Load management through the utilisation of VSDs on water transfer schemes

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ABSTRACT

Title: Load management through the utilisation of VSDs on water transfer schemes

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Keywords: Demand-side management, water transfer scheme, electricity cost savings, pump control philosophy, and Variable Speed Drive(s)

South Africa is a water scarce country and due to this, large water transfer schemes were built to supply major parts of the country with raw and potable water. The Department of Water and Sanitation directly control some major water transfer schemes in South Africa, with some others being managed by regional water boards. Water transfer schemes are high energy consumers due to large pumps utilised to pump water over great distances with significant static head.

With the current electricity situation in the country, Eskom invested in demand-side management interventions, among others, to ease the load on the electrical grid during peak hours. The pump stations that form part of water transfer schemes were identified by energy services companies as possible viable sites for the Eskom funded demand-side management interventions.

A pump station that utilises Variable Speed Drive technology for pump control was identified for possible load management. The selected pump station supplies key water consumers such as Eskom and Sasol. Therefore, any water transfer deficit due to load management interventions must be avoided, making a load shift intervention the only viable option.

To develop an optimised control philosophy that utilises the Variable Speed Drive technology, tests were conducted on the pump station. Data gathered from these tests was used for the verification of a simulation built to test the optimised control philosophy. The data was also used to calculate adjusted flow set points used as control inputs for the optimised control philosophy. From this it was concluded that the utilisation of Variable Speed Drives for load management on this large pump station is possible in this particular pump station.

After the proposed strategy was simulated and optimised, control and maintenance constraints limited the implementation of the optimised strategy. The simulation however, indicated that an annual electricity cost savings of around R 3.3 million can be achieved.

Due to these constraints, it was not possible to implement the load management initiative for a significant part of 2016, resulting in about half of the possible financial savings being lost. The optimised control philosophy was however, implemented on one operational high-lift pump set and three low-lift pumps. A daily peak period saving of 2.29 MW was achieved on the pump station with a daily cost saving of R10 000 during the high demand season. The transfer deficit due to the peak period cutback was successfully neutralised through an off-peak comeback load.

The dam levels were kept at the required set point by matching the flow of the high and low-lift pumping stations. This was all achieved by only manipulating the speed of the pumps through the Variable Speed Drives, according to pre-calculated station flow set points.

Load management through the utilisation of Variable Speed Drives on water transfer schemes is thus a viable demand-side management intervention. The optimised control philosophy can easily be incorporated into the existing control of pumping stations equipped with Variable Speed Drives.

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
DSM	Demand-Side Management
DWBd	Desilting Works/Balancing Dam
DWS	Department of Water and Sanitation
EnMS	Energy Management System
ESCOs	Energy Services Companies
GWS	Government Water Scheme
HL-PS	High-Lift Pump Station
HMI	Human Machine Interface
IBTs	Inter-Basin Transfer Schemes
LCC	Life Cycle Costs
LL-PS	Low-Lift Pump Station
LS	Load Shift
MV	Medium Voltage
NEMA	National Electrical Manufacturers Association
NERSA	National Energy Regulator of South Africa
NPSH	Net Positive Suction Head
OPEC	Organization of the Petroleum Exporting Countries
PC	Peak Clip
PI	Proportional Integral
PLC	Programmable Logic Controller
PS	Pump Station

PTB	Process Toolbox
PWM	Pulse Width Modulated
RPS	RPM vs Power vs Station Flow
SCADA	Supervisory Control and Data Acquisition
ToU	Time of Use
USA	United States of America
VFD	Variable Frequency Drive
VSDs	Variable Speed Drives
WMA	Water Management Area
WSS	Water Supply Strategy
WTP	Water Treatment Plants
WTS	Water Transfer Scheme

NOMENCLATURE

Symbol	Unit	Description
P	W	Pump Power
Q	m^3/s	Flow Rate
P_e	W	Electrical power
V	V	Potential Difference
I	A	Electrical Current
pf	-	Power Factor
g	m/s^2	Gravitational Constant
N_0	RPM	Rotational Speed
H_0	m	Pressure Head
D	m	Impeller Diameter
P_h	W	Hydraulic Power
ρ	kg/m^3	Density of Liquid
η	-	Efficiency
T	Nm	Torque
ω	rad/s	Angular Velocity
f	Hz	Line-power Frequency
p	-	Number of Poles
LCC	R	Life Cycle Cost
C_{ic}	R	Initial Cost
C_{in}	R	Installation/Commissioning Cost
C_e	R	Energy Cost

C_o	R	Operating Cost
C_m	R	Maintenance Cost
C_s	R	Downtime/Loss of Production
C_{env}	R	Environmental Cost
C_d	R	Decommissioning Cost

Chapter 1 – Background

Power station with water supply dam in foreground[1]

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[1] iStock Image

1.1 Introduction

In South Africa, water transfer schemes convey water over long distances. This water is used by numerous consumers such as agriculture, municipalities and electricity generation. Some of these consumers are situated lengthy distances from water sources, be it natural or constructed. The need to supply water users from these distant sources necessitates water resource management.

The management of the water sector is entrusted to the South African Department of Water and Sanitation (DWS). They operate numerous pumping stations, reservoirs and large capacity dams, to ensure the stable supply of water. The pumping stations utilise energy intensive electrical pumps to convey water over distance and from low to high geographical areas [1].

Over recent years, the electricity sector in South Africa experienced periods where the demand nearly reached the supply capacity. Such an event can lead to an overload of the national power grid, and subsequently lead to a national blackout. To prevent such an event, the primary electricity supplier in South Africa introduced initiatives such as demand side management (DSM) [2].

One of the aims of these initiatives is to reduce the peak period demand of large electricity consumers. Energy Services Companies (ESCOs) provides this service through funding from the power utility.

1.2 South Africa’s electricity situation and load management initiatives

Electrical energy has become an integral and important part of today’s heavily industrialised society, supporting industries and economic systems [3]. As one of Africa’s largest economies, South Africa depends on electricity to support the economy [4].

Eskom supplies more than 90% of South Africa’s electricity with maximum installed generation capacity of 42 GW. In Figure 1 on the following page, a comparison is given between the generation methods used by Eskom [5].

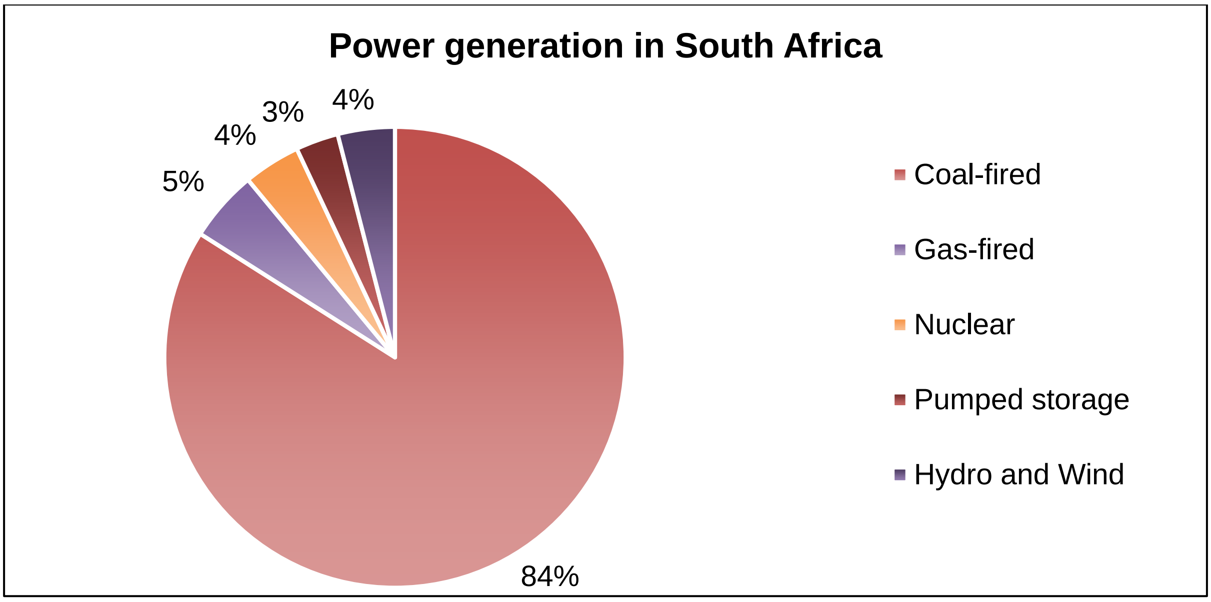

Figure 1: Power generation methods utilised in South Africa (Adapted from [5])

From Figure 1 it is clear that the majority of the South African power is generated by coal-fired power stations. This is mainly due to the large coal deposits found in South Africa. These deposits equal more than two thirds of the Southern Hemisphere's coal reserves [6].

Eskom, the national electricity utility, supplies electricity to more than 5 million households and industries in South Africa [7]. It is important for them to ensure a sufficient supply of electricity is available to these consumers. In the event of electricity demand exceeding supply, Eskom risks a blackout of the national power grid. To prevent such an event in the short term, Eskom implements load shedding [8].

In 2007 and 2008 South Africa's electricity demand neared Eskom's maximum generation capacity, necessitating the implementation of load shedding. The cause for this crisis was attributed to lack of coal supply to Eskom, skill shortages and the increase in electricity demand linked to the economic growth. Eskom focused on improving plant maintenance and performance while also increasing the coal supplies to power stations. These steps resulted in the suspension of load shedding in May of 2008 [7],[9].

In November 2014, load shedding was again implemented after a coal silo at the Majuba power station collapsed. Diesel shortages, construction delays on the Medupi and Kusile power stations, and breakdowns of critical components resulted in extended load shedding periods [9],[10].

Load shedding is mostly implemented during the peak load periods. These peak periods can be seen in Figure 2 as spikes in the daily load profiles. In winter, the electricity demand can increase by as much as 4000 MW. To counter this demand spike, Eskom adjusted their maintenance schedules so that extra generating capacity becomes available during the winter months [11].

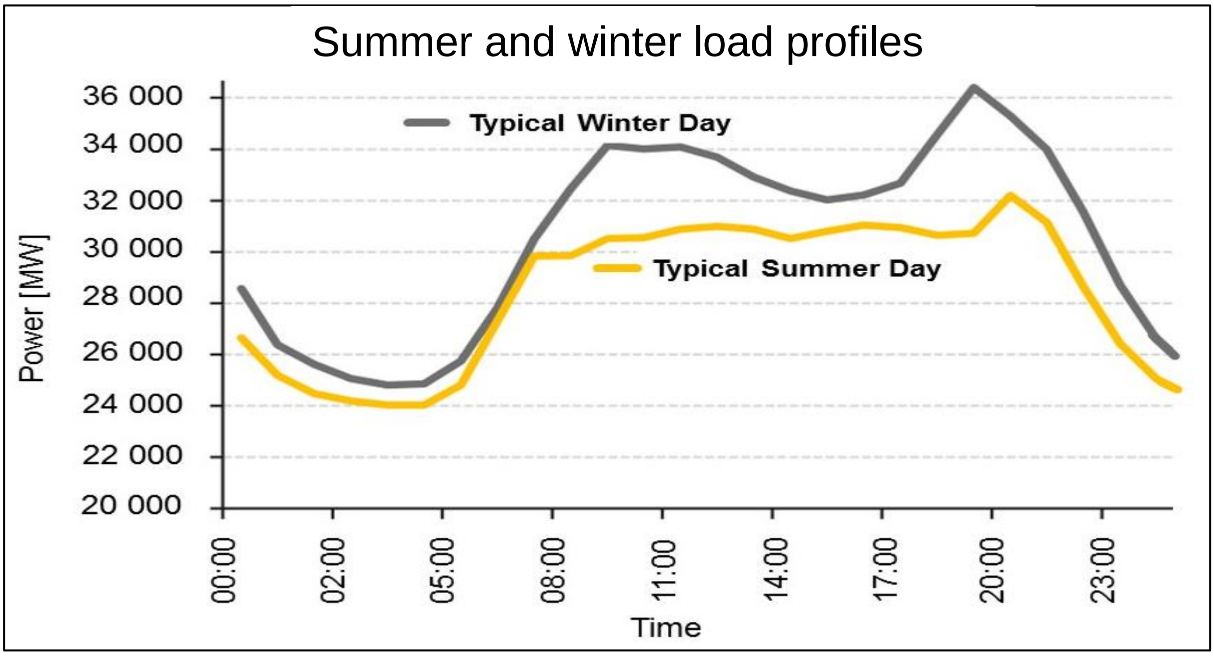

Figure 2: Load profile for South Africa (Adapted from [12])

To match the demand profile of the country, Eskom operates two kinds of power stations as shown in Figure 3. The base-load power stations supply constant power over 24 hours while the peak-load stations can add electricity to the grid on short notice [13]. The base-load power stations are usually coal-fired or nuclear, with the peak-load stations being smaller gas turbine or hydro-power generators.

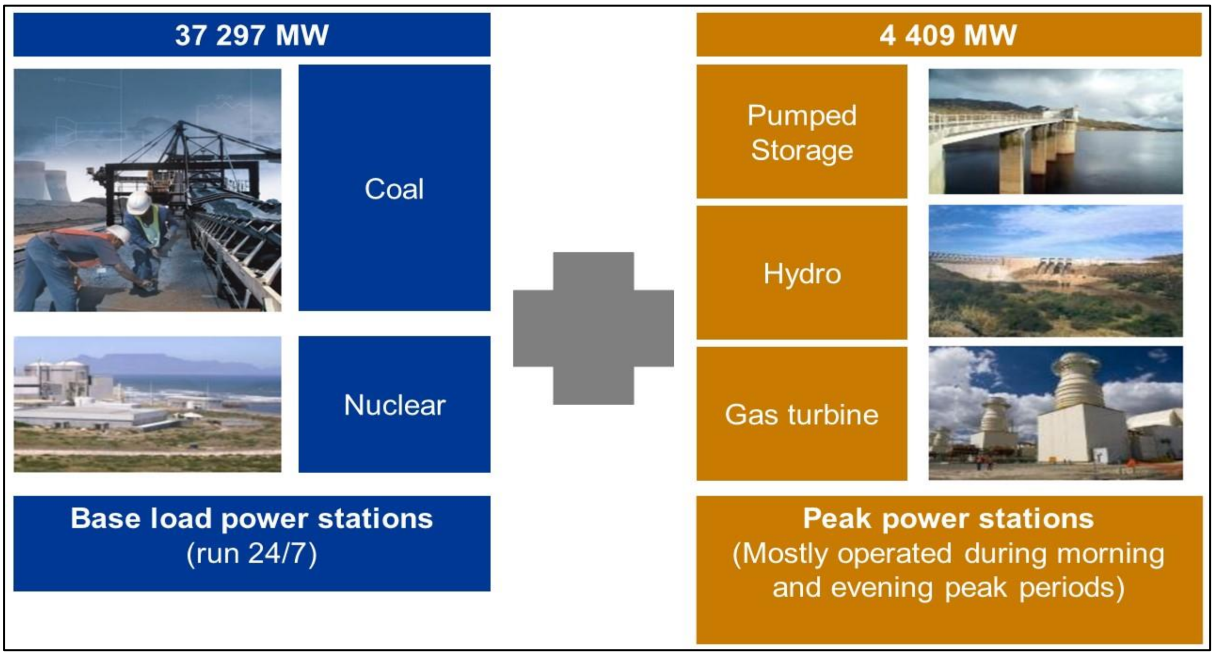

Figure 3: Power stations operated by Eskom (Adapted from [2])

The diesel shortage previously mentioned has a great impact on gas turbine peak power stations shown in Figure 3. It limits the power that Eskom can supply to the national grid on short notice due to a fuel shortage at some of these stations. This decreases the already reduced generation reserves which Eskom has during the peak periods.

To mitigate this high demand during peak time, Eskom introduced Time of Use (ToU) tariff structures. These ToU tariff structures are widely used in developed countries and encourage consumers to decrease their electricity consumption during peak periods. This reduces the electricity demand on the national grid [14],[15].

ToU tariff structures implemented by Eskom includes, but are not limited to Ruraflex, Nightsave Urban and Megaflex [16]. For this study, focus will only be placed on the Megaflex structure as this is the tariff Eskom uses to bill the pumping station which forms part of this study. The Megaflex tariff structure is divided into three periods namely peak, standard and off-peak as shown in Figure 4.

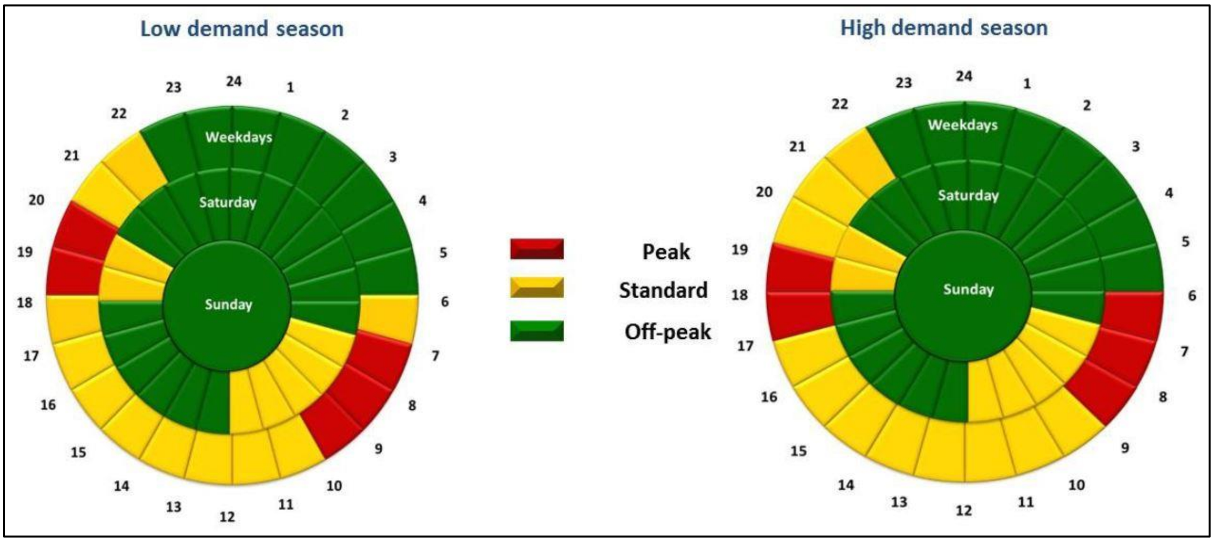

Figure 4: Megaflex tariff periods [16]

High and low demand seasons are also designated for this tariff structure. The low demand season includes the summer months of September to May, and the high demand season the winter months of June to August. During the high demand season, Eskom bills its customers more for each unit of energy consumed compared to the low season months [16]. This is visually illustrated in Figure 5 on the following page.

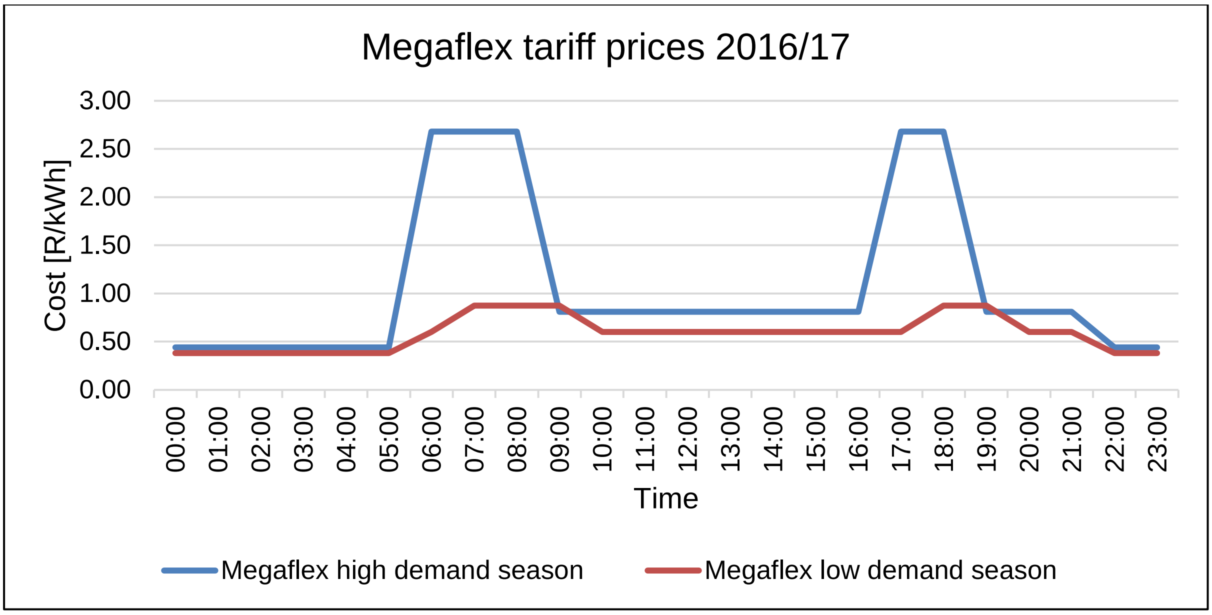

Figure 5: Megaflex tariff prices (Adapted from [16])

In addition to the ToU tariff structures, Eskom also introduced the DSM initiative. A policy introduced in 2004 by the National Energy Regulator of South Africa (NERSA) allowed DSM to become a licensed condition of all electricity suppliers in South Africa. This policy also presented the role of ESCOs in the South African energy sector [17],[18].

ESCOs were conceived after the 1970's energy crisis in the United States of America (USA) due to Organization of the Petroleum Exporting Countries (OPEC) oil restriction and the Iranian revolution. The OPEC restrictions and the revolution lead to major increases in oil prices which prompted major industries to use energy more efficiently, which brought about the development of ESCOs [17],[18].

The objective of ESCOs is to provide energy solutions to clients [19]. These solutions include DSM initiatives where the ESCO enters into an agreement with Eskom to manage a specific power consumer's energy demand. These DSM initiatives include peak clipping, energy efficiency and load management interventions [20].

When reducing the power consumption over the course of 24 hours, an electricity efficiency intervention is realised. Such an intervention can be realised through the installation of more efficient equipment and optimised operation of current equipment. Energy cost savings are realised as the overall daily electricity consumption is reduced. A typical daily energy efficiency profile is presented in Figure 6 on the following page.

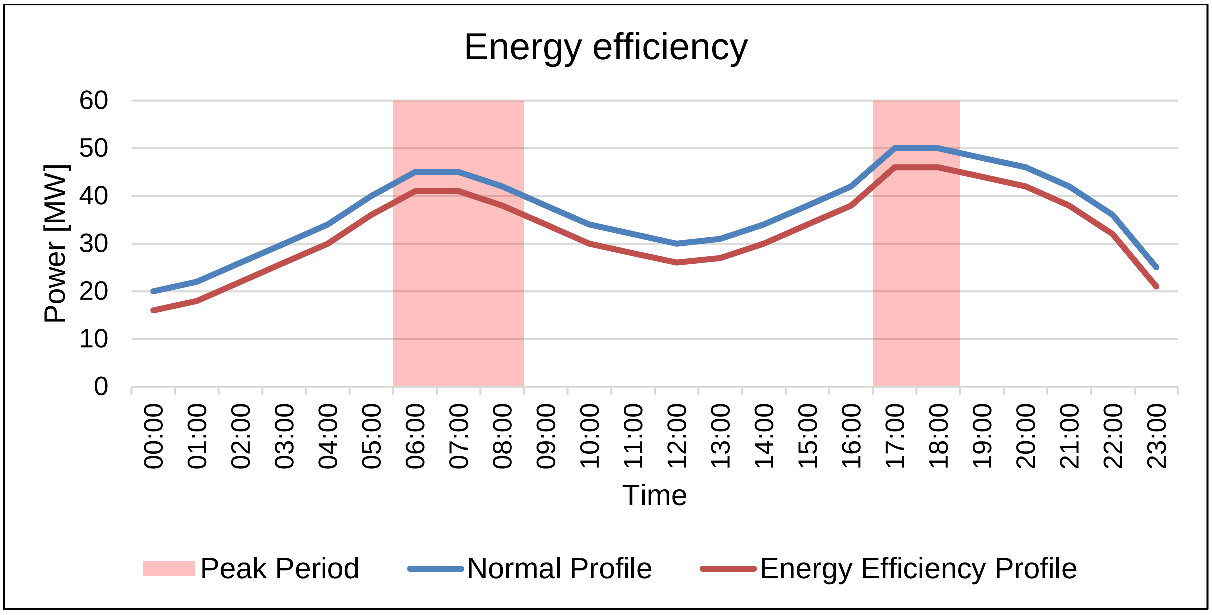

Figure 6: Energy efficiency daily profile

A peak clip intervention is aimed at reducing the peak electricity demand of a specific consumer. The disadvantage of this intervention is that production associated with electricity usage is lost due to the clip and not recovered. A typical peak clip profile is presented in Figure 7. Electricity savings is realised through peak load management and reducing the overall daily energy consumption.

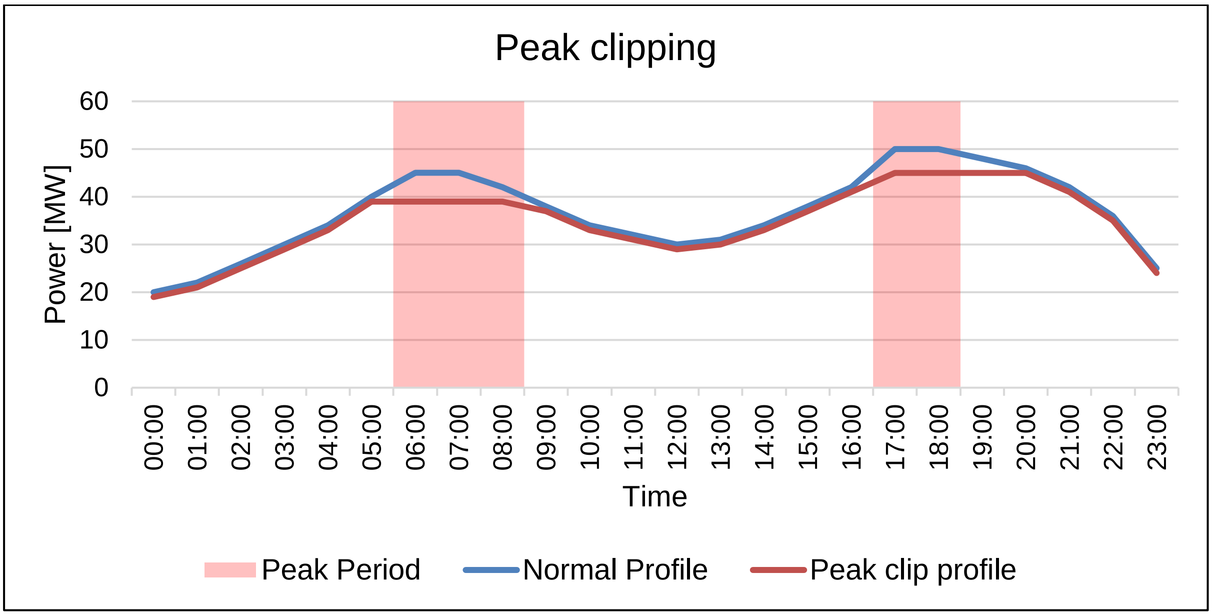

Figure 7: Peak clipping daily profile

For some industries it is unacceptable to lose production due to the peak clip. In such cases a load shift intervention is used. Such an intervention recovers the reduced peak time electricity during the off-peak time. Such an intervention will be energy neutral for a normal operational day, provided that the load shift was implemented correctly. The term energy neutral refers to when the daily energy consumption of the optimised profile match the energy consumption of the normal profile.

A typical load shift power profile is presented in Figure 8. Electricity cost saving is realised through peak load reduction [21].

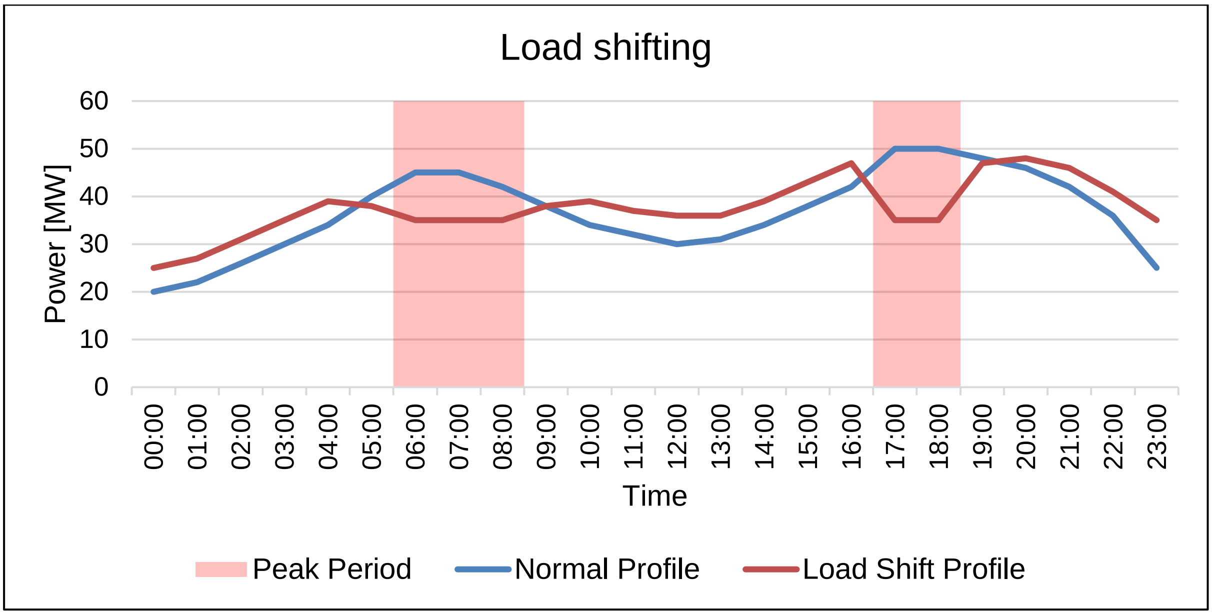

Figure 8: Load shift daily profile

From 1985 to 1995, a peak load reduction of 29 GW was realised by more than 500 utilities in the USA. The cost for building additional power stations to meet the equivalent demand would have cost one and a half times more than the cost of implementing the DSM interventions. DSM strategies have also been successfully implemented in other developed countries [22].

One energy consumer in the South African industry is the DWS. They operate energy intensive pump stations that transfer high volumes of water from one part of the country to another. These pump stations were identified by some ESCOs as sites where DSM projects could be implemented. To better understand how these pump stations are operated, the water transfer systems in South Africa must first be understood.

1.3 Water transfer in South Africa

It is well known that South Africa is a water scarce country. Our average yearly rainfall of 492mm is well under the global average of 985mm [23]. Figure 9 below illustrates the distribution of rainfall in South Africa. From this it is clear the majority of the rain falls in the eastern parts of the country.

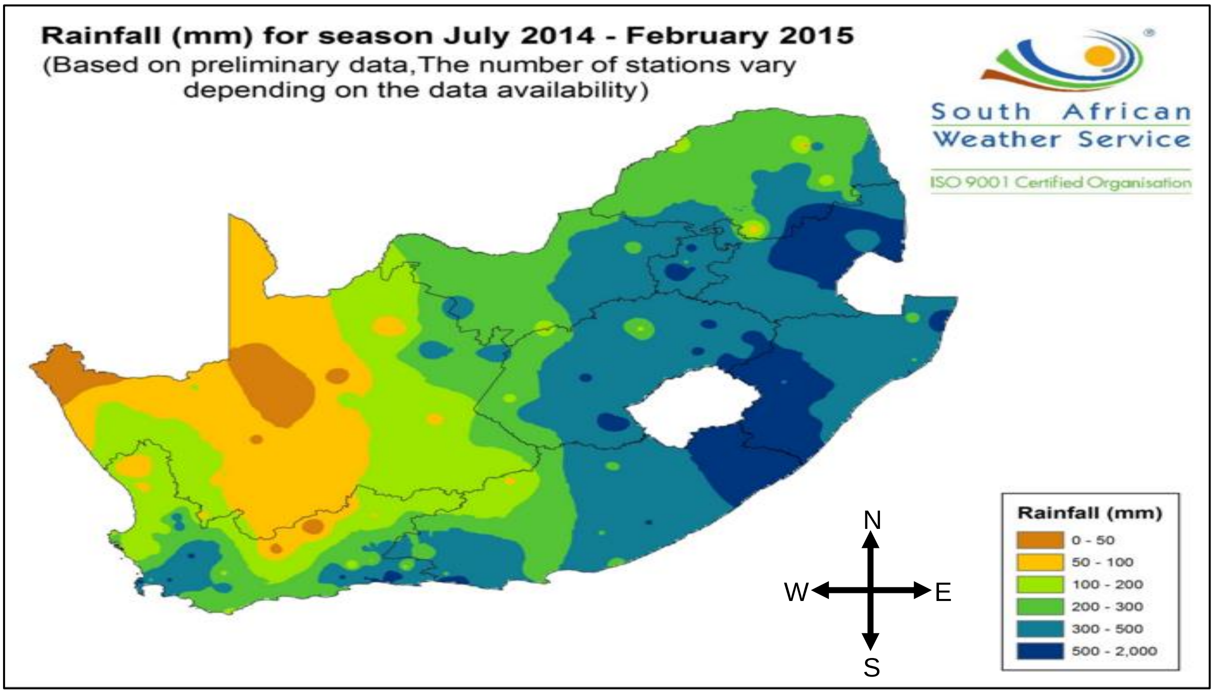

Figure 9: South African rainfall map [24]

Due to uneven rain distribution, large volumes of water are conveyed from the higher-rainfall regions to the drier regions. Inter-basin transfer schemes (IBTs) involve mass conveyance of water from one geographical catchment area to another. In semi-arid countries, under which South Africa is classified [25], IBTs are usually seen as the only solution to the uneven distribution of aquatic resources relative to the population centres [26].

These IBTs and related water transfer infrastructure need continuous management and maintenance to ensure reliable water availability to the end users. South Africa is divided into 19 Water Management Areas (WMAs). The authorities of WMAs are responsible for managing the water resources within their designated area, ensuring sufficient water transfer to the end users [18],[27].

The DWS is the custodian for the overall water resources in South Africa. This implies that all the WMAs are required to report to DWS regarding their management plans and policies. DWS is responsible for the formulation and implementation of policies aimed at sustainable water resource management throughout South Africa. It is stipulated in the National Water Act that their primary function is water transfer for industrial, domestic, agricultural and mining purposes [28].

The major consumers of water in South Africa are illustrated by the pie chart in Figure 10. Within each sector the water usage is split between several end users. For example, in the agricultural sector the water used to irrigate crops are split between multiple farms. The same applies to municipalities, as they supply water to multiple households. Implementing water conservation policies and efficient infrastructure control in these sectors are inhibited by this.

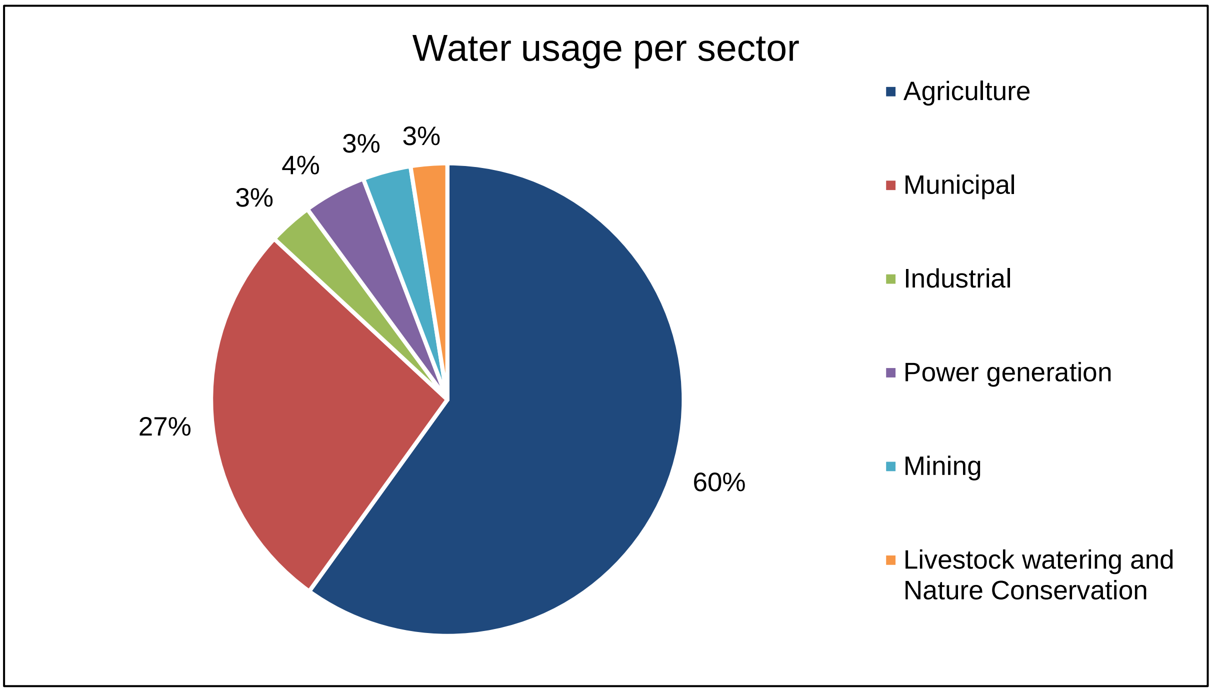

Figure 10: Water usage per sector in South Africa (Adapted from [27])

However, the power generation sector can be seen as a single end user, as Eskom owns more than 90% of this sector. Eskom thus consumes about 4.3% of the water in South Africa and supplying water to Eskom is seen by DWS as being of strategic importance for South Africa and its people. Some pumping schemes in South Africa supply water exclusively for use by Eskom's power stations [29].

Implementing good and efficient control strategies on the pumping stations within these schemes is more achievable compared to the other water consuming sectors. This is due to the fact that most of these stations are operated by DWS or Eskom, thus eliminating the need to work with multiple end users or water consuming entities.

Eskom requires large volumes of water for daily operation, thus the significant percentage of water allocated to them. As previously stated under Section 1.2, the majority of Eskom's power is generated by coal-fired power stations. The majority of water used by Eskom is for the cooling of these power stations. In 2012 Eskom's total water use per second amounted to 10 000 litres, of which most was used for cooling [30]. The three main types of cooling used on these power stations are [31]:

- Once-through
- Closed cycle (recirculating)
- Dry cooling

In Table 1 the amount of water withdrawn and consumed per MWh of generated electricity for each cooling method is given.

Table 1: Water requirements for cooling per MWh for conventional coal power plants [32]

Once-though		**Closed-cycle**		**Dry-cooling**	
Withdrawal [m^3]	Consumption [m^3]	Withdrawal [m^3]	Consumption [m^3]	Withdrawal [m^3]	Consumption [m^3]
75.5 – 189.27	0.38 – 1.2	1.89– 4.54	1.82– 4.16	N/A	N/A

Eskom has selected the dry cooling option for their most recent power stations Kusile and Medupi. This will reduce the added water demand they will need in the future when these stations go operational. Dry cooling is however, a much more expensive process of cooling down the power stations, thus indicating Eskom's commitment to reduce their water consumption [33],[34].

In addition to Eskom implementing water efficient strategies for their new fleet of power stations, DWS has also utilised more energy efficient technologies on their more recently built pumping stations. These technologies include the use of modern Variable Speed Drives (VSDs) that allow for better and more efficient control of a pump station's flow.

Through efficient and optimised control of their pump stations, DWS can reduce their electricity demand significantly. Incorporating the ToU structures into the control strategies, the DWS will realise significant energy cost savings. These finances can then be used to further optimise and upgrade old infrastructure, ensuring more efficient conveyance of water.

1.4 Objectives of this study

The objectives of this study can be summarised as follows:

- Investigate and understand the diverse DSM interventions implemented on pumping systems and the effect of such interventions on the IBTs;
- Investigate the advantages and disadvantages of using VSDs on pumping systems to ensure optimised VSD control;
- Identify a suitable pumping station utilising VSDs that can be used as a case study;
- Determine the case study's system characteristics and constraints through investigations and on-site tests;
- Develop an optimised control philosophy that incorporates the increased control range supplied through the use of VSDs;
- Build a simulation to test the control philosophy and verify the simulation data with data from a practical test;
- Simulate a typical pumping day to establish a baseline to which the other optimised control philosophy's simulation can be compared;
- Simulate the optimised control philosophy;
- Discuss factors that inhibit the successful implementation of DSM load management interventions on the case study, and the resultant possible financial loss;
- Recommend possible additional optimisation on the system and possible further studies.

1.5 Overview of dissertation

Chapter 1 serves as a brief introduction to the study. In this chapter a brief overview is given on the South African electricity situation and types of load management interventions. This is followed by an introduction to the water sector in South Africa, and how it is an integral part of power generation. Finally the objectives of the study are presented at the end of Chapter 1.

Chapter 2 explores the infrastructure and functionality associated with the conveyance of bulk water. The application of VSDs on pumping systems, as well as their advantages and disadvantages are researched. Chapter 2 concludes with the discussion of previous load management interventions on water transfer schemes.

Chapter 3 describes the process of investigating and identifying a suitable pump station for use as a case study. The potential for load management initiatives is then determined through the development of practical tests, leading to the development of a suitable control philosophy. A simulation is then developed for testing the optimised control philosophy.

Chapter 4 provides a detail investigation into the case study and then discusses the results of the tests developed in Chapter 3. A load management scenario based on the optimised control philosophy is then simulated and discussed. Constraints that prevented the successful practical implementation of the load management are then discussed.

This dissertation concludes with Chapter 5 and further recommendations are given.

Chapter 2 – Background to load management and VSDs

Knelpoort Dam, situated in the Free State, South Africa.[2]

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[2] Photo captured by author.

2.1 Introduction

Nearly 20% of the world’s energy demand are consumed by pumping systems. These pumping systems provide domestic, industrial, agricultural and numerous other sectors with their fluid-conveyance needs [35]. Thus it is clear that pumping systems are an integral part of our daily lives. South Africa is no different with its Inter Basin Transfers and pumping systems.

The majority of pumping systems require control of flow or pressure, or both, in the system. This control can be done through a number of methods, including VSDs. Added benefits of VSDs are improved process control, condition monitoring, improved energy efficiency and reduced Life Cycle Costs (LCC).

VSDs do have drawbacks, especially on the electrical grid. Harmonics can cause power supply problems and damage sensitive equipment and motors, but can be mitigated by applying appropriate preventative methods. With new technology advancements, Medium Voltage (MV) VSDs can control motors of up to 100 MWs and are increasingly used in the petrochemical and mining industries amongst others [36].

Incorporating the use of VSDs into load management interventions opens new possibilities for DSM strategies. Understanding and studying previously implemented DSM initiatives provides crucial background before continuing the study. Also, the infrastructure and functionalities of IBTs need to be understood.

This chapter looks at IBTs, VSDs and previous studies conducted on water transfer schemes. First the transfer schemes and its components will be discussed, with focus on VSDs. The chapter will then conclude with a brief discussion of a number of previous studies.

2.2 Inter-basin transfer scheme infrastructure and functionality

South Africa's key centres for economic and social development are generally situated where natural occurring water sources are scarce. Due to this, IBTs were developed to convey water from areas with relative abundance to areas where water is relatively scarce [37].

To give an overview of an IBT, with relevance to this study, a simple layout of an IBT is provided in Figure 11. In South Africa, the IBTs controlled by government are also referred to as Government Water Schemes (GWS). In Figure 11 the water basin, pumping infrastructure, water storage facilities and water consumers are shown.

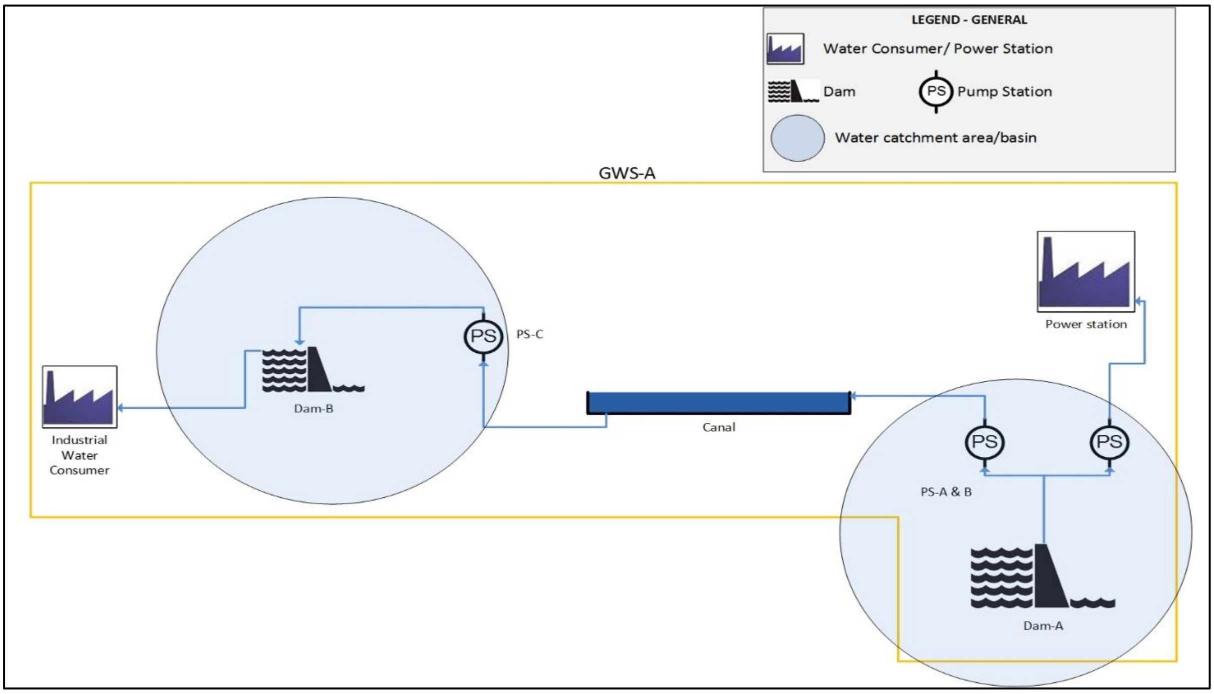

Figure 11: Generic layout of an IBT

In the above layout, the dams represent both a water source and storage facility. In some cases water is also stored in reservoirs. Pump stations transfer the water from an adjacent source through pipelines, canals or natural rivers to a water storage facility. The core pumping infrastructure used to transfer water in these IBTs will be discussed in this section, with focus on pumping systems utilising VSDs.

Centrifugal pumps

For applications where gravity is not sufficient for supplying water, pumps are installed [38]. The most commonly used pump for conveying liquids is the centrifugal pump. These pumps utilise a simple principle of flinging liquid entering the hub of an impeller towards the edge of the impeller [39].

The liquid is flung to the peripheral of the pump by the centrifugal force generated by rotation of the impeller [40]. The fluid accelerates as it flows from the hub of the impeller towards the edge [41], resulting in a static pressure difference. The operational principle of a centrifugal pump is illustrated in Figure 12 below.

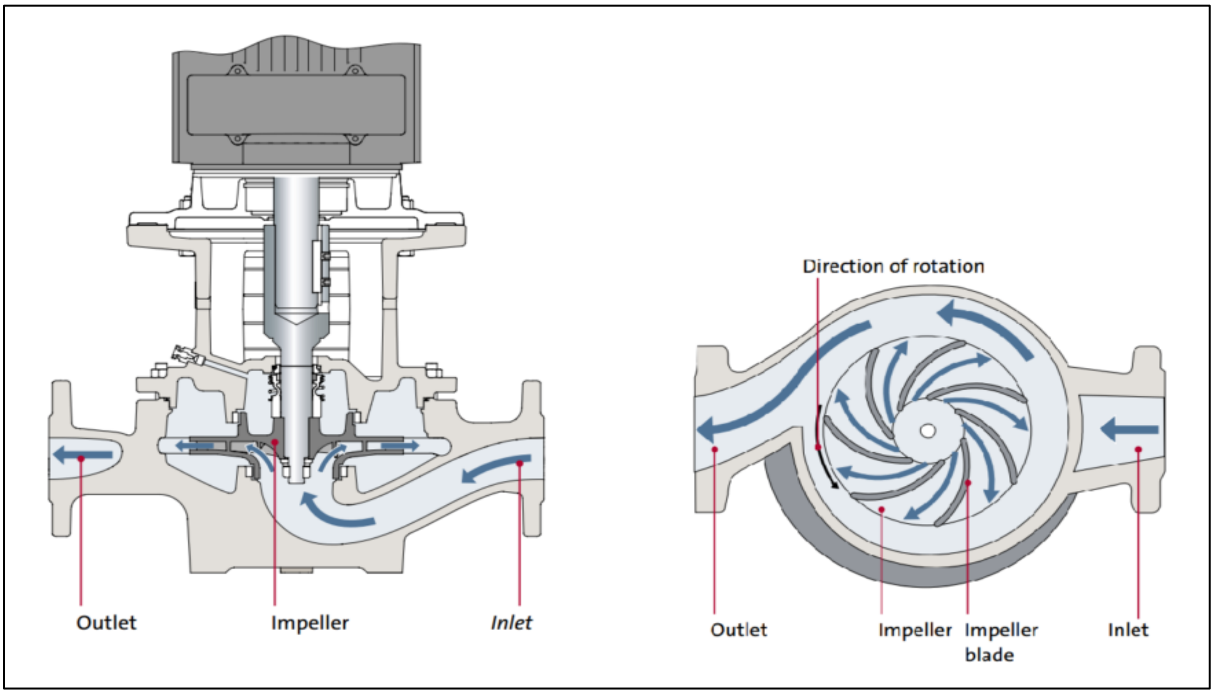

Figure 12: Operation principle of a centrifugal pump [42]

Multiple impellers can be added to the drive shaft of the pump to create a multistage centrifugal pump. These pumps are used when the required delivery pressure is higher than the efficient design of a single stage pump. In such an arrangement the stages are arranged in series, with one stage discharging into the inlet of the next stage. This design allows for increased pumping head. A multistage centrifugal pump is illustrated in Figure 13 on the following page. It also shows the flow of a liquid through the pump.

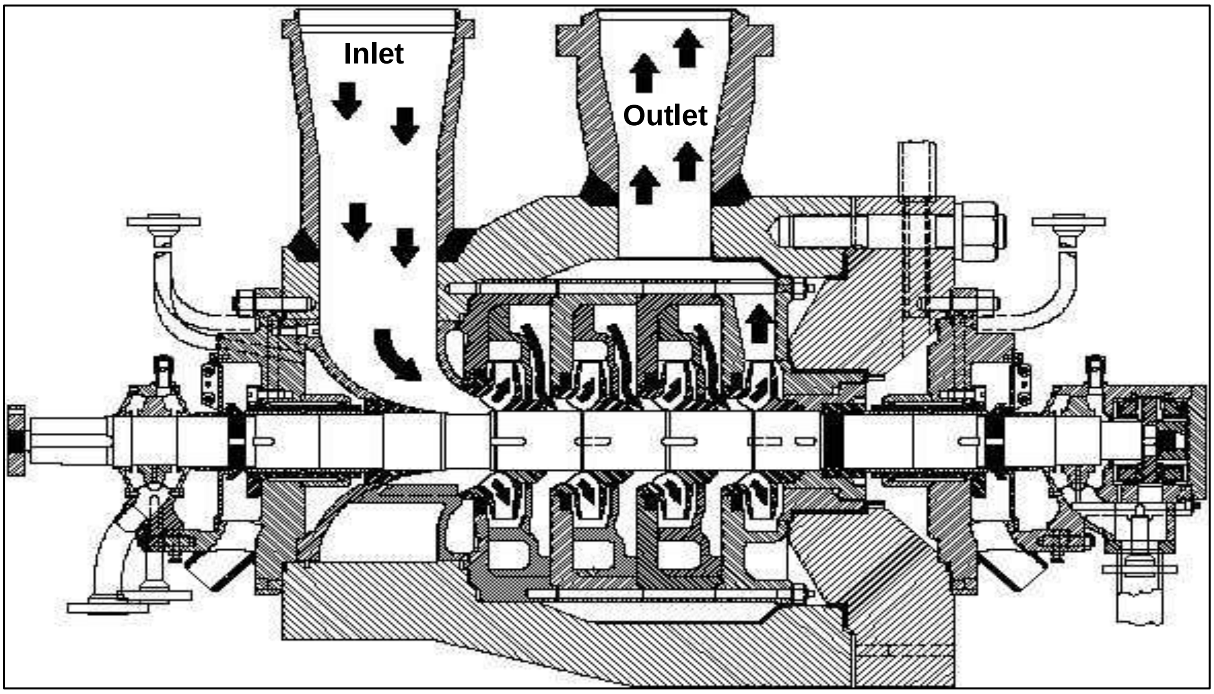

Figure 13: Multistage centrifugal pump [43]

Split case centrifugal pumps are also extensively used in the industry. These pumps utilise a double suction impeller designed to reduce axial thrust on the motor that drives it. This increases the life of the motor, pump-seals and bearings by reducing the resultant forces on these components. High efficiency is also obtained through this impeller design, as it halves the flow through each suction intake [44]. An illustration of the design can be seen in Figure 14.

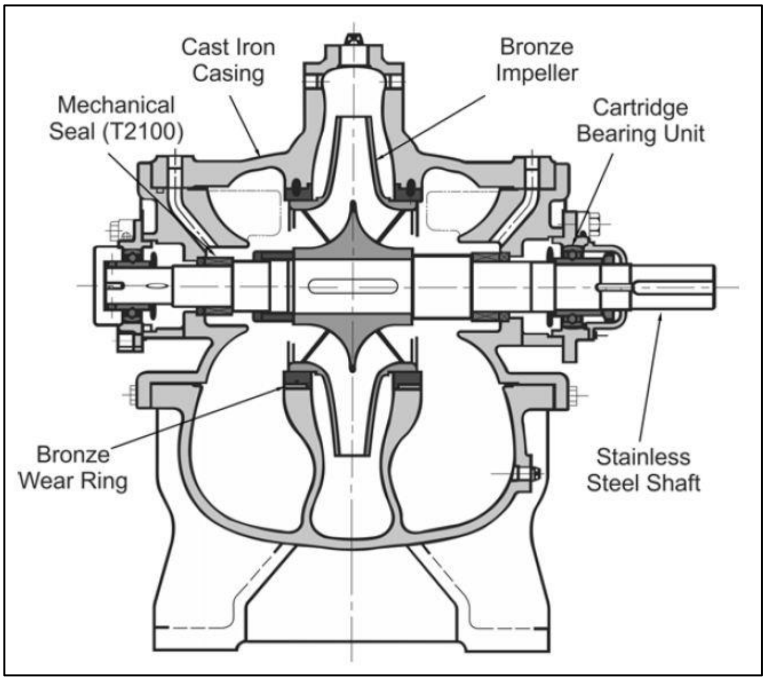

Figure 14: Horizontal split case pump [45]

The volute casing can be opened for easy inspection and repairs. The manner in which this casing is opened determines the type of pump, namely a vertical or horizontal split case pump. The design also has the suction and discharge flanges directly opposite to each other, simplifying the piping arrangements [46]. Different pumping applications require pumps that are specifically chosen or designed for that application.

To determine the best pump for a specific application, the required flow rate and pressure head are used. The shape of the pump’s casing and impeller blades govern these characteristics. A typical characteristic curve of a centrifugal pump is shown in Figure 15. By plotting the pump efficiency, head, power and net positive suction head (NPSH) required against the flow rate of a particular pump, the optimal point for pumping can be determined [47][48][49].

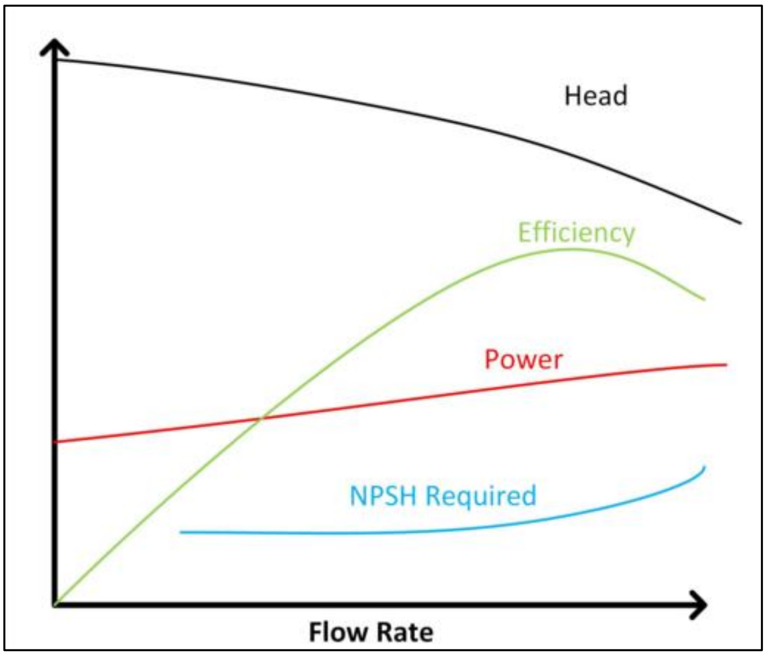

Figure 15: Pump characteristic curve for centrifugal pumps [47]

A pump’s characteristic curve can be altered by changing the rotational speed or diameter of the impeller. The flow rate of a pump is related to the impeller diameter, rotational speed, pressure head and pump power [48]. The centrifugal pump affinity laws govern the relation that exists between these parameters [49],[50]:

Equation 1

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2}$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{Q_1}{Q_2}\right)^2$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

Where:

$Q =$ Flow Rate (m^3/s)

$D =$ Impeller Diameter (m)

$N =$ Rotational Speed (RPM)

$H =$ Pressure Head (m)

$P =$ Pump Power (W)

In the case where the rotational speed is increased and the new corresponding power consumption of the pump is required, the fourth equation is used. For this P_1 and N_1 are the initial power consumption and rotational speed, with N_2 being the new rotation speed of the pump. P_2 is then calculated as the resultant power consumption at the new rotational speed. The same subscript numbering applies to the other parameters.

IBTs usually requires water being pumped over long distances and over various geographical features. These features include hills and mountains, which result in a high static pressure head. A high flow is also often required to supply the consumer with ample volumes of water. The high flow rate and pressure head result in high power requirements for the pumps. This power can be determined through the hydraulic power equation given in Equation 2 [40]:

Equation 2

$$P_h = \frac{\rho \cdot g \cdot Q \cdot H}{\eta}$$

Where:

P_h = Hydraulic Power (W)

ρ = Density of Liquid (kg/m^3)

g = Gravitational Constant (m/s^2)

Q = Flow Rate (m^3/s)

H = Hydraulic Head (m)

η = Pump Efficiency (-)

Multiple pumps are usually connected when a single pump is unable to supply the required pressure head or flow. Connection of multiple pumps can be configured in series, parallel or a combination of these. When identical pumps are configured in series, the pressure head of the system is increased.

This is usually utilised when a booster pump is used to supply sufficient suction pressure to a secondary pump. Pumps in series have synchronised flow rates that correspond to the generated system head [51]. The system characteristic curve of pumps configured in series can be seen in Figure 16.

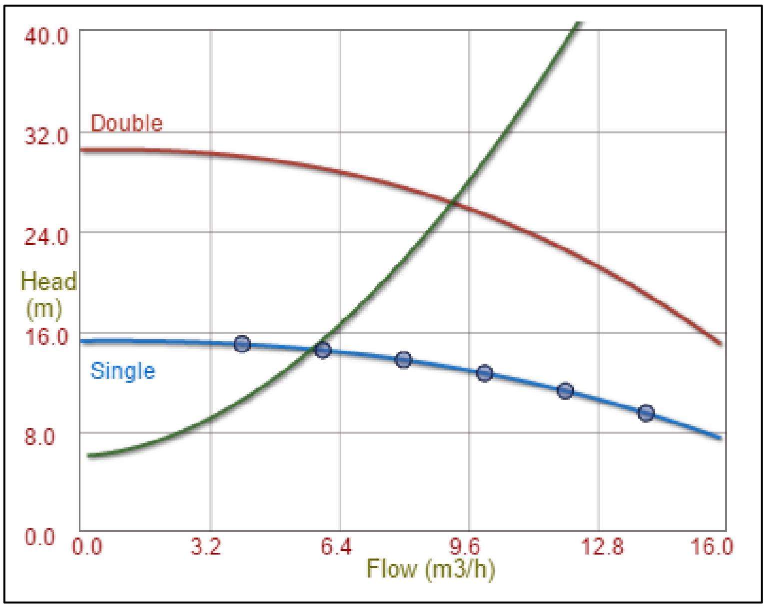

Figure 16: Characteristic curve for pumps in series [51]

For pumps configured in parallel, the flow is added at a constant head. The combined pumps can therefore deliver a higher flow rate compared to a single pump [52]. This is a configuration commonly utilised for bulk water transfer. Figure 17 presents the characteristic curve for parallel operated pumps.

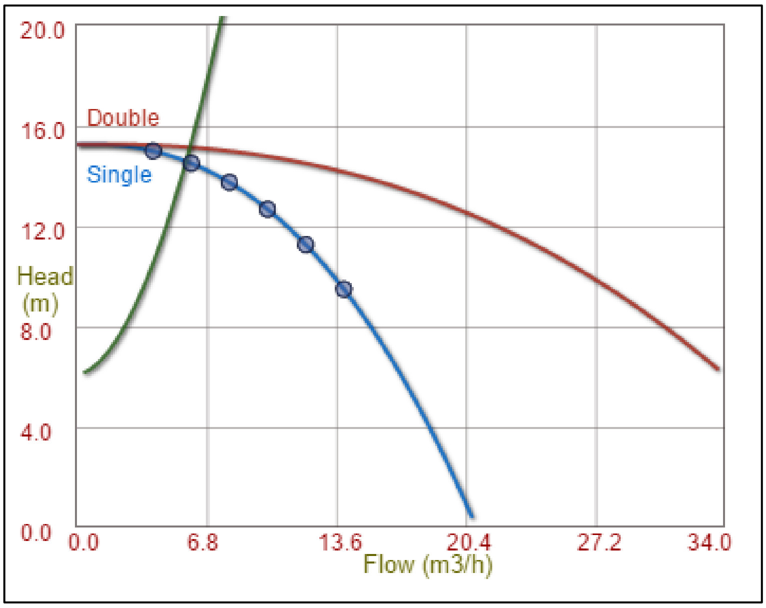

Figure 17: Characteristic curve for pumps in parallel [51]

In some instances it is necessary to combine the above mentioned configurations to overcome the flow and pressure demands. It is thus important to choose the correct pumps and pump configurations based on the required flow and delivery pressures. Pumps are usually driven by electric motors, which will be discussed next.

Motors

Several driving mechanisms for pumps exist, but for the purpose of this study focus will placed on electrical motors. These motors convert electrical energy into mechanical energy through the interaction of magnetic flux and electric current [53]. These motors are classified into two categories: alternating current (AC) and direct current (DC) [54]. For this study, focus will be placed on AC motors.

AC motors can be further sub-divided into induction and synchronous motors. Induction motors are cheap to produce and rugged, whereas the synchronous motors have a more complex design and require exciters. The synchronous motors provide a better overall power factor and are more efficient for high power requirements [55].

The most common used motors to drive pumps are the squirrel-cage induction motors. The construction of this motor consists of a stator wound in a particular number of poles and phases. It also includes a rotor that has either cast bars or brazed bars implanted in it [56]. Figure 18 show the components of an electrical induction motor.

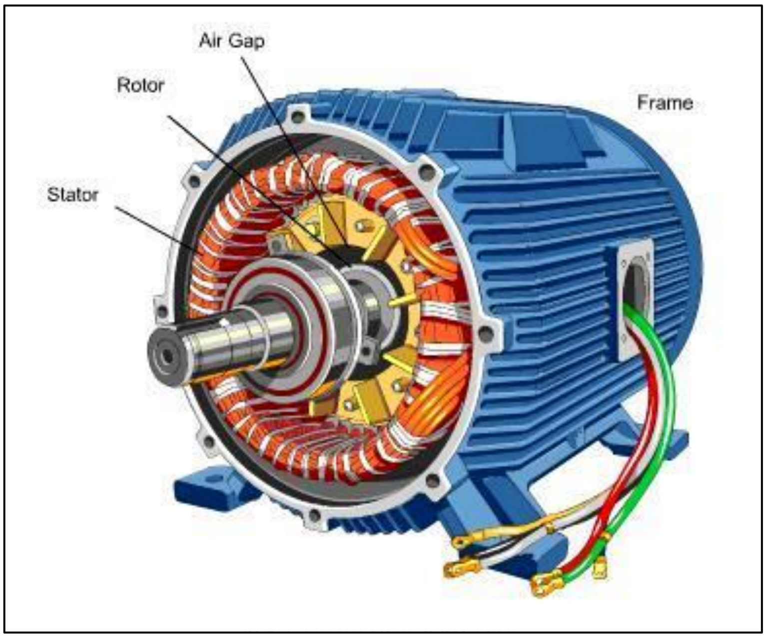

Figure 18: Electrical motor design

A magnetic flux is produced in the airgap (see Figure 18) between the stator and rotor when the motor is connected to a suitable power source. This rotating flux induces a voltage into the short circuited rotor bars, resulting in the circulation of a current. Torque is then produced when this current and the magnetic flux interacts [56].

The power necessary for a specific torque requirement is given in Equation 3 [57]. It is clear from this equation that the angular velocity of the rotor also contributes to the power required by the motor.

Equation 3

$$P = T \cdot \omega$$

Where:

P = Power (W)

T = Torque (Nm)

ω = Angular Velocity (rad/s)

Angular velocity of 1 rad/s converts to a rotational speed 9.55 RPMs [58]. The rotational speed at which a squirrel-cage induction motor operates is lower than the synchronous speed by a specific slip factor [56]. The synchronous speed is defined by Equation 4 on the following page [56]:

Equation 4

$$N = \frac{f \times 60 \times 2}{p}$$

Where:

N = Speed (RPM)

f = Line-power Frequency (Hz)

p = Number of Poles (-)

From Equation 4 it can be deduced that the speed of the motor, with a set number of poles, will change as the frequency supplied to the motor varies. This varying of an induction motor's speed is widely used on pumps for flow control. This follows from the affinity laws described in Equation 1 that show a significant power reduction can be realised by reducing the speed of a pump to match the required system flow. A widely used method to achieve this is through the utilisation of VSDs [59].

2.3 Use of VSDs on pumping systems

Varying flow rates are often a requirement for pumping systems. In many cases the maximum required flow for the system is used to select the pumps and pumping configuration. On average, the pumping system only operates at a fraction of its maximum installed capacity and some kind of flow control is necessary [59].

Several methods of flow control are available on pumping systems of which the most commonly used ones are throttling, bypassing, on-off control and VSD control. Figure 19 provide illustrations of the mentioned pump control methods. The methods in the following example are applied on identical pumps, thus the only constant variable are the flow.

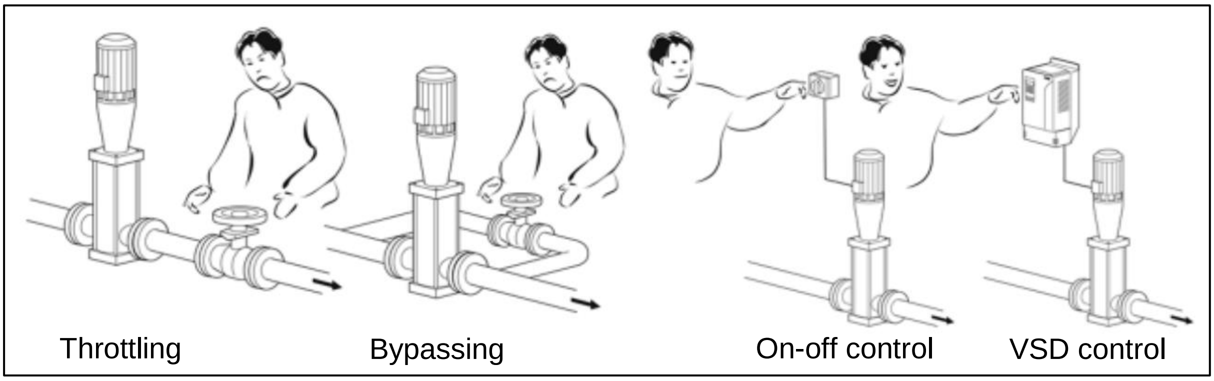

Figure 19: Methods for pump flow control [59].

The resultant power consumption for each of these methods differ. In Figure 20, the red arrows indicate the effect that each flow control method has on the pump characteristic curve. The green square represents the power consumption of the pump after the corresponding flow control method is applied.

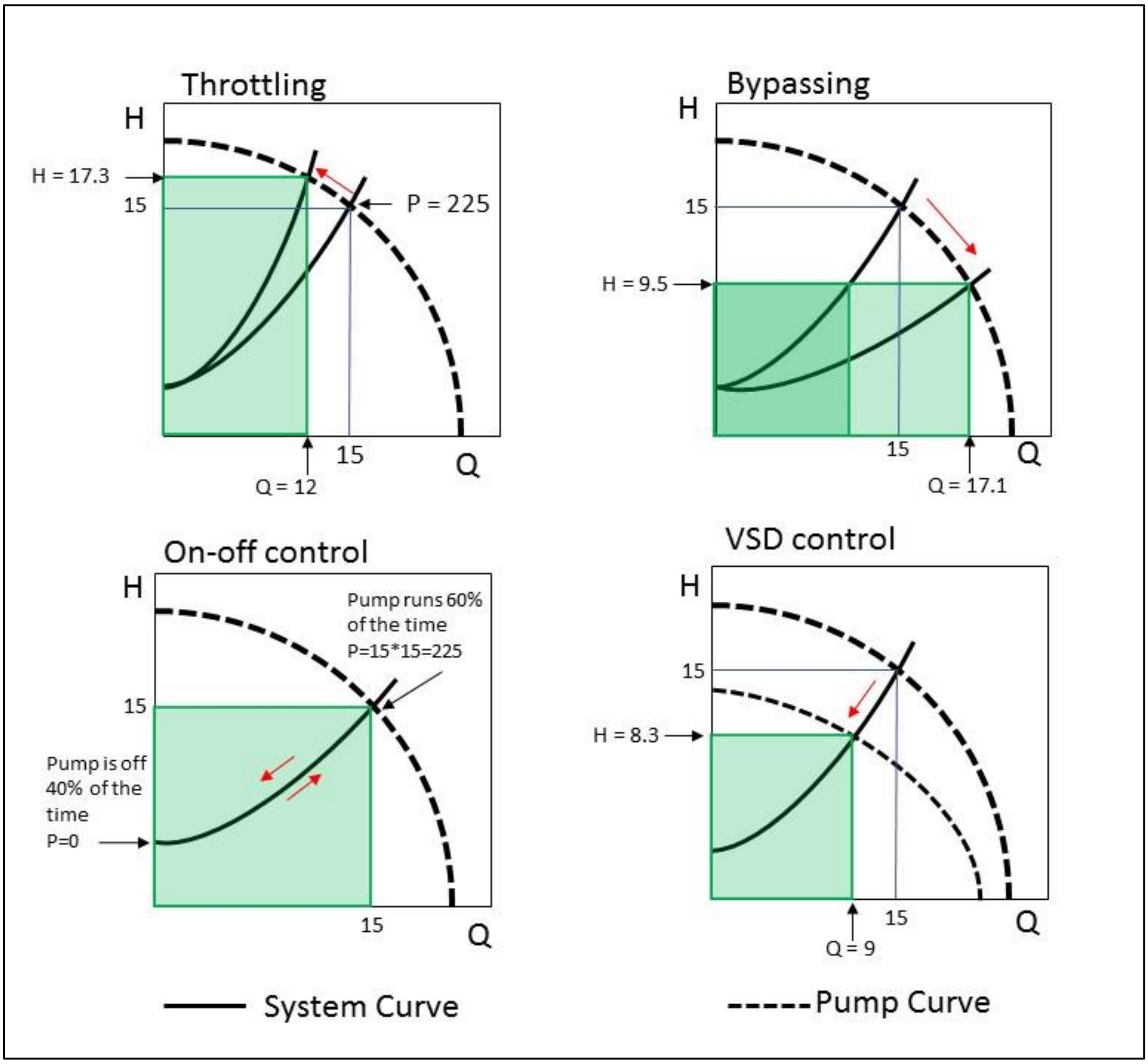

Figure 20: Power consumption for flow control methods. (Adapted from [59])

The power consumption (P) of each method can be calculated by multiplying the flow (Q) with the head (H). This corresponds with the area between the x- and y-axes and the operating point of the pump. The relative power consumption of each method then calculates to:[59],[60]

- **No Control:** P = 15 x 15 = 225
- **Throttling:** P = 12 x 17.3 = 207.6
- **Bypassing:** P = 9.5 x 17.1 = 162.5
- **On-off control:** P = (60% x 225.0) + (40% x 0.0) = 135.0
- **VSD Control:** P = 9 x 8.3 = 74.7

From the above results, it is clear that VSD control is the most energy efficient method for flow control on centrifugal pumps. The pump affinity laws explain this energy saving through speed reduction. These laws state that the power of a pump varies in proportion to the cube of the speed. Therefore, reducing the speed of a pump will result in a power reduction equal to the cube of the speed change. This means that a pump running at 70% of its maximum speed will consume $(0.7)^3$ = 34% power [61].

In addition to power savings, VSDs also provide the following benefits to a pumping system:

Reduced maintenance through smooth starting [61] - VSDs function as soft starters for pumps, eliminating the high peak current associated with conventional starting methods. This reduces stress on the electrical system and also reduces the mechanical stress on the motor and pump due to lower start-up torque.

Improved system reliability and performance[49],[62] - Reduced pump wear, especially on pumps and seals, is a direct result of any speed reduction by a VSD. Small process variations can quickly be matched to the process requirements in a system by a VSD, which improves the overall performance of the system.

Reduced risks of water hammering [59] - The main cause of water hammer is rapid changes in flow. This result is a pressure wave travelling inside the pipelines which can damage the pipes, valves and pipe supports. VSD allows gradual flow reduction to limit water hammering.

Reduced risk of cavitation on pumps [59] - Cavitation occurs in pumps when the static pressure drops below the liquid vapour pressure, causing vapour bubbles to form. These vapour bubbles then collapse, releasing high amounts of energy that knock small pieces of metal from surfaces inside the pump. Figure 21 show resultant damage that cavitation has on a pump impeller. With a VSD the suction pressure of a pump can be managed to prevent this drop in pressure.

Figure 21: Cavitation damage on a pump impeller [63]

From the above examples it is clear that VSDs improve several aspects of a pumping system. The above listed benefits are just some of the advantages of using VSDs, however, there are also some drawbacks associated with the used of VSDs. These drawbacks usually manifest in cases where the appropriate design and application of the VSDs are not considered. These drawbacks include:

Structural resonance [64] - When a pump and motor reach a resonance speed, excessive vibrations are generated. These resonance conditions are usually activated when the rotation speed matches with one of the system’s natural frequencies. With fixed speed applications, these frequencies are usually missed, but with VSDs the continuous operating speed range might coincide with one of these frequencies.

The resultant vibrations usually damage the bearing housings and support structures. Frame mounted pumps, multistage pumps and pumps with long shafts are more vulnerable to vibrations [65]. These natural frequency regions can be bypassed when programming the VSD.

Motor bearing damage [65],[66] – High frequency current pulses can be generated through the bearings of a motor controlled by a VSD, as illustrated in Figure 22. These pulses can result in metal from the bearings being transferred to the bearing lubricant. The result of this is increased wear on bearings, which shortens the operational life of the bearings.

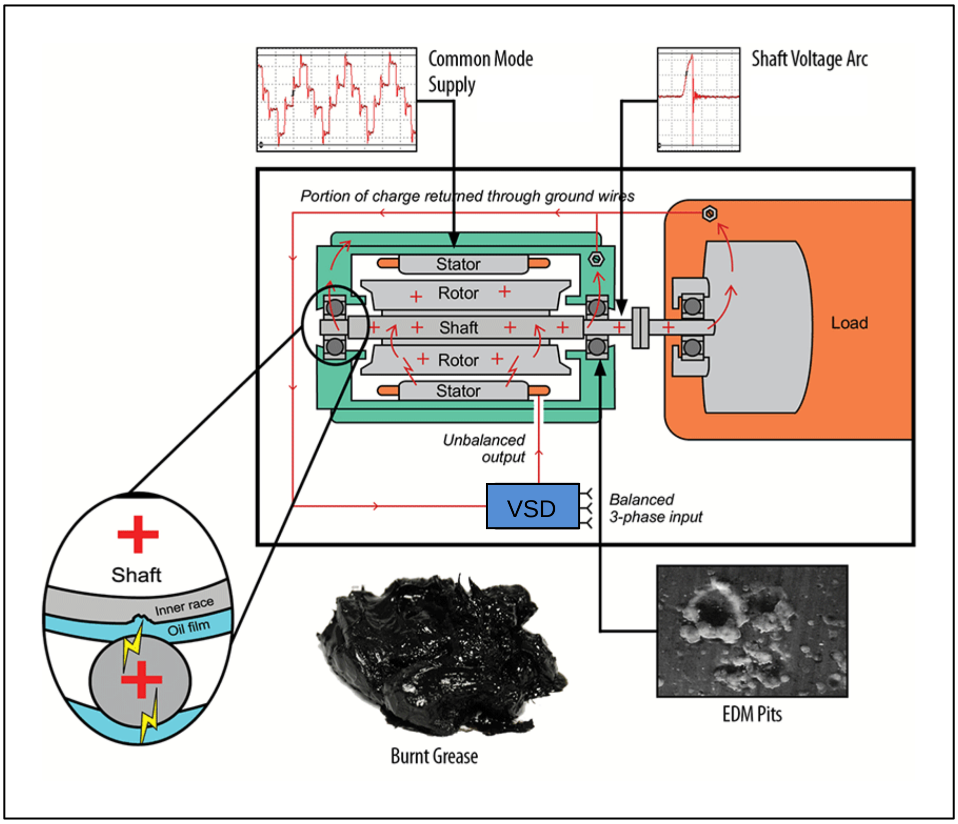

Figure 22: Electrical motor bearing damage [66]

This phenomenon is typically only seen in high voltage motors. To prevent this damage, the VSD must be properly grounded, the motor bearings properly insulated, symmetrical motor cables used and an inverter output installed.

Motor insulation damage [65] **–** Thermal stress can lead to insulation damage in motors. This usually occurs when a motor is run at lower speed, resulting in the cooling fan also operating at low speed. This reduces the cooling of the motor, therefore slower running motors have the tendency to overheat.

Voltage spikes can also lead to insulation damage. These spikes lead to deterioration of the insulation over time. The best way to mitigate the voltage spikes is to follow the National Electrical Manufacturer's Association (NEMA) cable length guidelines. Figure 23 illustrates the damage caused to winding insulation due to a voltage surge.

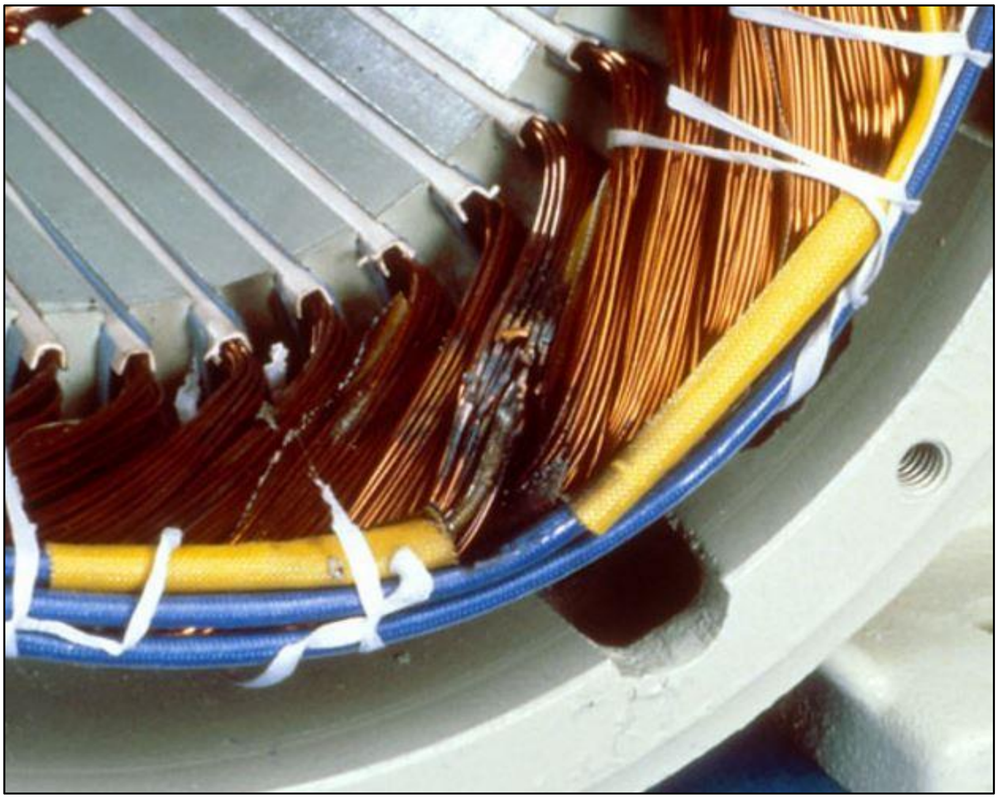

Figure 23: Damage to winding insulation due to voltage surge [67]

The above mentioned considerations of utilising VSDs on pumping systems highlighted the positive and negative effects of VSDs on the actual pumping infrastructure. It also highlighted how VSDs can improve energy efficiency on pumping systems through better flow control.

In the next section, some electrical considerations regarding the use of VSDs will be discussed. In addition to this, the costs linked to the use of VSDs will be discussed to determine the viability of installing this technology on pumping systems.

2.4 Electrical and cost considerations for VSDs

A key aspect of this study is linked to VSDs, more specifically the Variable Frequency Drive (VFD) type. These sub-sets of VSDs change the frequency of the power supply to manipulate the rotational speed of the motor [65]. Figure 24 illustrates the different types of VSDs used in the industry. For the purpose of this study, focus will only be placed on the voltage source types of VSDs.

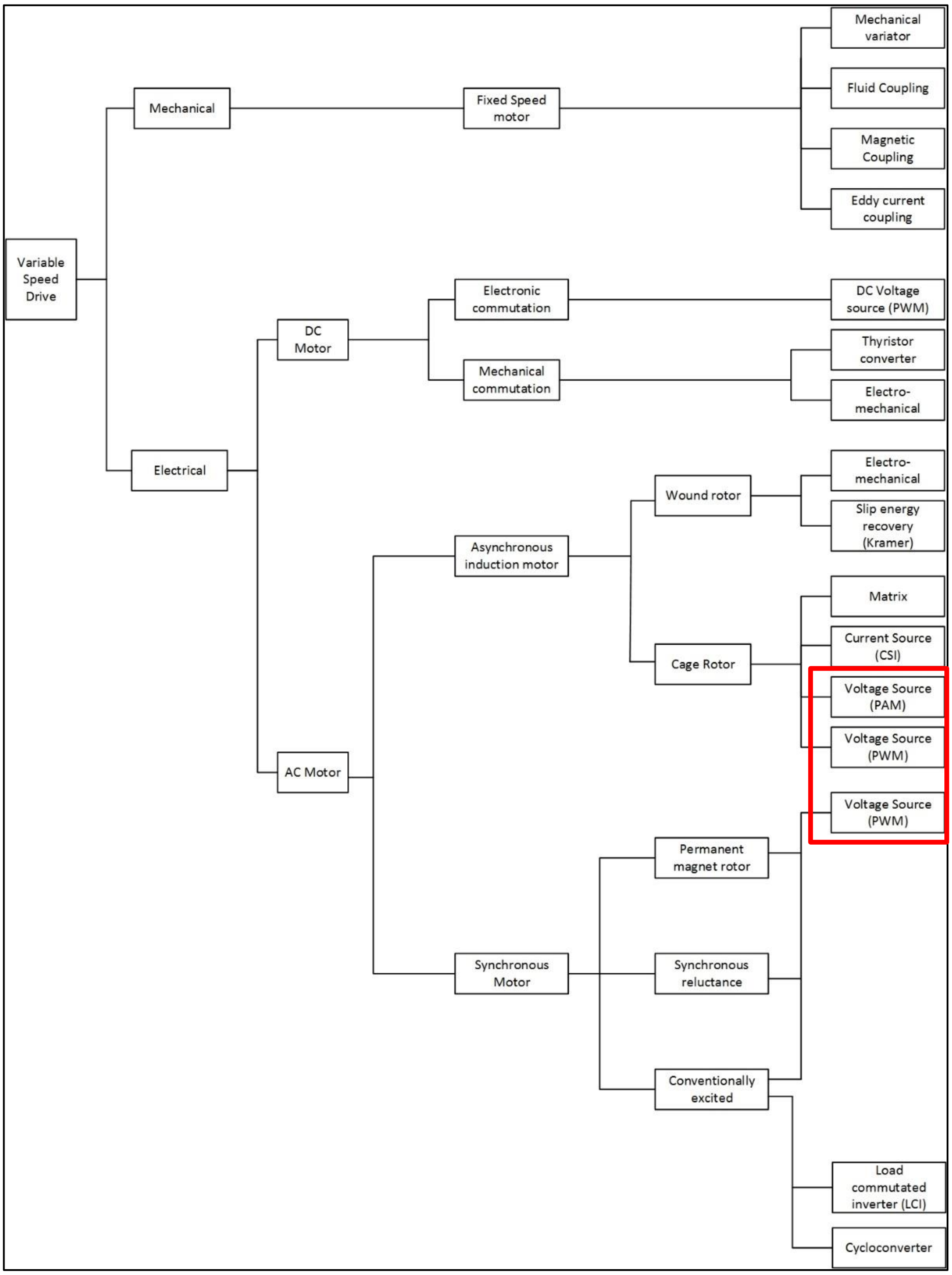

Figure 24: VSD types (Adapted from [64])

The pulse width modulated (PWM) inverter type of voltage source VSD is predominantly used. These VSDs create successive fixed voltage pulses with varying time duration. The resultant frequency of the wave is determined by the sum of the widths and the intermediate off phases. The AC sine wave's effective voltage is given by summation of the pulse areas. As illustrated in Figure 25, changing the width of the pulses, different wave lengths of AC current can be simulated to imitate variable frequencies to control the motor speed. [65]

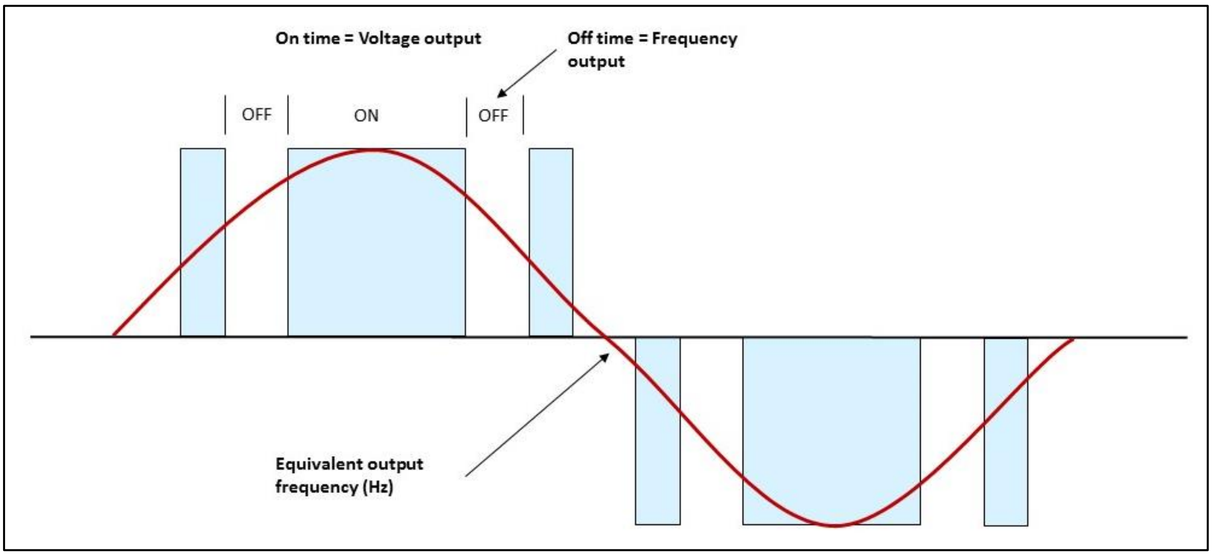

Figure 25: PWM generated waveform (Adapted from [65])

However, the high rate of switching in the PWM waveform can lead to problems in the pumping system's infrastructure. These problems include the deterioration of motor insulation and bearing failures described under Section 2.3. VSDs also generate "noise" in the form of voltage and current distortions [68].

The voltage distortion noise usually occurs in the supply line and can cause a malfunction in sensitive equipment such as computers and Programmable Logic Controllers (PLCs). Current distortion noise in the transformer generates heat in the transformer and its wiring. Figure 26 illustrates the effect of harmonic distortion on the power supply. Each sine wave represents a different order of harmonics [68].

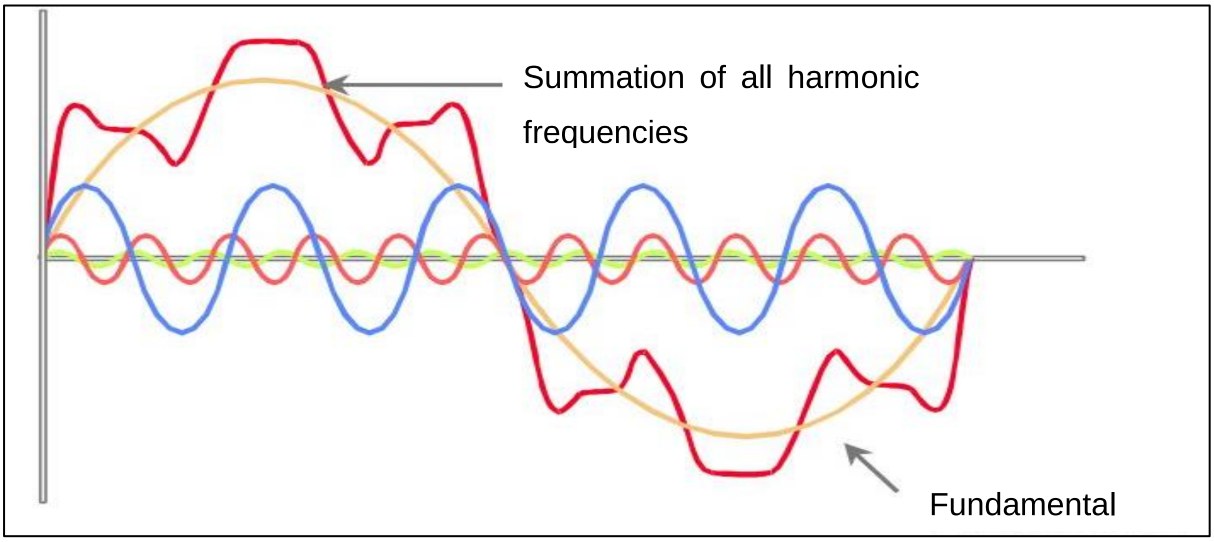

Figure 26: Harmonic distortion in VSDs [68]

The orange line represents the fundamental sine wave coming from the main power supply. The blue sine wave represents the 5th harmonic and the pink wave the 7th harmonic. As the number increases, the amplitude of the harmonic wave decreases. Lower amplitude waves cause less damage. Addition of all the sine waves results in the red line, showing the distortion caused by the harmonics [68].

A smoother sine wave is preferred, but the remedial actions to produce such a smooth line might not justify the additional costs. This leads to possible compromises in the managing of harmonics to save on initial capital costs. However, this initial capital cost is usually a small part of the LCC of the pump station. VSDs have proven to be instrumental in limiting the LCC of a pump station [59],[68].

The three major contributors to the LCC of a pump stations are energy cost, initial investment and maintenance [59]. However, there are more factors that also contribute to the LCC of a pump station as can be seen in Equation 5 below [59]:

Equation 5

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d$$

Where:

LCC = Life Cycle Cost

C_{ic} = Initial Cost

C_{in} = Installation and Commissioning Cost

C_e = Energy Cost

C_o = Operating Cost

C_m = Maintenance Cost

C_s = Downtime, Loss of Production

C_{env} = Environmental Cost

C_d = Decommissioning Cost

Figure 27 illustrates an estimated comparison between the different contributors to a pump station’s LCC. From this it is clear that maintenance and energy are the major costs over a pump station’s life cycle. For this study focus will be placed on these two expenses. There is no need to look at the initial costs of the pump station as the study focuses on the operation of an already established pump station.

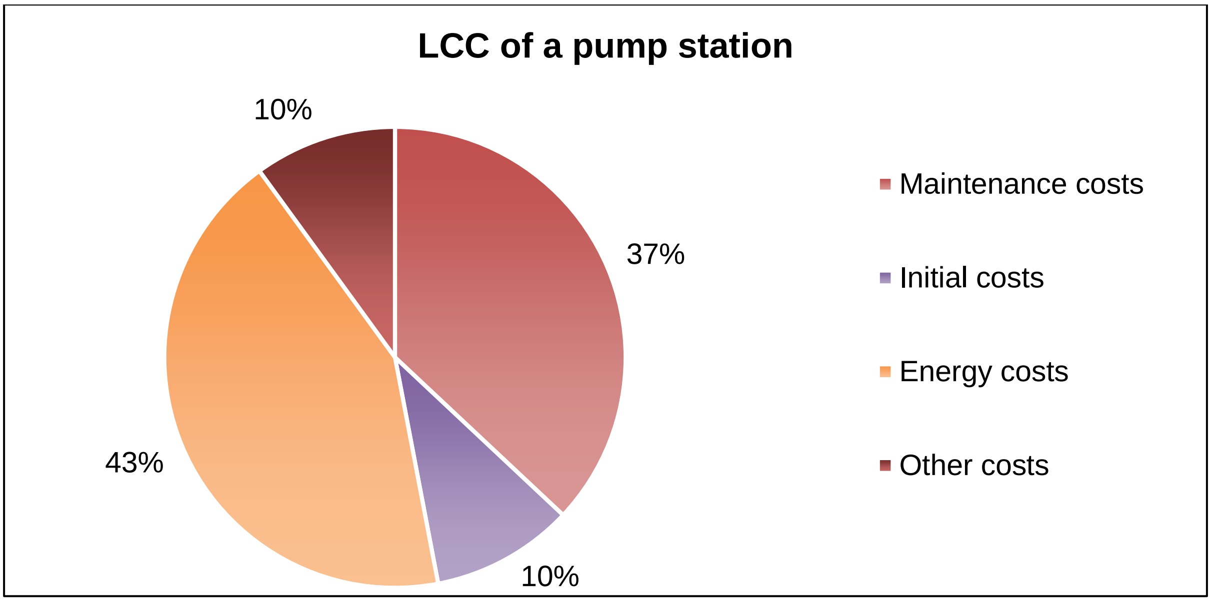

Figure 27: Typical LCC for a medium sized industrial pump (Adapted from [35])

VSDs can reduce maintenance costs on pumps and pumping infrastructure by limiting water hammering and cavitation. Care should however be taken to ensure the vibration and electrical drawbacks of a VSD are dealt with. Harmonics must be kept within accepted limits to prevent damage to the motor, power supply and supporting infrastructure. Managing pump speed also increases the life cycle of the pump as it is unlikely for a pump to run at maximum speed over the full course of its operational cycle.

If the pumps in a pump station run more than 2000 hours a year, the LCC are often dominated by the energy costs [35]. Using more efficient pumping methods, such as VSD control, can significantly reduce this portion of the LCC. In the previous section the benefits of using VSDs to control flow, among other benefits, was discussed. When the costs of installing VSDs are compared to the energy savings it can produce, it is found to be relatively low [59].

In the next section, previous work done to save and manage energy consumption on pump stations will be discussed. Some of the studies were conducted on mine dewatering stations, some on clear water pump stations and some on bulk water transfer schemes. These studies will provide better insight on how to save and manage the costs of energy consumed by pump stations.

2.5 Load management on water transfer schemes

Over recent years, several DSM initiatives were implemented on several water transfer schemes, be it mine dewatering systems or bulk water transfer schemes. Load shifting, as part of DSM load management strategies, was a particularly popular discussion point due to rising energy costs and the introduction of ToU tariffs [69].

The following section summarises previous research done on water transfer schemes. All of this research focused on managing energy consumption through the implementation of appropriate load management strategies.

Nortje, A [70] – identified four pumping stations with a combined installed capacity of 36.5 MW. These pumping stations are operated by DWS and convey water to key power stations. These stations form part of IBTs as it conveys from one water catchment area to the area where the majority of power stations are situated. After initial investigations it was found that these stations presented a prime opportunity for implementing DSM interventions.

Through the implementation of a load shift strategy, the national power grid was relieved of 12.3 MW during the evening peak period on weekdays. This was achieved by shifting the load from the peak periods to the off-peak periods. It was then further calculated that an annual energy cost saving of approximately R4.7 million may be expected due to the DSM intervention. From this study, it is clear that a significant cost saving can be realised through effective implementation of a DSM intervention.

Breytenbach, J [71] – focused on integrating electricity cost savings on a local water distribution facility. He developed an investigation methodology combined with an integrated strategy for implementing a cost saving intervention on water distribution facilities. He also discussed the inefficient control philosophies followed by the water distribution utility.

After simulating a proposed integrated control strategy, he optimised the approach for implementing load management. Process constraints and increased water demand resulted in limited implementation of the proposed strategy.

Els, L [72] – focused on water treatment plants (WTPs) that supply potable water to various end users. The high lift pumping stations on these WTPs were identified as the major power consumers. Optimised pump control and operation were found to produce significant cost savings. While researching plant optimisation strategies, he found that optimising the filter washing methods increased the filter backwash cycle by 34%.

The significance of ToU tariff structures was also proven by achieving a possible R990 000 annual cost saving by switching to a ToU tariff structure. Through his integrated control strategies, he also managed to achieve an evening peak load reduction of 2.21 MW.

Zwiegers,T [7] – implemented a load management strategy in 2015 on a large canal pumping scheme that supplies farmers with irrigation water. The scheme is controlled by DWS and is situated in the Upper Orange WMA. An investigation was done to determine the site specific requirements and challenges. A simulation was then used to determine if implementing the project is viable.

An Energy Management System (EnMS) was installed at the site, but it was decided that it would not automatically start and stop the pumps. This was due to the complex pumping system, so it was decided to use the EnMS to recommend pump stop and start times to the operator. He achieved an evening peak load reduction of 4.67 MW.

Duvenhage, DF [18] – aimed at determining the interaction between Water Supply Strategies (WSSs) set out by DWS and DSM interventions. He identified that WSS and DSM interventions aim to regulate the operation of the same system, thus the need to determine if it is able to integrate these two processes.

Through comparison of the goals of WSSs and DSM interventions, he found, that a water transfer schemes' primary goal is to deliver water to the consumer-base as set out in the WSS. When this goal is met, DSM interventions can be implemented on the water transfer scheme, but only after the effects of the load management intervention was found to have little influence on the water transfer schemes' primary goal.

He then analysed two case studies. Through the analysis, it was found that the implementation of an energy neutral load shift will have little negative effect on the transfer target of a water transfer scheme, as long as the transfer targets are not too high. In short, if the water transfer scheme has spare capacity, a load shift project is viable and significant savings can be achieved.

Feldman, M [73] – highlighted that the main factor in energy management is the ToU tariff structures. Implementing this he found that this increases pressures in the supply network during off-peak hours, resulting in increased water loss through leaks. He found that through correct utilisation of VSDs, improved system design and efficient pump operation, the energy efficiency of the system is improved.

Viholainen, J [74] – developed energy-efficient control strategies for VSD parallel pumping systems. He concentrated on energy-efficient methods on variable speed controlled parallel pumps. Initially he studied suitable operation conditions for variable speed controlled parallel pumps, followed by determining the output of each parallel pump through characteristic curve estimation. He found that the energy efficiency of pumping can be increased without installing new and more efficient components. Energy efficiency can be achieved through adoption of suitable control strategies.

The knowledge gained from these studies is of great importance when formulating a new approach for load management. This study aims at utilising modern technology, such as VSDs, to improve energy efficient water transfer and energy management. By learning from previous work, the best approach for conducting the study can be identified and potential problems mitigated.

From the above studies the impact of proper load management is clear. This impact is not only realised from the power supplier's point of view, but the user also benefits through annual cost savings. Optimising pump control through simulation leads to efficient load management strategies that can be easily implemented. Mr Duvenhage [18] also highlighted the fact that a load management intervention must be planned around the transfer target of a water transfer scheme.

2.6 Conclusion

In this literature study the main infrastructure of water transfer schemes was presented and discussed. How VSDs fit into the pumping industry was then introduced and the benefits of using VSDs discussed. The potential power, and consequently cost savings, were also discussed as benefits for utilising VSDs.

Certain concerns regarding the use of VSDs were discussed. The major concern was the managing of harmonic distortion caused by VSDs. It was however, concluded that these concerns can be sufficiently mitigated through the correct processes, such as installing filters and isolation transformers.

The effects of VSDs on the LCC of a pumping system was discussed. It was concluded that VSDs could potentially greatly contribute to the reduction in LCC. This is due to the fact that VSDs reduce energy and maintenance costs of pumping systems, with both of these being the major contributors to the overall LCC.

Finally, previous studies regarding DSM initiatives on water transfer schemes were reviewed. These studies provided information regarding the importance of proper investigation and implementation for integrated load management strategies. In addition, it also highlighted that a water transfer schemes annual transfer target is an important point to consider throughout the whole planning, simulation and implementation phases of any load management strategy.

In the next chapter the methodology followed to develop an optimised control philosophy will be discussed to achieve DSM savings. The investigation, development and simulation procedures are also presented and explained.

Chapter 3 – Control philosophy development for WTSs using VSDs

Sunset over Swartvlei in the Western Cape, South Africa[3]

Photo taken by author[3]

3.1 Introduction

In this chapter, the development of a control philosophy on a Water Transfer Scheme-B utilising VSDs on its pump station-A, is discussed. The new control philosophy introduces load management to the daily operations of the Water Transfer Scheme, without reducing the daily water delivery target.

Water Transfer Scheme-A will be investigated as a system, and how it fits into the bigger Government Water Scheme-A. This will provide insight on the interactions between Water Transfer Scheme-A and the Government Water Scheme, as well as the current control philosophy of Water Transfer Scheme-A's pump station.

To develop a new control philosophy for Water Transfer Scheme-A, the system's characteristics are first determined through a series of tests. These characteristics then provide insight on how the Water Transfer Scheme's system reacts to different control inputs. A control philosophy can then be developed that incorporates the new load management initiative.

System flowcharts are used to develop an optimised control philosophy that incorporates VSD technology into the control. To verify the proposed control strategy before implementation, a simulation is developed and solved. The simulation then provides analysis of the proposed control philosophy.

3.2 Investigation of a water transfer system

During the investigation of the Water Transfer Scheme the plant layout and current operation is confirmed. This information is required to determine possible constraints and variables that influence the water transfer scheme's operations. Through thorough understanding of the water transfer scheme's operations, any scope for possible load management initiatives can be identified. This scope then leads to the development of an optimised control philosophy.

Government water scheme layout

Due to client confidentiality, the Government Water Scheme, Water Transfer Schemes, pump stations, power stations and other water users will be given pseudonyms as seen in Figure 28. Government Water Scheme-A supplies Eskom's power stations and other industrial water consumers with raw water. To better understand and analyse a specific pump station, one has to look at the Government Water Scheme as a whole.

Figure 28 illustrates the interaction between each section of the Government Water Scheme. The arrows indicate the direction of water flow from one section to the other. To simplify the overall Government Water Scheme system, it was divided into smaller Water Transfer Schemes.

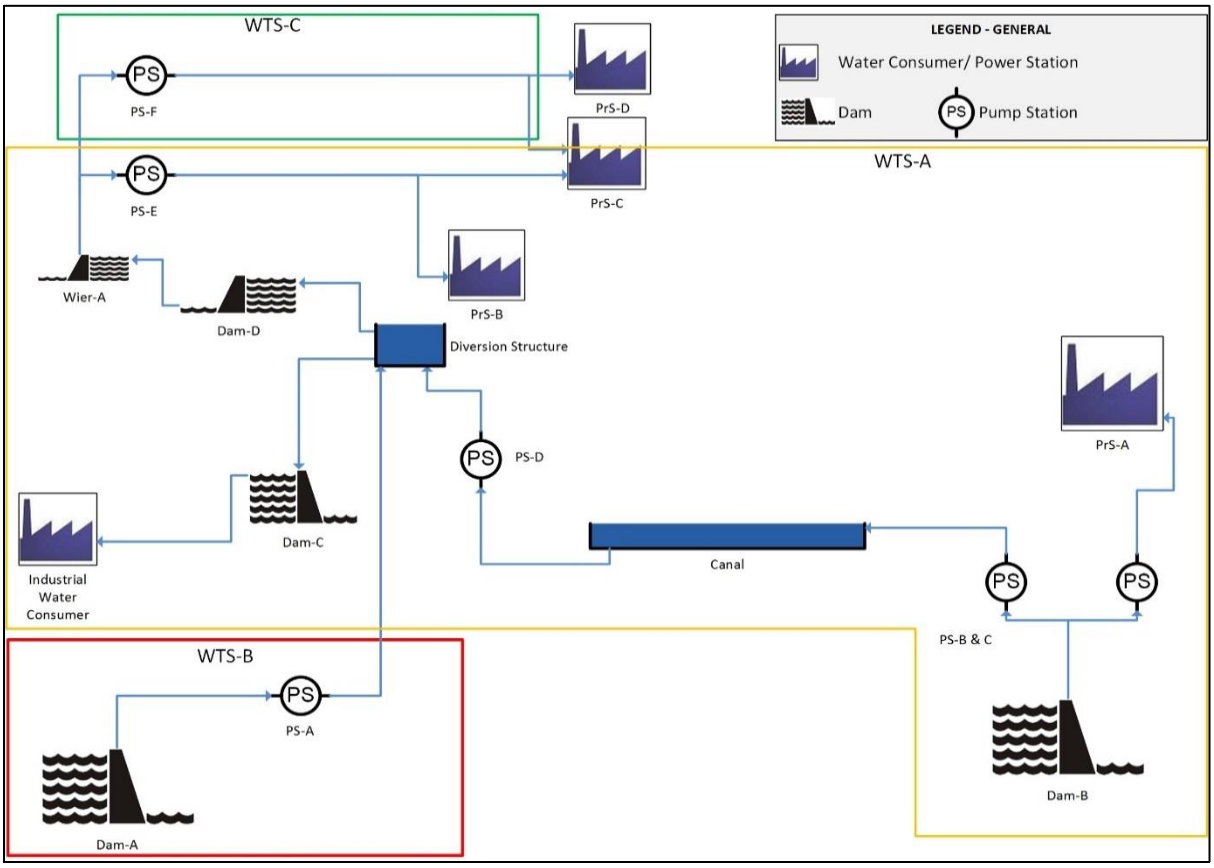

Figure 28: GWS-A with augmentation schemes WTS-B & C

From Dam-B, water is transferred by Pump Station-C directly to Power Station-A while Pump Station-B sends water to a canal that feeds Pump Station-D. From here the water is conveyed to a diversion structure that diverts the incoming water to Dams-C and -D. Dam-C supplies a major industrial client while Dam-D sends water through the natural river to Wier-A. Pump Station-E then extracts water from Weir-A and transfers it to Power Stations-B and -C.

Pump Station-F was built as the Water Transfer Scheme-C augmentation project for supplying water to Power Stations-C and -D. This was done due to fact that Pump Station-F can supply the power stations with higher quality water than their usual source. The pump station was built on the same site as Pump Station-E and also draws water from Wier-A.

Pump Station-A was built as part of Water Transfer Scheme -B to augment Water Transfer Scheme -A from a different water catchment area. Water from Pump Station-A is conveyed to the diversion structure, where it connects into Water Transfer Scheme -A. This added capacity and provided the key water users with a more reliable source of water. This also allowed DWS to do necessary upgrades on the canal system between Pump Stations-B and -D.

Within Government Water Scheme-A, only Pump Stations-A and -F are fitted with VSDs. Pump Station-F has VSDs fitted to the three pumps that supply Power Station-C, with no VSDs fitted on the other two pumps. Pump Station-A has VSDs fitted on all four of the high-lift main pumps and the six low-lift pumps, which provided a perfect case study.

Plant layout and description

The next step in the investigation is to obtain a site specific layout and description to better understand the operations of Water Transfer Scheme-B. In Figure 29, it is clearly shown that Pump Station-A has the following three sections with the interactions between these components influencing the efficiency of the daily operations.

Section A: High-lift pump station (HL-PS)

Section B: Desilting Works and Balancing dam (DWBd)

Section C: Low- lift pump station (LL-PS)

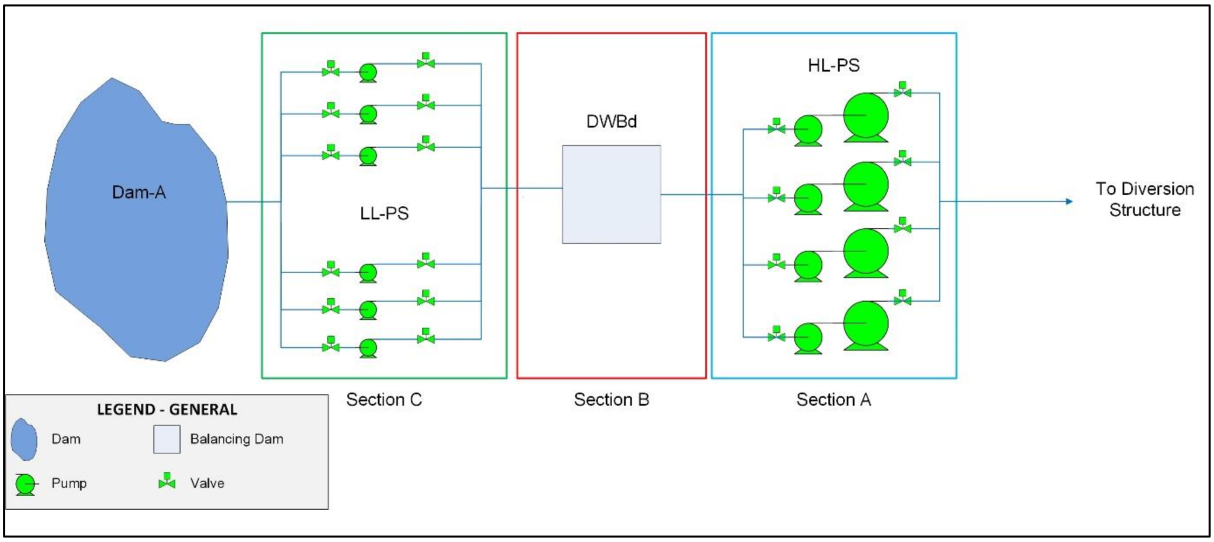

Figure 29: Pump Station-A layout with section description

The Low-lift pump station is located next to Dam-A. Here water is drawn from the dam and transferred to the Desilting Works. The High-lift pump station then extracts water from the Desilting works and conveys it to the diversion structure as previously shown in Figure 28. The relative sizes of the pumps indicate their relative power consumptions.

When looking at the relative sizes of the pumps, it can be seen that Section A is a major contributor of Pump Station-A's power consumption. More focus is thus placed on this section during the control philosophy development. The other sections can however, not be ignored due to the continual interactions between the sections.

It is essential to keep the balancing dams as full as possible during any load management intervention. The reason for this is that low dam levels reduce the effective desilting time of the volume of water that enters the dam. The levels of each channel can be monitored from the High-lift pump station control room.

The HL-PS is controlled by a Supervisory Control and Data Acquisition (SCADA) system in the control room. On this SCADA the following relevant information is displayed:

- Rotational speed of all running main pumps;
- Status of each pump set;
- Power usage of the main pumps;
- Suction and discharge pressures;
- Total station outflow;
- Desilting Works/Balancing dam levels.

From the SCADA, the High-lift pump station pumps can be stopped and started and the VSD speed can be changed. Condition monitoring of each pump set is done from the SCADA. For inclusion of the booster pumps' power in the calculations, data was retrieved from a test conducted during the commissioning of Pump Station-A.

By adding the data retrieved from the SCADA and the test data, the total power of the High-lift pump station is calculated. The absence of power meters at the Low-lift pump station led to the installation of portable DENT loggers on the electrical incomers. These loggers were used to calculate the power of the Low-lift pump station and then add it to the High-lift pump station power. This then equates to the total power of Pump Station-A.

The DENT loggers log the average current and voltage of each phase every five minutes. A logger was installed on each of the two incomers at the Low-lift pump station. By applying Equation 6 [7] on the data for each incomer, the power for each incomer can be calculated. Adding the power of the two incomers then gives the total power of the Low-lift pump station.

Equation 6

$$\boldsymbol{P_e = (\sqrt{3}\, V\, I\ \times pf)/1000}$$

Where:

P_e: Electrical power (kW)

V: Potential Difference (V)

I: Electrical Current (A)

pf: Power factor (-)

Following the investigation, the next section will explain how the load management potential was assessed. This is key in determining the viability of implementing a load management initiative.

3.3 Assessment of load management potential

Pump Station-A is billed by Eskom in accordance to their Megaflex ToU based tariff structure. It essentially divides each day of the week into peak, standard and off-peak hours. This can then be utilised to generate electricity cost savings for the client by reconfiguring the control philosophy of Pump Station-A.

The reconfigured control will focus on pumping more during the standard and off-peak hours than the peak hours. This necessitates assessment of the current operating procedure for Pump Station-A. By analysing this procedure, any possible scope for load management utilising the ToU structure can be determined. To determine the current operating procedure the following points need investigation:

- Influence of other Water Transfer Schemes on Water Transfer Scheme-B;
- Weekly water transfer target of Water Transfer Scheme-B;
- Current daily operation required to reach weekly transfer targets.

The yearly transfer target of Pump Station-A is calculated by contracted consulting engineers. To achieve this yearly target, Pump Station-A needs to pump at a constant rate of 5.0 m^3/s throughout the year. This is achieved through constant speed control on the VSDs. Using this constant flow target, the weekly target can be calculated to about 3 million m^3. As the maximum capacity of Pump Station-A is 5.4 m^3/s, there is scope for a load management intervention.

The extra capacity of 0.4 m^3/s allows for a comeback load associated with a typical load shift intervention. This extra capacity is utilised during the off-peak hours to eliminate the transfer deficit due to the load reduction during peak hours. Combining the comeback load with the load reduction results in the load shift intervention being realised. This is visually illustrated in Figure 30 below. The graph in Figure 30 shows the daily flow profile instead of the power profile, thus in this instance the load shift is seen as being a water transfer neutral load shift. The daily power consumption will however, follow the same profile as it is directly related to the flow.

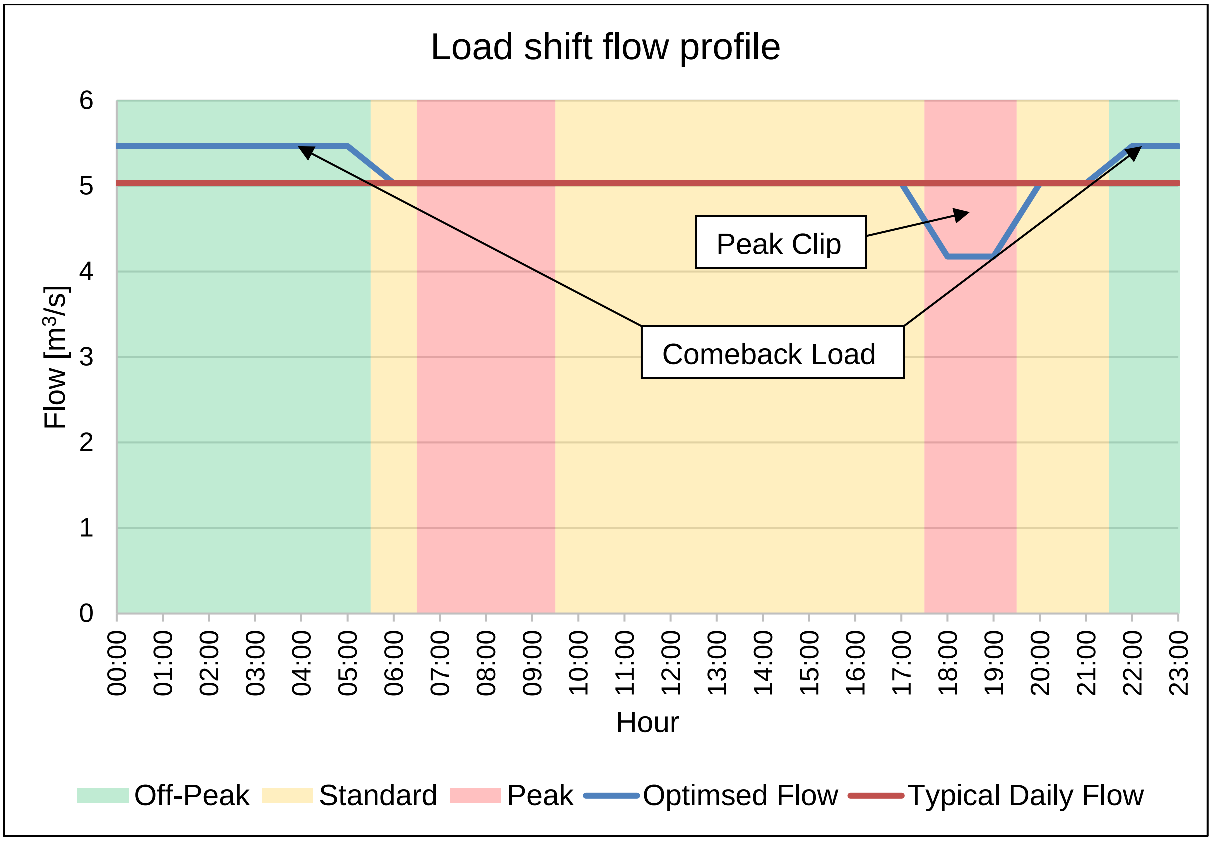

Figure 30: Load shift flow profile

In Figure 30 it is shown that the comeback load is initiated in the off-peak periods. The area between the optimised profile and the typical profile for the comeback load is equal to the area between these profiles for the peak clip. This shows that the load management intervention is transfer neutral. To be able to implement the above intervention, the system must be thoroughly understood.

It was proposed to conduct tests to better understand the system and develop an optimised control strategy before a prolonged intervention is implemented. The first test conducted was a peak clip (PC) test to determine the interaction between the sections of Pump Station-A. In addition, this test also shows the maximum load reduction that can be achieved during the peak hours. For this test no comeback load is initiated to recover the water transfer loss.

Peak Clip (PC) test

Due to the fact that Pump Station-A utilises VSD technology, the usual method of conducting a PC test was not suitable. Switching the pumps on and off regularly results in pump cycling that should be avoided. It was proposed to do the PC test by reducing the speed on the VSDs for both the High- and Low-lift pump stations from 18:00 to 20:00.

The developed procedure considers every system constraint. All the necessary readings for relevant data acquisition was identified. This data was then used to determine key indicators, such as the transfer deficit due to a peak load reduction. These indicators were then considered during the development of the optimised control philosophy.

Procedure for Peak Clip test

The procedure developed for conducting a PC test on a pump station that utilises VSDs is as follows:

1. Reduce VSD speeds as listed below at 18:00:
    a. High-lift pump station VSDs by 20% and,
    b. Low-lift pump station VSDs to a RPM setting that results in constant Balancing dam levels.
2. Take the readings of the following parameters every 15 minutes from the Human Machine Interface (HMIs):
    a. Balancing dam levels,
    b. High-lift pump station main pump HMI power readings,
    c. Total outflow of the pump station.
3. At 20:00, increase the VSD Speeds:
    a. High-lift pump station VSDs back to pre-test setting,
    b. Low-lift pump station VSDs back to pre-test setting.
4. Take last readings at 20:15 as listed under point 2.

Data Logging for Peak Clip test

Table 2 was used to summarise this data for analysis and calculation. In this table the balancing dam (DWBd) levels, High- and Low-lift pumping station VSD speed settings and the flow can be noted for each time interval. The flow for the Low-lift pumping station was not available due to a faulty flowmeter.

Table 2: Peak clip test data template

	DWBd levels [m]			VSD speeds [RPM]		HL-PS power [kW]		Logged flow rate [m^3/s]
Time	**Dam 1**	**Dam 2**	**Dam 3**	**HL-PS**	**LL-PS**	**Av. Main pump**	**Av. Booster pump**	**Average HL-PS flow**
17:45	2.6	2.6	2.6	1350	895	4533	1365	5.13
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…
20:15	2.6	2.5	2.5	1350	895	4533	1365	5.13

As explained under Section 3.2, the total High-lift pumping station power was calculated by adding the power data for the booster pumps to the main pump power data. The power data for the Low-lift pumping station was retrieved from DENT loggers. From this combined data, the total power usage of Pump Station-A during the Peak Clip-test was calculated. The insight gained from the first test prompted the next test and the control philosophy development.

3.4 Control philosophy development for Water Transfer Scheme-A

The test described below was done to help the development of a control philosophy, which utilises the VSD functionality, for Pump Station-A. Separate control for the High- and Low-lift pumping stations was developed through the use of process flow charts to simplify the process. It was decided to control the High-lift pumping station according to the ToU tariff structure and the Low-lift pumping station according to Balancing dam levels, in addition to the High-lift pumping station outflow.

RPM vs. Power vs. Station flow (RPS) Test

To determine the extent of utilisation that can be expected from the VSDs on Pump Station-A, a test was conducted to determine the system characteristics of the High-lift pumping station. It was decided to only focus on the High-lift pump station, as the Low-lift pump station will mirror its control to keep the Balancing dam levels constant. The main outcome of the test is to determine the influence of VSD speed and the number of running pump sets on the total station outflow and power.

The procedure below was developed to ensure optimal data acquisition, as with the first test. The necessary tables for the data acquisition were developed prior to the test for quick and easy recording of HMI readings.

Procedure for RPS test.

The procedure developed for conducting a RPS test on a pump station utilising VSDs are as follows:

1. Start the first pump set:
   a. Set VSD speed to minimum RPM,
   b. Allow the system to stabilise due to speed change.
2. Take the readings of the following parameters after 10 minutes from the HMIs:
   a. VSD Speed,
   b. Total station flow,
   c. Main pump power.
3. Increase VSD speed by 50 RPMs.
   a. Take reading as stated under point 2.
4. Repeat points 2 and 3 until the maximum RPMs are reached.
5. Start next pump:
   a. Set VSD speed at 1000 RPM,
   b. Allow the system to stabilise due to speed change.
6. Repeat points 2 to 5 until all available pump sets are running at maximum RPMs.

Data logging for RPS test

A table was developed for each combination of running pump sets. Table 3 only shows partial data for one running pump set. The complete data tables for one, two and three running pump sets can be seen in Appendix B. This data was then used to determine the system characteristics.

Table 3: RPS test data

1 Pump				
1000 RPMs				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
1442	1442	1850	1124	2974
1050 RPMs				
Total Flow [l/s]	Flow/Pump [l/s]	Power/ Pump [kW]	Booster Pump Power [kW]	Total Power [kW]
1590	1590	2130	1198	3328
… RPMs				
Total Flow [l/s]	Flow/Pump [l/s]	Power/ Pump [kW]	Booster Pump Power [kW]	Total Power [kW]
…	…	…	…	…
1350 RPMs				
Total Flow [l/s]	Flow/Pump [l/s]	Power/ Pump [kW]	Booster Pump Power [kW]	Total Power [kW]
2330	2330	4335	1385	5720

The results from the RPM vs Power vs Station flow (RPS) test is used to calculate specific flow set points for each time interval in a day. These results are then used in a simulation that simulates the whole of Pump Station-A to validate the proposed control. System flowcharts visually depict this control and also simplify the development process.

Control philosophy flowcharts

The control for the Low- and High-lift pump stations was developed with a control flowchart for each. This was done to split the development process into two smaller sections that allow better analysis and problem solving for each section. Firstly the control for the High-lift pump station will be looked at and its corresponding flowchart in Figure 31 is displayed on the following page.

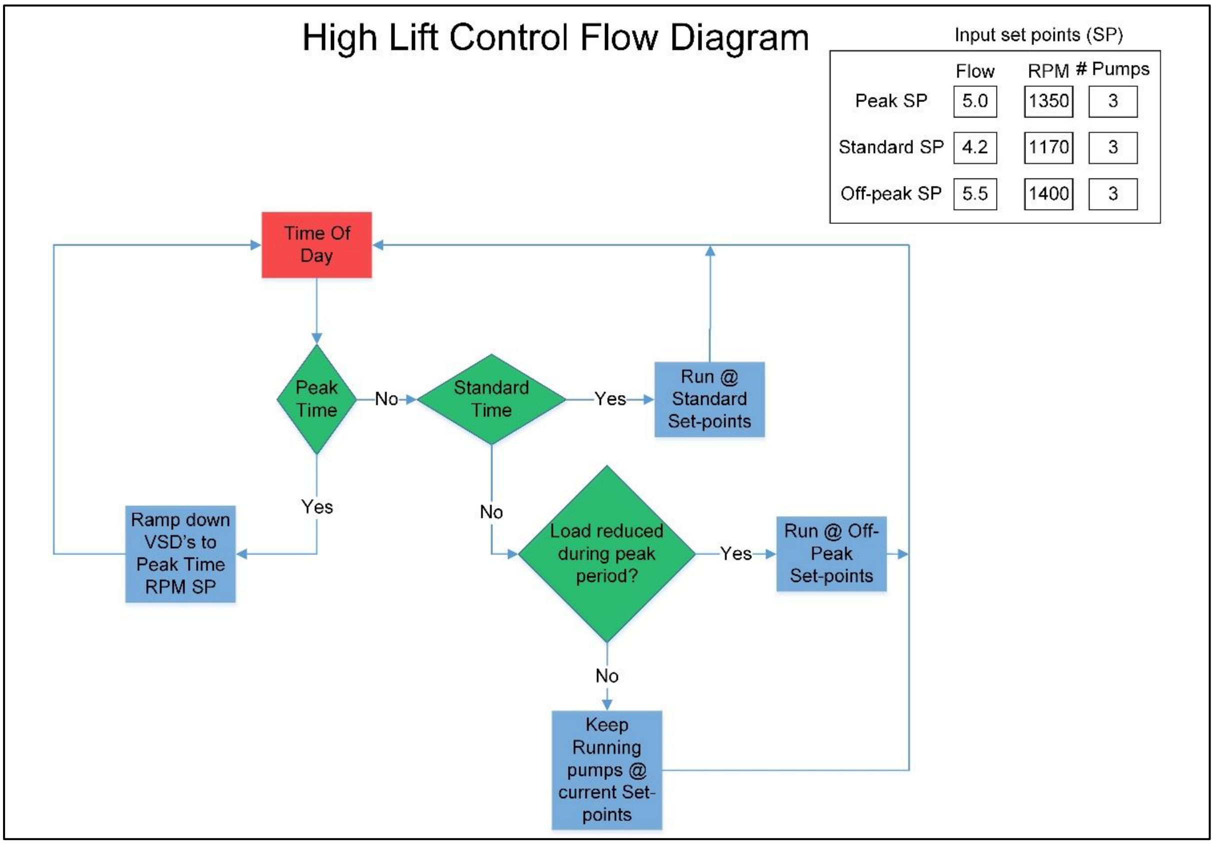

Figure 31: Control flowchart for the high-lift pump station

It was decided to develop the control for the HL-PS around the ToU tariff structure from Eskom. This allowed for easy control by utilising set points calculated for different scenarios. These set points are calculated for multiple scenarios by utilising the data from the RPS test. Station flow set point for each time period is calculated and inserted into the input box in Figure 31. The corresponding VSD speed and number of required pump sets are then determined and also added to the input box.

The controller, which can be an operator or a PLC, will then check the current time to determine which ToU time period is applicable. If it is peak time, the controller run the pumps at the peak-time set points.

During the standard time period the controller will operate the pump station according to the standard time set points. In the case that the controller detects neither a peak nor standard time bracket, it will check if a load reduction occurred during the previous peak time period. If this was the case, the controller would run the pump station at the off-peak set points as provided. When a load reduction did not occur, the controller would run the pump station at the current selected set points.

After the control for the High-lift pump station was finalised, the control for the Low-lift pump station was developed. It was decided to control the Low-lift pump station according to the Balancing dam levels and the High-lift pump station total station outflow. The flowchart developed for the Low-lift pump station can be seen in Figure 32 below. The only input for this control is the level set point required for the Balancing dam levels.

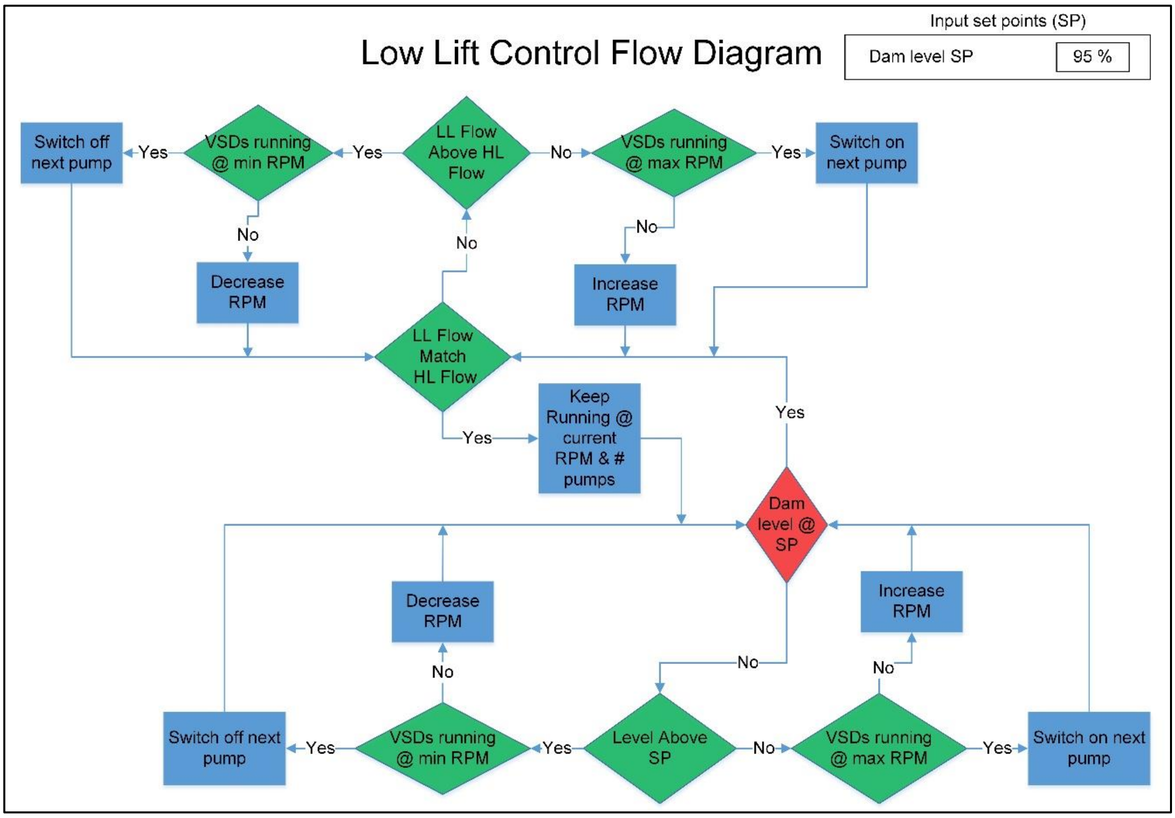

Figure 32: Control flowchart for low-lift pump station

The controller would check whether the level is above or below the set point. If the level is above, the controller would check if the VSDs are running at minimum speed. If this is not the case the controller will reduce the VSD speed in intervals of 25 RPMs until the minimum RPMs are reached. If the levels are not dropping due to the reduced speed and the minimum RPMs are reached, the controller would stop a pump and repeat the cycle.

In the case of the levels of the Balancing dams being below the specified set point, the controller would do the exact opposite to the above. If a low level is detected, the controller would check if the VSDs are running at maximum speed. If this is not the case, the controller would increase the speed in intervals of 25 RPMs until the maximum RPMs are reached. If the levels are not increasing due to the increased speed and the maximum RPMs are reached, the controller would need to start the next pump and repeat the cycle.

When the Balancing dam levels are at the given set point, the controller will start controlling the Low-lift pump station according to the High-lift pump station’s total station outflow. By matching the Low-lift pump station’s flow with the High-lift pump station’s flow, it will ensure that the dam levels stay constant. This control follows the same logic as for the control according to Balancing dam levels. The only difference is that it uses the High-lift pump station’s outflow as the controlling set point.

It should be noted that the term “controller” used above can refer to an automatic controlling unit such as a PLC or manual control through an operator. Ideally the control should be programmed on a PLC for full automation, but in the case that such control is unavailable, the same logic can be followed by a human operator.

After the control logic is finalised, a simulation is used to test it. This simulation provides valuable insight into the proposed control philosophy’s capabilities. It will also point out any possible limitations that might have been overlooked during the development phase. By managing these shortcomings before conducting the actual load shift intervention, prevents any possible events that might result in a failure.

3.5 Simulation of developed control philosophy

To test the control philosophies developed for the High- and Low-lift pump stations, a simulation was built using a simulation package known as Process Toolbox (PTB). This software was developed by TEMM International to simulate and optimise load management interventions on water and air networks.

Figure 33 on the following page, illustrates the layout of Pump Station-A as it was constructed in the simulation. The layout is divided into the Low-lift pump station (LL-PS), Balancing dam (DWBd) and the High-lift pump station (HL-PS). Detailed views of the sections are shown along with explanations of each section’s simulation inputs. For higher quality layouts, please refer to Appendix C for full page layouts of each section.

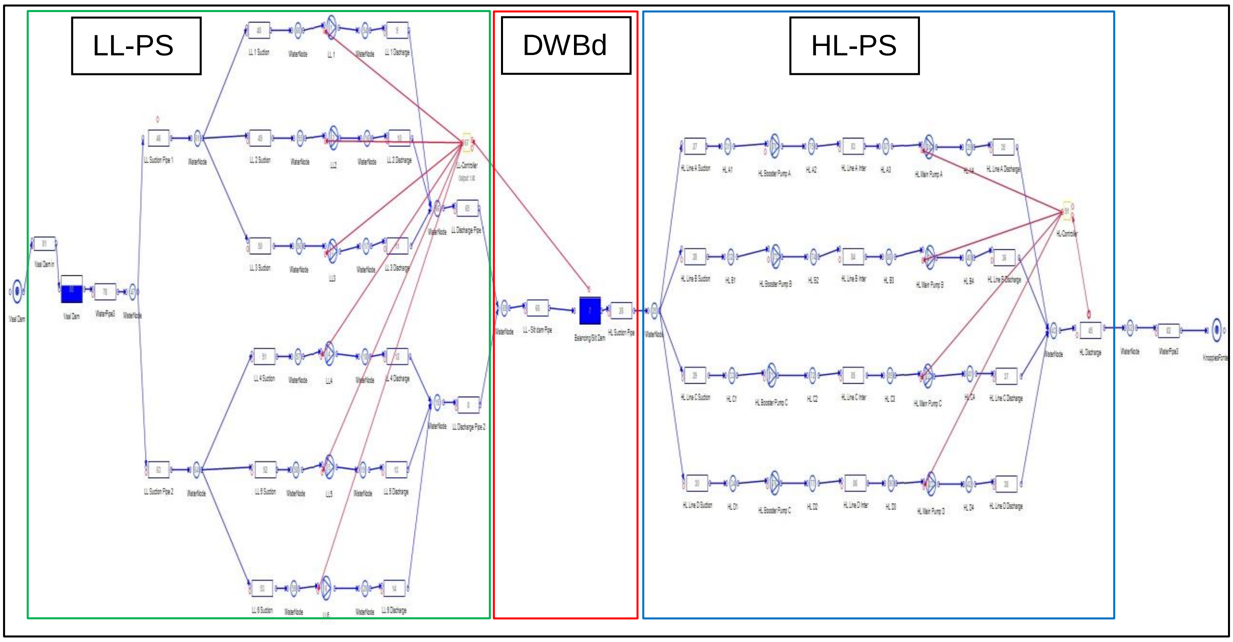

Figure 33: PTB simulation layout for Pump Station-A

The High-lift pump station’s main and booster pumps, as well as the Low-lift pump station’s pumps, were assumed to be respectively identical. This simplifies the construction of the simulation model by eliminating the need to customise each component. The disadvantage of doing this is that the simulation results might differ from data retrieved on site. It was therefore decided that the percentage difference should be less than 10% for the simulation to be considered accurate.

In Figure 34 on the following page, the layout for the High-lift pump station in the simulation is shown. Note that the controller only controls the main pumps according to the flow through the high-lift discharge pipe. The Proportional and Integral (PI) controller is used to simulate the VSD control due to its ability to change the speed fraction of each pump under its control. Red squares indicate pumps that are not available for control, as in the case with a standby or off-line pump.

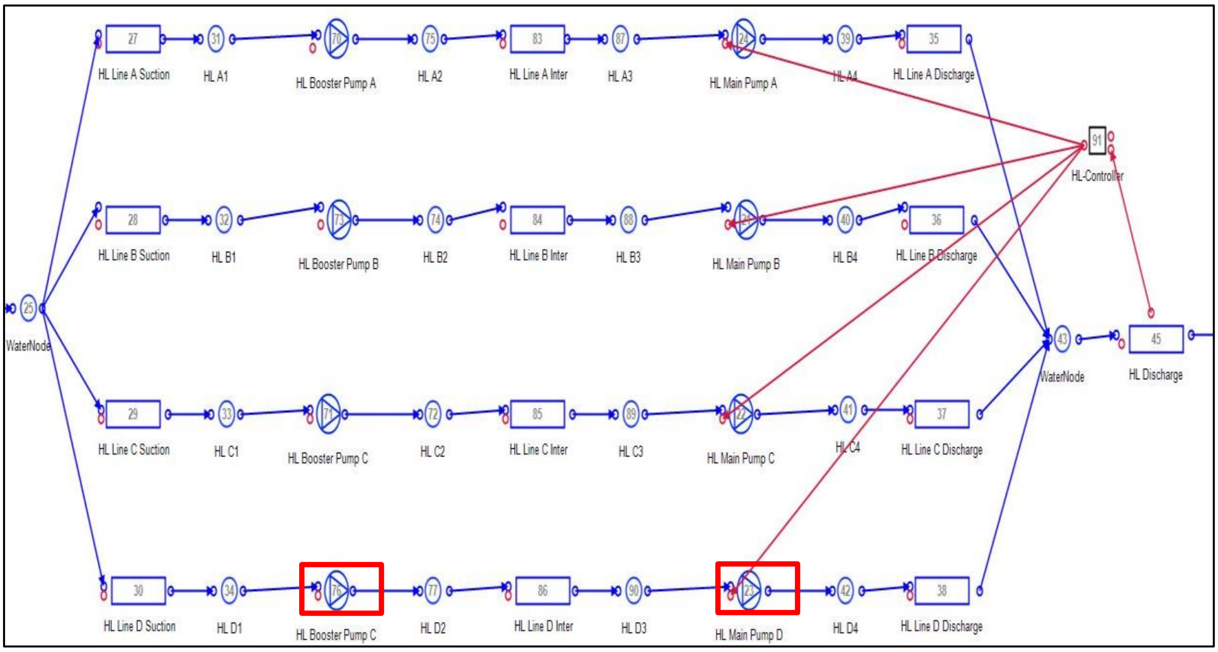

Figure 34: PTB Simulation layout for the high-lift pump station

Station outflow set points are given as input to the PI controller, as indicated by the red arrow from the pump to the controller. These values are calculated from the data acquired during the RPS test previously discussed. The controller then matches these flow set points by altering the speed fraction of the pumps. Just as the VSDs on site run the pumps at a synchronised speed, the PI controller will assign similar speed fractions to all the pumps.

A similar PI controller is used for controlling the Low-lift pump station as seen in Figure 35 on the following page. The only difference is that it controls according to the Balancing dam levels. It adjusts the speed fraction of the pumps under its control to keep the dam level as close to the calculated set points. As with the High-lift pump station controller, the pumps within the red squares are not available for control.

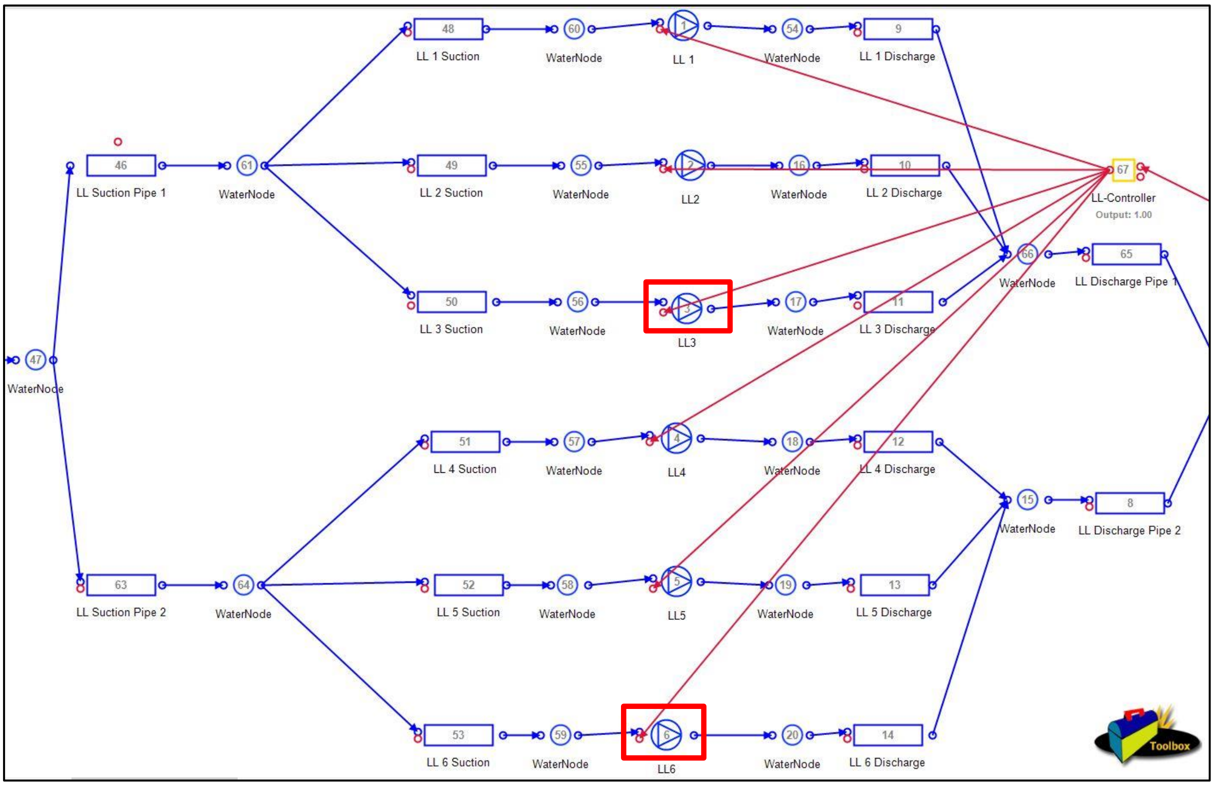

Figure 35: PTB simulation layout for the low-lift pump station

The hourly set points for the dam level is kept constant. High dam levels allow optimum desilting functionality to occur. Due to this, it is expected that any speed reduction at the High-lift pumping station will trigger a speed reduction at the Low-lift pumping station to keep the balancing dam level at the required set point.

It is expected that this will result in both the High- and Low-lift pumping stations' power profiles matching that of the 24-hour flow profile. This is supported by the fact that an increase in flow will result in an increase in power consumption. The simulated power consumption of Pump Station-A will be used to determine the possible impact of the optimised load management intervention. Before the simulated data can be trusted, the simulation must be verified.

To verify the simulation, it is compared to real time data. It was therefore decided to simulate the Peak Clip test and compare the data from the simulation with data gathered during the test. Comparing Pump Station-A's total power and the High-lift pump station's discharge pressures with corresponding simulated data will give an accurate representation of the simulation's accuracy.

The verification of the simulation and the simulation of the optimised control philosophy will be presented and discussed in Chapter 4. Two days are simulated, the first simulated day allows the system to stabilise and then gives a second simulated day that more closely represents the reality.

3.6 Conclusion

This chapter described the methodology behind the development of an optimised control philosophy on a water transfer scheme utilising VSDs on its pumps. The developed control focused on load management through the incorporation of the Eskom ToU billing structure.

Firstly, an overall scheme and site investigation led to the identification of possible constraints and limitations, such as lost communications and breakdowns. This investigation developed the best procedures to conduct the necessary tests. These procedures ensured optimum data acquisition and test results.

The first test was a PC test used to define the interactions between each section within Pump Station-A. This test gave an overview of how control inputs at one point in the system translates to other points. The second test was a RPS test used to determine the system characteristics. These characteristics include the relationship between station flow, VSD speed, delivery pressure, and power consumption.

From the two tests, an optimised control philosophy was developed through process flowcharts. A simulation determines if this control is a viable solution. In the next chapter the results of the above tests and simulation will be discussed and analysed. From this analysis a conclusion for the study will be formulated and recommendations will be made.

Chapter 4 – Results

Mountains near Clarens, South Africa[4]

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[4] Photo taken by author

4.1 Introduction

In Chapter 3 the methodology for investigating a Water Transfer Scheme was described. The investigation first focused on the Government Water Scheme as a whole and then singled out Water Transfer Scheme-B's Pump Station-A as a viable option for a case study. In this chapter the implementation and results of the methodology developed in Chapter 3 on the case study of Pump Station-A are described.

As in the methodology, the results of the tests are presented and discussed after the investigation. These results are then used in MS-Excel calculations to determine input parameters for the simulation. The simulation results are then presented and analysed. In addition, constraints that influence effective implementation of load management strategies are discussed.

The main constraints are identified and an alternative implementation is done to test the optimised control philosophy. From this data the relevant conclusions are drawn regarding the optimised control philosophy.

4.2 Case study investigation

As discussed in Chapter 3, Pump Station-A provided the best scenario for a case study. The interaction of Pump Station-A on Government Water Scheme-A was described. More focus was then put on Pump Station-A in the site specific investigation. Here it was shown that for simplicity Pump Station-A was divided into three sections.

Section A is the High-lift pump station. As seen in Figure 36, the High-lift pump station has four parallel pump sets (Set-1, -2, -3 and -4) each consisting of two pumps in series. Only three sets are allowed to run at once, while the fourth pump set is on standby. Each set has a booster and a main pump, with a combined maximum design flow output of 5.4 m^3/s for the three pump sets.

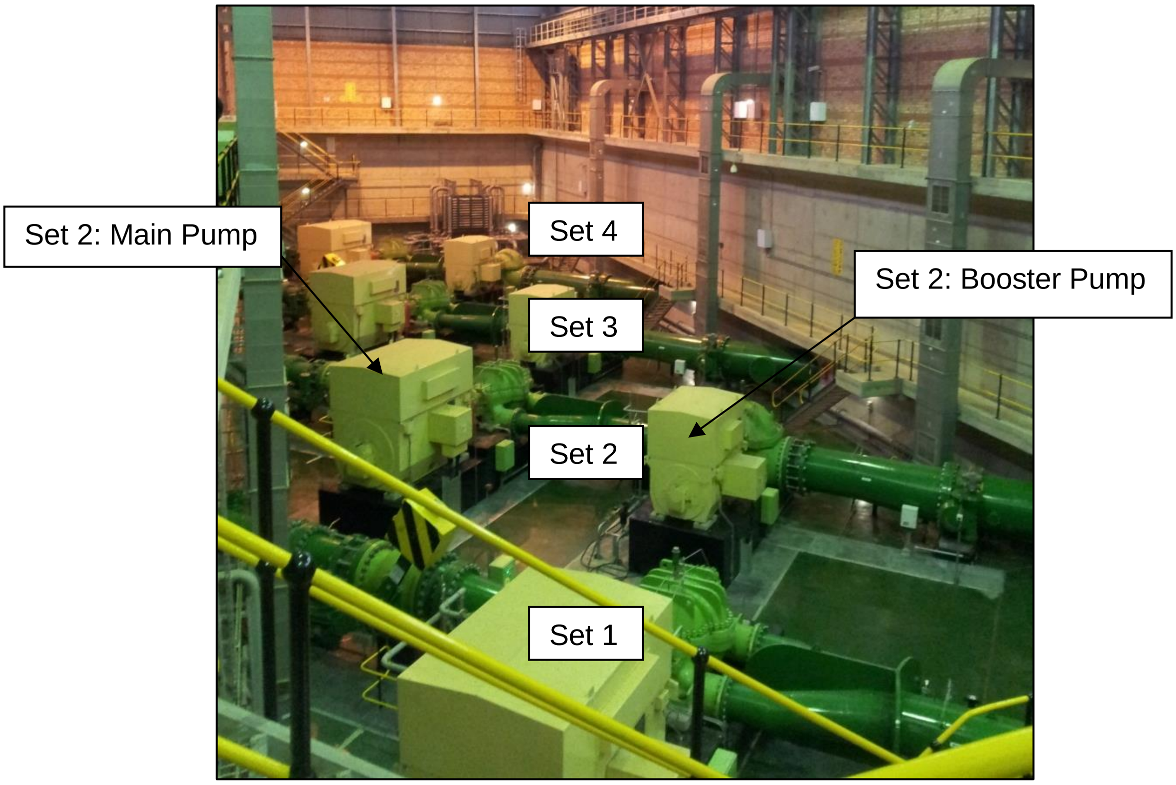


Figure 36: High-lift pump station pump sets

The booster pump is a Sulzer SM 802-900 with flow capacity of 1.8 m^3/s and a static head of 60 m. The main pump is a Sulzer pump with a synchronised flow capacity of 1.8 m^3/s and static head of 288.5 m. Both of these pumps are split-case centrifugal pumps. The booster pump is driven by a water-cooled Alstom 1 450 kW, eight-pole, 6.6 kV fixed speed electric motor. The main pump is driven by a water-cooled Alstom 6 615 kW, four-pole, 6.6 kV electric motor fitted with a VSD.

The VSDs are programmed so that they run all the pumps at matched speeds and is controlled from the SCADA system. In addition to the SCADA, each pump set has its own HMI control panel. These HMIs can control their corresponding pump sets and are used for condition monitoring. If the rotational speed is adjusted on one of the HMIs, the other HMIs match this speed. Each HMI displays the power of its corresponding main pump, the station outflow, and delivery and suction pressures.

The SCADA also display the levels of the Balancing dam. As previously mentioned, the High-lift pump station draws its water from the Balancing dam and its levels should remain as high as possible to allow optimum desilting. The Balancing dam is a three-channelled dam, as illustrated in Figure 37, that can hold up to 71 000 m^3 of water.

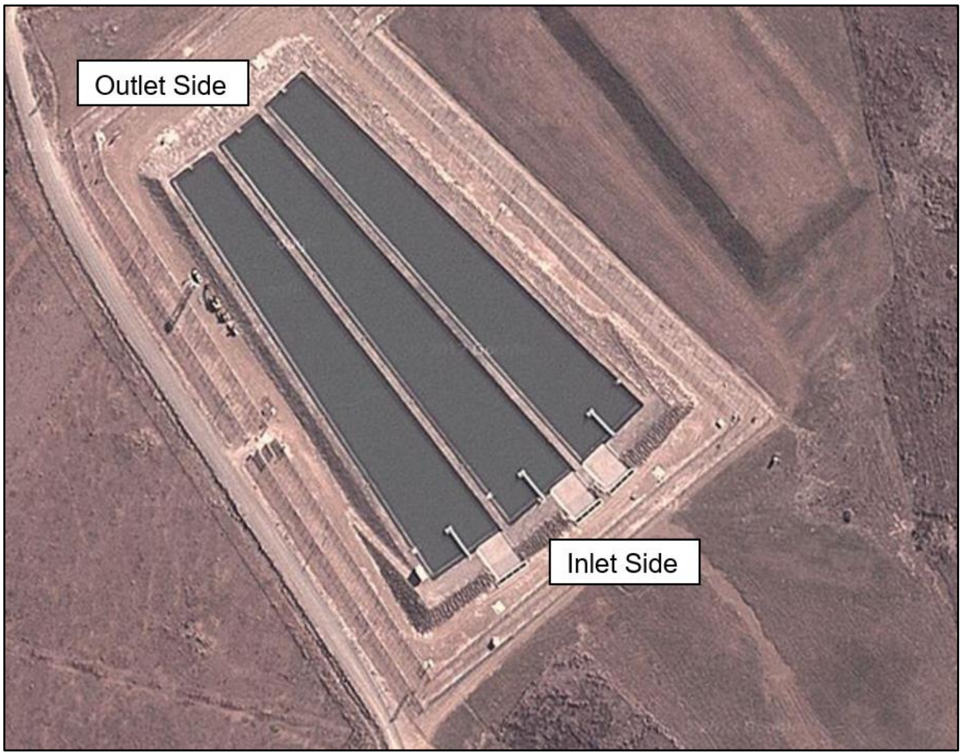


Figure 37: Aerial view of Desilting Works/Balancing dam

The channels have an upward slope from the inlet to the outlet side. This allows sediment that settles at the bottom to gravitate to the inlet side. Through this process, water with the lowest concentration of sediment accumulates on the outlet side. Here the High-lift pump station extracts water for pumping. The Balancing dam is kept full by the Low-lift pump station that supplies it with water from Dam-A.

The Low-lift pump station was constructed with and an underwater approach channel. This channel has a sand trap leading up to the inlet chamber. Inside the station, two pumping wells were constructed to house the six pumps. As depicted in Figure 38, each pit has three pumps 24 m below the water level of the dam which provide the pumps with sufficient suction head.

The Low-lift pump station has 6 Sulzer SMV 602-507 split-case pumps with a static head of 33 m. These pumps have a combined flow of 8.1 m^3/s and each pump is driven by a 550 kW, six-pole, 6.6 kV Alstom electric motor. Each motor is connected to its own Allen Bradley VSD for better control and to improve efficiency.

Figure 38: Low-lift pump station well with 3 pumps

The Low-lift pump station utilises a HMI panel for manual control of the six VSDs. This was due to a fire incident that rendered the permanent low-lift control room inoperable. Only the rotational speed of each pump can be changed on this HMI. The only useful information that can be obtained from the HMI is the number of running pumps and the current rotational speed. No power or flow data is displayed on the HMI.

Due to the above mentioned fire incident and other mechanical and electrical issues at the High-lift pump station, Pump Station-A was not able to run at full capacity for long periods of the year. Tests, as described in Chapter 3, were then conducted on the system to ensure no unnecessary risks are taken during the implementation of the load management initiative.

4.3 Discussion of test results

The methodology for the tests described in Chapter 3 was followed during each test. In the following section the results of these tests are presented and discussed. The PC test was done first to determine how the system reacts to a control change at the High-lift pump station.

PC test

The data logged during the test (refer to Section 3.3) was used to calculate the following results. From this data the interactions between the three sections of Pump Station-A were determined. The most important outcome of this test was to determine the necessary control inputs that would result in consistently high Balancing dam levels. The data recorded during the test for each 15 minute time interval can be seen in Appendix A.

From this data, Figure 39 was generated. From this figure it is clear that it was possible to keep the Balancing dam's levels constant at around 2.5 m for the duration of the test. This was achieved by reducing the speed of the Low-lift pump station VSDs for the duration of the test to match the Low- and High-lift pump station outflows.

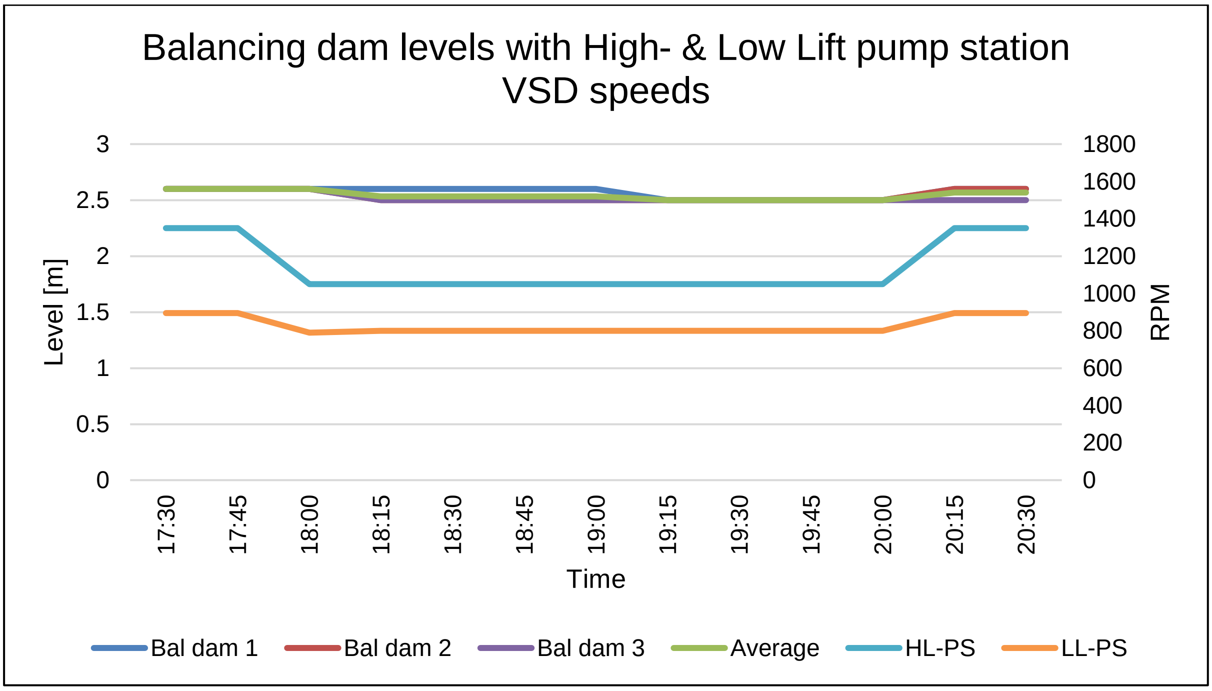


Figure 39: Balancing dam levels and VSD speeds for PC test

Flow data for the Low-lift pump station was not however available, but the constant Balancing dam levels indicate that the flow from Low-lift pump station matched that of the High-lift pump station. It is therefore possible to keep the Balancing dam levels constant by reducing the Low-lift pump station VSD speed when reducing the High-lift pump station VSD speed.

During the PC test there was a deficit in water transferred compared to the normal pumping schedule. It is important to quantify this loss so that the necessary comeback load needed for a successful load-shift can be determined. Table 4 shows the average flow before the test and the average flow during the test. These two values are used to calculate the accumulative transfer deficit during to the test.

Table 4: Station flow

	HL-PS Flow [m^3/s]
Avg. before 18:00	5.13
Avg. during test	3.36
Transfer deficit (m^3)	12,762.30

It is clear that a significant volume of water was not transferred due to the test and this will accumulate from day to day if it is repeated. This transfer deficit must be neutralised by a comeback load during the off-peak hours to realise the successful load shift intervention. To be able to calculate the necessary comeback load, the system characteristics for Pump Station-A must be determined.

RPS test

The data retrieved from this test was used to determine the system characteristics of the High-lift pump station at Pump Station-A. As previously mentioned, it was decided to focus only on the High-lift pump station as it contributes to most of Pump Station-A's power consumption. Through this compartmentalisation of Pump Station-A, the test procedures were shortened and simplified. This ensured that the influence of the test on the daily transfer target was minimised.

The data was collected according to the procedure set out under Section 3.4. The tables that show the captured data points can be seen in Appendix B. This data was used to generate the graph in Figure 40 on the following page. The graph plots the total High-lift pump station power against its total outflow, as the VSD speed is increased. Each line represents a different combination of running pump sets. There is no line depicting the running of all four pump sets, because as previously stated, this is prohibited.

It is expected that the relation between power and flow should follow the affinity laws. It was however found that the affinity laws could not predict the actual test data with sufficient accuracy. This inaccuracy could be contributed to the configuration of the pumps, for example, only the main pump's impeller speed is changed and not the booster pump connected with it in series.

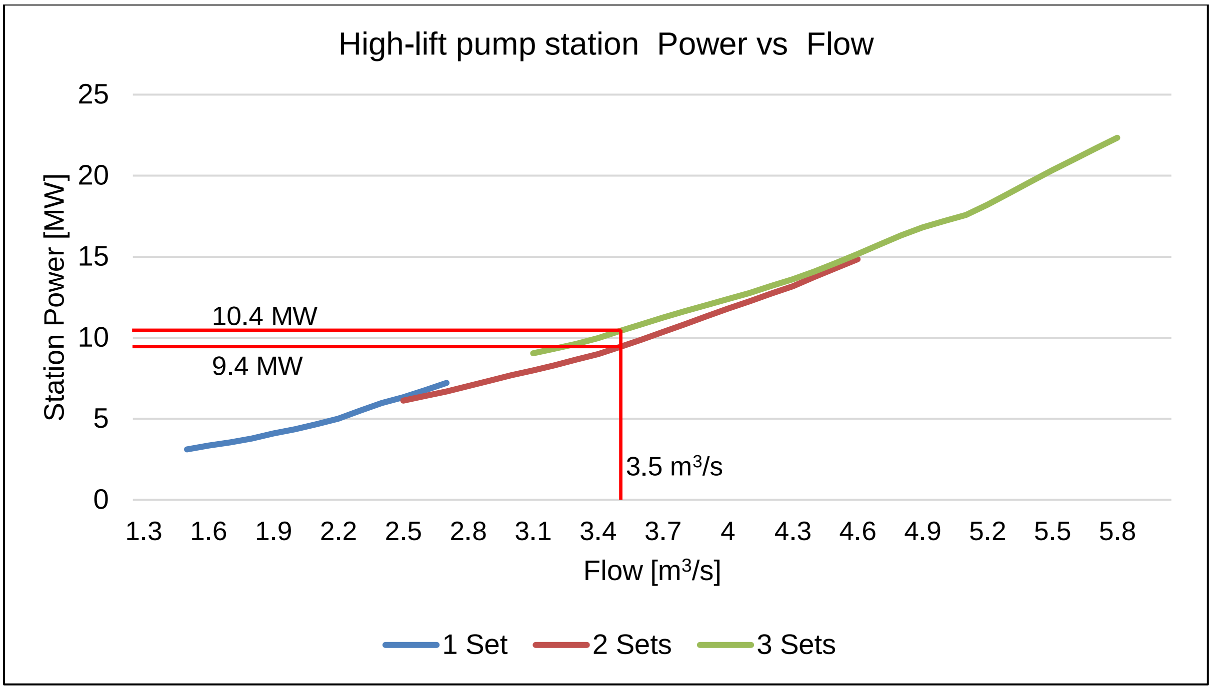


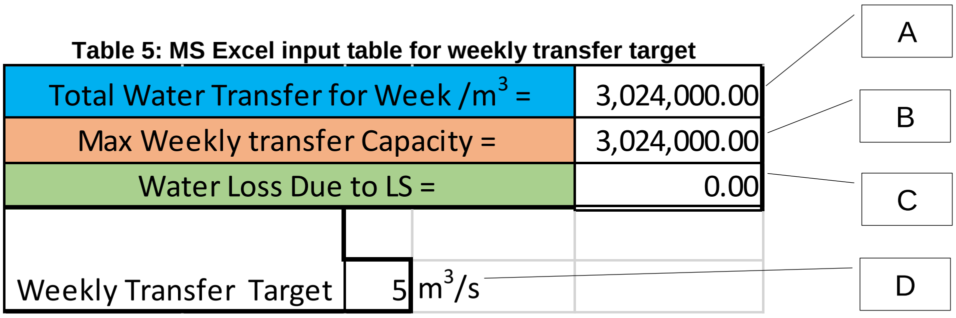
Figure 40: High-lift pump station power vs flow

When looking at the red lines on the above graph, it is clear that for a required flow of 3.5 m^3/s it is better to operate with two pumps at a higher RPM, than three pumps running at a lower RPM. This results in about 1 MW of power saved.

It is thus preferable to run the High-lift pump station pumps at the combination with the lowest curve. So for the flow range of 2.5 m^3/s to 4.5 m^3/s, it is better to run two pump lines. This was considered during the process of calculating the best load shift scenario for a standard operational day.

The solver functionality of MS-Excel was used to calculate the flow required for each time schedule of a weekday, Saturday and Sunday. The solver seeks a solution that ensures no transfer deficit occurs over a week (Monday to Sunday). Table 5 below shows the table in MS-Excel where the weekly average weekly transfer target (D) is entered.

Table 5: MS Excel input table for weekly transfer target

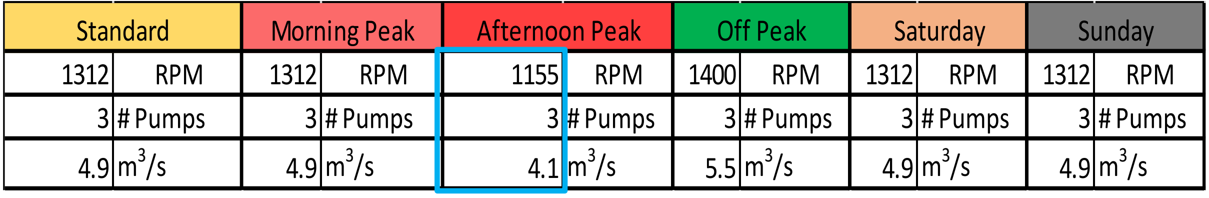


Total Water Transfer for Week /m^3 =	3,024,000.00	A
Max Weekly transfer Capacity =	3,024,000.00	B
Water Loss Due to LS =	0.00	C
Weekly Transfer Target	5 m^3/s	D

The maximum weekly transfer (B) is then calculated from this. The solver then matches the total weekly transfer (A) with B. When A and B are equal, there is no resultant water loss (C) due to the load shift. The results are then displayed as shown in Table 6. The flow required for each time schedule is shown in the bottom row of the table.

Note that during the off-peak period the flow is 5.5 m^3/s, which is 0.1 m^3/s more than the design capacity. This is due to the linear interpolation method used in calculating the flow. This is however, within an acceptable 2% deviation for calculated values.

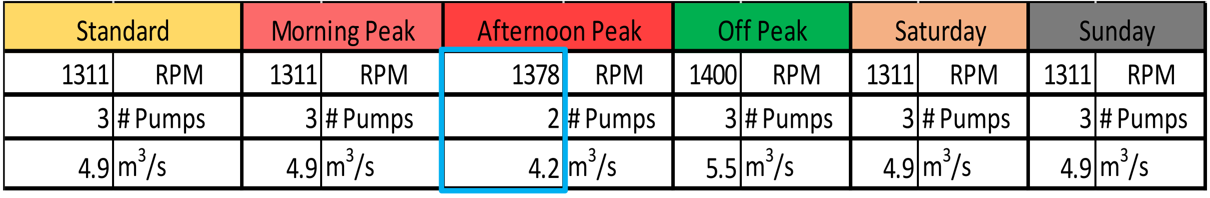
Table 6: MS Excel output for three pump sets running during evening peak period



Standard		Morning Peak		Afternoon Peak		Off Peak		Saturday		Sunday	
1312	RPM	1312	RPM	1155	RPM	1400	RPM	1312	RPM	1312	RPM
3	# Pumps	3	# Pumps	3	# Pumps	3	# Pumps	3	# Pumps	3	# Pumps
4.9	m^3/s	4.9	m^3/s	4.1	m^3/s	5.5	m^3/s	4.9	m^3/s	4.9	m^3/s

For the evening peak period, the required flow amounts to 4.1 m^3/s. This is within the range where running only two sets will consume less energy. A solution was then found for a scenario where only two sets are operated during the afternoon peak. The results for this calculation is shown in Table 7 below.

Table 7: MS Excel output for two pump sets running during evening peak period



Standard		Morning Peak		Afternoon Peak		Off Peak		Saturday		Sunday	
1311	RPM	1311	RPM	1378	RPM	1400	RPM	1311	RPM	1311	RPM
3	# Pumps	3	# Pumps	2	# Pumps	3	# Pumps	3	# Pumps	3	# Pumps
4.9	m^3/s	4.9	m^3/s	4.2	m^3/s	5.5	m^3/s	4.9	m^3/s	4.9	m^3/s

When comparing the actual savings that can be achieved through this solution, it was not considered a viable option. Only 200 kW of extra saving could be achieved, which does not justify running two pump sets at a higher speed for an extra two hours a day. This puts added strain on the bearings of these pumps, which will lead to increased maintenance. Thus, focus was placed on only reducing speed during peak time on the three operational pump sets rather than switching off a set.

The graph in Figure 41 shows the proposed load shift for three pump sets running during peak time, thus no pumps are switched off for the peak period. The calculated power consumption and flow of the High-lift pump station for each time interval of the day is depicted with the blue and red lines respectively. The profile of the graph follows the profile of a classic load shift intervention that focuses only on the evening peak period.

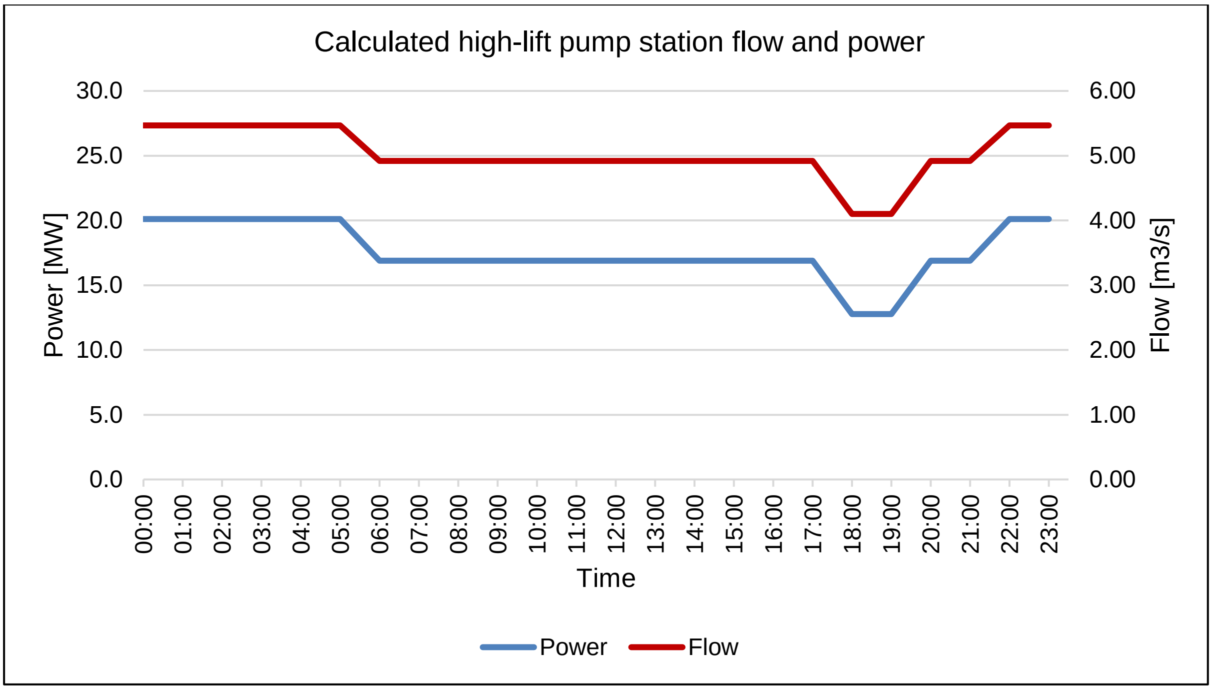


Figure 41: Daily load shift profile as calculated in Excel

The data used to draw the graph in Figure 41 was calculated through interpolation on the data points retrieved during the RPS test. Interpolation is a mathematical method that allows the forecasting of a value between two known values. To simplify the code used in MS-Excel, it was decided to utilise linear interpolation. Equation 7 is the adapted linear interpolation formula used to calculate the flow at a certain RPM value:

Equation 7

$$Q \approx Q_0 + \frac{RPM - RPM_0}{RPM_1 - RPM_0}[Q_1 - Q_0]$$

With:

Q:	Required flow
RPM:	RPM value from which the required flow must be calculated
Q_0, RPM_0:	Lower known corresponding flow and RPM values
Q_1, RPM_1:	Higher known corresponding flow and RPM values

The above equation was also used to calculate the power of each pump at a specific RPM setting. To accomplish this the flow values (Q) was substituted with power values (P).

Due to the fact that only data for the High-lift pump station was acquired during the RPS test, the power data calculated through this interpolation method only relates to the High-lift pump station. To see the effects of load management intervention on the whole of Pump Station-A, the PTB simulation discussed in Chapter 3 is used. In this simulation the High-lift pump station, Balancing dam and Low-lift pump station are included to give a better overall representation of the system.

4.4 Discussion of simulation results

As mentioned under Section 3.5, the simulation must first be compared to data retrieved from the actual system. The data acquired from the PC test was used to verify the simulation model. If the simulation results corresponds to within 10% of the test results, it can be assumed to be accurate enough for testing additional scenarios.

Verification of simulation

Flow data retrieved during the PC test was entered into the PI-controller that controls the High-lift pump station's main pumps. The PI-controller then matches the flow of Pump Station-A to the provided flow set points by altering the speed fraction of the High-lift pump station's main pumps. Figure 42 below shows the power and discharge pressure profiles of the PC test and the PTB simulation.

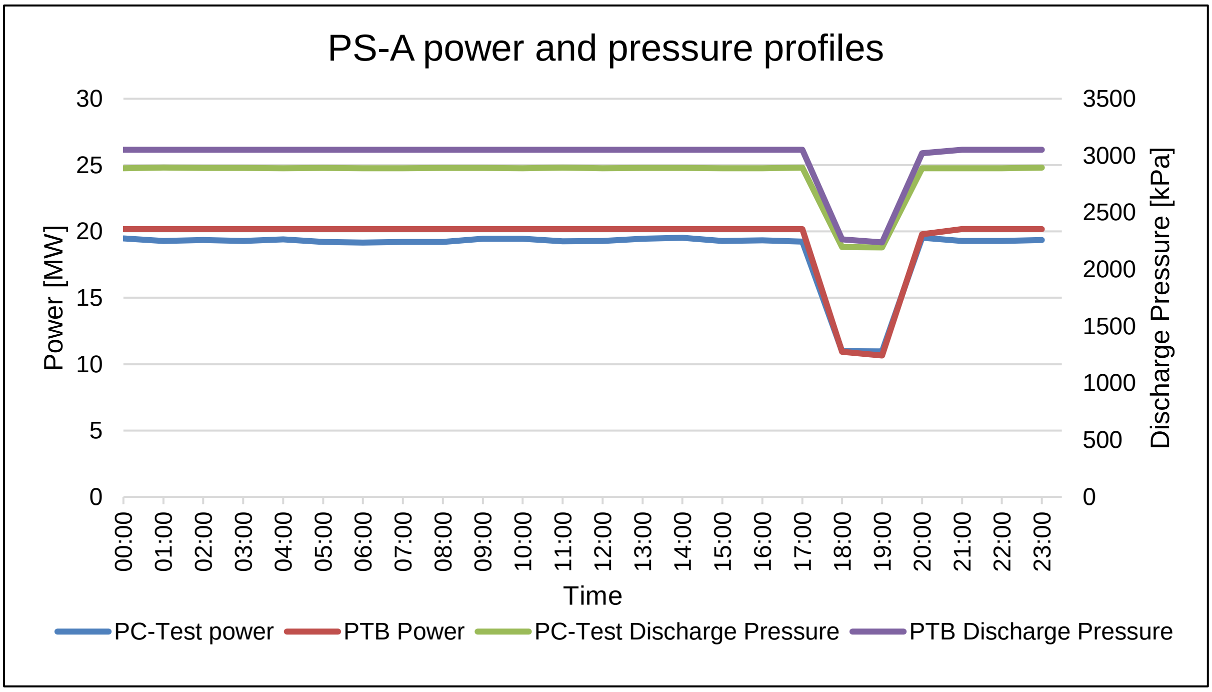


Figure 42: PC test and PTB simulation power profiles

Referring to Table 8, it is clear that the power data of the PTB simulation and the PC test show a deviation less than 10% for each time interval. This is also true for the discharge pressures. The calculated load reduction during the peak time only shows a 2% deviation between the test and PTB values. It can therefore be safely assumed that the simulation is accurate to test different load management scenarios.

Table 8: PC test and PTB simulation result comparison

	Power [MW]			Discharge Pressure [kPa]		
Time	**PC test**	**PTB**	**% Dev**	**PC test**	**PTB**	**% Dev**
00:00	19.47	20.18	4%	2888	3052	5%
01:00	19.29	20.18	4%	2895	3052	5%
02:00	19.35	20.18	4%	2891	3052	5%
03:00	19.28	20.18	4%	2891	3052	5%
04:00	19.40	20.18	4%	2888	3052	5%
05:00	19.22	20.18	5%	2891	3052	5%
06:00	19.15	20.18	5%	2890	3052	5%
07:00	19.21	20.18	5%	2890	3052	5%
08:00	19.21	20.18	5%	2892	3052	5%
09:00	19.45	20.18	4%	2892	3052	5%
10:00	19.45	20.18	4%	2889	3052	5%
11:00	19.27	20.18	5%	2893	3052	5%
12:00	19.27	20.18	5%	2889	3052	5%
13:00	19.45	20.18	4%	2891	3052	5%
14:00	19.52	20.18	3%	2891	3052	5%
15:00	19.28	20.18	4%	2888	3052	5%
16:00	19.34	20.18	4%	2890	3052	5%
17:00	19.22	20.18	5%	2893	3052	5%
18:00	10.97	10.94	0%	2195	2263	3%
19:00	10.96	10.65	-3%	2193	2237	2%
20:00	19.53	19.80	1%	2890	3020	4%
21:00	19.29	20.18	4%	2888	3052	5%
22:00	19.29	20.18	4%	2889	3052	5%
23:00	19.35	20.18	4%	2893	3052	5%
Peak Clip	8.25	8.42	2%			

The next step after verification of the simulation model is to simulate a baseline. This baseline is then used to compare the simulated load management scenarios with. As the annual target of Pump Station-A is 5.0 m^3/s, this flow value was assigned to the High-lift pump station controller and the simulation was solved to simulate the baseline. The next step is to solve the proposed load management intervention.

Simulation of proposed load management intervention

As explained under Section 3.5, the calculated flow profiles were entered as set points for the High-lift pump station controller. After the simulation was solved, the profile in Figure 43 below was drawn from the simulation output values. In this figure the baseline profile is compared to the optimised weekday and weekend profiles. Further calculations show that the optimised control results in a daily average saving of 5.3 MW for weekdays on Pump Station-A, which includes the High- and Low-lift pump stations.

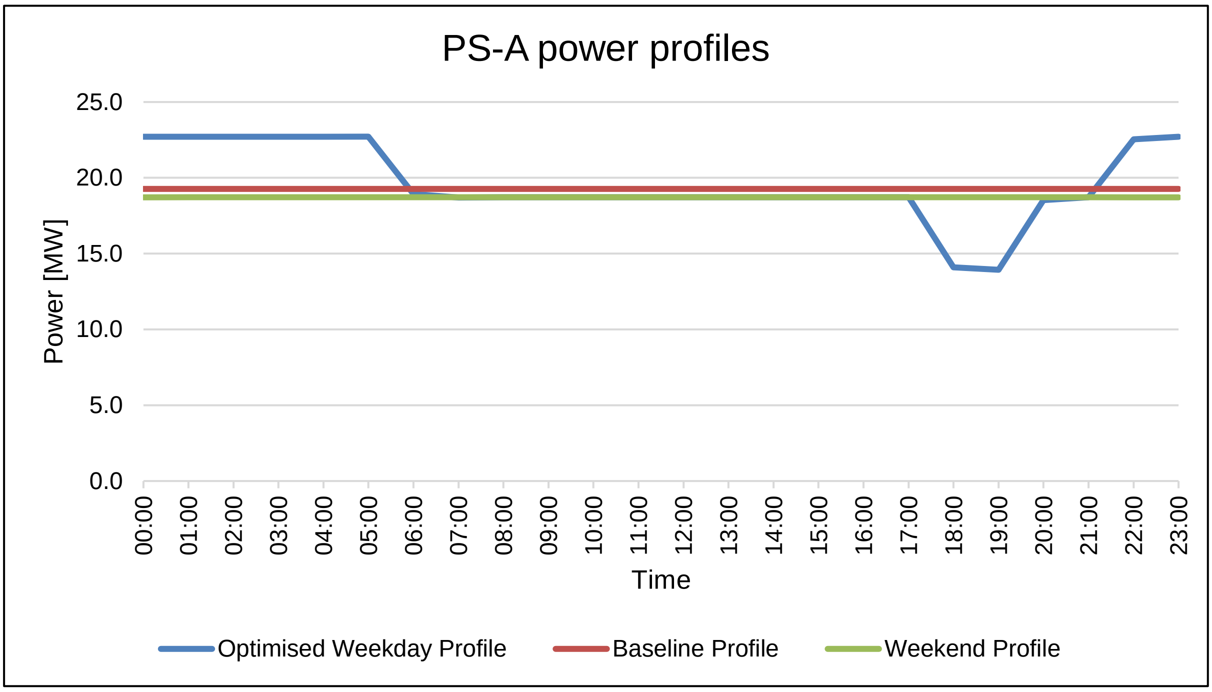


Figure 43: Simulated power profiles for Pump Station-A

The accumulative weekly energy consumption was also calculated. This amounted to 3 237 MWh for the baseline and 3 256 MWh for the optimised control philosophy. Comparison of these totals results in 19 MWh more energy consumed by the load intervention strategy. The fact that more energy is consumed leads to the assumption that the operational energy cost will also increase.

However, when the power costs are compared, this increased energy cost is not realised. By applying the tariffs given in the 2016/17 Eskom tariff book [16], weekly savings of R 141 000 and R 30 000 are respectively calculated for high and low demand seasons. These amounts are for standard weeks with no holidays. The annual savings that can be realised by applying the proposed load management intervention amounts to about R 3.3 million. Next, one must consider the weekly water transfer for Pump Station-A calculated from the simulation.

The weekly cumulative water transfer for the baseline and optimised profile amounts to 3 024 000 m^3, with no resultant water transfer deficit. Thus it is clear that this is a transfer neutral load shift, and not an energy neutral load shift. To better understand why more energy was needed to reach the weekly transfer target, the specific power consumption is calculated for the weekday optimised and baseline profiles. This quantifies the energy required for each cubic meter of water pumped and is shown in Figure 44.

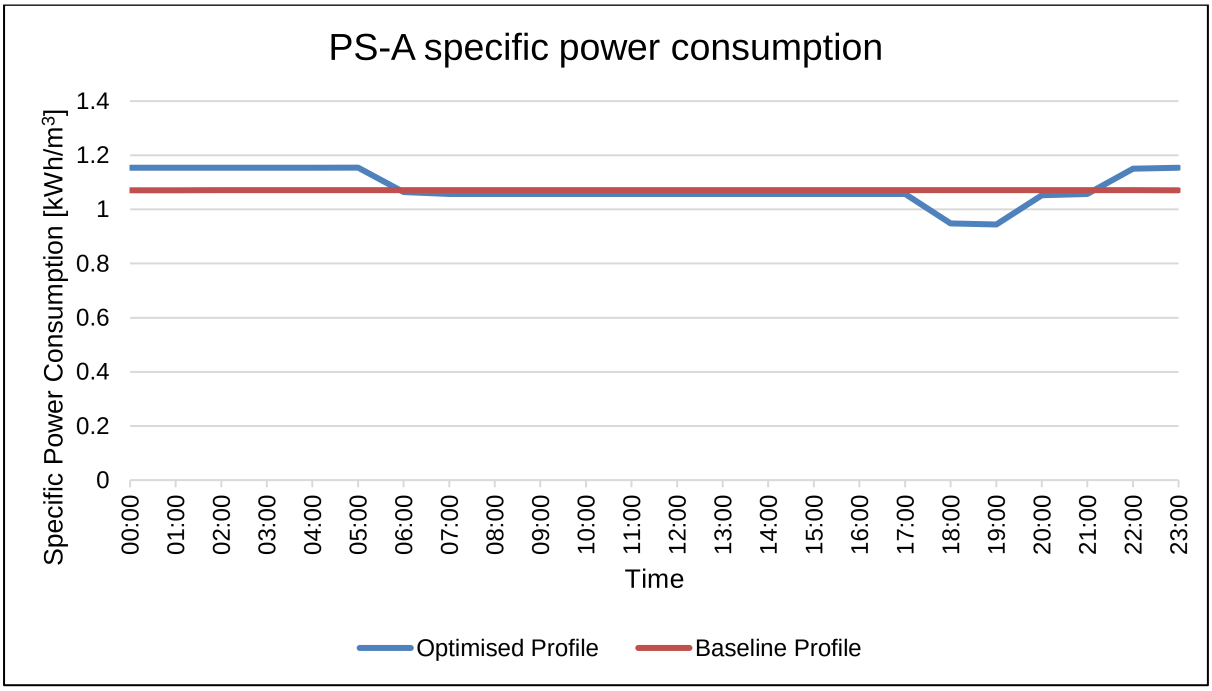


Figure 44: Pump Station-A specific power consumption

From the above figure it is clear that the specific power consumption of Pump Station-A follows the same profile as the power profile shown in Figure 43. Calculating the daily average specific power consumption for the baseline and optimised profile gives respective averages of 1.10 kWh/m^3 and 1.08 kWh/m^3. This 0.02 difference in average daily specific power consumption accumulates over a week, which then results in the extra 19 MWh of energy consumed per week.

This extra power consumption does not result in extra annual energy costs. This can be attributed to the difference in energy cost for peak and off-peak periods. The Eskom tariffs for high and low demand seasons are given in Table 9. Energy cost for the peak times is six times more expensive than that for the off-peak times.

Table 9: Eskom tariffs for the 2016/17 period [16]

Season	Period	Off-Peak	Peak	Standard
		[c/kWh]	[c/kWh]	[c/kWh]
High Demand	06/16 - 08/16	44.1	268.06	81.21
Low Demand	09/16 - 05/17	38.18	87.44	60.19

The difference in energy tariffs are utilised by shifting some of the pumping load out of peak time to off-peak time. The extra daily energy consumed occurred during off-peak time, and the consumption of energy during peak time was significantly reduced. Through this, monthly and annual operating costs can be significantly reduced for a large energy consumer such as Pump Station-A.

Through optimisation of Pump Station-A’s control philosophy, the above savings can be realised. The simulation uses a controller that mimics the control available through the VSDs installed at Pump Station-A. The VSDs allow a load management intervention that does not require switching pumps on and off. This allows for a unique approach to load management on large energy consumers when they are utilising VSD technology. Implementing the simulated load management strategy would be the next step.

Pump Station-A can however, only implement the load management initiative if it has at least three of its four high-lift pump sets available. The operators of Pump Station-A however, struggles to maintain this availability. This results in potential savings going to waste and unnecessary financial costs. The utilisation of Pump Station-A was calculated for the years 2014, 2015 and the first half of 2016. This relates to the availability of the pumps, as they utilise all the available pump sets up to a maximum of three.

4.5 Constraints for successful implementation of load management

The fact that at least three high-lift pump sets must be available before any load management intervention can be considered, greatly limits successful load management initiatives. Figure 45 shows the utilisation of Pump Station-A over the last two years. The red line indicates a monthly utilisation of above 65%, which is required before any load management intervention is possible.

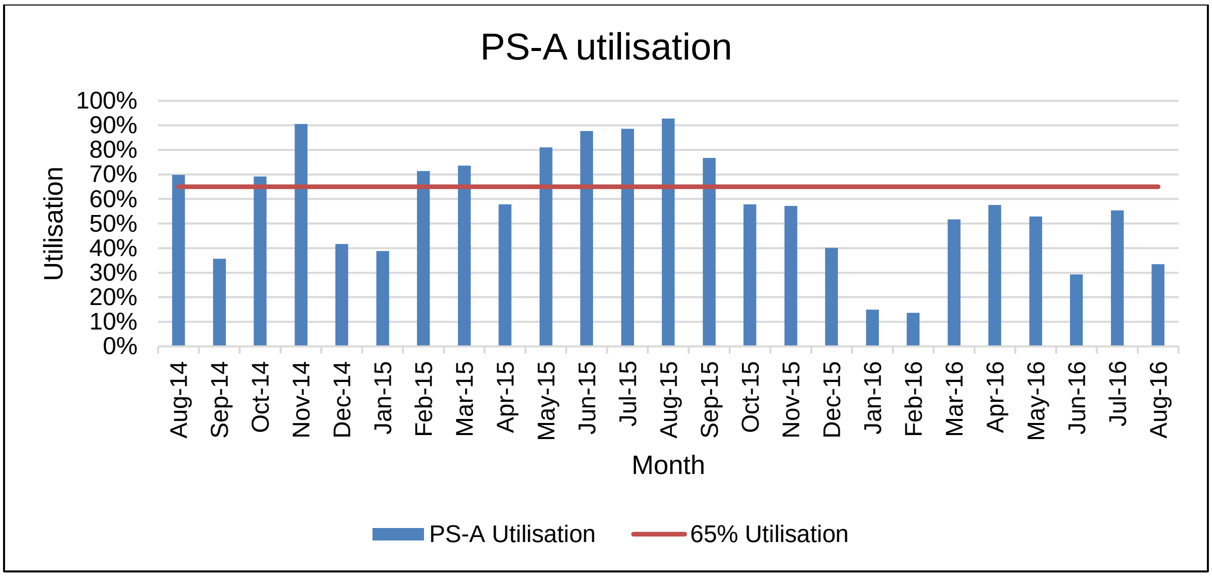


Figure 45: Pump Station-A utilisation

During the above period, 15 months showed a utilisation of less than 65%. This equates to 60% of the months where no load management initiatives could be implemented. Lost load management opportunities directly influence possible financial savings on the annual operational costs for Pump Station-A.

Focusing on the first part on 2016, it is clear that all possible cost savings were lost due to low pump availability. This equates to almost half of the calculated R 3 300 000 annual saving opportunities being lost. On Pump Station-A the main problem for this low utilisation during 2016 was VSD failures and pump mechanical problems.

Improved pump availability can be realised through introduction of good preventative and predictive maintenance schedules. These schedules can be incorporated into the optimised control philosophy by altering between the four pumps over a period of four weeks. Each pump will then be on standby for a week every five weeks, during which the necessary maintenance can be done.

Presently no altering between pumps on Pump Station-A is done, so the pumps are operated until failure. This results in two or more pumps failing simultaneously, which directly reduces the utilisation below the required 65%. As previously stated, this limits load shift initiatives, but it was decided to test the control philosophy on the available pump sets.

During the month of August 2016, load management on one high-lift pump set was approved by DWS on specific days. It was used to determine the viability of introducing a control philosophy that utilises the VSD technology to realise load management. To realise the load shift, flow set points for each time of day was calculated for one pump set. The set points for each time period are given in Table 10 below.

Table 10: Flow set points for load shifting one high-lift pump set

Standard		Morning Peak		Afternoon Peak		Off Peak		Saturday		Sunday	
1300	RPM	1300	RPM	1000	RPM	1350	RPM	1310	RPM	1310	RPM
1	# Pumps	1	# Pumps	1	# Pumps	1	# Pumps	1	# Pumps	1	# Pumps

Figure 46 represents a day where the load management intervention was realised on one available high-lift pump set. This load shift was realised only through manipulating the VSD speed of the pump during certain times of the day according to the values shown in Table 10.

The baseline for this load shift intervention was scaled to be energy neutral instead of transfer neutral. The reason for this is that Eskom, who approves the baselines, only look at the evening peak demand reduction. In addition, the data from the flowmeters of the pump station could not be verified. This could lead to erroneous scaling according to station flow.

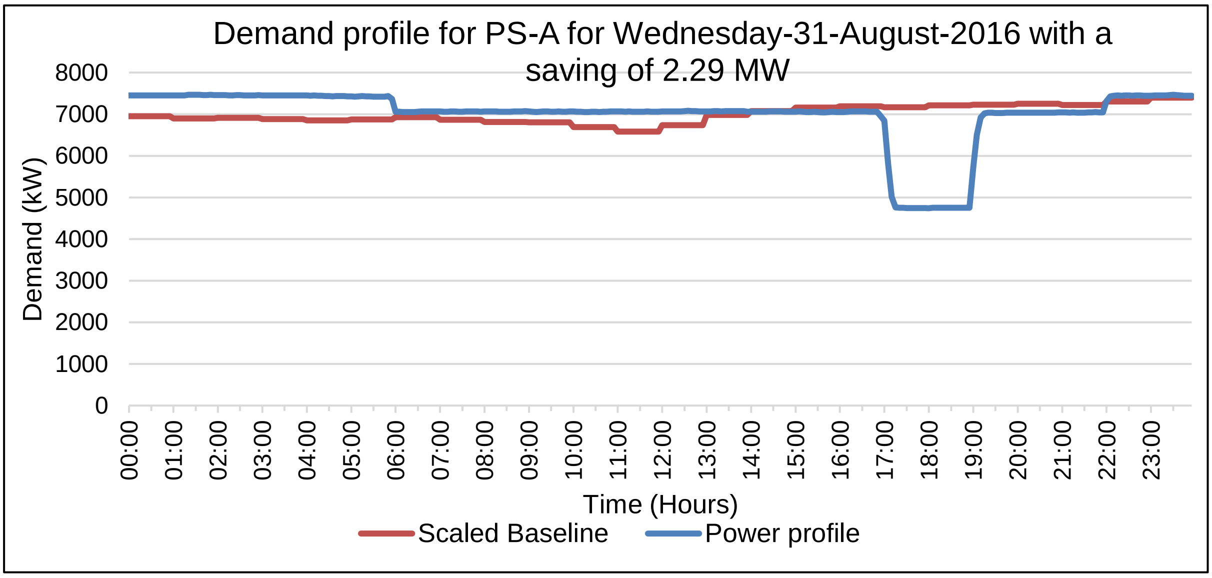


Figure 46: Pump Station-A load shift on one high-lift pump set

Operating according to the calculated set points a 2.29 MW evening peak load reduction was realised, and a comeback load was implemented during the off peak periods. This resulted in no water transfer deficit for the day. Financial savings of about R 10 000 per day during the high demand season and R 3 000 during the low demand season is realised through this.

4.6 Conclusion

This chapter first described the case study in detail. Specifications were given for each section of Pump Station-A to better understand the interaction of the sections. Following the case study, description of the results of two tests were presented and discussed.

The first test discussed was a PC test to determine the influence of a High-lift pump station VSD speed change on the whole of Pump Station-A. From the test it was concluded that to keep the Balancing dam levels constant, a corresponding VSD speed change at the Low-lift pump station was also required. Thus the Low-lift pump station control will mirror the High-lift pump station control to ensure stable Balancing dam levels. Reducing the VSD speeds resulted in a water transfer deficit of about 13 000 m^3 over the two hour testing period.

The RPS test was conducted next to determine the system characteristics of the High-lift pump station. It was decided to focus on the High-lift pump station for this test, simplifying the test procedure and ensuring quick and efficient data acquisition. The data gathered from the RPS test was then used to calculate optimised station flow set points for Pump Station-A. These set points were then used as inputs for a simulation.

Before simulating the optimised load management intervention, the simulation was first calibrated by using real test data from the PC test. The simulation was tweaked until the simulation outputs corresponded to within 10% of the test results. Following the calibration of the simulation, the optimised station outflow set points were put into the simulation and solved.

The simulation data showed an average weekday saving of 5.3 MW during the evening peak period, which is within acceptable range from the required 5.4 MW saving. Due to the load management intervention being transfer neutral, the simulation indicated that 19 MWh more energy was required to prevent a weekly transfer deficit. Utilising the Eskom ToU billing structure does however, result in financial savings although more energy was used.

An annual energy cost saving of up to R 3 300 000 is achievable through implementation of the optimised control strategy. Poor availability of the pumps resulted in implementation of the developed control philosophy on only one high-lift pump set for a few days.

Through this testing period, it was proven that load management can be successfully implemented on pump stations that utilise VSDs. The desired daily flow profile can be achieved through manipulation of the VSDs speeds, eliminating the need to switch pumps on and off.

Chapter 5 - Conclusion and recommendations

Sunset over the Orange River in the Northern Cape, South Africa[5]

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[5] Photo taken by author

5.1 Conclusion

Chapter 1 served as an introduction to this study. Information was given on the current electricity situation in South Africa and the solutions implemented by Eskom. DSM interventions incorporated with Time of Use (ToU) billing structures were discussed and how they can be used to benefit both the power utility and power consumer. Eskom, as the power utility, benefits from reduced peak demand and the power consumer benefits from a reduced electricity bill through better electricity load management.

Also discussed in Chapter 1 was South Africa's water sector. South Africa's unevenly distributed rainfall initiated the building of inter-basin Water Transfer Schemes that can convey water from one catchment area or basin to another. This was done to provide the industrial, municipal, agriculture, mining and the electricity generation sectors in low rainfall catchment areas with water from higher rainfall catchment areas.

The pump stations within these transfer schemes, mostly operated by the Department of Water and Sanitation, were identified as possible sites to implement DSM strategies. This follows from the high electricity consumption of these pump stations due to energy intensive motors that are needed to drive the pumps. With this background in mind, it was decided to focus on pumping stations that utilise VSD technology to control the pumps.

Chapter 2 provided more information on the infrastructure that typically forms part of an inter-basin transfer scheme. It introduced the reader to Government Water Schemes (GWSs) consisting of one or more IBTs. To convey the water from a lower geographical area within the water transfer scheme to a higher area, pumps are used. Centrifugal pumps are the main type used for these inter-basin water transfer schemes. To drive these pumps, electrical induction motors are mostly used for their simple design and reliability.

In older pumping stations, these motors were operated at a single speed depending on the number of poles in the motor and the frequency of the power supply. This presented a problem in scenarios where continuous control of station flow was needed. One way of solving this problem is through the use of VFDs. These drives can be classified as VSDs as they manipulate the rotational speed of an electric motor through variating the electric supply frequency to the motors.

Chapter 2 then further focused on the positive and negative considerations surrounding the utilisation of VSDs on pumping stations. This included the advantages of utilising VSDs on pumping schemes and the financial costs linked to VSDs. Focus was also placed on the negative impact that VSDs have on surrounding electrical and mechanical infrastructure, especially through the harmonics generated by the VSDs.

To conclude Chapter 2, previous load management initiatives on water transfer schemes were discussed. In this section a short description of each study was given to determine the outcomes of these studies. From this, important considerations were drawn that were applicable to this study. These considerations provided the guidelines by which this study was conducted.

In Chapter 3 the methodology for developing an optimised control philosophy was discussed. This philosophy focused on pump stations that utilise VSD technology. First the process of investigating and identifying suitable pump stations are given. This included looking at a GWS as a whole and identifying the inter-basin water transfer schemes within. These water transfer schemes were then investigated to identify suitable pump stations with installed VSDs.

The next step was to understand the operation and layout of the selected pump station. It was found that the pump station in this study consisted of a Low Lift pumping station, Balancing dams and a High Lift pumping station. To better understand the interactions between these sections, tests were developed.

The first test focused on determining the effect of a control input at the High Lift pumping station on the other two sections. The control input focused on reducing the VSD speed of the High Lift pumping station to mimic a peak load reduction. In addition to this, the water transfer deficit due to this two hour peak load reduction could be quantified through this test. This was needed to calculate the flow needed during the comeback load to ensure no transfer deficit occurs due to peak load reduction.

As the flow of Pump Station-A is determined by the High lift pumping station, and from power analysis showing that the High-lift pump station contributed about 90% of the overall power consumption, it was decided to only focus on the High-lift pump station. This simplified the procedure of the next test. The aim of this second test was to determine system characteristics of the High-lift pump station.

To determine these characteristics, the VSD speeds were reduced in increments. The influence of this incremental speed reduction on the power consumption and station flow was then noted. This procedure was then followed for the different pump combinations of one, two or three operational pumping sets.

The next step in Chapter 3 was to develop a control philosophy for the pumping station. It was decided to use system flow charts for the development of the control. Different control philosophies were developed for the High- and Low-lift pumping stations. The High-lift pumping station is controlled according to a fixed flow set point, whereas the Low-lift pump station is controlled according to the downstream Balancing dams' levels.

To test the developed control philosophies, a simulation was built. This simulation was discussed in the last part of Chapter 3. Process Toolbox, a simulation software package developed by TEMM International, was used to build the simulation. The simulation was built to include the high lift and low lift pumping stations, as well as the Balancing dams. It utilised a controller known as a PI-controller to simulate the variable speed control available through the use of VSDs.

In Chapter 4 this simulation was verified and tested. However, the case study was discussed first and focused on the specific pumping station. Through this, insight was gained into specific infrastructure installed on site and the site specific operations. This included how the pumps are controlled through the VSDs, only allowing synchronised rotational speed for all the pumps.

Next the results from the tests described in Chapter 3 were discussed. From the first test it was found that the Low-lift pumping station mimicked the control of the High-lift pumping station. For example, to ensure the Balancing dams' levels are at optimum operational level, a reduction in VSD speed at the high lift pumping station necessitated reducing the VSD speed at low lift pumping station.

The transfer deficit that occurred due to the VSD speed reduction was calculated to be almost 13,000 m^3. This deficit will accumulate over time if a comeback load is not introduced. As it was established during the investigation that no transfer deficits are allowed for Pump Station-A, a comeback load flow must be calculated to neutralise this.

Data collected from the second test allowed for the calculation of this comeback load flow. This test focused on determining the system characteristics of the high lift pumping station. Data from this test was used in MS-Excel calculations to determine the flow needed during a comeback load associated with a specific peak load reduction. In addition to this, a power vs flow graph was drawn up to illustrate the correlation between station power and flow with changing VSD speed.

From this graph the best combination between the amount of operating pump sets and the VSD speed was determined for a station specific flow. For example, it is more energy efficient to run two pump sets at a higher VSD speed than three pump sets at minimum VSD speed when a station flow of 3.5 m^3/s is required.

From the MS-Excel calculations the flow set points were calculated for each specific time period of a weekday, namely morning peak, standard, afternoon peak and off-peak times. A flow set point for weekend days was also calculated, with the aim of no resultant water deficit over the course of a week. These set-points can then be introduced to the controller of the pump station, be it an operator or PLC, as the optimised control philosophy. To test these optimised set-points the simulation was used.

However, before testing of the optimised control was done, the simulation was first calibrated to ensure it is tuned to site specific conditions and constraints. For this calibration the flow from the first test was used as inputs to the simulation. The simulation was then solved and adjusted until key characteristics such as power consumption and the Balancing dam's levels matched the data retrieved from the test to within 10%.

After calibration of the simulation, a baseline was simulated to which the optimised control simulation could be compared to. For this baseline, the average annual transfer target of 5.0 m^3/s was used as the set-point. After simulating a week at this set-point, the cumulative water transfer equated to 3 024 000 m^3 and the cumulative electricity power consumption was 3 237 MWh. This cumulative power consumption averaged out to 19.3 MWh over the course of a week.

Next the optimised flow set-points were introduced to the simulation and solved. The cumulative flow for the optimised control equated to 3 024 000 m^3, thus no transfer deficit resulted from the optimised control. No resultant water transfer deficit was the main objective of the optimised control philosophy and the simulation showed that this was possible. This was however, not the only objective and attention was also given to the realised evening peak power consumption and the comeback load during the off-peak period.

From the simulation it was found that an evening peak load reduction of 5.3 MW was feasible through implementation of the optimised control philosophy. It was however, also found that the cumulative weekly power consumption increased to 3 256 MWh from the 3 237 MWh for the baseline. It is thus clear that the overall weekly power consumption increased by about 19 MWh for the optimised control philosophy.

To determine the reason for this increased power consumption, the average specific power consumptions were calculated for the baseline- and the optimised power profiles. These amounted to 1.08 kWh/m^3 and 1.10 kWh/m^3 respectively. It was found that the increase in average power consumption for the optimised control philosophy was due to the high specific power consumption during the comeback load periods during off-peak hours.

The increased power consumption did not result in an increased electricity cost and the possible annual savings due to the optimised control was calculated to about R 3 300 000. This realised power cost saving was attributed to the fact that peak time power almost cost six times more than off-peak power during the winter months, and two times more during the summer months. It is thus clear that significant financial savings can be realised through the implementation of the optimised control philosophy that shift pumping load from peak time periods to off-peak periods.

Incorporating the installed VSD technology at the pumping station, the optimised control philosophy can be implemented by only changing the speed of the pumps. This eliminates the need to switch off pumps for two hours each day during peak time, reducing strain on electrical and mechanical infrastructure. The simulation proved that this is possible as the PI-controller was only allowed to change the speed fractions of pumps to meet output flow set points. During the practical implementation of the optimised control philosophy some constraints prevented successful implementation.

Chapter 4 concluded with a brief discussion of these implementation constraints and the financial impact it has due to lost financial savings. The main reason for the poor implementation was identified as insufficient maintenance and the lack of an adequate maintenance manual for the station. For the first six months of 2016 no load management could be implemented, which equates to half of the possible R 3 300 000 savings being lost.

It was however, proven through the simulation and the above practical implementation that load management through the use of VSDs on water transfer schemes is possible. The VSDs provide excellent variable control and eliminates the need to switch pumps on and off. Good maintenance is however, required to ensure reliable operation and prevent financial losses. From this some further recommendations can be made for additional studies.

5.2 Recommendations for further research

From the study it can be concluded that load management through the use of VSDs are possible. The VSDs actually provide much more variable control possibilities, proven by the fact that a load management intervention could be implemented on only one operating pump. Load management on only one pump is not readily accepted where conventional pump control methods are used such as on-off control. This is especially true for large pumping stations where standby pumps are not available.

Due to the lack of sufficient implementation opportunities during this study, it is recommended to further this study through on-site implementations of the optimised control philosophy. This will provide valuable real-time data for better analysis and further improvement of the control philosophy. The main constraint that inhibited the successful implementation of the control philosophy was unavailability of pumps due to breakdown of VSDs and mechanical seal failures.

It is therefore also recommended to study the effects of these breakdowns on possible load management interventions in more detail. Determining the main cause of these breakdowns can lead to the formulation of a solution to this problem. During this study one of the main reasons for the breakdowns was identified as inadequate maintenance of VSDs and pumping infrastructure. Further studies are however needed to determine other causes, such as the effect of using hard water as coolant for the mechanical seals.

Lastly, widening the study to include additional pumping stations as case studies will also provide more data and other constraints. From this the viability of installing VSDs on large scale pumping schemes can be determined. This will provide good insight into the limitations and other considerations regarding the installation of VSDs on current or planned pumping systems, such as the financial payback period and maintenance costs and plans.

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Appendix A: PC test data tables

	DWBd levels [m]			VSD speeds [RPM]		HL-PS power [kW]		LL-PS power [kW]	Logged flow rate [m^3/s]	Pressure [kPa]
Time	**Dam 1**	**Dam 2**	**Dam 3**	**HL-PS**	**LL-PS**	**Av. Main pump**	**Av. Booster pump (Rockwell)**	**Av. Power for 4 LL-PS pumps**	**Average HL-PS flow**	**Av. HL-PS discharge pressure**
17:45	2.6	2.6	2.6	1350	895	4533	1365	1591	5.13	2893
18:00	2.6	2.6	2.6	1050	790	2060	1198	1160	3.47	2193
18:15	2.6	2.5	2.5	1050	800	2080	1198	1150	3.35	2195
18:30	2.6	2.5	2.5	1050	800	2070	1198	1168	3.34	2194
18:45	2.6	2.5	2.5	1050	800	2060	1198	1175	3.34	2193
19:00	2.6	2.5	2.5	1050	800	2070	1198	1165	3.35	2193
19:15	2.6	2.5	2.5	1050	800	2090	1198	1154	3.35	2194
19:30	2.6	2.5	2.5	1050	800	2100	1198	1167	3.35	2196
19:45	2.6	2.5	2.6	1050	800	2080	1198	1180	3.35	2195
20:00	2.6	2.5	2.5	1050	800	2060	1198	1188	3.34	2195
20:15	2.6	2.5	2.5	1350	895	4533	1365	1598	5.13	2891

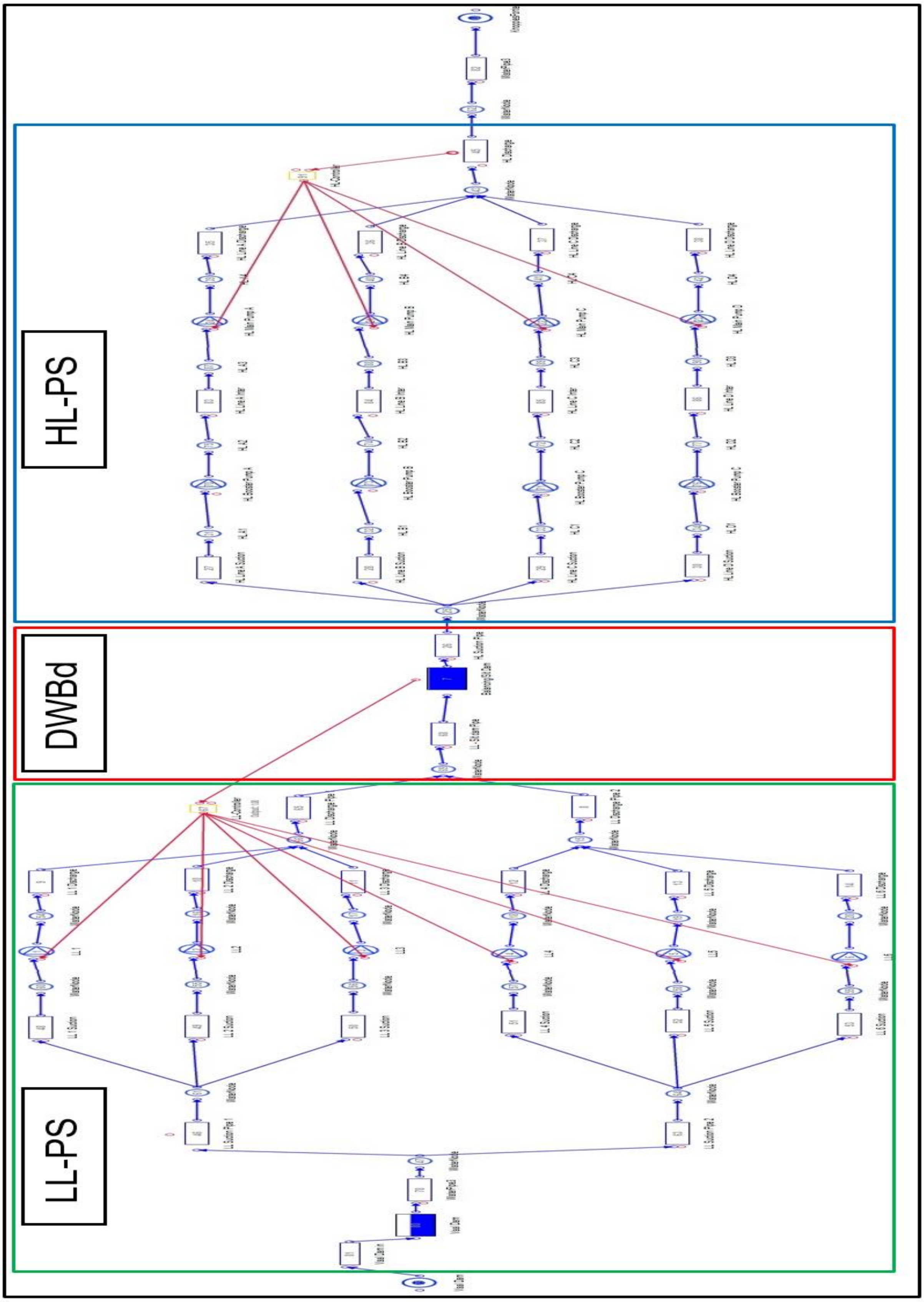
Appendix B: RPS test data tables

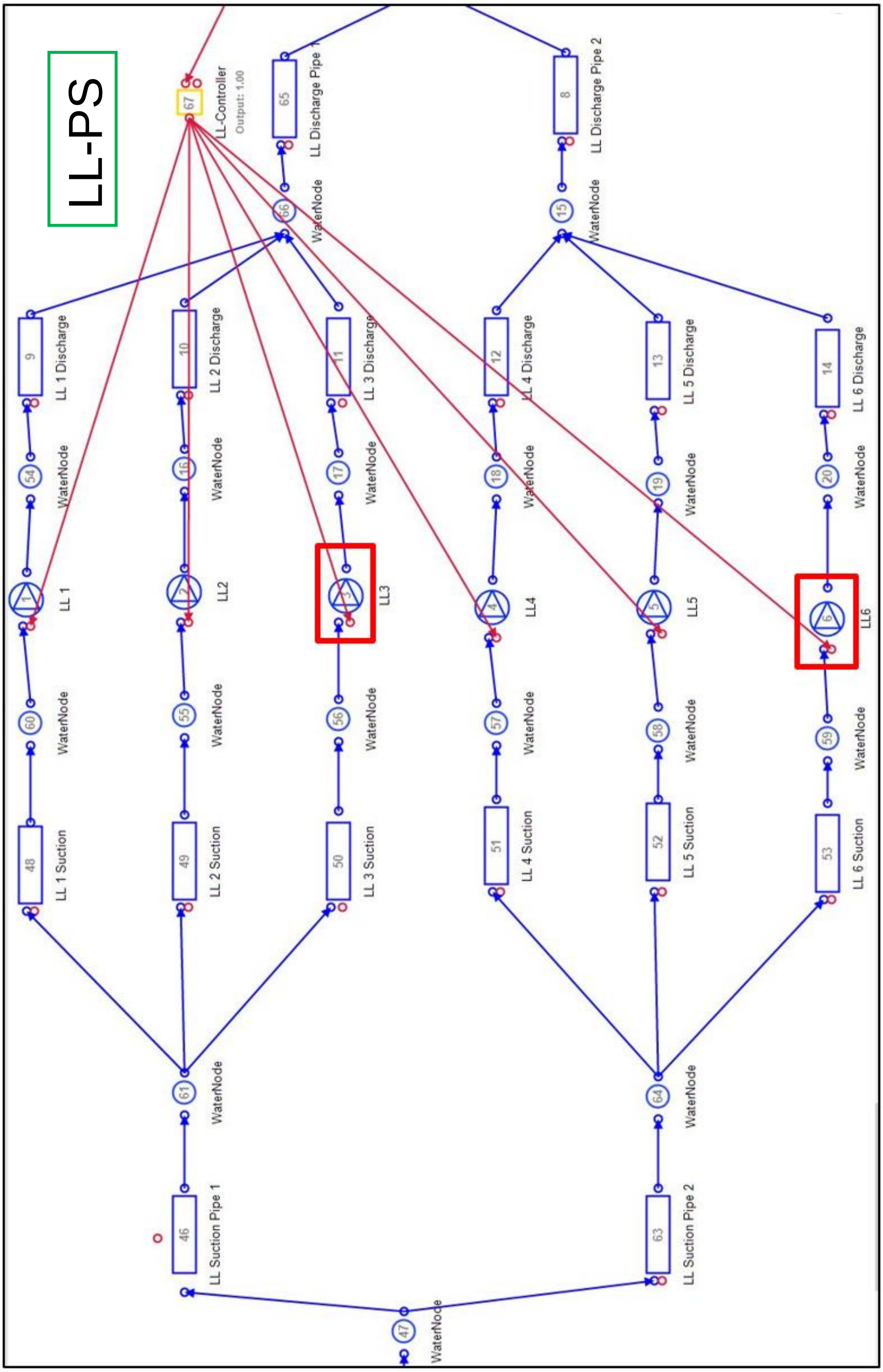
1 Pump				
1000 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
1442	1442	1850	1124	2974
1050 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
1590	1590	2128	1198	3328
1100 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
1780	1780	2430	1275	3705
1150 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
1875	1875	2735	1298	4033
1200 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
2012	2012	3090	1305	4395
1250 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
2135	2135	3460	1320	4780
1300 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
2260	2260	3855	1355	5210
1350 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
2330	2330	4335	1385	5720

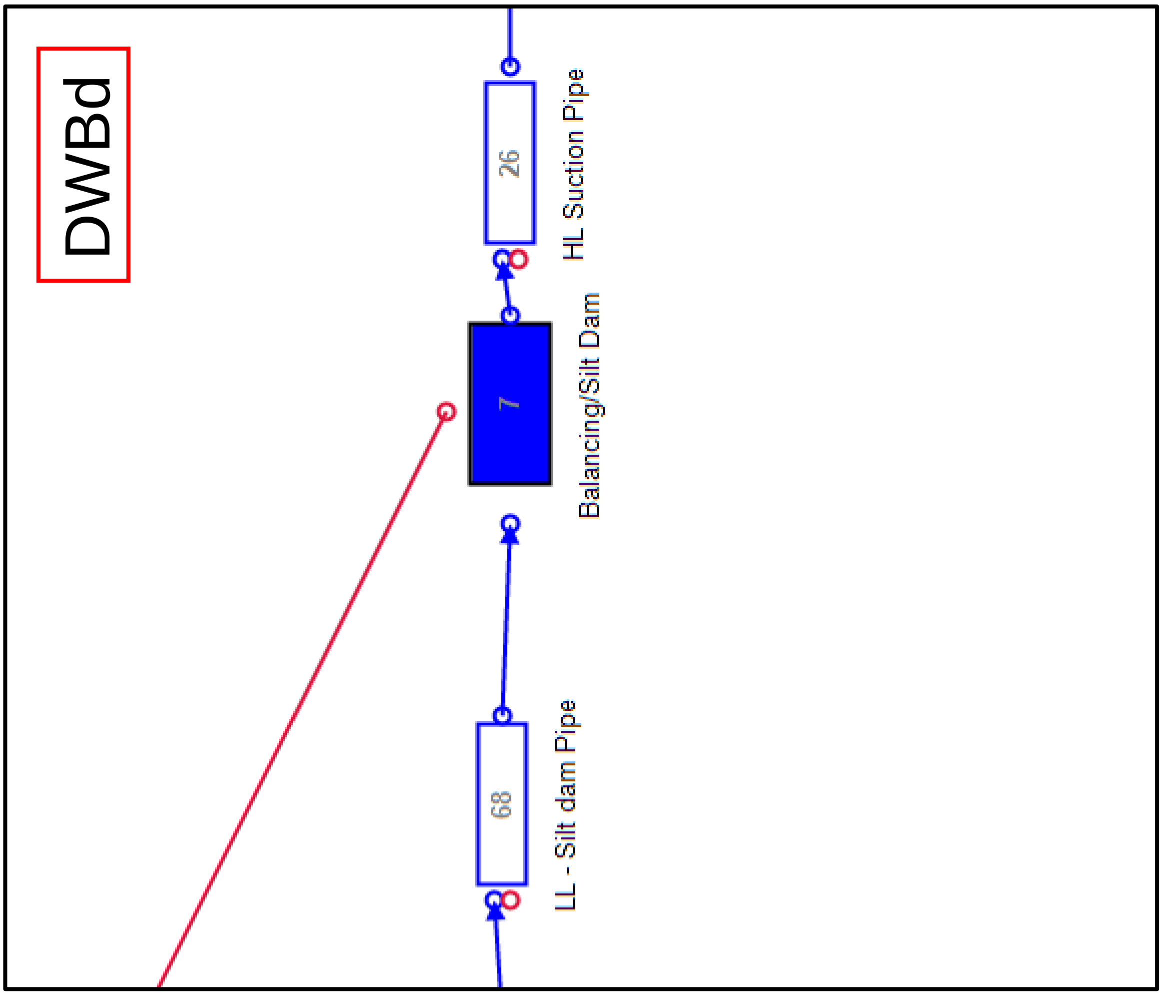
2 Pumps				
1000 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
2436	1217	1836	1124	5920
1050 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
2709	1354	2132	1198	6706
1100 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
2950	1475	2490	1275	7529
1150 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
3198	1598	2848	1298	8292
1200 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
3424	1712	3236	1305	9082
1250 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
3609	1804	3638	1320	9915
1300 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
3813	1906	4088	1355	10886
1350 RPM				
Total Flow [l/s]	Flow/Pump [l/s]	Av. Main Pump Power [kW]	Booster Pump Power [kW]	Total Power [kW]
4002	2001	4518	1385	11806

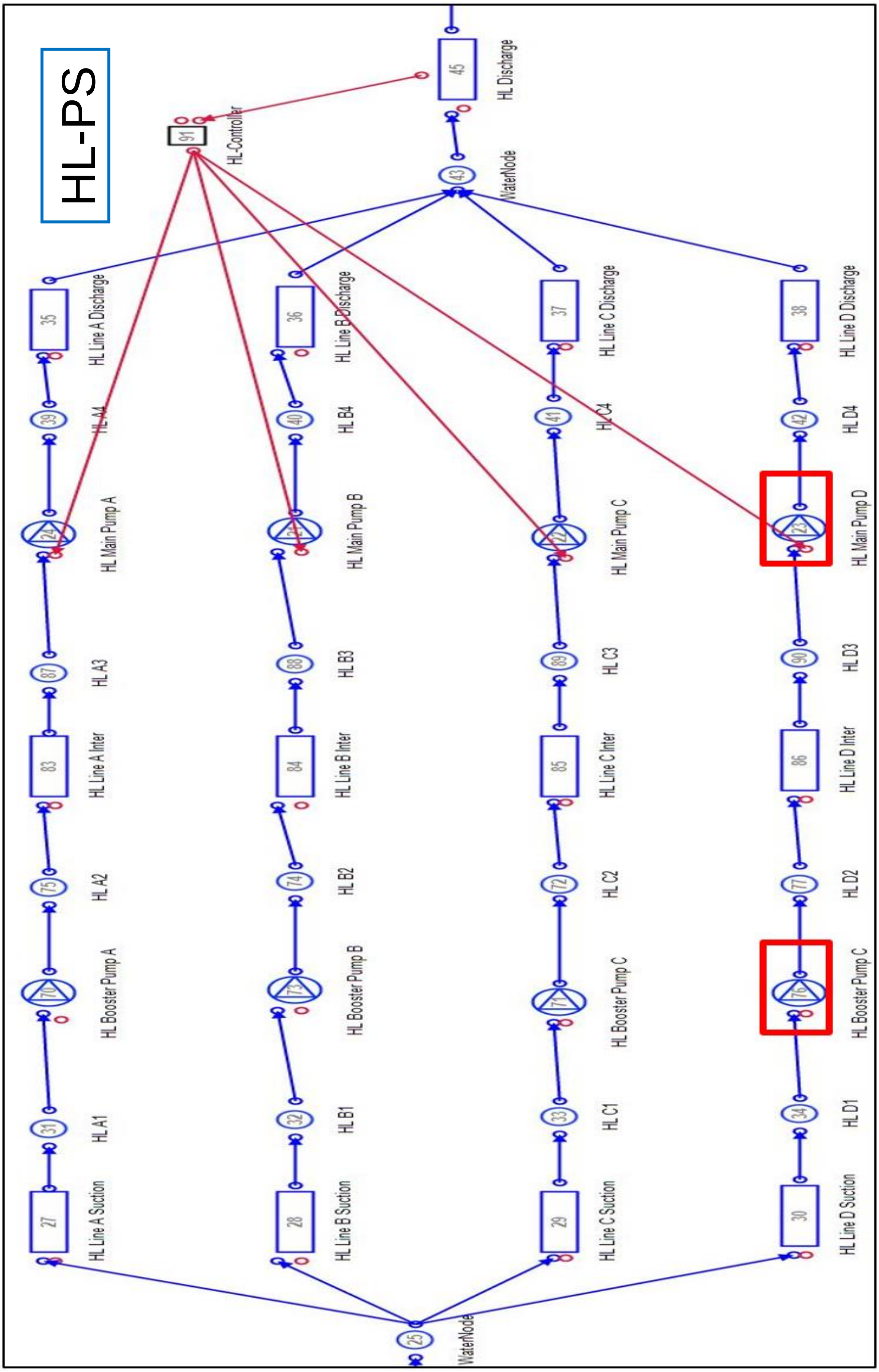
<table>
<tr><th colspan="5">3 Pumps</th></tr>
<tr><th colspan="5">1000 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>3105</td><td>1035</td><td>1845</td><td>1124</td><td>8907</td></tr>
<tr><th colspan="5">1050 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>3350</td><td>1117</td><td>2140</td><td>1198</td><td>9774</td></tr>
<tr><th colspan="5">1100 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>3756</td><td>1252</td><td>2505</td><td>1275</td><td>11340</td></tr>
<tr><th colspan="5">1150 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>4068</td><td>1356</td><td>2902</td><td>1298</td><td>12600</td></tr>
<tr><th colspan="5">1200 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>4356</td><td>1452</td><td>3373</td><td>1305</td><td>14034</td></tr>
<tr><th colspan="5">1250 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>4692</td><td>1564</td><td>3705</td><td>1320</td><td>15075</td></tr>
<tr><th colspan="5">1300 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>4971</td><td>1657</td><td>4150</td><td>1355</td><td>16515</td></tr>
<tr><th colspan="5">1350 RPM</th></tr>
<tr><th>Total Flow [l/s]</th><th>Flow/Pump [l/s]</th><th>Av. Main Pump Power [kW]</th><th>Booster Pump Power [kW]</th><th>Total Power [kW]</th></tr>
<tr><td>5128</td><td>1709</td><td>4533</td><td>1385</td><td>17753</td></tr>
</table>

Appendix C: PTB simulation layouts




LL-PS
67
LL-Controller
Output: 1.00
65
LL Discharge Pipe 1
8
LL Discharge Pipe 2
66
WaterNode
15
WaterNode
9
LL 1 Discharge
10
LL 2 Discharge
11
LL 3 Discharge
12
LL 4 Discharge
13
LL 5 Discharge
14
LL 6 Discharge
54
WaterNode
16
WaterNode
17
WaterNode
18
WaterNode
19
WaterNode
20
WaterNode
1
LL 1
2
LL2
3
LL3
4
LL4
5
LL5
6
LL6
60
WaterNode
55
WaterNode
56
WaterNode
57
WaterNode
58
WaterNode
59
WaterNode
48
LL 1 Suction
49
LL 2 Suction
50
LL 3 Suction
51
LL 4 Suction
52
LL 5 Suction
53
LL 6 Suction
61
WaterNode
64
WaterNode
46
LL Suction Pipe 1
63
LL Suction Pipe 2
47
WaterNode


DWBd
26
HL Suction Pipe
7
Balancing/Silt Dam
68
LL - Silt dam Pipe


HL-PS
91
HL-Controller
45
HL Discharge
43
WaterNode
35
HL Line A Discharge
36
HL Line B Discharge
37
HL Line C Discharge
38
HL Line D Discharge
39
HL A4
40
HL B4
41
HL C4
42
HL D4
24
HL Main Pump A
21
HL Main Pump B
22
HL Main Pump C
23
HL Main Pump D
87
HL A3
88
HL B3
89
HL C3
90
HL D3
83
HL Line A Inter
84
HL Line B Inter
85
HL Line C Inter
86
HL Line D Inter
75
HL A2
74
HL B2
72
HL C2
77
HL D2
70
HL Booster Pump A
73
HL Booster Pump B
71
HL Booster Pump C
76
HL Booster Pump C
31
HL A1
32
HL B1
33
HL C1
34
HL D1
27
HL Line A Suction
28
HL Line B Suction
29
HL Line C Suction
30
HL Line D Suction
25
WaterNode