1.29×10^{12}	3.84×10^{12}	4.14×10^{12}	1.37×10^{12}	1.32×10^{11}
	ohm.cm	Cell 2	2.36×10^{11}	5.57×10^{11}	6.78×10^{11}	2.66×10^{11}	2.67×10^{10}
	ohm.cm	Cell 3	1.97×10^{11}	5.11×10^{11}	6.33×10^{11}	2.60×10^{11}	2.20×10^{10}
	ohm.cm	Cell 4	2.11×10^{11}	5.20×10^{11}	5.90×10^{11}	2.49×10^{11}	3.43×10^{10}

The obtained resistivity profile for 10% moisture is plotted in Figure 5-7. Cells 2, 3 and 4 follow the same resistivity pattern through the varying temperatures. The graph shows that the resistivity is slightly below the exponent 12 mark at 125°C. 125°C is a typical ESP operating temperature; however, this value is still above the optimum resistivity range as prescribed for ESP operations.

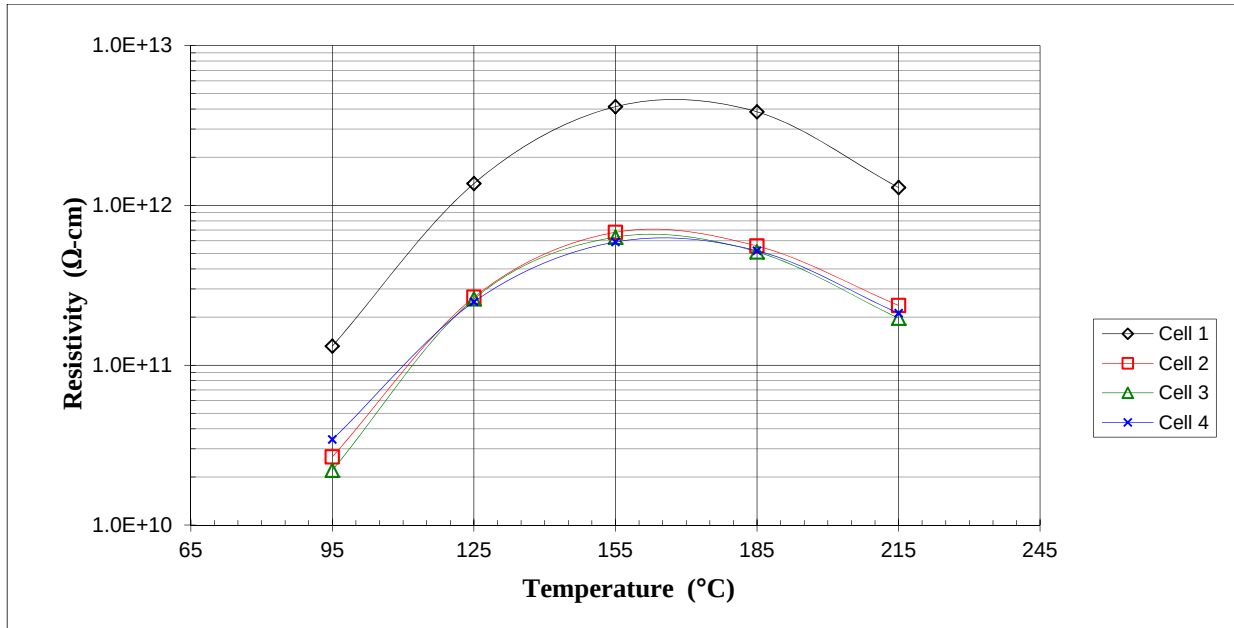


Figure 5-7: Ash resistivity profile at 13% moisture

Table 5-14 shows the averaged-out resistivity results from test cells 2, 3 and 4.

Table 5-14: Averaged-out resistivity profile at 13% moisture

Graph data - Cells 2-4 average

Temperature	°C	Oven	215	185	155	125	95
Resistivity	ohm.cm	Cell 2-4 Avg.	2.04×10^{11}	5.16×10^{11}	6.11×10^{11}	2.55×10^{11}	2.82×10^{10}

The resistivity profile for the averaged-out values is plotted in Figure 5-8; the resistivity profile is at 13%.

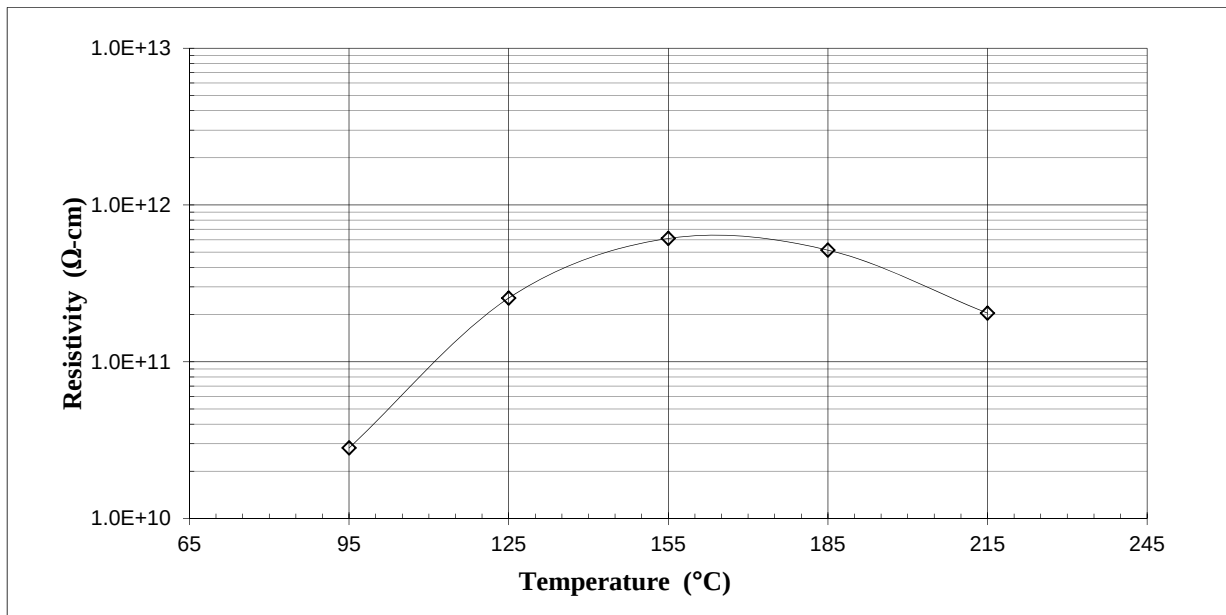


Figure 5-8: Averaged out resistivity profile at 13% moisture

▪ **0 to 13% moisture**

A comparison of how the resistivity is affected by moisture was conducted and found that moisture reduces the resistivity of the ash. The moisture coats the surface of the dust particles and this creates a path for the corona current to flow to ground. It is observed that, based on the typical operating criteria for the power station, the ash resistivity profile is above that of the documented optimum resistivity for which an ESP can operate optimally. Table 5-15, illustrates the obtained results for all the tests conducted for the different moisture set points.

Table 5-15: Resistivity profile of the ash for tested moisture set points

Temperature	°C	Moisture	215	185	155	125	95
Resistivity	ohm.cm	0%	1.38×10^{12}	5.75×10^{12}	2.26×10^{13}	6.26×10^{13}	9.31×10^{13}
	ohm.cm	7%	3.48×10^{11}	8.95×10^{11}	1.64×10^{12}	1.50×10^{12}	1.76×10^{11}
	ohm.cm	10%	2.58×10^{11}	6.51×10^{11}	1.07×10^{12}	6.28×10^{11}	3.54×10^{10}
	ohm.cm	13%	2.04×10^{11}	5.16×10^{11}	6.11×10^{11}	2.55×10^{11}	2.82×10^{10}

The resultant resistivity profiles are plotted in Figure 5-9, highlighting the reduction in resistivity as a result of moisture.

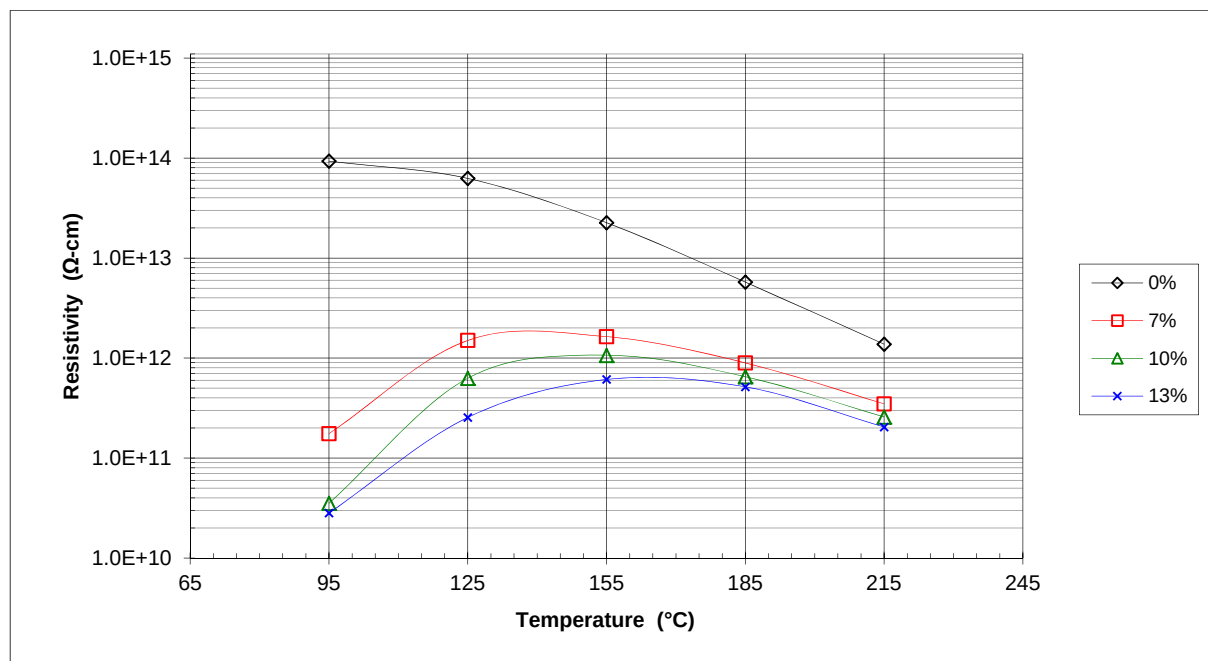


Figure 5-9: Ash resistivity profile for different moisture content

The desired resistivity range for efficient ESP operation is 1×10^8 to 1×10^{11} Ω-cm. The desired resistivity is achieved at low temperatures; however, ESPs operate at temperature ranges of 110 to 150°C. The high resistivity results indicate that the ESPs are operating under back-

corona effects. Therefore, it is difficult to achieve the set emissions limit of 75 mg/Nm³ due to particle re-entrainment resulting from the high resistivity.

5.2.4 Mixed kV ash resistivity results

In the mixed voltage/mixed-kV method, the measured voltage prior to spark-over is used to determine the ash resistivity of the ash sample as it represents the breakdown voltage of the dust layer. The test was conducted under constant temperature and moisture; at 125°C and 10% moisture. These are the average operating conditions in which the test power station's ESP operates. Table 5-16 illustrates the obtained results for the mixed kV test.

Table 5-16: Mixed kV test results.

MOISTURISER						
Water temperature		°C	55			
Moisture content in N ₂ gas flow		% vol.	13.3			
Moisture content in total gas flow		% vol.	10.3			
CONSTANT TEMPERATURES						
Temperature	Oven	°C	125	125	125	125
Voltage	Cell 1	kV	2.00	4.00	6.00	8.00
	Cell 2	kV	2.00	4.00	6.00	8.00
	Cell 3	kV	2.00	4.00	6.00	8.00
	Cell 4	kV	2.00	4.00	6.00	8.00
Current	Cell 1	A	1.47 x 10 ⁻⁸	3.23 x 10 ⁻⁸	5.73 x 10 ⁻⁸	8.25 x 10 ⁻⁸
	Cell 2	A	5.96 x 10 ⁻⁸	1.15 x 10 ⁻⁷	1.87 x 10 ⁻⁷	2.36 x 10 ⁻⁷
	Cell 3	A	6.03 x 10 ⁻⁸	1.15 x 10 ⁻⁷	1.87 x 10 ⁻⁷	2.62 x 10 ⁻⁷
	Cell 4	A	5.93 x 10 ⁻⁸	1.17 x 10 ⁻⁷	1.89 x 10 ⁻⁷	2.60 x 10 ⁻⁷
Field strength	Cell 1	kV/cm	4.1	8.3	12.4	16.6
	Cell 2	kV/cm	4.2	8.3	12.5	16.6
	Cell 3	kV/cm	4.0	8.1	12.1	16.2
	Cell 4	kV/cm	4.0	7.9	11.9	15.8
	Averages	kV/cm	4.1	8.2	12.2	16.3
Resistivity	Cell 1	ohm.cm	1.43 x 10 ¹²	1.30 x 10 ¹²	1.10 x 10 ¹²	1.02 x 10 ¹²
	Cell 2	ohm.cm	3.53 x 10 ¹¹	3.66 x 10 ¹¹	3.38 x 10 ¹¹	3.57 x 10 ¹¹
	Cell 3	ohm.cm	3.40 x 10 ¹¹	3.56 x 10 ¹¹	3.30 x 10 ¹¹	3.13 x 10 ¹¹
	Cell 4	ohm.cm	3.38 x 10 ¹¹	3.43 x 10 ¹¹	3.18 x 10 ¹¹	3.09 x 10 ¹¹
	Averages	ohm.cm	6.16 x 10 ¹¹	5.91 x 10 ¹¹	5.21 x 10 ¹¹	4.99 x 10 ¹¹

Graph data

Field strength	kV/cm		4.1	8.2	12.2	16.3
Resistivity	ohm.cm	Cell 1	1.43×10^{12}	1.30×10^{12}	1.10×10^{12}	1.02×10^{12}
	ohm.cm	Cell 2	3.53×10^{11}	3.66×10^{11}	3.38×10^{11}	3.57×10^{11}
	ohm.cm	Cell 3	3.40×10^{11}	3.56×10^{11}	3.30×10^{11}	3.13×10^{11}
	ohm.cm	Cell 4	3.38×10^{11}	3.43×10^{11}	3.18×10^{11}	3.09×10^{11}

The test results show that the resistivity of 3×10^{11} Ω-cm is slightly higher than the prescribed 1×10^{11} Ω-cm. Figure 5-10 illustrates the plotted graph for the obtained results.

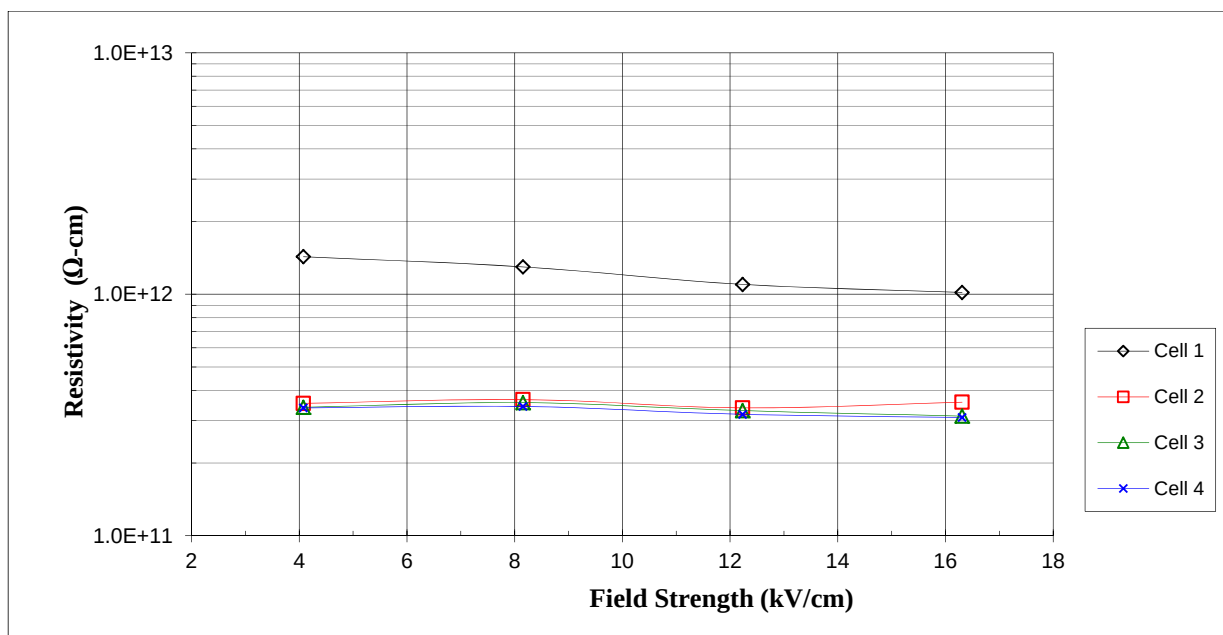


Figure 5-10: Mixed kV resistivity results

Table 5-17 presents the averaged-out resistivity values for the test sample for different voltages applied to the test samples during testing.

Table 5-17: Averaged-out resistivity results

Graph data - Cells 2-4 average

Field strength	kV/cm		4.1	8.2	12.2	16.3
Resistivity	ohm.cm	Cell 2-4 Avg	3.44×10^{11}	3.50×10^{11}	3.24×10^{11}	3.11×10^{11}

Figure 5-11 presents there graphical representation of the resistivity results for the mixed kV test. The spark-over voltage for the ash sample was found to be 8 kV. The obtained resistivity results at 125°C and 10% moisture indicate that the ESPs are operating on the borderline of optimum resistivity and high resistivity ash. There it is expected that the ESP should perform efficiently provided that it is in a good mechanical condition – all rapping systems functional and electrode alignment is within specification.

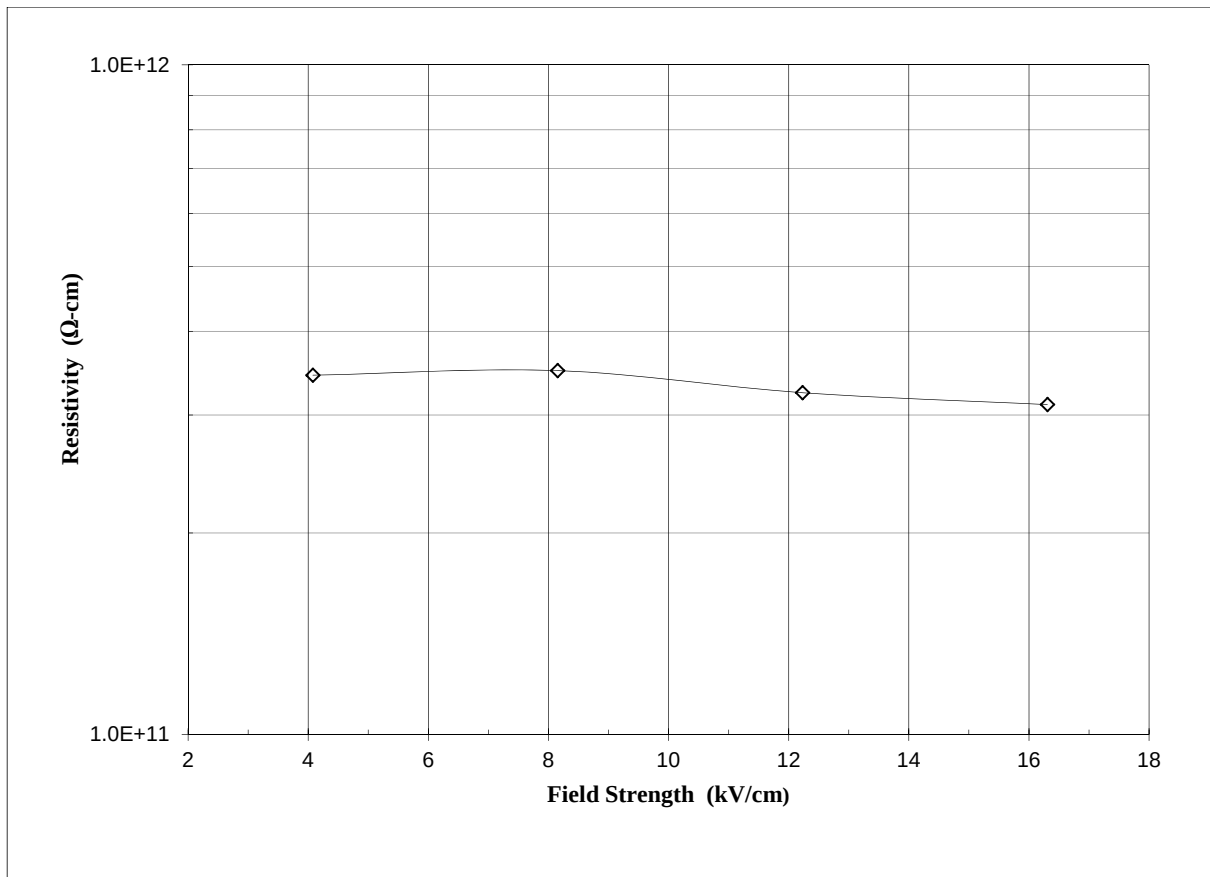


Figure 5-11: Graphical profile of the averaged out resistivity

5.2.5 Verification and validation

The obtained results were verified by comparing them with those obtained from the Southern Research Institute. The test was conducted for 6.1% moisture and the obtained results are displayed in Table 5-18.

Table 5-18: Resistivity result obtained by the Southern Research Institute

Southern Research Institute (SRI) – Resistivity measurements					
Descending test					
Date: 05 November 2013					
Sample:					Resistivity
A/L	Volts	Amps	°C	°F	ohm-cm
1.91	2000	3.15×10^{-6}	421	790	1.21×10^9
1.91	2000	7.10×10^{-7}	371	700	5.38×10^9
1.91	2000	1.30×10^{-7}	317	603	2.94×10^{10}
1.91	2000	3.40×10^{-8}	276	529	1.12×10^{11}
1.91	2000	8.60×10^{-9}	238	460	4.44×10^{11}
1.91	2000	2.80×10^{-9}	199	390	1.36×10^{12}
1.91	2000	1.30×10^{-9}	166	331	2.94×10^{12}
1.91	2000	8.80×10^{-10}	133	271	4.34×10^{12}
1.91	2000	1.50×10^{-9}	109	228	2.55×10^{12}
1.91	2000	7.80×10^{-9}	87	189	4.90×10^{11}

The test was conducted at 2 kV for descending temperature, with the lowest resistivity obtained at excessively high temperatures above 400°C and at 133°C the resistivity is in the range of exponent 12. The obtained results are plotted in Figure 5-12; the profile is similar to that obtained with the internal testing.

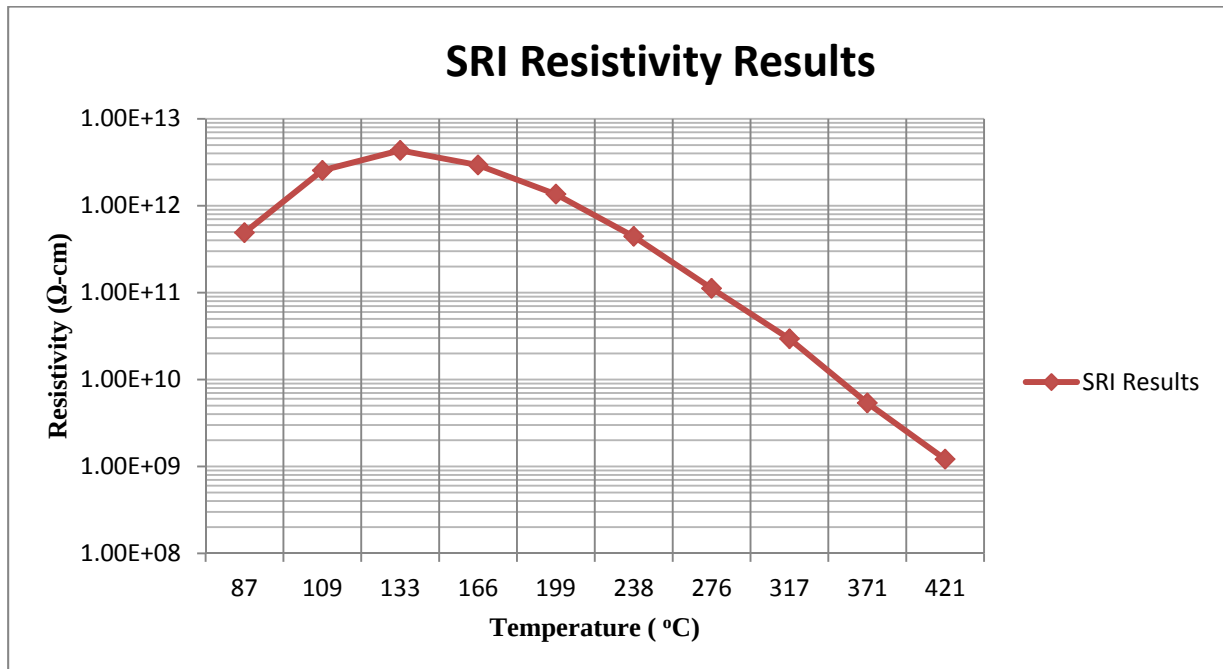


Figure 5-12: SRI resistivity results at 6.1% moisture

Testing conducted by the Southern Research Institute was conducted at 6.1% moisture. The obtained results are compared to those obtained internally in the testing conducted at RT&D at 7% moisture. Figure 5-13 plots the two resistivity results as obtained by the SRI and those obtained internally.

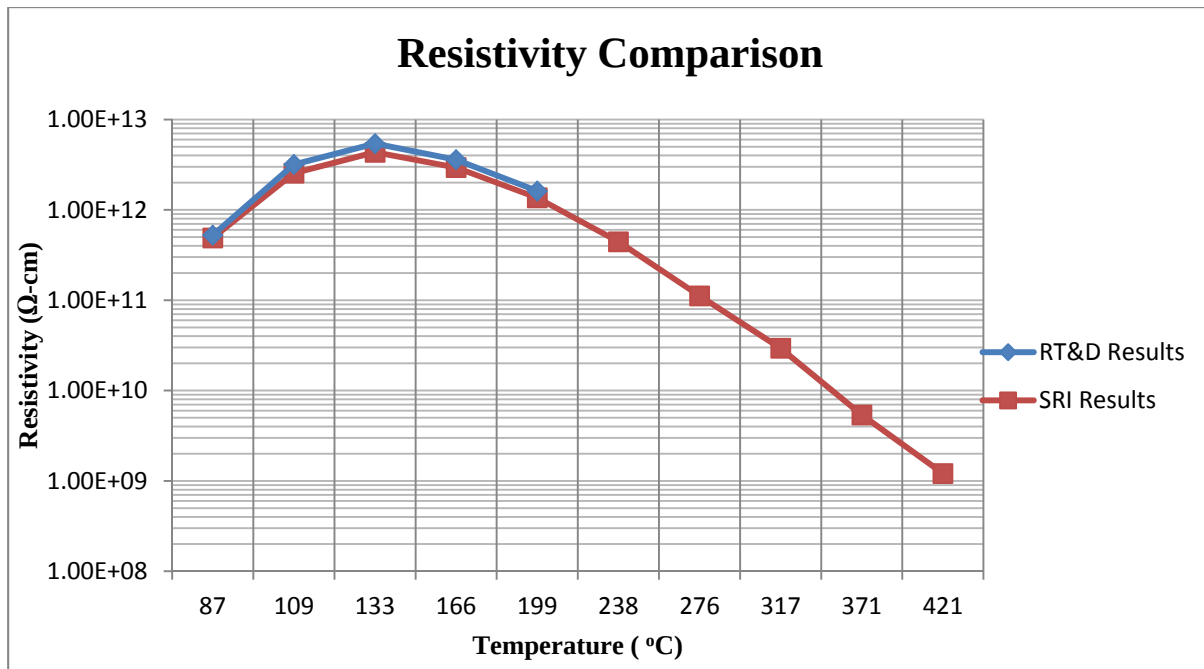


Figure 5-13: Resistivity result comparison from Eskom and Southern Research Institute

The resistivity profile of both the test results share a similar profile, although those obtained from the Southern Research Institute have more data plots as testing was done for temperatures above the 215°C. This is therefore used to verify the results obtained through Eskom's internal testing process and therefore the testing procedure was validated to obtain accurate results.

5.3 ESP performance testing for different power supplies

The ESP performance test was conducted for both power supply technologies; the test mainly focuses on the process parameters in terms of flue gas volume flow in and out of the ESP and other process conditions such as coal quality. Isometric sampling was conducted on the inlet and outlet duct of the ESP casings; these representative samples are used to determine the collection efficiency of the ESP. Particulate emission measurements were carried out employing procedures and equipment that comply with the requirements of EN 13284-1. The VDI correlation procedure was followed in the determination of the linear regression of the correlation spot check.

For the purpose of this dissertation, mainly the electrical parameter during the process of the efficiency test was used. The electrical condition of the ESP fields was monitored and analysed; this analysis was done to determine the performance of the fields relative to one another, while determining the overall ESP efficiency for both power supplies. Plant measurements are conducted in accordance with the following metering standards; Eskom

Metering Strategy; 240-48907866 and Metering and Measurement Systems for Power Stations in Generation Standard; 240-563590.

5.3.1 SO₃ plant performance

An important aspect of the plant performance, to ensure that low emissions can be obtained, was to ensure that the SO₃ plant was fully in service and dosing at 18 ppm. Figure 5-14 illustrates a screen print of the SO₃ plant during operation. The boiler load determines the dosage rate, and at full load (618 MW), the dosage rate is 55 kg/hr, which is equivalent to 18 ppm.

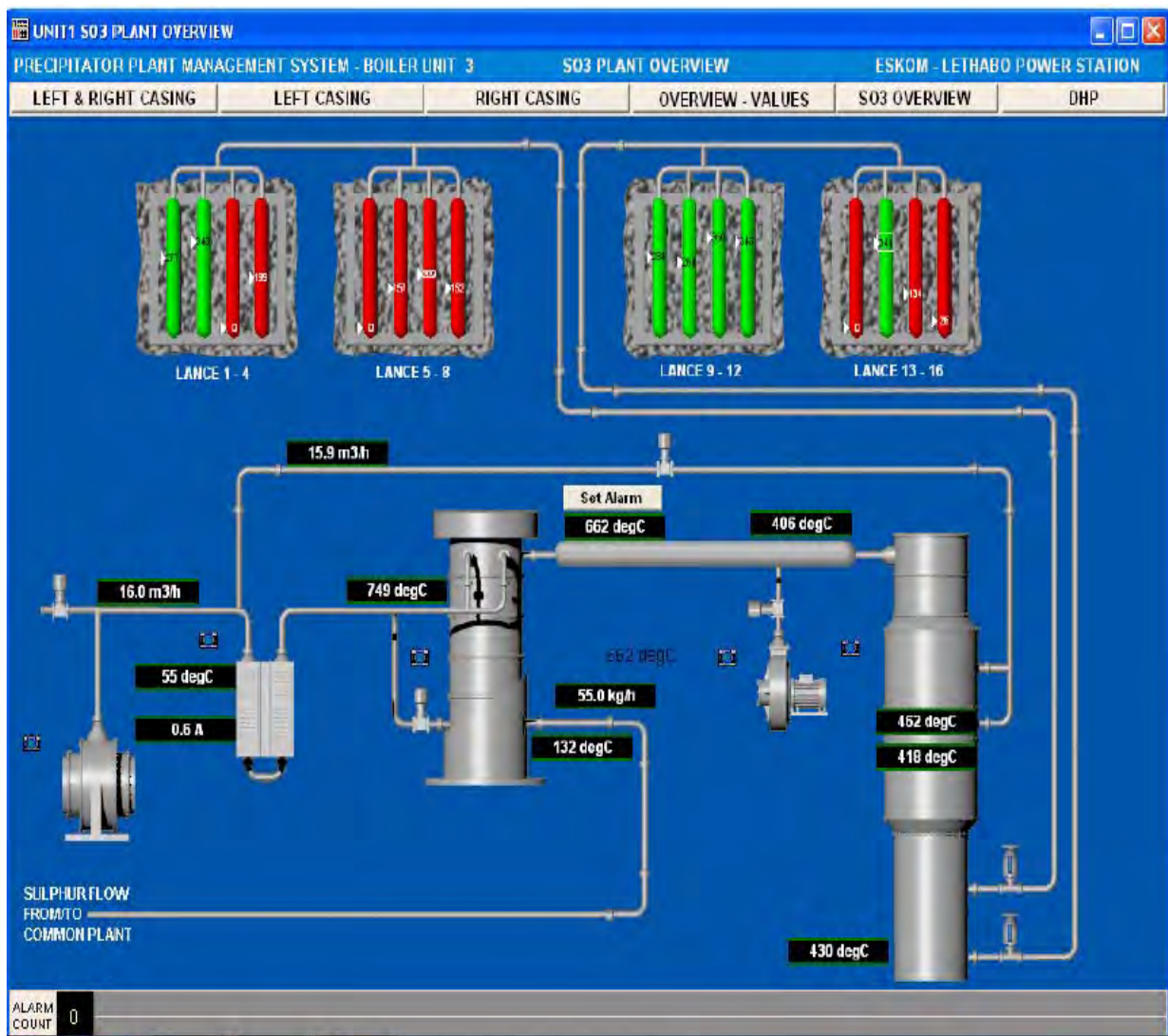


Figure 5-14: SO₃ plant performance snap shot

The SO₃ plant utilised to reduce the resistivity of the flue gas allows for the effective and efficient collection of the dust burden. Lowering the resistivity of the flue gas reduces sparking in the fields and therefore minimises the possibility of back corona occurring in the

fields. The lowered resistivity ensures that the charged particles that are collected easily lose charge once they reach the collector plate, which is earthed. The losing of the attained charge also ensures that the collected dust burden is collected easily during the rapping process.

5.3.2 Post-outage ESP performance with conventional TR sets

The acceptable performance criteria for conventional power supply transformers are indicated in Table 5-19. These performance criteria were developed based on plant performance history and experience.

Table 5-19: Convectional power supply performance criteria

Field	Secondary voltage	Secondary current
	Max Vs	Max Is
1	> 35	> 350
2	> 35	> 350
3	> 35	> 400
4	> 35	> 700
5	> 35	> 1000
6	> 30	> 1000
7	> 30	> 1200

It can be seen from the table that the expected current for the first four fields is less than 1 000 mA, and this is a result of the high flue gas burden seen by the first four fields and results in the conventional TR sets struggling to maintain currents above 1 000 mA. The expected voltage input into the fields is above 35 kV, even though the TR sets are rated for 70 kV_{Peak} and should theoretically produce 55 kV_{RMS}. Historical data has shown that conventional TR sets struggle to maintain voltage above 35 kV. The ideal performance criterion for an ESP is to have all the fields producing at least 55 kV with 1 700 mA; therefore, maximum power input would be 93.5 kW per field and 654.5 kW per casing.

The ESP efficiency test was conducted on 9 and 11 May 2014; Table 5-21 shows the measured historical data of the ESP performance at that time. The data shows the representative performance of the ESP plant for a period of seven days. The emission measurement and generated load and field performance are recorded into the historical data. The data is sampled and recorded for every 30 seconds. The data is subsequently averaged out for hourly performance and then daily average performance of each individual field.

Voltage-current curve measurements were conducted for each individual field; Table 5-20 shows the obtained results for the left hand outer casing. These results are analysed to determine the ESP field conditions.

Table 5-20: V-I curve results for LHO casing

LHO 1		LHO 2		LHO 3		LHO 4		LHO 5		LHO 6		LHO 7		Percentage
kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	%
														0
22.2	10	16.7	10	16.2	10	16.5	10	13	18	3	19	9	10	5
27	20	18.9	20	18	20	18.3	20	18	18	4	20	12	11	10
32.2	50	21.5	50	21.2	50	21.4	50	22	23	5	24	14	13	15
36.2	100	25.4	100	24.4	100	26.5	100	25	40	6	36	17	29	20
40.6	200	29	200	28.1	200	29.7	200	31	80	7	66	19	60	25
44.6	400	33.6	400	32.2	400	34.4	400	33	164	8	136	21	115	30
48.1	600	37.1	600	35.1	600	38.2	600	36	280	9	228	23	200	40
49.7	700	40.2	800	38.4	800	41.6	800	42	590	12	517	27	462	50
		44.5	1200	43	1200	46.9	1200	46	975	14	898	30	831	60
		48	1600	46.6	1600	51.3	1600	50	1285	16	1319	33	1246	70
		48.3	1700	47.4	1700	52.3	1700			18	1700	35	1642	80
Power (kW)	34.8		82.1		80.6		88.9		64.3		30.6		57.5	438.7

Figure 5-15 illustrates the voltage-current graph as plotted from the data obtained from Table 5-20. The shape of the plotted graphs illustrates the condition of each field, as they were during the ESP efficiency test. Ideally, the voltage current should be such that the voltage and current peaks are as high as possible, i.e. voltage of approximately 50 kV at a current of 1600 mA.

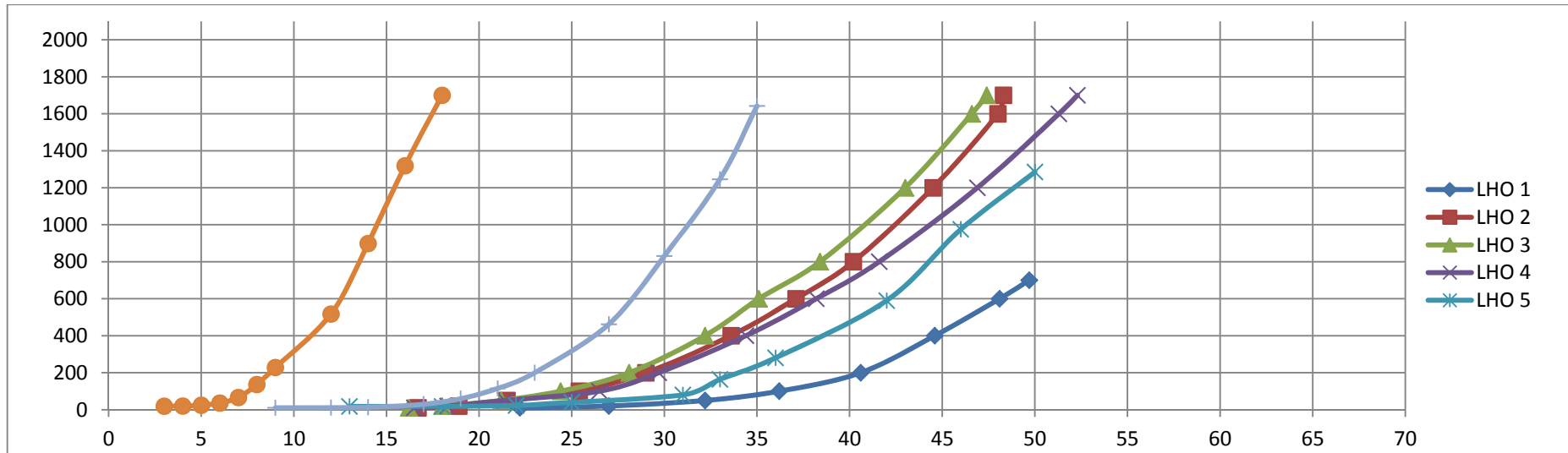


Figure 5-15: V-I curve plots for LHO casing

The interpretation of the plotted graphs for the LHO casing is as follows:

- LHO 1 had a high corona onset voltage of 36 kV, and the field is producing 50 kV at 700 mA.
- LHO 2 had an ideal V-I curve profile, produces full load secondary current at 48 kV.
- LHO 3 had an ideal V-I curve profile, produces full load secondary current at 47 kV.
- LHO 4 had an ideal V-I curve profile, produces full load secondary current at 52 kV.
- LHO 5 had a slightly high corona onset voltage of 33 kV, and the field was able to produce 1 200 mA at 50 kV.
- LHO 6 had a low corona onset voltage, and the field produces 18 kV at 1 700 mA. The reason for the low voltage reading is due to an electrode being misaligned.
- LHO 7 had a low corona onset voltage and was able to produce a maximum current at 35 kV.

All in the LHI casing had all seven fields, which is a 100% of the casing performing within specifications.

Table 5-21 presents the values obtained in performing V-I curve measurements on the LHI casing.

Table 5-21: V-I curve results for LHI casing

LHI 1		LHI 2		LHI 3		LHI 4		LHI 5		LHI 6		LHI 7		Percentage
kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	%
														0
21.8	10	29.7	10	25.4	10	23	10	9	9	13	20	11	22	5
26.3	20	31.4	20	26.7	20	25.9	20	19	10	17	21	14	23	10
32.2	50	34.8	50	30.2	50	28.7	50	23	12	21	22	18	27	15
35	100	38	100	33.9	100	31.5	100	26	23	24	30	21	30	20
38.8	200	41.6	200	37.7	200	34.7	200	29	58	26	48	23	54	25
41	351	45.1	400	41.8	400	38.1	400	32	142	28	86	25	94	30
		47.6	600	46.5	460	40.8	600	35	290	31	150	27	163	40
		49.1	800			43.3	800	39	722	35	360	30	384	50
		50.3	950			46.6	1200	42	1296	38	672	33	705	60
						47.2	1300	45	1700	41	1032	36	1075	70
										42	1371	38	1430	80
										44	1640	40	1700	90
Power (kW)	14.4		47.8		16.7		61.4		76.5		72.2		68.0	356.9

Figure 5-16 illustrates the voltage-current graph as plotted from the data obtained from Table 5-21.

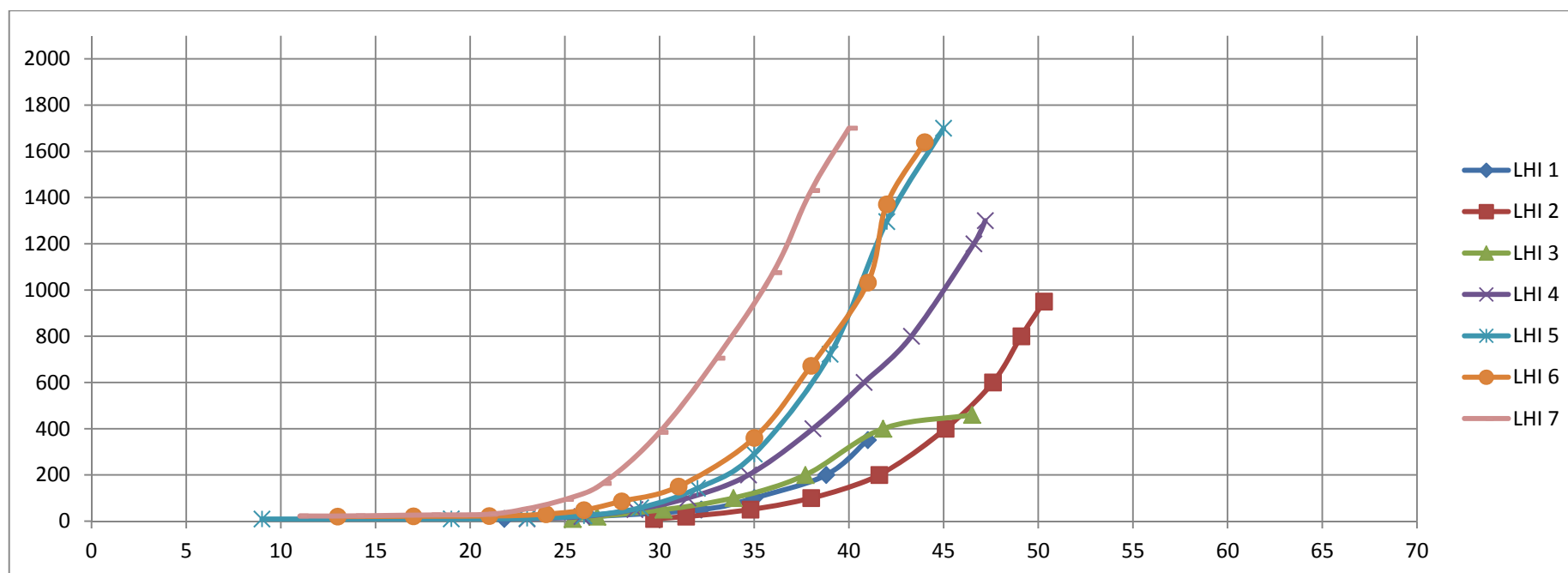


Figure 5-16: V-I curve plot for the LHI casing

The interpretation of the plotted graphs for the LHI casing is as follows:

- LHI 1 and 3 performed poorly and only managed to achieve a current of 400 mA at 42 kV and 460 mA at 46 kV, respectively. The probable cause for this low performance could have been a discharge electrode rapping system that was not functional at the time.
- The rest of the fields had ideal V-I curve profiles and were able to produce the desired output current and voltage.

All in the LHI casing had five fields out of seven fields, which is 71% of the casing performing within specifications.

Table 5-22 presents the values obtained in performing V-I curve measurements on the RHI casing.

Table 5-22: V-I curve results for RHI casing

RHI 1		RHI 2		RHI 3		RHI 4		RHI 5		RHI 6		RHI 7		Percentage
kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	%
														0
19.6	10	25.5	10	24.2	10	21.7	10	11	13	4	21	8	17	5
23.6	20	27.5	20	26.8	20	23.2	20	17	15	8.6	22	12	19	10
29.3	50	31.5	50	29.7	50	25.5	50	20	19	10.4	24	15	22	15
33.2	100	33.9	100	31.9	100	27.7	100	23	29	12	35	18	35	20
36.2	200	36.8	200	34.8	200	30.4	200	26	60	13	64	20	66	25
39.6	400	39.1	400	37.7	400	33.4	400	29	140	15	135	22	120	30
42	600	41.5	600	39.9	600	35.7	600	31	255	16	245	24	206	40
43.9	800	43.7	800	42.1	800	38.1	800	35	582	18	560	27	483	50
46.4	1200	46.3	1200	45.1	1200	41.2	1200	38	1015	20	968	30	881	60
47.1	1300			47.2	1600	43.6	1600	40	1482	22	1426	33	1330	70
				47.7	1700	44	1700	43	1700	24	1700	35	1700	80
														90
Power	61.2		55.6		75.5		69.8		59.3		31.4		43.9	396.6

Figure 5-17 illustrates the voltage-current graph as plotted from the data obtained from Table 5-22.

The interpretation of the plotted graphs for the RHI casing is as follows:

- All the RHI casing fields were performing up to specification, with the exception of RHI 6, which exhibited signs of electrode misalignment, giving the casing 86% fields performing up to specification.

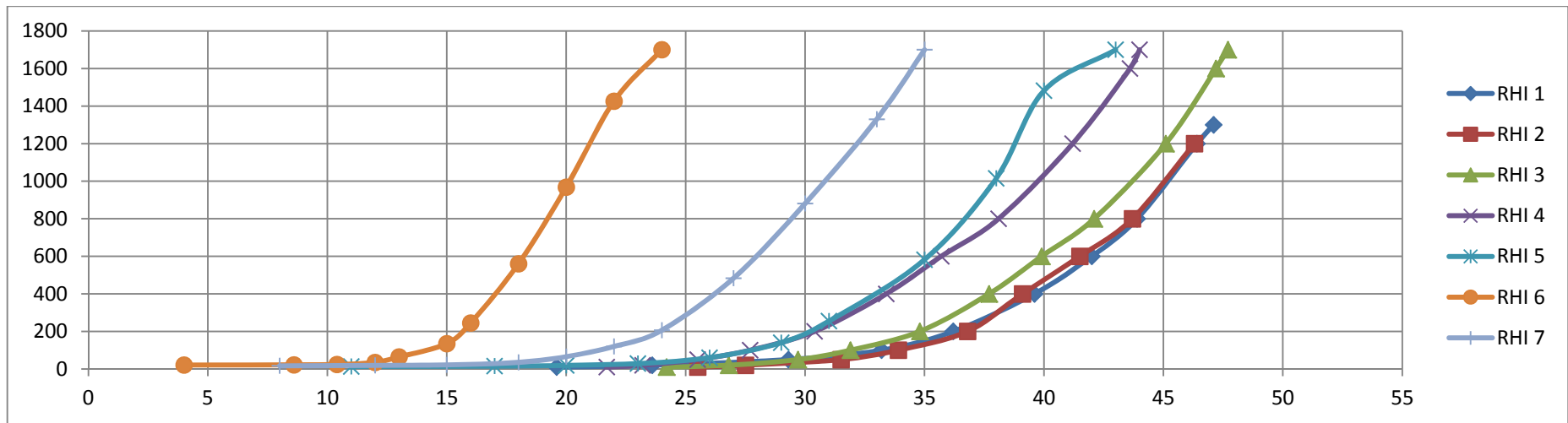


Figure 5-17: V-I Curve plot for the RHI casing

Table 5-23 presents the obtained values obtained in performing V-I curve measurements on the RHO casing.

Table 5-23: V-I curve measurement for the RHO casing

RHO 1		RHO 2		RHO 3		RHO 4		RHO 5		RHO 6		RHO 7		Percentage
kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	kV	mA	%
														0
19	10	16.2	10	15	10	15.4	10	8	15	4	23	13	23	5
22.7	20	18.6	20	17	20	16.6	20	9	16	5	24	16	49	10
26.7	50	21.5	50	19.3	50	18.8	50	11	20	6	27	18	83	15
30.3	100	24.7	100	21.6	100	21	100	13	32	7	40	20	137	20
33.7	200	28.3	200	24.4	200	23.8	200	15	62	8	72	22	222	25
37.1	400	32.2	400	27.4	400	27.1	400	16	128	9	134	24	326	30
39.1	600	35.3	600	29.7	600	29.7	600	18	231	10	230	26	464	40
40.4	800	38.2	800	32.2	800	32.5	800	21	512	12	532	29	800	50
42.5	1200	42.1	1200	35.5	1200	36.2	1200	24	874	14	950	32	1216	60
43.7	1592	44.8	1600	38.2	1600	39.7	1600	26	1272	15	1421	35	1643	70
		45.1	1700	38.7	1700	40.2	1700	28	1700	16	1700	36	1700	80
														90
Power	69.6		71.7		61.1		63.5		33.1		21.3		57.5	416.4 kW

Figure 5-18 illustrates the voltage-current graph as plotted from the data obtained from Table 5-23.

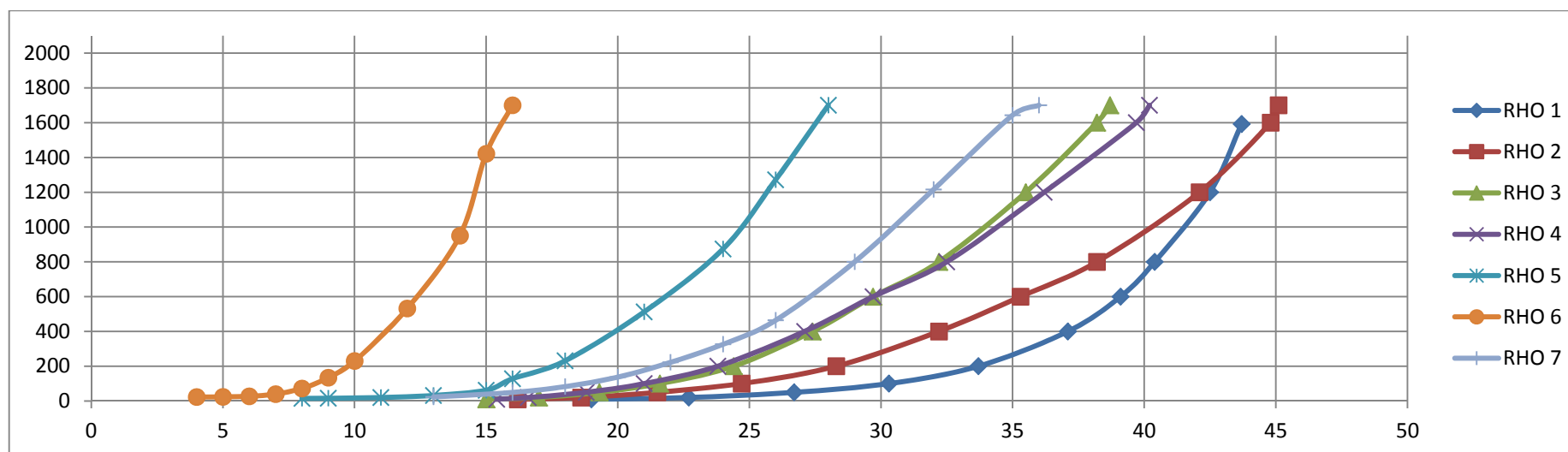


Figure 5-18: V-I Curve for the RHO casing

The interpretation of the plotted graphs for the RHO casing is as follows:

- The RHO casing's fields were all performing within acceptable specifications, with the exception of RHO 2 and 3, which had extremely high corona onsets.

All in the RHO casing had five fields out of seven fields, which is 71% of the casings performing within specifications.

Table 5-24: Conventional TR set ESP performance

	Eff Em	Gen load	LHO 1 Is	LHO 1 Vs	LHO 2 Is	LHO 2 Vs	LHO 3 Is	LHO 3 Vs	LHO 4 Is	LHO 4 Vs	LHO 5 Is	LHO 5 Vs	LHO 6 Is	LHO 6 Vs	LHO 7 Is	LHO 7 Vs	Total Casing Power Output (kW)
06/05/2014	64	589	82	39	778	46	286	33	396	46	450	45	137	18	1441	32	136
07/05/2014	52	531	141	43	1183	47	633	37	468	47	850	52	120	19	1433	32	198
08/05/2014	79	526	67	28	476	31	111	24	294	32	369	32	80	12	1030	22	64
09/05/2014	60	572	112	41	884	47	810	33	514	45	777	45	112	18	1519	31	180
10/05/2014	41	619	104	40	785	46	1561	32	433	46	1377	44	123	19	1680	33	228
11/05/2014	37	619	129	42	753	46	1439	32	451	47	1391	45	131	19	1679	32	227
12/05/2014	34	615	64	18	537	47	1332	33	439	47	1399	45	66	19	1674	32	210
			LHI 1 Is	LHI 1 Vs	LHI 2 Is	LHI 2 Vs	LHI 3 Is	LHI 3 Vs	LHI 4 Is	LHI 4 Vs	LHI 5 Is	LHI 5 Vs	LHI 6 Is	LHI 6 Vs	LHI 7 Is	LHI 7 Vs	
06/05/2014			196	54	279	30	123	38	657	45	1690	41	1589	37	1474	34	232
07/05/2014			203	55	325	29	205	38	728	45	1627	42	1572	38	1475	35	240
08/05/2014			197	39	246	20	305	27	600	31	1191	29	1182	27	1462	33	154
09/05/2014			209	54	283	31	151	38	480	46	1676	42	1504	37	1511	34	224
10/05/2014			143	35	250	30	70	38	275	47	1582	42	1415	37	1615	35	204
11/05/2014			83	29	305	30	87	39	442	46	1563	43	1541	39	1651	36	221
12/05/2014			136	52	239	31	82	39	584	46	1610	43	1601	40	1660	36	237
			RHI 1 Is	RHI 1 Vs	RHI 2 Is	RHI 2 Vs	RHI 3 Is	RHI 3 Vs	RHI 4 Is	RHI 4 Vs	RHI 5 Is	RHI 5 Vs	RHI 6 Is	RHI 6 Vs	RHI 7 Is	RHI 7 Vs	
06/05/2014			455	49	349	54	682	40	241	53	795	21	927	21	1340	32	161
07/05/2014			576	52	301	58	958	41	320	55	0	0	928	21	1414	32	169
08/05/2014			568	49	347	55	863	37	406	46	890	18	925	19	1565	29	176
09/05/2014			407	50	247	57	716	41	519	48	1604	43	1004	21	1260	31	218
10/05/2014			321	50	195	56	643	41	1352	46	1533	43	1132	21	1184	32	243
11/05/2014			318	50	274	56	680	42	1359	48	1560	43	1134	21	1181	32	253
12/05/2014			337	50	260	57	670	43	1071	46	1513	43	1465	22	1386	33	252
			RHO 1 Is	RHO 1 Vs	RHO 2 Is	RHO 2 Vs	RHO 3 Is	RHO 3 Vs	RHO 4 Is	RHO 4 Vs	RHO 5 Is	RHO 5 Vs	RHO 6 Is	RHO 6 Vs	RHO 7 Is	RHO 7 Vs	
06/05/2014			483	29	304	57	365	37	423	47	36	27	1673	20	7	0	99
07/05/2014			509	30	201	49	332	37	448	47	55	28	1657	20	0	0	92
08/05/2014			813	30	140	40	147	33	293	41	161	28	1496	18	630	10	84
09/05/2014			603	29	264	43	176	33	479	40	508	27	1500	19	1673	31	148
10/05/2014			878	26	699	56	268	35	1607	35	1598	25	1609	19	1666	34	252
11/05/2014			1004	29	735	57	411	38	1627	36	1567	25	1661	19	1671	34	273
12/05/2014			1059	30	752	57	381	37	1609	37	1561	26	1661	19	1673	34	275

The post-outage electrical performance with the conventional power supply was good and within the desired performance specification and this was evident in the efficiency test as the ESP managed to achieve 97% collection efficiency, equivalent to particulate emissions of 42.8 mg/Nm³.

However, the performance of the ESP fields as shown in Table 5-25 illustrates the electrical performance of the conventional TR sets. It is noted from Table 5-25 that the performance of the TR sets is not consistent, and therefore inhibits the ability of the ESP to maintain emissions consistently.

Post-HFPS installation ESP performance

The HFPSs were installed and commissioned over a period of five weeks; the installation and commissioning were conducted per casing. Optimisation of the ESP was conducted for a period of a week; optimisation involved changing the rapping regime from that which was implemented for the conventional power supply system. It was expected that the four fields with the newly installed HFPS technology would collect more dust burden and therefore the rapping frequency was increased. The rapping frequency of the last three fields was also changed accordingly, since the front four fields will collect the most dust burden, the rapping frequency of the rear fields was reduced. An additional rapping feature that was implemented was the power down rapping (PDR). This form of rapping occurs with the field de-energised and occurs after a set cycle of normal field rapping. The controller sends a signal to the HFPS to switch off, allowing the rapping to occur. The intention for implementing this rapping philosophy was to ensure that the collected plates are kept clean for improved collection efficiency. Table 5.25 illustrates the new rapping settings implemented for the installation of the HFPS.

Table 5-25: Rapping philosophy implemented for HFPS

Field	Normal rapping		PDR	
	Interval	Duration	Interval	Duration
1	6 min	35 sec	30 min	35 sec
2	10 min	35 sec	1 h	35 sec
3	30 min	35 sec	3 h	35 sec
4	3 h	35 sec	12 h	35 sec
5	8 h	35 sec	24 h	35 sec
6	24 h	35 sec	48 h	35 sec
7	48 h	35 sec	48 h	35 sec

It can be seen from Table 5-26 that the front four fields' power input into the fields has increased drastically compared to that of the conventional TR set power supply. The front fields are able to produce and maintain a secondary current of above 1 000 mA. The maximum output power for the individual casings was constantly above 300 kW, which the conventional TR sets were not able to achieve.

Table 5-26: ESP electrical performance with HFPS installed

	EFF EM	Gen load	LHO 1 Is	LHO 1 Vs	LHO 2 Is	LHO 2 Vs	LHO 3 Is	LHO 3 Vs	LHO 4 Is	LHO 4 Vs	LHO 5 Is	LHO 5 Vs	LHO 6 Is	LHO 6 Vs	LHO 7 Is	LHO 7 Vs	Total Casing Power Output (kW)
27/07/2014	34	476	258	30	827	34	968	34	912	34	1370	50	1696	17	1704	34	255
28/07/2014	36	557	209	29	1052	34	1120	34	1213	32	1371	50	1696	17	1704	34	273
29/07/2014	39	570	323	43	1434	47	1590	49	1652	47	1365	49	1695	16	1704	34	389
30/07/2014	46	618	248	40	1471	48	1505	49	1637	47	1358	49	1670	17	1678	34	384
31/07/2014	43	619	244	40	1512	47	1539	49	1618	47	1381	50	1676	17	1679	34	389
01/08/2014	39	617	199	38	1322	47	1259	48	1475	47	1375	49	1671	17	1679	34	353
02/08/2014	38	515	203	37	1402	47	1313	49	1348	47	1383	50	1677	17	1682	34	357
			LHI 1 Is	LHI 1 Vs	LHI 2 Is	LHI 2 Vs	LHI 3 Is	LHI 3 Vs	LHI 4 Is	LHI 4 Vs	LHI 5 Is	LHI 5 Vs	LHI 6 Is	LHI 6 Vs	LHI 7 Is	LHI 7 Vs	
27/07/2014			1063	43	604	46	422	42	535	44	1355	45	1378	43	1668	39	301
28/07/2014			1105	43	584	47	455	44	595	45	1543	46	1364	43	1669	40	317
29/07/2014			1438	44	679	48	515	45	785	46	1669	46	1399	42	1684	39	357
30/07/2014			1355	43	709	48	622	45	854	46	1678	45	1398	42	1686	39	359
31/07/2014			1410	43	1113	49	956	46	1280	47	1683	45	1393	42	1690	39	419
01/08/2014			1116	42	669	47	526	44	765	45	1629	46	1348	42	1673	39	332
02/08/2014			1107	43	736	48	598	45	847	45	1688	46	1270	41	1681	39	343
			RHI 1 Is	RHI 1 Vs	RHI 2 Is	RHI 2 Vs	RHI 3 Is	RHI 3 Vs	RHI 4 Is	RHI 4 Vs	RHI 5 Is	RHI 5 Vs	RHI 6 Is	RHI 6 Vs	RHI 7 Is	RHI 7 Vs	
27/07/2014			912	38	1202	47	1370	49	1474	47	1699	41	1679	22	1687	34	391
28/07/2014			737	38	1048	47	1214	50	1331	48	1699	41	1680	22	1699	34	366
29/07/2014			537	37	987	46	1159	49	1204	47	1697	41	1678	22	1698	34	342
30/07/2014			665	37	1069	46	1237	49	1304	47	1676	40	1657	22	1644	33	353
31/07/2014			1009	39	1274	47	1485	50	1459	48	1678	40	1673	22	1654	33	403
01/08/2014			754	37	995	46	1199	49	1170	47	1674	41	1666	22	1651	33	346
02/08/2014			627	37	910	46	1157	49	1125	47	1678	41	1674	22	1661	33	335
			RHO 1 Is	RHO 1 Vs	RHO 2 Is	RHO 2 Vs	RHO 3 Is	RHO 3 Vs	RHO 4 Is	RHO 4 Vs	RHO 5 Is	RHO 5 Vs	RHO 6 Is	RHO 6 Vs	RHO 7 Is	RHO 7 Vs	
27/07/2014			1464	43	1406	45	1568	46	1557	45	1697	27	1705	15	1705	34	399
28/07/2014			1467	44	1371	46	1563	46	1592	45	1701	27	1706	15	1705	34	402
29/07/2014			1504	43	1473	46	1611	47	1590	46	1700	27	1707	15	1704	34	410
30/07/2014			1532	43	1477	46	1607	48	1591	46	1672	27	1678	15	1682	34	410
31/07/2014			1550	43	1544	46	1619	48	1655	47	1668	27	1684	15	1681	34	420
01/08/2014			1446	44	1505	46	1597	47	1660	46	1665	27	1674	15	1679	34	411
02/08/2014			1412	44	1446	47	1601	48	1631	47	1672	27	1679	15	1681	34	411

- The LHO casing had five fields out seven performing within specification; 71% of the casing fields were performing to specification.

- LHI casing had five fields out of seven performing within specification; 71% of the casing fields were performing to specification.
- RHI casing had six fields out of seven performing within specification; 86% of the casing fields were performing to specification.
- RHO casing had five fields out of seven performing within specification; 71% of the casing fields were performing to specification.

5.4 Electrical performance for both technologies

The electrical performance comparison was conducted for all 28 fields; for the operation of a conventional TR set and that of an HFPS transformer. The analysis focuses on the power input delivered into the field, as well as the ripple effect contained in voltage delivered into the fields. The presented electrical waveforms were taken from the plant historian, which records the measured plant operating parameters in accordance with the Metering and Measurement Systems for Power Stations in Generation Standard; 240-563590. The graphs shown are from data collected during the ESP efficiency test for each power supply technology. The data is sampled every 30 seconds and averaged out to give an hourly average, which was used to plot the electrical performance. The unit was at a fixed load of 618 MW for both instances when data was captured. The data was taken for a period of 24 hours – from midnight to midnight. The data was put in the same table although the two overall ESP efficiency tests were conducted three months apart.

Tables 5-27 and 5-28 present the hourly average reading for the current and voltage measurements for both TR sets and HFPS transformer, respectively, while in operation during the ESP efficiency testing. No mechanical repairs were conducted on the ESP plant from the baseline efficiency test to the final efficiency test. The measured values are as a result of the performance of the power supply system, as the HFPS was retrofitted on the existing ESP plant. The data as presented in Table 5-27 was plotted for each field in order to quantify the differences in the electrical performances of the two systems.

Table 5-27: LHO casing electrical performance hourly averages for TR sets

	LHO Caring hourly average eletrical performace for TR sets													
	LHO 1		LHO 2		LHO 3		LHO 4		LHO 5		LHO 6		LHO 7	
Time	TR Set - LHO 1 Is	TR Set LHO 1 Vs	TR Set LHO 2 Is	TR Set LHO 2 Vs	TR Set LHO 3 Is	TR Set LHO 3 Vs	TR Set LHO 4 Is	TR Set LHO 4 Vs	TR Set LHO 5 Is	TR Set LHO 5 Vs	TR Set LHO 6 Is	TR Set LHO 6 Vs	TR Set LHO 7 Is	TR Set LHO 7 Vs
00:00 - 01:00	283.55	26.45	625.03	33.88	1110.50	20.87	413.12	31.37	918.45	30.05	78.10	12.50	1062.37	22.45
01:00 - 02:00	102.28	39.67	963.75	46.65	1659.88	31.82	471.22	47.52	1391.92	44.47	141.22	19.92	1707.62	33.93
02:00 - 03:00	81.02	40.22	955.55	47.38	1654.35	31.90	455.52	46.87	1416.90	45.05	126.30	19.95	1706.70	33.88
03:00 - 04:00	96.50	41.38	976.98	47.52	1655.33	31.82	458.73	47.35	1416.50	45.00	138.10	19.72	1707.47	33.52
04:00 - 05:00	97.93	41.58	1004.50	47.12	1645.63	31.70	460.37	46.98	1389.35	44.37	153.28	19.38	1706.57	33.30
05:00 - 06:00	96.22	41.47	919.13	47.65	1667.40	31.93	462.22	47.28	1414.22	44.98	163.55	19.82	1707.15	33.52
06:00 - 07:00	115.07	41.88	819.90	46.50	1661.70	32.45	482.37	48.40	1411.93	44.95	163.27	19.68	1706.93	33.30
07:00 - 08:00	92.77	40.83	914.23	47.20	1691.63	32.17	483.78	48.08	1382.28	44.33	166.83	19.35	1707.17	33.22
08:00 - 09:00	104.63	42.03	957.87	48.08	1625.50	31.60	474.43	47.80	1403.28	44.63	165.13	19.00	1707.68	33.00
09:00 - 10:00	99.12	40.95	931.30	47.53	1702.77	32.02	487.07	48.23	1402.15	44.13	146.72	19.03	1707.40	33.00
10:00 - 11:00	75.90	38.33	792.73	46.93	1656.98	31.85	485.35	48.93	1385.58	43.90	150.67	19.00	1707.83	33.00
11:00 - 12:00	69.65	38.52	731.53	45.98	1674.73	31.93	434.08	46.23	1402.30	44.12	146.07	18.98	1707.42	32.97
12:00 - 13:00	76.40	38.82	693.35	46.35	1645.87	31.83	409.07	46.48	1378.80	44.10	140.42	18.80	1704.97	32.62
13:00 - 14:00	88.87	39.77	737.95	46.20	1646.75	31.77	405.20	46.67	1402.55	44.85	150.40	18.78	1706.55	32.40
14:00 - 15:00	70.93	38.60	665.92	46.82	1651.70	31.98	357.73	45.47	1384.63	44.75	160.73	18.85	1706.72	32.25
15:00 - 16:00	79.45	39.60	678.77	46.40	1532.15	31.85	385.72	46.00	1407.40	45.03	159.18	19.00	1706.78	32.82
16:00 - 17:00	98.78	41.70	614.22	44.98	1452.08	31.90	389.45	46.53	1400.02	45.08	137.18	18.77	1706.65	32.88
17:00 - 18:00	95.22	40.55	580.15	45.43	1283.38	32.15	393.50	46.55	1382.57	45.40	59.83	19.00	1707.12	33.00
18:00 - 19:00	100.98	39.27	626.52	45.37	1432.37	33.08	413.08	47.32	1403.28	45.82	62.73	19.02	1707.17	33.00
19:00 - 20:00	89.10	40.25	583.88	45.55	1322.60	32.90	416.63	46.80	1380.10	45.08	65.43	19.05	1707.60	33.00
20:00 - 21:00	116.57	41.03	753.08	45.50	1418.30	32.93	422.10	47.05	1404.00	45.65	67.70	19.57	1707.40	33.00
21:00 - 22:00	105.47	41.52	748.55	46.10	1590.50	32.52	407.08	46.45	1400.72	45.33	70.33	19.57	1707.68	33.00
22:00 - 23:00	115.93	42.52	755.73	46.10	1535.72	32.35	440.37	48.15	1376.23	44.65	73.67	19.33	1707.62	33.00
23:00 - 00:00	137.52	43.28	800.33	47.18	1544.75	32.57	392.26	47.36	1398.61	45.07	76.84	19.15	1707.93	33.00

Table 5-28: LHO casing electrical performance hourly averages for HFPS

	LHO Caring hourly average eletrical performace for HFPS													
	LHO 1		LHO 2		LHO 3		LHO 4		LHO 5		LHO 6		LHO 7	
Time	HFPS-LHO 1 Is	HFPS-LHO 1 Vs	HFPS-LHO 2 Is	HFPS-LHO 2 Vs	HFPS-LHO 3 Is	HFPS-LHO 3 Vs	HFPS-LHO 4 Is	HFPS-LHO 4 Vs	HFPS-LHO 5 Is	HFPS-LHO 5 Vs	HFPS-LHO 6 Is	HFPS-LHO 6 Vs	HFPS-LHO 7 Is	HFPS-LHO 7 Vs
00:00 - 01:00	929.68	39.72	1585.60	40.92	1555.85	47.18	1179.27	47.31	1383.52	58.12	1620.72	17.10	260.57	9.22
01:00 - 02:00	1291.92	46.97	1672.37	42.75	1698.92	48.46	1472.15	52.89	1460.55	60.35	1711.48	18.00	9.77	3.93
02:00 - 03:00	1288.32	48.08	1667.87	42.67	1690.50	47.66	1535.22	52.52	1476.28	61.02	1658.92	17.53	9.38	3.67
03:00 - 04:00	1227.78	47.58	1642.47	42.30	1671.05	46.35	1636.83	53.28	1480.05	61.00	1686.68	17.30	10.07	3.98
04:00 - 05:00	890.95	45.81	1625.73	43.64	1678.07	46.67	1668.25	53.11	1455.88	60.45	1685.80	17.07	9.65	3.93
05:00 - 06:00	892.33	45.83	1625.73	43.64	1678.08	46.67	1668.25	53.10	1477.65	60.03	1685.68	17.00	1458.13	32.08
06:00 - 07:00	455.28	31.50	1539.40	46.21	1650.28	46.38	1679.45	53.45	1474.62	59.90	1651.78	16.75	1710.03	35.53
07:00 - 08:00	15.35	14.41	1403.23	48.06	1623.05	47.54	1649.52	52.74	1453.98	59.72	1683.73	17.00	1708.92	35.47
08:00 - 09:00	949.97	43.20	1675.82	44.82	1642.88	46.26	1655.88	53.52	1481.95	60.60	1683.78	17.00	1710.00	36.00
09:00 - 10:00	983.25	45.76	1636.65	43.10	1699.52	46.81	1642.02	52.08	1480.17	60.00	1684.57	17.00	1709.97	35.97
10:00 - 11:00	858.48	44.93	1665.83	44.49	1686.88	46.41	1671.10	52.87	1454.62	58.98	1663.83	16.90	1709.77	35.28
11:00 - 12:00	927.92	45.47	1629.48	43.83	1646.13	45.92	1671.10	52.92	1479.90	59.98	1677.62	17.00	1709.08	35.00
12:00 - 13:00	1031.70	48.61	1642.83	43.79	1670.73	46.34	1683.03	53.77	1459.48	59.15	1685.23	17.00	1709.65	35.05
13:00 - 14:00	1068.35	46.43	1644.15	43.35	1655.83	46.01	1645.32	52.76	1481.95	60.00	1688.35	17.00	1709.25	35.03
14:00 - 15:00	1052.17	48.52	1640.50	42.90	1670.95	45.89	1668.93	53.08	1482.22	59.93	1658.17	16.78	1709.18	35.00
15:00 - 16:00	790.88	43.79	1647.78	45.60	1697.13	46.92	1655.90	52.53	1461.20	58.98	1684.50	17.00	1709.68	35.00
16:00 - 17:00	850.22	45.05	1636.32	45.78	1685.03	47.18	1627.23	51.88	1479.42	59.98	1681.30	17.00	1709.77	35.00
17:00 - 18:00	631.03	39.76	1471.87	46.14	1639.25	46.34	1673.17	53.14	1474.03	59.83	1688.92	17.00	1709.75	35.00
18:00 - 19:00	15.83	13.45	794.10	46.20	1558.42	49.48	1536.95	50.89	1466.67	59.72	1660.42	16.92	1709.23	35.03
19:00 - 20:00	20.88	16.17	920.70	45.45	1427.40	49.50	1470.83	51.26	1478.33	60.08	1701.92	17.62	1709.77	35.02
20:00 - 21:00	16.87	15.26	1035.22	46.78	1323.13	49.54	1361.72	50.89	1478.42	60.78	1711.20	17.98	1707.78	35.15
21:00 - 22:00	23.65	15.99	1301.20	48.61	1556.83	49.77	1567.82	52.60	1496.42	60.97	1712.55	18.00	1710.75	36.00
22:00 - 23:00	21.57	17.30	1113.18	47.42	1521.00	49.51	1543.58	52.20	1456.60	60.10	1684.82	17.80	1710.43	36.00
23:00 - 00:00	24.77	17.02	1071.32	47.39	1568.50	50.87	1571.73	52.65	1481.30	61.00	1705.07	17.85	1710.51	36.00

- LHO 1 field electrical performance

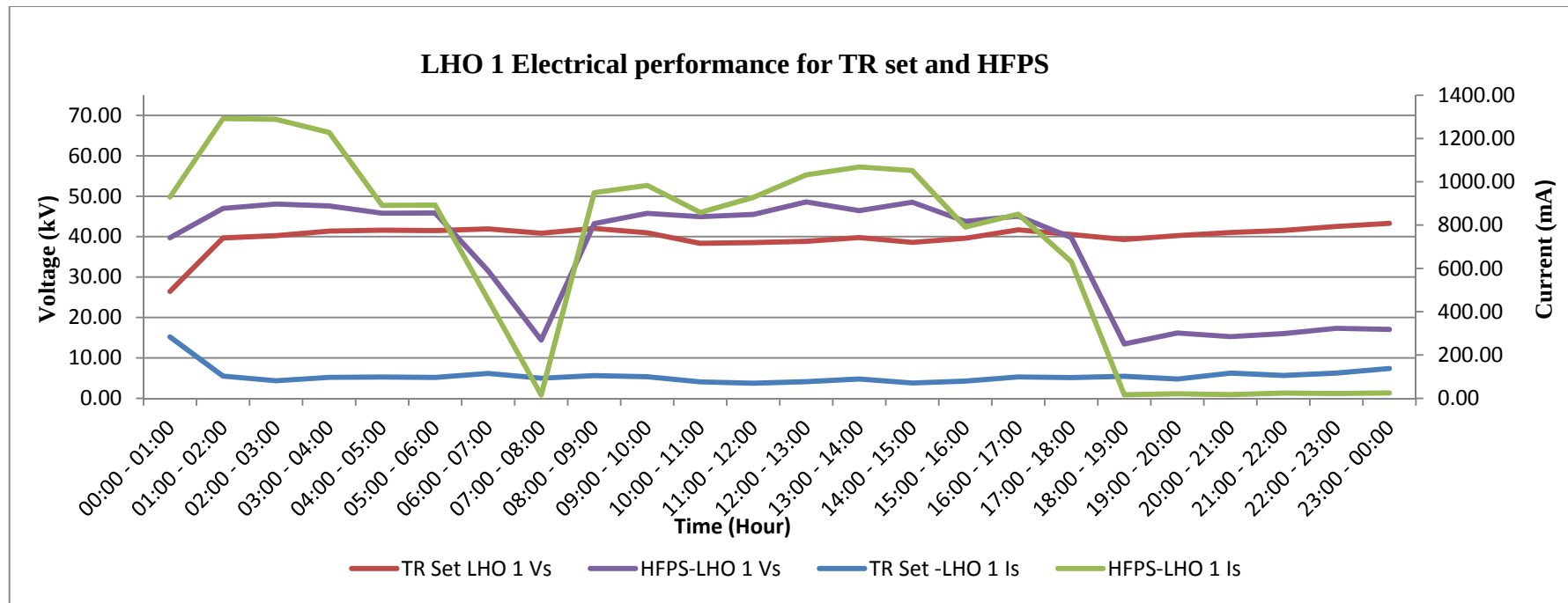


Figure 5-19: LHO 1 electrical performance for TR set and HFPS

Figure 5-19 was plotted making use of the data presented in Tables 5-27 and 28 to illustrate the difference in electrical performance of the LHO 1 field, when supplied by a TR set and when supplied by an HFT. It can be seen that the electrical performance of the LHO 1 field increased significantly. The current input into the field went from below 300 mA for a TR set and could be maintained above 600 mA, twice that which the TR set was able to supply. The voltage also increased from below 40 kV for a TR set, to above 40 kV, with the highest voltage being 48 kV supplied by an HFPS. This was a drastic improvement seen on the first field, with consideration that no mechanical repairs were conducted internally from when both measurements were conducted.

- **LHO 2 field electrical performance**

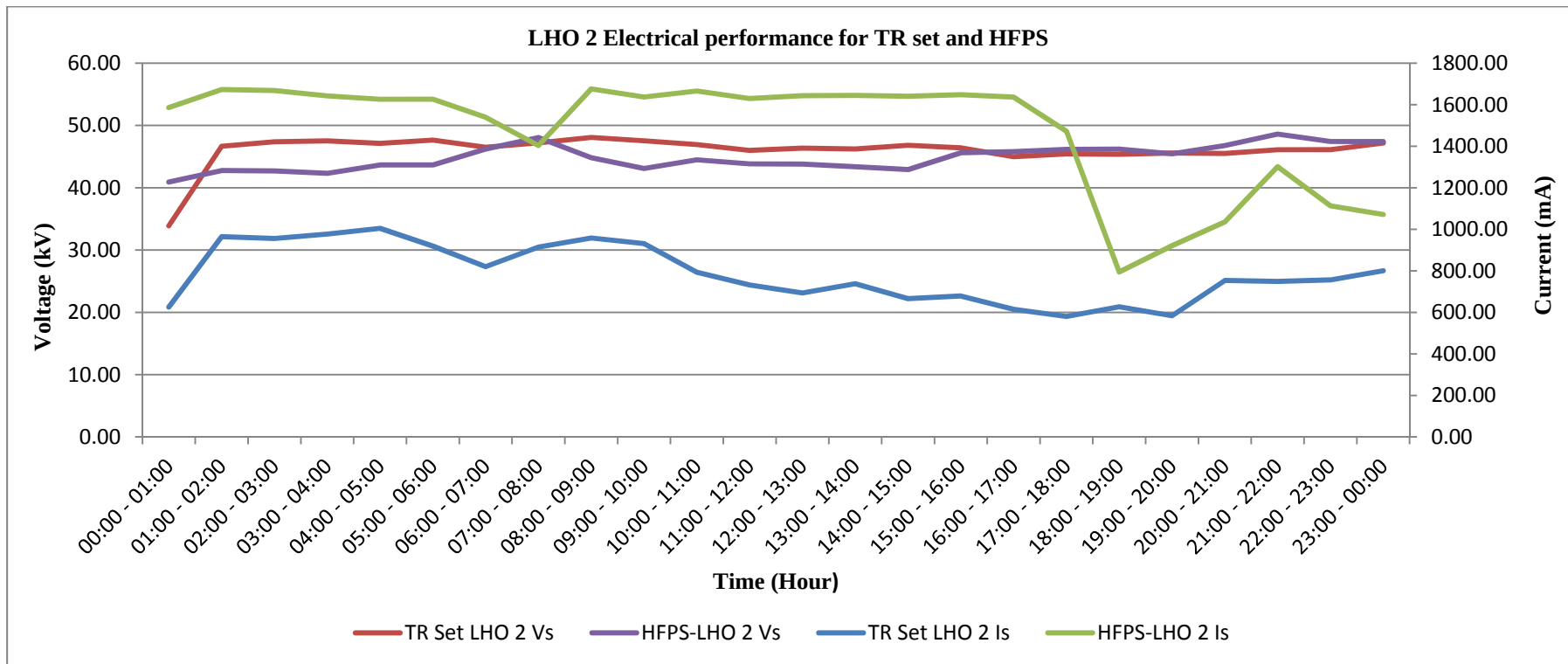


Figure 5-20: LHO 2 electrical performance for TR set and HFPS.

The current and voltage measurement as presented in Tables 5-27 and 28 for the LHO 2 field are for both power supply technologies. The data was used to plot the electrical performance of the LHO 2 field, as seen in Figure 5-20. The electrical performance of the LHO 2 field saw an improvement in the current and voltage when the HFPS was installed in place of TR set. The TR set was able to supply and maintain a current of approximately 900 mA; however, with the HFPS, it was able to produce current above 1 600 mA. The voltage input into the field did not change drastically, although the TR set was producing a little more voltage compared to the HFPS.

- LHO 3 field electrical performance

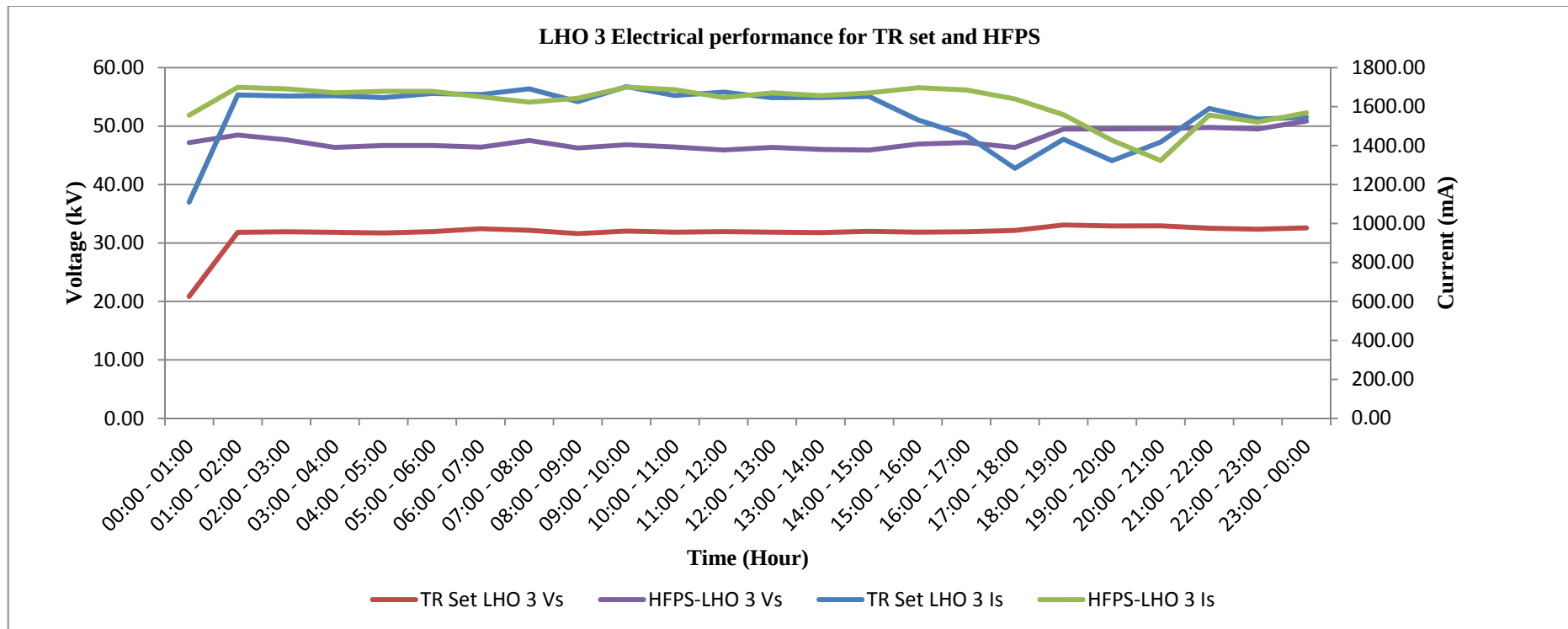


Figure 5-21: LHO 3 electrical performance for TR set and HFPS

Figure 5-21 represents a graphical plot of the LHO 3 electrical performance for both the TR set and HFP. The only significant difference that was noted from the two supply technologies was that the HFPS was able to input a higher voltage into the field than that of the TR set. The HFPS was able to maintain a voltage of above 47 kV, whereas the TR set could only maintain voltage below 30 kV. The current input into the field for both transformers was at a maximum. The higher voltage from the HFPS increases the electric field strength for the capturing of the charged dust particles.

- LHO 4 field electrical performance

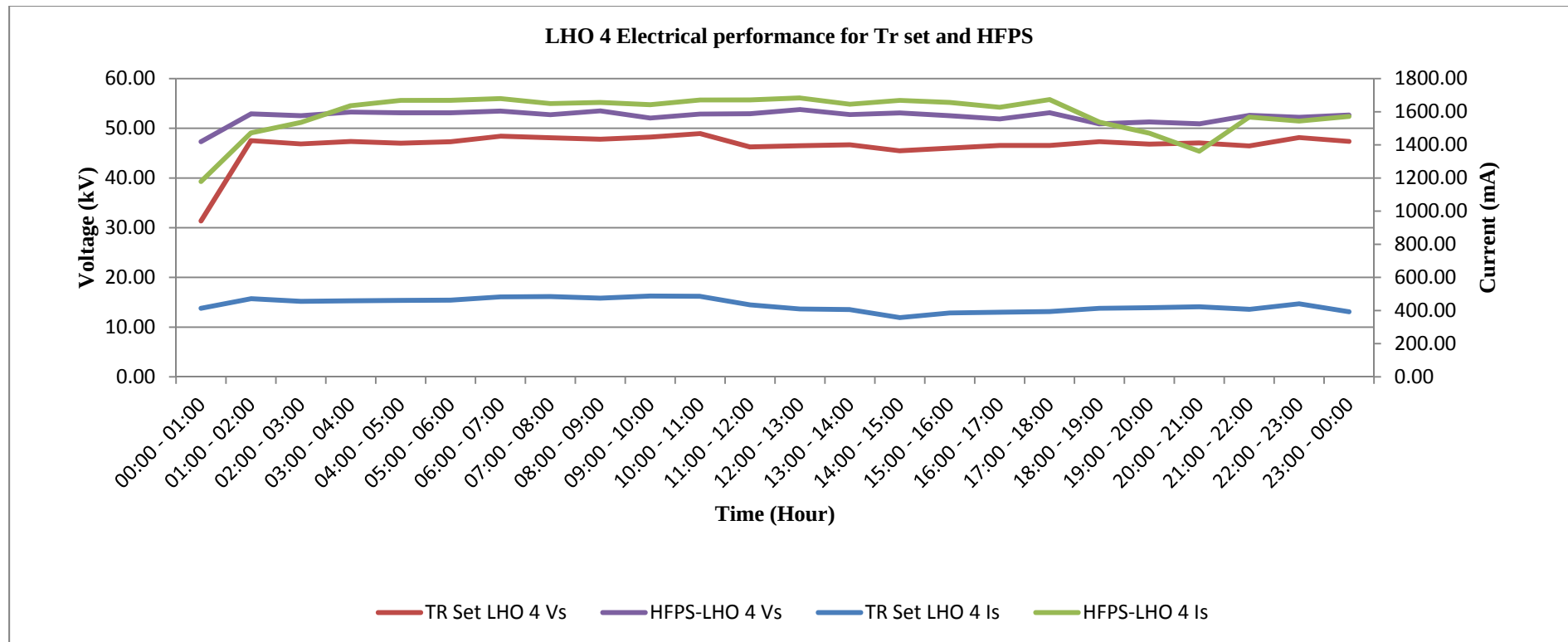


Figure 5-22: LHO 4 electrical performance for TR set and HFPS

The LHO 4's electrical performance is illustrated in Figure 5-22. The LHO 4's electrical performance improved significantly with the installation of the HFPS. The current input into the ESP field increased from approximately 400 mA to full-rated input current of 1 600 mA. The voltage input into the field also increased from around 48 kV to 53 kV.

- LHO 5 field electrical performance

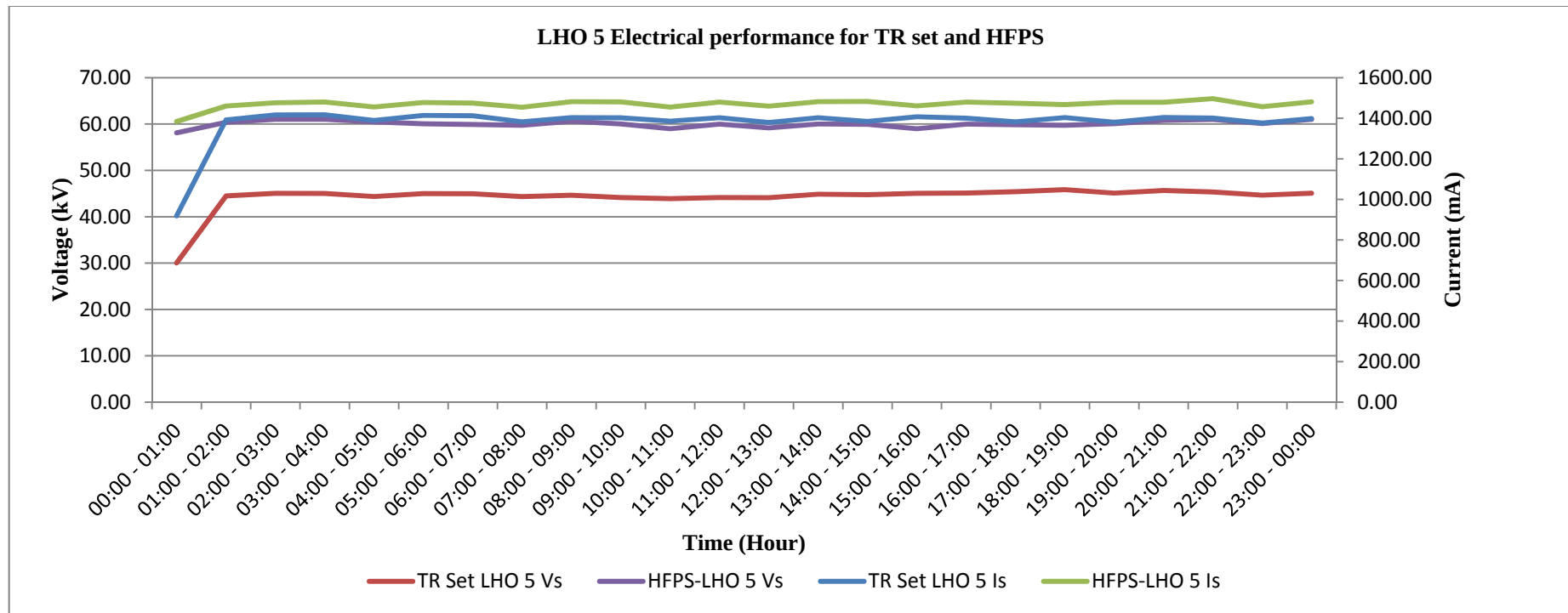


Figure 5-23: LHO 5 electrical performance for TR set and HFPS.

The LHO 5 field was not retrofitted with an HFPS; however, it was noted that the performance of this field also improved with the installation of the HFPS upstream of it, as can be seen in Figure 5-23. The voltage and current inputs into the field were significantly higher than when it was only TR sets operating in the casing. The improved performance of the front field, due to the increased power input into the field, ensures that the rear fields see less dust burden compared to when it was only TR sets in operation, and from there the improved electrical performance.

- LHO 6 field electrical performance

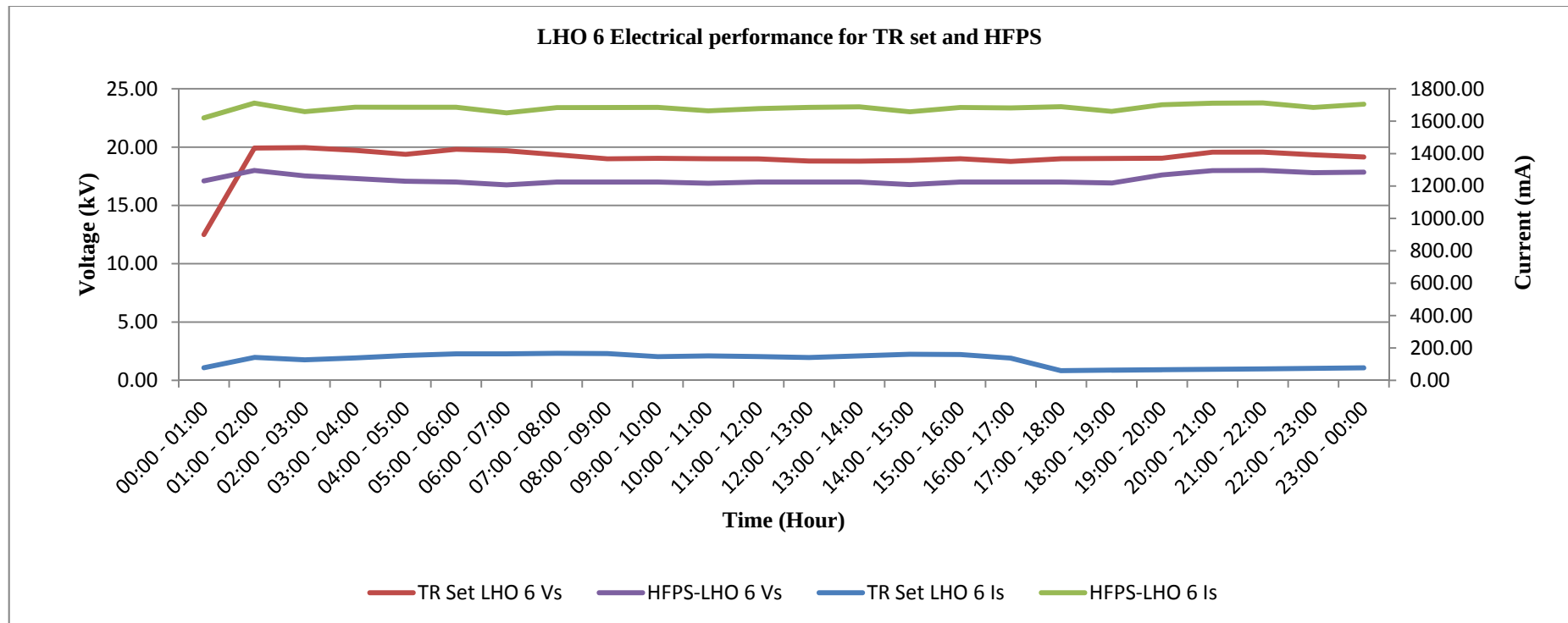


Figure 5-24: LHO 6 electrical performance for TR set and HFPS

The LHO 6 field was not retrofitted with an HFPS; however, it was noted that the performance of this field also improved with the installation of the HFPS upstream of it, as can be seen in Figure 5-24. The voltage and current inputs into the field were significantly higher than when it was only TR sets operating in the casing. The TR set was able to produce full current output and maintain this performance.

- LHO 7 field electrical performance

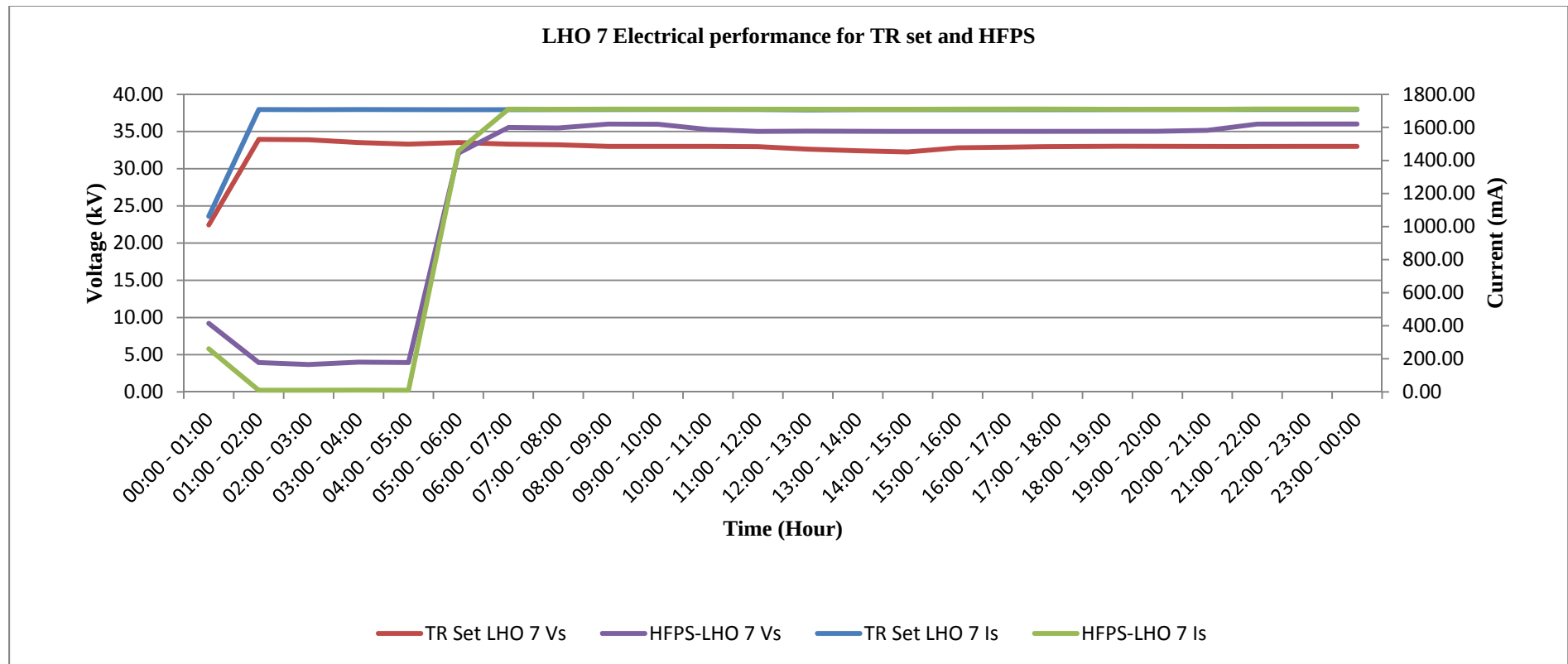


Figure 5-25: LHO 7 electrical performance for TR set and HFPS.

The electrical performance of LHO 7 is shown in Figure 5-25; the TR set had tripped in the early hours of the morning, from there the zero values plotted for the ESP test with HFPS installed. No significant difference was noted in terms of the field from baseline to the final test as the last field generally achieves full load performance due to the limited amount of dust burden that the field collects.

Table 5-29: LHI casing electrical performance hourly averages for TR sets

	LHI Casing hourly average electrical performance for TR sets													
	LHI 1		LHI 2		LHI 3		LHI 4		LHI 5		LHI 6		LHI 7	
	TR Set LHI 1 Is	TR Set LHI 1 Vs	TR Set LHI 2 Is	TR Set LHI 2 Vs	TR Set LHI 3 Is	TR Set LHI 3 Vs	TR Set LHI 4 Is	TR Set LHI 4 Vs	TR Set LHI 5 Is	TR Set LHI 5 Vs	TR Set LHI 6 Is	TR Set LHI 6 Vs	TR Set LHI 7 Is	TR Set LHI 7 Vs
00:00 - 01:00	112.57	37.87	206.10	20.73	133.12	25.35	312.80	47.90	971.82	29.05	1006.82	24.17	970.05	22.68
01:00 - 02:00	188.88	55.18	277.35	29.12	106.03	37.77	265.97	46.50	1693.08	42.27	1590.00	37.37	1557.42	34.80
02:00 - 03:00	203.73	53.87	274.12	30.28	83.43	38.38	373.50	47.07	1683.25	42.73	1587.95	38.23	1650.33	35.13
03:00 - 04:00	195.95	53.93	249.15	31.48	74.73	39.43	387.47	46.93	1701.78	43.02	1469.37	38.53	1706.47	35.30
04:00 - 05:00	192.93	53.77	241.07	30.52	86.23	38.90	350.93	47.20	1705.90	42.95	1556.55	39.03	1690.82	35.70
05:00 - 06:00	189.20	55.05	267.00	30.30	78.15	39.22	367.82	47.33	1608.93	42.73	1650.90	39.58	1684.23	35.77
06:00 - 07:00	198.18	54.17	256.93	30.52	89.07	39.32	360.53	47.28	1664.98	42.60	1661.42	39.77	1702.88	35.95
07:00 - 08:00	210.83	55.72	263.83	30.12	78.13	38.27	350.32	46.68	1673.83	42.98	1512.52	38.68	1697.20	35.98
08:00 - 09:00	236.52	54.90	281.15	31.57	81.65	38.72	379.12	47.28	1676.22	42.78	1606.17	39.50	1695.23	35.95
09:00 - 10:00	241.58	54.97	262.20	31.55	99.50	39.18	376.98	47.43	1634.50	43.25	1532.75	38.72	1672.62	35.87
10:00 - 11:00	247.75	53.52	278.52	31.48	94.35	39.63	356.15	46.53	1666.55	42.67	1606.62	39.07	1689.92	35.60
11:00 - 12:00	245.62	52.65	244.22	30.67	103.73	40.03	314.50	46.20	1644.47	42.57	1537.30	37.90	1699.93	35.00
12:00 - 13:00	252.37	52.37	224.48	30.07	70.37	38.20	254.43	44.55	1483.53	40.27	1311.30	36.33	1597.87	34.58
13:00 - 14:00	216.43	54.35	204.33	30.40	70.05	39.30	262.65	45.88	1640.42	41.52	1498.67	37.72	1644.75	34.80
14:00 - 15:00	249.57	52.23	185.38	31.07	50.67	37.47	244.80	46.57	1660.75	42.40	1467.85	37.32	1614.88	34.78
15:00 - 16:00	221.98	52.10	217.15	31.25	51.03	38.20	249.93	46.78	1624.18	42.88	1271.45	35.72	1589.68	34.90
16:00 - 17:00	30.87	2.03	170.02	29.45	31.93	37.22	144.67	47.77	1431.75	43.20	957.90	34.58	1474.07	35.43
17:00 - 18:00	0.00	0.00	217.63	29.58	29.93	37.50	138.23	47.75	1524.93	42.95	1211.37	37.68	1531.90	35.23
18:00 - 19:00	0.00	0.00	248.85	30.82	37.75	38.02	174.97	47.17	1538.43	43.25	1227.73	36.28	1602.95	35.70
19:00 - 20:00	0.00	0.00	269.32	30.82	42.03	38.97	189.20	47.33	1545.77	43.30	1410.42	38.00	1636.12	35.65
20:00 - 21:00	0.00	0.00	286.85	30.28	47.20	38.45	191.10	48.00	1509.15	43.02	1361.73	37.97	1650.10	35.72
21:00 - 22:00	0.00	0.00	290.20	31.00	47.45	39.38	179.20	46.85	1550.23	43.02	1193.35	36.95	1689.72	35.90
22:00 - 23:00	0.00	0.00	299.03	29.80	51.22	39.42	200.68	48.33	1619.20	43.97	1389.85	37.57	1662.22	35.92
23:00 - 00:00	0.00	0.00	283.87	30.05	53.21	38.97	176.00	47.51	1519.77	44.16	1344.00	37.62	1652.80	35.93

Table 5-30: LHI casing electrical performance hourly averages for HFPS

	LHI Casing hourly average electrical performance for HFPS													
	LHI 1		LHI 2		LHI 3		LHI 4		LHI 5		LHI 6		LHI 7	
	HFPS-LHI 1 Is	HFPS-LHI 1 Vs	HFPS-LHI 2 Is	HFPS-LHI 2 Vs	HFPS-LHI 3 Is	HFPS-LHI 3 Vs	HFPS-LHI 4 Is	HFPS-LHI 4 Vs	HFPS-LHI 5 Is	HFPS-LHI 5 Vs	HFPS-LHI 6 Is	HFPS-LHI 6 Vs	HFPS-LHI 7 Is	HFPS-LHI 7 Vs
00:00 - 01:00	1521.53	42.07	1469.27	47.32	976.08	45.22	863.23	43.64	1604.97	43.62	1291.50	40.38	1578.60	36.87
01:00 - 02:00	1588.55	44.27	1614.40	49.24	1461.02	48.82	1356.82	47.99	1702.32	46.00	1410.62	42.55	1698.90	39.98
02:00 - 03:00	1576.48	44.45	1647.32	49.64	1588.62	49.36	1547.48	48.09	1675.15	45.03	1382.57	41.43	1698.58	40.00
03:00 - 04:00	1462.47	43.77	1653.02	50.26	1661.70	49.54	1647.63	48.36	1691.52	45.00	1400.78	42.00	1697.37	39.90
04:00 - 05:00	588.53	42.13	1342.00	50.08	1518.82	47.78	1655.32	48.23	1693.73	45.00	1400.93	42.00	1696.02	39.17
05:00 - 06:00	577.75	42.09	1336.98	50.08	1544.50	48.47	1655.33	48.23	1686.88	44.93	1402.35	41.93	1696.42	39.00
06:00 - 07:00	366.45	39.20	823.38	47.95	1085.60	46.08	1489.15	47.19	1693.97	45.02	1378.60	41.00	1696.45	39.00
07:00 - 08:00	305.73	38.34	450.97	45.50	512.97	42.56	1042.40	45.72	1699.43	45.02	1403.08	42.00	1695.90	39.00
08:00 - 09:00	747.92	41.24	1028.68	49.54	922.45	46.19	1198.05	46.05	1679.03	44.30	1410.08	42.00	1697.10	39.12
09:00 - 10:00	682.05	41.29	1213.70	50.49	1188.33	47.22	1517.92	47.70	1698.73	44.92	1411.28	41.83	1698.40	39.00
10:00 - 11:00	845.25	42.81	1232.10	49.57	1239.40	46.81	1565.90	47.39	1699.25	44.48	1382.93	40.78	1698.62	39.00
11:00 - 12:00	628.42	42.47	1171.17	49.05	1141.73	45.93	1607.87	48.24	1673.70	43.67	1401.07	41.00	1696.02	39.00
12:00 - 13:00	754.42	40.98	1152.22	49.00	1154.38	46.75	1605.03	48.22	1700.80	44.02	1401.97	41.02	1696.03	39.00
13:00 - 14:00	1225.30	44.70	1480.20	49.68	1390.77	47.66	1636.20	47.54	1701.95	44.00	1399.73	41.00	1689.53	39.00
14:00 - 15:00	1093.48	42.69	1494.90	49.36	1554.23	48.67	1664.87	47.65	1673.73	43.75	1376.88	40.42	1688.58	39.00
15:00 - 16:00	654.68	40.94	1098.67	47.88	1230.05	46.50	1541.83	46.70	1701.42	44.00	1401.88	41.00	1693.22	39.00
16:00 - 17:00	611.18	41.21	923.10	48.13	930.72	44.72	1396.33	46.43	1700.25	44.00	1399.95	41.00	1694.08	39.00
17:00 - 18:00	419.38	39.77	678.33	47.40	737.08	43.95	1226.12	45.40	1672.10	43.58	1409.32	41.05	1696.30	38.98
18:00 - 19:00	209.07	36.94	245.02	42.51	200.40	39.56	521.98	43.16	1648.70	45.40	1384.57	41.38	1686.15	38.95
19:00 - 20:00	208.63	37.29	257.27	42.83	168.37	39.17	312.25	41.03	1531.82	45.70	1401.58	41.98	1671.80	38.67
20:00 - 21:00	238.30	37.14	278.17	43.10	161.68	39.05	279.85	42.21	1454.07	46.03	1386.12	41.90	1658.42	38.37
21:00 - 22:00	336.37	40.34	447.43	46.62	300.50	43.28	419.53	43.03	1648.28	46.42	1409.38	42.32	1690.70	39.00
22:00 - 23:00	266.08	37.94	353.35	45.36	208.97	42.27	387.60	42.74	1659.32	46.87	1377.70	42.13	1673.72	39.10
23:00 - 00:00	265.85	38.83	325.88	45.17	200.72	41.77	365.08	43.23	1574.03	46.44	1409.08	42.98	1684.64	39.23

Tables 5-29 and 5-30 present the hourly averaged reading for the current and voltage measurements for both TR sets and HFPS transformer, while in operation during the ESP efficiency testing for the LHI casing.

- **LHI 1 field electrical performances**

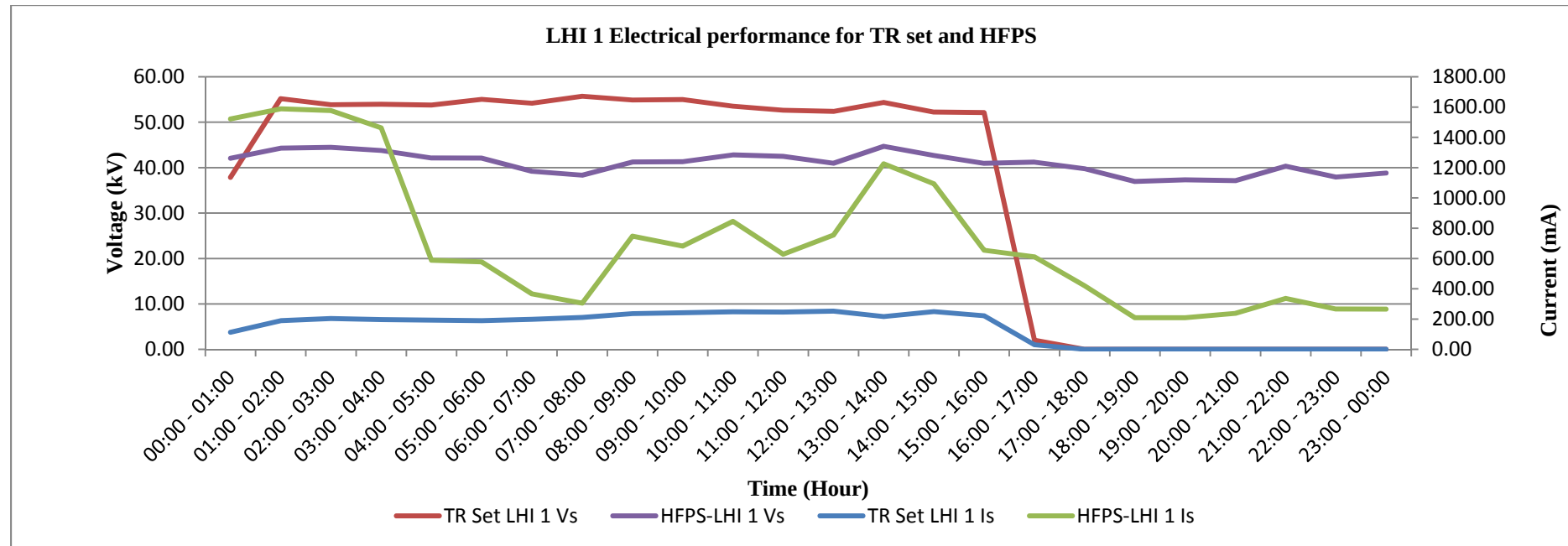


Figure 5-26: LHI 1 electrical performance for TR set and HFPS

The electrical measurements for the LHI 1's performance is illustrated in Figures 5-29 and 5-30. It was noted that at around 17:00, the TR set's reading went to zero, which indicates that the field had tripped at this stage. The installation on the HFPS on the LHI 1 did not result in an improved electrical performance, although the current was not stable due to excessive sparking, probably caused by a loose discharge electrode wire.

- LHI 2 field electrical performance

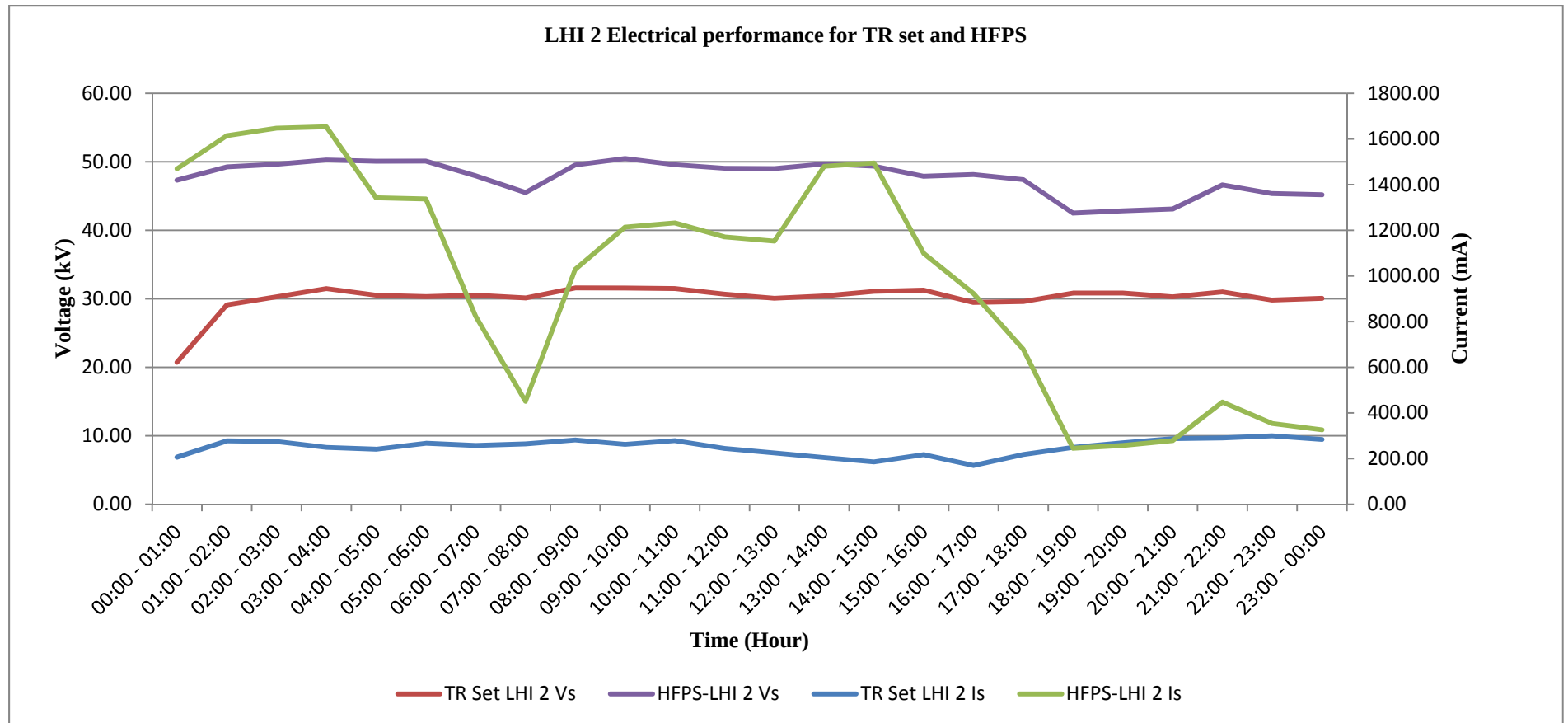


Figure 5-27: LHI 2 electrical performance for TR set and HFPS

The LHI 2's performance was similar to that observed on LHI 1, as can be seen in Figure 5-27. The field was sparking excessively, and therefore not allowing stable operating conditions. The TR set was able to maintain a consistent current as the controller allows for manual intervention and can be set to a point where it can operate without frequent trips due to sparking and arcing.

- **LHI 3 electrical performance**

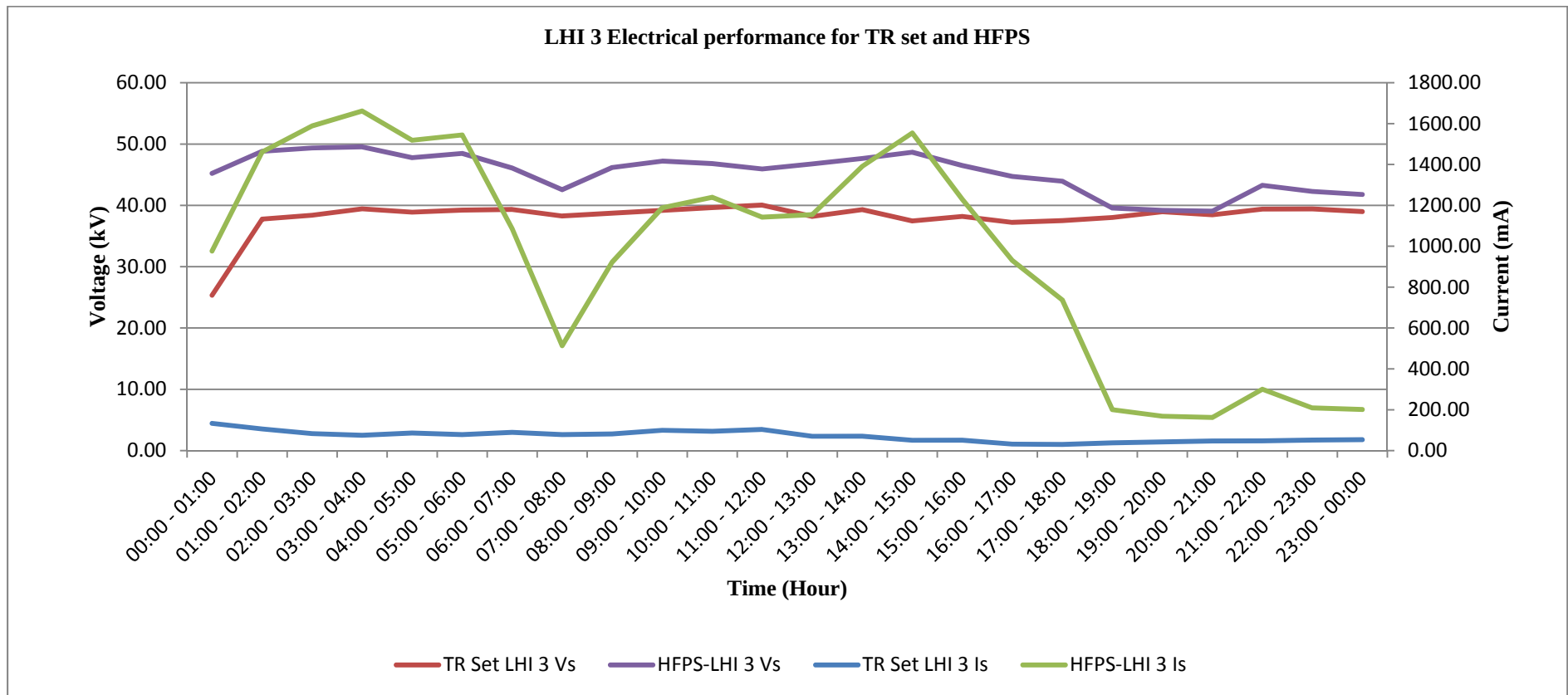


Figure 5-28: LHI 3 electrical performance for TR set and HFPS

Figure 5-28 presents the electrical performance of the LHI 3's field. Similar to that of LHI 1 and 2, this field was also experiencing a high spark rate. The HFPS was still able to maintain a higher electrical performance than that of the TR set, in these upset conditions.

- **LHI 4 electrical performance**

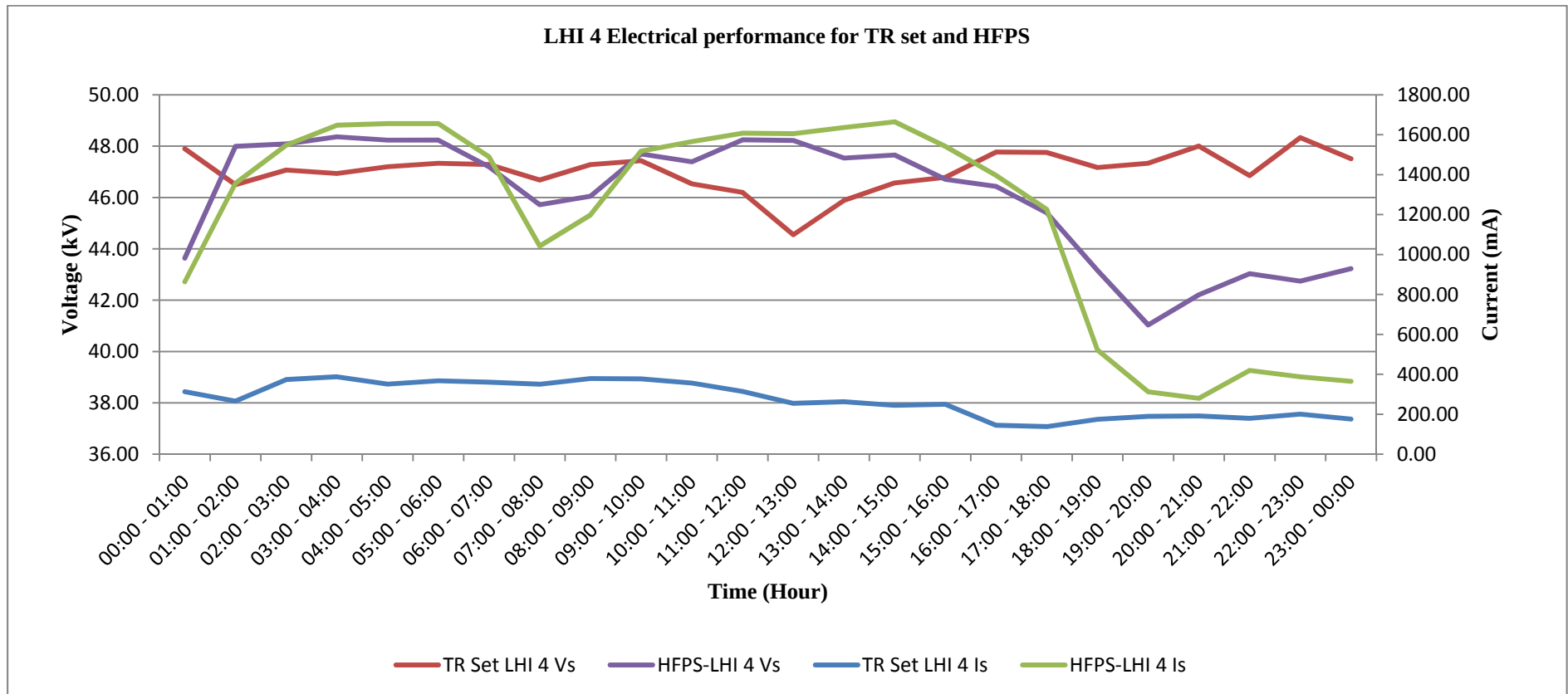


Figure 5-29: LHI 4 electrical performance for TR set and HFPS

Similar to all the other fields discussed, the installation of the HFPS resulted in improved electrical performance. Although this casing was experiencing excessive sparking, the HFPSs were able to maintain a higher electrical performance than that which was possible with the TR sets.

- **LHI 5 electrical performance**

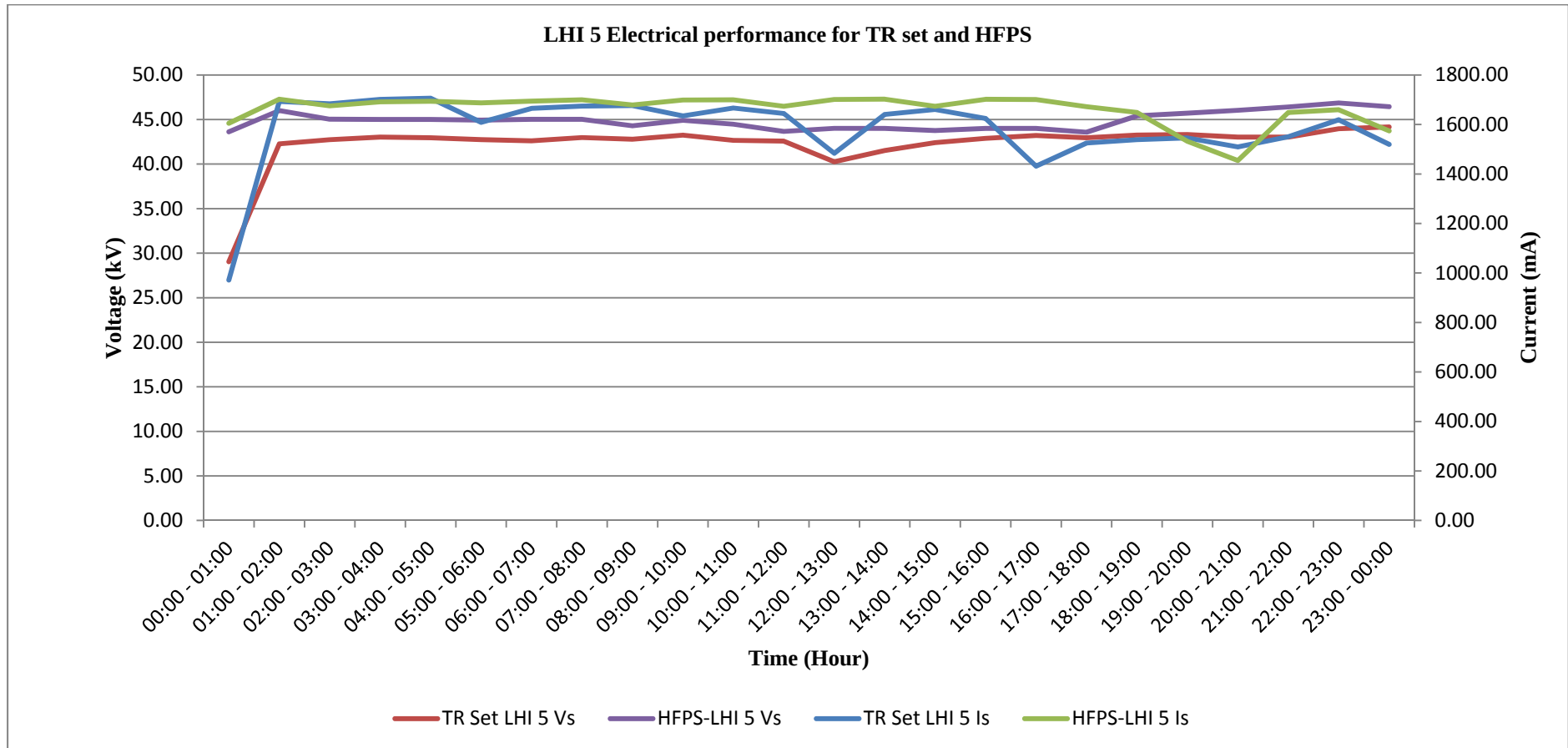


Figure 5-30: LHI 5 electrical performance for TR set and HFPS

The LHI 5 field was within specification for both instances when the ESP efficiency tests were conducted, as can be seen in Figure 5-30.

- **LHI 6 electrical performance**

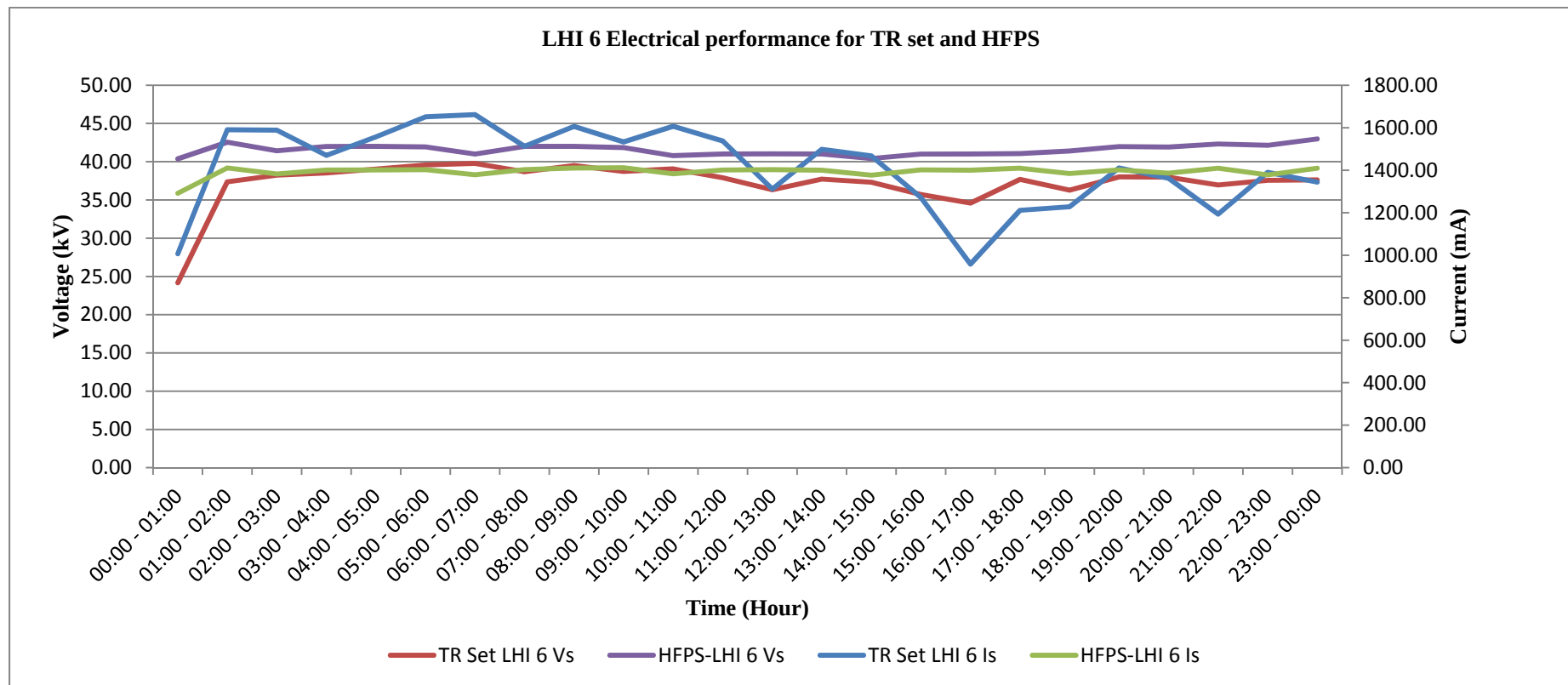


Figure 5-31: LHI 6 electrical performance for TR set and HFPS

The LHI 6 field was within specification for both instances when the ESP efficiency tests were conducted, as can be seen in Figure 5-31, although the current and voltage waveforms of the TR sets performance for the baseline testing showed signs of sparking in the field.

- **LHI 7 electrical performance**

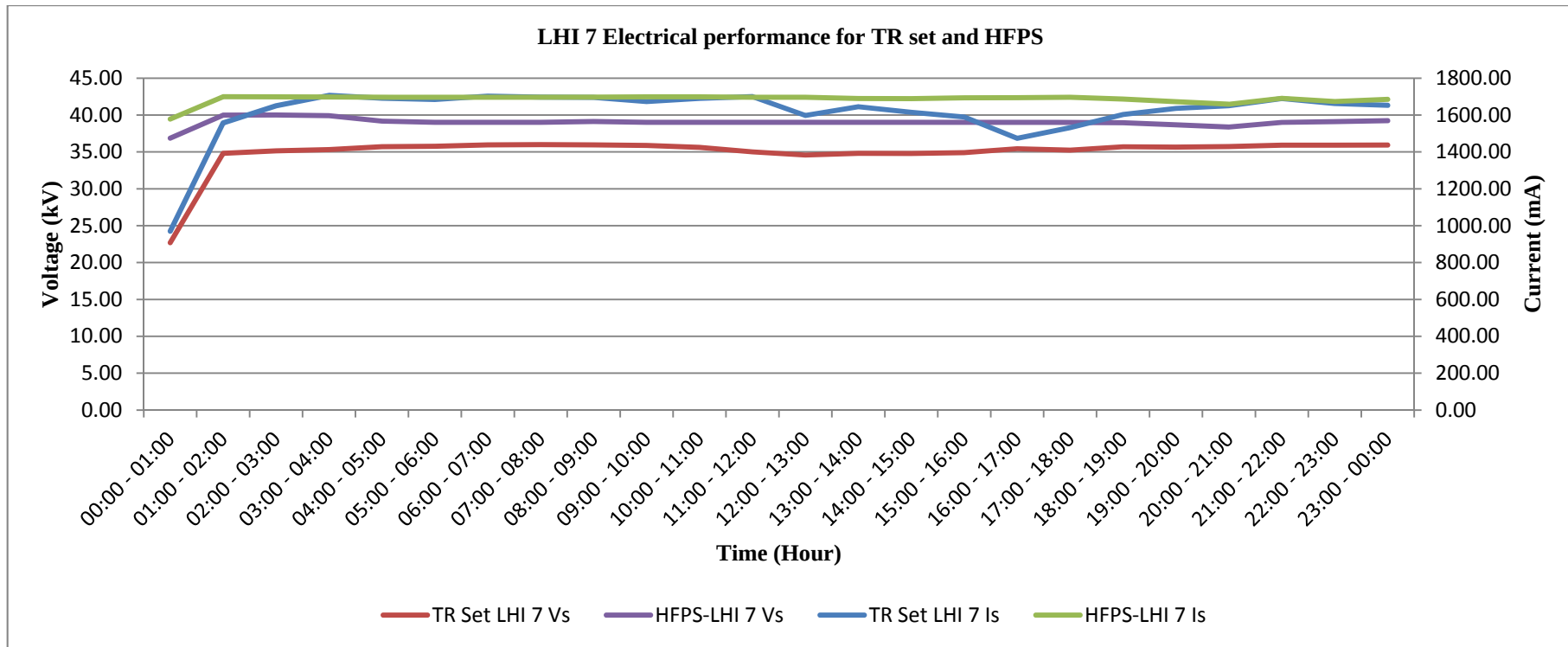


Figure 5-32: LHI 7 electrical performance for TR set and HFPS

The LHI 7 field's performance was within specification for both instances when the ESP efficiency tests were conducted, as can be seen in Figure 5-32. This sort of performance is expected in the last field of every casing, as it handles limited amounts of dust burden.

Table 5-31: RHI casing electrical performance hourly averages for TR set

	RHI casing hourly acerage electrical performance for TR sets													
	RHI 1		RHI 2		RHI 3		RHI 4		RHI 5		RHI 6		RHI 7	
	TR Set RHI 1 Is	TR Set RHI 1 Vs	TR Set RHI 2 Is	TR Set RHI 2 Vs	TR Set RHI 3 Is	TR Set RHI 3 Vs	TR Set RHI 4 Is	TR Set RHI 4 Vs	TR Set RHI 5 Is	TR Set RHI 5 Vs	TR Set RHI 6 Is	TR Set RHI 6 Vs	TR Set RHI 7 Is	TR Set RHI 7 Vs
00:00 - 01:00	426.52	34.97	188.07	56.45	497.53	30.28	1309.22	39.12	835.83	27.40	948.20	14.67	728.27	21.03
01:00 - 02:00	330.12	48.53	272.15	56.37	616.63	42.27	1618.05	47.18	1373.68	42.23	1135.93	21.13	1204.10	32.17
02:00 - 03:00	370.23	50.82	244.50	56.63	601.13	39.93	392.73	32.90	1552.63	43.67	1144.72	21.47	1205.98	32.62
03:00 - 04:00	381.17	51.68	207.82	56.67	572.45	40.05	1429.43	45.58	1512.22	43.37	1128.15	21.35	1205.82	32.58
04:00 - 05:00	343.73	51.68	180.38	56.37	600.87	40.62	1604.32	47.98	1427.93	42.40	1140.00	21.23	1205.57	32.70
05:00 - 06:00	340.85	51.45	164.28	55.60	629.07	40.90	1552.65	47.67	1619.20	44.40	1141.23	21.42	1204.43	32.80
06:00 - 07:00	324.25	51.57	185.85	56.57	651.32	41.32	1619.13	48.85	1605.82	43.55	1124.95	21.37	1205.58	33.00
07:00 - 08:00	315.50	51.98	212.20	57.03	724.08	42.33	1691.33	49.30	1562.48	43.55	1145.33	21.53	1205.25	33.00
08:00 - 09:00	325.93	51.78	185.28	57.17	582.30	39.87	1174.08	43.02	1649.50	44.13	1143.55	21.63	1204.33	33.00
09:00 - 10:00	315.38	51.32	174.87	56.85	577.13	39.88	615.10	36.02	1500.80	42.60	1143.52	21.25	1204.85	32.55
10:00 - 11:00	311.13	50.90	157.25	56.00	602.97	40.10	1657.02	49.33	1539.38	43.07	1144.22	21.05	1201.38	32.00
11:00 - 12:00	280.07	50.95	143.80	56.22	619.62	41.58	1579.98	47.88	1585.72	43.70	1145.20	21.05	1204.38	32.00
12:00 - 13:00	306.80	52.47	175.48	56.58	680.00	42.17	1635.52	49.20	1544.00	43.48	1144.15	21.13	1203.92	32.02
13:00 - 14:00	287.72	50.93	145.05	56.02	610.43	41.72	1649.02	49.50	1581.25	43.23	1145.20	21.03	1200.78	32.00
14:00 - 15:00	265.85	50.65	167.63	56.72	690.20	42.88	1590.63	48.82	1655.43	44.47	1140.43	21.02	1204.33	32.00
15:00 - 16:00	276.00	51.18	182.40	57.02	698.00	43.55	353.52	34.85	1469.28	42.80	1130.47	21.12	1204.18	32.05
16:00 - 17:00	293.62	50.32	187.70	56.40	697.10	43.02	1396.00	46.75	1629.43	44.30	1139.63	21.13	1204.50	32.00
17:00 - 18:00	308.37	49.55	172.12	56.28	718.33	43.82	1510.62	47.52	1524.88	43.32	1142.68	21.22	1204.87	32.15
18:00 - 19:00	313.90	49.97	168.17	55.20	657.18	43.35	1574.63	49.22	1586.80	44.15	1145.27	21.30	1204.42	32.77
19:00 - 20:00	289.07	49.98	159.57	55.50	651.42	42.68	1533.65	48.87	1542.38	42.97	1142.32	21.25	1193.32	32.70
20:00 - 21:00	311.80	48.27	158.90	55.53	677.65	43.17	1464.58	47.87	1619.52	44.38	1123.98	21.17	1204.68	32.92
21:00 - 22:00	335.70	51.22	202.30	56.90	707.18	43.98	1186.13	45.73	1560.10	43.82	1141.93	21.28	1204.85	33.00
22:00 - 23:00	329.68	49.70	294.77	56.35	672.95	42.72	747.35	41.38	1658.82	44.43	1143.48	21.65	1205.40	33.00
23:00 - 00:00	320.10	51.16	347.46	58.33	704.13	43.05	1559.51	48.85	1643.23	44.48	1142.59	21.67	1204.26	32.98

Table 5-32: RHI casing electrical performance hourly averages for HFPS

	RHI casing hourly acerage electrical performance for HFPS													
	RHI 1		RHI 2		RHI 3		RHI 4		RHI 5		RHI 6		RHI 7	
	HFPS-RHI 1 Is	HFPS-RHI 1 Vs	HFPS-RHI 2 Is	HFPS-RHI 2 Vs	HFPS-RHI 3 Is	HFPS-RHI 3 Vs	HFPS-RHI 4 Is	HFPS-RHI 4 Vs	HFPS-RHI 5 Is	HFPS-RHI 5 Vs	HFPS-RHI 6 Is	HFPS-RHI 6 Vs	HFPS-RHI 7 Is	HFPS-RHI 7 Vs
00:00 - 01:00	1551.43	43.32	1567.45	43.40	1652.45	43.98	1646.52	41.85	1694.42	42.15	1620.70	21.02	1611.75	32.28
01:00 - 02:00	1647.20	46.50	1638.30	43.84	1699.62	43.90	1405.00	39.55	1694.98	42.00	1710.45	22.10	1712.47	34.00
02:00 - 03:00	1670.73	47.11	1671.55	44.81	1643.02	42.36	1636.85	41.71	1692.47	42.00	1657.92	21.67	1712.07	34.00
03:00 - 04:00	1631.80	46.11	1652.80	44.13	1642.93	42.12	1635.08	41.12	1664.20	41.40	1679.07	22.00	1711.48	34.00
04:00 - 05:00	1620.67	47.60	1605.73	43.52	1642.88	42.38	1668.53	41.34	1696.05	42.00	1681.57	22.00	1712.00	34.00
05:00 - 06:00	1618.08	47.63	1634.05	44.22	1642.88	42.37	1668.55	41.35	1696.60	42.00	1686.28	22.00	1700.30	33.95
06:00 - 07:00	1348.98	46.24	1631.70	45.80	1696.70	43.90	1365.77	39.34	1666.08	41.38	1654.58	21.63	1689.08	33.90
07:00 - 08:00	1080.42	45.44	1574.23	46.10	1642.95	42.91	1620.80	41.52	1701.33	42.00	1681.47	22.00	1665.73	33.63
08:00 - 09:00	1527.73	48.04	1620.02	46.09	1671.18	43.88	1671.65	42.68	1711.88	42.05	1678.35	22.00	1556.05	33.33
09:00 - 10:00	1327.35	45.94	1618.40	46.79	1657.50	44.04	1351.88	39.59	1678.27	41.82	1684.30	22.00	1504.92	32.92
10:00 - 11:00	1225.52	45.77	1601.98	46.28	1669.70	44.30	1635.70	42.25	1691.82	42.00	1645.87	21.67	1549.22	33.13
11:00 - 12:00	1521.20	47.85	1644.55	46.96	1690.92	44.81	1357.00	39.69	1707.73	42.00	1677.87	22.00	1680.45	33.88
12:00 - 13:00	1548.15	48.20	1644.10	46.79	1642.98	43.81	1629.92	42.23	1675.53	41.45	1684.87	22.00	1618.62	32.82
13:00 - 14:00	1582.92	45.33	1647.48	46.70	1659.72	44.20	1679.05	42.86	1690.92	42.00	1680.75	22.00	1708.63	34.00
14:00 - 15:00	1617.57	46.59	1629.02	45.23	1671.17	43.94	1643.93	41.86	1688.42	42.00	1659.63	21.63	1708.40	33.98
15:00 - 16:00	1634.65	46.66	1652.58	45.88	1699.42	44.67	1323.10	39.25	1664.97	41.37	1694.30	22.00	1712.90	34.00
16:00 - 17:00	1606.02	46.95	1627.35	45.85	1642.78	43.33	1674.47	42.83	1688.00	42.00	1688.87	22.00	1702.70	33.82
17:00 - 18:00	1416.68	46.66	1601.47	46.44	1670.87	44.33	1640.17	42.13	1691.73	42.02	1685.80	22.00	1713.48	34.00
18:00 - 19:00	828.20	43.46	1524.87	47.06	1642.35	44.12	1506.48	40.75	1661.13	41.48	1655.32	21.63	1623.13	33.60
19:00 - 20:00	931.95	42.96	1497.87	46.79	1670.20	44.70	1430.17	40.11	1711.23	42.15	1685.78	22.00	1691.58	33.92
20:00 - 21:00	960.98	44.18	1564.35	47.33	1642.73	44.04	1697.60	43.18	1711.48	42.70	1693.22	22.00	1678.27	33.82
21:00 - 22:00	913.72	44.06	1522.85	47.51	1671.17	44.83	1614.52	41.71	1682.43	42.25	1704.03	22.07	1685.43	33.87
22:00 - 23:00	1085.30	43.70	1584.85	47.65	1639.28	44.29	1339.58	39.82	1708.30	42.93	1678.95	21.98	1648.23	33.55
23:00 - 00:00	1120.83	44.56	1562.45	46.54	1668.98	45.08	1638.25	42.34	1708.48	42.90	1688.49	22.00	1701.98	33.95

Tables 5-31 and 5-32 present the hourly average reading for the current and voltage measurements for both TR sets and HFPS transformer while in operation during the ESP efficiency testing for the RHI casing.

- **RHI 1 electrical performance**

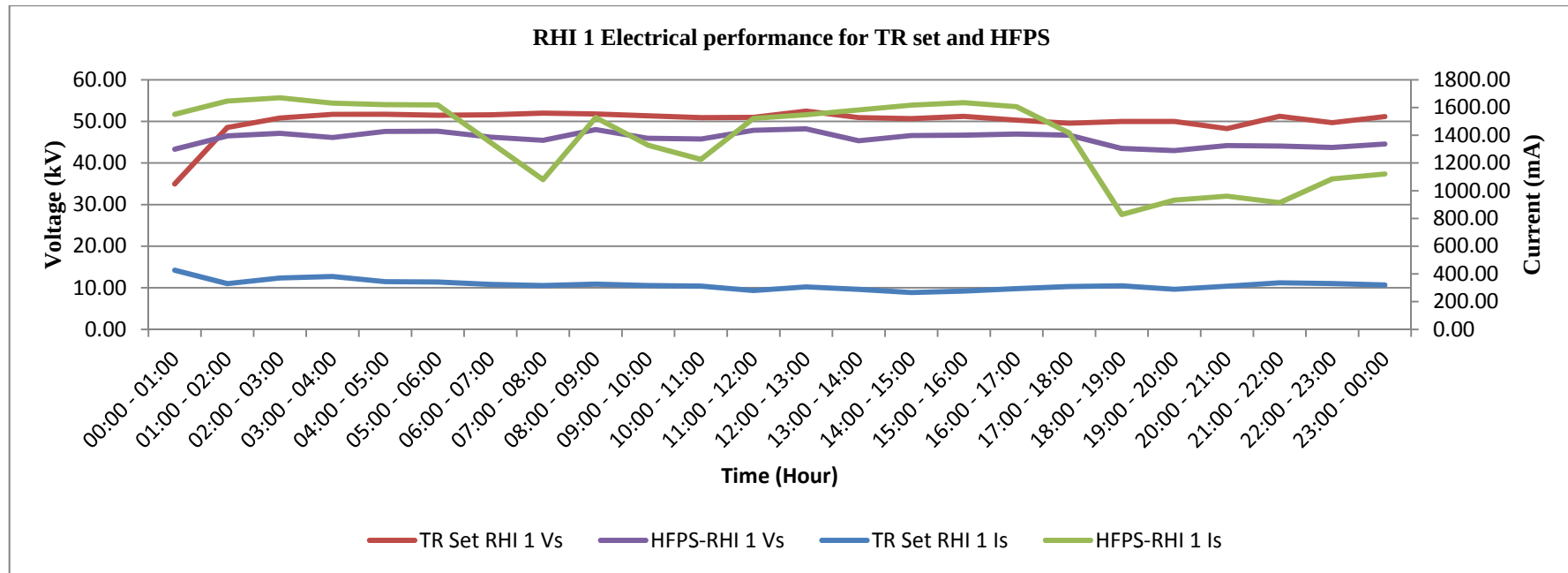


Figure 5-33: LHI 7 electrical performance for TR set and HFPS

The RHI 1's electrical performance is plotted in Figure 5-33. The TR set's performance for this field is typical of how low the electrical performance of the TR set can be; more especially, for the first field. The current input into the field was consistently below 350 mA with the TR set in operation. The installation of the HFPS saw the current input into the field increase to above 1 000 mA. The voltage of the TR set was

slightly above that which the HFPS could manage; however, due to the inability to produce a high enough current, the high voltage has no significant influence on the collection of dust burden.

- **RHI 2 electrical performance**

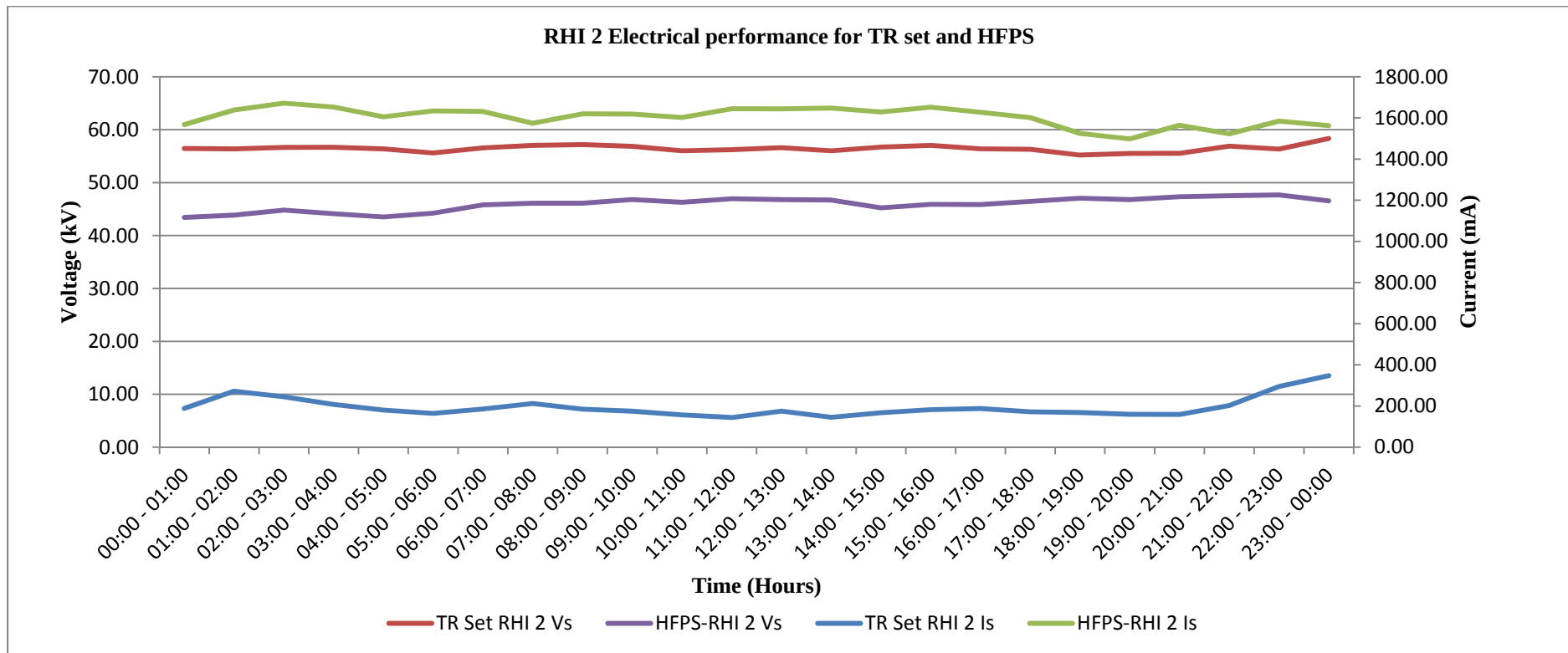


Figure 5-34: RHI 2 electrical performance for TR set and HFPS

Figure 5-34 presents the graphical representation of the data in Tables 5-31 and 32. It is noted that the electrical performance of the HFPS surpassed that of the TR set, with the HFPS being able to input full load current into the field. The TR set's voltage is significantly higher than

that of the of the HFPS, the reason being the controller algorithm is such that it forced the TR set to push the voltage as high as possible in order to achieve the desired 1 600 mA. Since the HFPS is able to achieve full load operational current, at a lower voltage, it simply maintains the voltage level at which the full load current was achieved.

- **RHI 3 electrical performance**

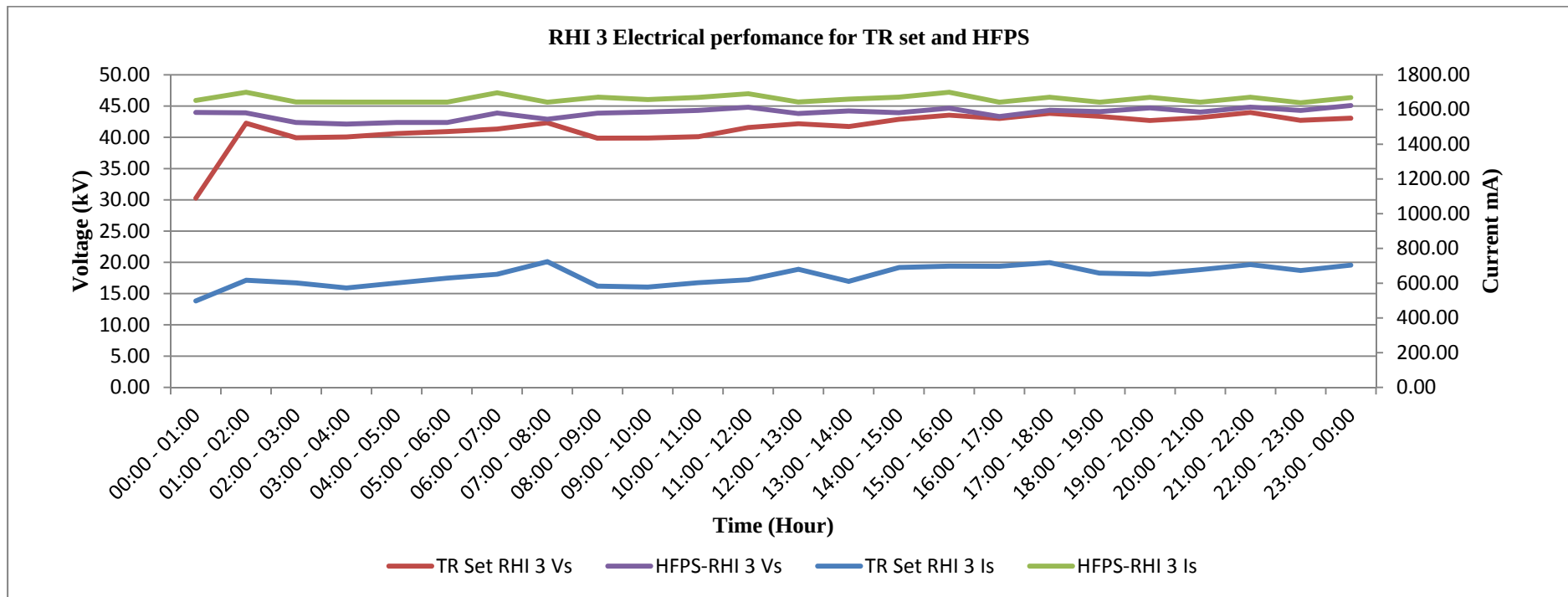


Figure 5-35: RHI 3 electrical performance for TR set and HFPS

RHI 3's electrical performance is plotted in Figure 5-35; it is noted that with the TR set in operation, the input current was significantly lower. The installation of the HFPS resulted in a maximum input current being fed into the field and maintained.

- RHI 4 electrical performance

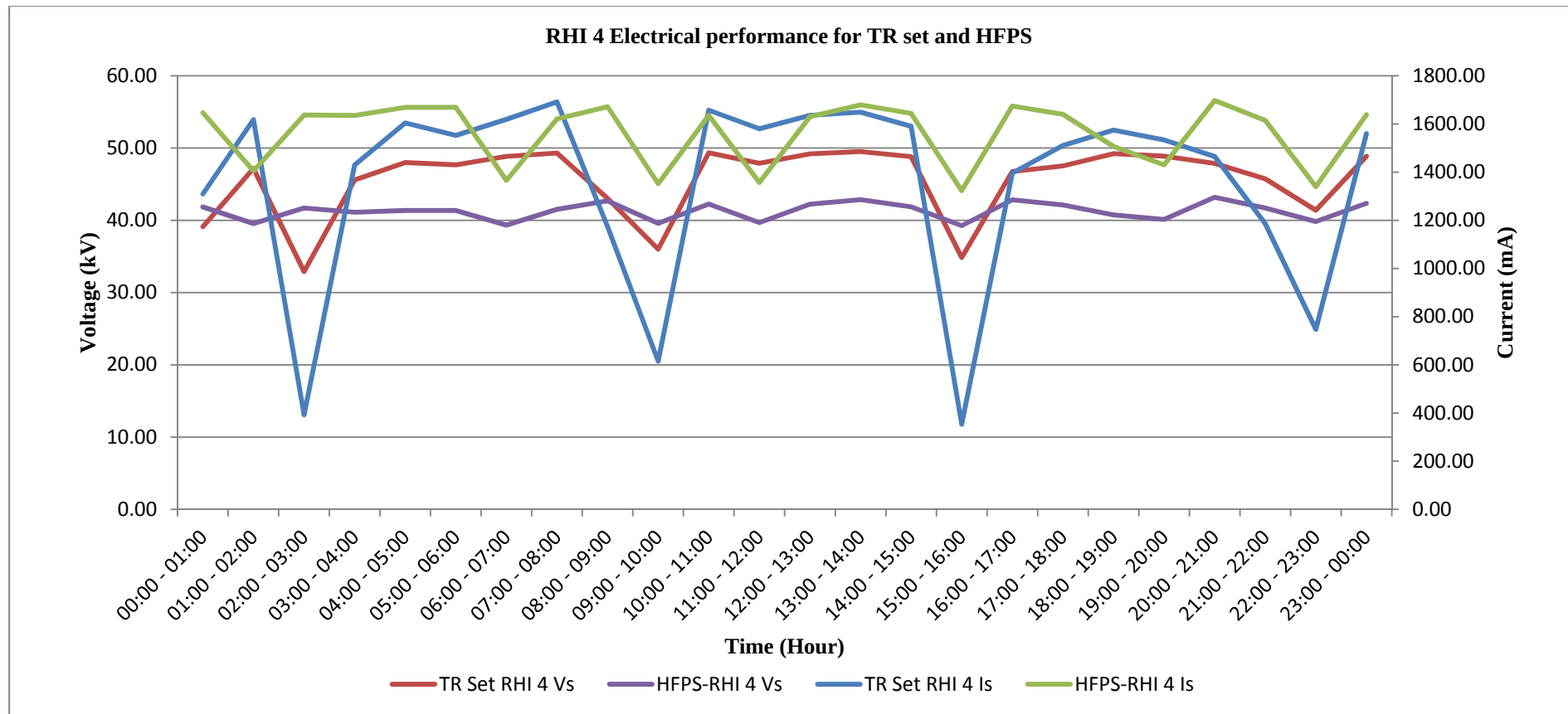


Figure 5-36: RHI 4 electrical performance for TR set and HFPS

The RHI 4's electrical performance was not stable for both power supply technologies, as seen in Figure 5-36. The performance of the field was within specification for both power supply technologies, although the field was experiencing excessive sparking resulting in frequent performance dips.

- RHI 5 electrical performance

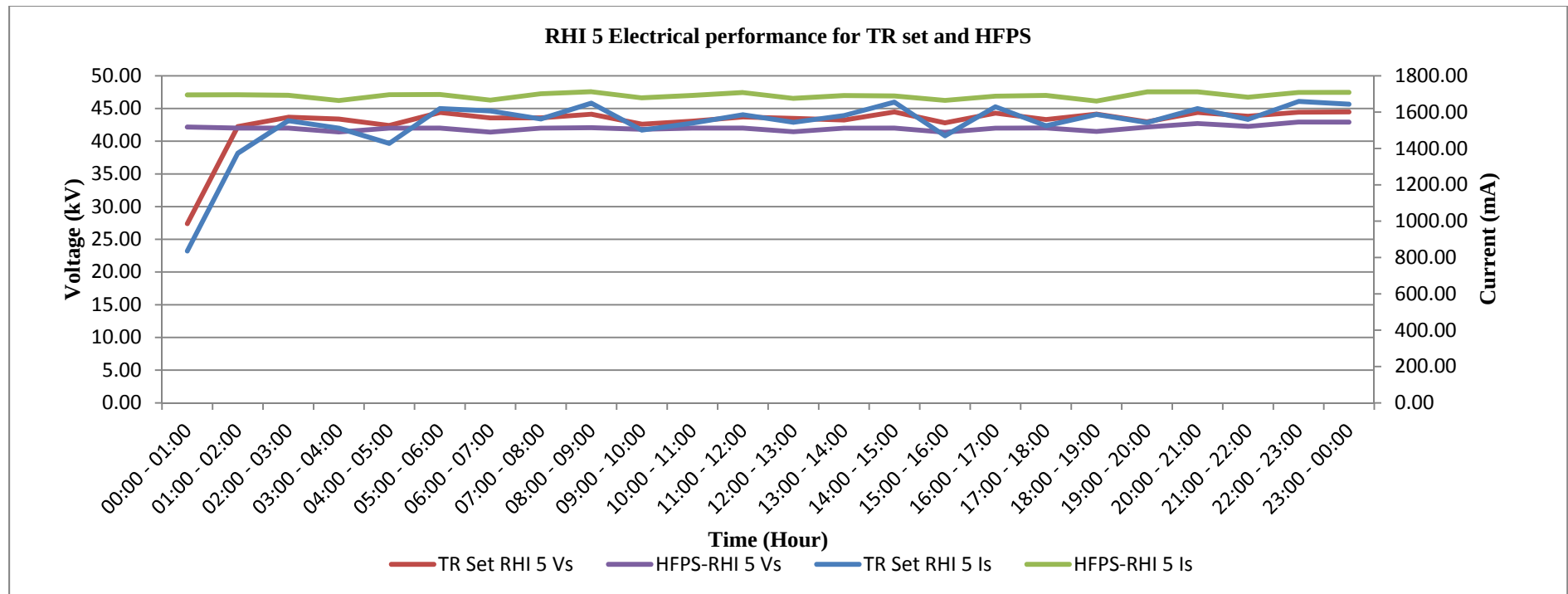


Figure 5-37: RHI 5 electrical performance for TR set and HFPS

No significant electrical performance changes were noted on the RHI 5's performance in both instances when the ESP efficiency tests were conducted, as shown in Figure 5.37. The performance of the field, however, was more stable during the final efficiency test conducted with HFPS installed. In the upstream of the casing, the stability can be attributed to the reduced dust burden that the field handles, which, in turn, minimised the sparking of the field.

- RHI 6 electrical performance

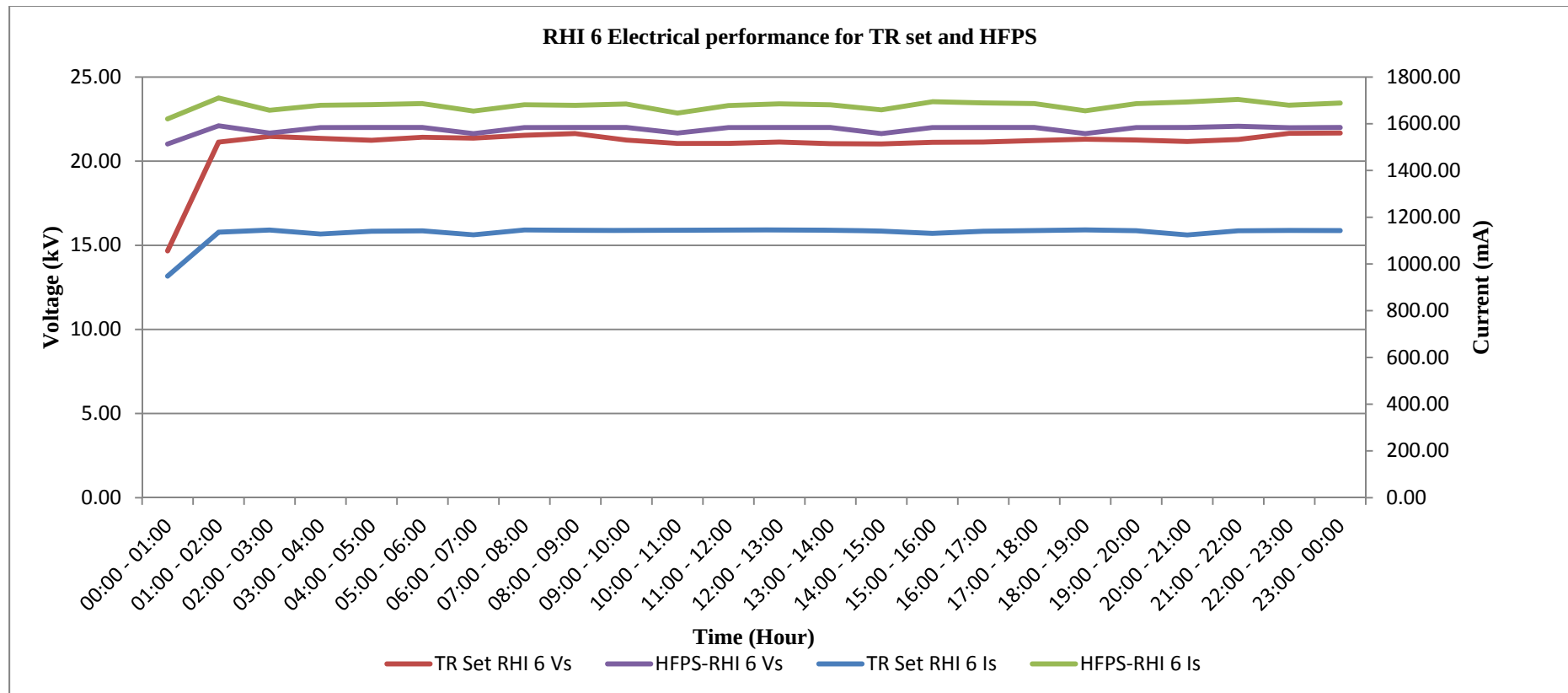


Figure 5-38: RHI 6 electrical performance for TR set and HFPS

Figure 3-38 shows the performance of the RHI 6's electrical measurements. The field power input significantly increased during the final ESP efficiency test as maximum current could be achieved by the TR set.

- RHI 7 electrical performance

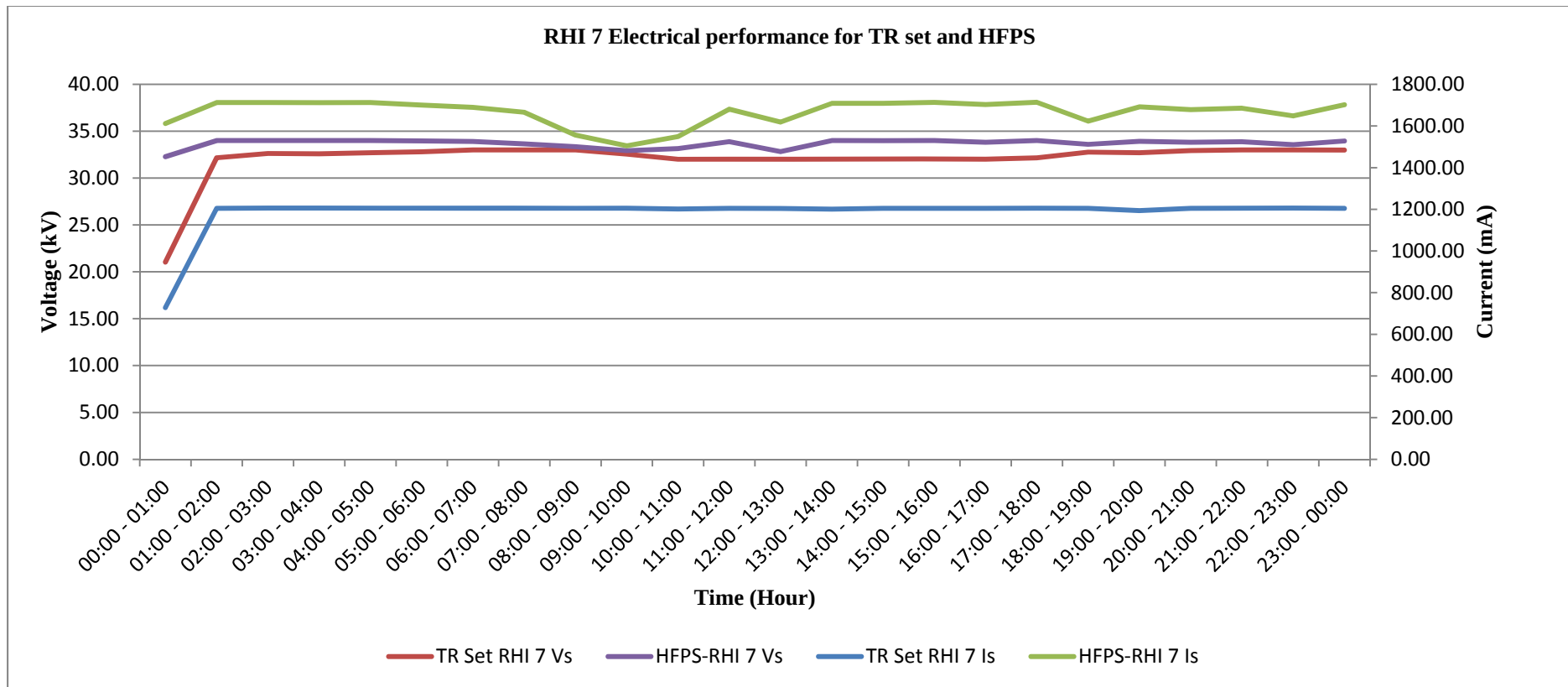


Figure 5-39: RHI 7 electrical performance for TR set and HFPS

The installation of the HFPS transformers on the first four fields resulted in the improved performance of the RHI 7 field's electrical performance. This is observed in Figure 5-39, with the TR being able to achieve full load current at a higher voltage than was previously achieved during the baseline test.

Table 5-33: RHO casing electrical performance hourly averages for TR set

	RHO Casing hourly average electrical performance for TR sets													
	RHO 1		RHO 2		RHO 3		RHO 4		RHO 5		RHO 6		RHO 7	
	TR Set RHO 1 Is	TR Set RHO 1 Vs	TR Set RHO 2 Is	TR Set RHO 2 Vs	TR Set RHO 3 Is	TR Set RHO 3 Vs	TR Set RHO 4 Is	TR Set RHO 4 Vs	TR Set RHO 5 Is	TR Set RHO 5 Vs	TR Set RHO 6 Is	TR Set RHO 6 Vs	TR Set RHO 7 Is	TR Set RHO 7 Vs
00:00 - 01:00	485.65	24.03	287.13	34.80	424.88	20.72	768.27	21.97	961.45	15.33	1068.57	12.25	977.42	22.37
01:00 - 02:00	585.53	24.93	788.55	56.03	279.42	32.67	1642.20	34.53	1686.05	24.42	1586.80	18.82	1662.25	33.53
02:00 - 03:00	561.22	24.80	807.60	56.85	221.15	32.08	1652.28	34.68	1706.72	24.93	1613.77	19.00	1705.17	34.05
03:00 - 04:00	617.95	24.28	754.15	57.22	228.88	32.85	1665.53	34.87	1707.02	25.15	1611.97	19.27	1706.15	34.35
04:00 - 05:00	635.83	24.63	740.37	57.27	227.42	32.98	1707.78	35.18	1684.40	24.93	1609.28	19.02	1707.87	34.17
05:00 - 06:00	603.37	24.30	741.88	57.40	208.53	32.55	1665.07	34.98	1705.00	25.02	1678.05	19.30	1705.62	34.37
06:00 - 07:00	623.03	23.95	707.23	55.72	204.32	32.83	1675.15	35.78	1706.12	25.05	1673.58	19.33	1705.32	34.50
07:00 - 08:00	668.65	24.80	727.90	57.23	186.42	33.62	1632.97	35.47	1680.95	25.28	1661.72	19.45	1704.98	34.67
08:00 - 09:00	659.20	24.07	718.97	57.57	179.73	32.93	1690.55	35.92	1705.98	25.18	1690.12	19.43	1703.93	34.70
09:00 - 10:00	651.07	23.93	692.75	57.25	180.73	32.98	1666.40	35.75	1706.83	25.32	1661.60	19.37	1697.20	34.67
10:00 - 11:00	735.33	25.10	663.82	55.58	165.62	33.08	1669.43	35.70	1688.33	25.02	1604.57	18.95	1672.55	33.88
11:00 - 12:00	673.78	25.33	652.43	55.53	158.77	32.40	1698.65	35.23	1707.62	25.00	1638.82	18.93	1683.00	33.80
12:00 - 13:00	840.45	25.72	644.18	56.23	155.83	32.08	1619.53	34.85	1654.35	24.72	1647.82	18.93	1703.15	33.53
13:00 - 14:00	677.05	24.87	584.63	53.77	143.00	32.13	1443.42	33.98	1573.15	24.15	1467.87	18.12	1702.53	33.37
14:00 - 15:00	925.17	23.40	655.05	55.77	169.88	34.93	1600.03	35.23	1693.63	24.98	1536.15	18.68	1704.18	33.12
15:00 - 16:00	1404.03	25.57	664.02	56.03	258.68	38.85	1669.95	35.72	1704.73	25.08	1547.28	18.62	1704.62	33.60
16:00 - 17:00	1323.68	26.62	715.52	56.52	292.80	38.30	1602.93	35.48	1706.43	25.43	1615.87	18.92	1680.95	33.75
17:00 - 18:00	1179.75	27.17	720.35	56.38	380.17	39.68	1607.60	35.83	1219.60	24.60	1672.78	18.98	1700.53	34.00
18:00 - 19:00	1155.28	27.00	765.55	57.27	396.23	39.58	1694.03	36.28	1002.83	22.63	1664.57	18.98	1672.17	33.43
19:00 - 20:00	1224.40	27.75	746.07	57.00	386.58	39.43	1678.10	36.25	1427.57	24.75	1673.83	18.88	1700.73	34.00
20:00 - 21:00	1245.72	28.53	738.70	57.07	379.28	38.90	1590.17	36.08	1632.02	25.23	1645.70	18.95	1672.37	33.58
21:00 - 22:00	1181.37	28.37	745.47	56.57	402.30	40.07	1655.37	36.15	1678.58	25.58	1670.37	19.27	1702.70	34.23
22:00 - 23:00	1217.65	28.25	784.58	57.30	379.90	40.53	1628.87	36.25	1707.00	26.00	1691.87	19.33	1704.45	34.28
23:00 - 00:00	1193.89	27.97	740.03	56.41	423.15	40.08	1635.57	36.31	1704.30	26.00	1686.56	19.44	1703.92	34.36

Table 5-34: RHO casing electrical performance hourly averages for HFPS

	RHO Casing hourly average electrical performance for HFPS													
	RHO 1		RHO 2		RHO 3		RHO 4		RHO 5		RHO 6		RHO 7	
	HFPS- RHO 1 Is	HFPS- RHO 1 Vs	HFPS- RHO 2 Is	HFPS- RHO 2 Vs	HFPS- RHO 3 Is	HFPS- RHO 3 Vs	HFPS- RHO 4 Is	HFPS- RHO 4 Vs	HFPS- RHO 5 Is	HFPS- RHO 5 Vs	HFPS- RHO 6 Is	HFPS- RHO 6 Vs	HFPS- RHO 7 Is	HFPS- RHO 7 Vs
00:00 - 01:00	26.88	9.85	1529.67	45.75	1528.97	40.16	1584.35	40.34	0.00	0.00	408.05	18.65	1626.78	32.80
01:00 - 02:00	15.97	10.51	1634.95	48.59	1660.88	42.58	1642.85	42.02	0.00	0.00	517.53	22.15	1712.72	35.00
02:00 - 03:00	19.22	11.36	1642.23	48.82	1699.50	43.16	1699.47	43.19	0.00	0.00	1374.47	28.12	1713.00	35.00
03:00 - 04:00	14.03	11.14	1626.78	49.05	1642.48	41.61	1671.13	42.33	0.00	0.00	1705.35	30.97	1712.85	35.00
04:00 - 05:00	15.38	10.90	1568.45	48.90	1645.20	42.07	1667.25	41.90	0.00	0.00	1525.72	29.70	1710.62	35.00
05:00 - 06:00	15.38	10.87	1565.50	48.87	1645.22	42.08	1667.27	41.89	0.00	0.00	1496.13	29.08	1713.42	34.58
06:00 - 07:00	15.32	11.16	1311.33	46.83	1698.63	43.52	1699.48	42.77	0.00	0.00	1594.27	29.47	1711.88	34.52
07:00 - 08:00	21.37	12.29	990.22	44.15	1641.25	43.14	1642.85	41.69	0.00	0.00	1711.72	30.27	1712.02	34.63
08:00 - 09:00	19.05	11.63	1044.18	44.13	1661.88	43.47	1675.27	42.72	0.00	0.00	1521.43	28.85	1711.32	34.75
09:00 - 10:00	16.97	11.11	1109.02	46.23	1636.35	42.92	1674.75	42.90	0.00	0.00	1472.93	28.92	1712.32	34.18
10:00 - 11:00	19.03	11.26	1311.63	46.04	1663.05	43.56	1661.23	42.99	0.00	0.00	1572.20	29.02	1710.28	34.13
11:00 - 12:00	17.72	11.05	1162.78	44.94	1661.12	43.65	1670.68	42.77	0.00	0.00	1711.05	30.02	1703.63	34.17
12:00 - 13:00	18.95	11.57	1100.32	44.99	1649.32	43.33	1688.67	43.32	0.00	0.00	1544.07	29.35	1712.70	34.07
13:00 - 14:00	22.20	11.45	1319.40	45.85	1648.33	43.04	1669.82	43.16	0.00	0.00	1475.68	29.92	1706.08	34.82
14:00 - 15:00	18.87	11.38	1378.70	45.82	1665.90	42.98	1641.90	42.59	458.77	14.82	1539.57	29.93	1712.30	35.00
15:00 - 16:00	19.47	11.46	1506.88	47.43	1649.60	42.77	1670.23	42.91	1063.47	35.35	1711.58	30.43	1710.17	34.75
16:00 - 17:00	16.88	11.21	1557.13	47.36	1646.85	42.91	1681.37	43.77	1081.83	35.65	1570.68	30.18	1713.03	35.00
17:00 - 18:00	16.08	11.40	1433.12	47.34	1669.48	43.15	1698.48	43.93	1029.12	35.30	1500.50	30.00	1713.05	35.00
18:00 - 19:00	18.10	11.44	1200.15	45.88	1631.75	42.64	1677.83	43.81	981.70	34.48	1536.78	30.05	1714.00	35.00
19:00 - 20:00	18.20	11.33	1173.95	45.94	1641.15	42.43	1685.17	43.57	1055.03	34.85	1710.72	31.00	1712.70	35.00
20:00 - 21:00	16.72	11.36	1106.00	44.97	1670.38	43.69	1670.42	43.07	1152.87	35.43	1589.95	30.12	1712.58	35.00
21:00 - 22:00	14.02	9.96	1044.87	44.91	1683.55	44.05	1670.90	42.89	1263.57	36.48	1499.25	30.00	1713.32	35.00
22:00 - 23:00	18.73	12.53	1150.53	46.27	1639.33	43.29	1642.50	42.49	1319.72	37.12	1490.45	29.72	1712.13	35.00
23:00 - 00:00	14.00	10.51	1219.43	46.82	1695.53	43.97	1671.03	43.08	1319.48	35.62	1645.23	30.49	1712.21	35.00

Tables 5-33 and 5-34 present the hourly average reading for the current and voltage measurements for both TR sets and HFPS transformer while in operation during the ESP efficiency testing for the RHO casing, and are used to plot the graphs for the performance of each of the RHO's fields.

- **RHO 1 electrical performance**

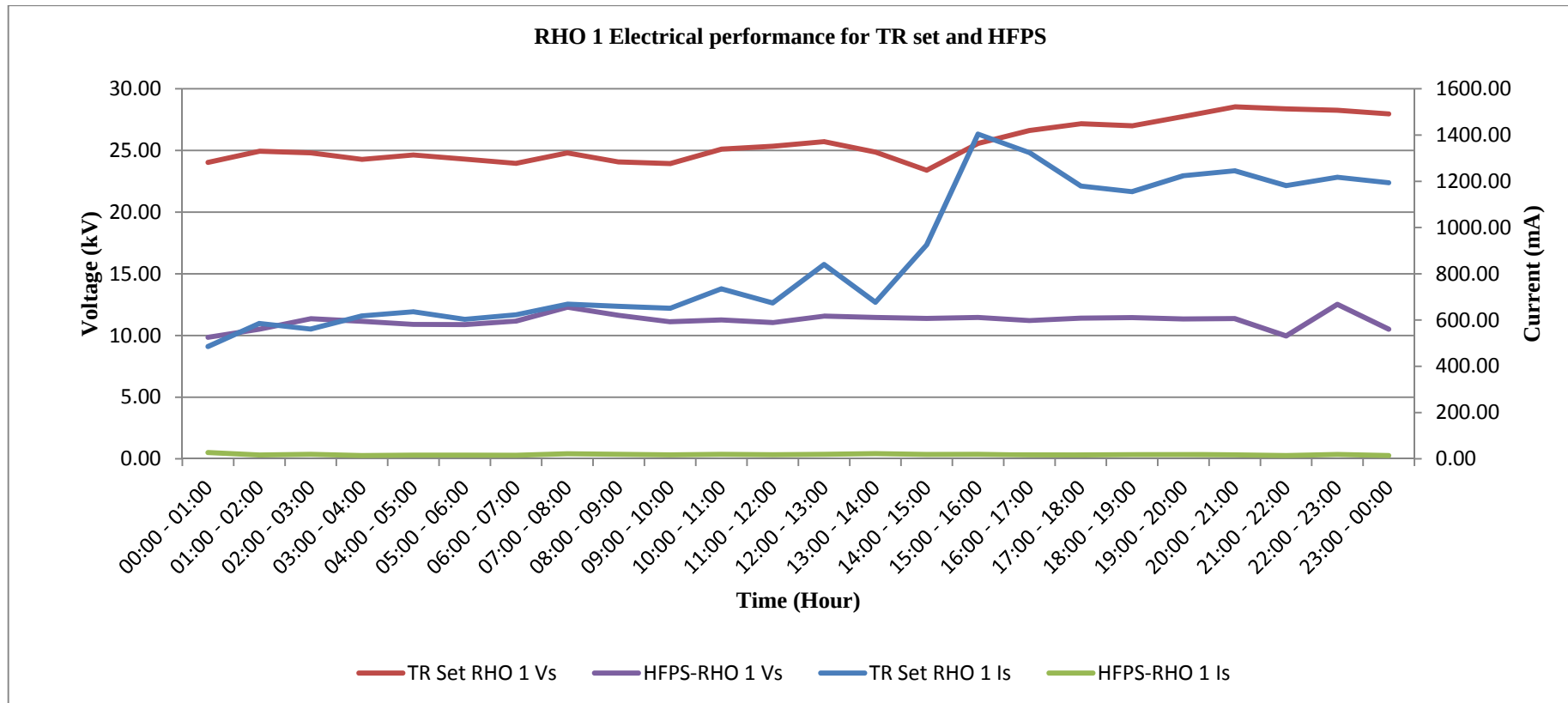


Figure 5-40: RHO 1 electrical performance for TR set and HFPS

Figure 5-40 illustrates the performance of the RHO 1 field. Unfortunately, the field experienced an internal fault when the HFPS was installed and therefore its performance could not be determined at the stage when the test was conducted.

- **RHO 2 electrical performance**

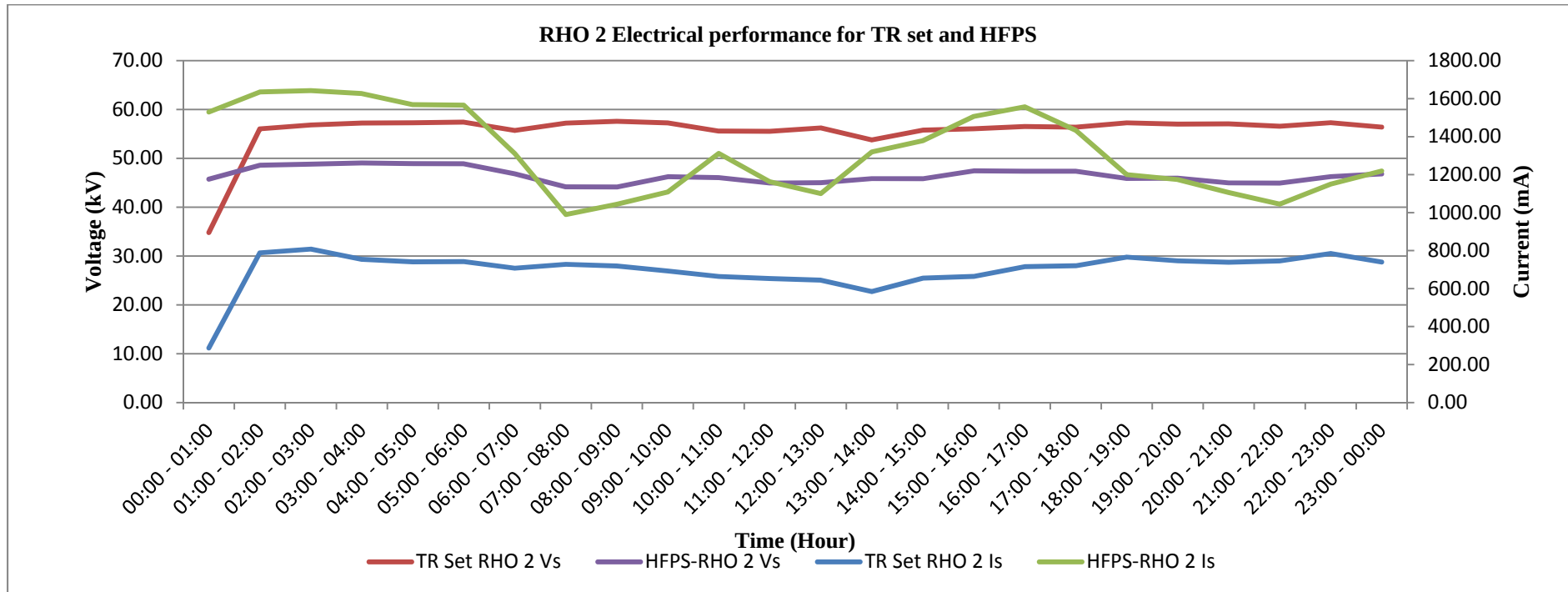


Figure 5-41: RHO 2 electrical performance for TR set and HFPS

Figure 5-41 illustrates the electrical performance data of the RHO 2 field. The performance of this field was within specification for both power supply technologies. The TR set was able to produce and maintain a current input of above 700 mA at a voltage level of 57 kV, which is exceptional performance for a TR set, more specifically because it is operating on the second field. The installation of the HFPS further improved the electrical performance of the field, with a current exceeding 1 000 mA.

- **RHO 3 electrical performance**

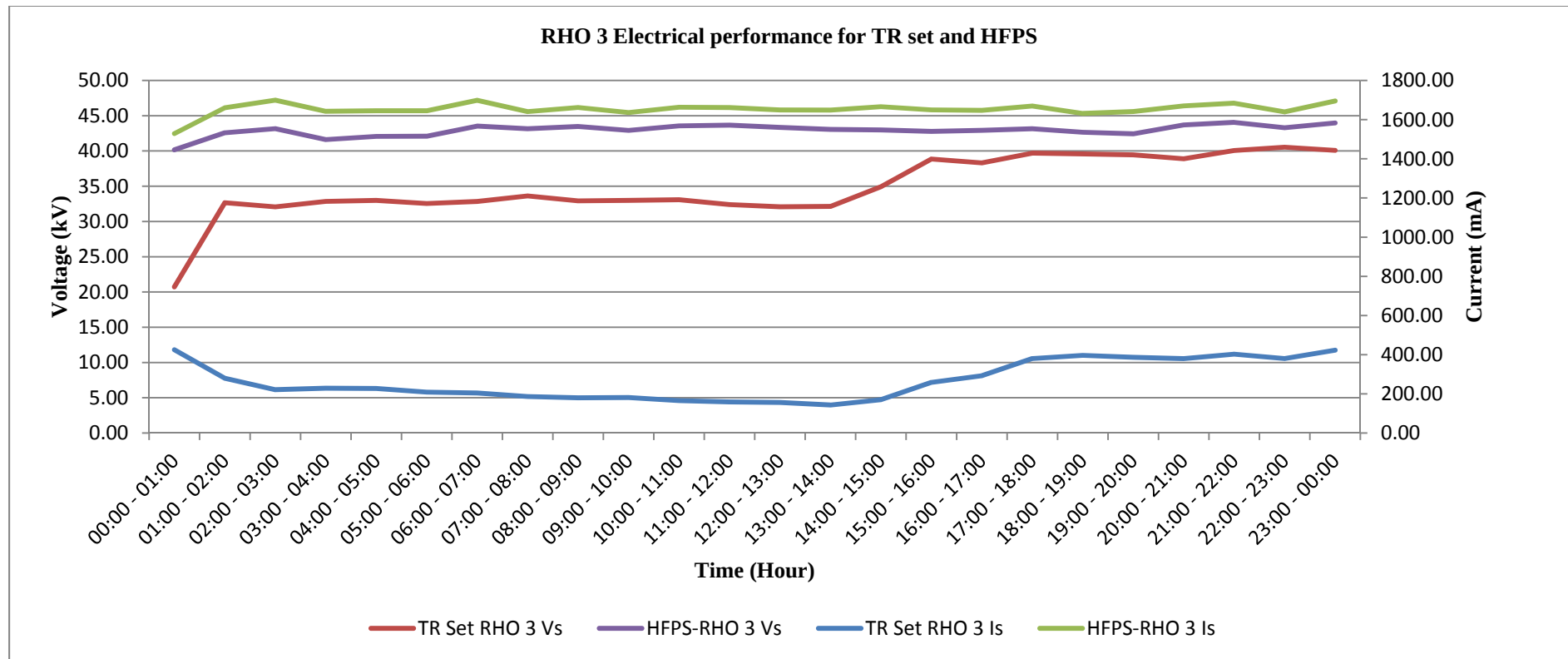


Figure 5-42: RHO 3 electrical performance for TR set and HFPS

Figure 5-42 illustrates the electrical performance data of the RHO 3 field. The TR set showed poor performance with a current input into the field being below 200 mA; such poor performance is typically due to an internal fault condition such as a defective rapping system. A shearing pin was replaced on the discharge electrode rapping system and, with the installation of the HFPS, the input current into the field went to maximum.

- **RHO 4 electrical performance**

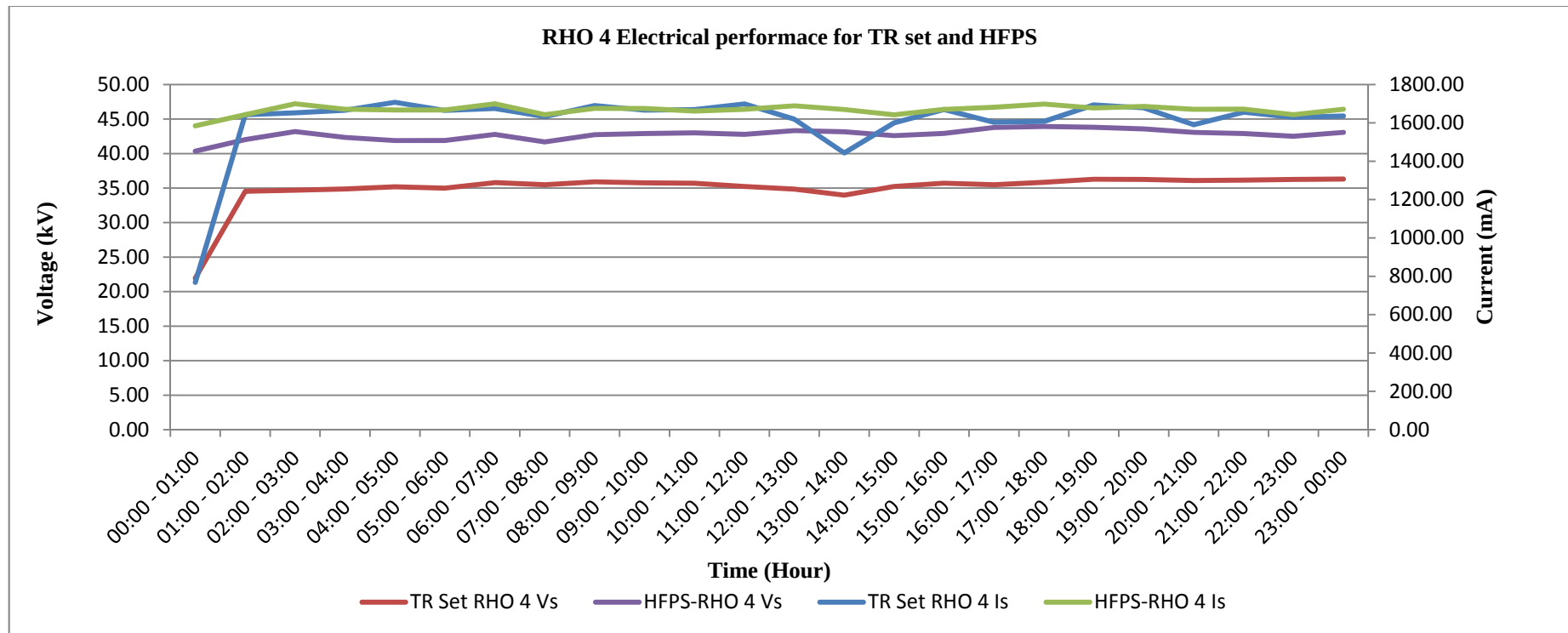


Figure 5-43: RHO 4 electrical performance for TR set and HFPS

Figure 5-43 illustrates the electrical performance data of the RHO 4 field. The RHO 4's performance was within specification with the TR set installed, as it was able to produce maximum current. The installation of an HFPS results in the HFPS also maintaining the maximum current; however, it also managed to increase the input voltage into the field.

- RHO 5 electrical performance

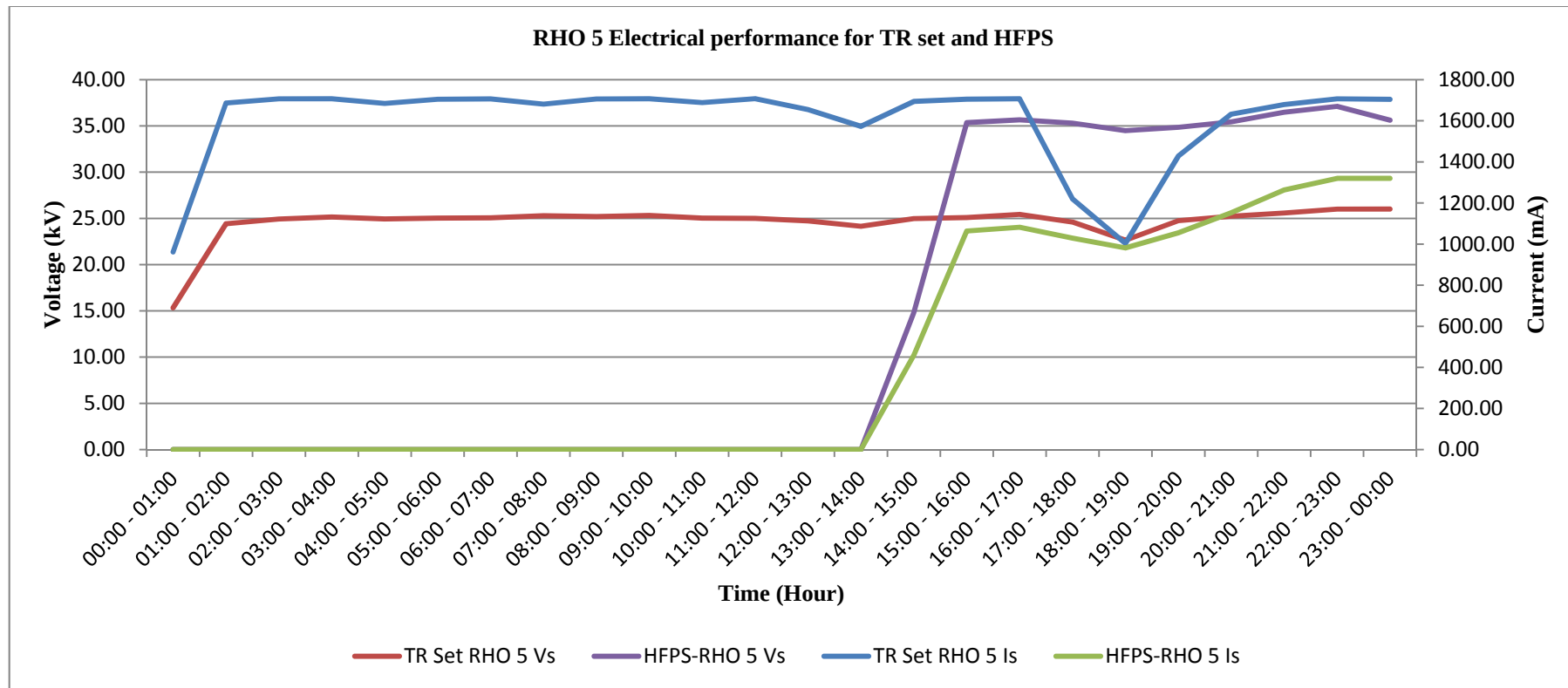


Figure 5-44: RHO 5 electrical performance for TR set and HFPS

At the time when the measurements were conducted, the RHO 5 had tripped due to under-voltage during the performance of the ESP efficiency test. The file was reset and put back in service; the performance of the field was within specification in both instances, as can be seen in Figure 5-44.

- **RHO 6 electrical performance**

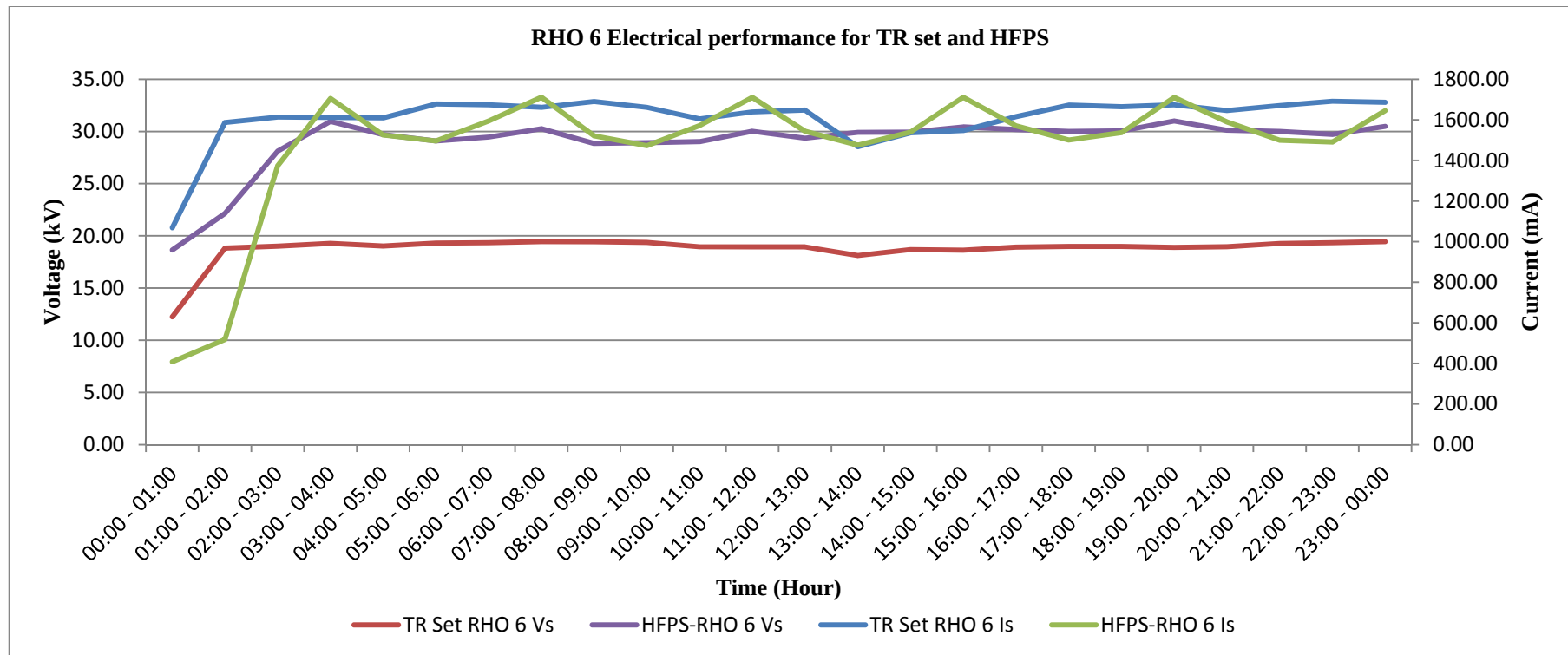


Figure 5-45: RHO 6 electrical performance for TR set and HFPS

The RHO 6's electrical performance is shown in Figure 5-45; the performance of the field improved with the installation of the HFPS on the upstream fields of the casings.

- **RHO 7 electrical performance**

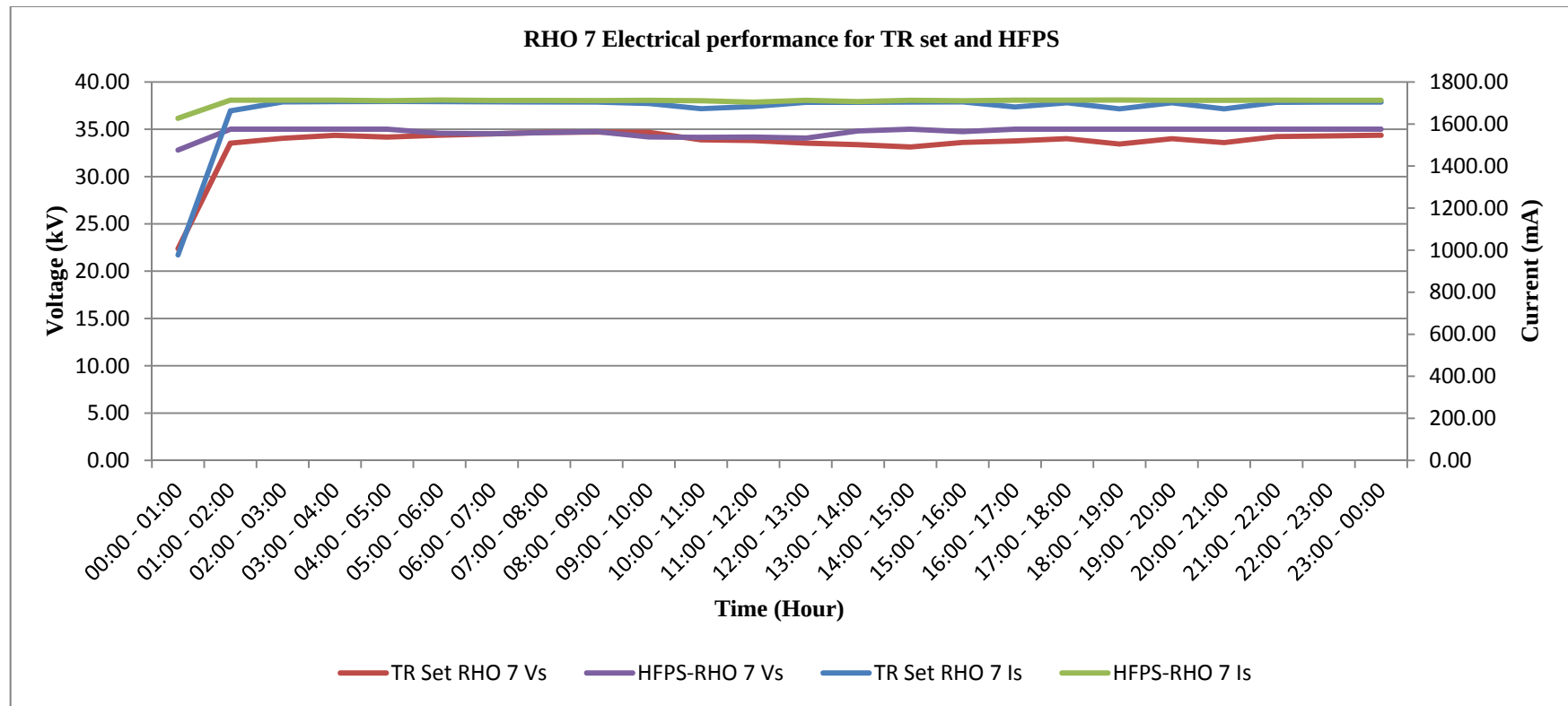


Figure 5-46: RHO 7 electrical performance for TR set and HFPS

The electrical performance of the RHO 7 is shown in Figure 5-46, and was within specification on both occasions during the ESP efficiency testing.

The overall electrical performance of the two power supply technologies has shown that the HFPS has a better electrical conversion efficiency as compared to that of the TR set. The power input into the fields significantly improved with the installation of the HFPS, as can be seen from Tables 5-24 and 5-26 for TR sets and HFPS, respectively.

The LHO casing had a maximum power input of 228 kW, with the TR set in operation, whereas the HFPS was able to produce a maximum power input of 389 kW. This gave a casing power input increase of 41%. The LHI casing had a maximum power input of 237 kW, with the TR set in operation, whereas the HFPS was able to produce a maximum power input of 419 kW. This gave a casing power input increase of 43%.

The RHI casing had a maximum power input of 253 kW, with the TR set in operation, whereas the HFPS was able to produce a maximum power input of 403 kW. This gave a casing power input increase of 37%. The highest power input into the RHO casing was 275 kW for conventional TR sets, whereas the highest for a casing with HFPS installed went up to 420 kW. This gave a casing power input increase of 35%.

The overall electrical performance increase of the ESP casings is expected to result in an improved collection efficiency of the ESP.

5.5 ESP efficiency

The ESP performance test was conducted for both power supply technologies; the test mainly focuses on the process parameters in terms of flue gas volume flow in and out of the ESP and other process conditions such as coal quality. Isometric sampling was conducted on the inlet and outlet duct of the ESP casings; these representative samples are used to determine the collection efficiency of the ESP.

Particulate emission measurements were carried out employing procedures and equipment that comply with the requirements of EN 13284-1. The VDI correlation procedure was followed in the determination of the linear regression of the correlation spot check. The baseline ESP efficiency test was conducted with conventional TR sets installed and thereafter a second efficiency test was conducted with HFPS installed.

5.5.1 Baseline ESP efficiency test

Five ESP efficiency tests were conducted on the unit while operating at full load of 618 MW generated load. Table 5-35 illustrates the obtained results from the isometric testing

conducted during the ESP efficiency test. The average efficiency of the ESP post-outage and with conventional TR sets was found to be 97.1%; emitting at 42.8 mg/Nm³, at an average boiler load of 619 MW.

Table 5-35: Isometric ESP efficiency test results

Test no.	Boiler Load	% of Total Air flow	Standard Deviation (% of Total air flow)	Effective emissions	Dust Concentration	Average isokineticity	average O ₂ Concentration at ESP inlet
	MW	kg/s	%	-	mg/Nm ³ at 10% O ₂	%	mm
1	618.8	580.6	1.4	73.7	30.3	97.8	4.8
2	619.2	572.7	1.2	34.3	18.1	98.2	4.3
3	618.9	581.4	1.1	40.5	19.2	95.9	4.4
4	619.1	573.6	1.0	32.0	22.9	96.7	4.5
5	619.2	575.1	1.1	33.7	15.4	96.8	4.6
Average	619.0	576.7	1.2	42.8	21.2	97.1	4.5

The performance of the ESP is influenced by a number of parameters; process conditions, both downstream of the ESP, electrical power delivered into the ESP fields and rapping philosophy. The analysis conducted in this dissertation focuses on the electrical performance of the ESP fields as well as the rapping philosophy utilised. The rapping philosophy utilised for the conventional power supply transformers, implemented while conducting the baseline efficiency test, is discussed in Chapter 4, section 4.3.5.

5.5.2 Post-HFPS ESP efficiency test

The ESP efficiency test was subsequently performed after the optimisation process had been completed. Table 5-36 provides the obtained results for the efficiency test conducted with the HFPS installed, on the first four fields of the ESP casings. The emissions were found to be 19.3 mg/Nm³ and were maintained at this level consistently. A reduction of 45% in particulate emissions from the baseline tests conducted with the conventional TR sets.

It can be, seen from Table 5-36 that the ESP was experiencing higher flue gas volume flows, as compared to those measured on the baseline efficiency test. For the post-HFPS installation efficiency test, the volume flow increased by up to 21% on some casings and the dust concentration increased by up to 22% on some of the casings. However, despite these increases in the process conditions, the obtained emissions were less than those obtained in the baseline tests, giving a 45% emission reduction from the baseline.

Table 5-36: ESP efficiency test results post-HFPS installation

Test no.	Boiler Load	% of Total Air flow	Standard Deviation (% of Total air flow)	Effective emissions	Dust Concentration	Average isokineticity	average O2 Concentration at ESP inlet
	MW	kg/s	%	-	mg/Nm ³ at 10% O ₂	%	mm
1	618.2	594.7	1.1	19.3	36.5	95.0	7.1
2	619.5	598.2	1.1	20.3	28.9	96.1	6.8
3	618.6	599.0	1.0	24.0	34.4	95.4	6.8
4	619.6	579.4	1.1	13.8	7.3	98.1	6.2
5	619.7	587.9	0.6	19.1	17.7	98.4	7.1
Average	619.1	591.8	1.0	19.3	25.0	96.6	6.8

5.6 Emissions performance comparison

Figure 5-51 illustrates the emission performance of the unit; it can be seen how the emissions reduced and were consistently maintained at low levels.

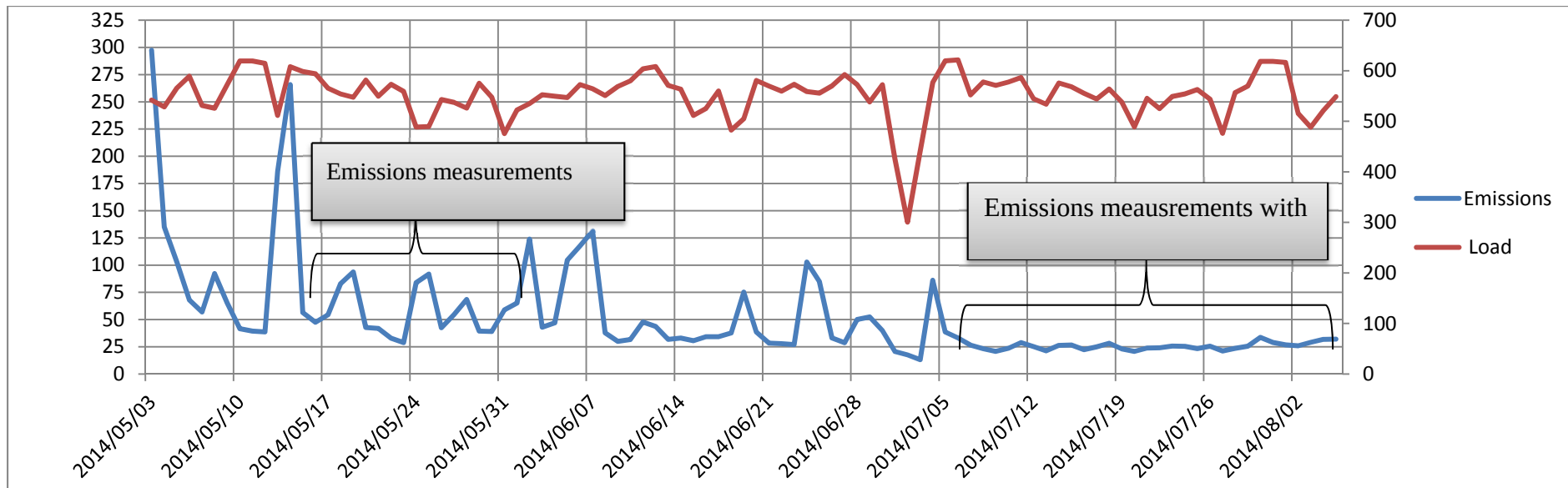


Figure 5-47: Emissions performance

The emissions recorded show that for the period in which the conventional TR sets were in operation the emissions were low; however, the inconsistency in the electrical performance of the TR sets resulted in a fluctuation of the emissions. At the time, when all 16 HFPS were installed and fully operational, it could be seen that the emissions reduced and were maintained; this is due to the consistency that the HFPS is able to maintain high electrical power input into the ESP.

The ESP efficiency test showed that the ESP was emitting 42.8 mg/Nm^3 with conventional TR sets installed, and 19.3 mg/Nm^3 with HFPS transformers installed in the front four fields of all the casings. The reduction in emission was 45%, which is extremely significant.

5.7 Techno-economic evaluation

Particulate emissions are governed by the air quality legislation, which requires the operation of a power station to comply with the stipulated emission limits at all times during operation. Failure to comply with stipulated emission limits as specified by legislation carries a stiff fine or even jail time. In order to comply with the set-out emission limits, power stations have resorted to taking load losses; reductions in boiler production capacity in order to reduce particulate emissions. The practice of taking load losses due to ineffective ESP performance is a costly exercise, as the power station loses revenue for every MW that is not generated. This chapter will discuss the exact cost implications of operating with ineffective ESPs that result in units having to take load losses in order to meet emission limits.

5.7.1 Cost of emissions

A power station that is rated for 618 MW, full-load production is required to maintain emissions below 100 mg/Nm^3 , daily. Therefore, if a unit is unable to maintain emissions below 100 mg/Nm^3 , a 118 MW load loss is typically taken during off-peak periods. Off-peak periods are from 10:00 am to 17:00 pm and 22:00 pm to 05:00 am. This means a unit can run on average 10 hours a day with a 118 MW load loss, which is equivalent to 1.2 GWhrs of power that is not generated during that period. That is 19% of the full load-generating capacity that is lost due to high particulate emissions.

Eskom has been struggling to meet the country's electricity demand since early 2007 until this day. A reduction in production is not ideal as it further puts pressure on the organisation and increases the likelihood of load shedding being implemented in the country. The revenue loss because of these load losses is also significant, as it limits Eskom's cashflow.

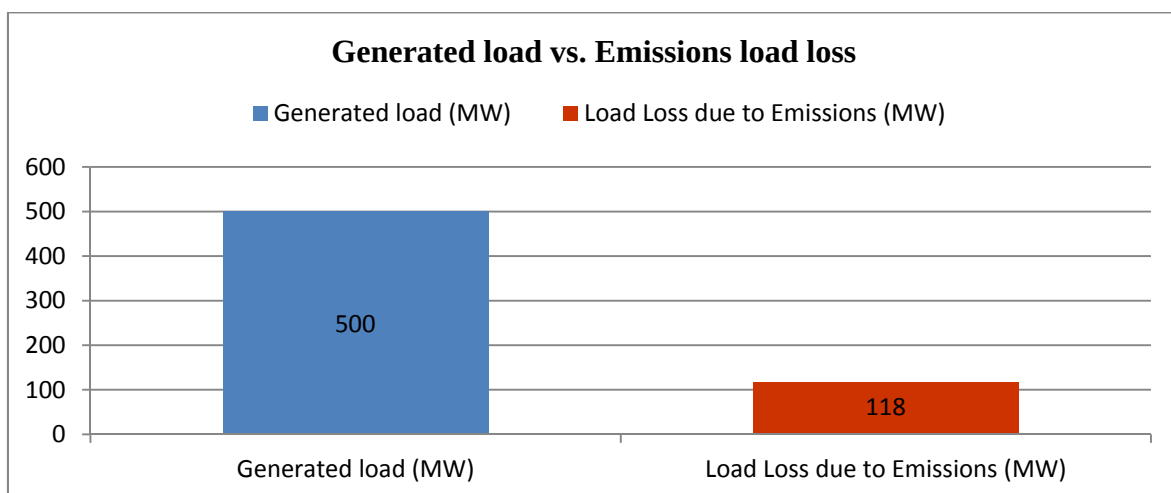


Figure 5-48: Graphical representation of the load loss and generated load in MW

A power station that charges R88.66 per MWhr, running a 118 MW for 10 hours on average a day, incurs a loss of R104 618.8 per day, which translates to R732 331.6 per week and R2 929 326.4 per month. This is a significant loss of revenue; 19% of the possible R15 341 726.40 that a unit operating without high stack emissions load losses can generate.

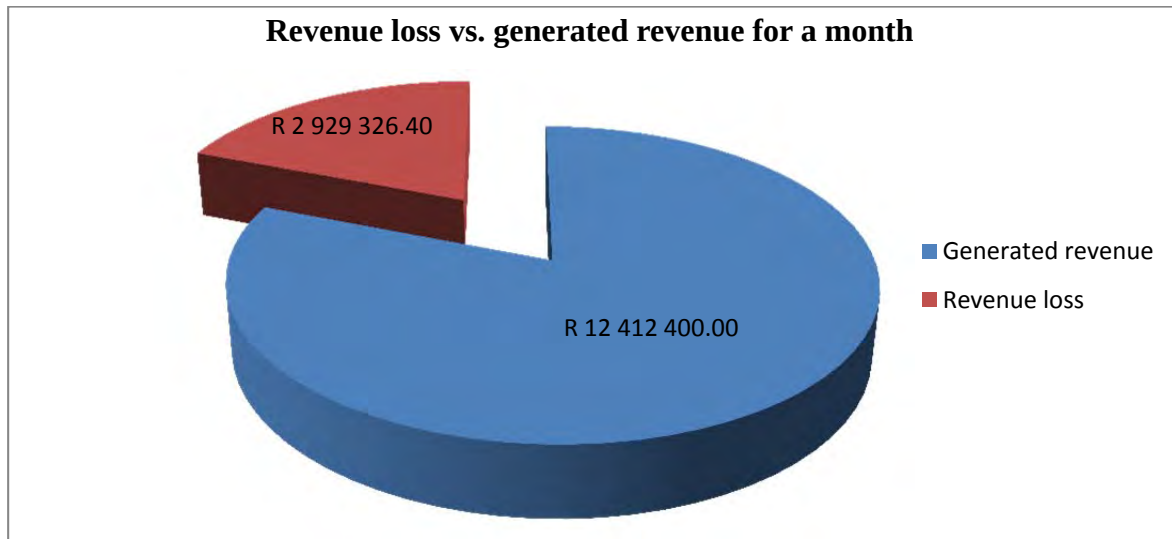


Figure 5-49: Graphical representation of the revenue loss and generated revenue

During the summer periods, emission levels become relatively high due to the high ambient temperatures that affect the process conditions, i.e. condensed back-end pressures requiring the boiler to fire more in order to produce the required MWs. This results in the ESP seeing a significant amount of flue gas volume flow results in ESP not being able to maintain low emissions. South African summer periods are from mid-October to mid-February, with a potential five months in which regular load losses can be taken to maintain emissions below legislation limits. Regular load losses for a period of five months would result in a revenue loss of approximately R16 000 000.

5.7.2 Return on investment

The cost of the HFPS retrofit project was R25 000 000 per unit and based on the revenue loss due to the frequency and duration of load losses that the power station takes in order to reduce particulate emissions. The station would be able to obtain a return on investment on money spent to retrofit existing ESPs with HFPS over a period of two years. The HFPS technology is able to consistently maintain emissions below the set emission limits and thereby eliminates the need to maintain emissions with a reduction of load.

5.8 Conclusion

The obtained results of the project were presented and discussed in this chapter, namely fly ash resistivity profiling and the effect of a high frequency power supply on electrostatic precipitator efficiency. Collected fly ash samples were tested from a selected power station in which the power technology supply system was to be tested. Resistivity testing and measurements were conducted making use of an in-house-built resistivity test oven, built in accordance with the resistivity test IEEE Standard (IEEE Standard 548-1984). The Southern Research Institute and many other publication have published that the optimum resistivity of dust burden for effective and efficient ESP dust collection is 1×10^8 to $1 \times 10^{11} \Omega\text{-cm}$. The ESP is designed to operate at a flue gas temperature of approximately 130°C ; however, this temperature may exceed the design operating value and therefore resistivity values obtained at 125 and 155 are taken as representative resistivity values that the ESPs are likely to experience during operation.

The obtained results were verified by comparing the resistivity profiles tested in house at 10% moisture and at the Southern Research Institute at 9% moisture. The same testing methodology of descending temperatures was implemented and the obtained resistivity profiles follow a similar pattern to one another.

The ESP performance testing was conducted for two types of power supply technologies; conventional transformer rectifiers (TR set) and high frequency power supply transformers (HFPS). A baseline ESP efficiency test was conducted with TR sets supplying the ESP system with power. The baseline test was conducted after an outage during which mechanical repairs were conducted on the ESP. The electrical performance was greatly improved as the electrodes were washed and were relatively clean. V-I curve measurements were taken during the efficiency test and the electrical performance found that all the casings were performing within specification. The rapping philosophy of the ESP was not changed. The ESP's collection efficiency was found to be 97% with TR sets. This was a good performance of the ESP; however, this good performance was mainly as a result of the mechanical repairs carried out on the ESP.

HFPS were installed while the unit was online, with the installation and commissioning conducted over a period of five weeks. Optimisation of the ESP system was conducted with changes made to the rapping philosophy of the system. It was expected that with the installation of HFPS that the front four fields would collect more dust burden than was

possible with the TR sets and that the rear fields would see far less dust burden. Therefore, the rapping philosophy was modified; the rapping interval of the front fields was reduced and that of the rear fields increased. The installation of the HFPS transformers significantly improved the electrical performance of the ESP fields. The majority of the front fields were able to produce a current of above 1 000 mA and at voltage ranges above 40 kV, and were able to consistently maintain this performance. A high electrical performance ensures effective collection of dust burden, as the high corona current charges the dust particles sufficiently for the electrical field to repel the charged particles for collection.

The importance of a good electrical performance of the ESP is highlighted by the Deutsch ESP efficiency formula, which shows that the greater the electric field present in an ESP, the higher the collection efficiency of the ESP will be. The improvement in the electrical performance was not exclusively on the front fields, but also the rear fields, with the front fields performing within specification, the rear field's performance improved. The high electrical input into the rear fields allows for the capturing of fine dust particles. A second efficiency test was conducted with the HFPS installed and found that the ESP's collection efficiency was 97%. Although the baseline test also gave 97% collection efficiency, the process condition of the second efficiency test needed to be correlated back to the baseline process conditions. Appendix G provides the correlation data implemented on the second efficiency test results.

The ESP baseline efficiency test showed that the ESP was emitting 42.8 mg/Nm^3 with conventional TR sets installed, and 19.3 mg/Nm^3 with HFPS transformers installed in the front four fields of all the casings. The reduction in emission was 45%.

The costs and legal liability involved with effectively managing emissions are high and require drastic changes in order to comply with set legislation. The use of old technology to manage emissions in an aging plant has resulted in significant revenue loss for the business. The degrading of coal quality over the years has also influenced the recent poor performance of the ESPs, and this further emphasises the need to implement new technologies that will increase power input into the ESPs to effectively collect dust particulates. The pilot project has proved to be value for money, as the implemented unit is currently able to continuously operate on full load without emission-related load losses. The ability of the unit to operate at full load also assists with power availability for the nation to relieve system pressure on the grid and further help to alleviate load shedding.

CHAPTER 6: CONCLUSION

The purpose of this chapter is to discuss the conclusions of the obtained results of the project in order to determine whether, or not the set out project objectives were, achieved. The findings of the project are concluded, the validation and verification are discussed and future research resulting from this project is recommended.

6.1 Introduction

The project objectives for this research dissertation were to determine the resistivity profile of fly ash from a power station in which a power supply technological analysis is to be conducted to quantify the reduction in emissions. The Department of Environmental Affairs has passed a bill that requires power stations to operate with emission levels of 100 mg/Nm³ per day by April 2015. The legislation also requires that power stations must further reduce their emissions levels and operate at a 50 mg/Nm³ daily average by 2020. In order to determine whether or not power plants will be able to achieve the legislated emission levels, this project was initiated to firstly determine the resistivity profile of the fly ash and to also practically investigate the implementation of two power supply technologies for ESP and to quantify the reduction in emissions as a result of the two technologies.

6.2 Findings

Ash resistivity profiling was conducted making use of an in-house Eskom-built resistivity test oven. The test oven was built in accordance with the IEEE Standard 548-1984. Testing was conducted making use of a descending temperature method. The reasoning behind conducting the testing through this methodology was that the flue gas burden goes through descending temperatures from the boiler through the ESP. Optimum resistivity for effective ESP operation and efficient dust burden collection is said to be within the range of is 1x10⁸ Ω-cm to 1x10¹¹ Ω-cm, as reported by the Southern Research Institute [3, 4].

The ESP is designed to operate at a flue gas temperature of approximately 130°C; however, this temperature exceeds the design operating value and therefore resistivity values obtained at 125°C and 155°C are taken as representative resistivity values that the ESPs are likely to experience during operation. The results obtained from the conducted tests, at 2 kV for different moisture contents, are as follows:

- At 0% moisture, the resistivity profile of the obtained ash sample was high.
- The resistivity profile at 7% was $1.64 \times 10^{12} \Omega\text{-cm}$ and $1.50 \times 10^{12} \Omega\text{-cm}$ at 155°C and 125°C , respectively. These results indicate that the resistivity is still higher than the required resistivity range as stipulated by the Southern Research Institute.
- The resistivity profile at 10% was $1.07 \times 10^{12} \Omega\text{-cm}$ and $6.28 \times 10^{11} \Omega\text{-cm}$ at 155°C and 125°C , respectively. The highest resistivity was obtained at 155°C ; however, a reduction in the resistivity was noted with an increase in moisture.
- A further reduction in resistivity was also noted at 13% moisture, with $6.11 \times 10^{11} \Omega\text{-cm}$ and $2.55 \times 10^{11} \Omega\text{-cm}$ at 155°C and 125°C , respectively. At this moisture content, the resistivity was within the desired resistivity range.
- An additional test was conducted for mixed kV at constant moisture of 10% and temperature of 125°C . The obtained results were that the resistivity was in the range of $3.11 \times 10^{11} \Omega\text{-cm}$ to $3.5 \times 10^{11} \Omega\text{-cm}$ and was found to have a breakdown voltage of 8 kV. The mixed kV test gave a more precise resistivity that the ESPs are likely to experience during operation, and therefore it can be concluded that the resistivity profile that the ESP experiences during operation is within the desired resistivity range.

The obtained results were verified by comparing the resistivity profiles tested in house at 10% moisture and at the Southern Research Institute at 9% moisture. The same testing methodology of descending temperatures was implemented and the obtained resistivity profiles follow a similar pattern to one another. The obtained resistivity was found to be within the required operating range for ESPs as stipulated by the Southern Research Institute.

The installation of the HFPS was a one-on-one replacement, without any ESP plant modification. The power output specifications of the supply transformers were identical, as this test was focusing on the implemented operating/control philosophy of the two technologies. The conventional TR set made use of a single-phase supply and thyristor control system, whereas the HFPS made use of a three-phase supply and utilised an IGBT control system. The overall electrical performance of the two power supply technologies has shown that the HFPS has a better electrical conversion efficiency compared to that of the TR set. The power input into the fields significantly improved with the installation of the HFPS, as can be seen from Tables 5-24 and 5-26 for TR sets and HFPS, respectively.

The LHO casing had a maximum power input of 228 kW, with a TR set in operation, whereas the HFPS was able to produce a maximum power input of 389 kW. This gave a

casing power input increase of 41%. The LHI casing had a maximum power input of 237 kW, with a TR set in operation, whereas the HFPS was able to produce a maximum power input of 419 kW. This gave a casing power input increase of 43%. The RHI casing had a maximum power input of 253 kW, with a TR set in operation, whereas the HFPS was able to produce a maximum power input of 403 kW. This gave a casing power input increase of 37%. The highest power input into the RHO casing was 275 kW for conventional TR sets, whereas the highest for a casing with HFPS installed went up to 420 kW. This gave a casing power input increase of 35%.

The increase in the power input of the HFPS compared to conventional TR sets into the ESP field was primarily due to the power supply and control system. The HFPS was able to produce a DC power output with little to no ripple, due to the fast switching of the IGBTs during operation. This was evident in the waveforms presented in Chapter 5, section 5.4. This saw the front fields being able to achieve a full input corona current of 1 700 mA that was maintained. The increased power input into the ESP was also evident in the collection efficiency of the ESP, as was obtained by the ESP efficiency test conducted for both supply technologies. The ESP baseline efficiency test showed that the ESP was emitting 42.8 mg/Nm^3 with conventional TR sets installed, giving the ESP a collection efficiency of 97%. The efficiency test results conducted with the HFPS in operation found that the ESP was emitting 19.3 mg/Nm^3 . The collection efficiency of the ESP was also 97% with HFPS in operation; however, it was noted that the process conditions had changed slightly. Due to the warmer period in which the final efficiency test was conducted, it was seen that the volume flow into the ESP had increased by 21%. Even with an increase in the volume flow, the ESP was able to maintain lower emissions than those obtained with TR sets in operation. The reduction in emission was determined to be 45%, because of implementing HFPS technology to the ESP.

6.3 Validation and verification

The validation and verification of the obtained results were conducted for both the resistivity testing results, as well as for the ESP performance testing. Relevant standards were complied with in order to ensure that the obtained data was accurately collected and recorded for analysis. Verification was achieved by means of comparison with results obtained from other accredited test institutes, as well as historical data from the design base of the ESP system.

6.3.1 Ash resistivity profiling verification and validation

Figure 6-1 illustrates the flow process utilised for the validation and verification of the obtained results.

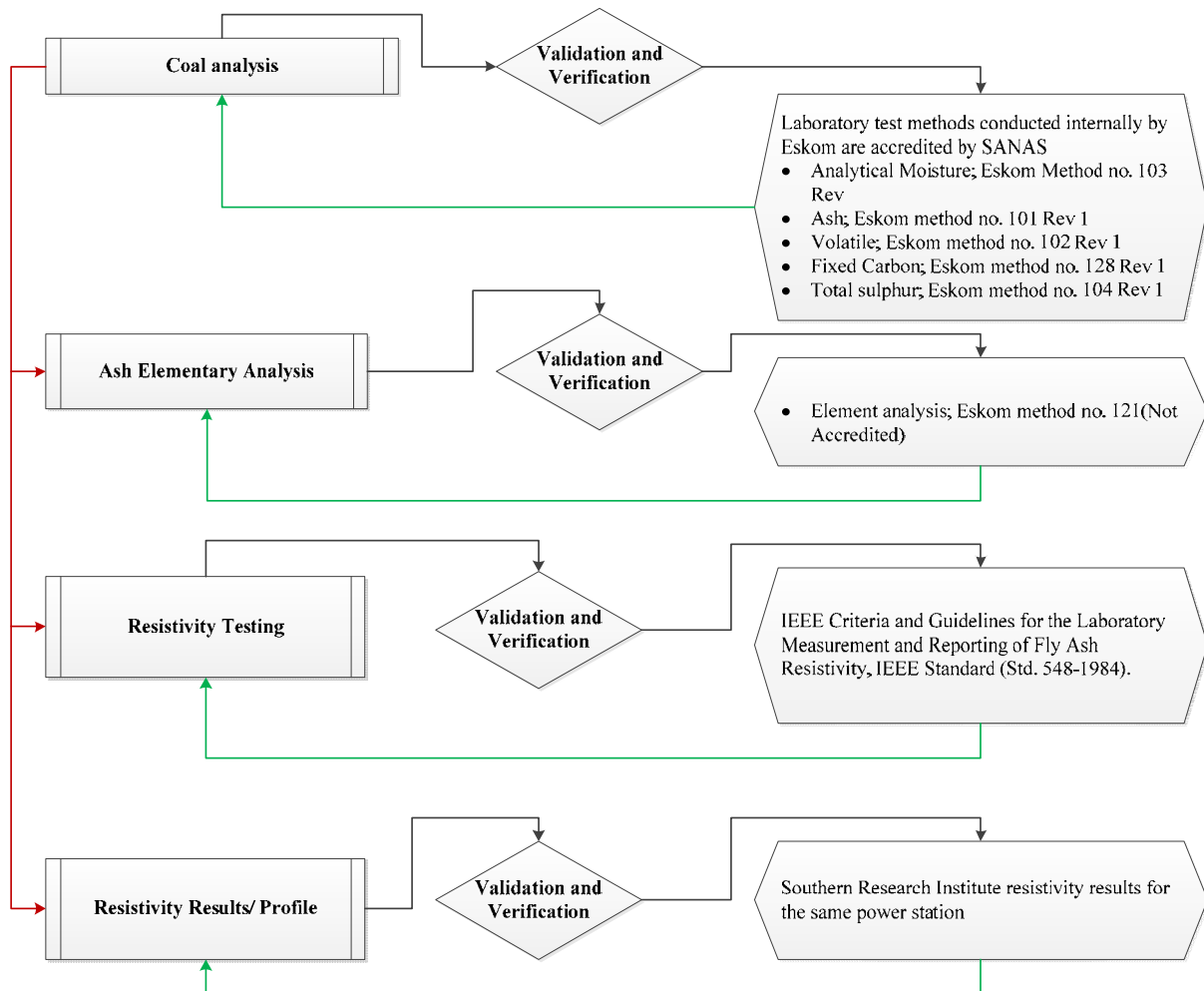


Figure 6-1: Validation and verification flow chart for resistivity testing

The laboratory tests conducted internally within Eskom on the coal and ash samples are accredited by the SANAS. The ash elementary analysis methodology used to analyse the ash, is yet to be accredited, although it was used for this project. The obtained results were analysed and compared to those of the design base used in the power station commissioning to determine how much the coal and subsequent ash have deteriorated over the years.

Ash resistivity measurements were conducted in accordance with IEEE Criteria and Guidelines for the Laboratory Measurement and Reporting of Fly Ash Resistivity, IEEE Standard (Std. 548-1984). The strict implementation of the said standard validates the data

obtained from the conducted testing. The obtained resistivity profile was plotted against that obtained from the Southern Research Institute for ash samples from the test power station.

6.3.2 Plant measurements

Figure 6-2 illustrates the process followed for the validation and verification of the obtained results for the power supply technology as well as an evaluation of the performance of ESPs.

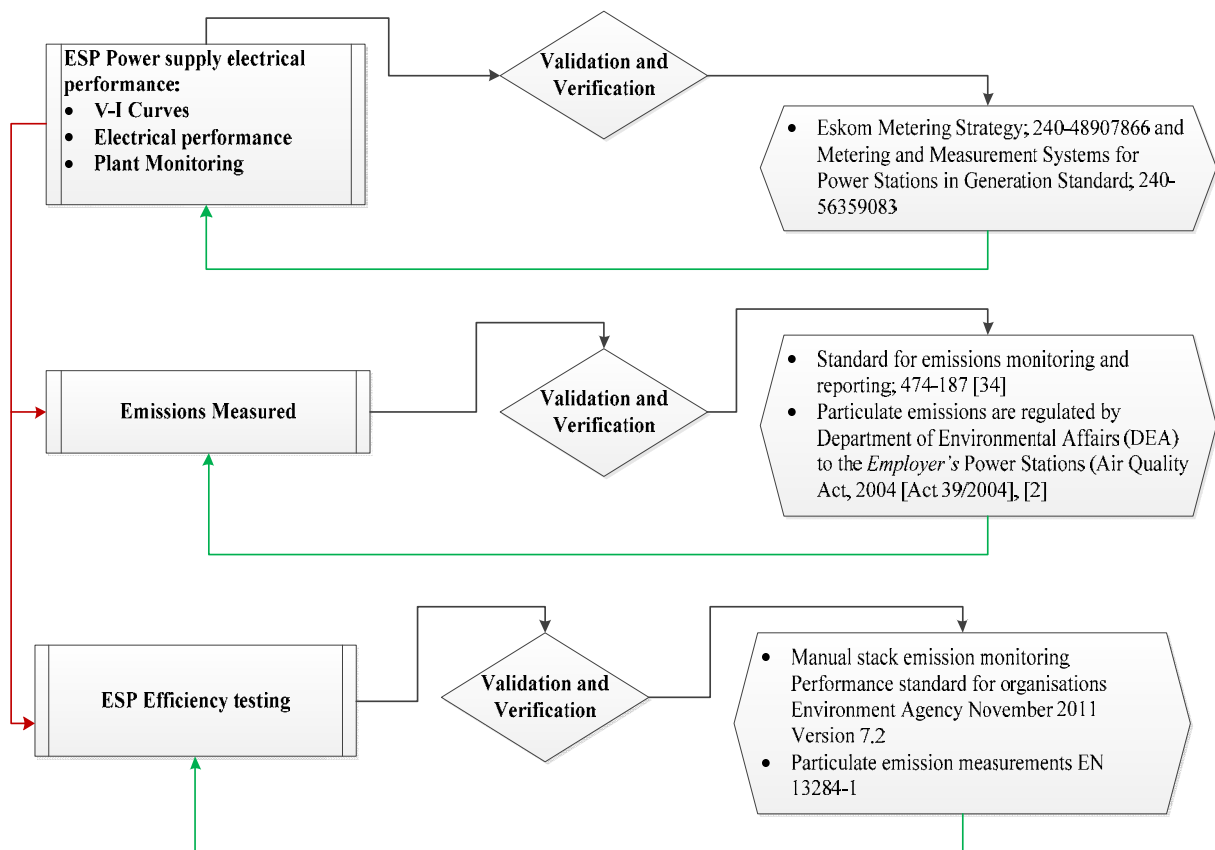


Figure 6-2: Validation and verification of ESP performance monitoring and testing

The plant performance and testing were conducted in accordance with Eskom's metering and measurement standards. The standards ensure that the measured electrical performance data is accurate and is therefore used to analyse the performance of the implemented power supply systems. The measured emissions from the plant monitoring system are in accordance with legislation. ESP efficiency tests are also conducted in order to verify the measured data from the plant monitoring system.

6.4 Recommendations

South Africa is largely dependent on electricity produced by coal-fired power stations. The challenge of maintaining particulate emissions below the required legislation limits will be

difficult. Most of Eskom's power stations are reaching the ends of their lives, with aging plant performance surfers. In particular, the ESP mechanical condition requires mechanical refurbishment in order to ensure that the ESPs perform to their maximum potential. Over the years, discharge electrode wires were cut out; mechanical wear on the rapping system has led to an unreliable system.

The electrical performance of ESP greatly improved with the installation of the HFPS transformers. However, the mechanical condition of the ESP fields had a significant influence on the operation of the ESP, particularly the rapping system. Failure of the rapping system results in dust build-up on the ESP electrodes, causing misalignment of the fields and results in the sparking of the fields. Therefore, in order to consistently maintain emissions below the required limits, great care must be taken to ensure that the mechanical functionality of the ESP plays a significant role in reducing particulate emissions. The HFPS technology has proven that it is capable of enhancing the electrical performance of ESPs in the Eskom environment.

6.5 Closure

This research project was based on laboratory testing of fly ash to determine its resistivity profile. The project also included the implementation of an industrial pilot project aimed at testing a new power supply technology on ESPs within the Eskom operating environment. The project was triggered by Government's revised stringent particulate emission legislation imposed on coal-fired power stations, which is aimed at reducing the country's carbon footprint.

The project involved the in-house laboratory testing of the collected ash's resistivity profile. Due to the deterioration of coal quality over the years, since the station was commissioned, the resistivity of the ash must be quantified to ensure that it is still within the required operating spectrum. The resistivity profile was determined to be within the required ESP spectrum of 1×10^8 to $1 \times 10^{11} \Omega\text{-cm}$.

The industrial pilot project, testing two power supply technologies on ESPs, aimed to quantify the reduction in emissions. The tests and plant operation showed that the installation of the HFPS increased the electrical power input into the ESP. The increase in electrical power resulted in a 45% reduction in particulate emissions, in comparison to when the ESP was operating with only TR sets installed. The HFPS transformer was able to produce and

maintain high electrical performances on the front four fields and this resulted in sustained low particulate emissions. Maintaining this sort of performance will ensure that the unit can operate at full capacity without a need to take emission-related load losses.

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APPENDICES

Appendix A: Turn-it-In report

11760052:Msc_Dissertation_Consolidated_rev_2.1.pdf			
ORIGINALITY REPORT			
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PMS - PRECIPITATORS LEFT CASING

PRECIPITATOR PLANT MANAGEMENT SYSTEM - BOILER UNIT 3 PRECIPITATOR LEFT CASING ESKOM - LETHABO POWER STATION

LEFT & RIGHT CASING		LEFT CASING		RIGHT CASING		OVERVIEW - VALUES		S03 OVERVIEW		DHP
PPMS SETUP		LH PRIMARY A/H TEMP		118 degC		DUST EMISSIONS CORLTD		18 mg/Nm ³		DUST EMISSIONS UNCR LTD
START/STOP CLEAN RAP		LH SEC A/H TEMP		151 degC		LH FD FAN FLOW		291 Kg/s		GENERATOR LOAD
NORMAL MODE 1: FULL LOAD		LH ID FAN INLET TEMP		118 degC		LH ID FAN AMPS		541 A		BOILER STEAM FLOW
		558 mA	1692 mA	1699 mA	1694 mA	1371 mA	56 mA	1705 mA		
		48 kV	45 kV	44 kV	55 kV	49 kV	18 kV	34 kV		
		56 SPM	18 SPM	0 SPM	15 SPM	0 Sp/min	0 Sp/min	0 Sp/min		
		32 kW	88 kW	85 kW	103 kW	67 kW	1 kW	57 kW		

B3

LEFT HAND CASING		INNER		OUTER		INNER		OUTER	
230 mA	651 mA	494 mA	1164 mA	1712 mA	1704 mA	1704 mA			
35 kV	47 kV	42 kV	44 kV	43 kV	44 kV	39 kV			
57 SPM	63 SPM	57 SPM	30 SPM	0 Sp/min	0 Sp/min	0 Sp/min			
10 kW	38 kW	26 kW	60 kW	73 kW	74 kW	66 kW	344 kW		

ALARM COUNT: 0

Boiler 3 Operator

3 % 09:05:20 AM
-224 % 2014/07/07

187

Appendix C: SAUPEC resistivity conference paper

FLY ASH RESISTIVITY PROFILING FOR SOUTH AFRICAN COAL FIRED POWER STATIONS

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Abstract: Particulate emission is a major problem in industrial processes, mainly power plants that make use of coal as a primary source of energy. Stringent emissions limits, set by government organisations requires industries to conform to these limits to ensure that air quality is, sustained and with minimum pollutant present. Electrostatic precipitators are typically, used to filter and collect these particulate emissions. Fly ash resistivity is a primary parameter in the collection of particulate emissions, and there is a resistivity range at which Electrostatic precipitator collection is most efficient and anything outside this range limits, their operation. High resistivity ash results in back-corona discharge, whilst low resistivity results in particle re-entrainment into the flue gas stream. The purpose of this paper is to investigate and obtain a fly ash resistivity profile for existing power plants in South Africa. Ash samples obtained from power plants are, tested making use of an ash-resistivity test oven, in accordance with IEEE standard 548-1984. This paper discusses obtained experimental results, to determine the resistivity profile at which South African power plant electrostatic precipitators operate. The electrical efficiency of the Electrostatic precipitator system is, evaluated based on the obtained resistivity profiles.

Keywords: Electrostatic precipitator, fly ash, resistivity, back-corona, re-entrainment

1. INTRODUCTION

Ash resistivity is a primary parameter in the effective collection of fly ash. It is dependent on a wide range of factors, such as coal quality and the combustions process. These factors determine the chemical composition of the produced ash.

ESP's have been design to operate at an optimum resistivity of at 1×10^8 to 1×10^{11} Ω -cm [1 and 2] for effective ESP performance (fly ash particles are charged and collected with high efficiency). Thus, any resistivity outside this range results in ineffective ESP collection, as the ash may fall in the range of low or high resistivity. Particle collection requires the particles to be, charged and retain the charge long enough in order to be, repelled by the electric field established in the inter-electrode spacing for collection.

Low resistivity ash, below 1×10^8 Ω -cm, is difficult to precipitate and collect. The reduced resistivity has been, found to be mainly due to the presence of metallic particles and un-burnt carbon in ash. The effect of low resistivity ash during precipitation is that, it easily attains a charge during the ionization process but tends to; rapidly lose the charge before collection. The charged particles need to retain a charge long enough to migrate to the collector plate

and the loss of charge results particle re-entrainment. Particle re-entrainment occurs when particles re-enter the flue gas stream and are not collected, exiting into the atmosphere. Similar problem exists for high resistivity ash, as particles do not easily attain a charge and thus cannot be collected. The problem of high resistivity was, solved with flue gas treatment to reduce the resistivity; the most effective and commonly used flue treatment is SO_3 injection into the flue gas stream.

The Southern research institute [3 - 6] was at the forefront in conducting research on the measuring of ash resistivity. IEEE Standard 548-1984 was, published as a guideline on conducting ash resistivity measurements on ash in controlled laboratory environment. Laboratory testing is, conducted making use of an, ash resistivity test oven. Prior to testing, the ash sample must be analysed for elemental composition, particle size distribution, and particle density.

2. MATERIALS AND METHOD

The methodology and materials used in obtained the presented results are, discussed in this section.

2.1 Ash resistivity profiling

The ash resistivity oven is, constructed such that it operates in conditions similar to those in fully, operational ESP plants. The oven parameter inputs are moisture, nitrogen, oxygen, and temperature conditions in which the ash is, exposed too during normal operating conditions.

Figure 2 and 3 shows the experimental set-up that is, applied in conducting ash resistivity measurements with connected gas cylinders to be, adjusted to model the operating conditions or parameters.

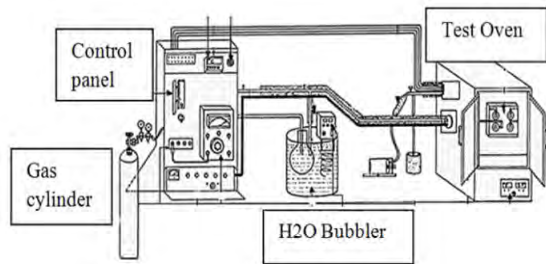


Fig. 2: Fly ash resistivity, test set-up apparatus [10]

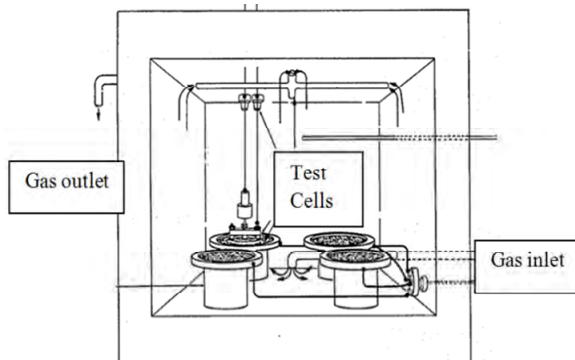


Fig. 3: Resistivity test oven, test electrode arrangement [7]

The measurements are, taken for descending temperatures, decrements of 30°C from 215°C to 95°C. Current measurements are, taken at every temperature set point for an applied voltage. An alternative test procedure with incrementing temperature is as follows [3 - 6]:

- The collected sample is, firstly sieved making use of a 180-μm sieve.
- The resistivity-measuring cell is, firstly weighed without the ash sample.
- The sieved samples are, packed into the resistivity measurement cell and weighed.

- Care is, taken to insure that the sample is evenly, distributed throughout the measurement cell.
- The resistivity, measuring cell with the ash sample is, placed inside the temperature-controlled chamber.
- The voltage lead and the electrometer are, connected to the measuring cell; a thermocouple is, connected to the measuring cell.
- Place the disc electrode on surface of the dust sample
- Set the temperature of the chamber to a temperature 215 °C, the setup is, left to run overnight.
- A nitrogen flow is, introduced during the heating up process, overnight.
- The other gases; CO₂, O₂ and moisture are introduced into the chamber and allowed to reach equilibrium over a 2 hour period.
- Without the voltage supply connected, leakage or induced current is, measured from the different cells and recorded.
- This leakage current is due to residual charge that is, obtained and retain by the ash elements in the heating process.
- A voltage supply is, introduced to each cell for a period of 60 seconds and 12 current measurements are, recorded.
- The recorded currents are, averaged out, to get a fair representation of the actual current that flows through the sample.
- This procedure is, repeated with every temperature decrement.
- The resistivity is determined by solving for equation 2; knowing the test electrode's dimensions and dust layer thickness, with the recorded current and voltage values.

Resistivity is, defined by the following formulation:

$$\rho_R = \frac{R \cdot A}{l} \quad (1)$$

Whereby, the ash resistivity (ρ_R) in *ohm-cm* is expressed as a function of the resistance (R), obtained by making use of Ohm's law ($R = \frac{V}{i}$), A being the area of the collector plate/ disc and the dust layer thickness (l). Substituting ohm's law, gives the following expression that can used to determine the ash resistivity:

$$\rho_R = \frac{\Delta V \cdot A}{i \cdot l} \quad (2)$$

The obtained resistivity results are, plotted as a function of the different temperature set points. An,

additional test is conducted whereby for a fixed temperature, the voltage is incremented until spark over occurs, whilst taking current measurements with every voltage increment. The voltage reading recorded before spark over occurs, taken as the electrical breakdown voltage of the dust layer, used in determining the resistivity as a function of varying electric field.

2.2 High resistivity effects on ESP's

The collected ash, during precipitation accumulates on the grounded collector plate. When, the dust layer builds up on the ESP collector plate, the resistivity also increases. The potential difference between the discharge electrode and collector plate builds up due to the increased resistivity, as leakage current is restricted from flowing to ground. This restriction results in collected charged particle not being able to dissipate their charge through the collector plate and thus leading to a charge build-up on the dust layer. The build up of positive surface charge increases to the point of electrical breakdown, resulting in back-corona. Back-corona is an abnormal gaseous discharge that occurs at the collector electrode and takes place in the presence of corona discharge. The back-corona discharge occurs when the electric field across the dielectric layer is higher than its breakdown strength [7 and 8]. Equation 3, describes the positive electric field that is, created due to charge build-up and acts to reduce the overall negative electric field established by the discharge electrode.

$$E_l = j\rho \quad (3)$$

This phenomenon is undesired, as the positive corona discharge also results in the collected dust particles being, dislodged. The dislodged particles are, re-entrained into the flue gas stream. Thus, reduces the collection efficiency of the system.

3. RESULTS

In this section, preliminary laboratory experimental results are, presented and discussed for ash samples obtained from two power plants.

Ash elementary analysis is, conducted on the ash samples. Table 1 lists the elemental composition of the fly ash samples. The elemental composition of the ash is not, used in the determination of the resistivity, though it is given that the composition influences the resistivity. No model accurate model is available that correlates the elementary composition to the resistivity for South African coal and ash. The

samples have small percentage deviations in their elemental composition.

Table 1: Fly ash elemental composition

% Elemental Composition	Sample A	Sample B
Silicon (SiO ₂)	53.4	54.8
Aluminium (Al ₂ O ₃)	27.5	25.4
Iron (Fe ₂ O ₃)	3.6	3.8
Titanium (TiO ₂)	1.5	1.4
Phosphorous (P ₂ O ₅)	0.28	0.44
Calcium (CaO)	6.5	7.4
Magnesium (MgO)	1.3	1.5
Sodium (Na ₂ O)	0.3	0.2
Potassium (K ₂ O)	0.8	1.1
Sulphur (SO ₃)	2.6	0.5

Test preparations involve the weighing of the ash samples in order to determine the packing density of each cell. Ash samples have different particle size distributions, which influence their respective packing densities. Table 2, represents the masses obtained for samples A and B. The packing densities of the two samples vary slightly, and this is mainly due to the variation in particle size distribution of the samples.

Table 2: Test cell dimensions and mass measurements

Sample A					
Cell #	Dia. (mm)	Dish mass (g)	Dish + dust mass (g)	Dust mass (g)	Packing density (g/cm ³)
1	76.2	99.3	121.1	21.80	0.99
2	70	116.7	135.8	19.10	1.03
3	70	118.8	135.8	17.00	0.89
4	70	115.9	135.2	19.30	0.99
Average				19.30	0.98
Sample B					
Cell #	Dia. mm	Dish mass (g)	Dish + dust mass (g)	Dust mass (g)	Packing density (g/cm ³)
1	76.2	99.4	111.7	12.30	0.56
2	70	116.9	135.4	18.50	1.00
3	70	118.9	139.6	20.70	1.09
4	70	116.0	122.0	18	0.93
Average				19.07	1.00

The test oven has been set-up with gas flow inputs and the oven gas composition is determined from plant operating conditions. Table 3, list the gas compositions and flow set-up for the test oven as determined from plant operating conditions. The gas pressures are, regulated at 400 kPa for the duration of the test.

Table 3: Gas flows used during testing

Gas	Flow (ml/min)
Nitrogen (N ₂)	8.7
Carbon dioxide (CO ₂)	13.8
Oxygen (O ₂)	4.6

The gas flow and temperature conditions were, allowed to settle for a period of 24 hours before testing could commence. The obtained results for both samples are as follows.

3.1 Resistivity profile at 2KV, sample A

The results show the average resistivity of the four test cells tested at 2 kV voltage supply. Figure 4, graphically illustrates the resistivity profile of sample A. It is, noted that at 0% moisture the resistivity is high, whereas with 7% moisture, the resistivity is decreased. Moisture provides a surface conduction path for current to flow through, hence the reduction in the sample's resistivity. The lowest resistivity observed at 95 °C but at 1.28 e¹² this is deemed to be high resistivity. South African power plant ESP's operates in temperature region of 115 °C to 150 °C, and based on the results, the resistivity is high at this range of temperatures for sample A.

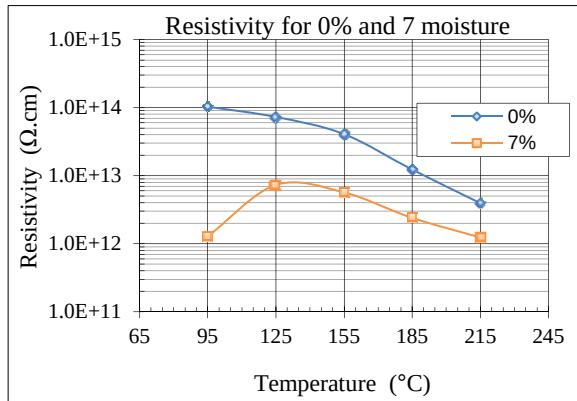
**Fig. 4: Resistivity profile at 0% and 7% moisture**

Table 4, lists the calculated experimental results for sample A. The reduction in resistivity when moisture is, introduced into the test oven is most significant at low temperatures and this may be caused by condensation in the system allowing more current to flow through the sample.

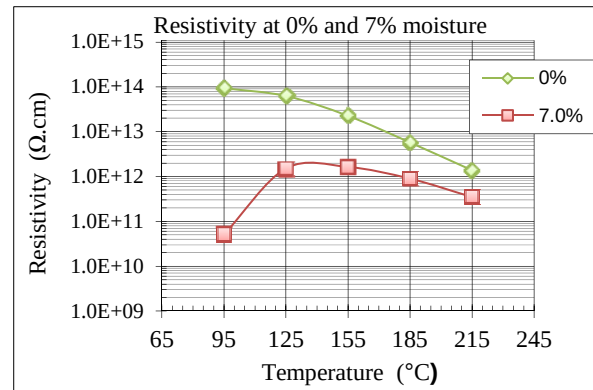
Table 4: Samples A experimental results

Oven Temp. (°C)		95	125	155	185	215
Sample A						
0% H ₂ O	I (A)	2.01e ⁻¹⁰	2.85e ⁻¹⁰	5.17e ⁻¹⁰	1.69e ⁻⁹	5.31e ⁻⁹

	ρ_R	1.03e ⁻¹⁴	7.31e ⁻¹³	4.09e ⁻¹³	1.24e ⁻¹³	3.96e ⁻¹²
	I (A)	1.62e ⁻⁸	2.82e ⁻⁹	3.63e ⁻⁹	8.59e ⁻⁹	1.66e ⁻⁹
7% H ₂ O	ρ_R	1.28e ⁻¹²	7.34e ⁻¹²	5.69e ⁻¹²	2.41e ⁻¹²	1.24e ⁻¹²
% ρ_R Reduction		98.76	89.97	86.09	80.51	68.67

3.2 Resistivity profile at 2KV, sample B

Sample B's resistivity has a similar profile to that of sample A, for 0% and 7% moisture. At 0% Moisture and low temperature the resistivity is at its highest, whereas, with 7% moisture and low temperature is at its lowest and within the stipulated ESP operating range. This highlights the importance of moisture in an ESP system, for the reduction of the ash resistivity

**Fig. 5: Sample B, resistivity profile at 0% and 7% moisture**

The calculated experimental results for sample B, are, presented in table 5. The results exhibit a similar pattern to those obtained for sample A, with the highest resistivity reduction observed at lower temperatures.

Table 5: Sample B experimental results

Oven Temp. (°C)		95	125	155	185	215
Sample B						
0% H ₂ O	I (A)	1.06e ⁻⁶	1.33e ⁻⁸	1.21e ⁻⁸	2.22e ⁻⁸	5.65e ⁻⁸
	ρ_R	9.31e ⁻¹³	6.26e ⁻¹³	2.26e ⁻¹³	5.75e ⁻¹²	1.38e ⁻¹²
7% H ₂ O	I (A)	4.87e ⁻⁶	3.21e ⁻⁸	1.87e ⁻⁸	3.07e ⁻⁸	7.55e ⁻⁸
	ρ_R	5.06e ⁻¹⁰	1.50e ⁻¹²	1.63e ⁻¹²	8.97e ⁻¹¹	3.48e ⁻¹¹
% ρ_R Reduction		99.95	97.60	92.76	84.40	74.71

3.3 Sample result comparison

The samples had, a similar percentage elementary composition, and as such, expected to exhibit similar

resistivity profile. Figure 6, illustrates the difference in resistivity profiles for both ash samples.

Sample A has a lower resistivity profile for 0% moisture at higher temperature as compared to that of sample B. However, sample B appears to have a lower resistivity profile when moisture is, introduced into the gas stream. The introduction of moisture, acts to coat the surface of the ash particles and thus reducing the resistivity of the ash samples. The reduction in resistivity means that, in ESP's more ionic current flows and improves the retention of the collected ash. However, the attained resistivity at 7% moisture may, be classified as high resistivity.

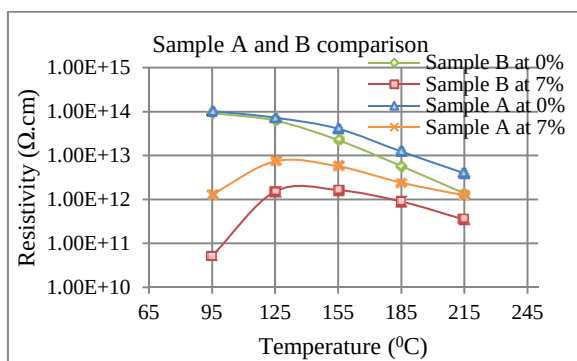


Fig. 6: Sample A and B resistivity profiles

The desired resistivity range for efficient ESP operation/ collection has been determined to be 1×10^8 to $1 \times 10^{11} \Omega\text{-cm}$ [1 and 2]. The above, obtained results indicate that South African power plants operate with high ash resistivity, when the ash has only been conditioned by moisture. The desired resistivity is achieved at low temperatures, but ESP's operate at temperatures averaging at 110°C to 150°C .

4. CONCLUSION

The preliminary results of samples A and B, indicates that South African ash has high resistivity for moisture conditioning. The desired resistivity range for efficient ESP operation is 1×10^8 to $1 \times 10^{11} \Omega\text{-cm}$. The desired resistivity is achieved at low temperatures, but ESP's operate at temperatures averaging at 110°C to 150°C . The high resistivity results indicate that the ESP's for both sample are operating under back-corona effects. Thus, making it, difficult to achieve, the set emissions limit of 75 mg/Nm^3 . Due to particle re-entrainment experienced high resistivity ash.

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Appendix D: Additional project photos



Figure 8-3: Largest electrostatic precipitator plant in Africa

Figure 8-3 shows a picture of the ESP casing for two units; this is a seven-field ESP and is regarded as the largest ESP to be constructed in Africa.



Figure 8-4: 380 V-board modification from 2-phase to 3-phase

ESP 380 V supply board modification that requires the installation of a third phase from the bus-bar to the first four ESP field switchgears.

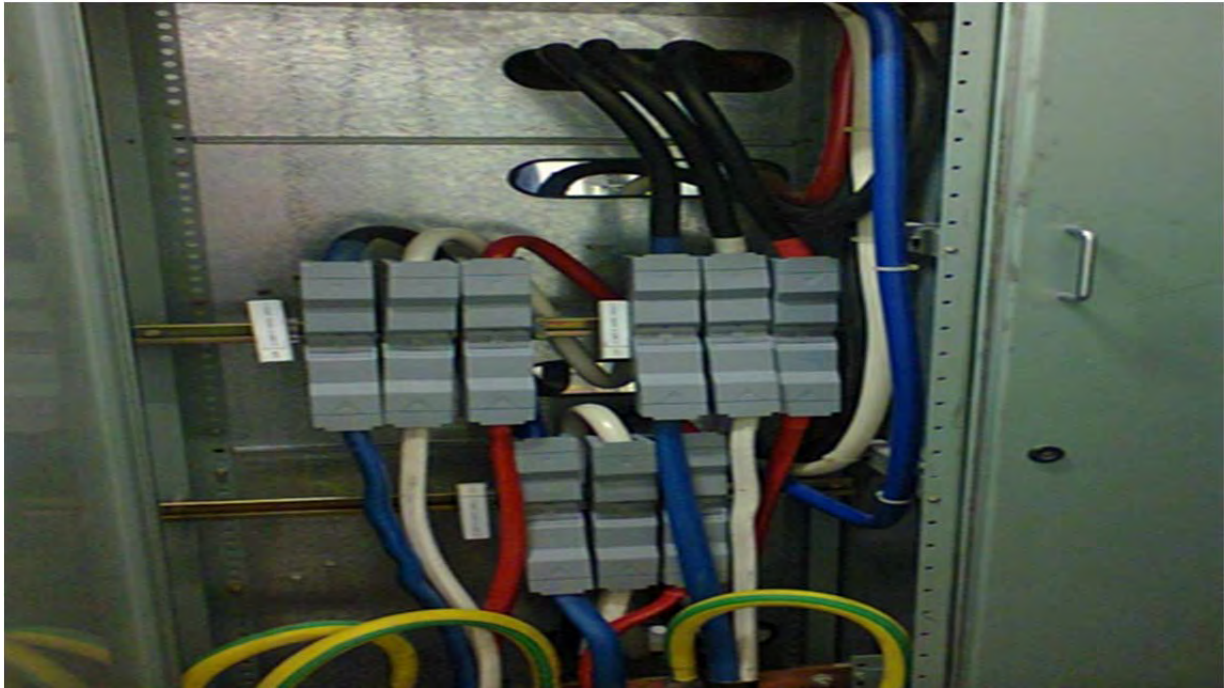


Figure 8-5: 380 V-board complete modification

Figure 8-5 shows the completed modification of the 380 V-board cabling modification.

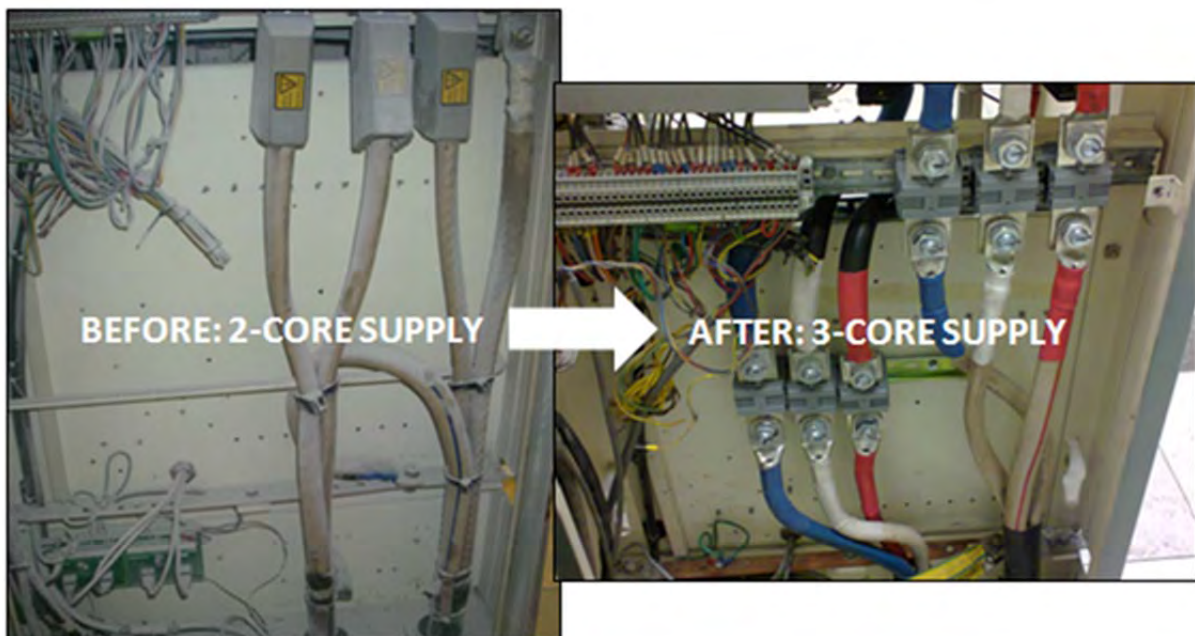


Figure 8-6: Control panel cabling modification

Figure 8-6 shows the modification carried out on the control panels of the first four fields of all casings, which involved the installation of a three-core cable and the installation of an earth cable.



Figure 8-7: HV ducting modification into the ESP electrodes

Figure 8-7 shows the modifications conducted on the HV leads that feed into the ESP fields.



Figure 8-8: Lifting of TR sets from the ESP roof for replacement by means of a crane

Figure 8-8 shows the lifting methodology utilised for the replacement of the TR sets, a crane hoists the TR sets from the roof to the ground and hoists the HFPS onto the roof as shown in Figure 8-9.



Figure 8-9: Hoisting of an HFPS onto the ESP roof for installation

Figure 8-10 shows the installation of a new cable rack in which the new cabling was installed that is coming from the control panel.

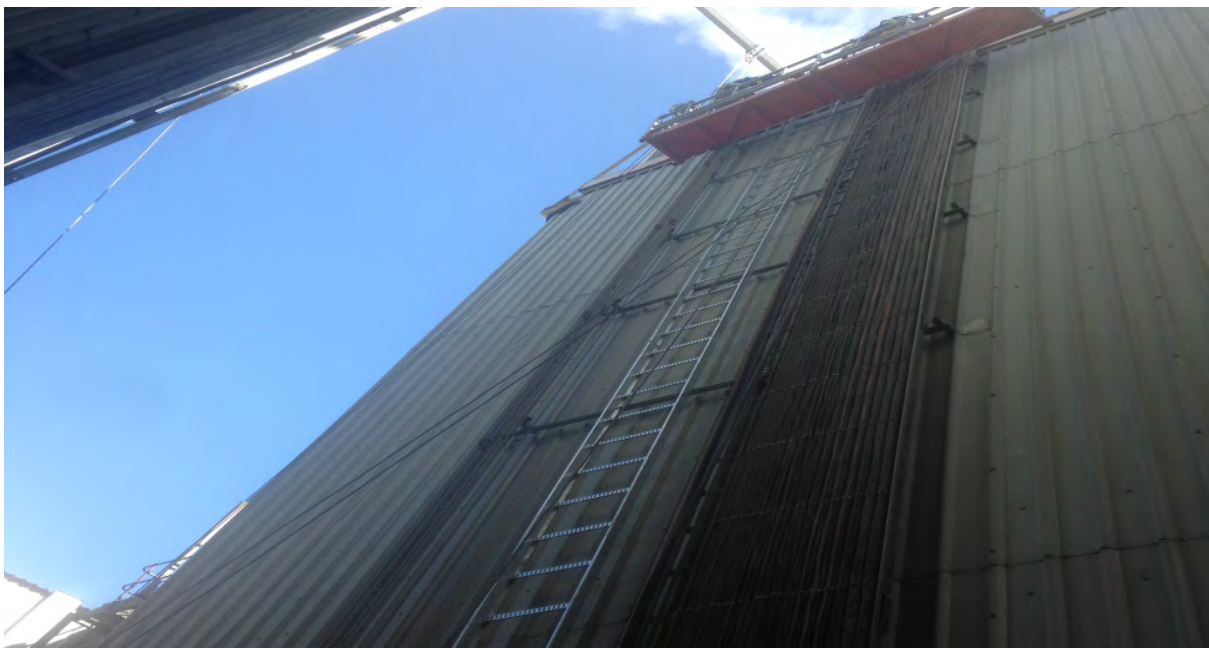


Figure 8-10: Installation of a new cable rack

Figure 8-11, shows the shock method that was applied in hoisting the three-core 185 mm² cable onto the roof of the ESP.



Figure 8-11: Sock method utilised for pulling the new 3-core cable onto the roof of the ESP

Figure 8-12 shows the modification carried out on the transformer trolley that was done to ensure that the HFPS fits the pre-existing structure of the ESP.



Figure 8-12: Modified HFPS mounting trolley

Figure 8-13 shows the installation of the HFPS into the casing.

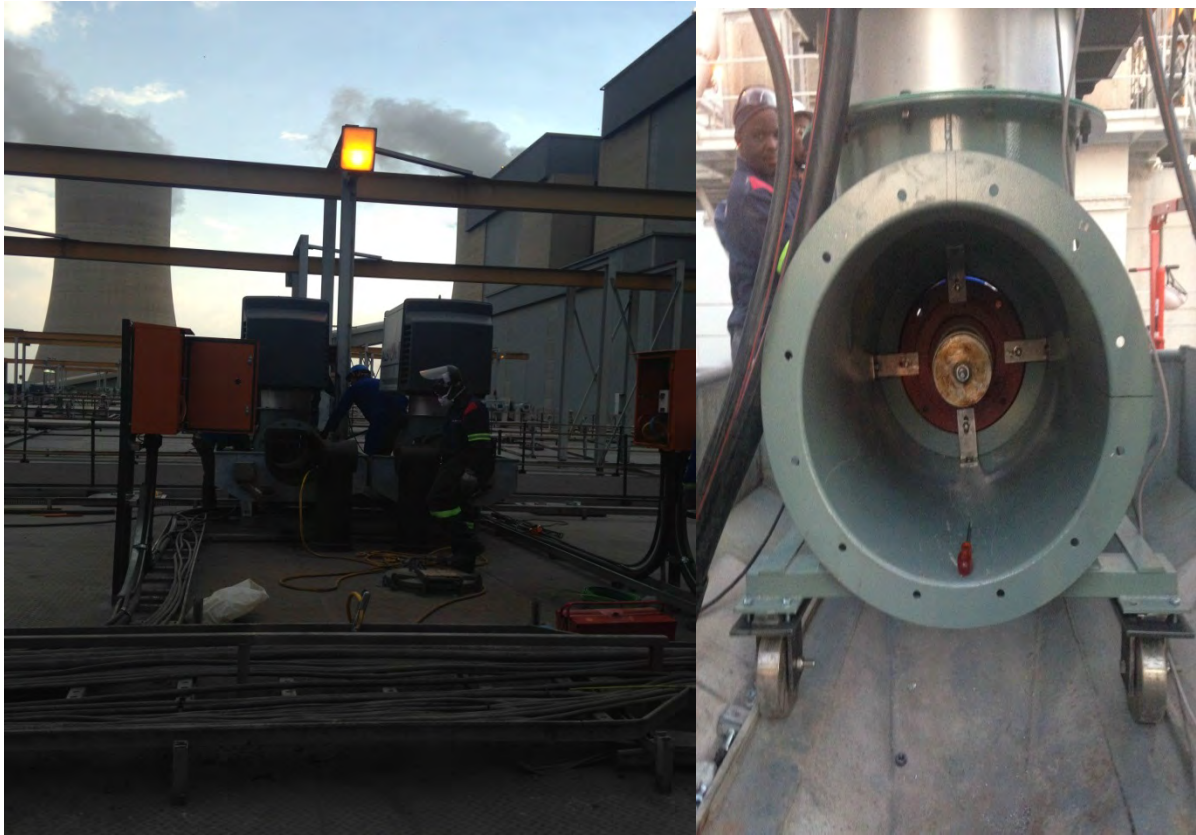


Figure 8-13: Installation of the HFPS transformer units

Figure 8-14 shows the earth connection as required for the HFPS.



Figure 8-14: Grounding of the HFPS transformer

Figure 8-15 shows two fully installed and commissioned HFPS transformers.



Figure 8-15: Installed HFPS transformers



Figure 8-16: Installed and commissioned HFPS transformers

A successful retrofitting project of HFPS on an existing ESP was conducted as can be seen in Figure 8-17.



Figure 8-17: Fully commissioned HFPS transformers on the first four fields of an ESP casing

Appendix E: Effect of high frequency power supply on electrostatic precipitator efficiency

EFFECT OF HIGH FREQUENCY POWER SUPPLY ON ELECTROSTATIC PRECIPITATOR COLLECTION EFFICIENCY AS COMPARED TO CONVENTIONAL TRANSFORMER RECTIFIERS

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Abstract: Particulate emission is a major problem in industrial processes, caused mainly power plants that make use of coal as a primary source of energy. Stringent emissions limits, set by government organisations requires industries to conform to these limits to ensure that air quality is, sustained and within minimum pollutant limits. Electrostatic precipitators (ESP) are, implemented as the main form of dust burden collection. In recent years, Eskom power stations have struggled to maintain particulate emissions below legislation limits, resulting in power stations having to de-load and reduce power generation production. A pilot project was initiated to investigate what the effects of a high frequency power supply will be on the ESP collection efficiency. This paper presents the results obtained from the implemented pilot project, whereby 16 high frequency power supply (HFPS) were installed in a 28 field ESP plant.

Key words: Electrostatic precipitator, Particulate emissions, High frequency power supply, Transformer rectifier

1. INTRODUCTION

Electrostatic precipitation (ESP) is a widely used technology for effective dust or fumes collection from industrial furnaces. Dust collection is, achieved by making use of electric forces to collect suspended dust particle in the flu gas streams. This collection process is achieved through the following three step process; i.) First stage of the process involves the charging of the suspended dust particle, ii.) Second stage of the process is the collection of the charged particles and iii.) The third and final stage involves the removal of the collected/ precipitated material for disposal or other use. This technology has, been in existence as early as 1906, with break through research conducted by Dr Frederick G. Cottrell and W. A. Schmidt. Dr F. G. Cottrell is an American born professor in chemistry and is, credited as being the inventor of the first electrostatic precipitator [1, 2].

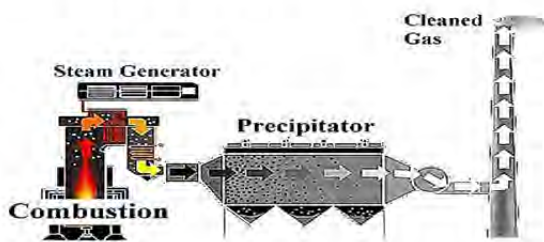


Figure 1: ESP plant as installed in a power station [3]

Figure 1, illustrates the position of an ESP plant in a fossil fired power station. Electric forces are, established between a discharge and collector plate arrangement; pathway for the flue gas stream also known as a field. The power station to be investigated for the purpose of this project makes use of a single stage, dry-type, parallel plate arrangement ESP and each unit has four parallel casing each having seven fields in a row, thus has 28 fields per unit.

A single stage ESP design is one whose arrangement allows for the charging and collection of dust particles to occur in the same region/ field [1, 2]. Each field in an ESP arrangement consists of a discharge wire/ active electrode and two collector plates/ electrodes on either side of the discharge electrode forming horizontal ducts. Figure 2 illustrates the ESP dust collection, principle operation.

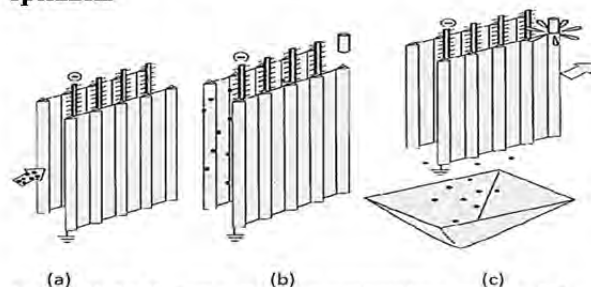


Figure 2: ESP dust collection, principle operation [7].

Suspended dust particles extracted inside the boiler/combustion chamber from the boiler by means of an induction fan and enter the ESP fields. The discharge electrodes are, connected to a high voltage negative DC supply in order to produce the corona needed for ionization. There are six fundamental principles involved inside the ESP to achieve dust particulate collection [1, 2]:

- Ionization - Charging of particles
- Migration - Transporting the charged particles to the collecting surfaces
- Collection - Precipitation of the charged particles onto the collecting surfaces
- Charge Dissipation - Neutralizing the charged particles on the collecting surfaces
- Particle Dislodging - Removing the particles from the collecting surface to the hopper
- Particle Removal - Conveying the particles from the hopper to a disposal point

Flue gas enters the ionization region, resulting in dust particles attaining a charge (negative) charge, and through the applied electric field, the charged dust particles migrate to the collector plate and subsequently lose their charge and removed through the rapping process [4].

The ionization process takes place when electrons within the vicinity of the corona discharge are excited/energized. The electron excitation results in electron collision, which causes an electron avalanche and these electrons, attach themselves to the suspended dust particle passing through the ionized inter-electrode space. The flue gas stream flows through the ionized chamber such that the suspended dust particles acquire a charge, thus particle separation. The particles attain a negative charge and deflecting them out of the flue gas stream, due to the presence of the electric field established by the presence of high voltage DC. The charged particles deflect and migrate to the positively charged collector plate under the influence of the electric field for collection. The collected dust burden is, retained on the collector plate and subsequently dislodged periodically by a rapping process. The rapping process makes use of a hammering system that strikes the collector plate, dislodging the dust burden into ash hoppers to be collected and transported to the ash dump. This process removes more than 98% of solid dust particles [1, 2, 4, 6].

1.1 Particulate emissions in South African context

Particulate emissions are, governed by the air quality legislation, which requires the operation of a power station to comply with the stipulated emissions limits at all times during operation. Failure to comply with stipulated emissions limits as specified by the legislation carries a stiff fine or even jail time. In order to comply with the set out emissions limits, power stations have

resorted to taking load losses; reduction in boiler production capacity in order to reduce particulate emissions. The practice of taking load losses due to ineffective ESP performance is a costly exercise, as the power stations lose revenue for every MW that is not generated. This also puts further constraints on the power grid; the inability to produce power has negative implications for the country. South Africa has had a power shortage crisis since 2007, which resulted in load shedding being implemented. The reduction in production load as a result of high stack emissions, further increases the pressure on an already constraint power grid, and contributes to load shedding.

2. ESP ELECTRICAL SUPPLY

The existing power supply system for the ESP's within the Eskom environment are what are termed conventional rectifier transformer sets. Rectifier transformers make use of 50 Hz mains frequency and are thyristor controlled to deliver the required corona power into the ESP fields. Due to the deterioration in plant and process conditions, the rectifier transformers have proven ineffective, as they are unable to supply and maintain the required corona power to effectively collect the dust particulates and ensure compliance to particulate emissions regulations. Figure 3 illustrates the electrical circuitry representation of a convention rectifier transformer, connection to an ESP field.

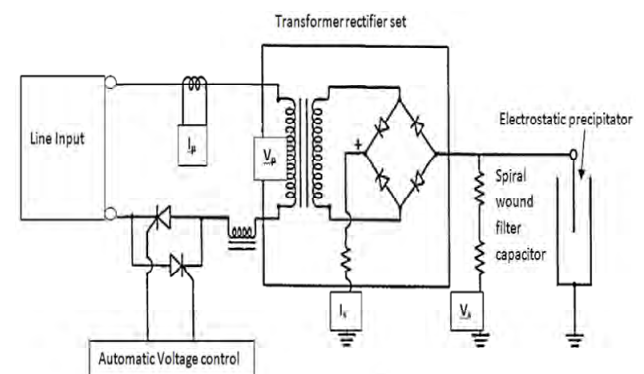


Figure 3: Electrical circuitry configuration of an ESP field (modified) [16]

The transformer set, delivers a high DC voltage that is, coupled with an AC ripple. The generated ripple has a 50 Hz mains frequency and the amplitude (peak-to-peak) of this ripple has been, found to be in the range of 30 to 40% of the output DC voltage [5]. This significantly reduces the average DC output voltage and limits ESP performance. The operating ESP voltage is primarily limited by sparking, and a spark typically occurs on the peak of the AC ripple voltage [1, 2]. The control system is design in such a way that, when a spark is, detected the control reduces a certain percentage of the voltage.

A high percentage, ripple voltage effect, results in significant voltage reduction when sparking occurs and

subsequent reduction in corona power. The reduced average voltage, results in the reduction in the effective electric field intensity that is required to repel the charged particulates for collection. This results in ineffective charging and collection of the dust particulate. The delivered corona power needs to be, optimized in order to improve the ESP collection efficiency.

ESP collection efficiency is, influenced by the generated electric field as stipulated by the Deutsch's efficiency formula [1, 2]. Thus, increasing the corona power; voltage and current, input into the ESP fields improves the collection efficiency of the field.

2.1 Power supply influence on ESP efficiency:

Deutsch's [1, 2] efficiency formula is primarily used in determining ESP collection efficiency, the efficiency is defined as a function of the migration velocity (ω), effective collection area (A) and the volumetric gas flow (Q), $e = 2.7182828$

$$\eta = 1 - e^{(-\omega \cdot (A/Q))} \quad (1)$$

Where:

$\ln$ = natural log – (base e)

Q = volumetric gas flow – (m^3/s)

A = total projected collecting electrode area – (m^2)

ω = effective particle migration velocity – (m/s)

The effective collection area of the ESP is fixed and is given by collector plate area, thus a redesign would be required, if it were to be used to influence the efficiency. An increased volumetric flow will reduce the overall efficiency; hence, the particle migration velocity is one aspect that can be, evaluated to optimise the collection efficiency. The migration velocity is, defined as is dependent on the displacement electric field and is, defined as:

$$\omega = K \cdot E_0 \cdot E_c \cdot a^2 \quad (2)$$

Whereby, E_0 is the charging electric field and E_c is the collection electric field, K is a constant and a , is the particle radius. Eskom makes use of single stage ESP's and for these ESPs, the charging and collection occurs simultaneously, thus;

$$E_0 = E_c \quad (3)$$

Hence, the particle migration velocity can be, expressed as:

$$\omega = K \cdot E^2 \cdot a^2 \quad (4)$$

The relationship between the electric field and the migration velocity highlights the fact that, the removal and retention of dust burden is directly dependent on the corona ionisation and the electric field strength. The velocity of a charged particle moving through an electric field is proportional to the applied voltage. Thus, high levels of electrical energization need to be, maintained in order improve the collection efficiency of the system.

White [5] also states that the migration velocity can be, defined as a function of the corona current and the kV input with the superimposed ripple voltage. Thus, further highlighting the importance of the voltage ripple effect on the collection efficiency:

$$\omega = (I_{DC}) \cdot (kV_{peak}) \cdot (kV_{DC}) \quad (5)$$

Increasing the particle migration velocity can only be, achieved by increasing the electric field and this is, achieved by increasing the kV input into the ESP fields. The particle size is a quantity that is process dependant and cannot be, varied at will. Therefore, the migration velocity of a charged particle moving through an electric field will be proportional to the square of the applied voltage.

The operating ESP voltage level is, limited by the occurrence of flashovers, and as such, the voltage is required to be high enough that some sparking occurs. Sparking results in loss of power, thus reducing the corona input required for ionization.

The operating DC voltage is typically limited by the sparking that occurs during operation, sparking occurs at the peak of the voltage ripple. However, the collection efficiency is at its highest when the voltage is closest to the spark inception voltage, i.e. peak voltage of the ripple. Sparking results in loss of power and as a result, less power is used for the corona. Reducing the ripple to be near the spark over voltage will increase the effective DC input voltage. Increasing the DC input voltage results in an increased intensity of the effective collection electric field present in the inter-electrode spacing. The electric field repels the charged particles and the strength of the electric field will influence the particle migration velocity. Migration velocity is the velocity at which the charged particle is drawn toward the collector plate; a high migration velocity is desired to effective particle collection.

The ripple effects, plays a vital role in increased kV input into the ESP fields and high Frequency switching appears to provide the capability to increase the kV supply the ESP fields. The voltage ripple is inversely proportional to the switching frequency and the load capacitance. The corona current does not vary significantly in ESP operation and is a function of the change in charge with time.

$$i = \frac{dq}{dt} \quad (6)$$

Charge can be, expressed as a function of capacitance and potential difference; the potential difference refers to the voltage ripple's peak-to-peak quantities as they represent the time constant for voltage decay within the capacitor.

$$q = C\Delta V \quad (7)$$

Substituting the charge function into current gives the following expression for voltage ripple:

$$i = \frac{dq}{dt} = C \frac{dV}{dt} = C \frac{\Delta V}{\Delta t} \quad (8)$$

$$\Delta V = \frac{\Delta t \cdot i}{C} \quad (9)$$

Δt is the conduction/ switching time of a semiconductor and this determines the voltage ripple frequency.

$$\Delta t = \frac{1}{f} \quad (10)$$

Hence:

$$\Delta V = \frac{i}{f \cdot C} \quad (11)$$

ESP's operating with convention 50 Hz transformers will obviously have a higher voltage ripple as compared to transformer sets operating at high frequency range. As previously stated, the quantity of the ripple influences the overall average DC output voltage, which is dependent on the resonance capacitance. The influence of the produce ripple can be, expressed as follows:

$$V_{avg} = \sqrt{(V_{DC})^2 \pm (V_{DC} \times \%V_{ripple})^2} \quad (12)$$

Thus, the ripple affects the ionization and collection process as a whole.

The Corona power is, significantly increased by effectively reducing the voltage ripple and increasing the ESP input DC voltage. White defines the corona power as a product of the input voltage and the corona current flow.

$$W = (I_{DC}) \cdot (KV_{DC}) \quad (13)$$

$$W = (I_{DC}) \cdot \left(\frac{KV_{max-peak} + KV_{min-peak}}{2} \right) \quad (14)$$

KV_{DC} is the average DC system voltage input

A higher, average power supply into the, ESP fields, the stronger and more intense electrostatic field. This means that the time needed to treat a particle can be much shorter compared to conventional transformers. This in return results in more effective particle charging. The higher the electrical field strength the faster is the migration velocity (the velocity at which the charged particle is drawn towards the collector electrode). The ESP efficiency is, calculated using the Deutsch formula and it is a function of the migration velocity as indicated in equation 1. [1, 2, 8-14, 16]

3. HFPS PILOT PROJECT SCOPE

The pilot test project required the retrofitting of 16 HFPS transformers on a 28 field ESP, with four casings. Each casing consists of 7 fields, and the first four front fields are to be retrofitted with HFPS transformers. Figure 4, illustrates the ESP plant power supply transformers configuration.



Figure 4: ESP power supply arrangement

The scope required to be executed in order to retrofit the HFPS transformers involved electrical, mechanical and control & instrumentation work. Work was conducted during an outage; unit was shut-down for maintenance. Maintenance work was also conducted on the internals of the ESP, in order to restore its internal mechanical condition.

3.1 Electrical modification

Two substations supply power to ESP transformers, each substation supplying the LH or RH casing respectively. Inside the substation, the 380 V supply from the 380 V precipitator board is connected to the precipitator control cabinets (also referred to as the High Tension panel or HT panel) of each transformer; 14 control panels per substation. From the HT panels, cables are, routed to the precipitator roof, where the precipitator transformer-rectifiers are located.

The electrical system was, configured to supply single phase 380 Vac, as the conventional TR require single-phase power. The installation of the HFPS requires a 3-phase supply and thus the plant had to be modified such that it supplies 3 phase. Work carried out required the modification of the supply boards, installing new cabling from the bus-section to the control cubicle and all the way to the precipitator roof.



Figure 5: HFPS transformer installation

The installation and commissioning of the HFPS transformers was, conducted while the unit was online. The online installation and commissioning was, done on a casing-by-casing basis; the first four TR sets were isolated and decommissioned. Installation started on the fourth field, moving upstream; from fourth field to the first field. The reason for implementing this installation methodology was for safety reasons. The upstream fields have to be isolated, in order to avoiding charge carry-over that can discharge of fields worked on and possibly create an unsafe working environment. Upon completion of the HFPS transformers, a settling and proving period was, observed for a period of about 2 to 3 months weeks, while monitoring the performance of the ESP.

3.2 Control and Instrumentation modification

The signals from the HFPS controllers had to be, interfaced with the existing precipitator plant management system (PPMS). The PPMS consists of a PLC (Sixnet) as an automatic control system and a SCADA (Citect) using communications interfaces of Modbus (CANbus) and Ethernet. The rapping on all seven fields is, managed and controlled by the existing PPMS. The electrical parameters on the newly installed are HFPS on the first four fields are controlled by the HFPS controllers and the last three fields will still be controlled by the existing PPMS. The HFPSs controllers are, interfaced to the SCADA via the existing PLC. The

PLC was, expanded/ programmed to accommodate the new HFPS controllers. Figure 6, illustrates the configuration of the control and instrumentation integrated into the existing control and monitoring system.

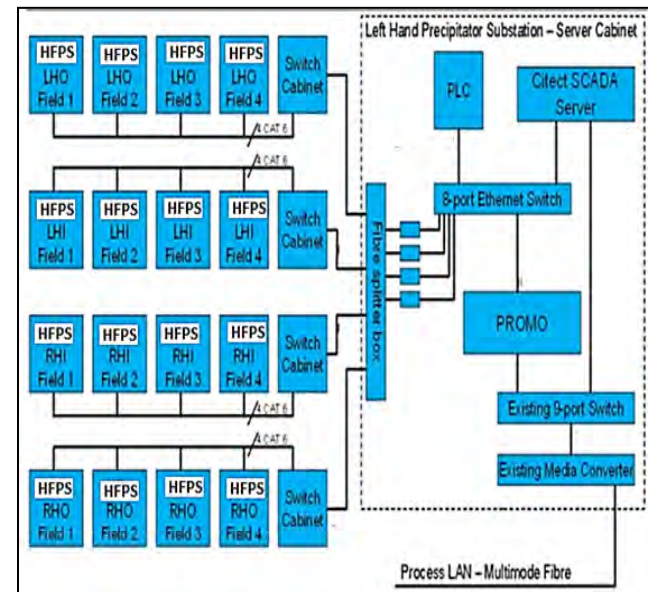


Figure 6: HFPS control system configuration

The control system of the HFPS provides the following information to the PPMS, for monitoring purposes.

- Primary current
- Primary Voltage
- Secondary Current
- Secondary Voltage
- Sparking and Arc rate
- Power output
- Fault indication

The control thereof of the HFPS is, achieved by the use of the ProMo system; this is to optimize the HFPS by changing settings, as and when required. The ProMo system was, integrated into the PPMS, as it can only control the HFPS transformer, whereas the fifth, sixth and seventh fields still made use of the PPMS. This system has the capability to plot V-I curves, in order to analyse the status and conditions of the fields with HFPS. Similarly, to the PPPMS, different modes of operations can be selected; continuous or pulsing mode, depending on the operating conditions. Pulsing mode, is typical implemented whenever, the ESP is receiving high resistivity ash in instances when the SO₃ plant is not available to condition the flue gas. For the purpose of this projected, the pulsing mode operation and effectiveness thereof was, not evaluated.

3.3 Rapping Philosophy

The rapping philosophy implemented in the station, is a queuing rapping philosophy. Queuing refers to the

sequence in which rapping is triggered for the fields, this philosophy is to ensure that two fields in the same casing never rap during the same time interval and thus reduces emissions rapping spikes. The front fields (Fields 1, 2 and 3) collected most of the flue gas, and thus have to be, rapped more frequently as compared to the rear fields. The queuing process, gives priority to the front fields, meaning if ever there is a scenario where the sixth field is, triggered to start rapping at the same time as field 2, field 7's rapping will be, delayed and thus allowing field 2 to rap firsts and field 7 will only rap once field 2 has completed its rapping. This rapping process is, controlled by the PPMS, based on the timer setting input on the AVC for each field.

The PPMS has several programmes loaded on it and these programmes control the performance of the ESP fields, particularly for rapping. Programmes 1, utilized during normal operation on the unit and each program has specific rapper timer settings; intervals and duration. The implemented operating programmes utilized are as follows:

Table 1: Rapping philosophy for TR set

Field	Interval (Minutes)	Duration (Seconds)	Vs Lim	Rap enabled
1	10	35	0	Rap 1
2	18	35	0	Rap 1
3	30	35	0	Rap 1
4	55	35	0	Rap 1
5	95	35	0	Rap 1
6	170	35	0	Rap 1
7	1440	1	0	Rap 1

The HFPSs were, installed, and commissioned over a period of 5 weeks, the installation and commissioning was, conducted per casing. Optimisation, of the ESP was, conducted for a period of a week; optimisation involved changing the rapping regime, from that which was, implemented for the conventional power supply system. It was, expected that the four field with the newly installed HFPS technology would collect more dust burden and thus, the rapping frequency was increased.

The rapping frequency of the last three fields was, also changed according; since the front four fields will collect the most dust burden, the rapping frequency of the rear fields was reduced. An additional rapping feature that was, implemented was the power down rapping (PDR). This form of rapping occurs with the field de-energised and occurs after a set cycle of normal field rapping. The controller sends a signal, to the HFPS to switch of allowing the rapping to occur, the intention for implementing this rapping philosophy was to ensure that the collected plates are, kept clean for improved collection efficiency. Table 1, illustrates the new rapping settings implemented for the installation of the HFPS.

Table 2: Rapping philosophy implemented for HFPS

Field	Normal rapping		PDR	
	Interval	Duration	Interval	Duration
1	6 min	35 sec	30 min	35 sec
2	10 min	35 sec	1 h	35 sec
3	30 min	35 sec	3 h	35 sec
4	3 h	35 sec	12 h	35 sec
5	8 h	35 sec	24 h	35 sec
6	24 h	35 sec	48 h	35 sec
7	48 h	35 sec	48 h	35 sec

4. ESP EFFICIENCY TESTING

ESP efficiency tests were, conducted by an external party, for both conventional TR set and HFPS power supplies. An ESP efficiency test, is a Gravimetric test (EPA Method 17) [6, 15], that measure the volume dust burden entering the ESP and that exiting the ESP. The percentage difference of the outlet as compared to the inlet is an indication of the collection efficiency of the ESP system.

A baseline line, ESP efficiency test was, conducted with conventional TR set power supply. A post HFPS installation, ESP efficiency test was, also conducted, to determine performance of the ESP. These tests, were conducted under identical loading conditions, however they were conducted approximately 4 months apart and the resulted obtained results were correlated by making use of Eskom approved correction curves. The following procedure was conducting the efficiency tests:

4.1 Required Operating Conditions

All the tests were, carried out at 618 MW unit load, with the plant having operated steady at this load for a period of 24-hours and during the testing period. Plant parameters were, recorded and monitored during the testing period were:

- ESP fields in service
- Electrical condition of fields (Obtained from PPMS)
- Secondary current (Is), Secondary voltage (Vs)
- Process conditions; inlet and outlet temperatures, mill configuration, O₂'s

4.2 Isokinetic dust sampling

Five isokinetic tests were, carried out at each duct; with each inlet duct being equipped with four sampling ports and the outlet duct having six sampling ports. Four sets of sampling equipment were, used simultaneously and placed so that two casings are, traversed sequentially by one set of equipment [15].

- Set 1 – ESP LH Inlet Inner and Outer ducts sequentially
- Set 2 – ESP RH Inlet Outer and Inner ducts sequentially
- Set 3 – ESP LH Outlet Inner and Outer ducts sequentially
- Set 4 – ESP RH Outlet Outer and Inner ducts sequentially

An effort was, made to start and stop the isokinetic sampling simultaneously on all casings, more especially the corresponding inlet and outlet positions on a specific ESP Casing. A probe was, inserted to the deepest point in the traverse where sampling started. The traversing started simultaneously on the RH Outer and LH Inner and progressed to the RH Inner and LH Outer. The obtained data was, captured for each ducting, analysed and averaged out to determine the combine collection efficiency of the ESP. These results will be the bases of determining and quantifying the exact reduction or lack thereof, in the ESP as, a result of implementing two types of power supply technologies.

5. ESP EFFICIENCY TEST RESULTS

The ESP performance test was, conducted for both power supply technologies; the test mainly focuses on the process parameters, in terms of flue gas volume flow in and out of the ESP and other process conditions such as coal quality. Isometric sampling was, conducted on the inlet and outlet duct of the ESP casings, these representative samples are, used to determine the collection efficiency of the ESP.

Particulate emission measurements were, carried out employing procedures and equipment that comply with the requirements of EN 13284-1 [16]. The VDI correlation procedure was, followed in the determination of the linear regression of the correlation spot check. The baseline ESP efficiency test was, conducted with conventional TR sets installed and thereafter, a second efficiency test was, conducted with HFPS installed.

5.1 Baseline ESP efficiency test with TR set

Five ESP efficiency tests were, conducted on the unit, while operating at full load of 618 MW generated load. Table 2, illustrates the obtained results from the isometric testing conducted during the ESP efficiency test. The average efficiency of the ESP post outage and with conventional TR sets was, found to be 97.1%; emitting at 42.8 mg/Nm³, at an average boiler load of 619 MW.

Table 3: Isometric ESP efficiency test results

Test no.	Boiler Load	% of Total Air flow	Standard Deviation (% of Total air flow)	Effective emissions	Dust Concentration	Average isokineticity	average O2 Concentration at ESP inlet
	MW	kg/s	%	-	mg/Nm ³ at 10% O2	%	mm
1	618.8	580.6	1.4	73.7	30.3	97.8	4.8
2	619.2	572.7	1.2	34.3	18.1	98.2	4.3
3	618.9	581.4	1.1	40.5	19.2	95.9	4.4
4	619.1	573.6	1.0	32.0	22.9	96.7	4.5
5	619.2	575.1	1.1	33.7	15.4	96.8	4.6
Average	619.0	576.7	1.2	42.8	21.2	97.1	4.5

5.2 Post HFPS installation ESP efficiency test

The ESP efficiency test was, subsequently performed after the optimisation process had, been completed. Table 4, gives the obtained results for the efficiency test conducted with the HFPS installed, on the first four fields of the ESP casings. The emissions were, found to be 19.3 mg/Nm³ and were, maintained at this level consistently.

Table 4: ESP efficiency test results post HFPS installation

Test no.	Boiler Load	% of Total Air flow	Standard Deviation (% of Total air flow)	Effective emissions	Dust Concentration	Average isokineticity	average O2 Concentration at ESP inlet
	MW	kg/s	%	-	mg/Nm ³ at 10% O2	%	mm
1	618.2	594.7	1.1	19.3	36.5	95.0	7.1
2	619.5	598.2	1.1	20.3	28.9	96.1	6.8
3	618.6	599.0	1.0	24.0	34.4	95.4	6.8
4	619.6	579.4	1.1	13.8	7.3	98.1	6.2
5	619.7	587.9	0.6	19.1	17.7	98.4	7.1
Average	619.1	591.8	1.0	19.3	25.0	96.6	6.8

It can, be, seen from table 4, that the ESP was experiencing higher flue gas volume flows, as compared to those measured on the baseline efficiency test. For the post, HFPS installation efficiency test the volume flow have increased by up to 21% on some casings and the dust concentration have increased by up to 22% on some of the casings. However, despite these increases in the process conditions, the obtained emissions were less than those obtained in the baseline tests, giving a 45% emissions reduction from baseline.

5.3 Electrical performance for both technologies

A field by field electrical performance was conducted for the front four fields. The electrical performance was taken post outage for the conventional TR sets and subsequently post optimization of the HFPS. The voltage and current measurements were taken for an hour's operation during the ESP efficiency test.

The electrical performance comparison was, conducted for each of the first four fields; for the operation of a conventional TR set and that of a HFPS transformer. The analysis focuses on the power input delivered into the field, as well as the ripple effect contained in voltage delivered into the fields. The presented electrical

waveforms were taken from the plant historian, which records the measured plant operating parameters in accordance to the Metering and Measurement Systems for Power Stations in Generation Standard; 240-563590.

The graphs shown are from data collected during the ESP efficiency test for each power supply technology. The data is sample at every 30 seconds and averaged out to give an hourly average, which was used to plot the electrical performance. The unit was at a fixed load of 618 MW, for both instance when data was captured.

▪ LHO 1 field electrical performance

Table 5, illustrates the collected electrical data during the process of conducting the ESP efficiency tests. The data was taken for a period of 24 hours; from midnight to midnight. The data was put in the same table although the two overall ESP efficiency tests were conducted 3 months apart.

Table 5: LHO 1 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

Time	LHO 1			
	TR Set - LHO 1 Is	TR Set - LHO 1 Vs	HFPS - LHO 1 Is	HFPS - LHO 1 Vs
00:00 - 01:00	283.55	26.45	929.68	39.72
01:00 - 02:00	102.28	39.67	1291.92	46.97
02:00 - 03:00	81.02	40.22	1288.32	48.08
03:00 - 04:00	96.50	41.38	1227.78	47.58
04:00 - 05:00	97.93	41.58	890.95	45.81
05:00 - 06:00	96.22	41.47	892.33	45.83
06:00 - 07:00	115.07	41.88	455.28	31.50
07:00 - 08:00	92.77	40.83	15.35	14.41
08:00 - 09:00	104.63	42.03	949.97	43.20
09:00 - 10:00	99.12	40.95	983.25	45.76
10:00 - 11:00	75.90	38.33	858.48	44.93
11:00 - 12:00	69.65	38.52	927.92	45.47
12:00 - 13:00	76.40	38.82	1031.70	48.61
13:00 - 14:00	88.87	39.77	1068.35	46.43
14:00 - 15:00	70.93	38.60	1052.17	48.52
15:00 - 16:00	79.45	39.60	790.88	43.79
16:00 - 17:00	98.78	41.70	850.22	45.05
17:00 - 18:00	95.22	40.55	631.03	39.76
18:00 - 19:00	100.98	39.27	15.83	13.45
19:00 - 20:00	89.10	40.25	20.88	16.17
20:00 - 21:00	116.57	41.03	16.87	15.26
21:00 - 22:00	105.47	41.52	23.65	15.99
22:00 - 23:00	115.93	42.52	21.57	17.30
23:00 - 00:00	137.52	43.28	24.77	17.02

Figure 7 was plotted making use of the data presented in table 5, to illustrate the different in electrical performance of the LHO 1 field, when supplied by a TR set and when supplied by an HFT.

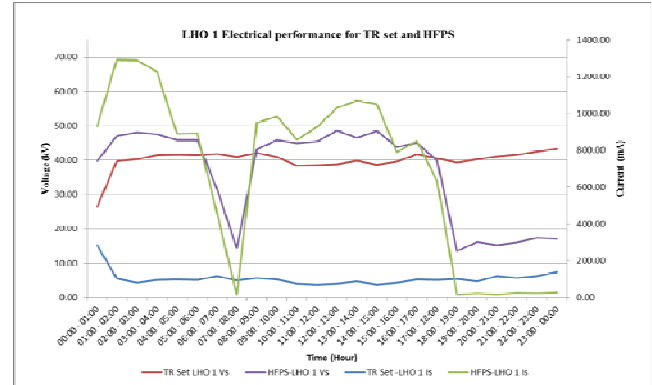


Figure 7: LHO 1 electrical performance for TR set and HFPS.

It can be seen from figure 7, that the electrical performance of LHO 1 field increased significantly. The current input into the field went from below 300 mA for a TR set and could be maintained above 600 mA twice that which the TR set was able to supply. The voltage also increase from low 40 kV for a TR set, to above 40 kV, with the highest voltage being 48 kV supplied by a HFPS. This was a drastic improvement seen on the first field, with consideration that no mechanical repairs were conducted internal from when both measurementS were conducted.

▪ LHO 2 field electrical performance

Table 6 illustrates the collected electrical data during the process of conducting the ESP efficiency tests.

Table 6: LHO 2 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

Time	LHO 2			
	TR Set LHO 2 Is	TR Set LHO 2 Vs	HFPS - LHO 2 Is	HFPS - LHO 2 Vs
00:00 - 01:00	625.03	33.88	1585.60	40.92
01:00 - 02:00	963.75	46.65	1672.37	42.75
02:00 - 03:00	955.55	47.38	1667.87	42.67
03:00 - 04:00	976.98	47.52	1642.47	42.30
04:00 - 05:00	1004.50	47.12	1625.73	43.64
05:00 - 06:00	919.13	47.65	1625.73	43.64
06:00 - 07:00	819.90	46.50	1539.40	46.21
07:00 - 08:00	914.23	47.20	1403.23	48.06
08:00 - 09:00	957.87	48.08	1675.82	44.82
09:00 - 10:00	931.30	47.53	1636.65	43.10
10:00 - 11:00	792.73	46.93	1665.83	44.49
11:00 - 12:00	731.53	45.98	1629.48	43.83
12:00 - 13:00	693.35	46.35	1642.83	43.79
13:00 - 14:00	737.95	46.20	1644.15	43.35
14:00 - 15:00	665.92	46.82	1640.50	42.90
15:00 - 16:00	678.77	46.40	1647.78	45.60
16:00 - 17:00	614.22	44.98	1636.32	45.78
17:00 - 18:00	580.15	45.43	1471.87	46.14
18:00 - 19:00	626.52	45.37	794.10	46.20
19:00 - 20:00	583.88	45.55	920.70	45.45
20:00 - 21:00	753.08	45.50	1035.22	46.78
21:00 - 22:00	748.55	46.10	1301.20	48.61
22:00 - 23:00	755.73	46.10	1113.18	47.42
23:00 - 00:00	800.33	47.18	1071.32	47.39

The current and voltage measurement as presented in table 6 are for both power supply technologies. The data was used to plot the electrical performance of the LHO 2 field; as seen on figure 8.

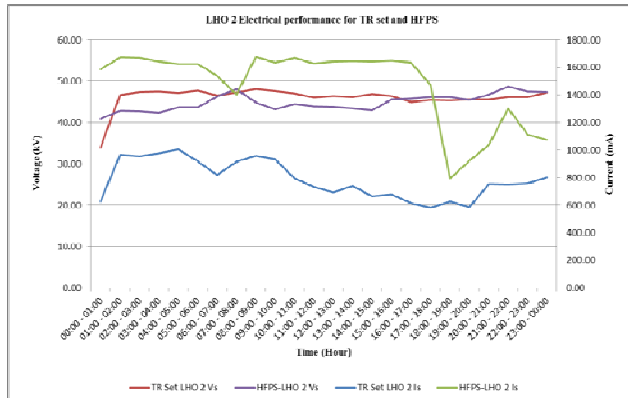


Figure 8: LHO 2 electrical performance for TR set and HFPS.

The electrical performance of the LHO 2 field, saw an improvement in the current and voltage, when the HFPS was installed in place of TR set. The TR set was able to supply and maintain a current of about 900 mA, however with the HFPS was able to produce current above 1600 mA. The voltage input into the field did not change drastically, although the TR set was producing a little more voltage as compared to the HFPS.

▪ LHO 3 field electrical performance

Table 7: LHO 3 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

LHO 3				
Time	TR Set LHO 3 Is	TR Set LHO 3 Vs	HFPS-LHO 3 Is	HFPS-LHO 3 Vs
00:00 - 01:00	1110.50	20.87	1555.85	47.18
01:00 - 02:00	1659.88	31.82	1698.92	48.46
02:00 - 03:00	1654.35	31.90	1690.50	47.66
03:00 - 04:00	1655.33	31.82	1671.05	46.35
04:00 - 05:00	1645.63	31.70	1678.07	46.67
05:00 - 06:00	1667.40	31.93	1678.08	46.67
06:00 - 07:00	1661.70	32.45	1650.28	46.38
07:00 - 08:00	1691.63	32.17	1623.05	47.54
08:00 - 09:00	1625.50	31.60	1642.88	46.26
09:00 - 10:00	1702.77	32.02	1699.52	46.81
10:00 - 11:00	1656.98	31.85	1686.88	46.41
11:00 - 12:00	1674.73	31.93	1646.13	45.92
12:00 - 13:00	1645.87	31.83	1670.73	46.34
13:00 - 14:00	1646.75	31.77	1655.83	46.01
14:00 - 15:00	1651.70	31.98	1670.95	45.89
15:00 - 16:00	1532.15	31.85	1697.13	46.92
16:00 - 17:00	1452.08	31.90	1685.03	47.18
17:00 - 18:00	1283.38	32.15	1639.25	46.34
18:00 - 19:00	1432.37	33.08	1558.42	49.48
19:00 - 20:00	1322.60	32.90	1427.40	49.50
20:00 - 21:00	1418.30	32.93	1323.13	49.54
21:00 - 22:00	1590.50	32.52	1556.83	49.77
22:00 - 23:00	1535.72	32.35	1521.00	49.51
23:00 - 00:00	1544.75	32.57	1568.50	50.87

Table 7 illustrates the collected electrical data during the process of conducting the ESP efficiency tests.

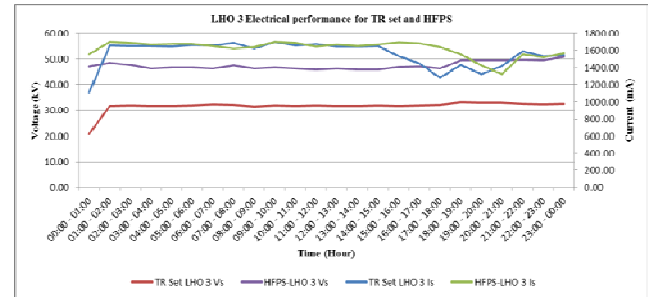


Figure 9: LHO 3 electrical performance for TR set and HFPS.

Figure 9 represent a graphical plot of the LHO 3 electrical performance for both TR set and HFP. The only significant difference that was noted from the two supply technologies was that the HFPS was able to input a high voltage into the field than that of the TR set. The HFPS was able to maintain a voltage of above 47 kV, whereas the TR set could only maintain voltage a low 30 kV. The current input into the field for both transformers was at maximum. The higher voltage, from the HFPS increases the electric field strength for the capturing of the charged dust particles.

▪ LHO 4 field electrical performance

Table 8: LHO 4 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

LHO 4				
Time	TR Set LHO 4 Is	TR Set LHO 4 Vs	HFPS-LHO 4 Is	HFPS-LHO 4 Vs
00:00 - 01:00	413.12	31.37	1179.27	47.31
01:00 - 02:00	471.22	47.52	1472.15	52.89
02:00 - 03:00	455.52	46.87	1535.22	52.52
03:00 - 04:00	458.73	47.35	1636.83	53.28
04:00 - 05:00	460.37	46.98	1668.25	53.11
05:00 - 06:00	462.22	47.28	1668.25	53.10
06:00 - 07:00	482.37	48.40	1679.45	53.45
07:00 - 08:00	483.78	48.08	1649.52	52.74
08:00 - 09:00	474.43	47.80	1655.88	53.52
09:00 - 10:00	487.07	48.23	1642.02	52.08
10:00 - 11:00	485.35	48.93	1671.10	52.87
11:00 - 12:00	434.08	46.23	1671.10	52.92
12:00 - 13:00	409.07	46.48	1683.03	53.77
13:00 - 14:00	405.20	46.67	1645.32	52.76
14:00 - 15:00	357.73	45.47	1668.93	53.08
15:00 - 16:00	385.72	46.00	1655.90	52.53
16:00 - 17:00	389.45	46.53	1627.23	51.88
17:00 - 18:00	393.50	46.55	1673.17	53.14
18:00 - 19:00	413.08	47.32	1536.95	50.89
19:00 - 20:00	416.63	46.80	1470.83	51.26
20:00 - 21:00	422.10	47.05	1361.72	50.89
21:00 - 22:00	407.08	46.45	1567.82	52.60
22:00 - 23:00	440.37	48.15	1543.58	52.20
23:00 - 00:00	392.26	47.36	1571.73	52.65

Table 8 illustrates the collected electrical data for LHO 4 during the process of conducting the ESP efficiency tests.

The LHO 4's electrical performance is, illustrated on figure 10; as per data presented on table 8.

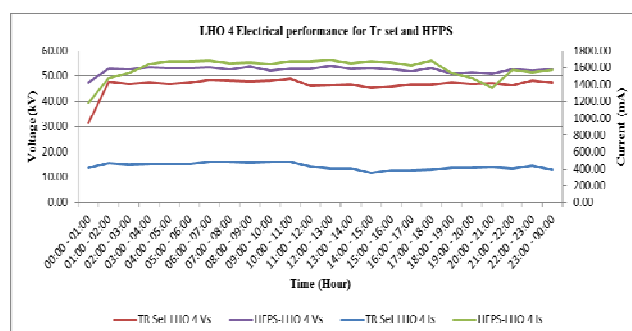


Figure 10: LHO 4 electrical performance for TR set and HFPS.

The LHO 4's electrical performance improved significantly with the installation of the HFPS. The current input into the ESP field increased from around 400 mA to full rated input current of 1600 mA. The voltage input into the field also increase from around 48 kV to 53 kV.

▪ LHI 1 field electrical performances

Table 9: LHI 1 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	LHI 1			
	TR Set LHI 1 Is	TR Set LHI 1 Vs	HFPS-LHI 1 Is	HFPS-LHI 1 Vs
00:00 - 01:00	112.57	37.87	1521.53	42.07
01:00 - 02:00	188.88	55.18	1588.55	44.27
02:00 - 03:00	203.73	53.87	1576.48	44.45
03:00 - 04:00	195.95	53.93	1462.47	43.77
04:00 - 05:00	192.93	53.77	588.53	42.13
05:00 - 06:00	189.20	55.05	577.75	42.09
06:00 - 07:00	198.18	54.17	366.45	39.20
07:00 - 08:00	210.83	55.72	305.73	38.34
08:00 - 09:00	236.52	54.90	747.92	41.24
09:00 - 10:00	241.58	54.97	682.05	41.29
10:00 - 11:00	247.75	53.52	845.25	42.81
11:00 - 12:00	245.62	52.65	628.42	42.47
12:00 - 13:00	252.37	52.37	754.42	40.98
13:00 - 14:00	216.43	54.35	1225.30	44.70
14:00 - 15:00	249.57	52.23	1093.48	42.69
15:00 - 16:00	221.98	52.10	654.68	40.94
16:00 - 17:00	30.87	2.03	611.18	41.21
17:00 - 18:00	0.00	0.00	419.38	39.77
18:00 - 19:00	0.00	0.00	209.07	36.94
19:00 - 20:00	0.00	0.00	208.63	37.29
20:00 - 21:00	0.00	0.00	238.30	37.14
21:00 - 22:00	0.00	0.00	336.37	40.34
22:00 - 23:00	0.00	0.00	266.08	37.94
23:00 - 00:00	0.00	0.00	265.85	38.83

Table 9 presents the electrical measurements for the LHI 1's performance. It is noted that at around 17:00, the TR

sets reading went to zero, which indicates that the field had tripped at this stage.

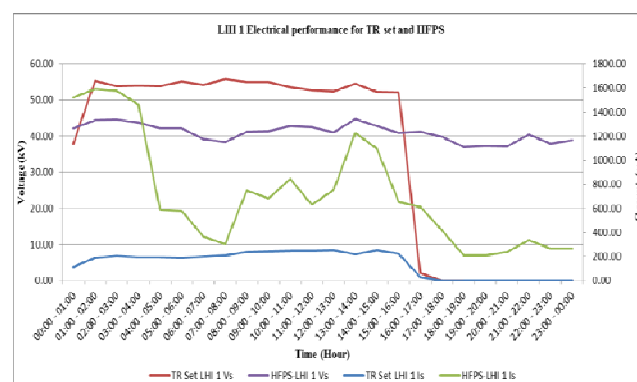


Figure 11: LHI 1 electrical performance for TR set and HFPS.

The installation on the HFPS on the LHI 1 did not result in an improved electrical performance although the current was not stable. Due to excessive sparking, probably caused by a loose discharge electrode wire.

▪ LHI 2 field electrical performance

Table 10: LHI 2 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	LHI 2			
	TR Set LHI 2 Is	TR Set LHI 2 Vs	HFPS-LHI 2 Is	HFPS-LHI 2 Vs
00:00 - 01:00	206.10	20.73	1469.27	47.32
01:00 - 02:00	277.35	29.12	1614.40	49.24
02:00 - 03:00	274.12	30.28	1647.32	49.64
03:00 - 04:00	249.15	31.48	1653.02	50.26
04:00 - 05:00	241.07	30.52	1342.00	50.08
05:00 - 06:00	267.00	30.30	1336.98	50.08
06:00 - 07:00	256.93	30.52	823.38	47.95
07:00 - 08:00	263.83	30.12	450.97	45.50
08:00 - 09:00	281.15	31.57	1028.68	49.54
09:00 - 10:00	262.20	31.55	1213.70	50.49
10:00 - 11:00	278.52	31.48	1232.10	49.57
11:00 - 12:00	244.22	30.67	1171.17	49.05
12:00 - 13:00	224.48	30.07	1152.22	49.00
13:00 - 14:00	204.33	30.40	1480.20	49.68
14:00 - 15:00	185.38	31.07	1494.90	49.36
15:00 - 16:00	217.15	31.25	1098.67	47.88
16:00 - 17:00	170.02	29.45	923.10	48.13
17:00 - 18:00	217.63	29.58	678.33	47.40
18:00 - 19:00	248.85	30.82	245.02	42.51
19:00 - 20:00	269.32	30.82	257.27	42.83
20:00 - 21:00	286.85	30.28	278.17	43.10
21:00 - 22:00	290.20	31.00	447.43	46.62
22:00 - 23:00	299.03	29.80	353.35	45.36
23:00 - 00:00	283.87	30.05	325.88	45.17

Table 10 presents the electrical measurements for the LHI 2's performance.

LHI 2's electrical performance is presented on figure 12, plotted from data acquired from table 10.

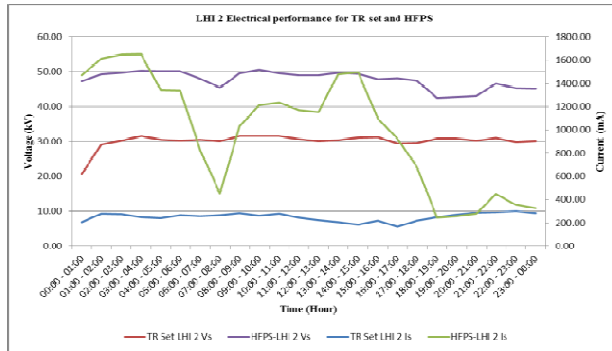


Figure 12: LHI 2 electrical performance for TR set and HFPS.

The LHI 2's performance was similar to that observed on LHI 1. The field was sparking excessively, thus not allowing stable operating conditions. The TR set was able to maintain consistent current as the controller allows for manual intervention and can be set to a point where it can operate without frequent trips due to sparking and arcing.

▪ LHI 3 electrical performance

Table 11: LHI 3 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	LHI 3			
	TR Set LHI 3 Is	TR Set LHI 3 Vs	HFPS-LHI 3 Is	HFPS-LHI 3 Vs
00:00 - 01:00	133.12	25.35	976.08	45.22
01:00 - 02:00	106.03	37.77	1461.02	48.82
02:00 - 03:00	83.43	38.38	1588.62	49.36
03:00 - 04:00	74.73	39.43	1661.70	49.54
04:00 - 05:00	86.23	38.90	1518.82	47.78
05:00 - 06:00	78.15	39.22	1544.50	48.47
06:00 - 07:00	89.07	39.32	1085.60	46.08
07:00 - 08:00	78.13	38.27	512.97	42.56
08:00 - 09:00	81.65	38.72	922.45	46.19
09:00 - 10:00	99.50	39.18	1188.33	47.22
10:00 - 11:00	94.35	39.63	1239.40	46.81
11:00 - 12:00	103.73	40.03	1141.73	45.93
12:00 - 13:00	70.37	38.20	1154.38	46.75
13:00 - 14:00	70.05	39.30	1390.77	47.66
14:00 - 15:00	50.67	37.47	1554.23	48.67
15:00 - 16:00	51.03	38.20	1230.05	46.50
16:00 - 17:00	31.93	37.22	930.72	44.72
17:00 - 18:00	29.93	37.50	737.08	43.95
18:00 - 19:00	37.75	38.02	200.40	39.56
19:00 - 20:00	42.03	38.97	168.37	39.17
20:00 - 21:00	47.20	38.45	161.68	39.05
21:00 - 22:00	47.45	39.38	300.50	43.28
22:00 - 23:00	51.22	39.42	208.97	42.27
23:00 - 00:00	53.21	38.97	200.72	41.77

Table 11 presents the electrical measurements for the LHI 3's performance.

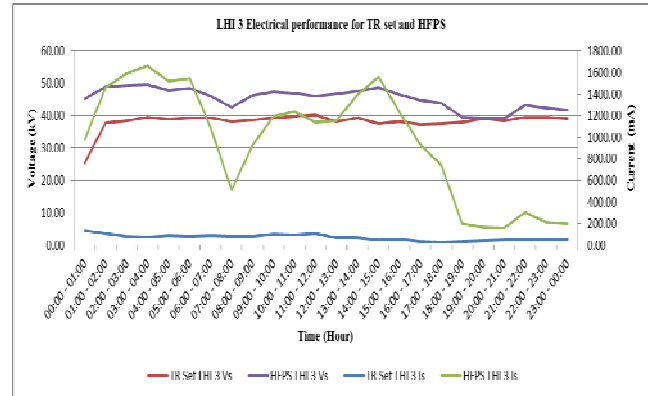


Figure 13: LHI 3 electrical performance for TR set and HFPS.

Figure 13 presents the electrical performance of the LHI 3's field. Similar to that of LHI 1 and 2, this field was also experiencing a high spark rate. The HFPS was still able to maintain a higher electrical performance than that of the TR set, in these upset conditions.

▪ LHI 4 electrical performance

Table 12: LHI 4 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	LHI 4			
	TR Set LHI 4 Is	TR Set LHI 4 Vs	HFPS-LHI 4 Is	HFPS-LHI 4 Vs
00:00 - 01:00	312.80	47.90	863.23	43.64
01:00 - 02:00	265.97	46.50	1356.82	47.99
02:00 - 03:00	373.50	47.07	1547.48	48.09
03:00 - 04:00	387.47	46.93	1647.63	48.36
04:00 - 05:00	350.93	47.20	1655.32	48.23
05:00 - 06:00	367.82	47.33	1655.33	48.23
06:00 - 07:00	360.53	47.28	1489.15	47.19
07:00 - 08:00	350.32	46.68	1042.40	45.72
08:00 - 09:00	379.12	47.28	1198.05	46.05
09:00 - 10:00	376.98	47.43	1517.92	47.70
10:00 - 11:00	356.15	46.53	1565.90	47.39
11:00 - 12:00	314.50	46.20	1607.87	48.24
12:00 - 13:00	254.43	44.55	1605.03	48.22
13:00 - 14:00	262.65	45.88	1636.20	47.54
14:00 - 15:00	244.80	46.57	1664.87	47.65
15:00 - 16:00	249.93	46.78	1541.83	46.70
16:00 - 17:00	144.67	47.77	1396.33	46.43
17:00 - 18:00	138.23	47.75	1226.12	45.40
18:00 - 19:00	174.97	47.17	521.98	43.16
19:00 - 20:00	189.20	47.33	312.25	41.03
20:00 - 21:00	191.10	48.00	279.85	42.21
21:00 - 22:00	179.20	46.85	419.53	43.03
22:00 - 23:00	200.68	48.33	387.60	42.74
23:00 - 00:00	176.00	47.51	365.08	43.23

Table 11 presents the electrical measurements for the LHI 3's performance. It is noted the performance decreased after 17:00.

Figure 14 presents the performance of the LHI 4 as illustrated by the value of table 12.

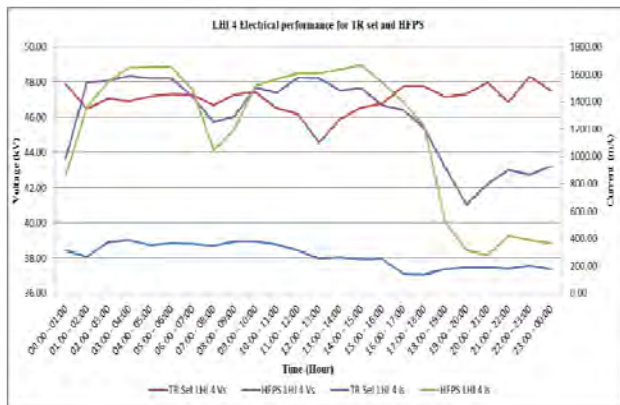


Figure 14: LHI 4 electrical performance for TR set and HFPS.

Similarly to all the other fields discussed, the installation of the HFPS resulted in improved electrical performance. Although this casing was experiencing excessive sparking, the HFPSs were able to maintain a high electrical performance than that which was possible with the TR sets.

- RHI 1 electrical performance

Table 13: RHI 1 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	RHI 1			
	TR Set RHI 1 Vs	TR Set RHI 1 Is	HFPS-RHI 1 Vs	HFPS-RHI 1 Is
00:00 - 01:00	426.52	34.97	1551.43	43.32
01:00 - 02:00	330.12	48.53	1647.20	46.50
02:00 - 03:00	370.23	50.82	1670.73	47.11
03:00 - 04:00	381.17	51.68	1631.80	46.11
04:00 - 05:00	343.73	51.68	1620.67	47.60
05:00 - 06:00	340.85	51.45	1618.08	47.63
06:00 - 07:00	324.25	51.57	1348.98	46.24
07:00 - 08:00	315.50	51.98	1080.42	45.44
08:00 - 09:00	325.93	51.78	1527.73	48.04
09:00 - 10:00	315.38	51.32	1327.35	45.94
10:00 - 11:00	311.13	50.90	1225.52	45.77
11:00 - 12:00	280.07	50.95	1521.20	47.85
12:00 - 13:00	306.80	52.47	1548.15	48.20
13:00 - 14:00	287.72	50.93	1582.92	45.33
14:00 - 15:00	265.85	50.65	1617.57	46.59
15:00 - 16:00	276.00	51.18	1634.65	46.66
16:00 - 17:00	293.62	50.32	1606.02	46.95
17:00 - 18:00	308.37	49.55	1416.68	46.66
18:00 - 19:00	313.90	49.97	828.20	43.46
19:00 - 20:00	289.07	49.98	931.95	42.96
20:00 - 21:00	311.80	48.27	960.98	44.18
21:00 - 22:00	335.70	51.22	913.72	44.06
22:00 - 23:00	329.68	49.70	1085.30	43.70
23:00 - 00:00	320.10	51.16	1120.83	44.56

Table 13, represents the electrical data for the RHI 1's performance.

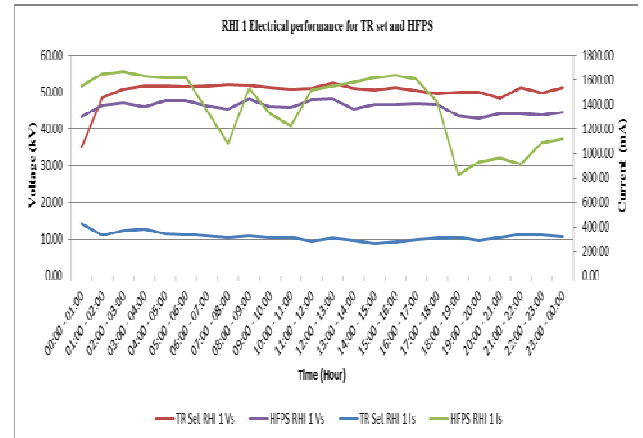


Figure 15: RHI 1 electrical performance for TR set and HFPS.

The RHI 1's electrical performance is plotted on figure 15. The TR set's performance for this field is typical of how low the electrical performance of the TR set can be more especially for the first field. The current input into the field was consistently below 350 mA with the TR set in operation. The installation of the HFPS saw the current input into the field increase to above 1000 mA. The voltage of the TR set was slightly above that which the HFPS could manage, however due to the inability to produce a high enough current; the high voltage has not significant influence on the collection of dust burden.

- RHI 2 electrical performance

Table 14: RHI 2 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	RHI 2			
	TR Set RHI 2 Vs	TR Set RHI 2 Is	HFPS-RHI 2 Vs	HFPS-RHI 2 Is
00:00 - 01:00	188.07	56.45	1567.45	43.40
01:00 - 02:00	272.15	56.37	1638.30	43.84
02:00 - 03:00	244.50	56.63	1671.55	44.81
03:00 - 04:00	207.82	56.67	1652.80	44.13
04:00 - 05:00	180.38	56.37	1605.73	43.52
05:00 - 06:00	164.28	55.60	1634.05	44.22
06:00 - 07:00	185.85	56.57	1631.70	45.80
07:00 - 08:00	212.20	57.03	1574.23	46.10
08:00 - 09:00	185.28	57.17	1620.02	46.09
09:00 - 10:00	174.87	56.85	1618.40	46.79
10:00 - 11:00	157.25	56.00	1601.98	46.28
11:00 - 12:00	143.80	56.22	1644.55	46.96
12:00 - 13:00	175.48	56.58	1644.10	46.79
13:00 - 14:00	145.05	56.02	1647.48	46.70
14:00 - 15:00	167.63	56.72	1629.02	45.23
15:00 - 16:00	182.40	57.02	1652.58	45.88
16:00 - 17:00	187.70	56.40	1627.35	45.85
17:00 - 18:00	172.12	56.28	1601.47	46.44
18:00 - 19:00	168.17	55.20	1524.87	47.06
19:00 - 20:00	159.57	55.50	1497.87	46.79
20:00 - 21:00	158.90	55.53	1564.35	47.33
21:00 - 22:00	202.30	56.90	1522.85	47.51
22:00 - 23:00	294.77	56.35	1584.85	47.65
23:00 - 00:00	347.46	58.33	1562.45	46.54

Electrical performance of the RHI 2 field is shown on table 14.

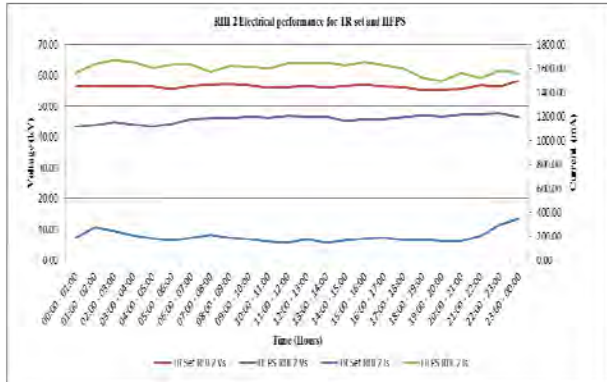


Figure 16: RHI 2 electrical performance for TR set and HFPS.

Figure 16, presented the graphical representation of the data on table 14. It is noted that the electrical performance of the HFPS surpassed that of the TR set, with the HFPS being able to input full load current into the field. The TR sets voltage is significantly higher than that of the HFPS, reason being the controller algorithm is such that was force the TR set to push the voltage as high as possible in order to achieved the desired 1600 mA. Since the HFPS is able to achieve full load operational current, at a lower voltage, it simple maintains the voltage level at which the full load current was achieved.

▪ RHI 3 electrical performance

Table 15: RHI 3 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

RHI 3				
	TR Set RHI 3 Is	TR Set RHI 3 Vs	HFPS-RHI 3 Is	HFPS-RHI 3 Vs
00:00 - 01:00	497.53	30.28	1652.45	43.98
01:00 - 02:00	616.63	42.27	1699.62	43.90
02:00 - 03:00	601.13	39.93	1643.02	42.36
03:00 - 04:00	572.45	40.05	1642.93	42.12
04:00 - 05:00	600.87	40.62	1642.88	42.38
05:00 - 06:00	629.07	40.90	1642.88	42.37
06:00 - 07:00	651.32	41.32	1696.70	43.90
07:00 - 08:00	724.08	42.33	1642.95	42.91
08:00 - 09:00	582.30	39.87	1671.18	43.88
09:00 - 10:00	577.13	39.88	1657.50	44.04
10:00 - 11:00	602.97	40.10	1669.70	44.30
11:00 - 12:00	619.62	41.58	1690.92	44.81
12:00 - 13:00	680.00	42.17	1642.98	43.81
13:00 - 14:00	610.43	41.72	1659.72	44.20
14:00 - 15:00	690.20	42.88	1671.17	43.94
15:00 - 16:00	698.00	43.55	1699.42	44.67
16:00 - 17:00	697.10	43.02	1642.78	43.33
17:00 - 18:00	718.33	43.82	1670.87	44.33
18:00 - 19:00	657.18	43.35	1642.35	44.12
19:00 - 20:00	651.42	42.68	1670.20	44.70
20:00 - 21:00	677.65	43.17	1642.73	44.04
21:00 - 22:00	707.18	43.98	1671.17	44.83
22:00 - 23:00	672.95	42.72	1639.28	44.29
23:00 - 00:00	704.13	43.05	1668.98	45.08

Table 15, illustrates the electrical performance data of the RHI 3 field.

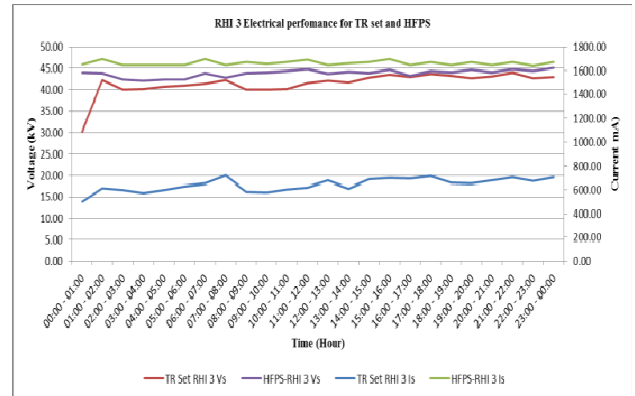


Figure 17: RHI 3 electrical performance for TR set and HFPS.

RHI 3's electrical performance is plotted on figure 17, it is noted that with the TR set in operation, the input current was significantly low. The installation of the HFPS resulted in maximum input current being fed into the field and maintained.

▪ RHI 4 electrical performance

Table 16: RHI 4 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	RHI 4			
	TR Set RHI 4 Is	TR Set RHI 4 Vs	HFPS-RHI 4 Is	HFPS-RHI 4 Vs
00:00 - 01:00	1309.22	39.12	1646.52	41.85
01:00 - 02:00	1618.05	47.18	1405.00	39.55
02:00 - 03:00	392.73	32.90	1636.85	41.71
03:00 - 04:00	1429.43	45.58	1635.08	41.12
04:00 - 05:00	1604.32	47.98	1668.53	41.34
05:00 - 06:00	1552.65	47.67	1668.55	41.35
06:00 - 07:00	1619.13	48.85	1365.77	39.34
07:00 - 08:00	1691.33	49.30	1620.80	41.52
08:00 - 09:00	1174.08	43.02	1671.65	42.68
09:00 - 10:00	615.10	36.02	1351.88	39.59
10:00 - 11:00	1657.02	49.33	1635.70	42.25
11:00 - 12:00	1579.98	47.88	1357.00	39.69
12:00 - 13:00	1635.52	49.20	1629.92	42.23
13:00 - 14:00	1649.02	49.50	1679.05	42.86
14:00 - 15:00	1590.63	48.82	1643.93	41.86
15:00 - 16:00	353.52	34.85	1323.10	39.25
16:00 - 17:00	1396.00	46.75	1674.47	42.83
17:00 - 18:00	1510.62	47.52	1640.17	42.13
18:00 - 19:00	1574.63	49.22	1506.48	40.75
19:00 - 20:00	1533.65	48.87	1430.17	40.11
20:00 - 21:00	1464.58	47.87	1697.60	43.18
21:00 - 22:00	1186.13	45.73	1614.52	41.71
22:00 - 23:00	747.35	41.38	1339.58	39.82
23:00 - 00:00	1559.51	48.85	1638.25	42.34

Table 16, illustrates the electrical performance data of the RHI 4 field.

The RHI 4's electrical performance was not stable for both power supply technologies, as seen on figure 18.

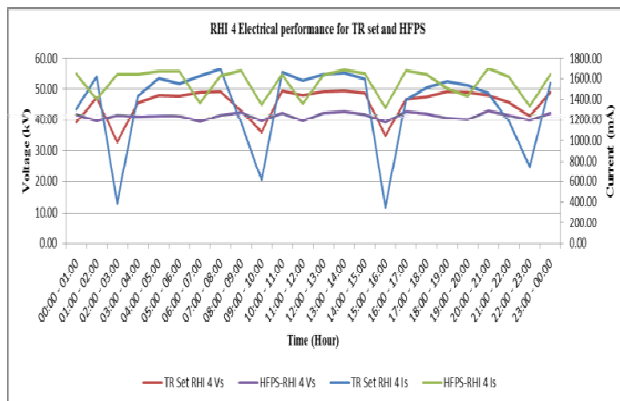


Figure 18: RHI 4 electrical performance for TR set and HFPS.

The performance of the field was within specification for both power supply technologies, although the field was experiencing excessive sparking resulting frequent performance dips.

▪ RHO 1 electrical performance

Table 17: RHO 1 current and voltage measurement during the ESP efficiency tests for TR set and HFPS.

	RHO 1			
	TR Set RHO 1 Is	TR Set RHO 1 Vs	HFPS-RHO 1 Is	HFPS-RHO 1 Vs
00:00 - 01:00	485.65	24.03	26.88	9.85
01:00 - 02:00	585.53	24.93	15.97	10.51
02:00 - 03:00	561.22	24.80	19.22	11.36
03:00 - 04:00	617.95	24.28	14.03	11.14
04:00 - 05:00	635.83	24.63	15.38	10.90
05:00 - 06:00	603.37	24.30	15.38	10.87
06:00 - 07:00	623.03	23.95	15.32	11.16
07:00 - 08:00	668.65	24.80	21.37	12.29
08:00 - 09:00	659.20	24.07	19.05	11.63
09:00 - 10:00	651.07	23.93	16.97	11.11
10:00 - 11:00	735.33	25.10	19.03	11.26
11:00 - 12:00	673.78	25.33	17.72	11.05
12:00 - 13:00	840.45	25.72	18.95	11.57
13:00 - 14:00	677.05	24.87	22.20	11.45
14:00 - 15:00	925.17	23.40	18.87	11.38
15:00 - 16:00	1404.03	25.57	19.47	11.46
16:00 - 17:00	1323.68	26.62	16.88	11.21
17:00 - 18:00	1179.75	27.17	16.08	11.40
18:00 - 19:00	1155.28	27.00	18.10	11.44
19:00 - 20:00	1224.40	27.75	18.20	11.33
20:00 - 21:00	1245.72	28.53	16.72	11.36
21:00 - 22:00	1181.37	28.37	14.02	9.96
22:00 - 23:00	1217.65	28.25	18.73	12.53
23:00 - 00:00	1193.89	27.97	14.00	10.51

Table 17, illustrates the electrical performance data of the RHO 1 field. It was noted that by the time the HFPS was installed, that field had an internal fault, which was subsequently repaired during an opportunity.

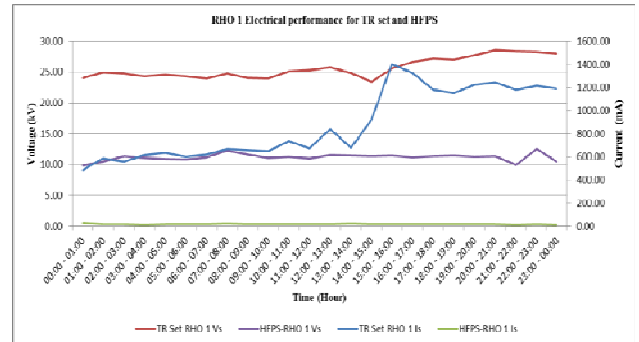


Figure 19: RHO 1 electrical performance for TR set and HFPS.

Figure 19 illustrates the performance of the RHO 1 field, unfortunately the field experienced an internal fault when the HFPS was installed and thus its performance could not be determined at the stage when the testing was conducted.

▪ RHO 2 electrical performance

Table 18: RHO 2 current and voltage measurement during the ESP efficiency tests for TR set and HFPS

	RHO 2			
	TR Set RHO 2 Is	TR Set RHO 2 Vs	HFPS-RHO 2 Is	HFPS-RHO 2 Vs
00:00 - 01:00	287.13	34.80	1529.67	45.75
01:00 - 02:00	788.55	56.03	1634.95	48.59
02:00 - 03:00	807.60	56.85	1642.23	48.82
03:00 - 04:00	754.15	57.22	1626.78	49.05
04:00 - 05:00	740.37	57.27	1568.45	48.90
05:00 - 06:00	741.88	57.40	1565.50	48.87
06:00 - 07:00	707.23	55.72	1311.33	46.83
07:00 - 08:00	727.90	57.23	990.22	44.15
08:00 - 09:00	718.97	57.57	1044.18	44.13
09:00 - 10:00	692.75	57.25	1109.02	46.23
10:00 - 11:00	663.82	55.58	1311.63	46.04
11:00 - 12:00	652.43	55.53	1162.78	44.94
12:00 - 13:00	644.18	56.23	1100.32	44.99
13:00 - 14:00	584.63	53.77	1319.40	45.85
14:00 - 15:00	655.05	55.77	1378.70	45.82
15:00 - 16:00	664.02	56.03	1506.88	47.43
16:00 - 17:00	715.52	56.52	1557.13	47.36
17:00 - 18:00	720.35	56.38	1433.12	47.34
18:00 - 19:00	765.55	57.27	1200.15	45.88
19:00 - 20:00	746.07	57.00	1173.95	45.94
20:00 - 21:00	738.70	57.07	1106.00	44.97
21:00 - 22:00	745.47	56.57	1044.87	44.91
22:00 - 23:00	784.58	57.30	1150.53	46.27
23:00 - 00:00	740.03	56.41	1219.43	46.82

Table 18, illustrates the electrical performance data of the RHO 2 field. The performance of this field was within specification for both power supply technologies. The TR set was able to produce and maintain a current input of above 700 mA at a voltage level of 57 kV, exceptional performance for a TR set more especially that it is operating on the second field. The installation of the HFPS further improved the electrical performance of the

field, with current exceeding a 1000 mA. Figure 20 presents the plotted data as shown on table 18.

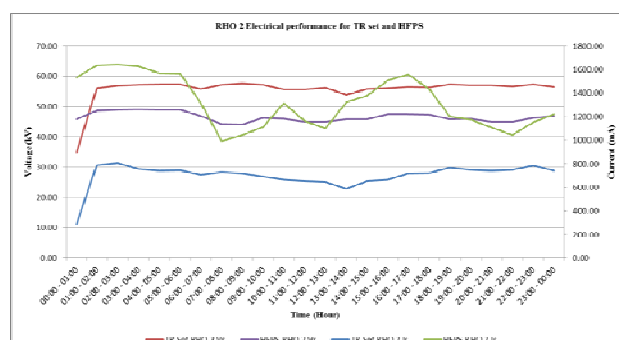


Figure 20: RHO 2 electrical performance for TR set and HFPS.

▪ RHO 3 electrical performance

Table 19: RHO 3 current and voltage measurement during the ESP efficiency tests for TR set and HFPS

	RHO 3			
	TR Set RHO 3 Is	TR Set RHO 3 Vs	HFPS RHO 3 Is	HFPS RHO 3 Vs
00:00 - 01:00	424.88	20.72	1528.97	40.16
01:00 - 02:00	279.42	32.67	1660.88	42.58
02:00 - 03:00	221.15	32.08	1699.50	43.16
03:00 - 04:00	228.88	32.85	1642.48	41.61
04:00 - 05:00	227.42	32.98	1645.20	42.07
05:00 - 06:00	208.53	32.55	1645.22	42.08
06:00 - 07:00	204.32	32.83	1698.63	43.52
07:00 - 08:00	186.42	33.62	1641.25	43.14
08:00 - 09:00	179.73	32.93	1661.88	43.47
09:00 - 10:00	180.73	32.98	1636.35	42.92
10:00 - 11:00	165.62	33.08	1663.05	43.56
11:00 - 12:00	158.77	32.40	1661.12	43.65
12:00 - 13:00	155.83	32.08	1649.32	43.33
13:00 - 14:00	143.00	32.13	1648.33	43.04
14:00 - 15:00	169.88	34.93	1665.90	42.98
15:00 - 16:00	258.68	38.85	1649.60	42.77
16:00 - 17:00	292.80	38.30	1646.85	42.91
17:00 - 18:00	380.17	39.68	1669.48	43.15
18:00 - 19:00	396.23	39.58	1631.75	42.64
19:00 - 20:00	386.58	39.43	1641.15	42.43
20:00 - 21:00	379.28	38.90	1670.38	43.69
21:00 - 22:00	402.30	40.07	1683.55	44.05
22:00 - 23:00	379.90	40.53	1639.33	43.29
23:00 - 00:00	423.15	40.08	1695.53	43.97

Table 19, illustrates the electrical performance data of the RHO 3 field. The TR set showed poor performance with, with a current input into the field being below 200 mA, such poor performance is typical due to internal fault condition such as a defective rapping system. A shearing pin was replaced on the discharge electrode rapping system and with the installation on the HFPS, the input current into the field went to maximum. Figure 21 shows the contrasting performances of the two power supply systems.

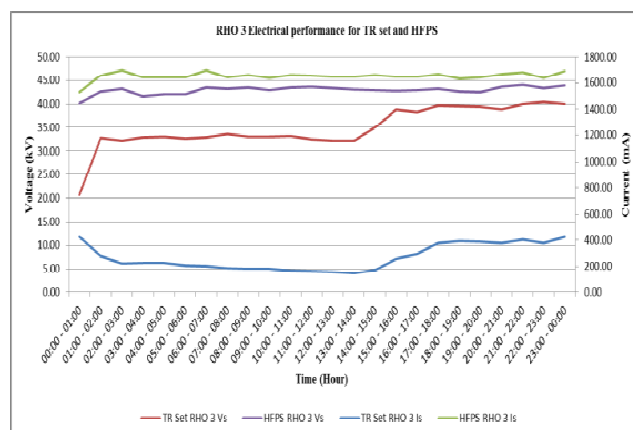


Figure 21: RHO 3 electrical performance for TR set and HFPS.

▪ RHO 4 electrical performance

Table 20: RHO 4 current and voltage measurement during the ESP efficiency tests for TR set and HFPS

	RHO 4			
	TR Set RHO 4 Is	TR Set RHO 4 Vs	HFPS RHO 4 Is	HFPS RHO 4 Vs
00:00 - 01:00	768.27	21.97	1584.35	40.34
01:00 - 02:00	1642.20	34.53	1642.85	42.02
02:00 - 03:00	1652.28	34.68	1699.47	43.19
03:00 - 04:00	1665.53	34.87	1671.13	42.33
04:00 - 05:00	1707.78	35.18	1667.25	41.90
05:00 - 06:00	1665.07	34.98	1667.27	41.89
06:00 - 07:00	1675.15	35.78	1699.48	42.77
07:00 - 08:00	1632.97	35.47	1642.85	41.69
08:00 - 09:00	1690.55	35.92	1675.27	42.72
09:00 - 10:00	1666.40	35.75	1674.75	42.90
10:00 - 11:00	1669.43	35.70	1661.23	42.99
11:00 - 12:00	1698.65	35.23	1670.68	42.77
12:00 - 13:00	1619.53	34.85	1688.67	43.32
13:00 - 14:00	1443.42	33.98	1669.82	43.16
14:00 - 15:00	1600.03	35.23	1641.90	42.59
15:00 - 16:00	1669.95	35.72	1670.23	42.91
16:00 - 17:00	1602.93	35.48	1681.37	43.77
17:00 - 18:00	1607.60	35.83	1698.48	43.93
18:00 - 19:00	1694.03	36.28	1677.83	43.81
19:00 - 20:00	1678.10	36.25	1685.17	43.57
20:00 - 21:00	1590.17	36.08	1670.42	43.07
21:00 - 22:00	1655.37	36.15	1670.90	42.89
22:00 - 23:00	1628.87	36.25	1642.50	42.49
23:00 - 00:00	1635.57	36.31	1671.03	43.08

Table 20, illustrates the electrical performance data of the RHO 4 field. The RHO 4's performance was within specification with the TR set installed, as it was able to produce maximum current. The installation of a HFPS result in the HFPS maintaining the maximum current as well, however it managed to increase the input voltage into the field as well. Figure 22, presents the graphical plot of the data presented on table 20, for the performance of the RHO 4 field.

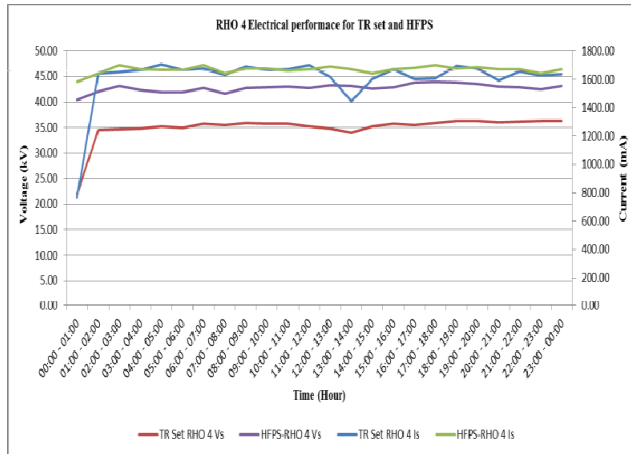


Figure 22: RHO 4 electrical performance for TR set and HFPS.

The overall electrical performance of the two power supply technologies has shown that the HFPS have a, better electrical conversion efficiency as compared to that of the TR set. The LHO casing had a maximum power input of 228 kW, with TR set in operation, whereas the HFPS was able to produce a maximum power input of 389 kW. This gave a casing power input increase of 41%. The LHI casing had a maximum power input of 237 kW, with TR set in operation, whereas the HFPS was able to produce a maximum power input of 419 kW. This gave a casing power input increase of 43%.

The RHI casing had a maximum power input of 253 kW, with TR set in operation, whereas the HFPS was able to produce a maximum power input of 403 kW. This gave a casing power input increase of 37%. The highest power input into the RHO casing was 275 kW for conventional TR sets, whereas the highest for a casing with HFPS installed went up to 420 kW. This gave a casing power input increase of 35%.

The overall electrical performance increase of the ESP casings is, expected to result in improved collection efficiency of the ESP.

5.4 Emissions performance comparison

Figure 39 illustrates the emissions performance of the unit, it can, be, seen how the emissions reduced and consistently maintained at low levels.

The emissions recorded shows that for the period in which the conventional TR sets were in operation the emissions were low; however the inconsistency in the electrical performance of the TR sets, resulted in a fluctuation of the emissions. At the time, when all 16 HFPS were installed and fully operation, it could be seen that the emissions reduced and were maintained, this is due to the consistency that the HFPS are able to maintain high electrical power input into the ESP.

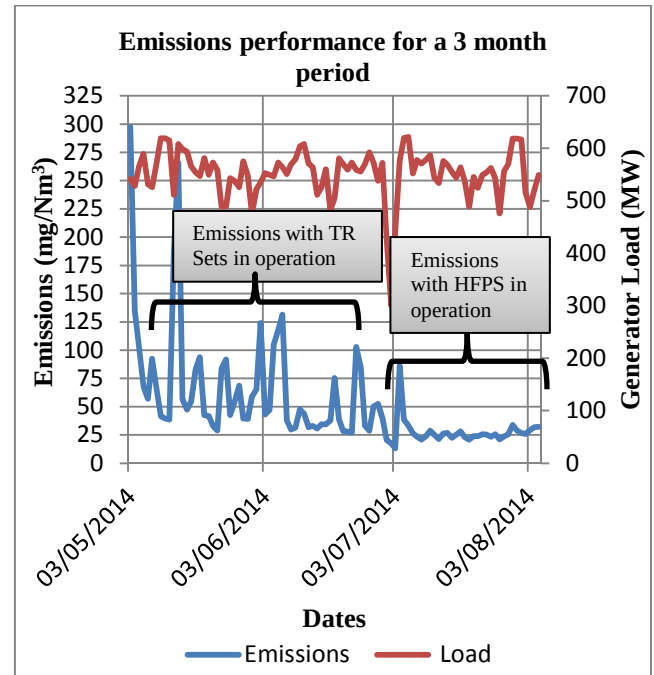


Figure 23: Emissions performance

The ESP efficiency test showed that the ESP was emitting 42.8 mg/Nm^3 with conventional TR sets installed, and 19.3 mg/Nm^3 with HFPS transformers installed in the front four fields of all the casings. The reduction in emission was 45%, which is extremely significant.

Particulate emissions are, governed by the air quality legislation, which requires the operation of a power station to comply with the stipulated emissions limits at all times during operation. Failure to comply with stipulated emissions limits as specified by the legislation carries a stiff fine or even jail time. In order to comply with the set out emissions limits, power stations have resorted to taking load losses; reduction in boiler production capacity in order to reduce particulate emissions. The practice of taking load losses due to ineffective ESP performance is a costly exercise, as the power station loses revenue for every MW that is not generated. This chapter will discuss the exact cost implications of operating with ineffective ESPs that result in units having to take load losses in order to meet emissions limits.

5.5 Cost of emissions

A power station that is, rated for 618 MW, full load production is required to maintain emissions below 100 mg/Nm^3 , daily. Thus if a unit is unable to maintain emissions below 100 mg/Nm^3 , a 118 MW load loss is typically taken during of peak periods. Off peak, periods are from 10:00 am to 17:00 pm and 22:00 pm to 05:00. This means a unit can run on average 10 hours a day with a 118 MW load loss, which is equivalent to 1.2 GWhrs of power that is, not generated during that period. That is

19% of the full load generating capacity that is lost, due to high particulate emissions.

Eskom has been struggling to meet the country's electricity demand since early 2007 until this day. A reduction in production is not ideal as it further puts pressure on the organisation and increases the likelihood of load shedding being implemented in the country. The revenue loss because of these load losses is also significant, as it limits Eskom's cash flow. Figure 24, illustrates bar graph representation of the generated load to the load loss taken as a result of high emissions.

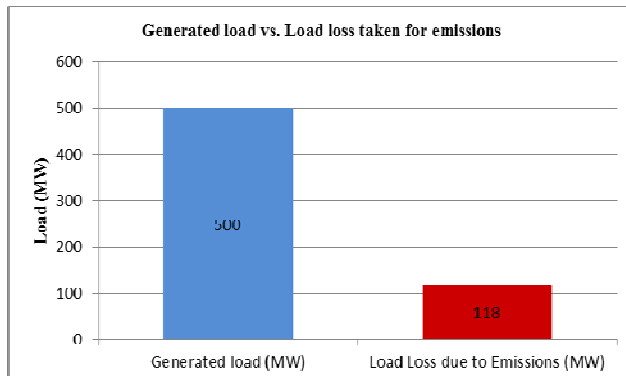


Figure 24: Graphical representation of the load loss and generated load in MW

A power station that charges R 88.66 per MWhr, running a 118 MW for 10 hours on average a day, incurs a loss of R 104 618.8 per day, which translates to R 732 331.60 per week and R 2 929 326.40 per month. This is a significant loss of revenue; 19% of the possible R 15 341 726.40 that a unit operating without high stack emissions load losses can generate. Figure 25; show the pie chart representation of this revenue loss, surfed as a result of emissions.

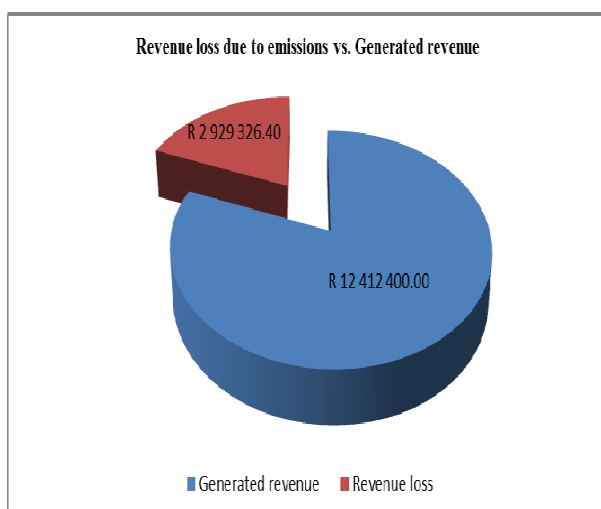


Figure 25: Graphical representation of the revenue loss and generated revenue

During the summer periods, emissions level become relatively high due to the high ambient temperatures, that affect the process conditions; i.e. condenser back end pressures requiring the boiler to fire more in order to produce the required MWs. This, results in, the ESP seeing a significant amount of flue gas volume flow result in ESP not being able to maintain low emissions. South African summer periods are from mid-October to mid-February, that a potential 5 months in which regular load losses can, be, taken to maintain emissions below legislations limits. Regular load losses for a period of 5 months would result a revenue loss of approximately R 16 000 000.

The return on investment for the project is realised within a two year period. The cost of the HFPS retrofit project was R 25 000 000, per unit and based on the revenue loss due to the frequency and duration of load losses that power station takes in order to reduce particulate emissions. The, station would be able to obtain a return in investment on money spend to retrofit existing ESPs with HFPS, over a period of 2 years. As the HFPS, technology is able to; consistently maintain emissions below the set emissions limits and thus, eliminating the need to maintain emissions with reduction of load.

6. CONCLUSION

The retrofit installation of the HFPS transformers on to an existing ESP plant resulted in increased power input into the ESP fields. The observed power input increase into the fields, is as a result of the HFSP ability to maintain high voltage and current inputs into the fields and its rapid response to sparking within the ESP.

Deutch's, ESP collection efficiency suggest that the collection efficiency is directly influenced by the power available to the ESP. The HFPS's ability to provide more power as compared to TR sets, resulted in a 45% reduction in particulate emissions.

The improved collection efficiency of the ESP, will result in a financial benefit for the power station, as the likelihood of taking prolonged load losses due to high emissions has been addressed by the installation of the HFPS transformers. Testing of the new power supply will continue into the summer period, where high ambient temperature adversely affect the combustion and result in high emission. The project will be deemed successful once it has been found that the HFPS can maintain low emissions below that stipulated in the legislation consistently, across all seasons.

However, it was noted that, mechanical defects present in an ESP significantly hamper the performance of the field, regardless of the power supply technology implemented. Thus, it is of utmost importance to make sure that an ESP is kept in a mechanically sound condition.

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Appendix F: Emission performance data used to plot Figure 5-47

Date	Emissions	Load
05/08/2014	32	549
04/08/2014	32	521
03/08/2014	29	488
02/08/2014	26	515
01/08/2014	27	616
31/07/2014	29	619
30/07/2014	34	618
29/07/2014	26	570
29/07/2014	26	570
28/07/2014	24	557
27/07/2014	21	476
26/07/2014	26	544
25/07/2014	23	563
24/07/2014	25	554
23/07/2014	26	549
22/07/2014	24	525
21/07/2014	24	545
20/07/2014	21	489
19/07/2014	23	538
18/07/2014	28	564
17/07/2014	25	544
16/07/2014	22	555
15/07/2014	27	568
14/07/2014	26	576
13/07/2014	21	534
12/07/2014	25	544
11/07/2014	29	587
10/07/2014	24	577
09/07/2014	21	571
08/07/2014	23	578
07/07/2014	27	552
06/07/2014	33	621
05/07/2014	39	620
04/07/2014	86	577
03/07/2014	13	441
02/07/2014	18	301
01/07/2014	21	425
30/06/2014	40	572
29/06/2014	52	538
28/06/2014	50	573
27/06/2014	29	592
26/06/2014	33	570
25/06/2014	85	556
24/06/2014	103	559
23/06/2014	27	573
22/06/2014	28	560
21/06/2014	28	570
20/06/2014	39	581
19/06/2014	75	505
18/06/2014	38	482
17/06/2014	34	560
16/06/2014	34	525
15/06/2014	31	512
14/06/2014	33	564
13/06/2014	32	571
12/06/2014	44	608
11/06/2014	48	604
10/06/2014	32	580
09/06/2014	30	569
08/06/2014	38	551
07/06/2014	131	564
06/06/2014	118	573
05/06/2014	105	547
04/06/2014	47	550
03/06/2014	43	553
02/06/2014	124	535
01/06/2014	65	522
31/05/2014	59	476
30/05/2014	39	548
29/05/2014	39	575
28/05/2014	68	526
27/05/2014	54	538
26/05/2014	42	543
25/05/2014	92	490
24/05/2014	84	489
23/05/2014	29	559
22/05/2014	33	573
21/05/2014	42	550
20/05/2014	43	581
19/05/2014	94	548
18/05/2014	83	554
17/05/2014	54	566