Evaluating the impact of solar photovoltaic generation on the power quality of mine power systems

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ABSTRACT

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The South African mining industry utilises numerous high-power electrical machines to extract minerals from the earth’s crust. The dependence of this industry on electricity necessitates the requirement of a reliable and high-quality energy supply around the clock to ensure efficient and safe mining operations. However, the looming crisis around the energy supply capability of the power utility, Eskom, escalating energy costs and South Africa's commitment towards the Paris Agreement on reducing greenhouse emissions are concerning towards the energy security required by the mining industry. Accordingly, after amendments in the generation limits for the private sector, renewable energy sources have become increasingly common within the South African mining industry to combat the previously mentioned problems. However, the integration of these renewable energy sources influences the power quality of the mine power system.

The deterioration of power quality in the mine power system can have a profound impact on various aspects of mining operations, such as production interruptions due to equipment maintenance or failure, safety implications, and grid compliance issues. Of the identified renewable sources that are integrated into mine power systems in South Africa, solar PV systems are the most common. Due to the electronic nature of these systems, they have a high probability of impacting the power quality of the entire integrated power system. Therefore, there is a need to evaluate the power quality impacts of solar photovoltaic systems integrated into mine power systems, since the power quality impacts of this integrated system are largely underdetermined in the literature. The power quality impacts of solar PV-integrated mine power systems were evaluated through the use of power system modelling software. This enabled the prediction of power quality changes from the integration of this system.

A methodology was determined based on existing literature to meet the study objectives. In this dissertation, a solar photovoltaic integrated deep-level mine power system was simulated to determine potential power quality impacts. The power quality impacts were quantified by first determining the operation of the mine power system, before the integration of the solar photovoltaic system for voltages and power factors at the main substation bus, then simulating the integrated system to determine any power quality effects that are caused by the integration solar photovoltaic system.

A deep-level mine case study was observed that adopted a 7.3 MW solar photovoltaic system without battery storage. An interactive power system simulation package was used and calibrated with empirical data obtained from the real-world mining power system. It was observed that the addition of the solar PV power plant affected the system voltage and power factor at the main substation bus, which is interfaced with the power utility. The simulation accurately predicted the system voltage and power factor of the integrated system, with results showing an increase in system voltage and power factors decreasing to concerning levels. This suggests that the addition of a solar photovoltaic powerplant with an existing deep-level mine power greatly affects the power quality of the system, especially during the time of solar power production.

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NOMENCLATURE

Symbol	Unit	Description
C	F	Capacitance
f	Hz	Frequency
I	A	Current
L	H	Inductance
MAE	%	Mean Absolute Error
P	W	Real Power
p.u.	Unitless	Per Unit
PF	Unitless	Power Factor
Q	VAR	Reactive Power
R	Ohm	Resistance
S	VA	Apparent Power
V	V	Volt

ABBREVIATIONS

AC	Alternating Current
AI	Artificial Intelligence
ANN	Artificial Neural Networks
CGIS	Copper Indium Gallium Selenide
CSP	Concentrating Solar Power
DB	Drybulb
DC	Direct Current
DFACTS	Distributed Flexible AC Transmission System
DMRE	Department Of Mineral Resources And Energy
DNI	Direct Normal Irradiation
DSTATCOM	Distributed Static Compensator
ESG	Environmental Social Governance
ETAP	Electrical Transient Analyser Program
GHG	Greenhouse Gas
IEC	International Electrotechnical Commission
IEEE	Institute Of Electrical And Electronical Engineers
IPP	Independent Power Producers
IRP	Integrated Resource Plan
ISI	Institute Of Solar Energy
km	Kilometer
KPI	Key Performance Indicator
LCL	Inductor-Capacitor-Inductor
LV	Low Voltage
MHSA	Mine Health And Safety Act
MPPT	Maximum Power Point Tracker
MV	Medium Voltage

OLTC	On-Load Tap Changing
p.u.	Per Unit
PC	Predictive Control
PCC	Point Of Common Coupling
PFC	Power Factor Correction
PGM	Platinum Group Metals
PI	Proportional Integral
POC	Point Of Connection
PPA	Power Purchase Agreement
PQ	Real-Power Reactive Power
PV	Photovoltaic
PWM	Pulse Width Modulation
SAWEO	South African Wind Energy Project
SVM	Space Vector Modulation
THD	Total Harmonic Distortion
VSD	Variable Speed Drive
WASA	Wind Atlas For South Africa
WB	Wetbulb

Chapter 1: Introduction

Figure 1: Underground mine shaft[1]

"Light tomorrow with today."

— Elizabeth Barret Browning

[1] Z Lombard, Personal photograph

1. INTRODUCTION

1.1. Preamble

In this section, the study's relevance is conveyed through the background given on the mining industry in South Africa and its dependence on the power utility, Eskom. Subsequently, drivers for the incorporation of renewable energy are discussed. The review then starts by discussing advancements in solar energy technologies and their applicability to a mine power system. Power quality, grid stability and reliability are then discussed through solar photovoltaic (PV) integration challenges which lead to the need for the study. Similar studies and applications of solar power plants are then reviewed, where shortcomings and contributions are analysed. Lastly, the aim and objectives are discussed.

1.2. Mining in South Africa

South Africa's abundance of mineral reserves is pivotal for the existence of some 2000 operational mines and plays a crucial role in the country's economic growth [1]. According to the Department of Mineral Resources and Energy (DMRE), South Africa has the world's largest deposits of platinum group metals (PGM) (87.7%), manganese (80%), chromium (72.4%) and gold (29.7%) [2]. These minerals are found in underground geological formations such as the Bushveld complex (PGM), the Witwatersrand basin (gold), the Transvaal supergroup (iron ore), the Karoo basin (coal), etc. [2].

Ore extraction from these formations employs either surface (open-cast) or underground mining methods [3]. Since the mechanisation of mines in the early 19th century, both methods have necessitated electricity to power their machinery [4]. Subsequently, an escalating array of electrical equipment has been integrated to enhance the efficiency of ore extraction [5].

The mining sector, therefore, relies significantly on the power utility, Eskom, as its primary electricity source. This dependency is highlighted in Eskom's 2023 integrated report [6]. According to the report, the mining sector consumed 15% (28.26 TWh) of the total electrical energy generated by Eskom in 2023, as illustrated in Figure 2. With this, energy expenditure can be up to 30% of the total cost of production in the mining industry, according to Daniel Limpitlaw in his publication on renewable energy in the mineral sector [7]. This emphasises the sector's substantial reliance on power utility.

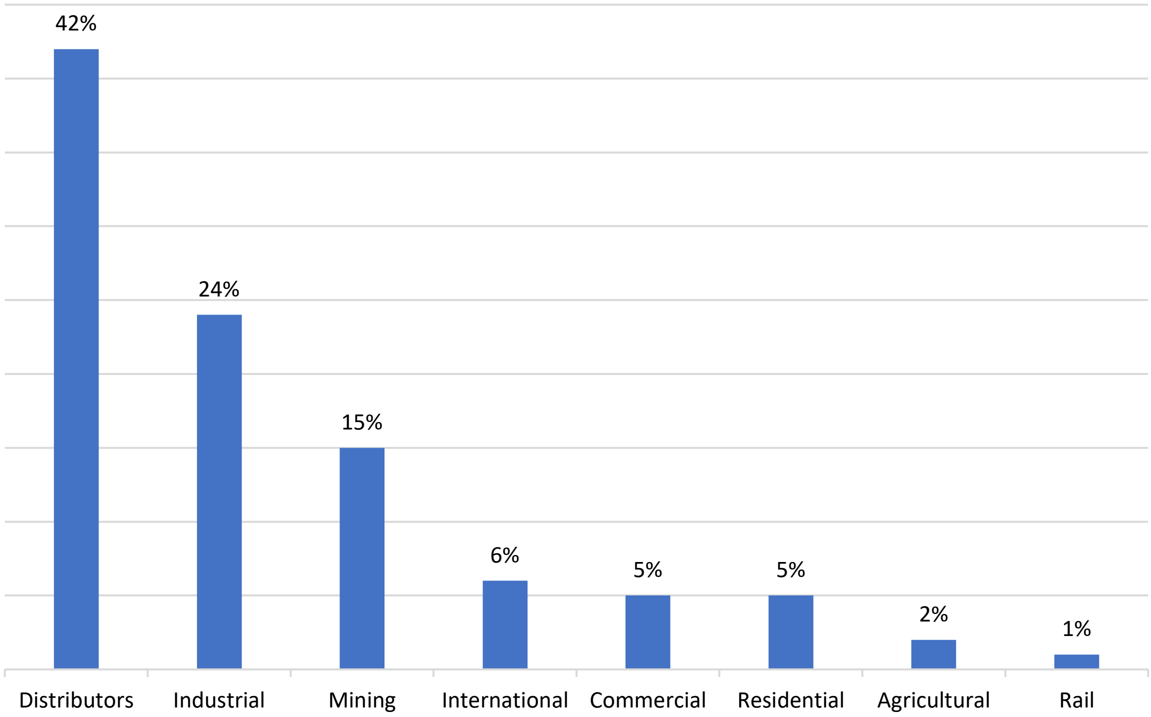


Figure 2: Power consumption of different sectors in South Africa [6]

In addition to the mining sector's reliance on electricity, the sector's pronounced energy intensity is illustrated by its utilisation of 3.22 GW of energy daily. Notably, a single mine can exhibit a substantial demand, reaching as high as 60 MW [6].

The main contributor to the high energy intensity is underground mining operations, where they utilise 30% to 40% more energy compared to open-cast mines [8]. This is evident as underground mines employ extensive ventilation systems, dewatering systems, and compressed air systems for their operations. Additionally, there is a need to transport miners and mined ore from the depths of the mine [9]. Gold and platinum mines generally stand out as the most energy-intensive operations [9].

1.3. Electricity in South Africa

The power utility, Eskom, accounts for 92% of the installed generation capacity in South Africa and predominantly generates electricity from the burning of fossil fuels, such as coal [10]. Eskom is responsible for generating, transmitting, and distributing electrical energy that is to be sold to the country's customers [11].

The dependency of the mining industry on Eskom is a concern, since contributing factors such as an increase in population, lack of maintenance, debt and mismanagement of the power utility led to rolling blackouts that started in 2009 [12]. Alongside the blackouts, yearly price hikes have seen a tariff increase of 653% between 2008 and 2022, with an increase of 9.61% for 2023 [6].

The mismatch of demand and supply forced the power utility to implement national load-shedding and load curtailment to manually reduce the demand, mitigate a grid frequency loss, and avoid a national grid blackout. Load shedding is electricity interruptions and load curtailment is the requirement of large electricity-consuming companies to reduce their demand by a percentage between 5% and 20% of their nominal load. The interested reader can refer to part 9 of the second edition of NRS 048-9:2019 for further details [13].

In 2023, load shedding and load curtailment were implemented over 280 days, compared to the 2022 total of 65 days, emphasising the lack of generating capacity [6]. Figure 3 illustrates the escalation over the past five years.

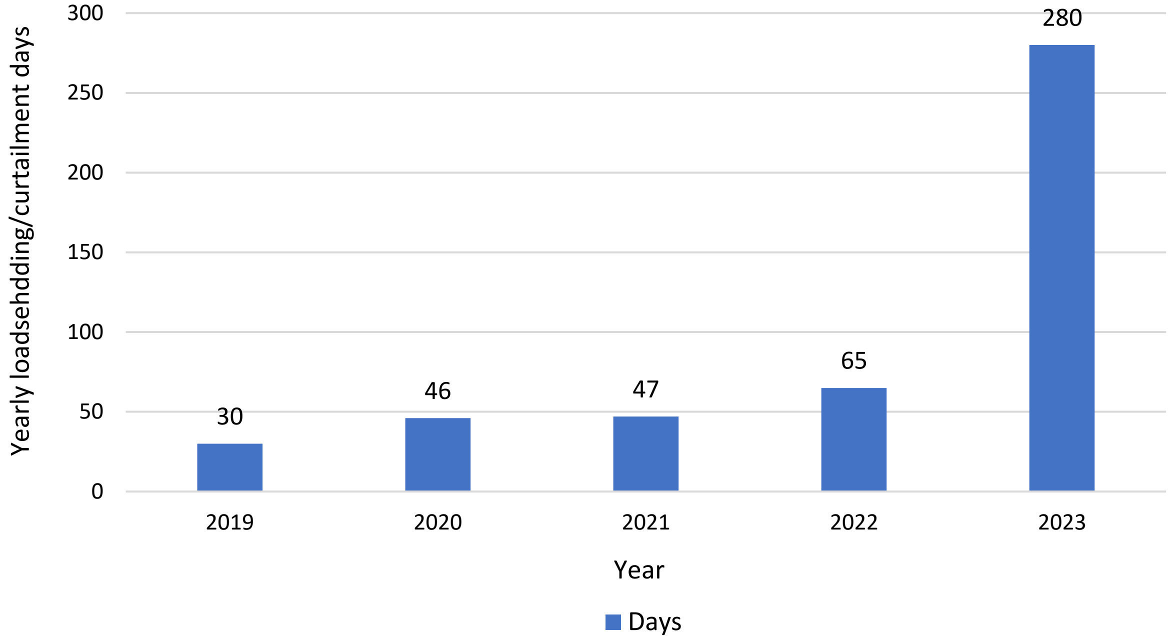


Figure 3: Load shedding and load curtailment over the past five years [6]

Accordingly, the dependence of the mining industry on Eskom is affecting this industry twofold. Firstly, the requirement of a stable electricity source is paramount for sustaining mining operations [5]. Secondly, the profitability of the industry is negatively impacted by the tariff increases, leading to the narrowing of operation margins. These contributing factors raise electricity security concerns and decrease profit margins [12].

Moreover, environmental considerations, notably South Africa's dedication to the Paris Agreement and its ambitious net-zero emission target by 2050, is another concerning factor for Eskom. According to the agreement, the government is compelling industries such as Eskom, which accounts for 47% of the national greenhouse gas (GHG) emissions, to implement decarbonisation measures [14]. The Carbon Tax Act [15], will play a pivotal role in achieving these targets, which are levied on the emission of GHGs.

The implementation of the carbon tax act poses a substantial risk to Eskom coal-based power plants, potentially leading to the closure of these plants that fail to meet the mandated emissions standards, as per the Paris Agreement on climate change [16]. This implies that approximately 16 GW, constituting 33% of the total generating capacity, is currently under the imminent threat of shutdown [6].

Building on the issues alluded to, renewable energy stands to alleviate both environmental and energy supply shortage concerns. Renewable energy sources encompass a diverse array of naturally occurring sources that harness the Earth's inexhaustible and replenishable energy cycles. Unlike finite fossil fuels, renewable energy draws power from everlasting processes such as sunlight, wind, water, and geothermal heat. Therefore, incorporating renewable energy is pivotal for an economically sustainable, carbon-friendly, and socially acceptable country [16].

In 2010, as a strategic response to Eskom's generation and current environmental challenges, the DMRE incorporated independent power producers (IPPs) into South Africa's comprehensive long-term strategy for electricity generation known as the Integrated Resource Plan (IRP) [17].

The key objective behind the inclusion of IPPs is to enhance the national generation capacity and carbon-neutral objectives by incorporating renewable sources from investments of the private sector [17], [18].

This initiative aims to address the supply-demand mismatch and carbon reduction goals, promoting a more balanced and resilient electricity infrastructure [16]. To achieve this, the DMRE had to bring forth changes to regulations governing the amount of power an IPP can produce. In 2021, the DMRE amended Section 3 of Schedule 2 of the Electricity Regulation Act, increasing the generation capacity of an IPP from 1 MW to 100 MW [19].

The DMRE continued to advocate for the removal of the generation limit, owing to the generation projects within the mining industry as strategic integrated projects to help minimise the demand required from Eskom. With this, in January of 2024, the DMRE amended the Electricity Regulation Act again, by removing the generation limit of an IPP [20].

The South African mining industry is progressively acknowledging these factors driving the transition toward alternative and renewable energy sources [21]. Consequently, the mining sector must align itself with the climate change objectives outlined by the Minerals Council, encompassing economic, environmental, and social considerations, distinctive to the South African mining sector [14].

1.4. Renewable energy

Following the renewable energy drivers mentioned in the previous section, the mining industry aims to improve its energy security, reduce energy cost volatility, and improve its environmental social governance (ESG) status [22]. This is done by exploring solar photovoltaics, wind turbines, biomass, and hydropower systems, each offering unique attributes that cater to diverse geographical, climatic, and infrastructural contexts [22].

1.4.1. Available renewable energy resources

In the past decade, solar photovoltaics and onshore wind energy costs have been reduced by 85% and 56% respectively, which is mainly due to the advancements of these technologies over the past two decades [23]. Accordingly, solar and wind energy technologies have recently become the most economical source of renewable energy concerning cost per kWh produced in many parts of the world [22].

The characteristics of the mines concerning their geographical location predominantly dictate the types of renewable energy resources used. Countries such as the USA, Chile, Australia, and Canada, that have a high yield in mineral production, show that solar energy has the highest potential to be incorporated [22]. Delving further into the South African context, the overview by Bodunrin *et al*. [24] shows that wind and solar have a firm potential for producing a significant amount of energy.

Wind energy has, for many years, been an energy source in South Africa, and the South African Wind Energy Project (SAWEP) was formed to quantify the energy potential [24]. Through SAWEP, a detailed Wind Atlas for South Africa (WASA) was developed [25]. WASA, depicted in Figure 4, showed that South Africa has the potential to produce 6 GW of energy through wind power alone, which is competitive towards solar power [24].

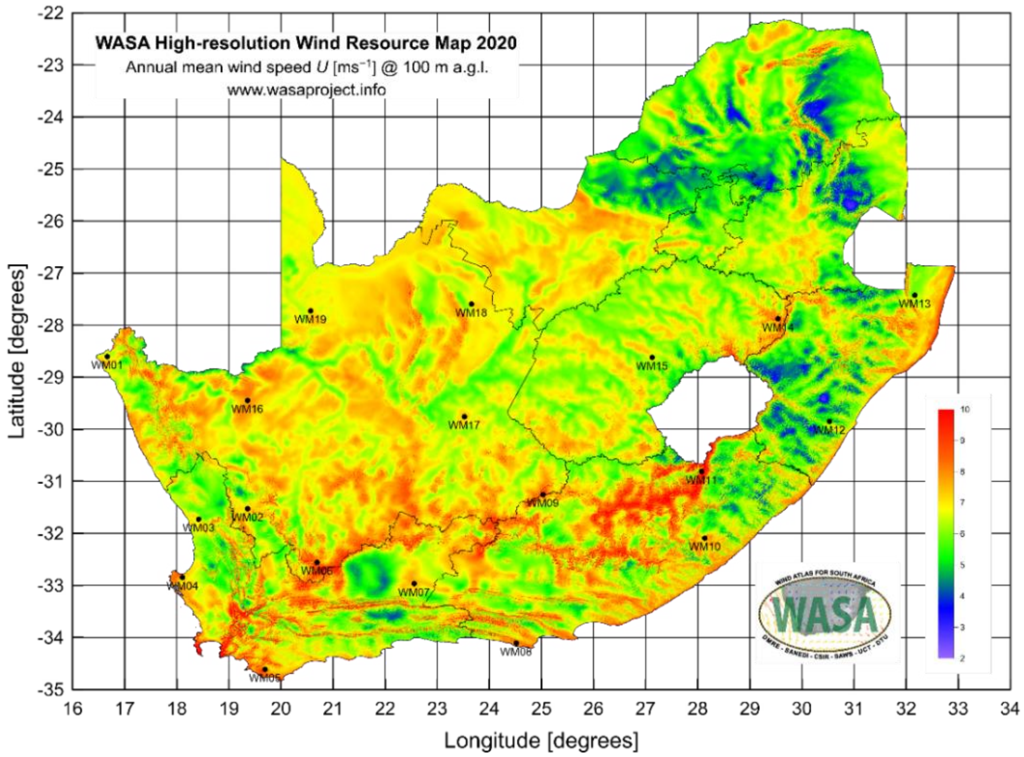


Figure 4: WASA high-resolution map[2] [24]

South Africa is also known for its abundant solar energy resources, with over 2 500 hours of sunshine per year. According to the Direct Normal Irradiation (DNI) map developed by the World Bank Group, depicted in Figure 5, the PV power potential in South Africa is substantial [24].

Figure 5 shows the solar radiation received per unit area of different regions in South Africa. This information is important for the developers of solar energy to determine the amount of energy that a particular region can generate. Accordingly, the Northern Cape has the highest potential, peaking at 3 287 kWh/m^2, while Kwazulu-Natal has a modest potential peaking at around 1 400 kWh/m^2.

[2] WASA; Wind Atlas for South Africa (WASA) SANEDI (wasaproject.info)

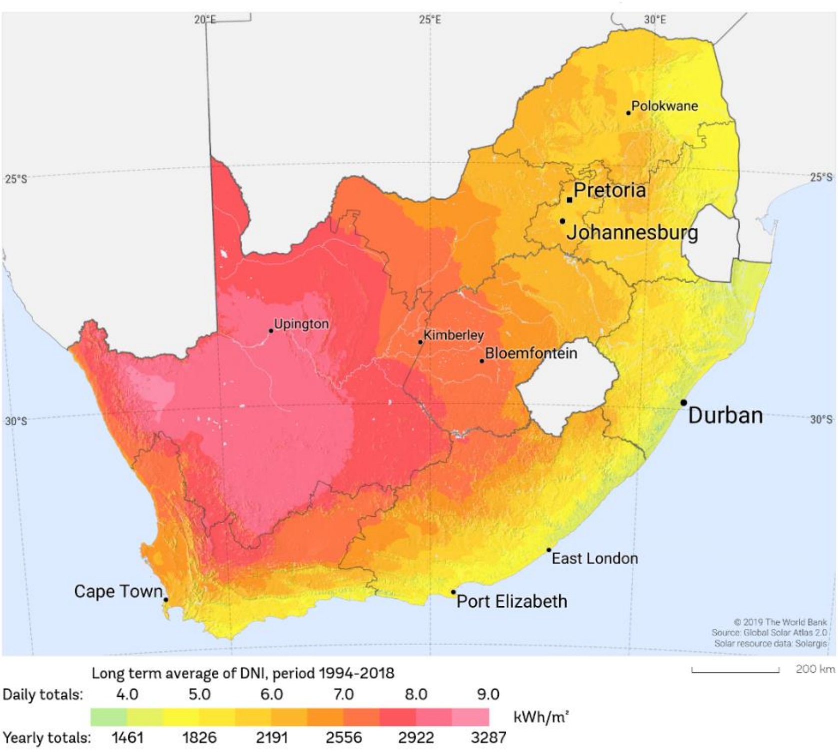


Figure 5: South Africa's Direct Normal Irradiation map[3] [24]

Solar energy can be utilised in three methods, namely photovoltaics, concentrating solar power (CSP), and solar heating [24]. However, many factors such as costs, construction lead-time, efficiency, and land surface area influence the application of each technology. The review done by Chu [26], states that each solar technology has its advantages and drawbacks and the most suitable technology for a particular region should be considered. According to the DMRE, most solar energy installations utilise photovoltaics[4] in the South African context [27].

From the assessment done by Limpitlaw [28], it is evident that solar PV and wind energy are most favourable to be incorporated in the South African mining industry. Moreover, there is limited literature about the utilisation of CSP, biomass, and hydropower systems within the South African mining context.

[3] Solar resource map by Solargis; Global Solar Atlas
[4] IPP projects from the DMRE; IPP Projects - Project Database (ipp-projects.co.za)

1.4.2. Adoption of renewable energy resources within the South African mining industry

Several prominent mining companies, including Harmony, Sibanye-Stillwater, Anglo American, Goldfields, and Impala Platinum, among others, are adopting a combination of solar and wind energy resources to supply their operations through the procurement of an IPP [29]. The IPP is responsible for supplying the mine with renewable energy through a power purchase agreement (PPA). The adoption of PPAs simplifies the process for mining companies, as they are not burdened with project financing; rather, they simply purchase power from the IPP [30].

Table 1 describes the renewable energy projects adopted by the top mining houses in South Africa.

Table 1: Mining houses adoption of renewable energy

Company		Wind (MW)	Solar PV(MW)	Source
Harmony	Installed	-	30	[31]
	Planned	1	193	[31]
Sibanye Stillwater	Installed	-	-	
	Planned	192	75	[32]
Anglo American	Installed	-	100	[33]
	Planned	420	80	[33]
Goldfields	Installed	-	40	[34]
	Planned	-	-	
Impala	Installed	-	-	
	Planned	-	100	[35]
Kumba Iron Ore	Installed	-	-	
	Planned	-	78	[36]

As indicated in Table 1, the IPP plan has been effectively embraced by the mining industry, with a projected generation capacity exceeding 2 200 MW anticipated before the year 2025 [37].

The widespread adoption of renewable energy within each respective mining operation not only aligns them with environmental objectives, but also alleviates strain on the power utility and contributes to a notable improvement in energy security [34].

As depicted in Table 1, the adoption of solar PV power plants is more prevalent when compared to wind power. This is mainly due to the location of mines concerning the available renewable sources. In this context, solar PV is more feasible in terms of land area, project timeline, predictability, and cost [38].

1.5. Advances in solar PV technology

All large-scale solar PV power plants include four essential components, namely the PV array, inverter, passive filter, and a step-up transformer [39]. The single-line diagram depicted in Figure 6 is a typical utility-scale solar PV power plant without battery energy storage.

This system contains arrays of solar PV panels, transforming solar energy into electricity, which connects through common DC (direct current) buses to a junction box. From the junction box, DC power is distributed to the inverters. The inverter can be multiple, to form a string of smaller inverters or centralised where one or two larger inverters are used. The inverter converts the DC output of the solar array to AC (alternating current). The AC output is filtered, commonly through an LCL (Inductor-Capacitor-Inductor) filter to suppress switching harmonics evident in both voltage and current. The filtered AC is then connected to a step-up transformer, which in turn supplies the end user [40].

Each component is essential to produce high-quality electricity for the end user. The ongoing development and technological advances have significantly contributed to this, elevating the efficiency of these systems [41].

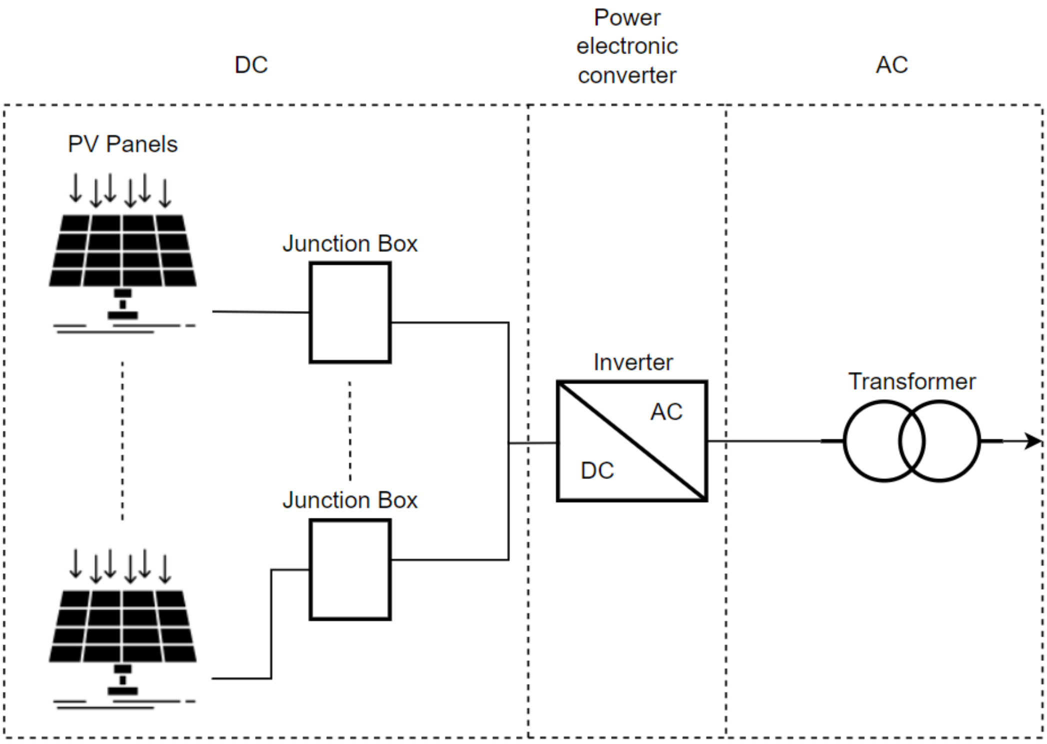


Figure 6: Typical solar PV components[5] [40]

1.5.1. PV-modules

The efficiency of modules is one of the most important aspects of a solar PV power system, dictating the required solar field area to achieve a predetermined power rating. PV technologies can be divided into crystalline and thin film categories [39]. From the silicon cell efficiency achieved in 1954 at 6%, recent years have seen advancements to 21% for polycrystalline cells and 25% for monocrystalline cells. Furthermore, thin film cells achieved an efficiency of 22% [39]. According to the Institute of Solar Energy (ISE), polycrystalline modules are the most prevalent in the industry, followed by monocrystalline and then thin film technologies [42].

The review by Thopil *et al.* [42] compared the techno-economic performance of monocrystalline, polycrystalline, and thin film copper indium gallium selenide (CGIS) cells in South Africa. A regression model for each PV technology was developed that incorporated

[5] Illustration by author.

solar irradiance and temperature. From the analysis, the thin film CGIS modules performed the best, producing on average 11.6% more energy than monocrystalline modules, where polycrystalline produced 2.7% more energy than monocrystalline.

The study by Okere *et al*. [43], presented a techno-economic analysis of the four emerging PV technologies namely bifacial PV, half-cell PV, heterojunction PV (thin film), and the industry's preferred monocrystalline PV cells. His study concluded that bifacial modules had the best performance in terms of kwh produced and degraded the least over 25 years, however, they were the most expensive to implement. Heterojunction modules were the most financially friendly to implement, however, required a larger surface area to produce the same amount of kwh as bifacial modules.

From these studies, it is evident that the choice of PV module is dictated by the solar irradiance level, land surface area availability, capital, and temperature. Therefore, the feasibility study of each solar PV power plant should include a detailed analysis of the current PV technologies to determine the best technology for the specific plant.

1.5.2. Inverters, maximum power point tracking, filters and transformers

In recent years, there has been a surge in interest surrounding the choice of inverter topology. Both string and central inverter topologies are currently used in large-scale power plants [39]. Each topology significantly impacts both the total energy output and the overall cost of the power plant.

The comparative study conducted by Atasoy *et al*. [44], investigated which inverter topology is optimum in a 10 MW solar PV power plant in Turkey. Their findings revealed that while both the string and central inverter topologies were viable, the string inverter topology demonstrated slightly lower costs and higher annual energy production, albeit with narrow margins. Additionally, the string topology exhibited reduced energy losses compared to the central topology.

Each inverter is interfaced with a maximum power point tracker (MPPT) on the DC side. The MPPT tracker is a DC-DC converter used to control the DC voltage with fluctuating solar irradiance. Different control methods have been experimented with in recent years, including the use of artificial intelligence (AI). The study conducted by Choutapalli *et al*. [45] reviewed different advanced control methods and illustrated that methods based on artificial neural networks (ANN) and AI have higher tracking efficiencies.

Furthermore, Meraj *et al*. [46] have recently investigated the latest advancements in inverter modulation control techniques for the power electronic switches in inverters. Their review delves into various modulation techniques, such as space vector modulation (SVM), pulse width modulation (PWM), and predictive control (PC), crucial for integrating renewable energy sources. He further states that harmonics in the voltage and current waveforms have grown into a prominent issue. It also becomes apparent that the chosen modulation technique directly impacts the power quality of the resulting AC waveform. This power quality issue can lead to inverter switch failure, transformer overheating and overall system failure.

1.6. Need for solar PV investigation: Grid integration challenges

As alluded to in the preceding sections, renewable energy sources are emerging as an important and key component, not only in the mining industry, but also in the utility sector, reshaping the trajectory of the future national and global energy landscape. The integration of renewable energy, such as solar PV, is therefore a long-term necessity.

The inherent variability, unpredictability, and uncontrollable attributes of renewable energy sources pose significant challenges to meeting the mining industry's demanding need for high-quality, uninterrupted energy, 24 hours a day [22].

After reviewing study [47], [48], [49], [50], [51], [52], [53], [54], it becomes apparent that the integration of solar PV plants into an existing power system can have a noticeable impact on the quality of supply. This impact arises because solar PV plants do not contribute to grid strength, primarily due to their lack of inertia in the system [55].

According to the IEEE (Institute of Electrical and Electronics Engineers), "*Power quality is the concept of powering and grounding sensitive equipment in a manner that is suited to the operation of that equipment and compatible with the premise wiring system and other connected equipment*" [56]. The IEC (International Electrotechnical Commission) states power quality is “*characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters*” [57].

In layman's terms, power quality refers to the quality of the voltage and current waveform delivered and consumed by loads of the power system, respectively. Power quality problems encompass a vast number of different phenomena, each with different solutions [58]. Power quality problems that are evident on the South African power grid are described in Table 2 [59]:

Table 2: Typical power quality problems [59]

Power quality problem	Description	Cause	Impact
Voltage sags	Short-term reduction in voltage (80-85% of nominal)	Motor starting, capacitor switching, breaker operation	Equipment failure, insufficient motor starting torque, etc.
Voltage swells	Short-term increase in voltage	Switching of large equipment, lightning	Reduced equipment life, equipment failure, etc.
Voltage flicker	Rapidly occurring voltage sags	Rapidly varying equipment loading	Disrupt control systems. Visual flickering of lights
Voltage regulation	The voltage difference between the sending and receiving end	Poor power factor, startup of large equipment	Higher voltage at light loads and lower voltage with larger loads
Power interruptions	Short-term zero voltage events, within 30 seconds	Network faults	Unable to use equipment
Power surges	Voltage surges above 110% of nominal	Large machines being turned off	Damage to cables and connected equipment
Power factor	A measure of how efficiently electrical power is consumed	The presence of large inductive or capacitive loads	Increased operational costs
Frequency variation	Involves a frequency variation from the nominal 50 Hz	Unstable frequency power sources, operation of large equipment	Power interruptions to regain nominal frequency, damaged equipment
Harmonics	Distortion of current and voltage waveforms	Power electronics, nonlinear loads	Excessive heating of transformers and motors, high neutral currents, etc.

Poor power quality will result in economic impacts, such as loss of production, equipment damage, penalties due to non-compliance, etc [60]. Therefore, operating a power system with good power quality is critical. The following sections provide an overview of common power quality issues associated with the integration of solar PV systems with an existing grid.

1.6.1. Voltage fluctuation

Voltage fluctuation is a typical concern of any power system; however, the integration of solar PV systems can accentuate these concerns [61]. Voltage-regulating equipment serves the purpose of keeping the voltage at a certain point at a prescribed voltage. This is essential to ensure a consistent voltage with changing loads.

The intermittency of solar PV systems has a direct effect on voltage regulation equipment, such as on-load tap changing (OLTC) transformers [62]. This is apparent since the fluctuating power output of the solar plant fluctuates the voltage at the point of connection, which may lead to excessive tap-changing operations of the OLTC transformer [57]. This in turn can significantly reduce the life expectancy of the tap-changing devices [62].

The study from M. Khalid [61], lists various voltage-related concerns such as those mentioned above, however, expands on the fact that the integration of solar increases the overall voltage of the system. He states that during peak solar generation periods with low demand, voltage increases can lead to system reliability and resilience problems [63].

1.6.2. Frequency variation

Traditional fossil fuel-based power plants provide inertia to the grid, due to their rotating machines, which help stabilise frequency fluctuations by resisting sudden changes in demand. In solar PV power plants, this is a significant challenge, since these systems cannot provide inertia support. This is apparent since solar PV systems do not have rotating machinery and thus cannot provide the same level of inertia support. As a result, rapid changes in solar irradiance can lead to frequency variations in the grid [64].

Munkhchuluun *et al*. [64] describe the need for a solar PV system to have adequate frequency control. In his review, he stated that the inability to maintain the fundamental frequency can lead to system-wide blackouts under certain circumstances.

1.6.3. Power factor

Power factor describes the overall efficiency of a power system [65]. It is defined as the ratio of real power (active power), P, to apparent power, S, in the system. Real power is the actual power consumed by the load and is measured in watts (W), while apparent power is the product of voltage and current in the system and yields the total power delivered/consumed and is measured in volt-amperes (VA).

Mathematically, power factor (PF) is described by Equation (1) [65]:

$$PF = \frac{Real\ power\ (P)}{Apparent\ power\ (S)} = cos^{-1}\ (\theta) \tag{1}$$

Where θ is the phase difference between the current and voltage waveforms, the power factor, PF, is a dimensionless unit from 0 to 1. Ideally, the power factor should equal unity (1), however reactive energy (VAR), Q, is required for inductive and capacitive loads and deteriorates the power factor. This deterioration is either leading (capacitive) or lagging (inductive).

When solar PV systems are connected to the grid, they predominantly contribute active power through a solar inverter. This effectively decreases the active power required from the utility [57]. However, in this configuration, the grid is used to supply the reactive power requirement of the power system leading to a decrease in power factor at the point of connection [66], [67]. During solar power generation, reverse power flow towards the power utility is evident, which can breach energy wheeling regulations set by the Electricity Regulation Act of South Africa [63]. This can lead to noncompliance with the regulations set by NERSA in terms of the allowable power factor deviation, which can further lead to penalties.

1.6.4. Harmonic distortion

Harmonics are unwanted electrical signals at different frequencies that occur in a power system in addition to the fundamental frequency of 50 Hz. These frequencies are integer multiples of the fundamental frequency and originate from power electronic devices that modify the fundamental sinusoidal waveform [68]. Harmonics cause additional heating in conductors, influence power factor, deteriorate dielectric insulation, and shorten the life of capacitor banks [69].

The power electronic nature of inverters injects harmonics into the grid, which can potentially produce voltage and current distortion problems [70]. To limit or reduce these unwanted signals, passive filters are employed.

1.7. Problem statement

Solar PV energy solutions have been applied to mine power systems to address the shortage of supply from Eskom, improve energy security, and reduce carbon emissions. However, the intermittent nature of solar PV power generation, coupled with its inability to contribute to grid strength, poses challenges in maintaining a consistent and high-quality power supply, which is crucial for uninterrupted mining operations.

Leading to the problem statement:

> The integration of solar PV systems into mine power networks presents challenges in maintaining power quality due to the inherent intermittency and lack of inertia associated with solar generation. These issues can disrupt the stability and reliability of power supply critical for mining operations. This study seeks to evaluate and predict the impacts of solar PV integration on power quality and develop simulation-based solutions to mitigate these challenges within a mine power system

This observation directs the focus of the study toward exploring the integration of solar PV power plants within a mine power system and assessing possible grid implications [7].

1.8. Mine power system investigation: Grid Characteristics

To understand the possible integration implications that a solar PV power plant can have on the mine power system, it is important to first give context to the electrical equipment, operation, and potential concerns of the existing mine power system.

1.8.1. Mine power system overview

The electrical power system of the mining industry is complex due to the requirement of high-power loads and non-linear loads, distributed across the mining complex [58]. The power consumption of a mine is highly variable and requires a robust and efficient power system [71].

The mining industry utilises machinery, such as mills, crushers, pumps, drills, fans, etc., that vary in power ratings and can be as large as 25 MW [58]. The different ratings of these components necessitate the requirement of different voltage levels within the power system to keep the system efficient [72]. Typical voltage levels found in mine power systems are low voltage (LV), which is less than 1 kV, and medium voltage (MV), which is between 1 kV and 44 kV [73]. The voltage levels depend on the distance to the machinery and their respective power ratings [74].

To change the voltage levels, transformers are used within substations [58]. Substations is an electrical term that encompasses transformers, switchgear, protections and controls, and monitoring and communication. It serves as an intermediate point between high-voltage transmission networks and lower-voltage distribution networks [75]. Substations are therefore critical components in an electrical system [76]. Substations are costly equipment in the power system infrastructure and require ongoing maintenance and tests to guarantee safety and compliance [77]

Traditionally, the high power-consuming mines in South Africa are grid-connected, meaning that they are connected to the power utility at the point of connection (POC), using the utility as the main source of electricity [78]. The POC is located at the main substation on the surface, which then supplies large surface loads such as the compressors, winders, refrigeration plants, and primary ventilation fans. This substation also supplies smaller substations, with feeder cables through shafts and tunnels.

This difficult environment and cyclic operation of the electrical equipment place unique demands on the mining power system and regulations need to be adhered to [58]. Accordingly, NERSA and the MHSA enforce constraints on the mine power system, such as:

- POC regulations: The POC is where the mining distribution system interfaces with the power utility [78]. At this point, NERSA provides certain regulations and conditions that need to be complied with to ensure that the mine power system interfaces correctly with that of Eskom [79].
- Safety regulations: Rigorous safety regulations enforced by the MHS, need to be understood by the electrical and mining engineer and implemented correctly to ensure the safety of mine employees [80].

These constraints ensure the correct interfacing between electrical devices to promote improved power quality of the mine power system. Eskom also uses these rules to penalise uncompliant customers.

1.8.2. Mine power system concerns

The integration and operational modes of all the electrical equipment discussed in the preceding section significantly impact the functionality of the mine power system. Without thorough planning and continuous analysis, these factors can lead to equipment damage and operational disruptions [81].

The power system concerns are typically encapsulated by power quality, which, as previously mentioned, quantifies the operation of the power system in terms of voltage regulation, voltage sag/swell, power factor, harmonics, and frequency regulation [58].

From the study performed by Wange *et al.* [82], concerns toward voltage regulation, sags, and swells were raised. This study evaluates the operation of long-distance low-voltage lines within a mine power system. Voltage drops were attributed to an increased resistance of feeder cables, caused by connecting additional electrical equipment. Consequently, the voltage at the receiving end is reduced, leading to challenges in starting electric motors and decreased torque output. Voltage swells are also highlighted as a concern, arising from the abrupt shutdown of large electrical machines, which can potentially damage cable insulation. Conversely, voltage sags are induced by the direct online starting of large electrical machines, posing the risk of undervoltage trips.

Non-linear loads, such as power electronic converters, are primarily used for vertical shaft hoisting systems and variable speed drives (VSDs). These devices are used to manipulate the voltage, current, and frequency source supplied to electric machines to control their speed and torque [83]. Hoisting machines are among the largest loads found in mine power systems and perform a pivotal role in transporting equipment and miners. Due to the intermittent use of these machines, voltage fluctuations are an evident issue due to the requirement for reactive energy [84]. Harmonics are also introduced due to the use of power electronic drives [58].

The presence of large induction or synchronous machines in the power system can significantly impact the power factor [85]. This is because these machines require reactive energy to establish the necessary magnetic fields within the machine [86]. Power factor can also be impacted by long distribution lines and requires adequate power factor correction to sustain an efficient operation of the power system [71].

Accordingly, the mine power system is susceptible to power quality issues and the addition or removal of electrical loads or sources will impact the system's power quality.

1.9. Power system modelling and simulation

The planning, design, and operation of a power system demand ongoing and thorough analyses to assess the current system performance and to gauge the efficacy of alternative strategies for system expansion [87]. Power system studies aim to achieve this. Power system studies encompass a range of analyses and assessments conducted to evaluate various aspects of electrical power systems. Power system studies include [88]:

1. Load (power) flow studies
2. Short-circuit studies
3. Stability studies
4. Motor-starting studies
5. Harmonic analysis studies
6. Switching transient studies
7. Reliability studies

These studies are paramount for ensuring the reliability, efficiency, and safety of power systems. A load flow study serves as the starting point of power system analysis, offering insights into vital parameters such as voltage, current, active and reactive power, and power factor [89]. It provides a comprehensive understanding of the system's operating conditions and serves as a foundation for subsequent analyses, including short-circuit, stability, motor starting, and harmonic studies [89].

Mine power systems are complex and have multiple buses and branches in which power can flow [73]. Figure 7 illustrates a one-line diagram of a typical mine power system.

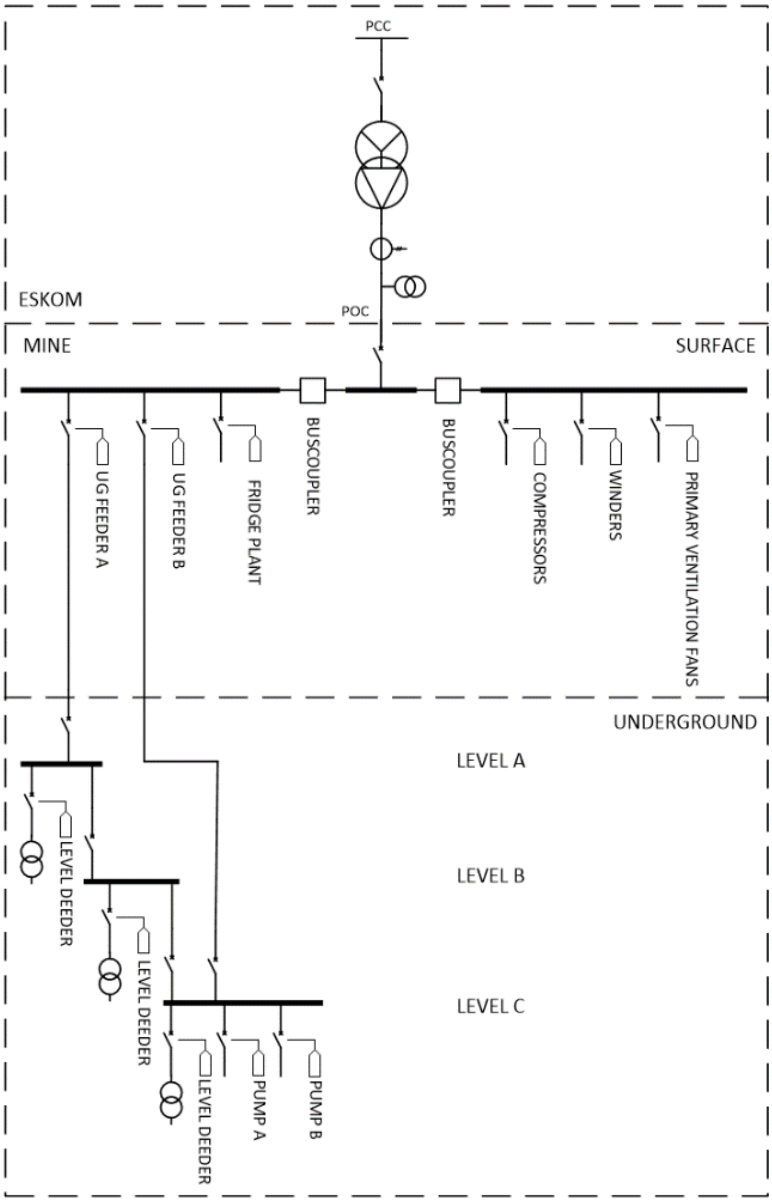


Figure 7: Typical mine power system one-line diagram. Adopted from [73] and loads of [9] and [90].

A one-line diagram, as depicted in Figure 7, is used to model the power system in computer programs. Computer programs are utilised to efficiently resemble the real-world power system using a simulation model [91]. Accordingly, computer programs, such as MATLAB, PowerWorld, ETAP and DIgSILENT can be used to simulate the power system load flow to determine the power quality of the system [92].

1.10. Need for the study, aim and objectives

A need, aim and objectives are formulated from the critical literature review of the relevant studies.

1.10.1. Need for the study

The investigation into power quality impacts on mine power systems reveals significant concerns related to poor power quality. Such issues can adversely affect the operation and maintenance of the system's equipment, impacting both the mine's economic performance and production efficiency. Therefore, the addition of renewable power, such as solar PV, can impact the power quality of the entire mine power system [81].

Therefore, the analysis of power quality is notably important to ensure that an electrical power system operates efficiently and reliably. Consequently, there is a need to thoroughly assess the power quality impacts of integrating solar PV power plant technologies into the current mine power system.

1.10.2. Aim

Various power quality indicators exist, however, from the studies reviewed, voltage and reactive power flow-related problems are prevalent in the mining industry and will be focused on. These problems will contribute to an inefficient mine power system that can potentially cause system downtime and equipment failure.

Therefore, the study aims to evaluate, predict, and provide solutions to the power quality changes of a solar PV integrated mine power system using a simulation model.

1.10.3. Objectives

The following study objectives are given to achieve the study aim:

1. Construct a simulation model to characterise the power quality of the mine power system:
    1.1 Establish power quality parameters for the mine power system.
    1.2 Compare and validate the simulation results to a real-world mine power system.
2. Assess the power quality changes of the solar PV integrated mine power system using the validated simulation model:
    1.1 Condition 1: Determine the voltage and power profile for a 24-hour time-step period.
    1.2 Condition 2: Determine the power quality changes for maximum loading conditions.
    1.3 Condition 3: Determine the power quality changes for minimum loading conditions.
2. Evaluate and provide solutions to the power quality changes.

1.11. Research Methodology

This study applied a case study research methodology to develop a comprehensive understanding of power quality problems in industry. The case study methodology can be defined as an "*empirical research method used to investigate a contemporary phenomenon, focusing on the dynamics of the case, within its real-life context*" [93]. While widely employed in social research, its utilisation has broadened to include numerous social science disciplines and engineering design research [94]. Figure 8 provides a high-level overview of the research methodology applied in this study [95].

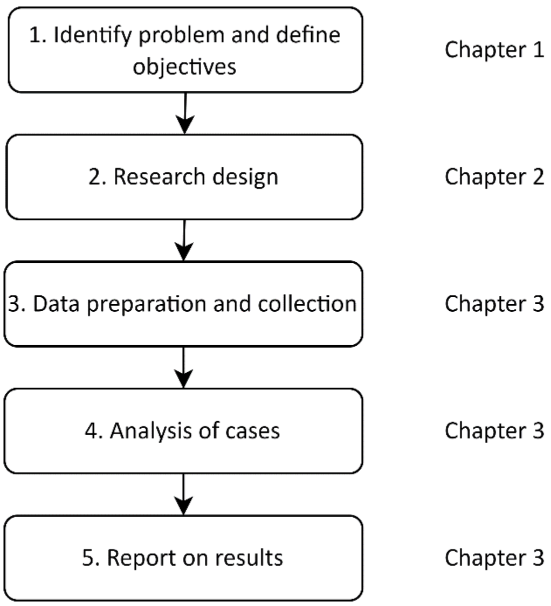


Figure 8: Case study research method (adapted from [93] and [96])

Each step in Figure 8 of the case study research method is applied throughout this document.

1.12. Dissertation outline

Chapter 1: Introduction

In this chapter, the first step of the case study research method is applied. First, introductory information is presented that leads to the problem statement. This is followed by a review of relevant literature to clearly define the study's aim and objectives. The introductory information provides background to the energy supply problems in South Africa and the dependence of the mining industry on the power utility. The energy supply shortage leads to the opportunity to integrate solar PV systems in the mine power system. Concerns regarding the power quality problems of integrating solar PV systems are explored, providing the problem statement. Lastly, the need for the study is defined followed by the study objectives.

Chapter 2: Literature Review

The literature related to the problem statement has been reviewed, and a state-of-the-art table has been compiled. This table highlights a significant gap in the literature where the impact of a solar PV power plant on power quality when interfaced with a mine power system, especially when supported by simulations, remains largely underexplored.

Chapter 3: Developing the Method

From the research objectives defined in Chapter 1, this chapter develops a method aimed at accomplishing these objectives. Step 2 of the case study method is applied in this chapter. A load flow method was developed to quantify the power quality impacts of converting the existing mine power system to a solar PV integrated power system. Implementing the developed method will enable a comprehensive understanding of the power quality changes when integrating a solar PV system.

Chapter 4: Implementation and Results

In this chapter, the developed load flow method of Chapter 2 was applied to a case study underground mine. First, the determined power system data was prepared and collected, accomplishing step 3 of the case study method. From the collected data a simulation model was developed and calibrated. The calibrated simulation model was used to quantify the power quality of the existing mine power system. The model output data was compared with the collected data to validate the power system model. Simulating the power system before and after the integration of the solar PV system concluded step 4 of the case study method. Finally, step 5 of the case study method is accomplished by reporting on the power quality results of the solar PV integrated mine power system.

Chapter 5: Conclusion

This chapter concludes with the findings of the study. The results of Chapter 3 are evaluated and compared to the study objectives defined in Chapter 1. The study needs are addressed and the main conclusions are discussed. Lastly, recommendations for further studies are presented.

Chapter 2: Literature Review

Figure 9: Mine substation point of supply[6]

"If you are working on something that you really care about, you don't have to be pushed.

The vision pulls you."

– Steve Jobs

[6] Z Lombard, Personal photograph

2. LITERATURE REVIEW

The objective of this section is to identify existing solutions to the problem statement. This involves verifying the knowledge base regarding the power quality impacts of integrating solar PV into mine power systems. To achieve this, a systematic approach is employed, consisting of three steps: identification of relevant studies, screening of these studies, and inclusion of the most pertinent studies [97].

The identification of studies is achieved through populating keywords such as solar PV, power quality, mine power systems, and load flow analysis in search engines such as the IEEE (Institutes of Electrical and Electronics Engineers) Explore, ScienceDirect and Google Scholar.

The next step is screening the identified studies. This step is essential for identifying the scope of previous research and pinpointing potential gaps in the existing literature. The study titles and abstracts were assessed based on the following criteria:

1. **Solar PV power plants:** Does the study investigate solar PV integrated systems (Section 1.6).
2. **Type of power system:** Whether the study incorporates mine power systems (Section 1.8).
3. **Power system analysis:** Is there an assessment of potential effects on power quality (Section 1.9)
4. **Simulation software:** Does the study employ simulation packages to determine and assess the potential power quality impact of solar PV power plants (Section 1.9).

The importance of these criteria was highlighted in the text leading to this section with the addition of simulation software. Simulation software can be key in assessing potential concerns before integrating solar PV systems. Hence, it is integrated into the search criteria.

The final step of the systematic research approach involves assessing the title, focus, contribution, and shortcomings of the screened studies. The comparison of these criteria will highlight clear gaps in the literature and the significance of this study. The selection of studies meeting these criteria have been meticulous, and they are described as follows:

- Title of the study.
- Author(s).
- Overview.
- Contributions and recommendations.

Experimental methodologies, the inclusion of specific power quality parameters, and results are discussed where necessary. This step is completed in the following section.

2.1.1. Critical review of previous studies

Study 1 (2023) [81]

Title: Power quality analysis of an open-pit mine electrical network: Case study Benguerir MinEx

Authors: A. Maghraoui, Y. Ledmaoui, O. Laayati, A. Chebak

Overview:

In this study, the power quality of an open-pit mine power system is investigated. The open-pit Benguerir mine in Morocco is the case study mine that utilises an assortment of electrical machines such as drills, conveyors, and crushers. The authors stress that these machines have a notable impact on the power quality of the mine's power system concerning voltage sags, surges, and harmonics. He also states that these concerns can lead to equipment damage and operational disruptions.

The study method utilised software modelling in ETAP (Electrical Transient Analyser Program). The methodology included assessments of the power system's load flow, harmonics and short-circuit currents. The main contribution of the load flow study was to compute power flows (real power (W), reactive power (VAR)), power factors, voltages, and currents at each bus under varying loads. The harmonic analysis gave insight into the current and voltage distortion resulting from power electronic devices to evaluate filters and to mitigate system trips. The short-circuit analysis determines the worst-case scenario of system faults and provides a means to correctly size protection devices.

The results of the study showed that areas of the power system had overloaded transformers and overvoltage buses. Solutions to the problems, such as changing transformer taps, were then implemented in the simulation package and provided to the mine. The effects of harmonics and short-circuit currents were used correctly in size filters and protection devices.

Contributions and shortcomings:

The study did not incorporate a solar PV integrated mine power system. However, the authors alluded that further work to assess the incorporation of solar PV on the stability of the power system will be required. Furthermore, the study utilised simulation software to evaluate the system but did not verify the simulation with actual data from the mine. ETAP was identified as a possible simulation program. A load flow analysis was used.

Study 2 (2023) [57]

Title: A comprehensive review of power quality mitigation in the scenario of solar PV integration into the utility grid

Authors: K. Jha, A.G. Shaik

Overview:

In this study, power quality challenges and mitigation techniques are reviewed from the integration of solar PV systems with the utility grid. The study first quantifies power quality problems that can arise from the integration of solar PV systems, such as voltage sag, voltage imbalance, inrush current, voltage flicker, harmonics, poor power factor, and frequency variation.

Secondly, the study reviews seven DFACTS (distributed flexible AC transmission system) devices that can be utilised to improve the power quality of the distribution grid to meet the standards set in IEEE 929, IEEE 1547 and IEC 61727 documents. Thirdly, the study determined that the performance of the grid-tied inverter depends on the control algorithms used between the DFACTS device and the inverter to improve power quality.

The study concludes that utilising a distributed static compensator (DSTATCOM) coupled with adaptive signal processing-based control is superior compared with the other methods. This system improves the load balancing, transient stability, and reactive power compensation of the distribution system, thereby improving power quality. This system is also the most cost-effective solution and is more apparent in distribution systems.

Contributions and shortcomings:

The study provided power quality problems caused by integrating solar PV power systems and comprehensively reviewed mitigation strategies. The study further only discussed the integration of these DFACTS technologies into potentially weak distribution systems and did not include mine power systems. The study did not discuss any simulation methodologies.

Study 3 (2016) [98]

Title: Effects of photovoltaic systems on power quality

Authors: K. Rahimi, S. Mohajeryami, A. Majzoobi

Overview:

In this study, the intermittent nature of solar PV systems is investigated. The study aims to determine the impacts of changing solar irradiance on the voltage and current power quality at the PCC (point of common coupling). Furthermore, the effect of cable impedance between the solar PV power plant and the PCC is assessed.

The study methodology incorporates a case study power system, with the solar PV power plant connected to the PCC of a utility grid. The software package MATLAB is utilised to simulate the integrated power system under varying solar irradiance. The model is also used to determine the impact of transmission length on power quality between the solar PV power plant and the utility.

The results of the study show that in the area of the PCC, the power quality of the current and voltage waveforms decreased, with an increase in cloud coverage of the solar PV arrays. In the study, the total harmonic distortion (THD) of the current waveforms increased from 1.25% to 6.14%. The study also indicated that an increase in cable length (increase in line impedance) between the solar PV power plant and the PCC caused the THD of the voltage waveform to increase.

Contributions and shortcomings:

The study reviewed the power quality effects of cloud coverage on the solar PV array and increased cable length between the solar PV power plant and the PCC. Valuable insight into solar intermittence is gained, however, the dynamic loading of the utility system is not incorporated. MATLAB was used for simulating the system.

Study 4 (2018) [99]

Title: Potential power quality impacts on LV distribution networks with high penetration levels of solar PV

Authors: D. Chathurangi, U. Jayatunga, M. Rathnayake, A. Wickramasinghe, A. Agalgaonkar, S. Perera

Overview:

In this study the power quality impacts due to the installation of solar PV systems within a low voltage (LV) urban distribution network are determined. The study first elaborates on the potential power quality concerns that solar PV systems present, however, focuses on voltage rise, power factor at the distribution transformer, and power loss. The case study utilises an urban network in Sri Lanka, that has more than 40% solar PV capacity concerning the capacity of the supplying transformer. A detailed approach to modelling the system is given, incorporating load and solar PV modelling.

To understand the power quality integration impacts of solar PV systems on power quality, the study utilised DIgSILENT PowerFactory simulation software. The simulation of the system was carried out with dynamic loading characteristics and with different levels of solar PV penetration levels. The simulation results were validated with available field data measurements and were found to have marginal differences.

The study results show that with an increase in penetration of solar PV systems, the voltage rise caused can violate grid standards. The power factor at the supplying transformer dropped during times of high solar generation to between 0.0 and 0.4 lagging. This is exacerbated by higher penetration of solar, which can increase the power factor to 0.8 leading, which is not permitted by grid regulations.

Contributions and shortcomings:

The study gave good insight into modelling solar PV systems. The method of simulating urban power systems with DIgSILENT to obtain power quality impacts was also shown to be effective since the results were validated with the actual system. A load flow analysis was used.

Study 5 (2023) [100]

Title: On the impacts of renewable energy on distribution power systems and the effects of energy storage systems

Authors: A. Harb, W.A. Saliek, M. Alhusseini

Overview:

The study conducted by A. Harb *et al*. focuses on the integration of battery energy storage systems with a solar PV power plant to improve the power quality of the system. The study first elaborates on the potential problems of integrating renewable energy into a distribution system concerning its intermittent power supply. Reliability, safety, stability, and quality concerns are highlighted.

A hybrid solar PV with a battery energy storage system is proposed to improve the power quality of the integrated system. The study proposed a methodology to simulate the integration of the system into a German Jordanian grid. The simulation is carried out with a DIgSILENT and incorporates a 1 MW battery storage system. The simulation was carried out over the dynamic loading of the system and elaborated on four cases:

A. Case 1: Normal grid operation
B. Case 2: Off-grid (no supply from the utility)
C. Case 3: Short circuit fault scenario
D. Case 4: Outage of supplying transformer with 50 % PV

In analysing the response of the battery-PV system, the study showed an improved response to load changes and mitigation of frequency and voltage fluctuations, thereby improving the power quality of the system.

Contributions and shortcomings:

The study proved through simulation that the grid-connected hybrid solar PV battery system was efficient in improving the power quality of an urban distribution system. The study utilised a load flow simulation.

Study 6 (2019) [101]

Title: The results of the implementation of the system for monitoring the quality of electricity in mining enterprises

Authors: A.S. Semenov, M.N. Semenova, O.V. Ferorov

Overview:

In this study, power quality monitoring systems were implemented at a diamond mine in Mirny, Russia. The goal of the study was to continuously monitor the power quality of some large electricity consumers, such as the hoist and mills present at the mine. The requirement of the analysis arose due to the need to identify sources of power quality deterioration.

The study employed a methodology which first determines installation sites requiring monitoring, then continuously monitors this equipment, and finally analyses the results, where the results produce power quality indicators.

By comparing the results from the study, it is evident that the hoist and mills exceeded acceptable voltage limits, power factor limits, and harmonic limits set by the grid code. From the results, the study developed guidelines for the assessment of power quality to improve the energy efficiency of the mine power system. In the five years of monitoring at the specific mine, the study no only allowed for the solving of a technical problem in the operation of the equipment, but also indicated the economic benefit of energy savings on transformer power losses. Further, the study deduced that improved frequency-controlled electric drive systems should be developed for use in the mine power system.

Contributions and shortcomings:

The study showed the importance of utilising a constant power quality monitoring system for the mine's electrical equipment to improve and mitigate potential problems. The study did not incorporate renewable energy sources but showed the necessity for a continuous supply of electricity to continue mining operations.

Study 7 (2016) [102]

Title: Energy quality and efficiency of an open pit mine distribution system: Evaluation and solution

Authors: P. Aqueveque, E.P. Wiechmann, J.A. Henriquez, L.G. Munoz

Overview:

The study conducted by Aqueveque *et al*. investigated the frequent shutdowns of the open pit mine's shovels with the hypothesis that poor power quality is responsible. Previous studies conducted at the mine indicated that harmonics and high amounts of reactive energy are present in the system. Accordingly, the study aimed to produce a precise diagnosis of the power system to identify the problem.

The study considered power quality monitoring, system modelling, and equipment technologies as part of the methodology. The study also utilised power system analysis simulations that were based on field measurements. These studies showed that harmonic distortion and voltage regulation are the root cause of the equipment shutdowns. The study then compared different solutions such as reactive power compensation, cable resize and larger substations by adding additional feeder cables. The end solution was to implement an additional feeder.

The implemented solution yielded a more efficient power system with improved voltage regulation and harmonic distortion. Furthermore, the solution showed energy savings totalling 10.7 GW · year.

Contributions and shortcomings:

This study produced valuable information on problem-solving and simulation techniques to evaluate the open-pit mine power system. Furthermore, the study gave solutions to power quality problems present in the system that are verified with field measurements. A load flow study was conducted. The study did not incorporate a solar PV system.

Study 8 (2016) [103]

Title: Mitigation of power quality problems in underground mines using different control strategies

Authors: T. Sukanth, Dr. S. Jayanthu, Dr. A. Jayalaxmi

Overview:

In this study, the addition of a distribution static compensator (DSTATCOM) is investigated in an underground coal mine to improve the power quality at the receiving end. The underground coal mining industry is characterised by large loads such as crushers, continuous miners, mining shovels, etc. that are far away from supplying transformers. The high demand and far distances cause voltage drops and harmonic distortion at the load centres, which cause the equipment to trip, negatively impacting production. This is especially seen with continuous miners that are sensitive to voltage fluctuations.

The study methodology this study employs shows the design, modelling, and implementation of a D-STATCOM to improve the power quality of the system. The study further compared PI (proportional integral) and hysteresis control methods for the D-STATCOM device. The study utilised MATLAB to simulate the system using data obtained from an underground coal mine. The results of the modelling showed the voltage and current profiles of the system.

The study concluded that the D-STATCOM device effectively improved the power quality of the system providing the following advantages:

- Increase in equipment life
- Reduced electricity bill
- Improved efficiency (power factor)

- Improved voltage regulation

Contributions and shortcomings:

This study improved the power quality at the load centres of an underground coal mine. The study incorporated MATLAB as a simulating tool to assess the advantages of the D-STATCOM device. The study did not incorporate renewable energy assessments.

Study 9 (2020) [68]

Title: Ensuring quality of electricity in gold mines and mills

Authors: A. Pichuev, Y. Schevyrev, E. Zaugolnikova

Overview:

In this study, the current problems of ensuring good power quality at gold mines and gold-extracting factories are considered. The case study Kuranakh mine is an open-pit gold mine with a gold processing mill. The mine utilises large single-bucket excavators that are far from supplying transformers. The excavated material is transported to the mills for processing. The study investigates the impact of power quality on the machinery.

The need for the study arose according to the requirement to stabilise the mill and voltage supply to the excavators. The study employed a method of surveying the site and obtaining measurements of power quality. During the survey, it was apparent that the mills and excavators violated voltage, harmonics, and power standards. The study further elaborates on the impact of poor power quality on the deterioration of dielectric materials, additional heating of transformers, increased system losses, and reactive compensation device (capacitor bank) failure.

From the observations, there is an urgent need to modernise and pay special attention to the operation of the equipment on the power system, to mitigate problems such as equipment failure/downtime and safety concerns.

The study offers a solution to address power quality issues by recommending the implementation of power quality regulators to meet regulatory standards.

Contributions and shortcomings:

The study showed the requirement of closely monitoring the power quality of the power system to avoid equipment failure and downtime. The study used a MATLAB simulation to estimate the system losses from the harmonic distortion present.

Study 10 (2014) [104]

Title: Voltage regulation in mine power distribution systems: Problems and solutions

Authors: L. Moran, J. Espinoza, R. Burgos

Overview:

In this study, the operational characteristics of a copper surface mine power system are provided. The power system contains long-distance cables supplying shovel and drilling machines from centralised step-down transformers. The cyclic operation of these large power-rated machines can easily use 1.6 times the average power of the mine. This kind of loading continuously gives power quality problems concerning voltage fluctuations, harmonics, and power factor issues. Poor power quality often leads to system protection interference, causing the mining equipment to lose supply. Restarting the system requires electricians to switch the panel on again, which in turn increases loss of production.

The study aims to propose a solution to the power quality problem at the mine. The study methodology first assesses the mine power system, and secondly, field measurements are obtained and used within a load-flow simulation. The simulation provides insight into voltage at each bus and transformer load factors.

From the simulated results and field measurements, mitigation criteria were established:

3. Power ratings of transformers and cables should encapsulate not only reactive power but voltage drops as well. In other words, P-V characteristics must be used.
4. Series active power compensation aims to deliver more stable voltages at equipment terminals by reducing fluctuations.

Contributions and shortcomings:

This study demonstrated the impacts of voltage regulation within the mine power system through comprehensive voltage, current, power measurements, and equipment malfunction. Effects of power quality on the operation of the mine were shown. A load-flow study was conducted to show the impacts of poor power quality and to identify problem areas.

Study 11 (2021) [105]

Title: The use of solar energy in the copper mining processes: A comprehensive review

Authors: O. Behar, R. Pena, S. Kouro, W. Kracht, E. Fuentealba, D. Sbarbaro

Overview:

This study reviewed the feasibility of adding solar PV generation and thermal technologies to the copper mining industry in Chile. The study started by addressing the drivers for renewable energy, such as highly variable energy prices, concern about the industry's carbon footprint, and falling ore grades. The addition of renewable energy is aimed at reducing their risks, according to the aforementioned drivers.

The review discussed alternative solar energy systems, such as PV and thermal technologies since the copper mines are situated in high solar radiation regions. Solar PV and CSP technologies are used for energy generation and are typically financed by private companies and paid through PPAs. Thermal technologies were used for heating purposes in the copper processing system.

The study concluded that adding these solar technologies could solve the present energy-related and carbon footprint problems. The study alluded that these systems can be integrated into the current copper mining industry without extensive system changes.

Contributions and shortcomings:

This study reviewed the application of renewable energy sources to the copper mining industry in Chile. The study did not mention potential power quality concerns regarding the integration of solar PV technologies. The study did not use a simulation package.

Study 12 (2022) [106]

Title: A review of renewable energy practices in the Australian mining industry

Authors: A. Strazzabosco, J.H. Gruenhagen, S. Cox

Overview:

In this review, the adoption of renewable energy sources within the Australian mining industry is quantified. The review first mentioned drivers for the integration of renewable energy such as rising energy costs and the requirement to reduce their carbon footprint. The review also surveyed inhibiting factors towards the adoption of renewable energy.

According to the review, only 7% of the mines were planning to or had adopted renewable energy. During 2021, only 15 active renewable energy systems were active. Subsequently, it was determined that solar PV systems were the preferred energy system. The slow adoption rate is owed to the off-grid nature of the mines. The intermittent nature of solar PV systems and expensive battery storage systems results in infeasible solutions for off-grid mines.

Contributions and shortcomings:

The study reviewed the adoption rate of renewable energy sources within the Australian mining industry. The review gave valuable insight into concerns of off-grid systems, however, it did not assess possible power quality issues that can also be drivers for the slow adoption rate. The study did not use any simulation software.

Study 13 (2021) [107]

Title: A cost-benefit analysis of implementing a 54 MW solar PV plant for a South African platinum mining company: A case study

Authors: S.S.S. Barnard, A.M. Smit, S.L. Middelburg, M.J. Botha

Overview:

A cost-benefit analysis was done for the implementation of a 54 MW solar PV plant at a South African Platinum mine. The study stated that increasing energy tariffs, power cuts and the introduction of carbon tax were seen as drivers for renewable energy. These parameters were included in the study's cost-benefit analysis with the accompanying solar PV irradiance map of South Africa.

The study analysed two cases. The first case was to proceed with Eskom as their only source of energy and the second case was to implement the 54 MW solar PV system. The study found that adopting the solar PV system over 20 years can yield a ZAR 563 205 994 (11%) carbon tax saving and a ZAR 5 614 426 335 (10%) reduction in electricity costs.

Contributions and shortcomings:

The study provided an empirical method to determine the cost-benefit of implementing a solar PV system at a South African mine. The study did not discuss power quality indicators and did not use a power system simulation.

Study 14 (2022) [108]

Title: Integration of renewable energy into the copper mining industry: A multi-objective approach

Authors: J. Vergara-Zambrano, W. Kracht, F.A. Diaz-Alvarado

Overview:

In this study, a methodology to design a solar-biogas hybrid renewable energy system is proposed. This system accounts for the variability and intermittency of renewable energy systems and is applied to a copper mine.

The results show that the hybrid system is an attractive option to supply electricity to the case study copper mine. A caveat to the system is the supply and storage of the biogas to supply the generators. The system can also not be operated without a utility grid connection. However, the hybrid system still aids in reducing carbon emissions and reduces overall electricity costs.

Contributions and shortcomings:

The study proposed a methodology to design a hybrid solar-biogas system integrated into a copper mine power system. The study did not provide power quality assessments of the integrated system.

2.1.2. Analysis of the critical review

The state-of-the-art table, Table 3, compares and summarises the important points of each of the ten studies discussed in the preceding section. Additionally, it highlights the existing gap in the literature.

Table 3: State-of-the-art power quality impacts of solar PV power plants

Study	**Power Quality**	**Type of Power System**		**Solar PV Power Plant**	**Simulation**	**Focus**
		Mine	**Other**			
Study 1 [81] Maghraoui *et al*.		Surface mine				Open-pit mine power quality evaluation using ETAP.
Study 2 [57] Jha *et al*.			Utility			A comprehensive review of power quality improvement devices.
Study 3 [98] Rahimi *et al*.			Utility			Reviews the impact of solar intermittency on power quality.
Study 4 [99] Perera *et al*.			Urban distribution			Simulation of power system with DIgSILENT.
Study 5 [100] Harb *et al*.			Urban distribution			Integrating a battery storage solution to improve power quality.
Study 6 [101] Semenov *et al*.		Diamond mine				Continuous power quality monitoring to identify potential grid problems.

Study 7 [102] Aqueveque *et al*.		Surface mine				Investigated power quality issues with load flow studies.
Study 8 [103] Sukanth *et al*.		Coal mine				Investigated the effectiveness of D-STATCOM in improving voltage regulation.
Study 9 [68] Pichuev *et al*.		Surface gold mine				The study showed the importance of closely monitoring power quality.
Study 10 [104] Moran *et al*.		Surface copper mine				Investigated the power quality impacts using a load-flow study.
Study 11 [105] Behar *et al*.		Surface copper mine				Investigated the feasibility of solar resources in the copper mining industry.
Study 12 [106] S. Cox *et al*.		Surface mine				The study reviewed the adoption rate of renewable energy sources.
Study 13 [107] A.M. Smit *et al*.		Platinum mine				A cost-benefit analysis of implementing a 54 MW solar PV system at a platinum mine.
Study 14 [108] W. Kracht *et al*.		Copper mine				Provides a method to design a hybrid solar-biogas system.

Table 4: Legend for the state-of-the-art

Legend	
	The study considered the criterion
	The study did not consider the criterion

From the studies reviewed, it is evident that the integration of renewable energy, such as solar PV, can introduce problems to the power quality of an electrical system, which formed the need to investigate the impacts of solar PV systems on existing mine power systems.

Power quality analysis is vital for maintaining the efficient and dependable operation of electrical power systems across numerous industries. Nonetheless, research gaps exist within the field that require attention. For instance, while numerous studies have investigated the effects of power quality disturbances on electric power systems in general, there remains a shortage of research investigating these impacts on specific sectors like the mining industry.

While some articles offer an overview of power quality issues within the mining industry, there are few detailed case studies or real-world examples to emphasise the importance of power quality in a solar PV integrated mine power system. Closing these gaps could offer valuable insights for enhancing power quality management practices in the mining industry integrated with solar PV systems.

Accordingly, from Table 3, it is clear that there is a gap in the literature where the power quality impact of a solar PV power plant interfaced with the mine power system, aided by simulations, is largely underdetermined.

Chapter 3: Developing the method

Figure 10: Mine substation point of supply[7]

"Believe you can and you are halfway there."

– Theodore Roosevelt

[7] Z Lombard, Personal photograph

3. DEVELOPING THE METHOD

3.1. Preamble

In this chapter, a power quality evaluation methodology is formulated to forecast the power quality changes in the power system of a mine upon integrating a solar PV power plant. This chapter is completed following Step 2 of the case study methodology outlined in Figure 8. Each step of the method in Section 3.2 is intricately formulated from the literature to achieve the objectives of this study. Each step forms part of the flow diagram presented in Section 3.4, summarising the developed study method.

3.2. Method development

Power system analysis is a fundamental tool to plan, design, and evaluate the performance of a power system, whether it be interconnected with the national grid or islanded [109]. Power system analysis, as mentioned in Chapter 1.9, encompasses several studies, each providing insights into different power system operational characteristics. Therefore, a power system analysis method needs to be chosen upon the aims and objectives of the required analysis.

The study aims to accurately quantify the power quality changes upon the integration of a solar PV plant with the existing mine power system, particularly focusing on voltage and reactive power flows. To achieve this a load flow analysis is proposed [110].

A load flow analysis emerges as the optimal choice to achieve the defined study objective [109]. The load flow analysis utilises a simulation model that accurately replicates the real-world power system to determine the following [111]:

1. Steady-state bus voltages and phase angles
2. Component loading
3. Real and reactive power flows and losses
4. Undervoltage and overvoltage conditions
5. Performance under normal, maximum, minimum, and startup conditions

6. Performance under different operating configurations
7. Power factor requirements

The core of the method development will form around the requirement of the load flow analysis. The following sections will holistically explain each step required to conduct a load flow analysis to satisfy the objectives of the study.

3.2.1. Step 1: Define the power system operation

Mine power systems can be extensive and complex, as alluded to in the previous section, necessitating a clear definition of the mine power system operation. Therefore, it is crucial to have a simplified visual representation of the entire system to understand the operation of the system under different operating modes [112]. The one-line diagram is used for this purpose.

The one-line diagram in Figure 7 illustrates a typical operational mine power system. The one-line diagram is used to illustrate multiphase systems using a single line [111]. This diagram, therefore, illustrates multiple pieces of equipment found in a power system, such as transformers, buses, generators, reactors, loads, switchgears, cables, etc. Accordingly, an accurate and up to date one-line diagram is crucial to conduct a power system analysis [87]. The one-line diagram needs to accurately illustrate the existing mine power system and the operational change. This will be important information required for Step 6 and Step 7.

This study evaluates the power quality impact of converting the conventional mine power system (base case) to an integrated solar PV mine power system (operational change). Therefore, the mine power system will change with the addition of the solar PV power plant. Accordingly, this change needs to be shown on the one-line diagram.

Summary of Step 1 in Figure 11.

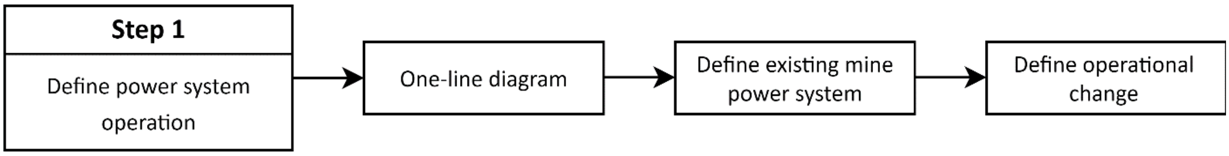


Figure 11: Step 1 summary

3.2.2. Step 2: Benchmark the power system

After the mine power system is fully characterised and operational changes are identified, the system needs to be benchmarked [113]. Benchmarking is required to create an accurate representation of the current system [114]. Benchmarking is the process of standardising the current operating system parameters and developing performance indices which are then used to calibrate a system model. In turn, the system model provides a method to compare changes in the power system's power quality.

To standardise the operations of the mine power system, empirical data is collected and any conditions that may influence operation are noted. Mine power systems typically have metering installed on all the incomers and loads in the main substation [9]. Therefore, access to historical data on the power system is crucial for conducting a meaningful power system analysis [112]. Mines typically utilise SCADA (Supervisory Control and Data Acquisition) systems to collect and store data from various sensors across the mine [115]. Typical measurements include voltage, real power, reactive power, power factor, and frequency [91]. Additionally, loads or sources that do not have metering installed can be measured by portable measuring tools, such as a DENT logger.

A summary of Step 2 is depicted in Figure 12 below.

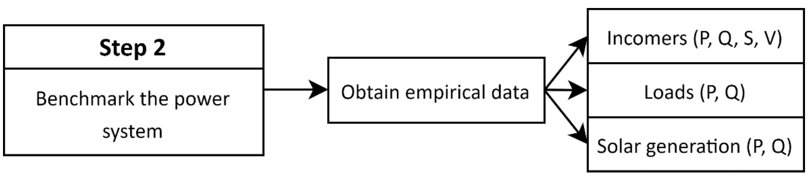


Figure 12: Summary of Step 2

3.2.3. Step 3: Determine Key Performance Indicators (KPIs)

From the benchmarked system, KPIs need to be determined. The KPIs are selected to validate the system model and to determine the impact of the operational changes [111]. Changing the loads or sources of any power system will influence the voltage, power flows, and power factor of the system [91]. Therefore, these parameters should be considered as KPIs to evaluate changes in the system operation. These parameters also form part of the power quality indicators [116].

Incorporating national power utility standards/constraints are important KPIs to ensure high-quality power quality [117]. Constraints on the operation of the power system are imposed by the grid code and electricity quality of the supply code (NRS048 – 2), respectively [78]. These constraints serve as boundaries for which parameters such as voltage and power factor should be kept within [118]. According to the quality of supply code, voltage, and power factor at the point of connection, they should be kept within the limits described in Table 5.

Table 5: Voltage limits at the POC [118]

Nominal voltage, U_N (kV)	Maximum voltage (kV)	Minimum voltage (kV)
400	420	$0.85U_N$
275	300	
220	245	
132	145	
88	100	
66	72.5	
< 44	U_N + 10%	

The grid code stipulates the power factor limits at the POC. At this point, the power factor shall, at all times, be 0.9 lagging or higher, and a leading power factor is not accepted [78].

A summary of Step 3 is depicted in Figure 13.

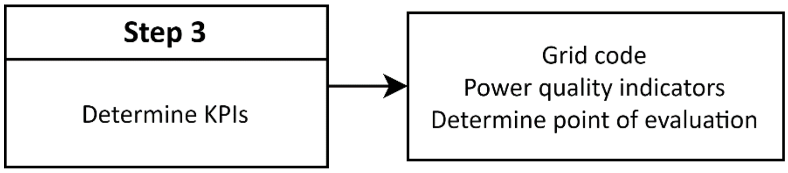


Figure 13: Summary of Step 3

3.2.4. Step 4: Determine system model input data

The operational equipment within the mine power system needs to be defined to enable fair comparison with the developed case study power system. The operational equipment will serve as inputs for the power system model and may include transformer data, bus data, branch data, source data (utility, generators such as solar PV), load types, and overall system operation data [111]. The input data needs to be collected systematically and thoroughly to yield accurate data. Parameter uncertainty should be taken into account and unknown parameters should not be neglected. These parameters need to be entered with conservative assumptions and sound judgment.

The subsequent steps provide a comprehensive overview of the input data needed to construct an accurate load flow analysis [111]. These steps will also be followed systematically when constructing the simulation model. Once collected, this input data should be systematically integrated into the one-line diagram, facilitating an efficient process for populating the simulation model.

Step 4.1: System data

Power system analysis is often performed using a per unit (p.u.) representation, normalising actual voltages, amperes, and ohms to simplify analysis [119]. The p.u. system is particularly useful when dealing with complex power systems with different voltage levels and equipment ratings. Converting system data into p.u. representation involves choosing a base MVA and base voltage. This selection determines the base impedance and base current for the system.

Accordingly, the following equation is used to convert the system into the p.u. representation [119]:

$$p.u. = \frac{Actual\ value}{Base\ value} \tag{2}$$

Select a base MVA according to system ratings and a voltage base according to the voltage level of each region. Converting the current and impedance values to p.u. is done as follows [119]:

$$I_{base} = \frac{S_{base}}{\sqrt{3}\,V_{base}} \tag{3}$$

$$Z_{base} = R_{base} = X_{base} = \frac{V_{base}^2}{S_{base}} \tag{4}$$

Step 4.2: Bus data

Buses serve as the nodes within an electrical power system and are categorised according to their load and/or generation conditions [89]. Bus data encompasses details for each bus, including the connected loads and shunts. The following data needs to be acquired to mitigate reference problems:

1. Bus number
2. Bus name
3. Bus classification (swing/load/voltage controlled)
4. Bus nominal voltage (kV)

The bus classification will become clear in the subsequent steps.

Step 4.3: Source data

Slack/swing source

To compute the load flow simulation, a slack bus is required [87]. A power system model requires one slack bus per isolated subsystem. A slack bus serves as a reference point for the calculation of the load flow problem. The slack bus is typically chosen at the bus where the largest rated generator is connected, where the nominal voltage is close to 1 p.u., and the voltage angle is chosen to be 0 degrees. The slack source is typically referred to as an infinite source since it needs to supply all the loads of the system and provide power balance. The slack/swing source is typically the utility connection point [109].

For power systems studies it is required to obtain the following data:

1. Generation identification
2. Generator ratings (rated MW, MVA, power factor and efficiency)
3. Maximum reactive power output
4. Minimum reactive power output
5. Short circuit ratings

Voltage-controlled source

Large power systems can have more than one power source. Power sources can include the utility, diesel generators, solar PV systems, etc. Each source has a specific power rating and a means to control voltage. During the load flow calculation, the power and voltage is kept constant at the generator terminals whilst adjusting the reactive power supply between its Q_{min} and Q_{max} rating. Since the study aims to evaluate the operational change due to the addition of a solar PV power plant, this plant will constitute the voltage-controlled bus [99].

Inverter and solar module data are required to determine the generation limits of the solar PV power plant. Therefore, the voltage control setup for the power plant is essential to provide an accurate simulation model. The following input data is required:

1. PV module ratings
2. PV module quantity
3. Inverter ratings
4. Inverter quantity and connection
5. Operation mode (voltage control, power factor control, MVAR control, constant unity power factor)
6. Harmonic ratings

Step 4.4: Branch data

Branch data is required since it describes connecting elements that can be in series between the buses of the power system. Branch data can include transmission lines, cables, capacitors, and transformers. In power system analysis software, to improve accuracy, branches that are in series should be treated as separate elements connected between separate buses [111].

Impedance values are crucial parameters for conducting a successful analysis, underscoring the necessity for accuracy in their determination. Utilising component libraries can help mitigate uncertainties and ensure precise impedance values for meaningful analysis [120].

Cable/transmission line data

Cable and transmission line data are obtained by analysing existing mine diagrams, cable data sheets, and site audits. Data required includes:

1. Bus identifiers
2. Length of branch for transmission lines and cables (km)
3. Conductor size (mm^2)
4. Material type
5. Phase (single or three phase)
6. Impedances (R, L, C)
7. Power ratings

Transformer data

Transformer ratings and tap settings are required. Changing the transformer tap positions adds or subtracts transformer windings to control the secondary voltage. This can lead to primary and secondary voltages that do not match the system-defined nominal voltages. This requires an off-nominal tap representation on the power system model. The off-nominal taps can also require adjusting the impedance of the transformer. Required data includes:

1. Transformer identification
2. Rated MVA

3. Z% impedance rating on the MVA bus
4. X/R ratio
5. Tap settings
6. Connection type
7. Primary and secondary voltage ratings

The transformer X/R ratios are used to calculate the resistance (Ω), R, and reactance (Ω), X, of the transformer on the given Z% impedance. However, the X/R ratio is commonly omitted from the transformer nameplates. To work around this, transformer X/R ratio tables can be used [121]. The transformer modelling guide published by Shaarbafi *et al.* [121], surveyed 900 transformers to provide transformer X/R ratios. Their results correlate with the IEEE C37.010 standard. This standard is currently being used by ETAP, which is a proprietary software package used industry [122]. Figure 14 provides the updated transformer X/R ratios.

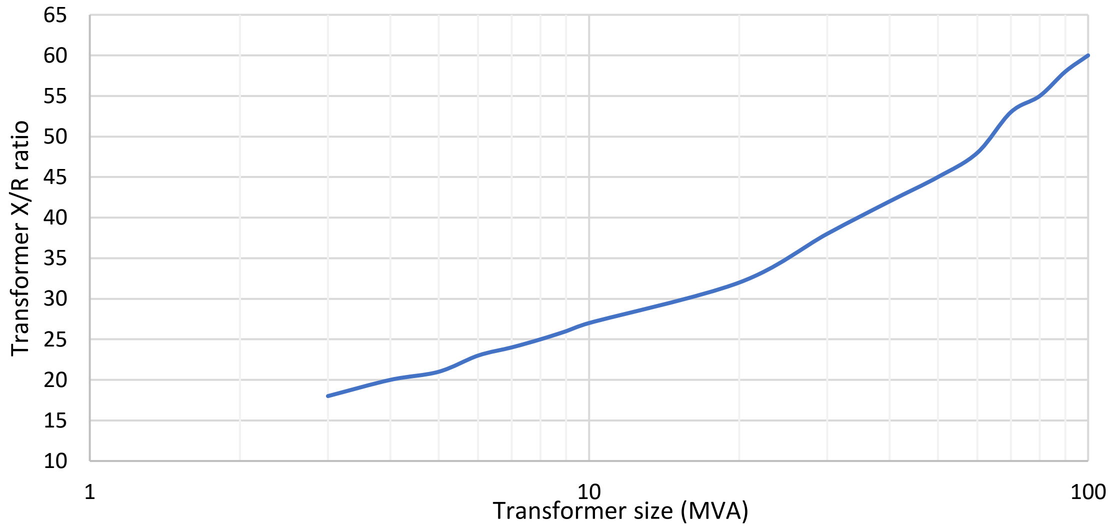


Figure 14: Transformer X/R ratio (adapted from [121])

The X/R ratios from Figure 14 and the nameplate Z% can be used in the following equation to determine the resistance and reactance values:

$$Z\% = \sqrt{X^2 + R^2} \tag{5}$$

Step 4.5: Load bus (PQ-bus)

Voltage magnitudes and phase angles are typically calculated during the analysis of a power system model according to changes in the overall loading of the power system. Therefore, the loads of the power system need to be determined. A load bus or a PQ bus is a bus where the real (P) and reactive (Q) powers are known [87]. The load flow software computes the voltage magnitude and voltage phase angle.

The following load data is required to represent the loads of the system:

1. Load identification
2. Load quantity
3. Operating state (continuous, intermittent)
4. Real and reactive power ratings (MW, MVAR)

A summary of Step 4 is provided in Figure 15 below.

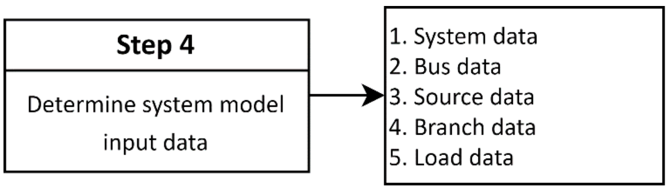


Figure 15: Summary of Step 4

3.2.5. Step 5: Evaluate simulation packages

Based on the study objectives, it is imperative to utilise a simulation package capable of modelling the transition from a conventionally supplied mine power system to a solar PV-integrated one. Therefore, it is essential to select a simulation package that aligns with these requirements.

Based on the literature review conducted in Chapter 2, several software packages have been identified as capable solutions for solving load flow problems, such as ETAP, DIgSILENT, and

MATLAB. Other software packages such as PowerWorld, EasyPower, MatPower, etc. are also available [123].

Given the extensive array of software packages available, establishing the selection criteria becomes imperative. The criteria should encompass the following [124]:

Table 6: Evaluation criteria

Criteria	Description
Accuracy of Calculations	The ability of the software to provide precise and reliable power flow results under various conditions.
User Interface	Ease of use, intuitiveness, and quality of the graphical interface for model setup and data input.
Scalability	Capacity to handle large and complex networks without performance degradation.
Compatibility	Compatibility with existing data formats, other software tools, and industry standards.
Speed of Computation	Time efficiency in performing simulations, especially for large-scale networks.
Reporting and Visualisation	Quality of output reports, data visualisation, and graphical representations of results.

The selection criteria will guide the engineer conducting the load flow analysis to choose a software package that aligns with the cost capability of their company, and which matches the system size and required level of accuracy.

A summary of Step 5 is depicted in Figure 16 below.

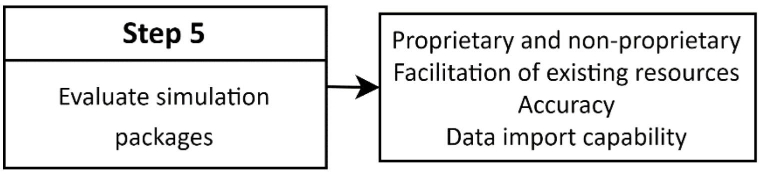


Figure 16: Summary of Step 5

3.2.6. Step 6: Construct and validate the base case simulation model

After selecting a simulation package, the next step involves constructing the base case simulation model using the one-line diagram in Chapter 3.2.1 (only the existing mine power system) and system model input data from Chapter 3.2.4. The skeleton of the simulation model is constructed first. The skeleton is essentially a digital copy of the one-line diagram, emphasising the importance of an accurate one-line diagram [100].

The load flow model is typically constructed in the following order: starting with a power source, followed by branches, buses, and loads, as depicted in Figure 17.

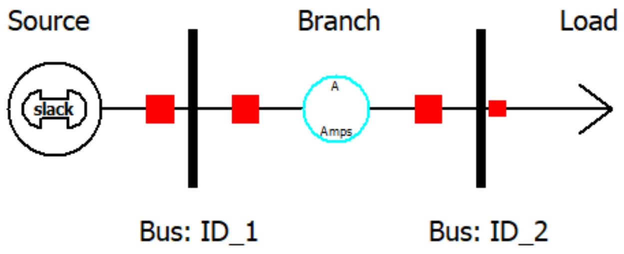


Figure 17: Simplified one-line diagram in a simulation package[8]

Within the simulation model, sources can be categorised into two types: slack/swing sources or voltage-controlled sources. The connected bus is then designated as either the slack/swing bus or the voltage-controlled (Power-Voltage) bus, respectively. Following the construction of these buses, the loads of the power system are incorporated. Loads are connected to a load (PQ) bus. Each respective bus is connected by a branch, which can take the form of a cable, transmission line, reactor, or transformer.

Once the one-line diagram is constructed within the simulation package, the next step involves incorporating the system model input data from step 2 (Chapter 3.2.4). Each set of input data for their respective components is then inserted into the simulation model. Figure 18 illustrates input data for a branch.

[8] Illustration by author on a simulation package.

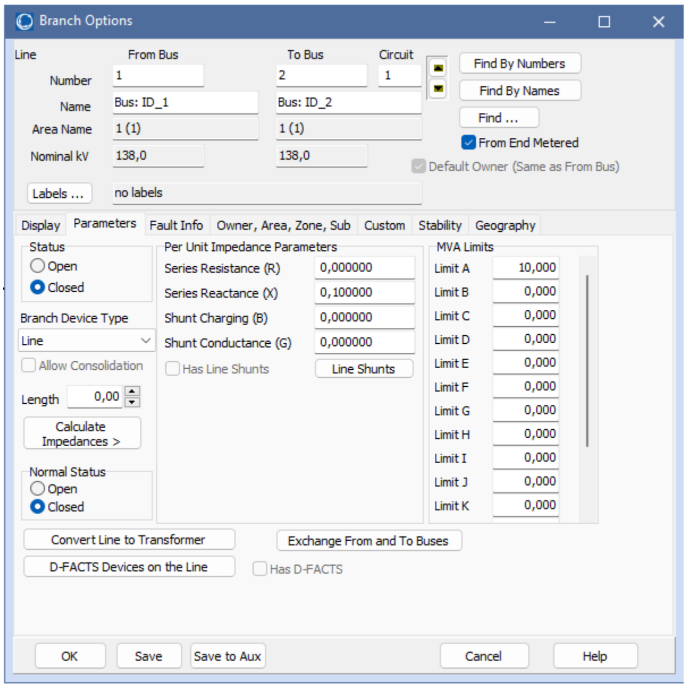


Figure 18: Branch input data[9]

Problem formulation

Once the one-line diagram is constructed with the relevant input data, a solver needs to be selected. Load flow analysis involves solving a system of non-linear algebraic equations that represent the power flow in the network [87]. These equations are derived from Kirchhoff's laws, power balance equations, and component characteristics. The equations describe the relationship between voltages, currents, and power injections at different buses in the network [87].

The system of non-linear equations is solved iteratively until the set of solutions converges to they are within a certain limit. Different techniques can be used within the load flow simulation to achieve the solution. Commonly used techniques are Newton-Raphson and Gauss-Seidel [89]. However, Guass-Seidel methods show poor convergence characteristics and Newton methods are preferred [89]. Modern software programs utilise different

[9] Illustration by author on a simulation package.

variations of the Newton method, namely Fast-Decoupled and Adaptive Newton Raphson techniques. Accordingly, an iterative solution technique must be chosen that converges with the constructed simulation model within a desired convergence accuracy.

Base case model validation

Once the one-line diagram is constructed with the relevant input data and an iterative solution technique is chosen, the simulation model can be calibrated. Calibration is required to ensure that the model produces accurate values compared with the real-world power system.

To calibrate the model, a 24-hour base case is chosen from the benchmarked data. The base cases represent the power system operating under current known operating conditions [111]. Required data for the base case is [125]:

1. Loading data (MW and MVAR)
2. Incomer power (MW and MVAR)
3. Bus voltage (kV)

To ensure an accurate power system simulation model, the model should be calibrated. Calibration is done by changing transformer tap ratios, network configurations, loading conditions, and generation conditions iteratively to match the simulation results with the benchmarked data at the POC [125]. The mean absolute error (MAE), equation (6), is used to determine the accuracy of the simulation model for each benchmarked parameter [117]:

$$MAE_{\%} = \frac{1}{k}\sum_{k=1}^{K}\left|\frac{A_k - S_k}{A_k}\right| \quad (6)$$

Here

$MAE_{\%}$	=	Percentage error (%)
K	=	Total number of data points

k	=	Total number of data points
A_k	=	Benchmarked data value
S_k	=	Simulated data value

Once the simulation model is calibrated to match the verified benchmarked system within a 10% MAE, the model is deemed validated [114]. If the base case does not fall within this limit, further calibration is required, or the system model input data needs to be reevaluated in Step 4. This validation indicates that the simulation accurately reproduces the power system in a real-world setting within an acceptable margin of error.

A summary of Step 6 is depicted in Figure 19 below.

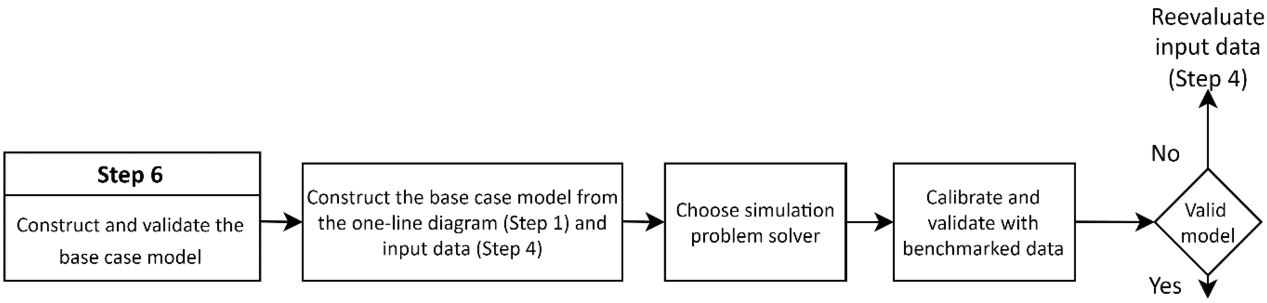


Figure 19: Summary of Step 6

3.2.7. Step 7: Construct the operational change simulation model

Step 7 aims to add the operational change to the base case simulation model developed in Step 6. The operational change illustrated by the developed one-line diagram of Step 1 is now implemented and will form the operational change simulation model. The solar PV system needs to be constructed similarly to the method described in Step 6. Each bus, branch and solar generation element is added according to Step 4.

To predict the power quality changes of the integrated solar PV mine power system, solar PV generation data is required. Studies, [126] utilised SolarGIS as a tool to provide a generation power profile of a solar PV system. SolarGIS utilises the DNI map as illustrated in Figure 5 to calculate the solar PV generation profile [127]. This tool requires the location of the solar PV farm and system size (kW_p) to calculate the solar PV generation profile[10] [128].

Accordingly, the obtained solar PV generation profile from the SolarGIS tool needs to be inserted into the operational change simulation model. This model utilises the same loading data as in Step 6, to enable a fair comparison between the two cases.

A summary of Step 7 is depicted in Figure 20.

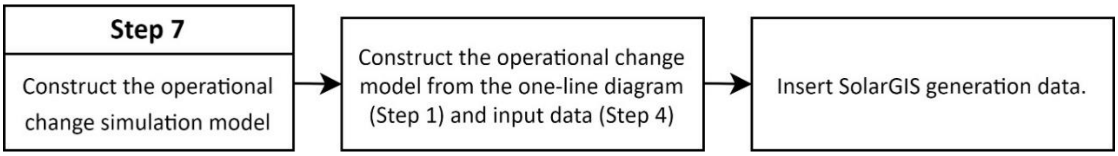


Figure 20: Summary of Step 7

3.2.8. Step 8: Evaluate results (KPI validation)

Once the operational change simulation model is successfully constructed, it enables the identification of the power quality changes upon integrating solar PV generation [99]. To fully understand the operational changes over all the operating conditions, three simulation conditions are selected, similar to study [100].

Condition 1 aims to compare the 24-hour profiles of the base case with the operational change simulation model to identify the power quality changes at the POC. **Condition 2** aims to provide the power quality change upon minimum loading conditions with varying solar generation power from 0% to 100% in increments of 25%. Similarly, **Condition 3** aims to provide the power quality changes upon maximum loading and varying solar generation power. Table 7 summarises the three conditions described.

[10] Global Solar Atlas

Table 7: Base case vs operational change impact on power quality at the POC

Condition	Solar PV power	Loading condition	Simulation	Outcome
1	Solar PV generation profile	Actual	24-hour time step simulation with actual loading conditions	Voltage, real power, reactive power, apparent power and PF at the POC
2	0%, 25%, 50%, 75%, 100%	Minimum	One-time point simulation with minimum loading conditions	
3	0%, 25%, 50%, 75%, 100%	Maximum	One-time point simulation with maximum loading conditions	

Finally, the power quality changes due to the operational change can be evaluated. The results of the three different conditions are tabulated and evaluated against the KPIs determined in Step 3. From this, the power quality impact due to operational change can be evaluated. Power quality concerns, due to breach of limitations set by the KPIs, should be noted along with possible recommendations to remediate these violations given.

A summary of Step 8 is depicted in Figure 21.

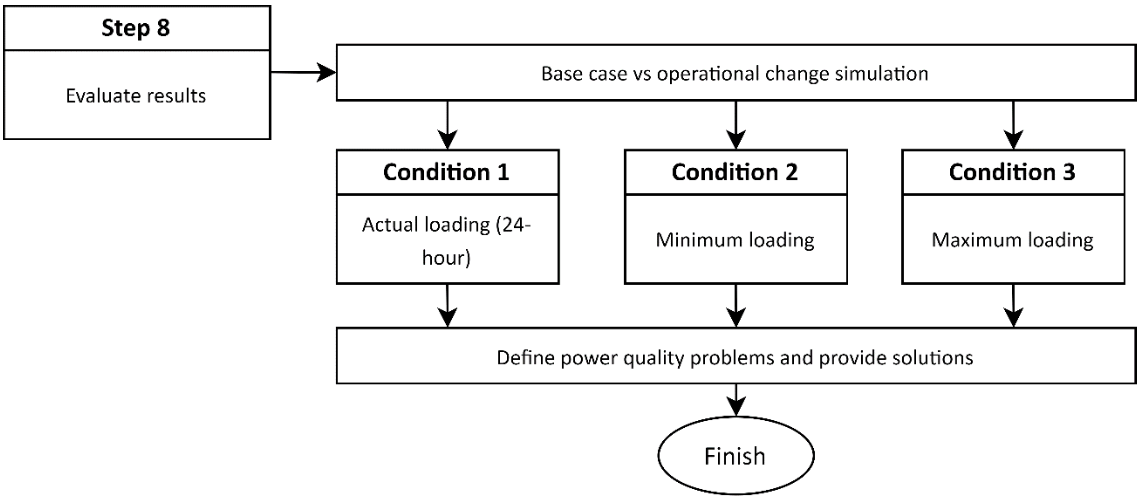


Figure 21: Summary of Step 8

3.3. Method verification

The power quality evaluation methodology, developed in Sections 3.2.1 to 3.2.8, is discussed in this section. This section aims to explain how the method achieves each respective study objective mentioned in Section 1.10.3.

Step 1 defines the operation of the current mine power system. This step elaborates on the requirement of a one-line diagram to comprehensively describe the mine power system. The one-line diagram illustrates the existing and solar PV integrated mine power system.

Steps 2 and 3 start to define study objective 1.1. To establish the power quality parameters for the current mine power system, the power system first needs to be benchmarked. From the benchmarked data, electricity regulations and equipment specifications for important power quality parameters are selected. Subsequently, KPIs need to be selected to measure the operational change.

Step 4 systematically describes the input data required to construct the simulation model. Each bus, branch, source and load element is characterised fully.

Step 5 involves assessing simulation packages that can effectively determine the necessary power quality outcomes. An electrical transient analysis program is needed to achieve this. Factors such as proprietary and non-proprietary, use of available resources, accuracy, and ease of use need to be incorporated into the selection process.

Step 6 involves constructing, calibrating, and validating the base case simulation model. Steps 4 through 6 define study objective 1.2. These steps aim to construct and calibrate the load flow simulation within 10% of the benchmarked real-world mine power system, therefore validating the load flow simulation model.

The methodology is designed to assess the impact of integrating a solar PV power plant on power quality. Therefore, it is imperative to measure the existing system both with and without the integrated solar PV system. Steps 7 and 8 are specifically created to accomplish this by analysing both systems under three conditions. Through this approach, the study aims to achieve the objectives related to study objectives 1.1, 1.2 and 1.3.

Finally, the results from Step 8 are comprehensively compared. This comprehensive comparison serves as a crucial tool for evaluating the power quality differences across the three operating conditions. The identified power quality changes are then systematically evaluated against the determined KPIs established in Step 3. Through this evaluation, any deviations from the specified constraints can potentially give rise to the issues outlined in Table 7. Consequently, addressing power quality parameters that fall outside these constraints becomes imperative. This process defines the essence of study objective 2, wherein the focus lies on proposing effective solutions to rectify any discrepancies in power quality parameters, thereby ensuring optimal system performance.

Table 8 summarises and illustrates how each step of the methodology accomplishes each respective study objective.

Table 8: Study objectives addressed in the methodology

Method steps no.	**Study objective**					
	1.1	1.2	2.1	2.2	2.3	3
1	✓					
2	✓					
3	✓					
4		✓				
5		✓				
6		✓				
7			✓	✓	✓	✓
8			✓	✓	✓	✓

3.4. Method Summary

Firstly, the method describes the use of a load flow analysis to achieve the objectives of the study. Thereafter, the method begins with investigating the operation of the conventional mine power system by developing a one-line diagram. The required operational changes are also determined. Using this information, input parameters for the load flow model are determined and collected from the case study mine.

After the conventional operation of the mine power system is comprehensively characterised, it becomes essential to proceed with benchmarking. This process involves establishing a baseline to facilitate a comparison of power quality effects before and after the integration of the solar PV power plant. Such a comparison will effectively illustrate any changes in power quality within the mine power system. Key benchmarking parameters for the mine power system include main busbar voltage, real power, reactive power, power factor, and frequency.

Once the system is benchmarked, it is paramount to establish KPIs. The KPIs will be used to determine the power quality changes of integrating the mine with a solar PV system. Therefore, the voltage and reactive power flows are important power quality KPIs for the case study.

Once all necessary model data is gathered, various simulation packages are evaluated. The most suitable software package is then chosen to calibrate and simulate the operation of the conventionally powered mine power system. Subsequently, an operational change simulation is developed by integrating the identified operational changes into the calibrated simulation model.

Following the implementation of the operational change, the final step in the methodology involves evaluating the results using predetermined KPIs. The evaluation aims to define the power quality changes from the benchmarked and operational change mine power systems. The detailed methodology steps of section 3.2 are summarised in the flow diagram in Figure 22.

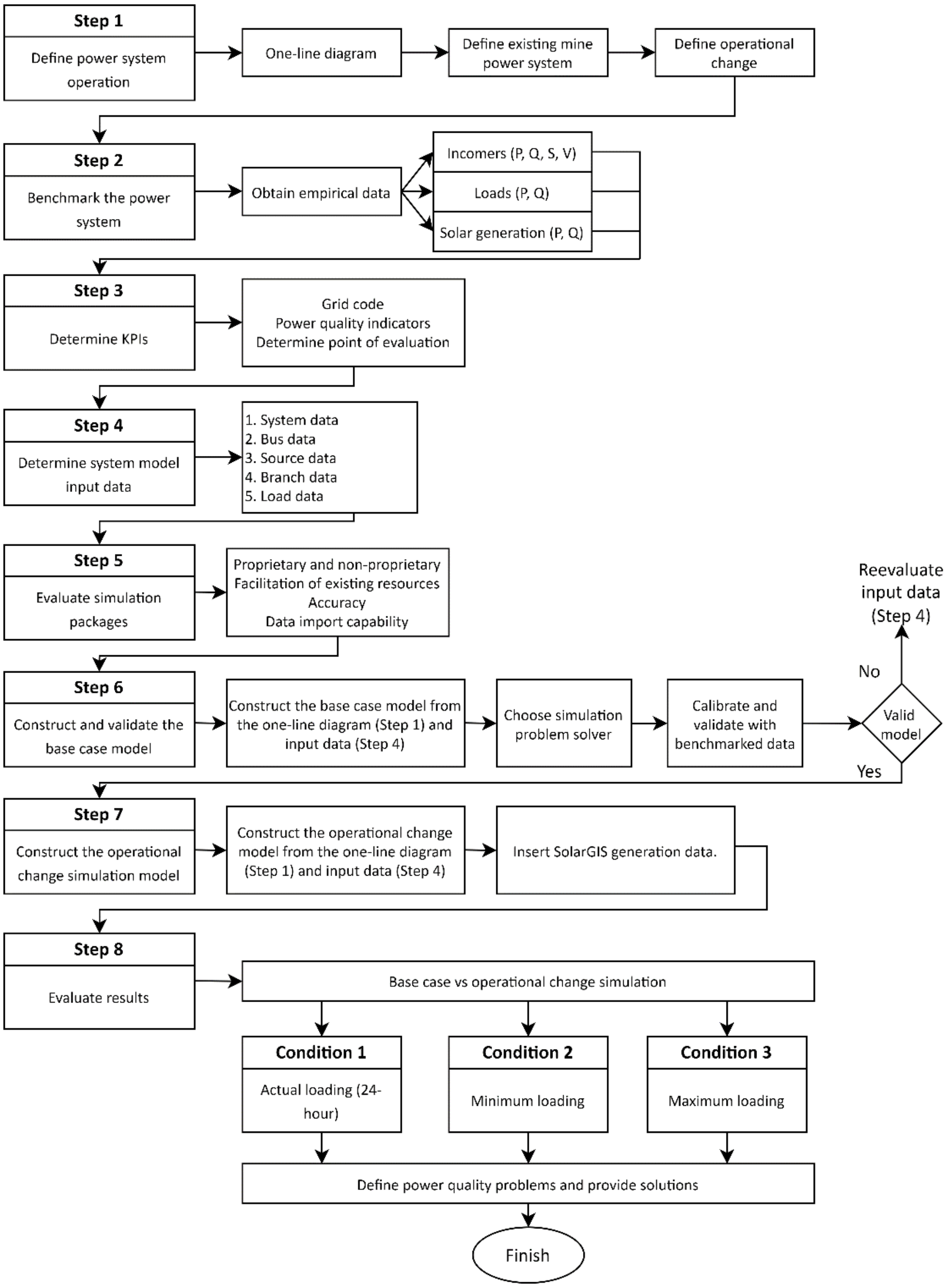


Figure 22: Flow diagram summary of the developed method

3.5. Conclusion

A methodology was developed from the literature to fulfil the specific requirements of the study objectives, illustrated in Table 8. The methodology is comprehensively detailed in section 3.2, describing each step required to evaluate the power quality of the mine power system. Subsequently, a method flow diagram was created to summarise each step.

Chapter 4: Implementation and Results

Figure 23: Solar PV arrays at a mine solar farm[11]

"Many of life's failures are people who did not realise how close they were to success when they gave up."

– Thomas A. Edison

[11] Z Lombard, Personal photograph

4. IMPLEMENTATION AND RESULTS

4.1. Preamble

In this chapter, the developed power quality analysis method was applied to a case study underground mine. This chapter is completed following Steps 3, 4 and 5 of the case study methodology outlined in Figure 8. The case study mine is a gold mine located in the North-West province of South Africa. The conventionally powered underground mine system was integrated with a 7.3 MW solar PV power plant. The conversion was done according to the drivers mentioned in Chapter 1.3.

4.2. Application of the developed method

The developed method, illustrated in Figure 22, is now applied to the case study mine. Each step of the method is critically explained, and additional information is obtained from mine personnel.

4.2.1. Step 1: Define the power system operation

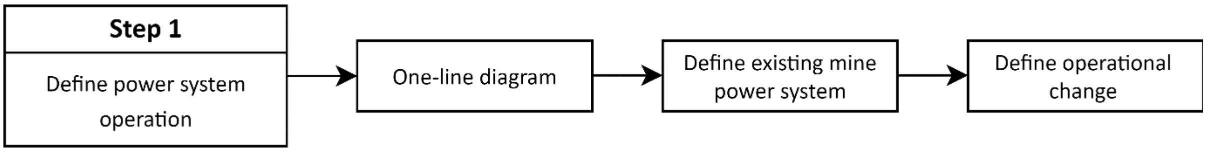


Figure 24: Summary of Step 1

The case study underground gold mine was conventionally fully powered by the power utility Eskom. The mine power system had to be integrated with an extra source of electricity, which in this case constituted a solar PV power plant, according to the drivers mentioned in Chapter 1.3. Therefore, the operational change of this case study was the integration of a solar PV power plant.

The one-line diagram for the case study mine is shown in Figure 25. The diagram was meticulously derived from existing drawings and field observations. In Figure 25, the existing mine power system (base case) and operational change from the addition of the solar PV power plant are indicated by the enclosed dashed lines.

The loads (LD1 to LD13), cables (C1 to C7), transmission lines (T1 and T2), transformers (TR1 to TR4), and sources depicted in Figure 25 are fully described in Step 4.

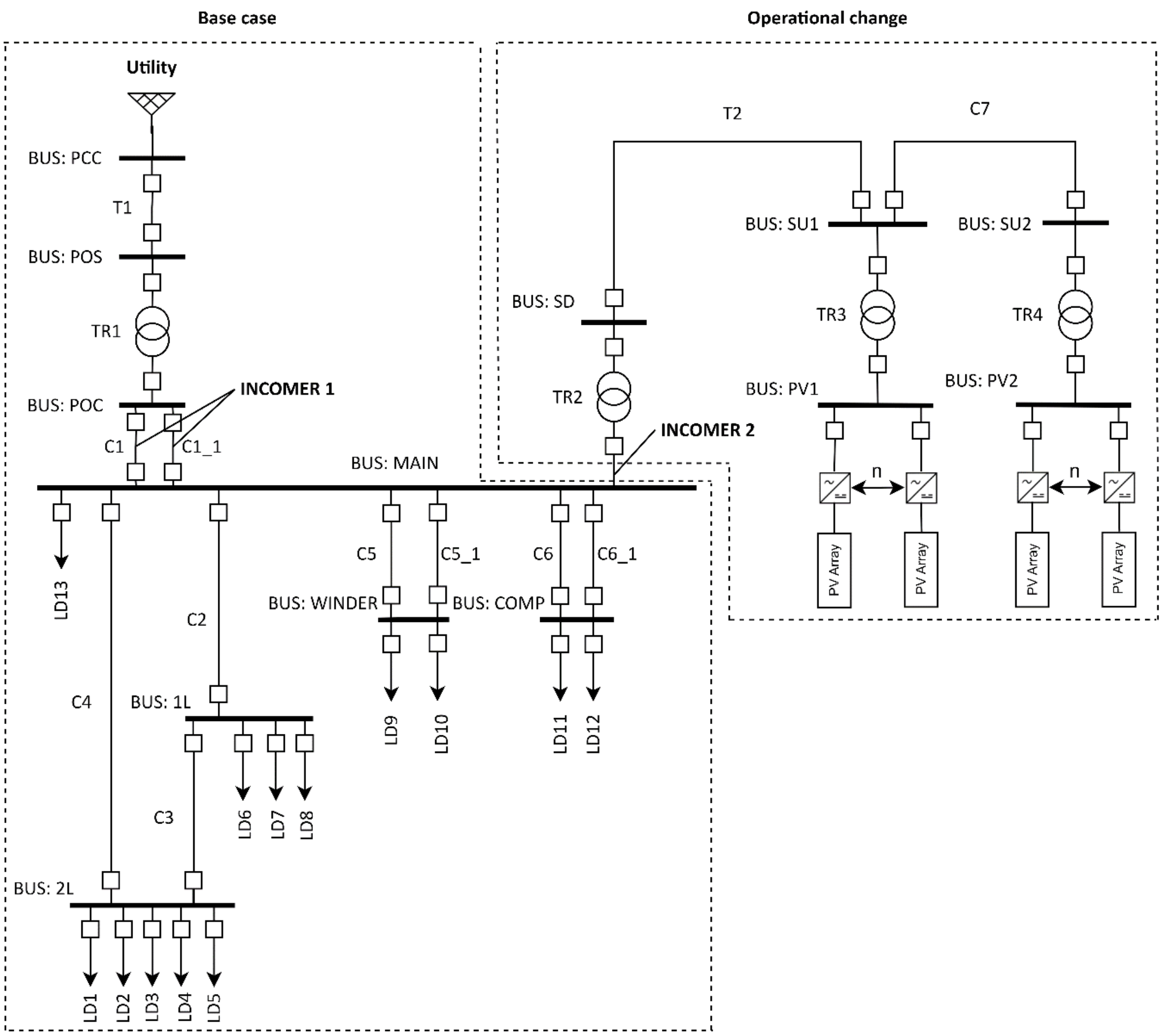
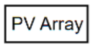


Figure 25: Case study mine one-line diagram

Table 9: Legend for Figure 25

Legend			
Utility connection		Circuit Breaker	
Transformer		Load	

Cable/transmission line		Inverter	
Bus		PV array	

4.2.2. Step 2: Benchmark the power system

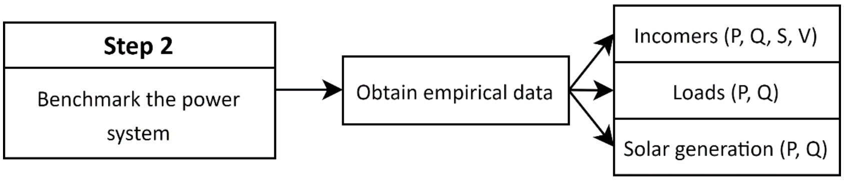


Figure 26: Summary of Step 2

Once the operation of the power system and input data are successfully obtained, the next step involves benchmarking the power system. This entails a comprehensive characterisation of both the power system's supply and loads. The benchmarked data serves dual purposes: not only does it provide a foundational understanding of the system's performance, but it also plays a pivotal role in subsequent calibration and validation processes.

To obtain empirical data for the case study, the metering systems at the case study mine were used. Metering systems were installed on all the electrical loads and supplies from the main system bus, as indicated in Figure 25. The metering systems are calibrated yearly since they are instrumental for billing purposes. Therefore, their accuracy is deemed adequate for this study.

Once a method for acquiring the empirical data has been identified, it is necessary to determine what measurements need to be taken. To conduct a load flow analysis, real power (MW) and reactive power (MVAR) for each load of the mine power system is required. The load data obtained is tabulated in the appendix (Table 23). Secondly, source data is also required and will be used to calibrate and validate the system model, therefore voltage (kV), real power, and reactive power from the incomer (at the POC) are required. Power data will ensure that a power balance is achieved.

To validate the operational change of the power system, generation data from the solar PV power plant is collected after implementation. Data required is voltage, real power, and reactive power.

The data is acquired over an interval of 30 minutes. These values are backfilled, meaning that for a value of x at time point 12:00 is the average of all measurements from 11:30 to 11:59 for the 30-minute interval.

Next, a time profile for the measurements is determined. Since mining operations circulate on a 24-hour profile, and loads are intermittently used throughout this profile, a 24-hour profile for the supply and load data is required. 24-hour load (LD) and incomer real power, reactive power and voltage empirical data were obtained from the case study mine power system, according to Figure 25.

4.2.3. Step 3: Determine KPIs

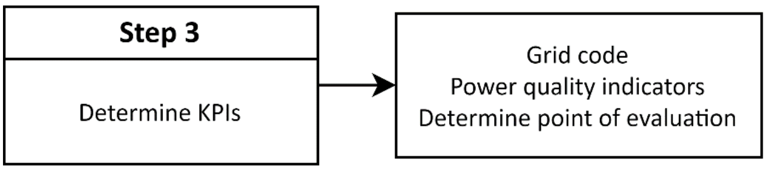


Figure 27: Summary of Step 3

The integration of the solar PV power plant with the existing mine power system will alter the voltage and power flows throughout the entire system. Hence, it's crucial to establish effective KPIs to compare these operational changes. The POC voltage and power flows are selected as important KPIs to compare the operational change, since it is at this point that Eskom measures energy usage for billing purposes. It is therefore important to adhere to the NRS048 – 2 and grid code at this point to avoid potential penalties.

The quality of supply code (NRS048 – 2) stipulates deviations of the voltage at the POC, summarised in Table 10.

Table 10: Voltage limits at the POC [118]

Nominal voltage, U_N (kV)	Maximum voltage (kV)	Minimum voltage (kV)
6.600	7.260	5.610

The South African grid code stipulates the power factor limits at the POC. The power factor at this point shall always be 0.9 lagging or higher [78].

4.2.4. Step 4: Determine system model input data

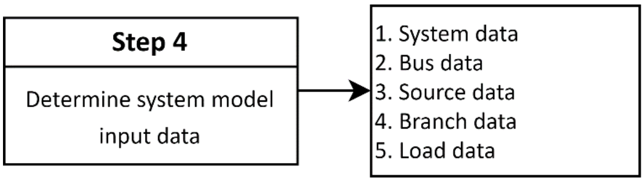


Figure 28: Summary of Step 4

In the subsequent sub-steps of step 2, the input data for the load flow model is determined. The data was obtained from equipment nameplates, site personnel, and site observations.

Step 4.1: System data

This step requires the selection of a system base MVA and base voltage. The base MVA is selected as 100 MVA. This value is chosen since it is commonly used in industry and avoids confusion over different values [111].

The base voltage is dependent on the area of the power system, and is therefore different at different nominal voltage zones. There are different voltage zones in the case study mine power system, as illustrated by Figure 29.

According to Figure 29, the following base voltages are chosen according to the rated voltage of each zone:

1. Zone 1 = $V_b = 44\ kV$
2. Zone 2 = $V_b = 6.6\ kV$
3. Zone 3 = $V_b = 33\ kV$

4. Zone 4 = $V_b = 0.8\ kV$

Using equation (4), the base impedance values are calculated for each zone:

1. Zone 1 = $Z_b = 19.360$
2. Zone 2 = $Z_b = 0.4356$
3. Zone 3 = $Z_b = 10.890$
4. Zone 4 = $Z_b = 0.0064$

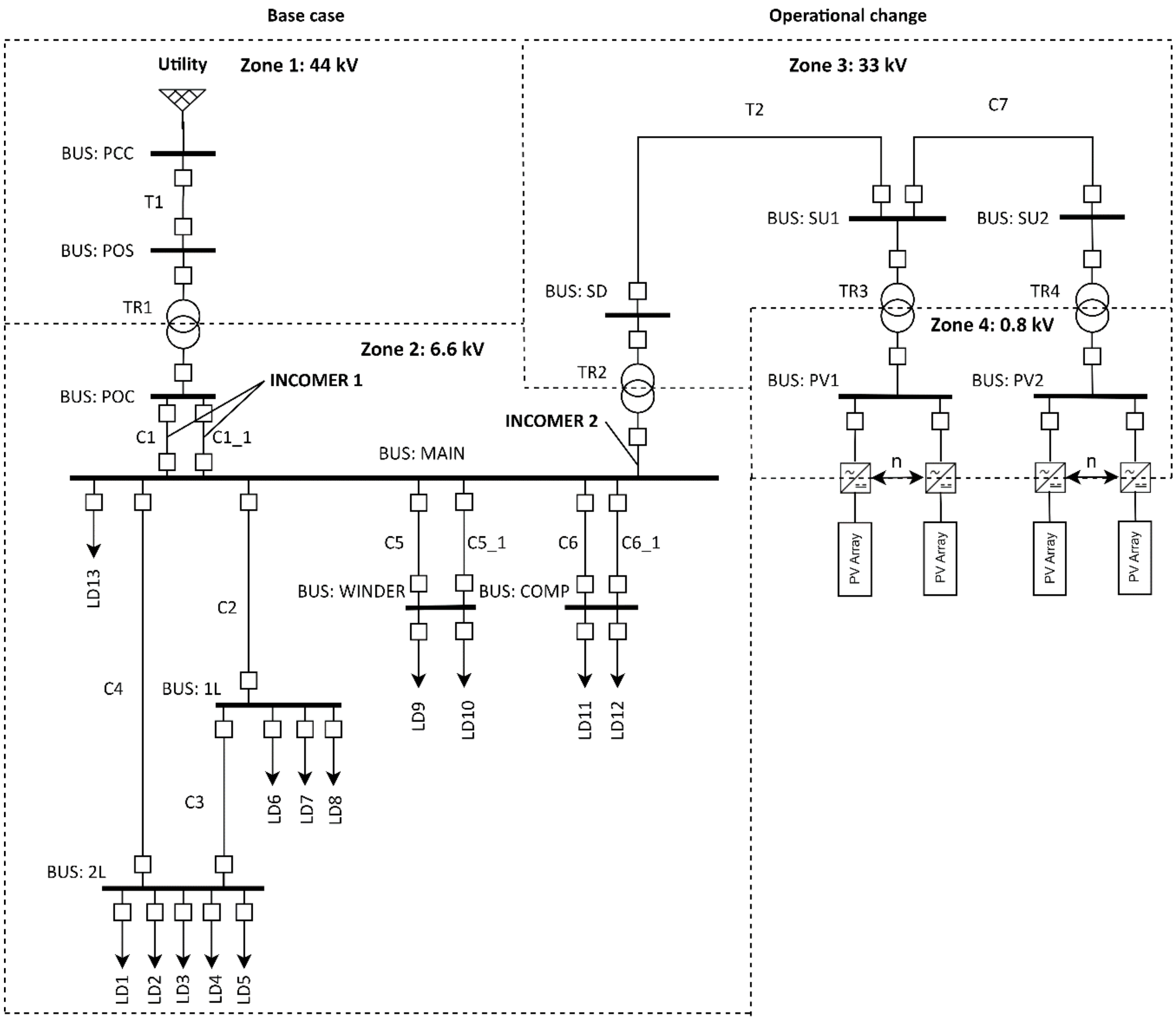
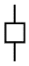
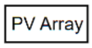


Figure 29: Voltage zones of the case study mine

Table 11: Legend for Figure 29

Legend			
Utility connection		Circuit Breaker	
Transformer		Load	
Cable/transmission line		Inverter	
Bus		PV array	

Step 4.2: Bus data

The bus data describes each bus of the power system in terms of the connected electrical equipment, such as sources, loads, and branches. Bus data was collected from the existing one-line diagrams and field observations. The bus data is described in Table 12.

Table 12: Bus data

Bus Number	Name	Classification	Nominal voltage (kV)
1	PCC	Slack	44
2	POS	Load	44
3	POC	Load	6.6
4	Main	Load	6.6
5	WINDER	Load	6.6
6	1L	Load	6.6
7	2L	Load	6.6
8	COMP	Load	6.6
9	SD	Load	33
10	SU1	Load	33
11	PV1	Voltage controlled	0.8
12	SU2	Load	33
13	PV2	Voltage controlled	0.8

Step 4.3: Source data

In this step, source data for the power system is collected. Source data in this case includes the power utility and the solar PV system. The power utility is described by the slack/swing source in Table 13, and the solar PV system is described by a voltage-controlled source in Table 15 to Table 14.

Slack/swing source

The case study mine power system is supplied by the power utility Eskom. The utility is chosen as the slack/swing source since it serves as an infinite bus to the system. The slack/swing source is described in Table 13.

Table 13: Utility data

ID	Rated kV	Classification	%V	MVAsc	X/R
Utility	44	Slack bus	100	2 625	10

Voltage-controlled source

The solar PV system proposed at the case study mine incorporates a string inverter system. This system comprises two skids, SU1 and SU2 with 13 and 25 inverters respectively. Each inverter can connect 12 strings with a maximum of 32 solar PV modules per string. The mine utilised single-axis mounting structures to improve the specific solar power received. The combined AC power output of the plant equals 7.3 MW. The solar PV system is designed to operate at unity power factor. Table 14 describes the solar PV system data obtained from the inverter and PV module data sheets.

Table 14: Solar PV power plant data

ID	SU1	SU2
Inverter quantity	13	25
Total AC inverter capacity (kW)	3 250	6 250
Strings per inverter	12	12
Total strings	156	300
Total PV modules	4 953	9 924
PV modules per string	32	33
Total DC PV power rating (kW)	2 675	5 359
Rated voltage DC (V)	1 160	1 160
Rated voltage AC (V)	800	800
Rated AC power (kW)	2 407	4 823

Power factor (Lagging %)	97	97
Classification	Voltage controlled bus	Voltage controlled bus

The inverters used for the system are described in Table 15.

Table 15: Inverter data

Inverter		
Output (AC)	Rated voltage (kV)	0.80
	Rated current (A)	180.50
	Rated kVA	250
	Frequency (Hz)	50
	THD (%)	<3
	Rated PF (%)	>99
	Rated efficiency (%)	99
Input (DC)	Max voltage (V)	1 500
	Min voltage (V)	500
	Nominal voltage (V)	1 160
	Number of MPPT	12
	Rated input current (A)	30*12[12]

The PV modules used for the system are described in Table 16.

Table 16: PV module data

Solar PV module	
Rated W	540
Rated voltage (V)	41.64
Open-circuit voltage (V)	49.60
Rated current (A)	12.96
Short-circuit current (A)	13.86
Efficiency (%)	20.80
Irradiance (W/m^2)	1 000 @ 25 °C

The efficiency curve of the inverter used is illustrated in Figure 30. The inverter's efficiency is improved when the MPPT voltage is at its highest rated value of 1 300 V.

[12] * Only compatible with Sungrow logger and iSolarCloud

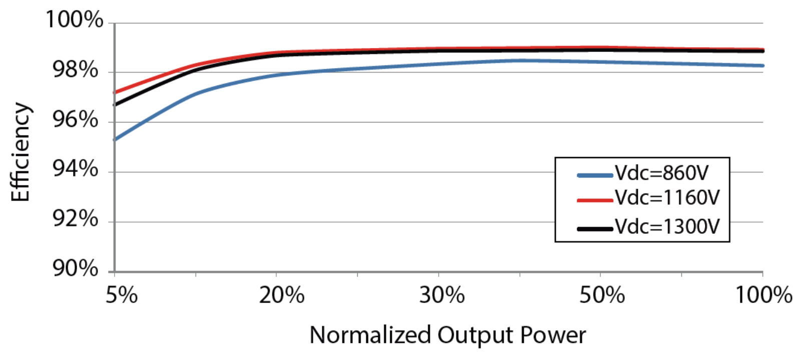


Figure 30: Efficiency curve for the inverter of Table 15

Step 4.4: Branch data

Branches describe cables, transmission lines, transformers, and reactors that interconnect two buses. The specified ratings of each component are acquired by consulting data sheets and equipment nameplates.

Cable/transmission line data

Transmission line and cable impedances are important parameters for the load flow simulation. These parameters affect the voltage and reactive power flows of the power system. Table 17 describes the transmission line and cable data of the case study mine power system. The calculated impedance base values from Step 1 are used to determine the p.u. impedances required for the load flow model.

Table 17: Transmission line/cable data

Transmission line/cable name	Bus-to-Bus	Rated Voltage (kV)	Capacity (MVA)	Length (km)	Size (mm^2)	Material type	Resistance (ohm/km)	Reactance (ohm/km)	$R_{p.u.}$	$X_{p.u.}$	Phase
T1	PCC-POS	44	22.86	21	78.83	Al	0.3064	-	0.3948	-	3
T2	SU1-SD	33	14.86	2.5	68.13	Al	0.4550	-	0.1044	-	3
C1 & C1_1	POC-MAIN	6.6	20.12	0.2	1 000	Cu	0.0490	0.0890	0.2025	0.3678	1
C2	Main-1L	6.6	5.83	0.8	300	Cu	0.0790	0.0830	0.1451	0.1524	3

C3	1L-2L	6.6	5.83	0.4	300	Cu	0. 0790	0.0830	0.0725	0.0762	3
C4	MAIN-2L	6.6	5.83	1.2	300	Cu	0. 0790	0.0830	0.2176	0.2287	3
C5 &C5_1	MAIN-WINDER	6.6	4.63	0.3	185	Cu	0.1280	0.0870	0.0882	0.0599	3
C6 & C6_1	MAIN-COMP	6.6	4.63	0.4	185	Cu	0.1280	0.0870	0.1175	0.0799	3
C7	SU2-SU1	33	15.15	0.275	120	Al	0.3250	0.2420	0.0082	0.0061	3

Transformer data

Transformers are used to change system voltages, therefore the primary and secondary voltages are collected from the transformer nameplate. Other parameters such as the rated MVA, Z% impedance and type of connection are collected from the nameplate.

The transformer X/R ratios are used to determine the resistance and reactance of each transformer respectively. Using Figure 14, the X/R ratios are read according to the transformer sizes utilised by the mine power system and populated in Table 18. The resistance and reactance values are calculated according to Equation (5).

Table 18: Two-winding transformer data

ID	Bus-to-Bus	Rated MVA	Primary kV	Secondary kV	Z%	X/R	X (p.u.)	R (p.u.)	Connection primary-secondary
TR1	POC-Main	20	44	6.6	10.60	32	0.1060	0.00331	YNd1
TR2	SD-Main	10	33	6.6	11.00	27	0.1100	0.00407	YNd11
TR3	SU1-PV1	6.3	33	0.8	10.03	23	0.1003	0.00436	Dy11
TR4	SU2-PV2	3.15	33	0.8	6.74	17	0.0674	0.00396	Dy11

Transformer tap settings are essential inputs as they control the main bus voltage. In the case study mine, the transformer lacks an automatic OLTC, so the tap settings are fixed. Resulting in no automatic voltage control of the main bus.

Step 4.5: Load bus (PQ-bus)

The case study mine power system has a total of 12 loads. Data for each component was obtained from their respective nameplates. A description of each load is given in Table 19:

Table 19: Load data

Description	ID	Quantity	Type	Rated MW	Rated kV
Winders	Man Winder	1	Synchronous	4.085	6.6
	Rock Winder	1	Synchronous	3.75	6.6
Compressors	Compressor 1	1	Synchronous	3.95	6.6
	Compressor 2	1	Induction	4.8	6.6
Dewatering pumps	1L Pump 1 - 3	3	Induction	1.3	6.6
	2L Pump 1 -5	5	Induction	0.925	6.6
Ancillary feeder	UG Feeder	1	Load	Benchmark data	6.6

4.2.5. Step 5: Evaluate simulation packages

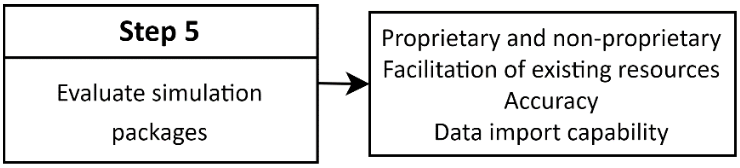


Figure 31: Summary of Step 5

A software simulation package, capable of solving a load flow problem, was needed for this application. It is required to solve the load flow problem, under various time step load data, to provide insights into the power quality of the mine power system.

Based on the selection criteria, PowerWorld was chosen to simulate the mine power system, both before and after the operational change. This decision was influenced by the fact that PowerWorld offers a proprietary software tool with a non-proprietary version capable of conducting load flow analysis. This feature is particularly valuable as it allows engineers to utilise the software on-site without incurring additional company expenditure.

This software package also yields accurate load flow results, illustrated by Kumar *et al*. [123] and Kuanar *et al*. [124] compared with proprietary packages, such as MATPOWER, NEPLAN and PYPOWER used in an IEEE 9-bus and 14-bus test power system. From their test, PowerWorld did not deviate more than 1% on voltage and voltage phase angle compared to the test power system results.

Additionally, PowerWorld offers a convenient feature for importing loading data in Excel format, facilitating the execution of time-step varying simulations.

4.2.6. Step 6: Construct and validate the base case simulation model

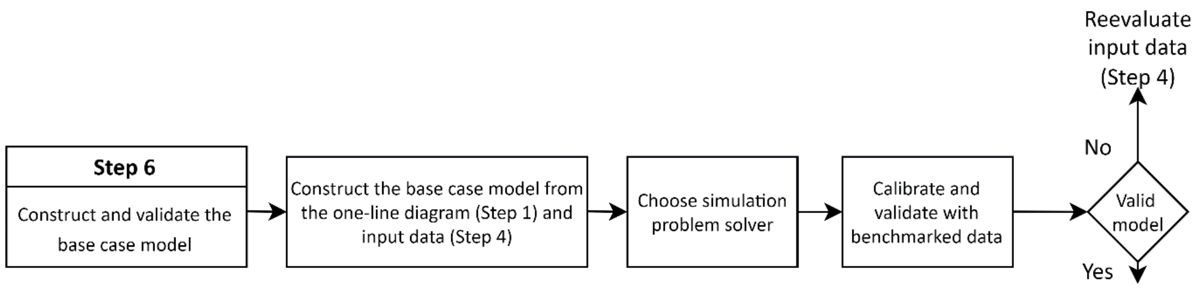


Figure 32: Summary of Step 6

The conventionally powered mine power system, depicted by the one-line diagram developed in Step 1, was replicated in a simulation model using the PowerWorld Simulator. This system will now be referred to as the base case. Step 2 was followed systematically to construct the base case model. First, the system buses were drawn in the simulation package and named according to the bus data in Step 2.2 (Table 12), depicted in Figure 33. Bus parameters such as nominal voltages and bus classification were inserted, as depicted in Figure 34.

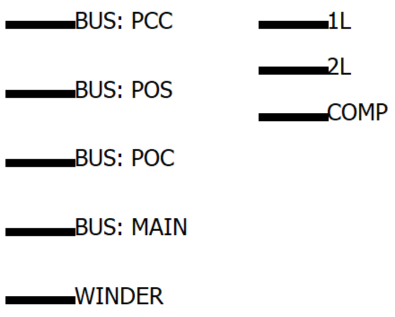


Figure 33: Construction of one-line diagram

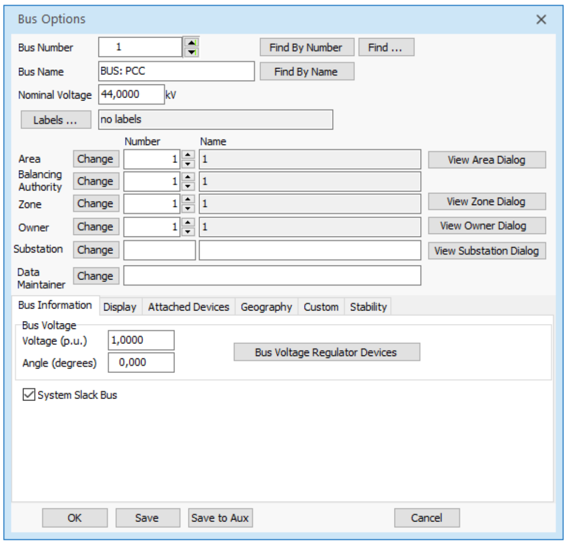


Figure 34: Bus data input dialogue

Next, Step 2.3 is executed. The base case mine power system relies solely on one power source, the utility provider, Eskom. This source will serve as the slack source since it serves as an infinite source. The slack source is inserted, as depicted in Figure 35. The input dialogue of the slack source, in Figure 36, has numerous settings. However, the voltage control method and voltage set points will be utilised for calibration purposes.

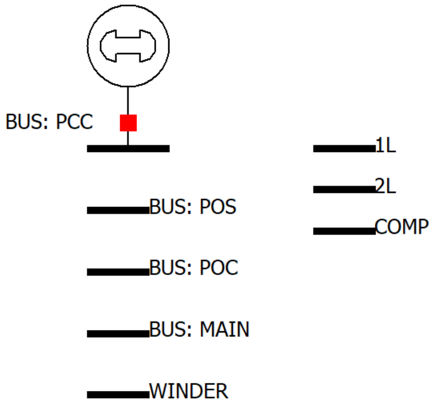


Figure 35: Construction of a slack source

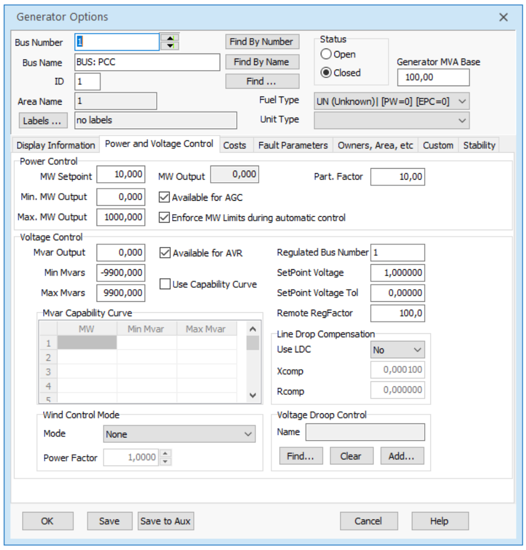


Figure 36: Slack source input dialogue

Step 2.4 contains all the branch data. Branch elements such as transmission lines, cables, and transformers are added, as depicted in Figure 37.

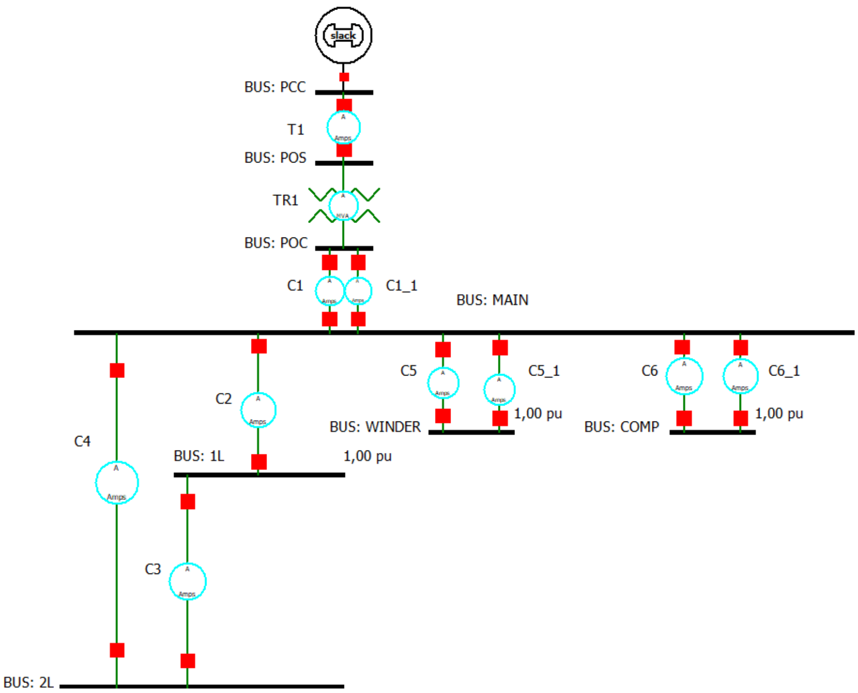


Figure 37: Branch one-line diagram

Once the branch elements are inserted, the impedances of each component are inserted from Table 17 and Table 18 into the input dialogues shown in Figure 38 and Figure 39 respectively.

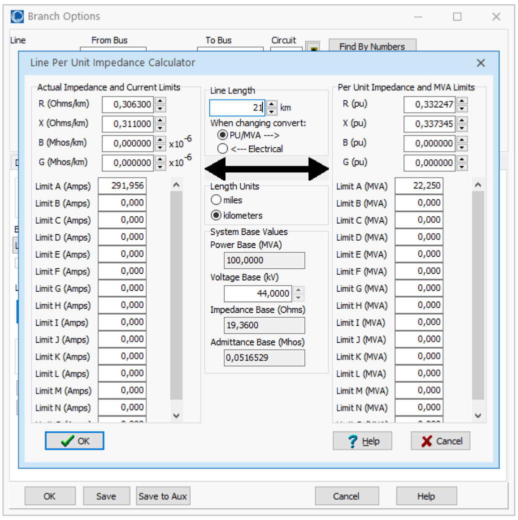


Figure 38: Transmission line/cable input dialogue

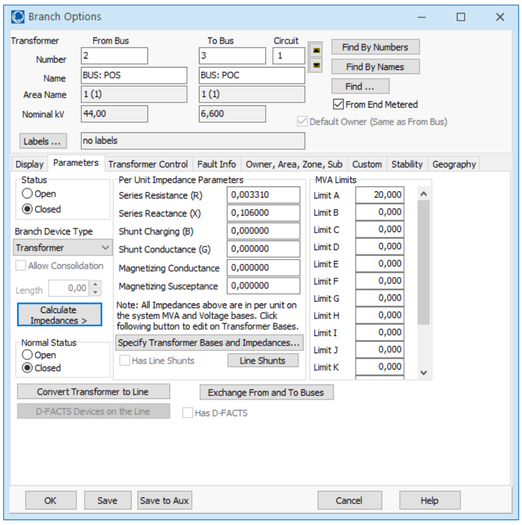


Figure 39: Transformer input dialogue

Finally, loads of the mine power system were inserted into the base case simulation model, as depicted in Figure 41. The loads were modelled as constant real power and reactive power loads. The load data from Step 2.5 was inserted into the input dialogue depicted in Figure 40.

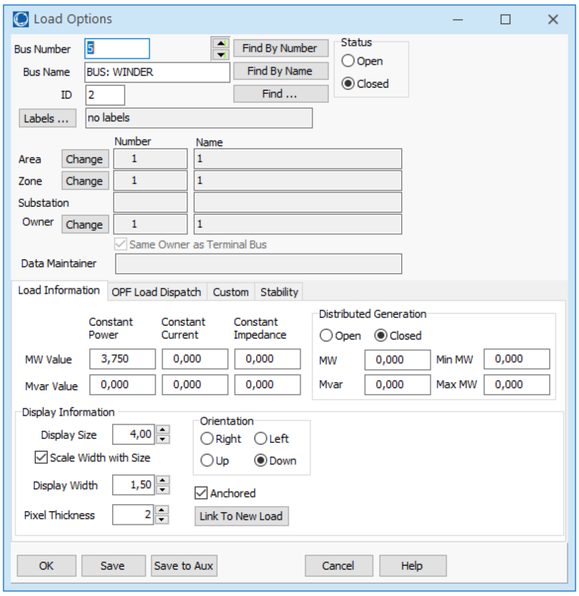


Figure 40: Load input dialogue

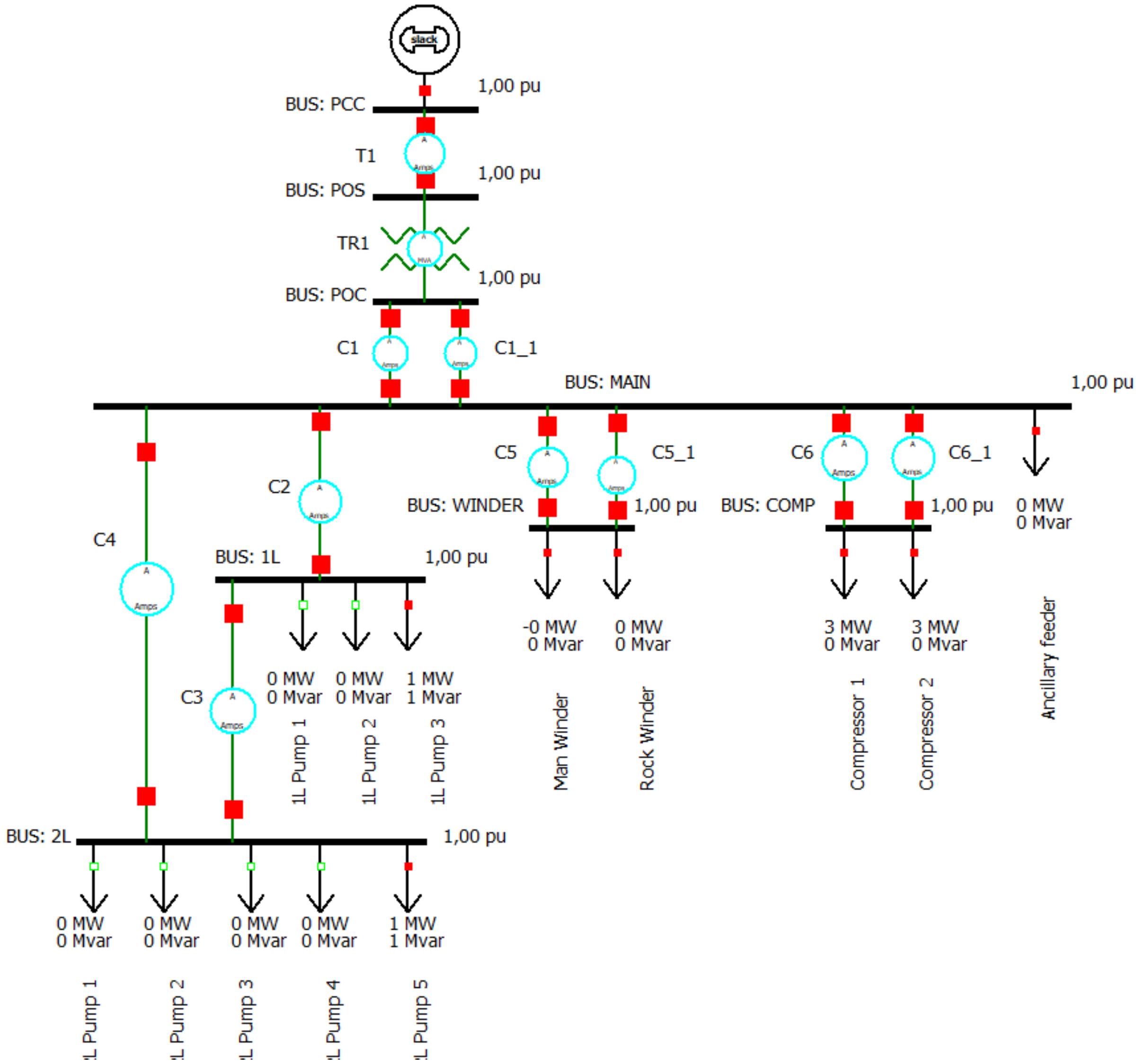


Figure 41: Completed base case mine power system

Problem formulation

The PowerWorld simulation package has different solvers built in, such as Newton and Gauss-Seidel methods. However, Newton's methods show fast convergence and accurate solutions, therefore this method was used in the simulation package [87].

Base case model validation

To achieve a model that can accurately represent the actual mine power system, the base case model needs to be calibrated. The 24-hour benchmarked loading data was inserted into all the respective loads of the base case simulation model. A 24-hour time step simulation was executed with the half-hourly benchmarked data.

First, the POC (BUS: POC) voltage was calibrated. To achieve this, the TR1 transformer tap positions were changed until the voltage of this bus accurately resembles the actual mine power system. It is important to note that the transformer TR1 utilises fixed taps, meaning that a predetermined tap value was selected that does not automatically control the POC voltage. The POC bus voltage is rated at 6.6 kV.

Figure 42 compares the actual benchmarked voltage profile with the base case simulated voltage profile. It is evident that the POC bus voltage is higher than the rated 6.6 kV norm averaging at 6.870 kV.

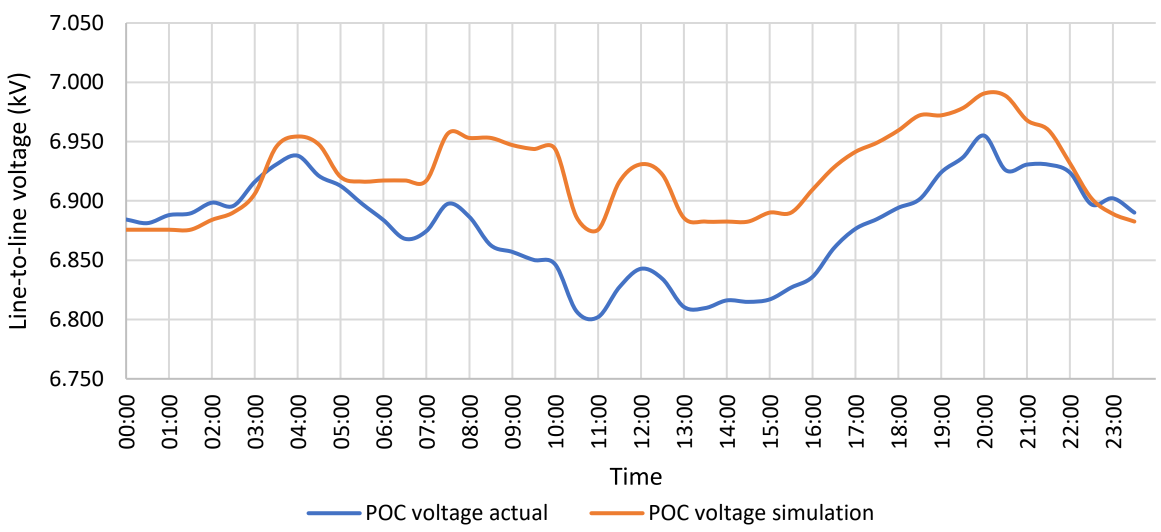


Figure 42: POC voltage actual vs simulation

Secondly, the power flow profiles were evaluated. The power flows are evaluated at the POC. The accumulative power flows were measured through cables C1 and C1_1. The apparent power, real power, reactive power and power factor are depicted in Figure 43, Figure 44, Figure 45, and Figure 46 respectively.

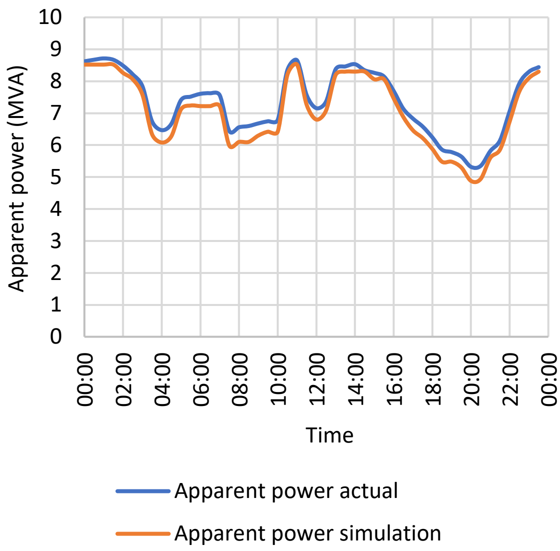


Figure 43: Apparent power actual vs simulation

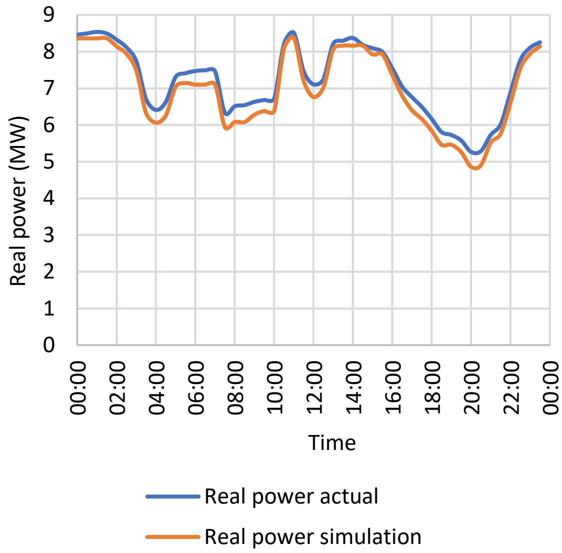


Figure 45: Real power actual vs simulation

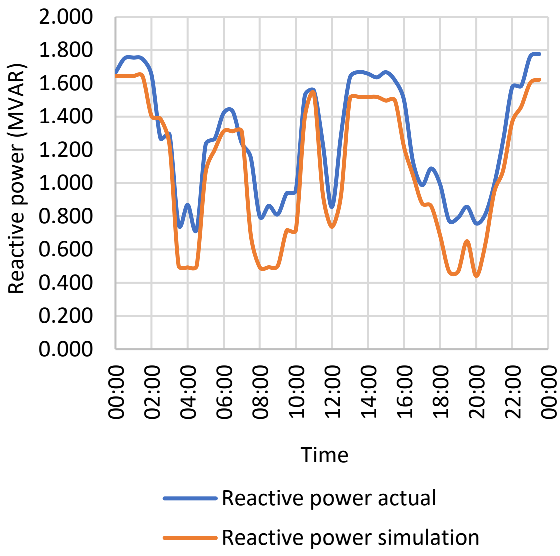


Figure 44: Reactive power actual vs simulation

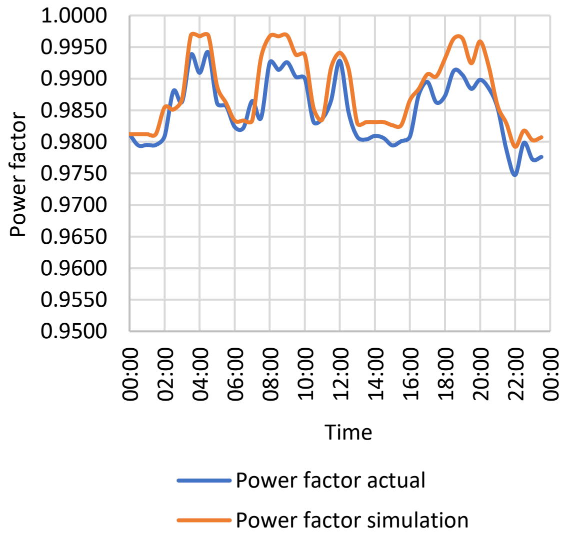


Figure 46: Lagging power factor actual vs simulation

Using the MAE formula from Equation (6) and the dataset provided in the appendix (Table 24), the MAE for voltage, apparent power, real power, reactive power, and power factor were calculated over a 24-hour period. The resulting MAE values from Table 24 are summarised in Table 20 below:

Table 20: Base case MAE results

Parameter	MAE (%)
Voltage (kV)	0.70
Apparent power (MVA)	4.10
Real power (MW)	3.81
Reactive power (MVAR)	9.91
Power factor	0.33

The power flows in Figure 43, Figure 45 and Figure 46 track the actual data within an MAE of 5%. The reactive power flow, Figure 44, has a larger MAE of 9.91% with differences extending to 43% in certain intervals. Mine loads such as pumps, fans and compressors operate in a steady state, meaning their operations do not change instantaneously. However, as mentioned in Section 1.8.2, the operation of the rock and man winders is transient. Their transient behaviour injects reactive power into the grid in intervals smaller than 30 minutes. Therefore, a larger reactive power difference is expected in certain intervals.

However, the simulation model was successfully constructed and validated to an actual mine power system with an MAE of less than 10%. Therefore, based on Table 20, it can be concluded that Study Objective 1.2 was met.

4.2.7. Step 7: Construct the operational change simulation model

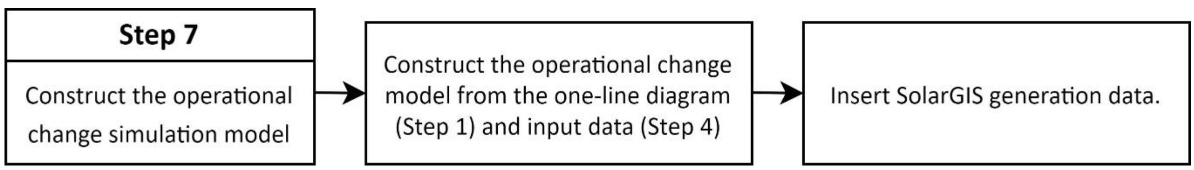


Figure 47: Summary of Step 7

Next, the operational change simulation model was constructed. The operational change simulation model was constructed from the calibrated base case model from Step 6. The operational change simulation model is depicted in Figure 48. In this model, the SolarGIS generation data was inserted into the two solar PV systems. The generation data was obtained by inserting the separate solar PV power plant sizes of 2 675 kW and 5 359 kW from Step 4 (Table 14) into the SolarGIS tool at the mine-specific location[13].

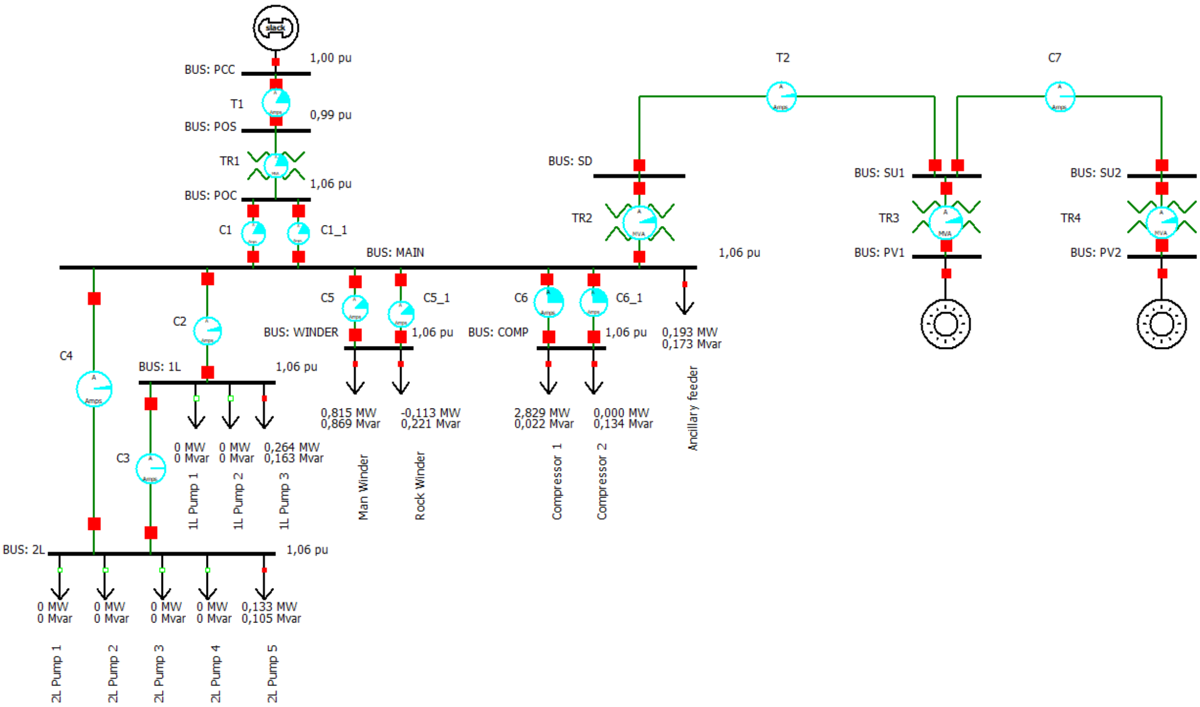


Figure 48: Constructed operational change simulation model

The benchmarked loading data used in Step 6 was inserted into the operational change simulation model with the accompanying solar PV generation data, depicted in Figure 48. Figure 49 illustrates the voltage at the POC (BUS: POC) from the simulation results.

[13] Global Solar Atlas

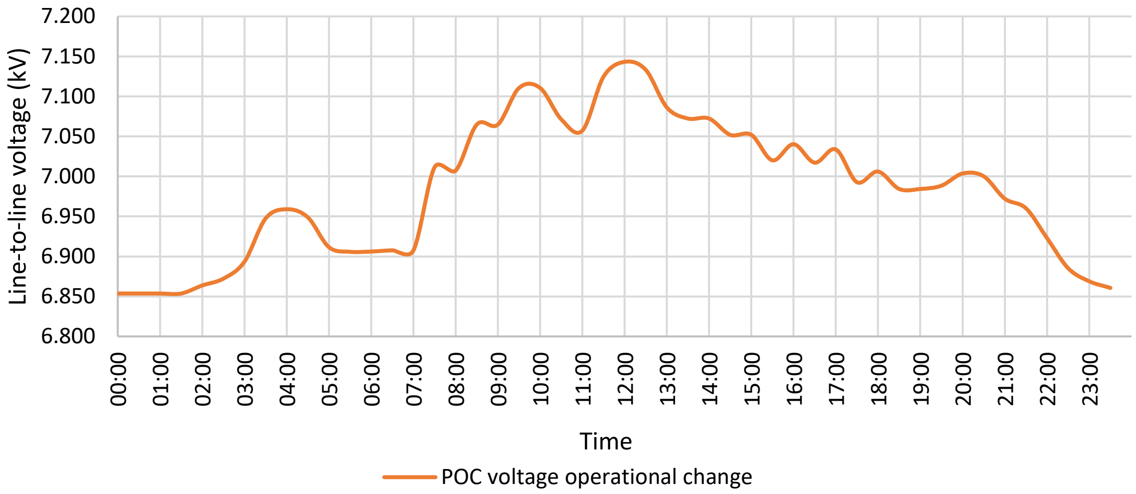


Figure 49: POC voltage operational change

Next, the power flow profiles were evaluated. The power flows are evaluated at the POC. The power flows were measured through cables C1 and C1_1. The apparent power, real power, reactive power, and power factor are depicted in Figure 50. In Figure 50, a poor power factor is evident during peak solar generation due to the decrease in real power while reactive power remains unchanged. This is caused by the unity power factor generation characteristics of the solar plant.

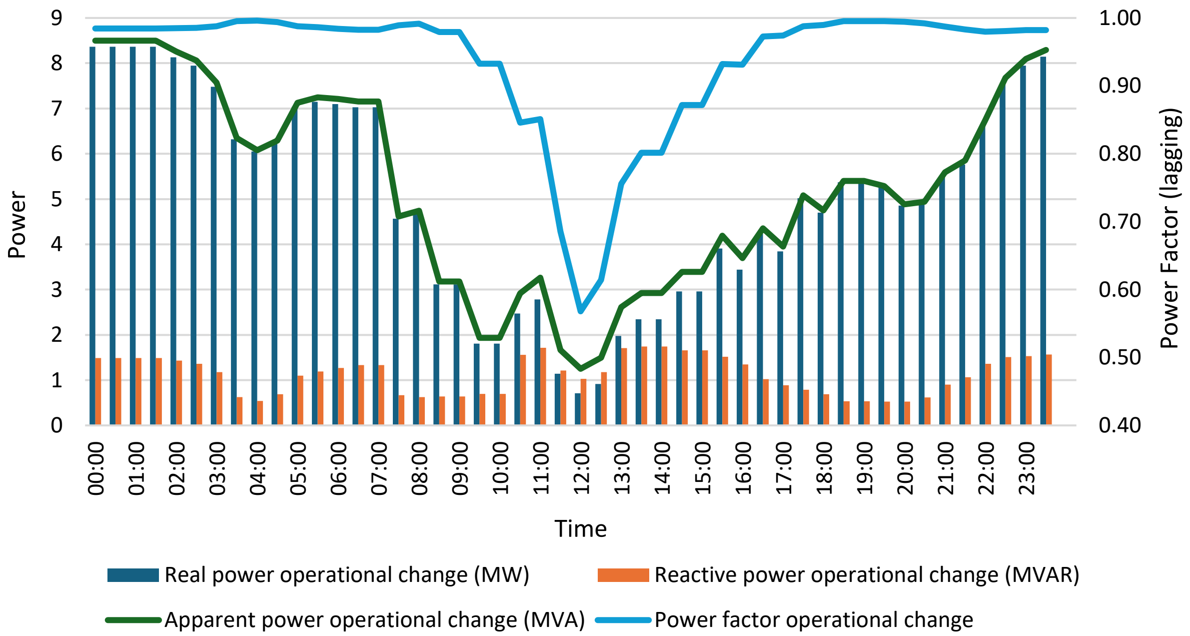


Figure 50: Operational change power flows

4.2.8. Step 8: Evaluate results (KPI validation)

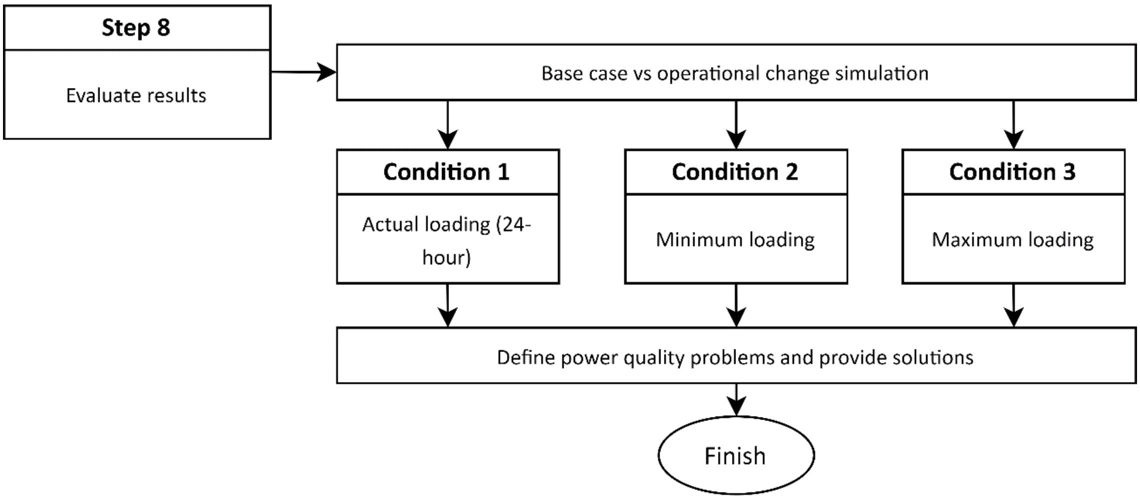


Figure 51: Summary of Step 8

Study objective 2 requires the identification of power quality changes due to the addition of a solar PV power plant to the existing mine power system. From Step 6 and Step 7, it was concluded that the constructed base case and operational change simulation models are accurate and can therefore be used to predict power quality changes.

The resulting comparative 24-hour voltage profile from the base case and operational change is depicted in Figure 52.

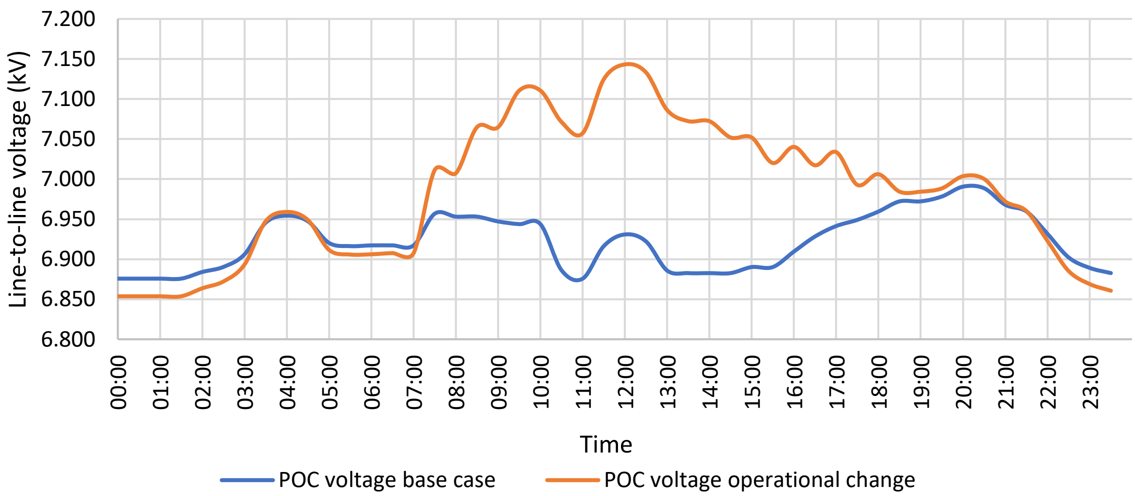


Figure 52: POC voltage base case vs operational change

From Figure 52., it is apparent that the voltage profile during the solar PV generation window of 07:00 to 18:00 increases the POC voltage to a peak of 7.143 kV over the base case peak of 6.950 kV. The increased voltage is due to the power generated by the solar PV system since the inverters operate at unity power factor. Although the voltage remains within the voltage limit of 7.260 kV, it represents a significant rise from the base case voltage.

The resulting power flows are depicted in Figure 53 to Figure 56. In the solar PV generation window between 07:00 and 18:00, it is evident that the utility's apparent power (Figure 53) and real power (Figure 54) drop in accordance with the solar power generated. However, since the solar PV power plant operates at a unity power factor, the utility is used as a reactive power source (Figure 54). This is the reason for the poor power factor during the generation window, depicted in Figure 56. With that said, the mine power system does not meet the power factor standard set in the NRS048 – 2 and the grid code of 0.8 lagging since a minimum power factor of 0.5680 lagging was observed at the POC.

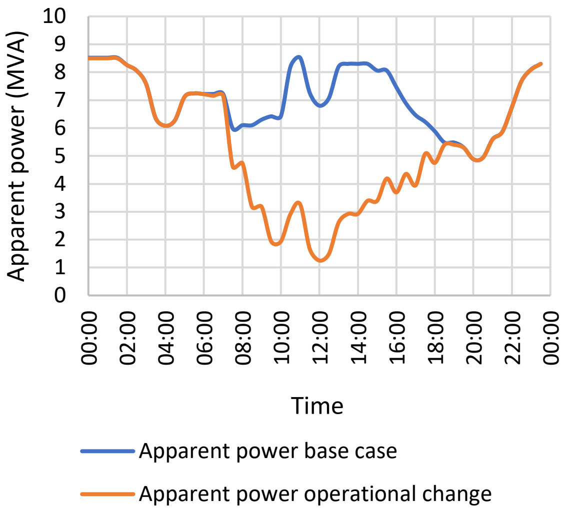


Figure 53: Apparent power base case vs operational change

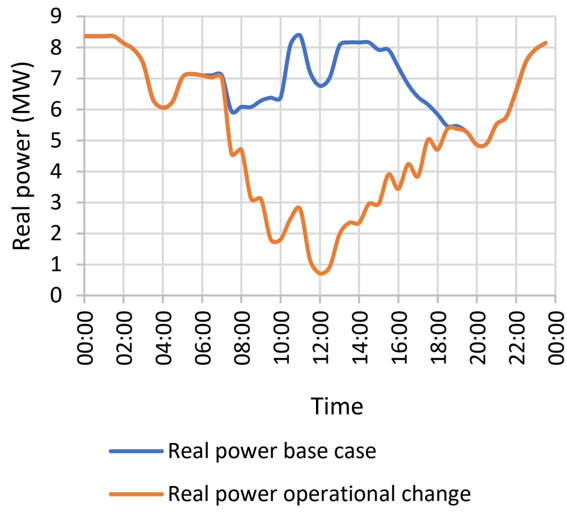


Figure 54: Real power base case vs operational change

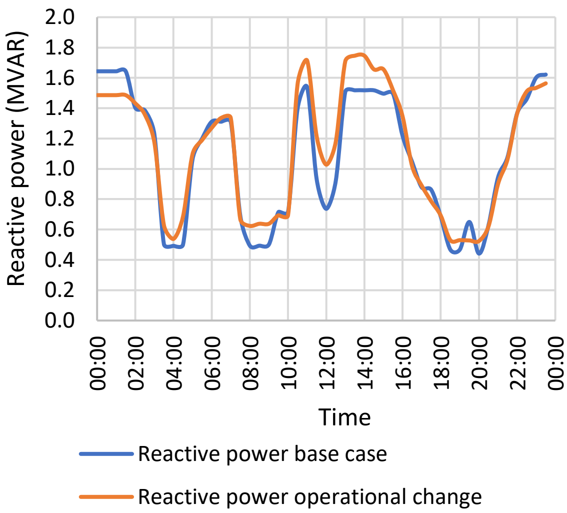


Figure 55: Reactive power base case vs operational change

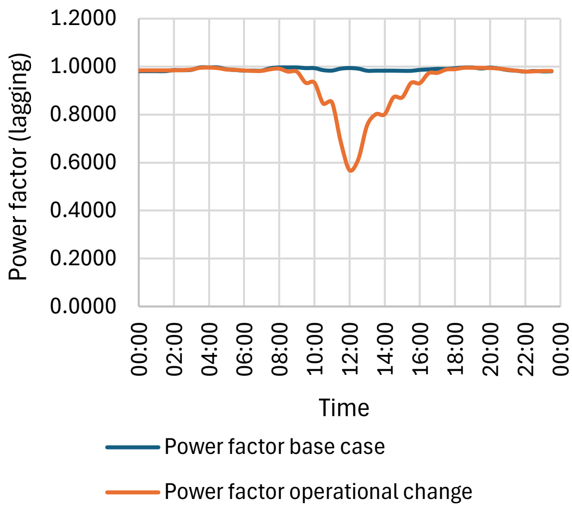


Figure 56: Power factor lagging base case vs operational change

From the 24-hour time step simulation it can be concluded that the solar PV power plant impacts the POC voltage and power factor during the generation window. Table 21 summarises the maximum, minimum, and average values for voltage and power factor at the POC for the 24-hour simulated profiles. From the results described in Table 21, it can be concluded that study objective 2.1 was achieved.

Table 21: Operational change data comparison

Parameter	Base case	Operational change
Voltage maximum (kV)	6.991	7.143
Voltage average (kV)	6.923	6.984
Voltage minimum (kV)	6.876	6.854
Power factor minimum	0.9790 lagging	0.5680 lagging
Power factor average	0.9880 lagging	0.9310 lagging
Power factor maximum	0.9970 lagging	0.9960 lagging

Following the 24-hour profile results, maximum and minimum loading conditions were simulated to achieve study objectives 2.2 and 2.3 respectively. Maximum and minimum loading conditions were obtained from the benchmarked measurements and inserted into the simulation model respectively. Each condition was simulated with varying solar PV generation power of 0%, 25%, 50%, 75% and 100%. The simulation results are tabulated in Table 22.

Table 22: Operational change loading and solar PV generation impact on power quality at the POC

Solar PV power	Loading	POC Voltage (kV)	Apparent power (MVA)	Real power (MW)	Reactive power (MVAR)	Power factor	
100%	Minimum	**7.238**	1.988	-1.868	0.680	0.9397	Lagging
	Maximum	7.068	3.046	1.886	1.886	0.7853	Lagging
75%	Minimum	7.186	0.652	0.310	0.574	**0.4752**	Lagging
	Maximum	7.013	4.350	3.966	1.786	0.9118	Lagging
50%	Minimum	7.132	1.362	1.268	0.496	0.9313	Lagging
	Maximum	6.957	5.817	5.554	1.782	0.9549	Lagging
25%	Minimum	7.077	2.896	2.860	0.458	0.9874	Lagging
	Maximum	6.898	7.358	7.158	1.706	0.9728	Lagging
0%	Minimum	7.019	4.494	4.470	0.460	0.9947	Lagging
	Maximum	6.837	8.953	8.782	1.744	0.9808	Lagging

Table 22 reveals that specific loading and generation conditions can result in probabilistic power quality outcomes. Minimum loading with a full generation supply will lead to voltages nearing the voltage limit of 7.260 kV. This limit can be exceeded if mining operational changes occur, such as the requirement for less compressed air leading to the use of only one compressor in this case. In certain conditions, the power factor at the POC is below the limit of 0.8 lagging. This can lead to high reactive energy charges and penalties from the utility.

It is clear from this evaluation that the integration of solar PV systems into an existing mine power system can lead to voltage and power factor quality problems. Excessive system voltages can break down the insulation of electrical components and decrease equipment operational time, as mentioned in Chapter 1.6. Further, utilising the power utility as an effective reactive power source can lead to penalties and higher reactive energy costs from the power utility. Little real power in this case is supplied through transformer TR1, which drives the transformer to operate in an inefficient region and can cause a reduction in operational life.

Now that the power quality impacts are determined from implementing the solar PV system, possible solutions are required to fully achieve study objective 3. The rated POC bus voltage is 6.6 kV. To achieve a bus voltage near 6.6 kV, a transformer tap changing control regime is suggested for TR1. This regime was inserted into the transformer control dialogue in PowerWorld. Accordingly, a POC voltage without the solar PV rise was obtained as depicted by the blue line in Figure 57.

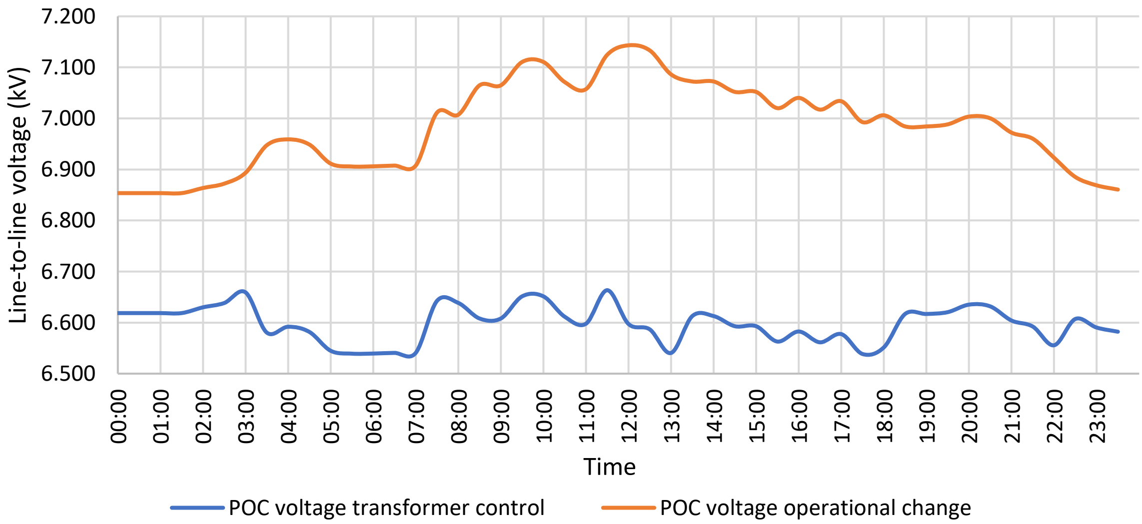


Figure 57: Comparison of POC voltage with transformer tap control

The next concern was the power factor at the POC that dropped below the allowable limit of 0.8 lagging. A PFC capacitor was proposed to solve this problem. This solution requires a controlled PFC device since the power factor only deteriorates during the solar PV generation window. A 1 MVAR-controlled capacitor was implemented in the simulation model that controls according to a power factor set-point of 0.85 lagging at the POC. The simulated results are depicted in Figure 58.

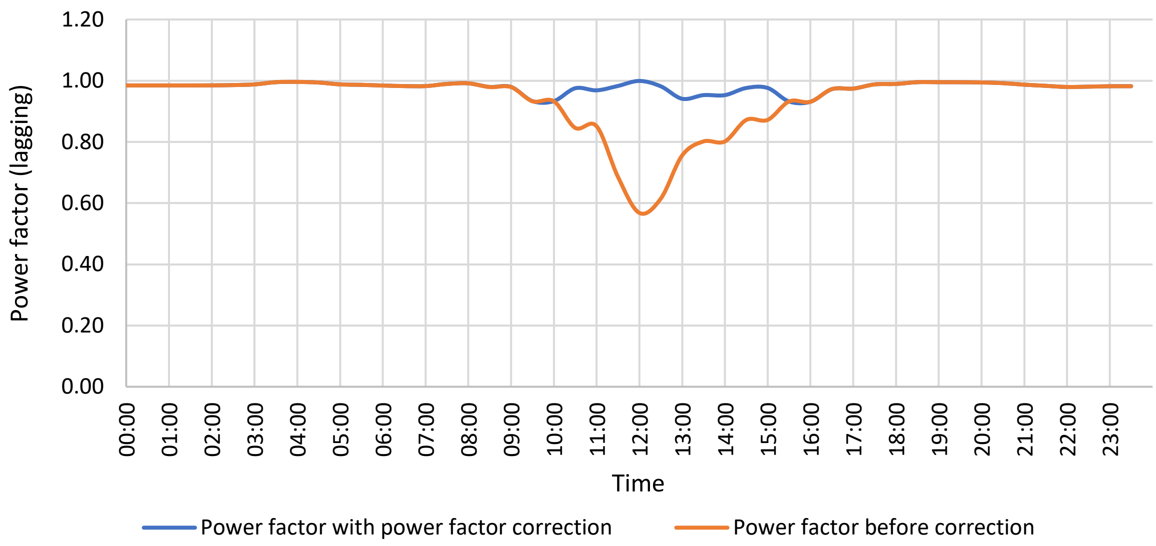


Figure 58: Comparison of power factor at the POC with power factor correction

Accordingly, the proposed solutions to the voltage and power factor problems were implemented in the simulation model and therefore achieved study objective 3. Through this, the simulation model predicted power quality problems before the integration of the solar PV system. The simulation model is a valuable tool for planning purposes. Additional costs to achieve a good system power quality can therefore be assessed before installing the solar PV system.

4.3. Study validation

To validate the methodology, the implemented solar PV system at the case study mine was benchmarked according to Step 2. The actual benchmarked loading data was inserted into the operational change simulation model of Step 7 with the predicted solar PV generation data. This was done to evaluate the effectiveness of predicting the power quality changes of the operational change simulation model.

Figure 59 compares the actual benchmarked voltage at the POC (BUS: POC) with the simulated operational change results. It is evident that the actual and simulated voltage profiles closely resemble each other.

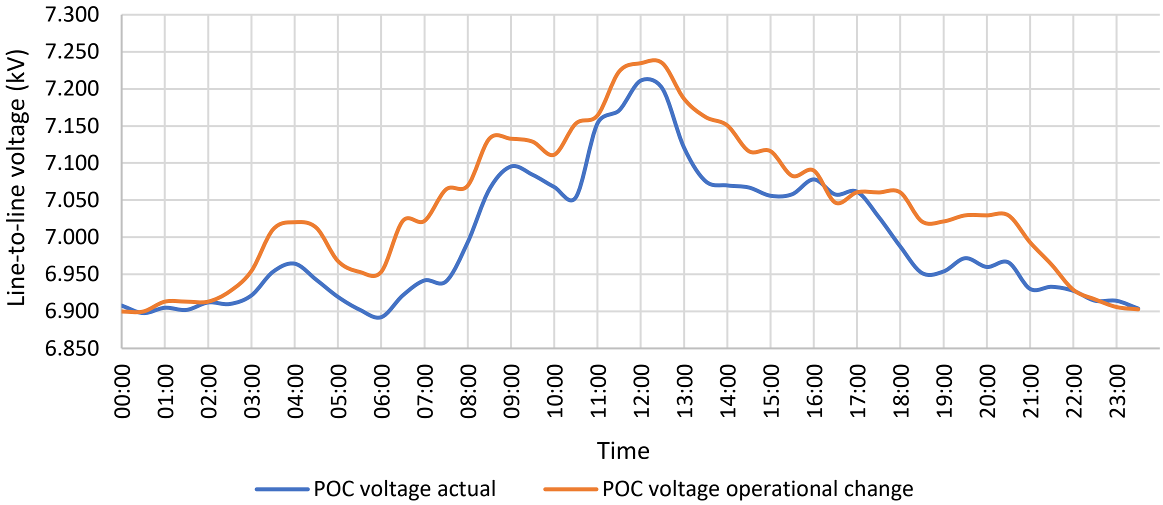


Figure 59: POC voltage actual vs operational change simulation

Next, the power flow profiles were evaluated. The power flows were measured through cables C1 and C1_1. The apparent power, real power, reactive power and power factor are depicted in Figure 60, Figure 61, Figure 62, and Figure 63 respectively.

Figure 60, Figure 61, and Figure 63 have some discrepancies, however, this is to be expected since the predicted solar PV generation data can differ from the real-world obtained values. This can be due to differences in weather conditions. The reactive power curves, Figure 62, have minimal differences since reactive demands from the loads are not affected by solar PV generation at the unity power factor.

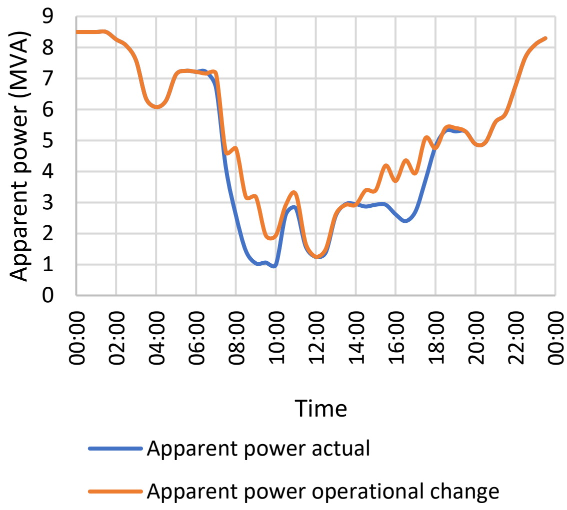


Figure 60: Apparent power actual vs simulation

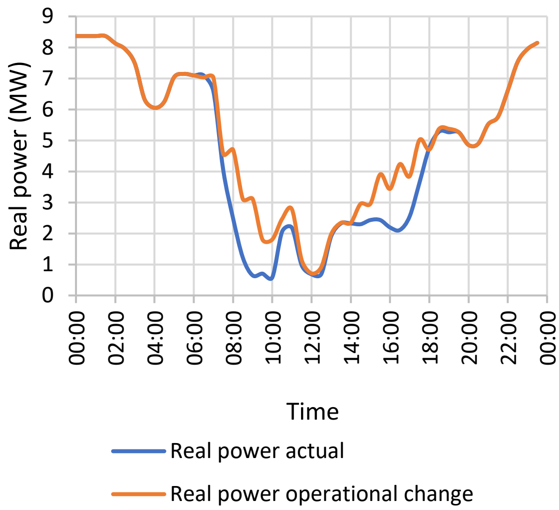


Figure 61: Real power actual vs simulation

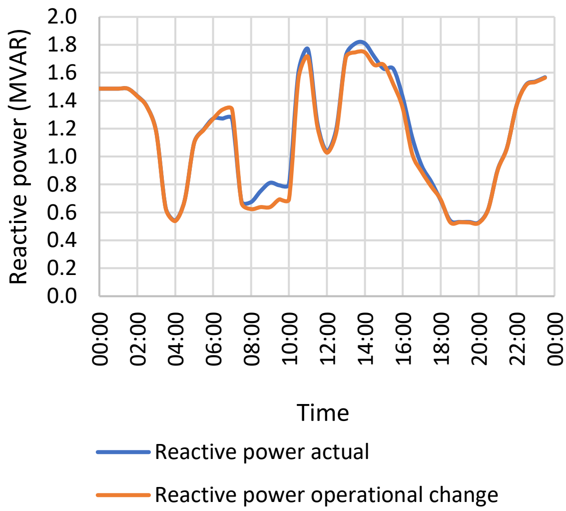


Figure 62: Reactive power actual vs simulation

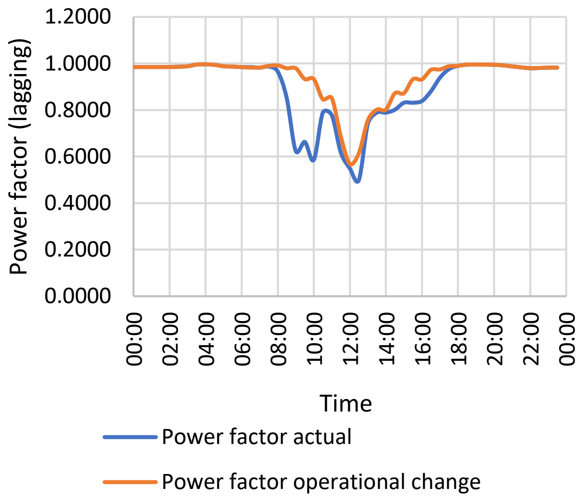


Figure 63: Power factor lagging actual vs simulation

The power quality evaluation methodology developed in Section 2 was successfully applied to the case study mine power system. Step 1 defines the operation of the mine power system. In this step, an accurate one-line diagram of the mine power system was created to fully characterise the operational change.

Steps 2 and 3 were successfully applied to the case study mine to obtain critical benchmark measurements. The measurement data provided a means to understand the operation of the power system to further establish KPIs. KPIs were determined from the grid code and the power quality supply (NRS048 – 2). From this, study objective 1.1 was achieved.

Steps 4 to 6 successfully described how to construct, calibrate, and validate the base case simulation model. The base case model was successfully calibrated to accurately resemble a real-world mine power system within a mean absolute error of 10%. Study objective 1.2 was accordingly achieved.

Steps 7 and 8 utilised the validated base case simulation model to predict the power quality changes of the operational change. This simulation model was used to provide a comparative 24-hour voltage and power flow profile at the POC for the existing mine power system and the integrated solar PV mine power system, achieving study objective 2.1.

Next, this model was used to provide voltages and power flows at the POC for maximum and minimum loading conditions with varying solar generation power, achieving study objectives 2.2 and 2.3. Finally, the results of study objectives 2.1 to 2.3 were used to evaluate the power quality changes of the integrated solar PV mine power system. Here, it was found that the voltage at the POC increased from 6.923 kV to a maximum of 7.143 kV during solar PV generation, which is narrowly under the limit of 7.26 kV. It was also evident that the power factor supplied by the power utility dropped to a minimum of 0.5680 lagging which exceeds the maximum of 0.8 lagging set by the grid code.

Solutions to the power quality problems were discussed and implemented in the simulation. POC voltages were lowered to the rated voltage of 6.6 kV by implementing tap-changing control to yield POC voltages that average at 6.598 kV. Power factor problems at the POC were improved by implementing controlled capacitor banks that stabilise the power factor at 0.9786 lagging. From this, study objective 3 was achieved.

From the validated method, it is apparent that the problem statement of the study was resolved by providing a means to evaluate the power quality of the solar PV integrated mine power system. From the evaluation, voltage and power factor problems were observed. Solutions to these problems were implemented to ensure a reliable and efficient power system.

4.4. Conclusion

Applying the power quality evaluation methodology to the case study mine power system revealed notable changes upon integrating solar PV systems. Specifically, there was an observed increase in POC voltage alongside a concerning decline in power factor at the utility measurement point. These alterations underscore the importance of considering power quality implications when integrating solar PV systems. Decreased power quality at the POC could potentially result in utility penalties and a shortened lifespan for electrical equipment.

Chapter 5: Conclusion

Figure 64: Mine substation[14]

"Make each day your masterpiece."

— John Wooden

[14] Z Lombard, Personal photograph

5. CONCLUSION

5.1. Preamble

This chapter highlights the main findings of the preceding chapters and elaborates on how the study objectives were achieved.

5.2. Study overview

The South African mining industry predominantly relies on the national power utility, Eskom, for an uninterrupted supply of electricity to their operations. However, the looming crisis surrounding the energy supply capability of the power utility, coupled with escalating energy costs and the utility's commitment to reducing greenhouse gas emissions, poses significant challenges to the energy security needed by the mining industry. To combat these problems the DMRE started the IPP program. The IPP’s primary goal was to add generation capacity to the national grid through renewable energy sources such as solar PV systems.

With the removal of the generation limit for IPPs and the mining industry's focus on enhancing their ESG status, electricity security, and energy cost volatility, integrating renewable energy from an IPP into their mine power system becomes imperative. Major mining companies in South Africa, including Anglo American, Harmony, Sibanye Stillwater, and Impala, have either already implemented these strategies or are in the process of planning large-scale renewable energy installations.

A significant problem with renewable energy lies in its inherent variability and unpredictability, as it relies on energy sources such as the sun or wind, which are subject to fluctuations. These complexities impact the power quality of an integrated solar PV power system.

Following the problem statement, the operation and power system concerns of mines were investigated. Through this investigation, it was seen that mine power systems are susceptible to poor power quality.

A literature review was conducted to examine the existing knowledge base regarding the power quality impact of solar PV systems on mine power systems, with a specific focus on understanding the implications and findings within this context. Simulation methods were also an important parameter. This led to the identification of the gap in literature where there is a need to thoroughly assess the impacts of integrating solar PV power plant technologies, concerning power quality, into the existing mine power systems.

The study aimed to evaluate the power quality changes of a mine power system integrated with a solar PV power plant to provide possible solutions. The following study objectives were determined to achieve this aim:

1. Construct a simulation model to characterise the power quality of the mine power system:
    - 1.1 Establish power quality parameters for the mine power system.
    - 1.2 Compare and validate the simulation results to a real-world mine power system.
2. Predict the power quality changes of the solar PV integrated mine power system using the validated simulation model:
    - 2.1 Condition 1: Determine the voltage and power profile for a 24-hour time-step period.
    - 2.2 Condition 2: Determine the power quality changes for maximum loading conditions.
    - 2.3 Condition 3: Determine the power quality changes for minimum loading conditions.
3. Evaluate and provide solutions to the power quality changes.

In Chapter 3, a power quality evaluation method was developed from the literature of Chapter 2. A case study research method was applied to achieve the objectives of the study.

In Chapter 4, the developed power quality evaluation methodology was applied to a case study underground gold mine in South Africa. The case study mine integrated a 7.3 MW solar PV system. The power quality changes due to the integration of this system were benchmarked and used to calibrate a load flow simulation model. The validated model was used to predict the power quality changes in current loading conditions. The results of the case study are summarised in the following section.

5.3. Findings

A conventionally powered mine power system (base case) and a solar PV integrated mine power system (operational change case) were defined by a one-line diagram and benchmarked according to the developed methodology. From this data, the power system operational limits were obtained for voltage and power factor at the POC that are required for the operational change evaluation. The solar PV integrated mine power system was shown to increase bus voltages and decrease power factors at the POC. Thereafter, the grid code and the quality of supply code (NRS048 – 2) were used to determine KPIs for the case study. The POC voltage limit of 7.260 kV and power factor of 0.8 lagging were important KPIs, achieving study objective 1.1.

Input data for the load flow simulation was collected for all the electrical components of the mine power system as described by the one-line diagram derived in study objective 1.1. From the one-line diagram and the input data, a base case and operational change simulation model were constructed. Each model was calibrated to within 10% of the benchmarked measurements. Accordingly, the models were deemed validated, achieving study objective 1.2.

The validated operational change simulation model was used to evaluate the power quality changes at the POC. Three cases were used for evaluation. Case 1 used actual loading data to plot a 24-hour voltage and power flow profile. From this profile, it was evident that during solar generation, the POC bus voltage increased from 6.880 kV to 7.152 kV. The power factor during this time also decreased from 0.9880 lagging to a minimum of 0.4998 lagging, achieving study objective 2.1.

Cases 2 and 3 used minimum and maximum loading conditions from the base case with varying solar generation power. The goal of this simulation was to determine if conditions exist for non-compliance with the KPIs (study objectives 2.2 and 2.3). Here it was found that certain loading conditions yielded power factors below the permissible limit of 0.8 lagging. Voltages consistently remained below the specified maximum of 7.260 kV, although in some instances, they approached this limit closely.

From a holistic perspective, the integration of the solar PV system altered the voltage and power flow profile of the mine power system. Throughout the solar generation period, voltages consistently increased, while power factors declined at the POC, achieving study objective 3.

5.4. Shortcomings

The study is limited to a single case study of a deep-level mine power system that incorporates a 7.3 MW solar PV system. While this provides valuable insights, it may not fully represent the diversity of mine power systems across South Africa, where varying sizes and configurations exist.

The power system model developed in this dissertation reveals reactive power discrepancies of up to 43% in certain intervals, despite a mean absolute error (MAE) of 9.91%. Consequently, machines that operate intermittently and are not in a steady state should be further analysed using transient studies to accurately capture their dynamic behaviour.

Additionally, the study does not account for the impact of energy storage systems, which could play a crucial role in mitigating the observed power quality issues by stabilising fluctuations in voltage and frequency. Furthermore, the study does not explore the economic or operational implications of these power quality changes on mining operations, such as how they might affect equipment maintenance costs, production efficiency, or compliance with grid regulations.

Including these aspects in future research would offer a more comprehensive understanding of the challenges and benefits of integrating solar PV systems into mining power infrastructures.

5.5. Recommendations for future work

The following recommendations for future work in the case study have been identified:

- **Other renewable resources:** This case study mine power system integrated a solar PV system, however, other renewable sources such as wind can also be incorporated.

Therefore, evaluating other renewable resources will produce valuable power quality evaluations.

- **Inverter control:** This case study mine power system used inverters that operated at unity power factor, therefore not regulating reactive power flows. Accordingly, evaluating the mine power system with an inverter that operates on a real power-reactive power (PQ) curve can provide improved power factors at the POC.
- **Power factor correction:** Mine power systems with power factor correction (PFC) reactors can potentially have even higher voltage profiles at the POC if they are not controlled. Therefore, the power quality evaluation of such a system can provide necessary control actions for the PFC reactor.
- **Battery energy storage solutions (BESS):** BESS can alleviate the variability and dispatchability of solar systems, however, they incur higher capital costs which will increase the cost of the power purchase agreement that the mine is undersigned [129].
- **Broaden the Scope of the Study:** Expand the research to encompass a wider variety of mine power system configurations and solar PV system sizes. This will enhance understanding of how the findings apply to different mining operations, improving the generalisability of the conclusions.
- **Investigate Energy Storage Benefits:** Examine the potential advantages of integrating energy storage systems to enhance the power quality of solar PV-integrated mine power systems. Energy storage could play a critical role in stabilising voltage and frequency fluctuations, thereby improving system reliability and efficiency.
- **Evaluate Operational and Economic Impacts:** Analyse the operational and economic effects of power quality changes on mining operations, focusing on areas such as equipment maintenance schedules, potential production interruptions, and compliance with grid standards. Understanding these impacts will provide insights into the cost-effectiveness and practicality of adopting solar PV technology in mining contexts.
- **Explore Alternative Control Strategies:** Investigate alternative control strategies and advanced power electronics solutions to address the power quality issues observed in solar PV-integrated mine power systems. This could involve developing innovative technologies to improve voltage stability, reduce harmonics, and enhance overall power quality.

5.6. Concluding remarks

The findings of this study offer critical power quality assessments regarding system voltages and power flows. These assessments will assist mine personnel involved in power system management in predicting voltage and power flow variations resulting from the integration of renewable energy sources before implementation. This proactive approach to planning will significantly aid in identifying and addressing potential voltage or power factor issues in advance, streamlining the planning phase, and enhancing overall system reliability.

The developed power system model can be further used to specify equipment ratings, such as cables, transformers, mini-substations, etc. for future developments. Contingencies for failure of equipment can also be simulated.

Additionally, the load flow methodology provided will form the basis for other studies such as short-circuit and motor-starting studies. These studies can help the mine personnel to further understand the operation of the power system and can be used to mitigate potential problems.

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7. APPENDIX

7.1. Data

Loading data for the mine power system simulation is tabulated in Table 23. Simulation model validation data for calculating the MAE are shown in Table 24.

Table 23: Load data

Time	CA2 Real Power (MW)	CA2 Reactive Power (MVAR)	CA3 Real Power (MW)	CA3 Reactive Power (MVAR)	Rock Winder Real Power (MW)	Rock Winder Reactive Power (MVAR)	Man Winder Real Power (MW)	Man Winder Reactive Power (MVAR)	UG4 Real Power (MW)	UG 4 Reactive Power (MVAR)	Pump 6 Real Power (MW)	Pump 6 Reactive Power (MVAR)	Pump 8 Real Power (MW)	Pump 8 Reactive Power (MVAR)
00:00	3.256	0.023	0.000	0.000	0.941	0.007	-0.106	0.196	0.191	0.166	1.116	0.613	1.289	0.647
00:30	3.279	0.023	0.000	0.000	0.904	0.006	-0.107	0.196	0.190	0.168	1.046	0.576	1.217	0.614
01:00	3.278	0.023	0.000	0.000	0.907	0.006	-0.108	0.195	0.191	0.169	0.988	0.546	1.143	0.580
01:30	3.268	0.022	0.000	0.000	0.890	0.006	-0.107	0.195	0.190	0.171	0.944	0.522	1.092	0.557
02:00	3.244	0.023	0.000	0.000	0.851	0.009	-0.108	0.196	0.191	0.175	0.899	0.498	1.068	0.547
02:30	3.224	0.023	0.000	0.000	0.841	0.005	-0.108	0.194	0.192	0.175	0.871	0.484	1.058	0.543
03:00	3.165	0.022	0.000	0.000	0.856	0.006	-0.107	0.195	0.190	0.178	0.604	0.345	0.779	0.414
03:30	3.086	0.022	0.000	0.000	0.685	0.005	-0.101	0.188	0.182	0.182	0.241	0.151	0.133	0.110
04:00	2.979	0.027	0.000	0.000	0.636	0.014	-0.099	0.181	0.174	0.183	0.208	0.131	0.091	0.090
04:30	3.035	0.023	0.000	0.000	0.485	0.001	-0.100	0.186	0.176	0.179	0.367	0.217	0.138	0.114
05:00	3.009	0.021	0.000	0.000	0.634	0.002	-0.104	0.195	0.186	0.175	0.797	0.447	0.575	0.317
05:30	2.998	0.023	0.000	0.000	0.766	0.004	-0.105	0.200	0.190	0.172	0.890	0.495	0.702	0.373
06:00	2.953	0.020	0.000	0.000	0.828	0.013	-0.104	0.203	0.189	0.173	0.868	0.483	0.621	0.335
06:30	2.835	0.021	0.000	0.000	0.811	0.005	-0.116	0.225	0.191	0.175	0.262	0.163	0.106	0.094
07:00	2.829	0.022	0.000	0.000	0.815	0.005	-0.113	0.221	0.193	0.173	0.264	0.163	0.133	0.105
07:30	2.835	0.024	0.000	0.000	0.793	0.005	-0.107	0.201	0.195	0.170	0.267	0.167	0.133	0.104
08:00	2.863	0.026	0.000	0.000	0.642	0.003	-0.101	0.194	0.194	0.169	0.259	0.160	0.125	0.101
08:30	2.917	0.027	0.000	0.000	0.590	0.014	-0.097	0.182	0.193	0.169	0.236	0.148	0.091	0.085
09:00	2.953	0.029	0.000	0.000	0.556	0.006	-0.097	0.174	0.190	0.168	0.265	0.164	0.096	0.088
09:30	3.011	0.028	0.000	0.000	0.535	0.003	-0.096	0.169	0.185	0.160	0.863	0.475	0.730	0.390
10:00	3.035	0.028	0.000	0.000	0.550	0.012	-0.095	0.169	0.185	0.159	0.935	0.511	1.012	0.513

10:30	3.037	0.029	0.000	0.000	0.549	0.004	-0.099	0.173	0.184	0.158	0.854	0.466	0.922	0.469
11:00	3.030	0.031	0.000	0.000	0.614	0.007	-0.101	0.173	0.185	0.159	0.775	0.423	0.702	0.366
11:30	3.018	0.030	0.000	0.000	0.493	0.010	-0.105	0.176	0.179	0.165	0.387	0.221	0.161	0.116
12:00	2.999	0.031	0.000	0.000	0.389	0.006	-0.107	0.188	0.174	0.165	0.286	0.167	0.078	0.077
12:30	2.997	0.032	0.000	0.000	0.435	0.005	-0.106	0.187	0.169	0.159	0.369	0.213	0.130	0.104
13:00	2.973	0.032	0.000	0.000	0.561	0.003	-0.106	0.187	0.179	0.157	0.749	0.415	0.624	0.333
13:30	2.945	0.032	0.000	0.000	0.673	0.004	-0.105	0.185	0.184	0.157	0.831	0.459	0.830	0.430
14:00	2.923	0.038	0.000	0.000	0.659	0.004	-0.106	0.183	0.186	0.156	0.895	0.490	1.049	0.529
14:30	2.907	0.042	0.000	0.000	0.662	0.004	-0.104	0.180	0.186	0.155	1.012	0.553	1.156	0.579
15:00	2.875	0.044	0.000	0.000	0.642	0.004	-0.101	0.180	0.186	0.157	1.007	0.550	1.194	0.596
15:30	2.774	0.049	0.000	0.000	0.719	0.011	-0.097	0.177	0.187	0.159	0.957	0.526	1.149	0.577
16:00	2.787	0.056	0.000	0.000	0.749	0.013	-0.094	0.176	0.187	0.161	0.848	0.468	1.057	0.533
16:30	2.836	0.043	0.000	0.000	0.776	0.006	-0.088	0.169	0.189	0.165	0.821	0.453	0.932	0.477
17:00	2.818	0.042	0.000	0.000	0.792	0.006	-0.086	0.170	0.191	0.165	0.689	0.384	0.745	0.389
17:30	2.809	0.038	0.000	0.000	0.802	0.017	-0.083	0.173	0.189	0.169	0.245	0.151	0.082	0.080
18:00	2.811	0.034	0.000	0.000	0.862	0.006	-0.079	0.176	0.187	0.168	0.190	0.122	0.046	0.063
18:30	2.801	0.031	0.000	0.000	0.929	0.008	-0.076	0.177	0.190	0.168	0.190	0.123	0.046	0.063
19:00	2.799	0.028	0.000	0.000	0.947	0.007	-0.076	0.183	0.189	0.171	0.185	0.117	0.047	0.064
19:30	2.763	0.027	0.000	0.000	0.651	0.009	-0.079	0.190	0.178	0.172	0.183	0.118	0.047	0.065
20:00	2.753	0.026	0.000	0.000	0.604	0.003	-0.082	0.187	0.173	0.177	0.181	0.116	0.047	0.067
20:30	2.759	0.025	0.000	0.000	0.560	0.002	-0.085	0.187	0.175	0.174	0.275	0.168	0.093	0.090
21:00	2.757	0.025	0.000	0.000	0.814	0.005	-0.090	0.190	0.188	0.175	0.513	0.295	0.378	0.224
21:30	2.815	0.029	0.000	0.000	0.949	0.006	-0.093	0.189	0.190	0.173	0.710	0.400	0.690	0.373
22:00	2.881	0.022	0.000	0.000	0.933	0.006	-0.096	0.190	0.190	0.171	0.971	0.541	1.113	0.569
22:30	2.943	0.028	0.000	0.000	0.992	0.059	-0.099	0.192	0.188	0.168	1.049	0.579	1.224	0.618
23:00	3.084	0.028	0.000	0.000	0.960	0.006	-0.103	0.195	0.191	0.169	1.104	0.607	1.291	0.650
23:30	3.200	0.023	0.000	0.000	0.913	0.007	-0.105	0.193	0.191	0.167	1.119	0.616	1.289	0.648

Table 24: Simulation validation MAE results

Time	Real power actual (MW)	Reactive power actual (MVAR)	Apparent power actual (MVA)	Real power simulation (MW)	Reactive power simulation (MVAR)	Apparent power simulation (MVA)	Power factor actual	Power factor simulation	POC voltage actual (kV)	POC voltage simulation (kV)	Real power difference	Reactive power difference	Apparent power difference	Power factor difference	Voltage difference
00:00	8.461	1.664	8.623	8.360	1.643	8.520	0.981	0.981	6.884	6.876	0.012	0.012	0.012	0.000	0.001
00:30	8.495	1.749	8.673	8.360	1.643	8.520	0.979	0.981	6.881	6.876	0.016	0.061	0.018	0.002	0.001
01:00	8.535	1.754	8.714	8.360	1.643	8.520	0.980	0.981	6.888	6.876	0.021	0.063	0.022	0.002	0.002
01:30	8.493	1.746	8.671	8.360	1.711	8.520	0.980	0.981	6.890	6.876	0.016	0.020	0.017	0.002	0.002
02:00	8.324	1.651	8.486	8.140	1.620	8.260	0.981	0.985	6.899	6.884	0.022	0.019	0.027	0.005	0.002
02:30	8.116	1.268	8.214	7.940	1.263	8.060	0.988	0.985	6.896	6.890	0.022	0.004	0.019	0.003	0.001
03:00	7.738	1.291	7.845	7.480	1.227	7.580	0.986	0.987	6.916	6.906	0.033	0.050	0.034	0.000	0.001
03:30	6.700	0.749	6.742	6.320	0.700	6.340	0.994	0.997	6.931	6.946	0.057	0.066	0.060	0.003	0.002
04:00	6.409	0.869	6.468	6.060	0.493	6.080	0.991	0.997	6.938	6.954	0.054	0.433	0.060	0.006	0.002
04:30	6.628	0.720	6.667	6.260	0.700	6.280	0.994	0.997	6.921	6.947	0.055	0.028	0.058	0.003	0.004
05:00	7.309	1.232	7.412	7.040	1.200	7.120	0.986	0.989	6.913	6.920	0.037	0.026	0.039	0.003	0.001
05:30	7.410	1.266	7.517	7.140	1.199	7.240	0.986	0.986	6.898	6.916	0.036	0.053	0.037	0.000	0.003
06:00	7.471	1.422	7.605	7.100	1.400	7.220	0.982	0.983	6.884	6.917	0.050	0.015	0.051	0.001	0.005
06:30	7.489	1.431	7.624	7.100	1.400	7.220	0.982	0.983	6.868	6.917	0.052	0.022	0.053	0.001	0.007
07:00	7.461	1.240	7.563	7.100	1.311	7.220	0.986	0.983	6.875	6.917	0.048	0.057	0.045	0.003	0.006
07:30	6.330	1.155	6.435	5.940	1.100	5.980	0.984	0.993	6.898	6.957	0.062	0.047	0.071	0.010	0.009
08:00	6.511	0.799	6.560	6.080	0.494	6.100	0.993	0.997	6.887	6.953	0.066	0.382	0.070	0.004	0.010
08:30	6.541	0.864	6.597	6.080	0.494	6.100	0.991	0.997	6.863	6.953	0.070	0.428	0.075	0.005	0.013
09:00	6.630	0.812	6.680	6.280	0.700	6.300	0.993	0.997	6.857	6.947	0.053	0.138	0.057	0.004	0.013
09:30	6.682	0.940	6.748	6.380	0.900	6.420	0.990	0.994	6.850	6.944	0.045	0.042	0.049	0.004	0.014
10:00	6.719	0.955	6.786	6.380	0.950	6.420	0.990	0.994	6.846	6.944	0.050	0.005	0.054	0.004	0.014
10:30	8.209	1.526	8.349	8.080	1.398	8.200	0.983	0.985	6.807	6.886	0.016	0.084	0.018	0.002	0.012
11:00	8.512	1.557	8.653	8.380	1.538	8.520	0.984	0.984	6.802	6.876	0.016	0.012	0.015	0.000	0.011
11:30	7.461	1.236	7.562	7.200	0.931	7.260	0.987	0.992	6.827	6.916	0.035	0.246	0.040	0.005	0.013
12:00	7.105	0.856	7.156	6.760	0.800	6.800	0.993	0.994	6.843	6.931	0.049	0.065	0.050	0.001	0.013

12:30	7.248	1.284	7.360	7.020	0.920	7.080	0.985	0.992	6.834	6.922	0.031	0.284	0.038	0.007	0.013
13:00	8.215	1.635	8.376	8.060	1.509	8.200	0.981	0.983	6.811	6.886	0.019	0.077	0.021	0.002	0.011
13:30	8.297	1.668	8.463	8.160	1.662	8.300	0.980	0.983	6.810	6.883	0.016	0.004	0.019	0.003	0.011
14:00	8.370	1.658	8.533	8.160	1.518	8.300	0.981	0.983	6.816	6.883	0.025	0.084	0.027	0.002	0.010
14:30	8.181	1.636	8.343	8.160	1.620	8.300	0.981	0.983	6.815	6.883	0.003	0.010	0.005	0.003	0.010
15:00	8.091	1.667	8.261	7.920	1.600	8.060	0.979	0.983	6.817	6.890	0.021	0.040	0.024	0.003	0.011
15:30	7.985	1.617	8.147	7.920	1.496	8.060	0.980	0.983	6.827	6.890	0.008	0.075	0.011	0.003	0.009
16:00	7.546	1.499	7.694	7.360	1.510	7.460	0.981	0.987	6.836	6.910	0.025	0.008	0.030	0.006	0.011
16:30	7.046	1.128	7.136	6.800	1.046	6.880	0.987	0.988	6.860	6.928	0.035	0.072	0.036	0.001	0.010
17:00	6.756	0.987	6.828	6.400	0.980	6.460	0.989	0.991	6.876	6.941	0.053	0.007	0.054	0.001	0.009
17:30	6.491	1.088	6.581	6.160	1.000	6.220	0.986	0.990	6.885	6.949	0.051	0.081	0.055	0.004	0.009
18:00	6.164	0.992	6.243	5.840	0.900	5.880	0.987	0.993	6.894	6.959	0.053	0.093	0.058	0.006	0.009
18:30	5.808	0.773	5.859	5.460	0.635	5.480	0.991	0.996	6.902	6.972	0.060	0.179	0.065	0.005	0.010
19:00	5.726	0.791	5.780	5.460	0.468	5.480	0.991	0.996	6.924	6.972	0.046	0.409	0.052	0.006	0.007
19:30	5.575	0.857	5.641	5.260	0.650	5.300	0.988	0.992	6.937	6.978	0.057	0.241	0.060	0.004	0.006
20:00	5.265	0.757	5.319	4.860	0.600	4.880	0.990	0.996	6.955	6.991	0.077	0.207	0.083	0.006	0.005
20:30	5.287	0.810	5.349	4.900	0.627	4.940	0.988	0.992	6.926	6.989	0.073	0.226	0.076	0.003	0.009
21:00	5.730	0.991	5.815	5.520	0.943	5.600	0.985	0.986	6.931	6.968	0.037	0.048	0.037	0.000	0.005
21:30	6.017	1.259	6.148	5.760	1.200	5.860	0.979	0.983	6.931	6.960	0.043	0.047	0.047	0.004	0.004
22:00	6.885	1.577	7.063	6.600	1.500	6.740	0.975	0.979	6.924	6.932	0.041	0.043	0.046	0.005	0.001
22:30	7.769	1.584	7.928	7.540	1.580	7.680	0.980	0.982	6.897	6.902	0.029	0.002	0.031	0.002	0.001
23:00	8.107	1.761	8.296	7.940	1.602	8.100	0.977	0.980	6.902	6.889	0.021	0.090	0.024	0.003	0.002
23:30	8.252	1.776	8.441	8.140	1.700	8.300	0.978	0.981	6.890	6.883	0.014	0.043	0.017	0.003	0.001
MAE (%)											**3.81**	**9.91**	**4.10**	**0.33**	**0.70**