# IMPROVEMENT OF STEADY STATE AND VOLTAGE STABILITY OF A STRONG NETWORK OVERLAYED WITH HIGHER VOLTAGE TRANSMISSION LINES USING PHASE SHIFTING TRANSFORMERS

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Dr. N. Mbuli                                        Prof. N.M. Ijumba

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# Abstract

This research work deals with the application of the phase shifting transformer in improving the steady state performance and voltage stability of transmission network that has transmission lines at different voltage levels running in parallel to each other.

Transmission power system networks are usually developed using lines built at a certain voltage level initially. As power demand requirements increase, building of the new lines at the same voltage level becomes necessary. However, lesser and lesser improvements in transfer capacity are realised when the additional lines are built. This prompts utilities to consider higher voltages for future lines as these have a higher transfer capacity. Utilities usually lay, i.e., they build in parallel, newer, higher voltage transmission lines along side the existing lower voltage ones.

Power flow in power system is mainly influenced by impedances of equipment. If the combined impedance of the existing, lower voltage transmission system is relatively less than the impedance of the newer, higher voltage ones, power may primarily flow through it rather than via the newer, parallel higher voltage transmission network. This may lead to a serious underutilisation of the newer infrastructure with a higher transmission capacity.

Transmission networks similar to the one described above are common throughout the world. This study was undertaken towards finding solutions to the problem of under utilisation of such transmission lines.

The study was performed by first reviewing the literature on the use of phase shifting transformers to redirect power flow in transmission networks throughout the world. This was followed by analysis of the theory on how and what determines the power flow in power networks. Several simulations of varying the phase of the phase shifting transformer were performed on the Cape network, as a case study, to investigate the impact on the power flow distribution and voltage stability performance of the 765 kV and 400 kV transmission lines carrying power to the Western Cape.

In this dissertation, it has been demonstrated that a phase shifting transformer can be used to alter the power flow patterns so that power flows are restructured or redistributed, such that power which originally flowed via the low impedance, lower voltage system is transferred to the parallel higher voltage transmission system of lines. It is shown that once the power flows are redistributed, steady state and voltage stability performance of the total system can be enhanced and an increase in its power transfer capacity can be realised.

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## List of Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| HVDC | High Voltage Direct Current Transmission |
| PSS/E | Power System Simulator for Engineering |
| TSO | Transmission System Operator |
| VSTAB | Voltage Stability Program |

## List of Symbols

| | |
|---|---|
| $C$ | Capacitance of the line |
| $I$ | Current |
| $S$ | Apparent power |
| $P$ | Active power |
| $Q$ | Reactive power |
| $Q_C$ | Capacitive reactive power |
| $V$ | Voltage |
| $V_i$ | Voltage at the sending end of the line |
| $V_j$ | Voltage at the receiving end of the line |
| $X_C$ | Charging impedance of the line |
| $X_L$ | Impedance of the transmission line |
| $\delta$ | Phase angle difference between sending-end and receiving-end voltages |
| $\omega$ | Radial frequency of the system |

# Chapter 1: Introduction

## 1.1. Initial Transmission System

A transmission power system network serves to transfer bulk electrical power to the load centres, from the power generating stations wherever they are located, which may be nearby or in remote locations.

Transmission lines are built to meet current and future load requirements as per load forecast. They are usually developed first by constructing transmission lines at a certain selected voltage. The selected voltage is determined based on the maximum power that needs to be transmitted by that transmission line.

The transmission lines, transformers and the other transmission equipment capacities are determined by their stability limits [1 - 6]. The stability limit of a transmission line is the maximum amount of power that can be transferred for which the power system will remain stable if a disturbance occurs [3, 4, 6]. The disturbances may be of different forms, for example, electrical faults which may occur in the power system, causing temporary loss of one part or more parts of the system, requiring other parts of the system to transfer more power than it is meant to transfer.

A well designed and operated transmission system network must be able to withstand any of the mentioned disturbances to a certain degree without loss of stability. A disturbed transmission system displays varying voltage levels and the power angle. If the instability situation is allowed to persist the unwanted voltages level may degrade further leading to part or entire electrical power system black out.

The most common form of instability in the transmission networks is the one of voltage instability and is the progressive reduction of voltages on the network buses [7]. The main contributing factor to voltage instability is the voltage reduction that occurs when active power and reactive power flow through the inductive reactance of the transmission network: this limits the capability of the transmission network to transfer power and leads to unstable voltages [6 - 8].

Even under normal operations, when load grows and the power demands at the receiving end increases, the current carried by the transmission system also increases. This increase in loading leads to lines reaching their transfer limits eventually.

## 1.2. Introduction of Higher Voltage Transmission Lines

The power transfer capacity of high voltage transmission lines is directly proportional to the square of the voltage level and the phase angle difference between the sending and receiving ends of the transmission line. It is also inversely proportional to the impedance of the transmission line.

As power requirements increase, the transfer limit of existing lines is reached, and building of additional transmission lines at the same voltages becomes necessary. However, as additional lines are built at the same voltage, lesser and lesser improvements in transfer capacity are realised. This leads to utilities considering building future lines at higher voltages as these have a higher transfer capability as discussed above.

In addition, to higher transfer capability, higher voltages allow more efficient transfer of electrical energy since, at higher voltages, for a given amount of power to be transferred, lesser current will flow, meaning lesser active power losses for the operation [2, 3].

Although higher voltage lines require more insulation and wider servitudes, the economics and environmental impact of moving to the higher voltage, in comparison to having a number of parallel transmission lines, are usually in favour of higher voltage option.

Transmission systems are operated under different loading conditions, ranging from high load to low load conditions. Under these conditions, the voltage levels at various locations in the system are affected. When an uncompensated transmission line is loaded above its surge impedance loading, the voltage level at the receiving end decreases, and when loaded below the surge impedance loading, the voltage increases.

Operation of transmission lines above their surge impedance loadings requires reactive power to be supplied to them in order to maintain the transmission voltage level within the required limits. Higher voltage transmission lines are able to supply this required reactive power because of their ability to supply higher charging current.

## 1.3. Power Flow Control Limitations

Power flows in transmission power system networks do not necessarily follow a specified transmission path, but are predetermined by the network topology. The flow is inherently determined by voltage levels, the impedance between sending and receiving ends and the power angle difference of the interconnected nodes or buses [9]. The ability to control these parameters offers the power system utilities many benefits including controlling the loading of the lines and better utilisation of the power system infrastructure.

In order to assert some form of control on the power flow, power system utilities utilise available technologies, transformers, inductors and capacitors in medium to long transmission lines to increase their capacity and to maintain voltages near rated values.

Power system networks are normally operated within 5% deviation from the nominal voltage level in order to protect equipment of the utilities and those of the users. Low voltage causes the customer motor currents to increase or motors to stall, and higher currents results in thermal damage to the end user motors. Therefore, utilities are obligated to provide power to end customers at prescribed voltage limits and, as a consequence, voltage variation offers the system operator a very limited control to influence power transfer throughout the power system network.

The remaining parameters, i.e., power system network impedance and power angle, remain the main parameters that can be controlled to substantially influence the amount and power transfer path throughout the power system network.

### 1.3.1 Series Impedance Control

As already discussed earlier, power flow through a transmission line is expressed in terms of the sending and receiving voltages, the phase angle difference between the said voltages and the total reactance between the sending-end and receiving-end busbars. Utilities primarily employ available technologies to reduce series reactance lines in order improve transmission lines power transfer capability. The use of series capacitors is well-established for this purpose. With the power electronics incorporated, forming what is called Flexible AC Transmission Systems, the thyristor controlled series capacitors can be used to optimize power flow through the transmission network systems, to control network voltages and to increase network stability [5, 6, 10].

### 1.3.2 Voltage Control

Voltage variation can be used to influence power flow through the power transmission system network. However, as it was earlier described voltages of the power system must be maintained within specified limits as a measure to protect end user equipment and own utilities power system equipment because they are designed to operate within specified voltage limits. Changing voltage can be a technique for altering power flow, and devices, such as shunt capacitors, are useful for this purpose.

### 1.3.3 Power Angle Control

The control of the power flow using power angle was recognised very long time ago [11] and throughout the development of the power transmission network power, system operators have utilised the phase shifting transformer to alter the voltage power angle to control the power flow. It is this method that is the central point of this research work.

## 1.4. Parallel Higher Voltage Transmission Lines

It has been described above, that the development of a transmission power system network usually starts at a certain high voltage level depending on the current and future power transfer capacity requirements. As the economy develops and power demand requirements increase, more and more of the transmission lines have to be added to enhance transmission capacity.

However, as the system is expanded at the original voltage level, beyond a certain point, additional transmission lines do not yield acceptable benefit to the power system transfer capacity.

At such a juncture, power system utilities usually consider introducing newer transmission lines at higher voltage level than was previously used. This is because of higher transfer capability at higher voltages and associated improvement in the efficiency of operation when higher voltages are used (e.g., saving in losses, less servitudes, less number of lines, etc.).

If higher voltage lines are commissioned, the resulting transmission network will a have a layout comprising a low impedance transmission network of parallel lines constructed at the original transmission voltage level operated in parallel with higher voltage transmission lines, constructed in later phases.

It has also been shown above that real power flow in any power system network is primarily determined by the power transmission network impedance characteristics. Therefore, the power flow in the above described system may tend to disproportionately flow in the lower voltage transmission lines, because the path through these lines are of lower impedance, despite the existence of newer, higher voltage transmission lines having higher power transfer capability. This may result in the underutilisation of the higher voltage transmission line or the entire corridor, and a generally lesser efficient operation.

The aim of this research is to investigate the utilisation of the phase shifting transformer in redirecting the power flow from the lower voltage, low impedance transmission system to the higher voltage transmission lines in parallel with the original network. It is believed that by implementing this restructuring of power flows using a phase shifting transformer, improvement in the overall steady state voltage and voltage stability performance of the total power corridor, comprising both existing lines and newer ones at higher voltage will be enhanced.

## 1.5. Structure of the Dissertation

Chapter 2 presents literature review of the existing literature on the use of phase shifting transformer to influence power flows in power networks. The aim is to establish different application of the phase shifting transformer in the control of power flow in the power system network.

The theory applicable to the use of the phase shifting transformer to control active power is reviewed in Chapter 3. It is then expanded to describe how a phase shifting transformer can be used to restructure power flows in higher voltage lines built in parallel with a low impedance network.

A case study was done on a large power system to assess the proposed use of the phase shifting transformer. The methodology used to conduct the study and gather data is explained in Chapter 4.

The results of the case study are presented and described in detail in Chapter 5.

The conclusions of the study are summarised in Chapter 6.

## 1.6. Publication

During the course of this research, one paper was prepared and presented at an international, peer-reviewed conference. This was the IEEE AFRICON 2011 conference held in Livingstone, Zambia during 15 - 18 September 2011. The paper is contained in Appendix 5 of this dissertation.

# Chapter 2: Review of Applications of Phase Shifting Transformers

## 2.1. Introduction

As discussed in Chapter 1, the intended purpose of this research work is to evaluate the possibility of using the phase shifting transformer to enhance the efficiency of a network consisting of a low impedance power transmission corridor with higher voltage transmission lines built in parallel with it. In this chapter some of the existing literature on the use of the phase shifting transformer throughout the world is reviewed and presented.

## 2.2. Initial Application of Phase Shifting Transformer

In order to increase reliability, to allow exchange of electrical power within the utility and with entities outside of utility, interconnection of the initially isolated power system networks is necessary [12]. However, complications such as instability due to transmission lines overloading, loop flows and parallel flows in the power transmission lines arise. Phase shifting transformers have been used or are being explored throughout the world to solve some of these problems.

The use of phase shifting transformers to control power flow was recognized early in the electrical power system development and early studies of its application were published in the 1930s [11]. Here, the author relates the problem of controlling power flows through the power system network which at that time had evolved from small power system networks that had originally being developed in isolation and was now becoming a large interconnected power system network.

In the original small systems, power flow control was easily achieved by initial power system development coordination, selecting parallel circuits, compensation or simply by having a proper system setup. But the advent of inter-company connections brought about connecting system that were not initial planned to be connected and resulted in the power system network characteristics that made it difficult to control the power flow.

The author discusses the power flow control by altering the transmission voltage phase angle and thereby achieving the control required in the system that had closed rings and parallel paths. The reference gives the description of the actual tests performed on an interconnected system involving five power companies and the results supported well, the proposition that the phase angle regulation can achieve the required power flow control in a system that have ring or parallel power flows.

## 2.3. Phase Shifting Transformers in Cross Border Power Flow Control

There are a considerable number of recent publications on studies and actual implementation of power flow control using phase shifting transformers on the interconnected grid of Belgium, France, Germany and Netherlands [13 - 19].

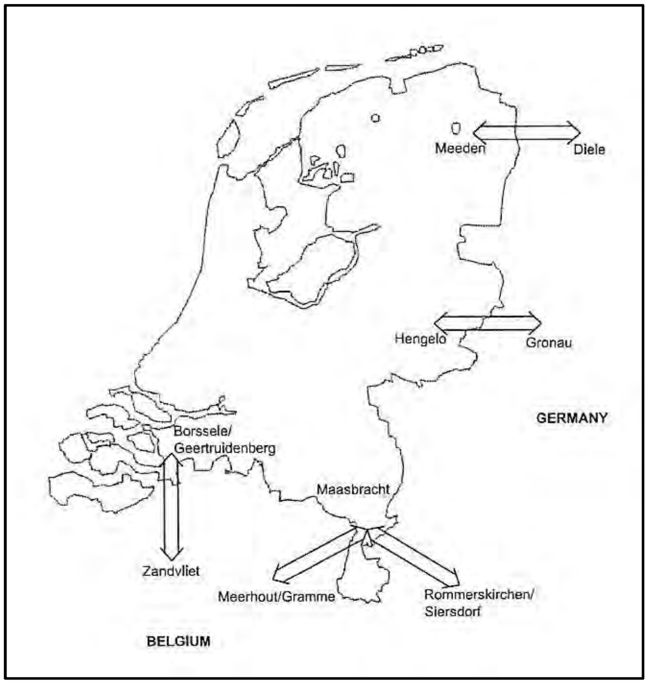

**Figure 1: Netherlands interconnections with its neighbouring countries [31]**

In these publications, it is indicated that as a result of deregulation of the European electricity industry, cross border trading is common and cross border interconnections are no longer only used to support the neighbouring electricity grid in times of emergency, but have become an integral part of the wholesale supply of electrical energy to users throughout the Western Europe. This has led to some inter-tie connections being overloaded to an extent that their initially intended purpose to enhance reliability of the interconnected systems is close to being compromised.

The above referenced countries' grids are connected as in Figure 1 above and Belgium is further connected to France in the South. The existing power flows showed that as a result of uncontrolled power flows on the interconnections, there are some unexpected power flows across some inter-ties leading to overloading whereas other inter-ties are carrying little load.

The publications showed in detail, and in support of each other, that the power flow through the electric power system does not follow a specified path, but follow a transmission path according to the electrically least resistive path. And because of this phenomenon, it is possible that transmission systems that have nothing to do with the energy sales become involved in the transmission of such energy, leading to the transmission capacity usage that has no business benefit at all from the energy trading transaction.

As a result of the uncontrolled power flows described above, the European transmission system operators instituted studies on how to influence such flows. The studies carried out showed that the use of phase shifting transformer to control the power flows, in such a manner that power flows are made to flow where intended has the benefits of alleviating the thermally overloaded interconnections and thus increasing the inter-country transmission transfer capacity for own use or energy trading.

Furthermore, in reference [16] the authors presented optimization methods that could be used to determine the best settings for a number of phase shifting transformers installed in meshed grids. This is because the studies showed that a control of power flow in one line affect the neighbouring transmission lines. These methods would enhance the utilisation of the total transfer capacity of the transmission lines because without analytical methods system operator tends to be very conservative when allocating transfer capacity. The system operators set safety margin on non-analytical methods, such as trial and error, rather than scientific based reasoning.

In reference [14], Verboomen, et al., discuss principles of the phase shifting transformers and their different forms that exist today. The different forms are based on how the phase shifting transformers are constructed and how they bring about the voltage angle control. The authors further discuss the case study of the phase shifting transformers installed on the Netherlands-Germany interconnection to control power flows and how the phase shifting transformer improved the power flow control on the said interconnection as discussed before.

In reference [13, 19], Van Hertem, et al., discuss the problems encountered by power system operators in deregulated electricity industries, such as the European one. They evaluated the use of the phase shifting transformers and High Voltage Direct Current Transmission [HVDC] systems to reduce the power system losses, in comparison with other power flow control devices.

The authors showed that power flow controlling devices including the phase shifting transformers can reduce the power system losses. However, in meshed power systems, the deployment of power flow control devices must be well coordinated for the benefit of all. Otherwise, if one Transmission System Operator were to operate a phase shifting transformer located in his local control area without looking or coordinating with his neighbouring control area, the latter phase shifting transformer operated may counteract the actions of the previous one. This is supported by Marinakis, et al., [20] whose work showed that control of phase shifting transformers by multiple transmission operators must be well coordinated for economic benefit of the overall transmission system network.

Verboomen, et al., [15, 17, 18, 21] propose analytical optimization methods that can be used to select optimal settings of multiple phase shifting transformers installed on multiple inter-connectors to control the power flow. This is in line with the observation that Van Hertem made in reference [13] above that each phase shifting transformer installed on the line has an influence on the power flows on the line it is installed at as well as neighbouring lines.

References [22, 23] discuss the phase shifting transformer application on the interconnections of the Austria, Croatia, France, Italy, Slovenia and Switzerland grids.

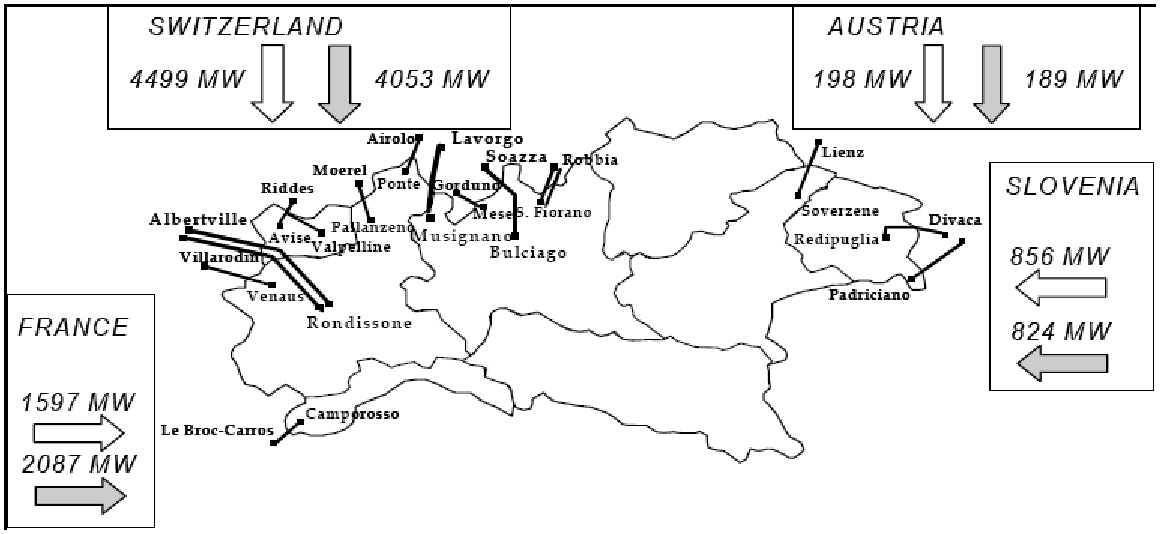

**Figure 2: Using Phase Shifting Transformers in the Italian Transmission System [35]**

The publications similarly express concerns on uncontrolled parallel power flows and overloading of some transmission facilities attributed to the deregulation of the electricity industry in the region. Because of non-deterministic nature of the electricity trading the countries, Transmission System Operators [TSOs] operate the transmission facilities well below their capacity levels to allow the system to carry these unallocated energy transfer and to allow the transmission system networks to cope with emergency energy transfer if some disturbances were to occur. Figure 2 above indicates the actual power imports distribution into the Italian power system network following an installation of a phase shifting transformer on the Italian network [23].

The phase shifting transformer enables the Italian Transmission System Operator to operate the transmission power system in a secure manner as the distribution allows more flows on the France-Italy inter-tie relieving the near thermally overloaded North-Western Italian transmission network [23].

| **Point of view/influence of Phase shifting transformer of electric power system of the Czech Republic** | **Stage 1**<br>(400 kV – 2xPST) | **Stage 2**<br>(400 kV – 2xPST<br>220 kV – 2xPST) |
|---|---|---|
| Regulation of cross border power flows according to requirements/plan | Partial | Full - value |
| Increase of possibilities of electricity export from Czech Republic | Utilizable | Considerable |
| Preventing of overloading the lines at n-1 regimes | Yes | Yes |
| Increase of cross border transmission capacities on profiles in Czech Republic | Partial | Considerable |
| Redistribution of cross border power flows in the power system | Yes | Yes |
| Control of flow relations between 400 kV and 220 kV networks in Czech Republic | Partial | Maximum |
| Reduction of losses in transmission network of Czech Republic as caused by transits | No | Yes |

**Table 1: Evaluation of Phase Shifting Transformers Application on Czech Republic Electric Power System [24]**

Other published applications [24] are of the interconnection of the Czech Republic and its neighbouring countries of Austria, Germany, Poland and Slovakia. Ptacek, et al., in this publication discuss similar experiences as the ones mentioned from the West European Transmission System Operators of transit flows increasing and, therefore, a need to control the power flows so as to ensure secure transmission facilities. The authors explored other technologies that could be used and compared them with phase shifting transformers and the use of phase shifting transformers proved to more viable and would benefit the Czech Republic power system if adopted. Table 1 above summarizes the benefits that could be obtained. The summary table illustrates the benefits that could be obtained at different stages of employing the phase shifting transformers.

## 2.4. Controlling Loop and Transit Flow Control

References [25 - 27], discuss the problem of non-authorized parallel power flows in the North American interconnected power system and how some installed phase shifting transformers could completely prevent the parallel power through unauthorised transmission systems. The authors also discussed the benefits obtained in some transmission lines whereby the phase shifting transformers installed in the system averted the overloading which would have caused the Transmission System Operator to load shed some customers.

In all the above application the phase shifting transformer is used to alleviate the problems of overloading and congestion of the inter tie transmission lines. The applications also uses the phase shifting transformers to alleviate the instability situation that result in overloading of other transmission network system following disturbance that trip out some parts of the transmission network.

The application uses the phase shifting transformer to direct power flow to some of the interconnecting transmission lines that are not heavily loaded. The applications proved to be more beneficial to the utilities concerned because they were implemented in one country. The alternative solution of building additional lines would have taken long time to build as negotiations would take too long as the inter-tie lines concerns more than one country.

## 2.5. Peak Power Demand Control Using Phase shifting Transformers

Publications [28, 29] discuss the applications of the phase shifting transformer in the Great Britain grid. In these applications, the phase shifting transformers are installed to avert the situation of thermal overloading of certain sections of the grid when system experiences faults that causes other lines to trip out.

## 2.6. Conclusion

In most of the application reviewed above, because of the deregulation of the electricity industry, the phase shifting transformers are used to control power flow across the inter-ties to alleviate overloading that may exist. They help to transfer power to other inter-ties that are carrying less power. The phase shifting transformers are also used to control the parallel power flows in transmission systems that are not supposed to be involved in that particular transfer of electricity.

The use of phase shifting transformer also proved to be more beneficial than building new transmission lines. They allowed better utilization of existing capacity. This is advantageous particularly because building of new lines may not always have enough government support and is usually met with a lot of resistance from the public, whereas phase shifting transformers utilise the land that is already being used by the Transmission System Operator or if additional land is required, it is very small compared to building a new line.

From the literature reviewed, the main benefits of controlling power flows using the phase shifting transformers are related to alleviation of loading, i.e., thermal constraints, and reduction of losses.

Further applications looked at the use of the phase shifting transformers to redirect the power flow to other inter-tie lines that are carrying little load thereby maintaining the reliability level of the interconnected systems, especially in inter-country flows.

Based on the literature review undertaken as presented in this chapter, no work has been done on the use of phase shifting transformers in parallel transmission networks overlayed with higher voltage transmission lines. In the following chapter the theory that supports the use of the phase shifting transformer in the improvement of the utilisation of the power transmission network comprising higher voltage lines in parallel with a low impedance network will be discussed.

# Chapter 3: Using Phase Shifting Transformers to Restructure Power Flow in Parallel High Voltage Transmission Lines

## 3.1. Introduction

The previous chapter dealt with the review some of the existing literature on the use of phase shifting transformers. In this chapter, the theory of how a phase shifting transformer is used to influence power flows is presented. This is extended to how a phase shifting transformer can be used to influence power flows in networks comprising higher voltage transmission lines built in parallel with a low impedance system of transmission lines.

## 3.2. Power Flow in Transmission Power System Networks

Power flow in transmission networks is governed by voltages at the sending and receiving-end buses, the angle difference between the buses, and the impedance, as illustrated in Figure 3 below [3, 4, 6].

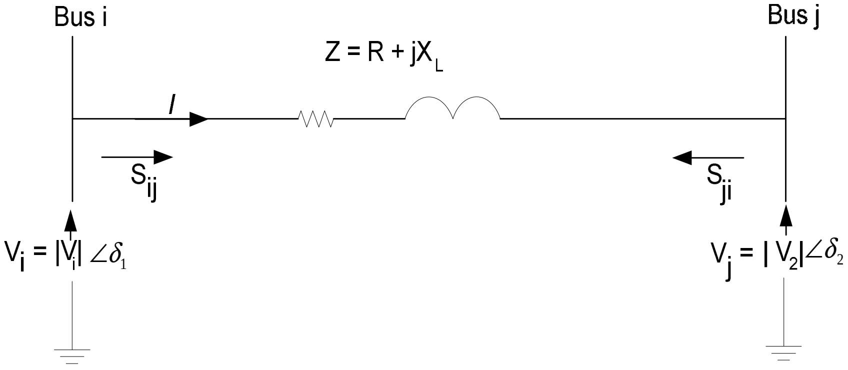

Figure 3: Power Through a Transmission Line

The current I flowing from bus i to bus j is expressed as

$$I = \frac{|V_i| \angle\delta_1 - |V_j| \angle\delta_2}{R + jX_L} \tag{3.1}$$

$$I^* = \frac{|V_i| \angle(-\delta_1) - |V_j| \angle(-\delta_2)}{R - jX_L} \tag{3.2}$$

The complex power at the receiving end of the transmission line is

$$S = P + jQ = |\,V_j|\ I^* \tag{3.3}$$

$$S = |V_j| \angle\delta_2 \,.\, \frac{|V_i| \angle(-\delta_1) - |V_j| \angle(-\delta_2)}{R - jX_L} \tag{3.4}$$

$$S = \frac{|V_j||V_i| \angle(\delta_2 - \delta_1) - |V_j|^2 \angle 0}{R - jX_L} \tag{3.5}$$

$$S = \frac{|V_i||V_j|}{R - jX_L} \angle(\delta_2 - \delta_1) - \frac{|V_j|^2}{R - jX_L} \tag{3.6}$$

If assumption is made that the line is a lossless line, i.e., $R = 0$, then

$$S = \frac{|V_i||V_j|}{-jX_L} \angle(\delta_2 - \delta_1) - \frac{|V_j|^2}{-jX_L} \tag{3.7}$$

$$S = \frac{|V_i||V_j|}{-jX_L} (\cos(\delta_2 - \delta_1) + j \sin(\delta_2 - \delta_1)) - \frac{|V_j|^2}{-jX_L} \tag{3.8}$$

$$S = \frac{|V_i||V_j|}{X_L}\sin(\delta_1 - \delta_2) - j\,\frac{|V_i||V_j|}{X_L}\cos(\delta_1 - \delta_2) + j\,\frac{|V_j|^2}{X_L} \qquad (3.9)$$

From equation $S = P + jQ$, it implies that from the above equation

$$P = \frac{|V_i||V_j|}{X_L}\sin(\delta_1 - \delta_2) = \frac{|V_i||V_j|}{X_L}\sin\delta \qquad (3.10)$$

And

$$Q = \frac{|V_j|^2}{X_L} - \frac{|V_i||V_j|}{X_L}\cos(\delta_1 - \delta_2) = \frac{|V_j|^2}{X_L} - \frac{|V_i||V_j|}{X_L}\cos\delta \qquad (3.11)$$

Where

$P$ = Active power transmitted through the transmission system in megawatts.

$Q$ = Reactive power transmitted through the transmission system in megavars.

$V_i$ = Voltage at the sending end of the line in kilovolts

$V_j$ = Voltage at the receiving end of the line in kilovolts

$X_L$ = Reactance of the transmission line in ohms

$\delta$ = Phase angle difference between sending-end and receiving-end voltages in degrees

### 3.2.1. Reactive Power Requirement in the Transfer of Active Power

Equation (3.10) shows that active power transfer increases when the power angle δ increases. Equation (3.11) shows that there is a decrease in reactive power when the power angle δ increases and this lead to a decrease in the transmission system voltages. It is, therefore, necessary to supply reactive power to the transmission system in order to maintain the voltages at required levels. This reactive power is normally supplied from reactive power sources like capacitor banks.

### 3.2.2. Higher Transfer Capacity of Higher Voltage Transmission Lines

There is a capacitive coupling between the phases of a transmission line resulting in capacitive current being supplied to the transmission line [2, 30]. This current is called charging current and can be written as

$$I_{ch} = j\omega CV \tag{3.12}$$

Where

$\omega$ = the radial frequency of the system

$C$ = the capacitance of the line

It therefore means that as a result of charging current, the transmission lines are able to deliver capacitive reactive power which can be expressed as

$$Q_c = \frac{V^2}{X_C} = \omega CV^2 \tag{3.13}$$

Where

$Q_C$ = the capacitive reactive power

$X_C$ = the charging reactance of the line

$V$ = the voltage of the transmission line

From the above expressions it is observed that the voltage of the transmission line has a significant impact on the capacitive reactive power generated by any transmission line as the capacitive power is related to the square of the transmission voltage.

The term $\omega C = b$ is called shunt susceptance and it reflects the amount of capacitive charging current that can be generated by the transmission line. This charging capacity of a transmission line is sometimes expressed as $V^2b$ and can range from 0.18 MVA/km for 230 kV line to 2.92 MVA/km for 765 kV transmission line [4].

From the preceding discussion, it can be concluded that higher voltage transmission lines produce more of the reactive power than a lower voltage transmission lines and will therefore be able to support transmission of more active power.

### 3.3. Active Power Flow Control Using Phase Shifting Transformers

From having seen which parameters can be altered to have an effect on the active power flow and how the changing of the phase angle at the sending and receiving ends have a significant influence on the active power flow, the review of how the phase shifting transformer influences the phase angle magnitude will be undertaken below. The phase shifting transformer controls the active power flow by injecting a voltage $\Delta V$ at $90^0$ to the network voltage [14, 31] as shown in Figure 4 below.

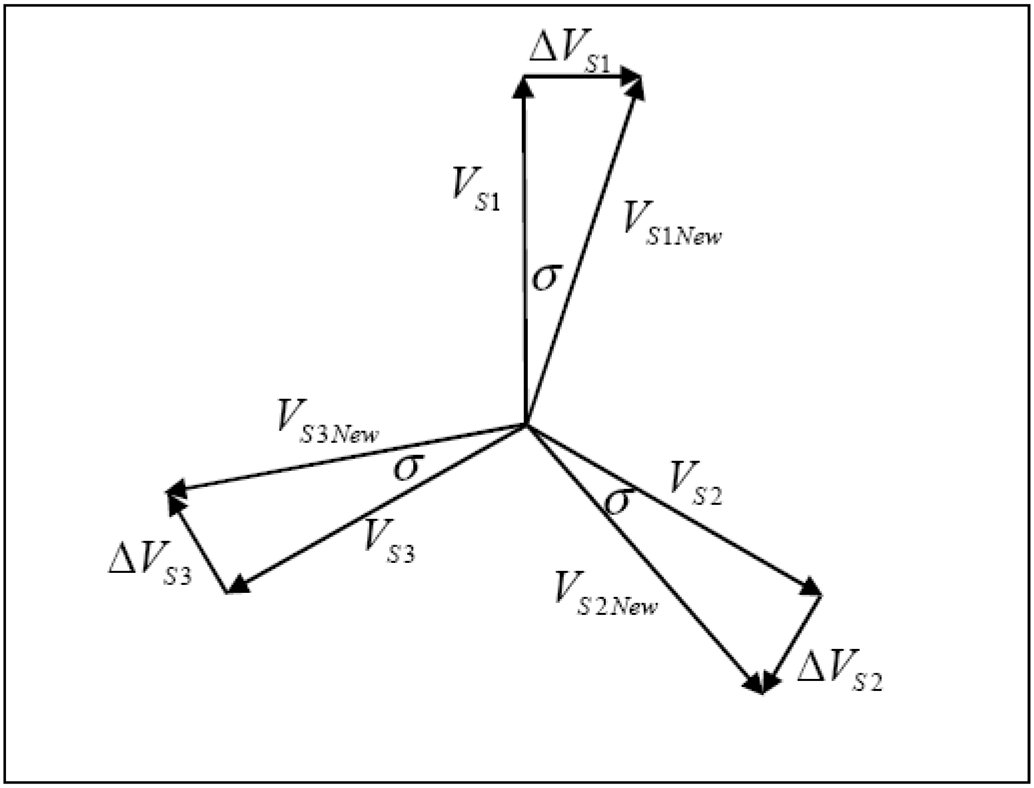

**Figure 4: Phasor diagram of a phase shifting transformer[14]**

The resulting output voltage $|V_{S1New}|$ is always larger than the input voltage $|V_{S1}|$, and the new output voltage $|V_{S1New}|$ is shifted by the angle σ with respect to the system voltage $|V_{S1}|$. The active power flow transfer formula (3.10) derived above is thus altered as shown below:

$$P = \frac{|v_i||v_j|}{X_L + X_{PST}} \sin(\delta \pm \sigma) \tag{3.14}$$

Where

$\sigma$ = the phase shift angle introduced by the phase shifting transformer

$X_{PST}$ = the phase shifting transformer impedance

In order to illustrate how the phase shifting transformer controls the power flow in a transmission power network, an example of a transmission network with two parallel lines and in one of the lines a phase shifting transformer is installed is demonstrated below. Figure 5 shows the two lines and a phase shifting transformer installed in line 1.

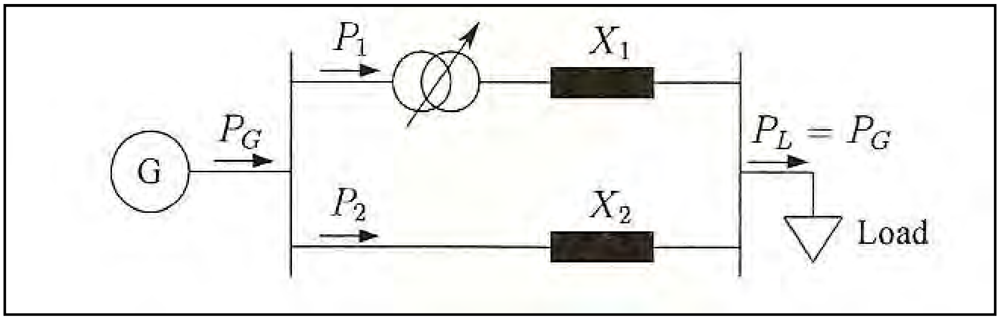

**Figure 5: Two parallel lines with one having a phase shifting transformer[16]**

From equation (3.10) and $P_G = P_1 + P_2$, it can be shown that if line 1 has a larger reactance than line 2 ($X_1$>> $X_2$) and their line resistances are neglected, then without the power flow control by the phase shifting transformer, line 2 will carry more power than line 2 as shown by the following:

$$\frac{P_1}{P_G} = \frac{X_2}{X_1+X_2}$$

$$P_1 = P_G \frac{X_2}{X_1+X_2}$$

$$P_1 = P_G \frac{X_2}{X_1\left(1+\frac{X_2}{X_1}\right)}$$

$$P_1 = P_G \frac{X_2}{X_1} \rightarrow 0 \qquad \text{If } X_1 >> X_2. \qquad (3.15)$$

And

$$\frac{P_2}{P_G} = \frac{X_1}{X_1 + X_2}$$

$$P_2 = P_G \frac{X_1}{X_1 + X_2}$$

$$P_2 = P_G \frac{X_1}{X_1\left(1 + \frac{X_2}{X_1}\right)}$$

$$P_2 = P_G \frac{X_1}{X_1} \rightarrow P_G \tag{3.16}$$

Equation (3.15) indicates that $P_1$ is approximately zero and equation (3.16) shows that $P_2$ is approximately equal to $P_G$, indicating that $P_2$ is far larger than $P_1$. Similarly, when the phase shifting transformer is installed on one of the transmission lines, the power through each line can be represented as follows:

$$P_1 = \frac{V_1 V_2}{X_1 + X_{pst}} \sin(\delta \pm \sigma) \text{ and } P_2 = \frac{V_1 V_2}{X_2} \sin\delta \tag{3.17}$$

The relationship between the power through each line and the total transmitted power is as shown below:

$$\frac{P_1}{P_G} = \frac{1}{1 + \left(\frac{X_1 + X_{pst}}{X_2}\right)\left(\frac{\sin\delta}{\sin(\delta \pm \sigma)}\right)} \tag{3.18}$$

$$\frac{P_2}{P_G} = \frac{1}{1 + \left(\frac{X_2}{X_1 + X_{pst}}\right)\left(\frac{\sin(\delta \pm \sigma)}{\sin\delta}\right)} \tag{3.19}$$

If $P_1 = \frac{V_1 V_2}{X_1} \sin\delta$ and $P_2 = \frac{V_1 V_2}{X_2} \sin\delta$ are drawn on the $P - \delta$ plane the following graphs are obtained for any value P and δ without and with phase shifting transformer installed.

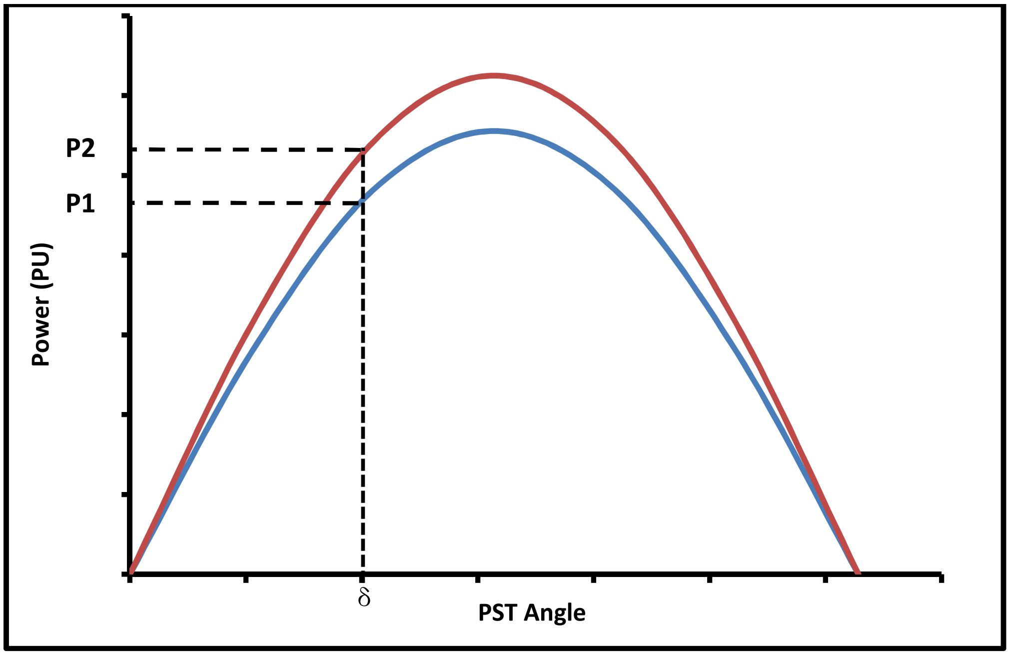

Figure 6: P-δ Graphs for Parallel Lines without Phase Shifting Transformer [16]

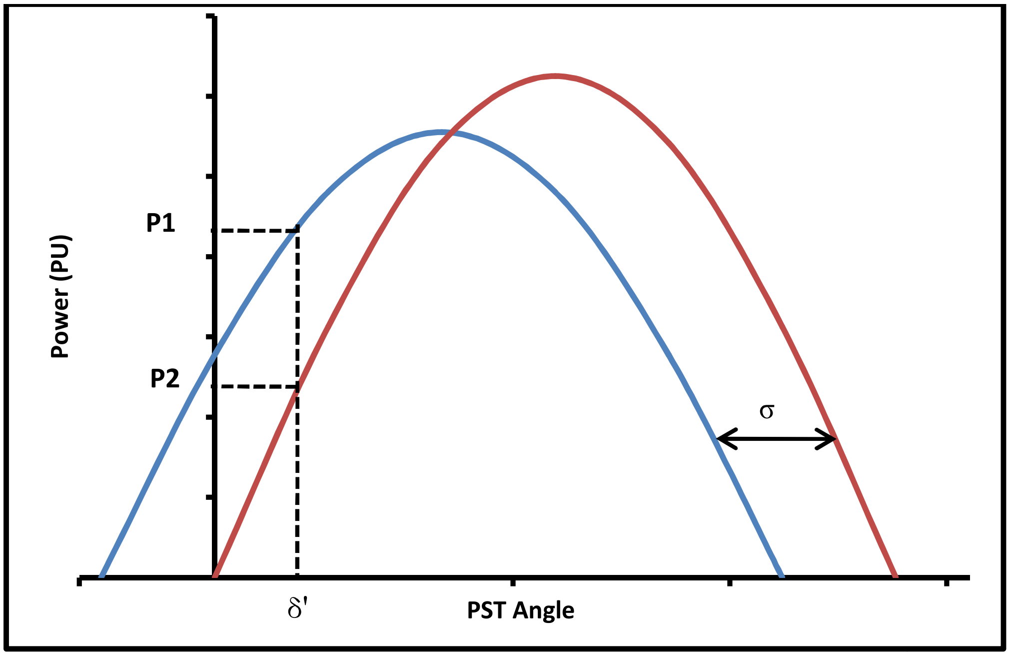

Figure 7: Two Lines with a Phase Shifting Transformer Installed in One [16]

The two graphs Figure 6 and Figure 7 show that the phase shifting transformer increases the power flow through line 1 as it decreases the power flow through line 2 at the same instance. Since the total transmitted power is not changed, the increased power in line 1 occurs at a different angle $\delta'$ in comparison to the original angle $\delta$. Therefore, power is shifted not actually changed.

### 3.4. Power Corridor Overlayed with Higher Voltage Transmission Lines

It was earlier discussed that power transmission networks are initially developed to meet current power system loading requirements and possible load forecast. The convention is that power transmission networks are developed starting at some chosen voltage level.

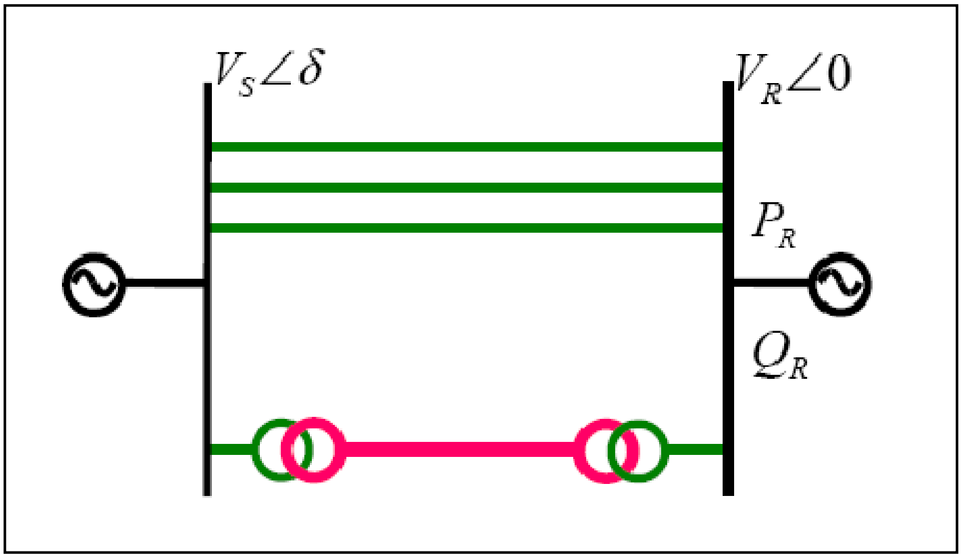

**Figure 8: Low Impedance Network Overlayed with Higher Voltage Transmission Line**

As demand for power at the receiving-end increases, the additional transfer capability based on the voltage stability tends to decrease as more lines are added. Furthermore, it is the practice by utilities throughout the world that when faced with this situation, higher voltage transmission lines are then considered and are usually overlayed over the existing lines thereby resulting in transmission network with parallel transmission lines at different voltages as illustrated in Figure 8 above.

In the above illustration, a number of lines that were built in the early phases of the development of the transmission system are shown in green and as the development of the system continued and the further improvement in the transfer capability is required, utilities overlay higher transmission line on the transmission system as shown in pink.

Because the lower voltage network in green is very mature and strong (low impedance), i.e., it consists of many lines in parallel, it is possible that the introduced higher voltage line may be seriously underutilised because the power flows, as predetermined by the system impedances substantially in the lower voltage lines. In this instance, the benefits, described in the section above, of using the higher voltage lines may not be realised. By introducing the phase shifting transformer as proposed in this work, it is expected that more power can be forced on to the higher voltage line. The benefits of using newer, higher voltage lines could then be realised. The system transfer capability can be improved, and so can efficiency of the network operation.

### 3.5. Conclusion

In this chapter, the theory that supports the application of phase shifting transformers was examined. It was discussed that by using the phase shifting transformer to alter the phase angle of the interconnected buses, power flow in various paths can be adjusted. The ability of the higher voltage transmission lines to carry more power transfer was also briefly described.

It was also described how a phase shifting transformer can be used to utilize a higher voltage transmission line built in parallel with an existing, low impedance network, thereby enhancing transfer capability of the entire system.

The following chapter will describe a methodology of a study to be carried out in a network that has higher voltage transmission line in a parallel with a  low impedance system to evaluate whether a phase shifting transformer could be used to enhance the transfer capability and efficiency of such a network.

# Chapter 4: Methodology of the Study

## 4.1. Introduction

The previous chapter described the electrical power transmission network characteristics that influence power flow through a transmission network. It was also shown how these characteristics can be influenced by utilising the phase shifting transformers to improve performance of the power system network. In this chapter, the methodology of the study carried out on a power system to assess the possibility of applying a phase shifting transformer to improve transfer capability and efficiency of a network, comprising a higher voltage transmission in parallel with a low impedance system, is discussed.

## 4.2. Cape Corridor

The topology of the South African power system is largely influenced by the abundance of coal reserves on the northern part of the country, dictating that the majority of the thermal power station be there, where these reserves are mined [32, 33]. This geographic location of power stations has led to the development of major transmission corridors that transport the power generated to the load centre located in the Western Cape as shown in Figure 9. The corridors to the Cape are made up of 400 kV and 765 kV transmission lines running in parallel to each other. The total line length from the northern part of the country, where the power stations are located, to the Western Caper, is in excess of 1500 kilometres [32].

The transmission system was initially developed at lower voltage of 400 kV and as the load demand increased additional lines were added. But, as explained in the previous chapter, the additional transfer capacity diminishes with the addition of more transmission lines.

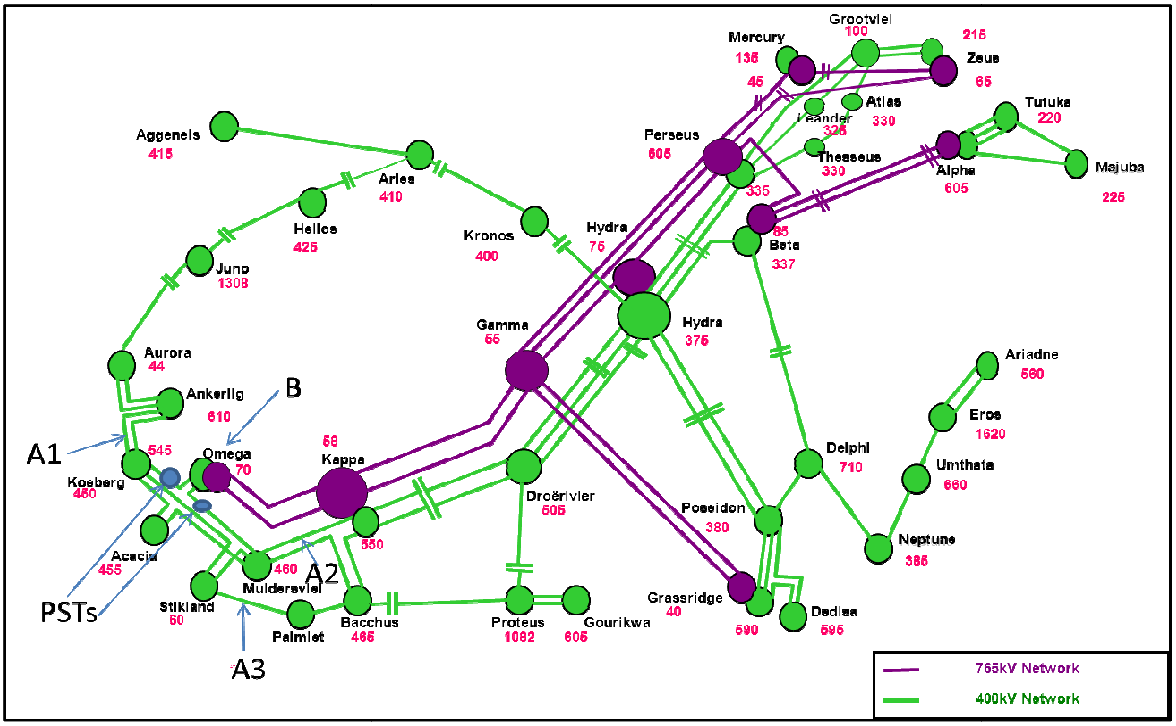

**Figure 9: Geographic Layout of the Cape Corridor [32]**

The higher voltage transmission lines were then considered and 765 kV transmission lines were overlayed on some of the existing 400 kV transmission lines resulting in the layout as shown in Figure 9 above. Because the 400 kV transmission lines are mature, i.e., a number of lines in parallel, and strong, i.e., form a system with relatively low combined impedance compared to the higher voltage 765 kV transmission lines, power flow is substantially more in the 400 kV than the preferred 765 kV transmission lines. This means a significant under-utilisation of the newer, higher transfer capacity 765 kV transmission lines exists.

By using the phase shifting transformers at the end of this corridor to move power from the lower voltage transmission lines to the higher voltage transmission lines, it is envisaged that the capability of the entire corridor will be improved. The higher voltage transmission lines have been shown to have more capacitive reactive power support. When the higher voltage transmission lines are carrying the bulk of the power, utilization of the entire 400/765 kV corridor and its voltage stability limit is expected to improve.

## 4.3. The Simulation Approach

A number of power system simulations were carried out to test the hypothesis proposed using the Cape network described above as the case study. Loadflows were carried out to assess the impact of the phase shifting transformer on voltages, line loadings and losses of both mature corridor (400 kV lines) and higher voltage transmission lines (765 kV). Voltage stability studies were also done to assess the impacts on voltage stability limits. Some aspects of the methodology followed are described below.

In this research work commercial grade Power System Simulator for Engineering (PSS/E) and Voltage Stability Program (VSTAB) softwares made available by Eskom were used for loadflow simulation and voltage stability studies.

The study grid network data was entered into the PSS/E. The single line diagram of the Cape corridor showing 400 kV and 765 kV parallel lines and their interconnection created from the entered network data. The phase shifting transformers were inserted into the network diagram at the end of the 765 kV corridor as indicated in the geographic layout Figure 9 shown before to enable monitoring of the resulting loadflow parameters as the phase shifting transformer angle is altered.

### 4.3.1. Power System Simulator for Engineering (PSS/E)

The Power System Simulator for Engineering (PSS/E) software was used in this study [35] to conduct loadflows. It is an integrated, interactive program simulating, analysing and optimising power system performance. The PSS/E software program contains several modules including power flow, optimal power flow, balanced and unbalanced fault analysis, dynamic simulation, extended term dynamic simulation, open access and pricing, transfer limit analysis and network reduction.

### 4.3.2. Voltage Stability Program (VSTAB)

Voltage Stability Program (VSTAB) is a voltage stability assessment package developed for large complex power systems. It provides information regarding both the proximity to and mechanisms of voltage instability. There are a number of features available in the VSTAB package. In this research work, only the module for voltage stability analysis using P-V curves is used.

### 4.3.3. Phase Shifting Transformer Modelling

The phase shifting transformer in PSS/E is modelled as a two node transformer with all its characteristics, all specified at the beginning of the simulation studies. The phase angle can be allowed to be automatically changed by the program or manually by the user. In this research studies, a Python program that altered the phase shifting transformer angle across the range $-20^0$ to $+20^0$ was compiled. Refer to Appendix 1.

### 4.3.4. Loadflow Studies

A Python loadflow simulation program for the base case, i.e., when the is no phase shifting transformer installed and for different phase shifting transformer angle settings was compiled for these studies and included in Appendix 2. The program automates multiple runs of loadflows, by undergoing the following steps:

- Read a loadflow case file
- Adjust the phase shifting transformer angle
- Run the loadflow simulations
- Report on voltages at substations of interest, noting any voltages outside required range
- Report on equipment loadings that exceed rating, for system healthy conditions
- Report on active power losses of the system

The detailed results of all the loadflows carried out are presented in Appendix 2.

### 4.3.5. System Losses

Within the Python loadflow simulation program compiled as described above, the system active power losses were also monitored and recorded for the base case, i.e., no phase shifting transformer installed, and for the different settings of the phase shifting transformer angles.

### 4.3.6. Voltage Stability Studies

Increase in load demand or power transfer causes voltage drop at a number of buses in the electric power system, therefore studies are always undertaken to ensure that this voltage drop does not progress and lead to a stage where the power system may be unable to maintain the required voltage level at all buses. The P-V curves is one of the most commonly used techniques used to study voltage stability.

The P-V curves plot the relationship between the power transfer and the bus voltage at the receiving bus bars. P-V curves provide the power transfer and voltage margins by using the knee point of the P-V curve. The maximum power that can be transferred at the critical voltage is obtained from the P-V curves.

In conducting the voltage stability studies, a group of simulation files required were prepared, namely, the Parameter file, the Load level increase file, the Interface file and the Contingency file. They are discussed briefly below:

- The Parameter file specifies the program control actions, solution parameters and the parameters output options.

- The Load level increase file specifies which buses' loads are increased and which bus voltages or equipment loadings and are monitored.

- The interface file specifies the interconnection of the different buses and branches in the area of interest which are being monitored during the execution of the simulation program.

- The Contingency file specifies the contingency that are performed by the program.

All files described above are contained in Appendix 3.

A raw data file was generated from the PSS/E program. This raw data file describes the interconnection of the entire Eskom network and specifies where the phase shifting transformer is installed and at what angle it is set. The raw data file is then converted into another file readable by the VSTAB program. This data file and VSTAB program described above are then loaded into the VSTAB and voltage stability simulations are them performed.

## 4.4. Conclusion

The methodology that is followed in this research work is described in this chapter. The Western Cape corridor, which will be used in conducting the case study described earlier, was described, including its topology and how voltages used in its development have evolved. Chapter 5 will present the results of the studies conducted.

# Chapter 5: Results and Discussions

## 5.1. Introduction

In the preceding chapter, the methodology that has been followed in carrying out the case study using the Cape network was outlined. This chapter presents the results of the studies done and discusses the findings.

## 5.2. Loadflow Results

The utilisation of the phase shifting transformer resulted in moving power flow from the lower voltage transmission lines to the higher voltage transmission lines as the phase shifting transformer angle is altered.

The detailed loadflow results are contained in Appendix 2. Positive values indicate the active power flow into the monitored area and power flowing out of the monitored area is reflected as negative values. The results are for the base case, in which a phase shifting transformer is not included in the network and for a case with the phase shifting transformer set at various angles. The aim of this was to assess the impact of varying the phase shifting transformer angle on the power flowing in the 400 and 765 kV transmission lines.

Figure 10 show the impact of varying the phase shifting transformer angle on the power flowing in the 400 kV and 765 kV lines. Referring to the figure, the following observations can be made:

Power flowing on the Koeberg Ankerlig 400 kV Lines 1 and 2 (blue)

- Without the phase shifting transformer installed, these lines carry a small amount of power into the study area.

- On inclusion of the phase shifting transformer and as the phase shifting transformer angle is increased, power flowing through these lines increases in proportion with the increase in the angle.

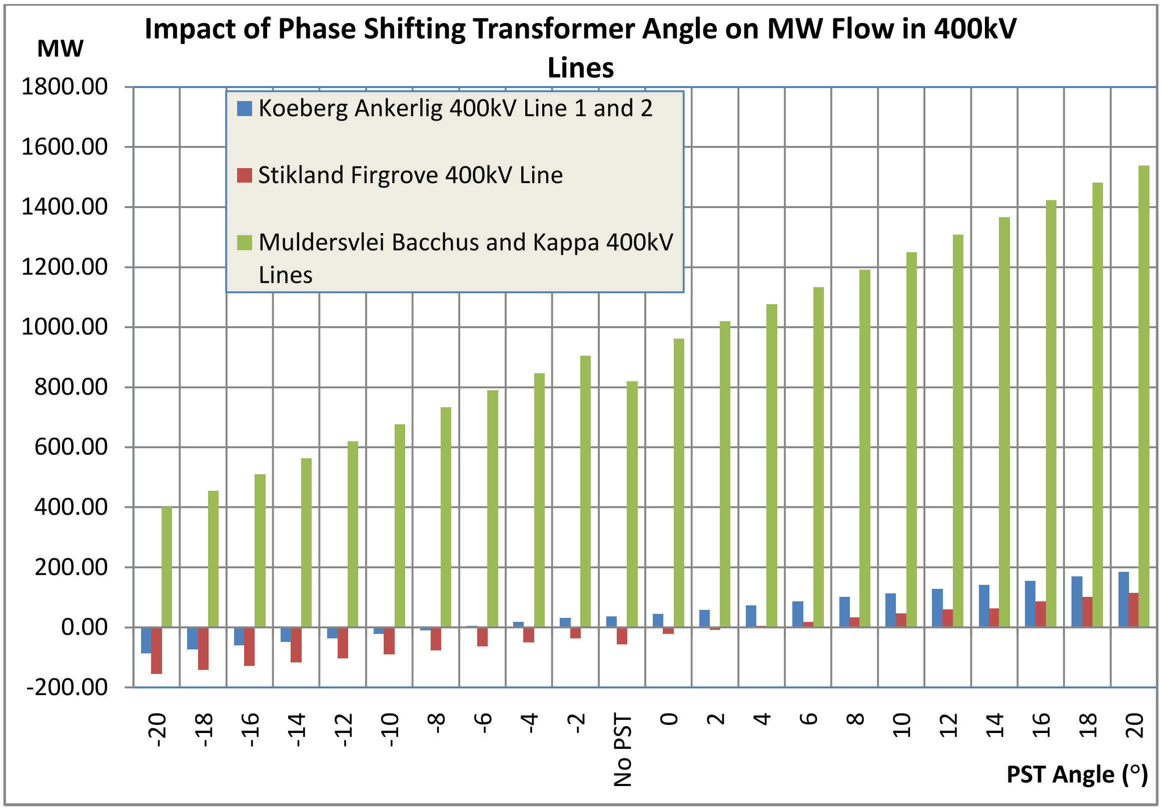

**Figure 10: Impact of phase shifting transformer angle on active power flow in 400 kV transmission lines**

Also, as the phase shifting transformer angle is reduced, it observed that the power flowing is reduced as well. At -6°, the power flow direction is reversed, and, as the angle is reduced further, increase in power, but in reverse direction to that in the base case occurs.

Power flowing on the Stikland Firgrove 400 kV line (red)

- Without the phase shifting transformer installed, this line takes a relatively small amount of power out of the study area. .

- Once the phase shifting transformer is incorporated, increasing its angle beyond 6°, leads to more power being channelled into the area via this line.

- As the phase shifting transformer angle is decreased, the power flowing through these lines decreases and at 2° is reversed. Further reduction of the angle leads to a progressive increase of reversed power flow.

Power flowing on the Muldersvlei Bacchus 400 kV and Muldersvlei Kappa 400 kV lines (green)

- These lines bring most of the power into the study area before the phase shifting transformer is considered.

- Increasing the angle of the phase shifting transformer leads to more power being imported into the study area via these lines.

- Reducing the angle serves to only reduce power into the area transported via these lines.

Figure 11 shows the impact of installing the phase shifting transformer, and varying its angle, on the power flowing into the area via the 765 kV lines. The following observations can be made:

- In the base case, the 765 kV is bringing in around 1000 MW of power into the study area.
- As the phase shifting transformer angle is increased the power flow decreases, until it reverses direction at phase shifting transformer angle +18°.
- Decreasing the phase shifting transformer angle below 0°, leads to a small drop in power flowing and, thereafter, a continuous increase is realised.

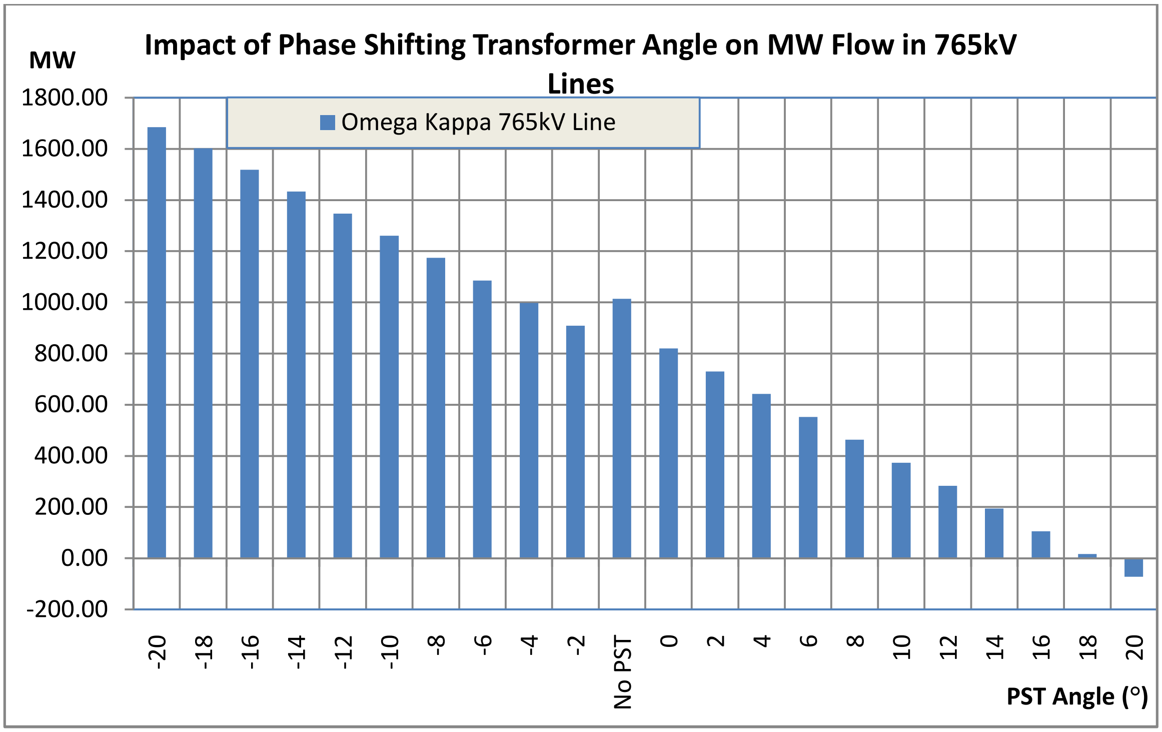

**Figure 11: Impact of phase shifting transformer angle on active power flow in 765 kV transmission lines**

Figure 12 shows the aggregated active power flowing on the 400 kV lines and aggregated active power flowing on the 765 kV transmission lines. Close assessment of the figure reveals that:

- Initially, without the phase shifting transformer, both the 400 kV and 765 kV lines bring power into the Cape.
- Generally, as the phase shifting transformer angle is increased, the active power flowing through the 765 kV lines decreases and more power is channelled via the 400 kV lines.
- As the phase shifting transformer angle is decreased, loading of the 765 kV lines tends to increase, while the loading of the 400kV lines is reduced.

Generally, care has to be taken to ensure that with the restructured power flows no loop flows should occur as the angle is changed. Also, care has to be taken to ensure that power reversing away from the load centre is avoided or is minimized.

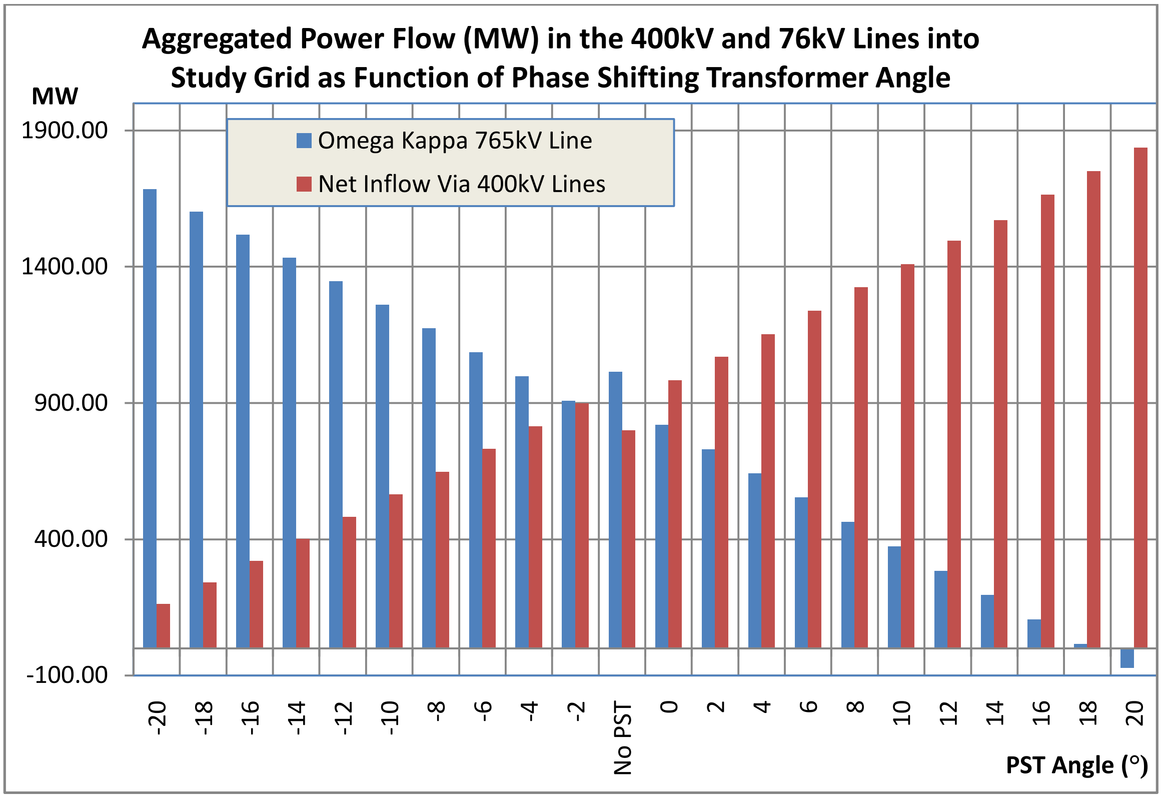

**Figure 12: Aggregated active power in the 400 kV and 765 kV transmission lines**

Figure 13 shows the utilisation of the 765 kV transmission lines as the phase shifting transformer angle is altered. The loading of the lines vary from 5% to 35% as the phase shifting transformer angle is varied from -20° to +20°.

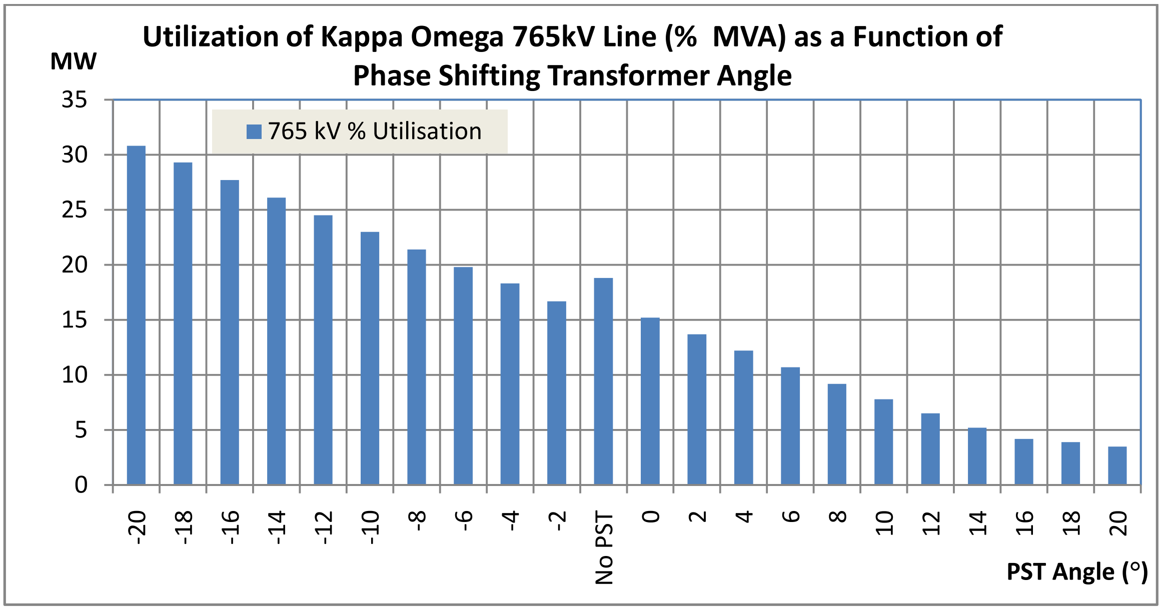

**Figure 13: Utilisation of the 765 kV (% MVA) as a function of phase shifting transformer angle settings**

### 5.3. Active Power System Losses

While performing the loadflow simulations, the power system losses were also recorded for the scenario when there is no phase shifting transformer used in the system and for the different angle setting of the phase shifting transformer. The results obtained are shown in Figure 14 below.

Figure 14 shows the change in the system active power losses as a function of the phase shifting transformer angle settings. The active power losses when there is no phase shifting transformer used in the transmission network is set at zero as it is the base case.

From the figure, it is observed that as the phase shifting transformer angle setting is increased active power system losses increase. When the phase shifting transformer angle is decreasing below 0°, losses are reduced. Levels equal to those of base case are reached at near -8°, and below this, saving in losses occur, with a reduction of 22 MW realised at -20°.

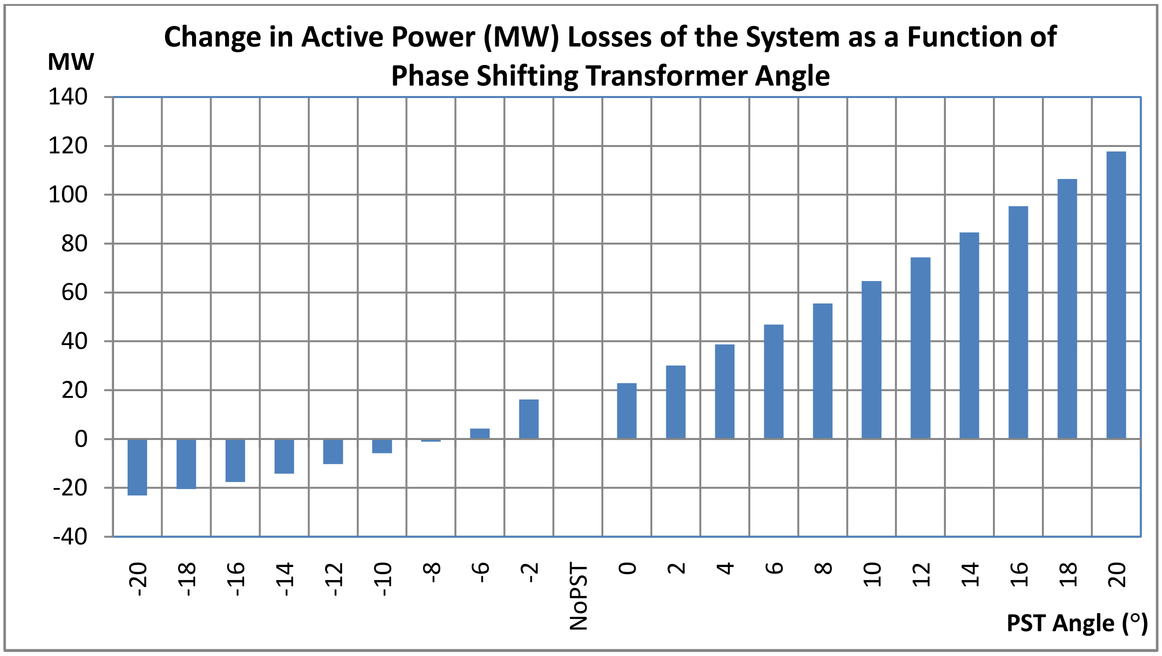

**Figure 14: Change in system active power losses as a function of the phase shifting transformer angle settings**

## 5.4. Voltage Stability Studies

In the simulation of voltage stability studies, the phase shifting transformer angle is manually changed and the voltage stability limits analysis performed by plotting the PV curves at each setting, for various contingencies, with the load increased at all areas being supplied by the study corridor.

The PV curves for 400 and 765 kV buses, before and after a phase shifting transformer is put in the system, are included in Appendix 4. The impact of varying the phase shifting transformer angle on of the voltage stability limit is shown in Figure 15.

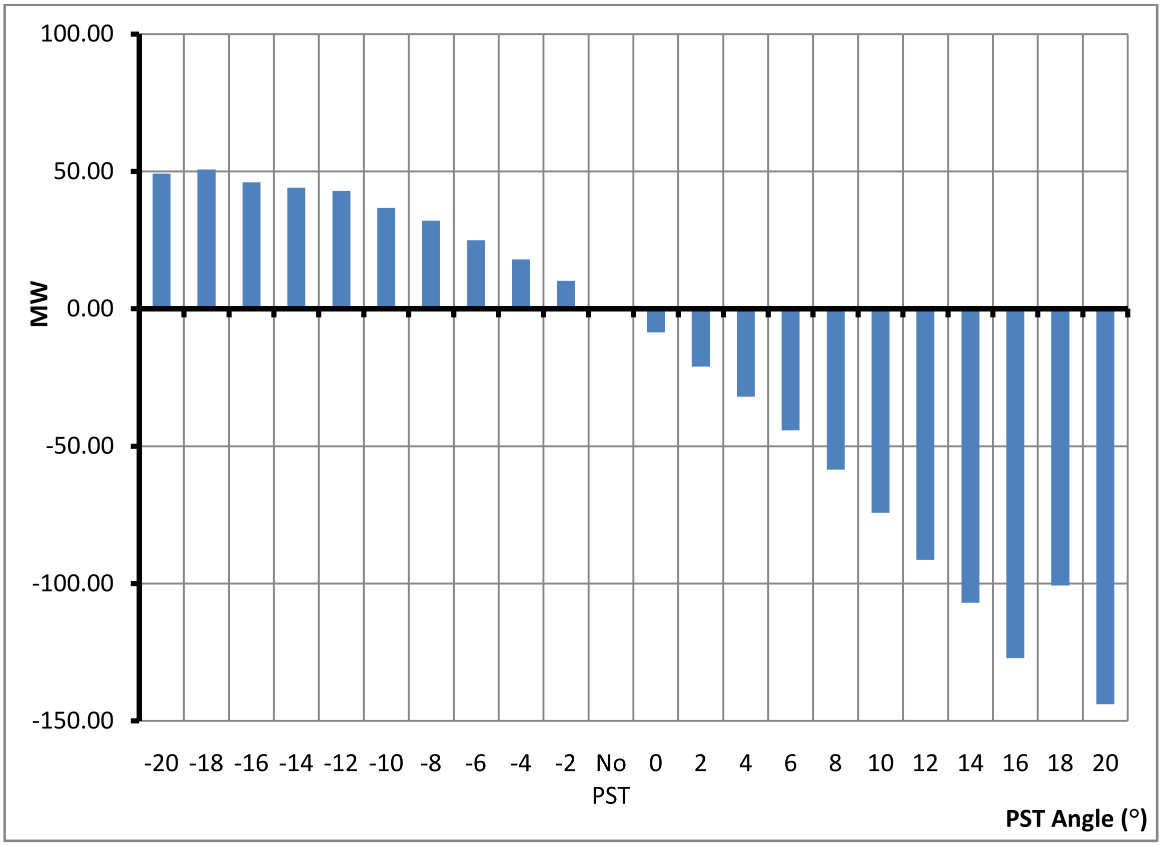

**Figure 15: Voltage Stability Limit as a Function of Phase Shifting Transformer Angle Settings**

The voltage stability results obtained shows the increase in voltage stability limits as the phase shifting transformer angle setting is changed progressively from zero to -20°. When the phase shifting transformer angle is increased from 0 through to +20°, the voltage stability limits obtained become progressively less than for the base case.

## 5.5. Conclusion

The results of the simulation studies performed on the power system network overlayed with higher voltage transmission have been presented in this chapter. The simulation studies performed entailed inserting the phase shifting transformer at the end of the corridor consisting of parallel 400 kV and 765 kV parallel transmission lines.

The aim of inserting the phase shifting transformer is to ensure substantial power transfer takes place in the higher voltage transmission, i.e., 765 kV transmission lines rather than in the 400 kV. The results of the impact of changes in the angle on active power losses have also been presented. The studies also investigated the influence of altering the phase shifting transformer angle on the voltage stability of the system.

The next chapter summarizes the purpose of the work carried out and draws the conclusions of the dissertation.

# Chapter 6: Conclusions and Recommendations

## 6.1. Conclusions

To recap briefly, this dissertation deals with low impedance networks that get expanded by building lines at a particular voltage to increase transfer capacity. At some point, the transfer capacity obtained by continuing to construct lines at the same voltage becomes less than satisfactory. This then leads to consideration of building additional lines at higher voltage as these have a higher transfer capability.

The problem that may arise in these situations is that the newer, higher voltage lines, although having better transfer capability, may be in parallel with a much stronger, lower voltage network. Power will then chose to flow in the lower voltage network, in the absence of any controls in the network, as dictated to by the network impedances. This may lead to inefficient utilisation of the power system.

The hypothesis put forward at the beginning of the study was that by using phase shifting transformers, it would be possible to introduce control of power in the network. Power flow control would be introduced, forcing more power on to the higher voltage lines, rather than permitting a natural power flow as dictated to by network impedances. This would yield improvement to the steady state and voltage stability performance of the system.

The work presented in this dissertation supports and proves the hypothesis. This dissertation has shown that a phase shifting transformer can be utilised to influence the power transfer through a network consisting of parallel corridors, one of lines at lower voltage, but low impedance (i.e., many lines in parallel), and another at higher voltage, but less mature (i.e., only a few lines in parallel). The following conclusions can further be drawn:

- By varying the phase shifting transformer, power flowing in the two parallel networks can be changed. At certain angles, less power will flow in the higher voltage lines, and power in this line can be increased at a certain range of phase shifting transformer angles.

- Similarly, varying the phase shifting transformer angle showed that active power system losses can be changed as the angle is varied. In some angle range, better saving in system losses can be realised, as opposed to other ranges.

- The results showed that the deployment of the phase shifting transformer does not produce significant changes in the power flows at low phase angles compared to when there is no phase shifting transformer installed in the system. This is because the introduction of the phase shifting transformer increases the impedance of the transmission system which is counteracted at higher phase shifting transformer angles.

- Finally, depending on the phase shifting transformer angle selected, a variation in the voltage stability limit of the network could be obtained. Similar to the second point, this is linked to the first point in terms of how power is distributed in the parallel networks described here. At certain phase shifting transformer angles, power flows are such that there will be better limits of voltage stability.

## 6.2. Recommendations

The study showed a ten percent increase in the utilisation of the 765 kV transmission lines and reduction in system losses by about 20 MW when the phase shifting transformer angle is at -20° compared to when there was no phase shifting transformer. The simulation results also showed an increase in the voltage stability of the transmission network by about 50 MW.

Despite the results in the improvement of the Eskom's power system network being insignificant compared to the overall system loading, an improvement of ten percent in the utilisation of a transmission system is considerable for this method to be explored further.

As the current work looked at the phase shifting transformers located at the end of the transmission corridor, further work could for instance be to investigate the optimum and more economic location of the phase shifting transformer to achieve better results.

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## Appendix 1: Python Program for Loadflow Simulations

Load flow program – No Phase shifting transformer

```
# File:"C:\MScEng\Loadflow.py", generated on SAT, OCT 08 2011  19:38, release 32.00.03

psspy.bsys(1,0,[0.0,0.0],0,[],5,[60,70,450,460,545],0,[],0,[])

psspy.lout(1,0)

psspy.bsys(1,0,[0.0,0.0],0,[],5,[60,70,450,460,545],0,[],0,[])

psspy.rate_2(0,0,1,1,1,1,0)
```

Load flow program – For different angles (-20-20) of phase shifting transformer

```
psspy.read (0, r"""c:\MScEng\Casefile.raw""")

psspy.report_output (2, r"""TEST_RESULTS""",[0,0])

for a in [-20,-19,-18,-17,-16,-15,-14,-13,-12,-11,-10,-9,-8,-7,-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20]:

print a

psspy.two_winding_data_3(545,90026,r"""2""",[_i,_i,_i,_i,_i,_i,_i,_i,_i,_i,1,_i,_i,_i,_i],[_f,_f,_f,_f,_f,a,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f],_s)

psspy.fdns ([0,0,0,1,1,0,-1,0])

psspy.bsys (1,0,[0.0,0.0],0,[],4,[60,70,450,460],0,[],0,[])

 psspy.lout (1,0)

 psspy.vchk (0,0,0.95,1.05)

 psspy.bsys (0,0,[220,765.],0,[],5,[70, 460, 545, 550,610],0,[],0,[])

 loss=psspy.systot ('LOSS')

 print ("'Active Power Losses in the form P+jQ are'")

 print loss

 psspy.bsys (1,0,[0.0,0.0],0,[],1,[545],0,[],0,[])

 psspy.list (1,0,21,0)
```

# Appendix 2: Loadflow Results

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| No phase shifting transformer | 60 | STIKL4 | 400 | 1.0027 | -90.5 | 150.5 | 1 | | 400 | -211.3 | -64.1 | 19 |
| | | | | 401.06 | | 31.5 | 459 | FGROVE4 | 400 | 55.6 | 53.2 | 6 |
| | | | | | | | 460 | MULDR4 | 400 | -340.3 | -126.1 | 31 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 172.7 | 52.7 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 172.7 | 52.7 | 36 |
| | 70 | OMEGA7 | 765 | 0.9978 | -84.6 | 0 | 58 | KAPPA7 | 765 | -1014 | -228 | 19 |
| | | | | 763.31 | | 0 | 90026 | OMEGA_D1 | 400 | 1014.3 | 228 | 52 |
| | 450 | KOEBG4 | 400 | 1.01 | -89.2 | 83.5 | 1 | | 400 | 211.7 | 35.3 | 18 |
| | | | | 404 | | 25 | 2 | | 400 | 548.1 | 169.6 | 48 |
| | | | | | | | 2 | | 400 | 581.5 | 177.2 | 51 |
| | | | | | | | 545 | OMEGA4 | 400 | -592.6 | -98.6 | 50 |
| | | | | | | | 610 | ANKERLI4 | 400 | -19.4 | -138.6 | 12 |
| | | | | | | | 610 | ANKERLI4 | 400 | -17.5 | -129.7 | 11 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 52.1 | 5 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52.5 | 5 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | -50.3 | 84 |
| | 460 | MULDR4 | 400 | 1.0074 | -89.9 | 220.3 | 60 | STIKL4 | 400 | 340.6 | 120.5 | 30 |
| | | | | 402.97 | | 58.5 | 455 | ACAC4 | 400 | 232.3 | 84.5 | 21 |
| | | | | | | | 465 | BACCH4 | 400 | -200.7 | -27.2 | 17 |
| | | | | | | | 545 | OMEGA4 | 400 | -420.2 | -64.1 | 36 |
| | | | | | | | 550 | KAPPA4 | 400 | -618.4 | -31.7 | 52 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 148 | 22.7 | 30 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 148 | 22.7 | 30 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | -209 | 4 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 150.1 | 23 | 30 |
| -20 | 60 | STIKL4 | 400 | 1.025 | -86.2 | 150.5 | 1 | | 400 | -316.6 | 154.6 | 29 |
| | | | | 410.01 | | 31.5 | 459 | FGROVE4 | 400 | 154.3 | 9.2 | 12 |
| | | | | | | | 460 | MULDR4 | 400 | -340.9 | -297.2 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 176.3 | 51 | 37 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 176.3 | 51 | 37 |
| | 70 | OMEGA7 | 765 | 0.9892 | -89.1 | 0 | 58 | KAPPA7 | 765 | -1685 | -220.6 | 31 |
| | | | | 756.72 | | 0 | 90026 | OMEGA_D1 | 400 | 1684.6 | 220.6 | 85 |
| | 450 | KOEBG4 | 400 | 1.01 | -84.2 | 83.5 | 1 | | 400 | 317.7 | -175.7 | 30 |
| | | | | 404 | | 25 | 2 | | 400 | 598.5 | 37.5 | 50 |
| | | | | | | | 2 | | 400 | 634.2 | 36.9 | 53 |
| | | | | | | | 545 | OMEGA4 | 400 | -927.2 | -194 | 79 |
| | | | | | | | 610 | ANKERLI4 | 400 | -42 | 1075.8 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -43.7 | 1004.4 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 53.6 | -0.5 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 54 | -0.5 | 22 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2351.5 | 235 |
| | 460 | MULDR4 | 400 | 1.035 | -85.6 | 220.3 | 60 | STIKL4 | 400 | 341.4 | 293.1 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 144.2 | 318.1 | 29 |
| | | | | | | | 465 | BACCH4 | 400 | -70.8 | -53.1 | 7 |
| | | | | | | | 545 | OMEGA4 | 400 | -752.6 | 423 | 71 |
| | | | | | | | 550 | KAPPA4 | 400 | -330.8 | -13.9 | 27 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 148.7 | 37.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 148.7 | 37.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1138.3 | 569 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 150.9 | 37.9 | 31 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -19 | 60 | STIKL4 | 400 | 1.025 | -86.4 | 150.5 | 1 | | 400 | -309.7 | 153.9 | 29 |
| | | | | 410.01 | | 31.5 | 459 | FGROVE4 | 400 | 148 | 9.7 | 12 |
| | | | | | | | 460 | MULDR4 | 400 | -341 | -297 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 176.1 | 50.9 | 37 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 176.1 | 50.9 | 37 |
| | 70 | OMEGA7 | 765 | 0.9912 | -88.8 | 0 | 58 | KAPPA7 | 765 | -1643 | -221.8 | 30 |
| | | | | 758.23 | | 0 | 90026 | OMEGA_D1 | 400 | 1643.3 | 221.8 | 83 |
| | 450 | KOEBG4 | 400 | 1.01 | -84.5 | 83.5 | 1 | | 400 | 310.8 | -175.5 | 30 |
| | | | | 404 | | 25 | 2 | | 400 | 594.9 | 37.6 | 50 |
| | | | | | | | 2 | | 400 | 630.5 | 37 | 53 |
| | | | | | | | 545 | OMEGA4 | 400 | -906.4 | -211.2 | 78 |
| | | | | | | | 610 | ANKERLI4 | 400 | -38.8 | 1075.5 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -40.7 | 1004.1 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 53.4 | -0.5 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 53.8 | -0.5 | 22 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2367.6 | 236 |
| | 460 | MULDR4 | 400 | 1.035 | -85.9 | 220.3 | 60 | STIKL4 | 400 | 341.5 | 292.9 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 150.1 | 317.6 | 29 |
| | | | | | | | 465 | BACCH4 | 400 | -79.2 | -52.6 | 8 |
| | | | | | | | 545 | OMEGA4 | 400 | -732.2 | 415.1 | 69 |
| | | | | | | | 550 | KAPPA4 | 400 | -349.1 | -14.8 | 29 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 148.8 | 37.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 148.8 | 37.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1129.3 | 565 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151 | 37.9 | 31 |
| -18 | 60 | STIKL4 | 400 | 1.025 | -86.7 | 150.5 | 1 | | 400 | -302.9 | 153.1 | 28 |
| | | | | 410.02 | | 31.5 | 459 | FGROVE4 | 400 | 141.6 | 10.3 | 11 |
| | | | | | | | 460 | MULDR4 | 400 | -341.1 | -296.8 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 175.9 | 50.9 | 37 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 175.9 | 50.9 | 37 |
| | 70 | OMEGA7 | 765 | 0.9931 | -88.5 | 0 | 58 | KAPPA7 | 765 | -1602 | -223 | 29 |
| | | | | 759.7 | | 0 | 90026 | OMEGA_D1 | 400 | 1601.7 | 223 | 81 |
| | 450 | KOEBG4 | 400 | 1.01 | -84.7 | 83.5 | 1 | | 400 | 303.9 | -175.2 | 29 |
| | | | | 404 | | 25 | 2 | | 400 | 591.4 | 37.7 | 50 |
| | | | | | | | 2 | | 400 | 626.7 | 37.2 | 53 |
| | | | | | | | 545 | OMEGA4 | 400 | -885.6 | -227.9 | 77 |
| | | | | | | | 610 | ANKERLI4 | 400 | -35.5 | 1075.2 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -37.7 | 1003.9 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 53.3 | -0.5 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 53.7 | -0.5 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2383.2 | 238 |
| | 460 | MULDR4 | 400 | 1.035 | -86.1 | 220.3 | 60 | STIKL4 | 400 | 341.6 | 292.7 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 156.1 | 317.1 | 29 |
| | | | | | | | 465 | BACCH4 | 400 | -87.6 | -52.1 | 8 |
| | | | | | | | 545 | OMEGA4 | 400 | -711.7 | 407.3 | 67 |
| | | | | | | | 550 | KAPPA4 | 400 | -367.6 | -15.4 | 30 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 148.9 | 37.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 148.9 | 37.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1120.8 | 560 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151 | 37.9 | 31 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -17 | 60 | STIKL4 | 400 | 1.025 | -86.9 | 150.5 | 1 | | 400 | -295.9 | 152.3 | 28 |
| | | | | 410.02 | | 31.5 | 459 | FGROVE4 | 400 | 135.2 | 11 | 11 |
| | | | | | | | 460 | MULDR4 | 400 | -341.2 | -296.7 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 175.7 | 50.9 | 37 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 175.7 | 50.9 | 37 |
| | 70 | OMEGA7 | 765 | 0.9949 | -88.2 | 0 | 58 | KAPPA7 | 765 | -1560 | -224.1 | 28 |
| | | | | 761.12 | | 0 | 90026 | OMEGA_D1 | 400 | 1559.9 | 224.1 | 79 |
| | 450 | KOEBG4 | 400 | 1.01 | -85 | 83.5 | 1 | | 400 | 297 | -174.9 | 29 |
| | | | | 404 | | 25 | 2 | | 400 | 587.8 | 37.8 | 49 |
| | | | | | | | 2 | | 400 | 622.8 | 37.3 | 52 |
| | | | | | | | 545 | OMEGA4 | 400 | -864.7 | -244 | 75 |
| | | | | | | | 610 | ANKERLI4 | 400 | -32.3 | 1075 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -34.7 | 1003.7 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 53.1 | -0.5 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 53.5 | -0.5 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2398.3 | 239 |
| | 460 | MULDR4 | 400 | 1.035 | -86.4 | 220.3 | 60 | STIKL4 | 400 | 341.7 | 292.6 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 162.1 | 316.7 | 29 |
| | | | | | | | 465 | BACCH4 | 400 | -96 | -51.4 | 9 |
| | | | | | | | 545 | OMEGA4 | 400 | -691 | 399.7 | 65 |
| | | | | | | | 550 | KAPPA4 | 400 | -386.1 | -15.7 | 32 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149 | 37.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149 | 37.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1113 | 556 |
| -16 | 60 | STIKL4 | 400 | 1.025 | -87.2 | 150.5 | 1 | | 400 | -289 | 151.5 | 27 |
| | | | | 410.02 | | 31.5 | 459 | FGROVE4 | 400 | 128.8 | 11.7 | 10 |
| | | | | | | | 460 | MULDR4 | 400 | -341.3 | -296.6 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 175.5 | 50.9 | 37 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 175.5 | 50.9 | 37 |
| | 70 | OMEGA7 | 765 | 0.9967 | -87.9 | 0 | 58 | KAPPA7 | 765 | -1518 | -225.2 | 28 |
| | | | | 762.5 | | 0 | 90026 | OMEGA_D1 | 400 | 1517.8 | 225.2 | 77 |
| | 450 | KOEBG4 | 400 | 1.01 | -85.3 | 83.5 | 1 | | 400 | 290 | -174.5 | 28 |
| | | | | 404 | | 25 | 2 | | 400 | 584.1 | 38 | 49 |
| | | | | | | | 2 | | 400 | 619 | 37.5 | 52 |
| | | | | | | | 545 | OMEGA4 | 400 | -843.6 | -259.7 | 74 |
| | | | | | | | 610 | ANKERLI4 | 400 | -29 | 1074.7 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -31.6 | 1003.4 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 53 | -0.5 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 53.4 | -0.5 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2412.8 | 240 |
| | 460 | MULDR4 | 400 | 1.035 | -86.6 | 220.3 | 60 | STIKL4 | 400 | 341.8 | 292.5 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 168.2 | 316.2 | 29 |
| | | | | | | | 465 | BACCH4 | 400 | -104.5 | -50.6 | 10 |
| | | | | | | | 545 | OMEGA4 | 400 | -670.2 | 392.3 | 64 |
| | | | | | | | 550 | KAPPA4 | 400 | -404.8 | -15.8 | 33 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.1 | 37.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.1 | 37.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1105.8 | 553 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.2 | 37.9 | 31 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -15 | 60 | STIKL4 | 400 | 1.025 | -87.4 | 150.5 | 1 | | 400 | -282 | 150.7 | 26 |
| | | | | 410.02 | | 31.5 | 459 | FGROVE4 | 400 | 122.4 | 12.5 | 10 |
| | | | | | | | 460 | MULDR4 | 400 | -341.3 | -296.6 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 175.2 | 50.9 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 175.2 | 50.9 | 36 |
| | 70 | OMEGA7 | 765 | 0.9985 | -87.6 | 0 | 58 | KAPPA7 | 765 | -1476 | -226.2 | 27 |
| | | | | 763.83 | | 0 | 90026 | OMEGA_D1 | 400 | 1475.5 | 226.2 | 75 |
| | 450 | KOEBG4 | 400 | 1.01 | -85.6 | 83.5 | 1 | | 400 | 282.9 | -174.2 | 28 |
| | | | | 404 | | 25 | 2 | | 400 | 580.5 | 38.1 | 49 |
| | | | | | | | 2 | | 400 | 615.1 | 37.7 | 52 |
| | | | | | | | 545 | OMEGA4 | 400 | -822.4 | -274.9 | 73 |
| | | | | | | | 610 | ANKERLI4 | 400 | -25.8 | 1074.4 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -28.6 | 1003.2 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 52.8 | -0.4 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 53.2 | -0.4 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2426.7 | 241 |
| | 460 | MULDR4 | 400 | 1.035 | -86.9 | 220.3 | 60 | STIKL4 | 400 | 341.8 | 292.5 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 174.2 | 315.7 | 30 |
| | | | | | | | 465 | BACCH4 | 400 | -113 | -49.8 | 10 |
| | | | | | | | 545 | OMEGA4 | 400 | -649.3 | 385.1 | 62 |
| | | | | | | | 550 | KAPPA4 | 400 | -423.6 | -15.7 | 35 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.1 | 37.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.1 | 37.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1099.1 | 550 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.3 | 38 | 31 |
| -14 | 60 | STIKL4 | 400 | 1.025 | -87.7 | 150.5 | 1 | | 400 | -275 | 149.9 | 26 |
| | | | | 410.02 | | 31.5 | 459 | FGROVE4 | 400 | 115.9 | 13.3 | 9 |
| | | | | | | | 460 | MULDR4 | 400 | -341.4 | -296.6 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 175 | 50.9 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 175 | 50.9 | 36 |
| | 70 | OMEGA7 | 765 | 1.0001 | -87.3 | 0 | 58 | KAPPA7 | 765 | -1433 | -227.2 | 26 |
| | | | | 765.11 | | 0 | 90026 | OMEGA_D1 | 400 | 1433 | 227.2 | 73 |
| | 450 | KOEBG4 | 400 | 1.01 | -85.9 | 83.5 | 1 | | 400 | 275.9 | -173.8 | 27 |
| | | | | 404 | | 25 | 2 | | 400 | 576.8 | 38.2 | 48 |
| | | | | | | | 2 | | 400 | 611.3 | 37.8 | 51 |
| | | | | | | | 545 | OMEGA4 | 400 | -801.1 | -289.5 | 71 |
| | | | | | | | 610 | ANKERLI4 | 400 | -22.5 | 1074.1 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -25.5 | 1002.9 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 52.7 | -0.4 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 53.1 | -0.4 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2440.2 | 243 |
| | 460 | MULDR4 | 400 | 1.035 | -87.1 | 220.3 | 60 | STIKL4 | 400 | 341.9 | 292.5 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 180.4 | 315.3 | 30 |
| | | | | | | | 465 | BACCH4 | 400 | -121.6 | -48.9 | 11 |
| | | | | | | | 545 | OMEGA4 | 400 | -628.2 | 378.1 | 60 |
| | | | | | | | 550 | KAPPA4 | 400 | -442.5 | -15.3 | 36 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.2 | 37.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.2 | 37.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1093 | 547 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.4 | 38 | 31 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -13 | 60 | STIKL4 | 400 | 1.025 | -88 | 150.5 | 1 | | 400 | -267.9 | 149.1 | 25 |
| | | | | 410.02 | | 31.5 | 459 | FGROVE4 | 400 | 109.3 | 14.2 | 9 |
| | | | | | | | 460 | MULDR4 | 400 | -341.5 | -296.7 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 174.8 | 50.9 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 174.8 | 50.9 | 36 |
| | 70 | OMEGA7 | 765 | 1.0018 | -87 | 0 | 58 | KAPPA7 | 765 | -1390 | -228.1 | 25 |
| | | | | 766.35 | | 0 | 90026 | OMEGA_D1 | 400 | 1390.2 | 228.1 | 70 |
| | 450 | KOEBG4 | 400 | 1.01 | -86.2 | 83.5 | 1 | | 400 | 268.8 | -173.4 | 27 |
| | | | | 404 | | 25 | 2 | | 400 | 573.2 | 38.4 | 48 |
| | | | | | | | 2 | | 400 | 607.4 | 38 | 51 |
| | | | | | | | 545 | OMEGA4 | 400 | -779.7 | -303.7 | 70 |
| | | | | | | | 610 | ANKERLI4 | 400 | -19.1 | 1073.9 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -22.4 | 1002.7 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 52.5 | -0.4 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52.9 | -0.4 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2453.1 | 244 |
| | 460 | MULDR4 | 400 | 1.035 | -87.4 | 220.3 | 60 | STIKL4 | 400 | 342 | 292.6 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 186.5 | 314.8 | 30 |
| | | | | | | | 465 | BACCH4 | 400 | -130.2 | -47.9 | 11 |
| | | | | | | | 545 | OMEGA4 | 400 | -607 | 371.2 | 58 |
| | | | | | | | 550 | KAPPA4 | 400 | -461.5 | -14.6 | 38 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.3 | 37.5 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.3 | 37.5 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1087.6 | 544 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.4 | 38 | 31 |
| -12 | 60 | STIKL4 | 400 | 1.025 | -88.2 | 150.5 | 1 | | 400 | -260.8 | 148.3 | 25 |
| | | | | 410.01 | | 31.5 | 459 | FGROVE4 | 400 | 102.8 | 15.2 | 8 |
| | | | | | | | 460 | MULDR4 | 400 | -341.6 | -296.8 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 174.5 | 50.9 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 174.5 | 50.9 | 36 |
| | 70 | OMEGA7 | 765 | 1.0033 | -86.7 | 0 | 58 | KAPPA7 | 765 | -1347 | -229 | 24 |
| | | | | 767.54 | | 0 | 90026 | OMEGA_D1 | 400 | 1347.2 | 229 | 68 |
| | 450 | KOEBG4 | 400 | 1.01 | -86.6 | 83.5 | 1 | | 400 | 261.6 | -173 | 26 |
| | | | | 404 | | 25 | 2 | | 400 | 569.5 | 38.5 | 48 |
| | | | | | | | 2 | | 400 | 603.5 | 38.2 | 51 |
| | | | | | | | 545 | OMEGA4 | 400 | -758.2 | -317.4 | 69 |
| | | | | | | | 610 | ANKERLI4 | 400 | -15.8 | 1073.6 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -19.3 | 1002.5 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 52.4 | -0.4 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52.7 | -0.4 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2465.4 | 245 |
| | 460 | MULDR4 | 400 | 1.035 | -87.7 | 220.3 | 60 | STIKL4 | 400 | 342.1 | 292.7 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 192.7 | 314.4 | 30 |
| | | | | | | | 465 | BACCH4 | 400 | -138.9 | -46.8 | 12 |
| | | | | | | | 545 | OMEGA4 | 400 | -585.8 | 364.6 | 56 |
| | | | | | | | 550 | KAPPA4 | 400 | -480.6 | -13.7 | 39 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.4 | 37.5 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.4 | 37.5 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1082.7 | 541 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.5 | 38 | 31 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -11 | 60 | STIKL4 | 400 | 1.025 | -88.5 | 150.5 | 1 | | 400 | -253.7 | 147.4 | 24 |
| | | | | 410.01 | | 31.5 | 459 | FGROVE4 | 400 | 96.2 | 16.2 | 8 |
| | | | | | | | 460 | MULDR4 | 400 | -341.7 | -297 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 174.3 | 50.9 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 174.3 | 50.9 | 36 |
| | 70 | OMEGA7 | 765 | 1.0048 | -86.4 | 0 | 58 | KAPPA7 | 765 | -1304 | -229.8 | 24 |
| | | | | 768.69 | | 0 | 90026 | OMEGA_D1 | 400 | 1304.1 | 229.8 | 66 |
| | 450 | KOEBG4 | 400 | 1.01 | -86.9 | 83.5 | 1 | | 400 | 254.5 | -172.5 | 26 |
| | | | | 404 | | 25 | 2 | | 400 | 565.8 | 38.7 | 48 |
| | | | | | | | 2 | | 400 | 599.5 | 38.4 | 50 |
| | | | | | | | 545 | OMEGA4 | 400 | -736.6 | -330.5 | 68 |
| | | | | | | | 610 | ANKERLI4 | 400 | -12.4 | 1073.3 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -16.1 | 1002.2 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 52.2 | -0.4 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52.6 | -0.4 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2477.2 | 246 |
| | 460 | MULDR4 | 400 | 1.035 | -88 | 220.3 | 60 | STIKL4 | 400 | 342.2 | 292.9 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 198.9 | 313.9 | 30 |
| | | | | | | | 465 | BACCH4 | 400 | -147.6 | -45.6 | 13 |
| | | | | | | | 545 | OMEGA4 | 400 | -564.4 | 358.1 | 55 |
| | | | | | | | 550 | KAPPA4 | 400 | -499.8 | -12.6 | 41 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.5 | 37.5 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.5 | 37.5 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1078.5 | 539 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.6 | 38.1 | 31 |
| -10 | 60 | STIKL4 | 400 | 1.025 | -88.8 | 150.5 | 1 | | 400 | -246.5 | 146.5 | 24 |
| | | | | 410.01 | | 31.5 | 459 | FGROVE4 | 400 | 89.6 | 17.3 | 7 |
| | | | | | | | 460 | MULDR4 | 400 | -341.7 | -297.3 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 174.1 | 51 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 174.1 | 51 | 36 |
| | 70 | OMEGA7 | 765 | 1.0063 | -86.1 | 0 | 58 | KAPPA7 | 765 | -1261 | -230.6 | 23 |
| | | | | 769.8 | | 0 | 90026 | OMEGA_D1 | 400 | 1260.8 | 230.6 | 64 |
| | 450 | KOEBG4 | 400 | 1.01 | -87.2 | 83.5 | 1 | | 400 | 247.3 | -172.1 | 25 |
| | | | | 404 | | 25 | 2 | | 400 | 562 | 38.8 | 47 |
| | | | | | | | 2 | | 400 | 595.6 | 38.5 | 50 |
| | | | | | | | 545 | OMEGA4 | 400 | -714.9 | -343.2 | 67 |
| | | | | | | | 610 | ANKERLI4 | 400 | -9.1 | 1073 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -13 | 1002 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 52.1 | -0.4 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52.4 | -0.4 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2488.5 | 247 |
| | 460 | MULDR4 | 400 | 1.035 | -88.2 | 220.3 | 60 | STIKL4 | 400 | 342.2 | 293.2 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 205.1 | 313.5 | 31 |
| | | | | | | | 465 | BACCH4 | 400 | -156.4 | -44.3 | 13 |
| | | | | | | | 545 | OMEGA4 | 400 | -542.9 | 351.9 | 53 |
| | | | | | | | 550 | KAPPA4 | 400 | -519.1 | -11.1 | 42 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.5 | 37.6 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.5 | 37.6 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1074.8 | 537 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.7 | 38.1 | 31 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -9 | 60 | STIKL4 | 400 | 1.025 | -89.1 | 150.5 | 1 | | 400 | -239.3 | 145.7 | 23 |
| | | | | 410.01 | | 31.5 | 459 | FGROVE4 | 400 | 82.9 | 18.5 | 7 |
| | | | | | | | 460 | MULDR4 | 400 | -341.8 | -297.6 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 173.8 | 51 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 173.8 | 51 | 36 |
| | 70 | OMEGA7 | 765 | 1.0077 | -85.9 | 0 | 58 | KAPPA7 | 765 | -1217 | -231.4 | 22 |
| | | | | 770.85 | | 0 | 90026 | OMEGA_D1 | 400 | 1217.2 | 231.4 | 62 |
| | 450 | KOEBG4 | 400 | 1.01 | -87.5 | 83.5 | 1 | | 400 | 240 | -171.6 | 25 |
| | | | | 404 | | 25 | 2 | | 400 | 558.3 | 39 | 47 |
| | | | | | | | 2 | | 400 | 591.6 | 38.7 | 50 |
| | | | | | | | 545 | OMEGA4 | 400 | -693.1 | -355.3 | 65 |
| | | | | | | | 610 | ANKERLI4 | 400 | -5.7 | 1072.7 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -9.8 | 1001.7 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 51.9 | -0.3 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52.3 | -0.3 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2499.3 | 248 |
| | 460 | MULDR4 | 400 | 1.035 | -88.5 | 220.3 | 60 | STIKL4 | 400 | 342.3 | 293.5 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 211.3 | 313 | 31 |
| | | | | | | | 465 | BACCH4 | 400 | -165.2 | -43 | 14 |
| | | | | | | | 545 | OMEGA4 | 400 | -521.3 | 345.8 | 51 |
| | | | | | | | 550 | KAPPA4 | 400 | -538.4 | -9.5 | 44 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.6 | 37.6 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.6 | 37.6 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1071.8 | 536 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.8 | 38.2 | 31 |
| -8 | 60 | STIKL4 | 400 | 1.025 | -89.3 | 150.5 | 1 | | 400 | -232.1 | 144.8 | 23 |
| | | | | 410 | | 31.5 | 459 | FGROVE4 | 400 | 76.2 | 19.7 | 6 |
| | | | | | | | 460 | MULDR4 | 400 | -341.9 | -297.9 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 173.6 | 51 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 173.6 | 51 | 36 |
| | 70 | OMEGA7 | 765 | 1.009 | -85.6 | 0 | 58 | KAPPA7 | 765 | -1174 | -232.1 | 21 |
| | | | | 771.87 | | 0 | 90026 | OMEGA_D1 | 400 | 1173.6 | 232.1 | 60 |
| | 450 | KOEBG4 | 400 | 1.01 | -87.8 | 83.5 | 1 | | 400 | 232.8 | -171.1 | 24 |
| | | | | 404 | | 25 | 2 | | 400 | 554.5 | 39.2 | 47 |
| | | | | | | | 2 | | 400 | 587.7 | 38.9 | 49 |
| | | | | | | | 545 | OMEGA4 | 400 | -671.3 | -367 | 64 |
| | | | | | | | 610 | ANKERLI4 | 400 | -2.3 | 1072.5 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -6.6 | 1001.5 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 51.8 | -0.3 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52.1 | -0.3 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2509.5 | 249 |
| | 460 | MULDR4 | 400 | 1.035 | -88.8 | 220.3 | 60 | STIKL4 | 400 | 342.4 | 293.8 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 217.6 | 312.6 | 31 |
| | | | | | | | 465 | BACCH4 | 400 | -174.1 | -41.5 | 15 |
| | | | | | | | 545 | OMEGA4 | 400 | -499.6 | 339.9 | 49 |
| | | | | | | | 550 | KAPPA4 | 400 | -557.8 | -7.5 | 46 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.7 | 37.7 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.7 | 37.7 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1069.3 | 535 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.9 | 38.2 | 31 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -7 | 60 | STIKL4 | 400 | 1.025 | -89.6 | 150.5 | 1 | | 400 | -224.9 | 143.9 | 22 |
| | | | | 410 | | 31.5 | 459 | FGROVE4 | 400 | 69.6 | 21 | 6 |
| | | | | | | | 460 | MULDR4 | 400 | -342 | -298.3 | 37 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 173.4 | 51 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 173.4 | 51 | 36 |
| | 70 | OMEGA7 | 765 | 1.0102 | -85.3 | 0 | 58 | KAPPA7 | 765 | -1130 | -232.8 | 21 |
| | | | | 772.84 | | 0 | 90026 | OMEGA_D1 | 400 | 1129.7 | 232.8 | 58 |
| | 450 | KOEBG4 | 400 | 1.01 | -88.2 | 83.5 | 1 | | 400 | 225.5 | -170.5 | 24 |
| | | | | 404 | | 25 | 2 | | 400 | 550.8 | 39.4 | 46 |
| | | | | | | | 2 | | 400 | 583.7 | 39.1 | 49 |
| | | | | | | | 545 | OMEGA4 | 400 | -649.4 | -378.2 | 63 |
| | | | | | | | 610 | ANKERLI4 | 400 | -1.1 - | 1072.2 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -3.4 | 1001.2 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 51.6 | -0.3 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 52 | -0.3 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2519.2 | 250 |
| | 460 | MULDR4 | 400 | 1.035 | -89.1 | 220.3 | 60 | STIKL4 | 400 | 342.5 | 294.2 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 223.9 | 312.2 | 31 |
| | | | | | | | 465 | BACCH4 | 400 | -182.9 | -40 | 15 |
| | | | | | | | 545 | OMEGA4 | 400 | -477.9 | 334.3 | 48 |
| | | | | | | | 550 | KAPPA4 | 400 | -577.3 | -5.4 | 47 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.8 | 37.7 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.8 | 37.7 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1067.5 | 534 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 151.9 | 38.3 | 31 |
| -6 | 60 | STIKL4 | 400 | 1.025 | -89.9 | 150.5 | 1 | | 400 | -217.6 | 142.9 | 22 |
| | | | | 409.99 | | 31.5 | 459 | FGROVE4 | 400 | 62.8 | 22.3 | 5 |
| | | | | | | | 460 | MULDR4 | 400 | -342 | -298.7 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 173.1 | 51 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 173.1 | 51 | 36 |
| | 70 | OMEGA7 | 765 | 1.0115 | -85.1 | 0 | 58 | KAPPA7 | 765 | -1086 | -233.4 | 20 |
| | | | | 773.77 | | 0 | 90026 | OMEGA_D1 | 400 | 1085.7 | 233.4 | 56 |
| | 450 | KOEBG4 | 400 | 1.01 | -88.5 | 83.5 | 1 | | 400 | 218.2 | -170 | 23 |
| | | | | 404 | | 25 | 2 | | 400 | 547 | 39.5 | 46 |
| | | | | | | | 2 | | 400 | 579.7 | 39.4 | 49 |
| | | | | | | | 545 | OMEGA4 | 400 | -627.4 | -388.8 | 62 |
| | | | | | | | 610 | ANKERLI4 | 400 | -4.6 - | 1071.9 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -0.2 | 1001 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 51.4 | -0.3 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 51.8 | -0.3 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2528.3 | 250 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 230.2 | 311.8 | 32 |
| | | | | | | | 465 | BACCH4 | 400 | -191.9 | -38.4 | 16 |
| | | | | | | | 545 | OMEGA4 | 400 | -456.1 | 328.8 | 46 |
| | | | | | | | 550 | KAPPA4 | 400 | -596.9 | -2.9 | 49 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 149.9 | 37.8 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 149.9 | 37.8 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1066.3 | 533 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152 | 38.3 | 31 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -5 | 60 | STIKL4 | 400 | 1.025 | -90.2 | 150.5 | 1 | | 400 | -210.3 | 142 | 21 |
| | | | | 409.98 | | 31.5 | 459 | FGROVE4 | 400 | 56.1 | 23.7 | 5 |
| | | | | | | | 460 | MULDR4 | 400 | -342.1 | -299.2 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 172.9 | 51 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 172.9 | 51 | 36 |
| | 70 | OMEGA7 | 765 | 1.0126 | -84.8 | 0 | 58 | KAPPA7 | 765 | -1042 | -233.9 | 19 |
| | | | | 774.65 | | 0 | 90026 | OMEGA_D1 | 400 | 1041.6 | 233.9 | 53 |
| | 450 | KOEBG4 | 400 | 1.01 | -88.9 | 83.5 | 1 | | 400 | 210.9 | -169.4 | 23 |
| | | | | 404 | | 25 | 2 | | 400 | 543.2 | 39.7 | 46 |
| | | | | | | | 2 | | 400 | 575.7 | 39.6 | 48 |
| | | | | | | | 545 | OMEGA4 | 400 | -605.3 | -398.9 | 61 |
| | | | | | | | 610 | ANKERLI4 | 400 | -8.0 - | 1071.6 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -3.0 - | 1000.7 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 51.3 | -0.3 | 21 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 51.7 | -0.3 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -899.9 | 2537 | 251 |
| | 460 | MULDR4 | 400 | 1.035 | -89.7 | 220.3 | 60 | STIKL4 | 400 | 342.6 | 295.2 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 236.5 | 311.3 | 32 |
| | | | | | | | 465 | BACCH4 | 400 | -200.8 | -36.7 | 17 |
| | | | | | | | 545 | OMEGA4 | 400 | -434.1 | 323.5 | 44 |
| | | | | | | | 550 | KAPPA4 | 400 | -616.5 | -0.2 | 50 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150 | 37.8 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150 | 37.8 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1065.7 | 533 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.1 | 38.4 | 31 |
| -4 | 60 | STIKL4 | 400 | 1.0249 | -90.5 | 150.5 | 1 | | 400 | -203 | 141.1 | 20 |
| | | | | 409.98 | | 31.5 | 459 | FGROVE4 | 400 | 49.3 | 25.1 | 4 |
| | | | | | | | 460 | MULDR4 | 400 | -342.2 | -299.8 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 172.7 | 51 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 172.7 | 51 | 36 |
| | 70 | OMEGA7 | 765 | 1.0137 | -84.5 | 0 | 58 | KAPPA7 | 765 | -997.4 | -234.4 | 18 |
| | | | | 775.48 | | 0 | 90026 | OMEGA_D1 | 400 | 997.4 | 234.4 | 51 |
| | 450 | KOEBG4 | 400 | 1.01 | -89.2 | 83.5 | 1 | | 400 | 203.6 | -168.8 | 22 |
| | | | | 404 | | 25 | 2 | | 400 | 539.4 | 39.9 | 45 |
| | | | | | | | 2 | | 400 | 571.7 | 39.8 | 48 |
| | | | | | | | 545 | OMEGA4 | 400 | -583.2 | -408.6 | 60 |
| | | | | | | | 610 | ANKERLI4 | 400 | -11.5 - | 1071.3 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -6.2 - | 1000.4 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 51.1 | -0.3 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 51.5 | -0.3 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2545.1 | 252 |
| | 460 | MULDR4 | 400 | 1.035 | -90 | 220.3 | 60 | STIKL4 | 400 | 342.7 | 295.8 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 242.9 | 310.9 | 32 |
| | | | | | | | 465 | BACCH4 | 400 | -209.8 | -34.9 | 17 |
| | | | | | | | 545 | OMEGA4 | 400 | -412.2 | 318.4 | 43 |
| | | | | | | | 550 | KAPPA4 | 400 | -636.2 | 2.7 | 52 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150 | 37.9 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150 | 37.9 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1065.7 | 533 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.2 | 38.4 | 31 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -3 | 60 | STIKL4 | 400 | 1.0249 | -90.8 | 150.5 | 1 | | 400 | -195.7 | 140.1 | 20 |
| | | | | 409.97 | | 31.5 | 459 | FGROVE4 | 400 | 42.5 | 26.7 | 4 |
| | | | | | | | 460 | MULDR4 | 400 | -342.2 | -300.4 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 172.4 | 51.1 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 172.4 | 51.1 | 36 |
| | 70 | OMEGA7 | 765 | 1.0147 | -84.3 | 0 | 58 | KAPPA7 | 765 | -953 | -234.9 | 17 |
| | | | | 776.28 | | 0 | 90026 | OMEGA_D1 | 400 | 953 | 234.9 | 49 |
| | 450 | KOEBG4 | 400 | 1.01 | -89.6 | 83.5 | 1 | | 400 | 196.2 | -168.2 | 22 |
| | | | | 404 | | 25 | 2 | | 400 | 535.6 | 40.1 | 45 |
| | | | | | | | 2 | | 400 | 567.6 | 40 | 48 |
| | | | | | | | 545 | OMEGA4 | 400 | -561 | -417.8 | 59 |
| | | | | | | | 610 | ANKERLI4 | 400 | -14.9 - | 1071 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -9.4 - | 1000.2 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 51 | -0.2 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 51.3 | -0.2 | 21 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2552.6 | 252 |
| | 460 | MULDR4 | 400 | 1.035 | -90.3 | 220.3 | 60 | STIKL4 | 400 | 342.8 | 296.4 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 249.3 | 310.5 | 33 |
| | | | | | | | 465 | BACCH4 | 400 | -218.8 | -33 | 18 |
| | | | | | | | 545 | OMEGA4 | 400 | -390.1 | 313.5 | 41 |
| | | | | | | | 550 | KAPPA4 | 400 | -655.9 | 6 | 54 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.1 | 38 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.1 | 38 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1066.4 | 533 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.3 | 38.5 | 31 |
| -2 | 60 | STIKL4 | 400 | 1.0249 | -91.1 | 150.5 | 1 | | 400 | -188.3 | 139.1 | 19 |
| | | | | 409.96 | | 31.5 | 459 | FGROVE4 | 400 | 35.7 | 28.2 | 4 |
| | | | | | | | 460 | MULDR4 | 400 | -342.3 | -301.1 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 172.2 | 51.1 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 172.2 | 51.1 | 36 |
| | 70 | OMEGA7 | 765 | 1.0157 | -84 | 0 | 58 | KAPPA7 | 765 | -908.6 | -235.3 | 17 |
| | | | | 777.03 | | 0 | 90026 | OMEGA_D1 | 400 | 908.6 | 235.3 | 47 |
| | 450 | KOEBG4 | 400 | 1.01 | -89.9 | 83.5 | 1 | | 400 | 188.9 | -167.6 | 21 |
| | | | | 404 | | 25 | 2 | | 400 | 531.8 | 40.3 | 45 |
| | | | | | | | 2 | | 400 | 563.6 | 40.2 | 47 |
| | | | | | | | 545 | OMEGA4 | 400 | -538.7 | -426.4 | 58 |
| | | | | | | | 610 | ANKERLI4 | 400 | -18.4 - | 1070.7 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -12.7 | -999.9 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 50.8 | -0.2 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 51.2 | -0.2 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2559.6 | 253 |
| | 460 | MULDR4 | 400 | 1.035 | -90.6 | 220.3 | 60 | STIKL4 | 400 | 342.8 | 297.1 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 255.6 | 310.1 | 33 |
| | | | | | | | 465 | BACCH4 | 400 | -227.8 | -31 | 19 |
| | | | | | | | 545 | OMEGA4 | 400 | -368 | 308.8 | 39 |
| | | | | | | | 550 | KAPPA4 | 400 | -675.7 | 9.4 | 55 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.2 | 38 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.2 | 38 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1067.6 | 534 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.4 | 38.6 | 31 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| -1 | 60 | STIKL4 | 400 | 1.0249 | -91.5 | 150.5 | 1 | | 400 | -181 | 138.2 | 19 |
| | | | | 409.95 | | 31.5 | 459 | FGROVE4 | 400 | 28.9 | 29.9 | 3 |
| | | | | | | | 460 | MULDR4 | 400 | -342.4 | -301.8 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 172 | 51.1 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 172 | 51.1 | 36 |
| | 70 | OMEGA7 | 765 | 1.0167 | -83.8 | 0 | 58 | KAPPA7 | 765 | -864 | -235.6 | 16 |
| | | | | 777.74 | | 0 | 90026 | OMEGA_D1 | 400 | 864 | 235.6 | 45 |
| | 450 | KOEBG4 | 400 | 1.01 | -90.3 | 83.5 | 1 | | 400 | 181.5 | -166.9 | 21 |
| | | | | 404 | | 25 | 2 | | 400 | 528 | 40.5 | 44 |
| | | | | | | | 2 | | 400 | 559.6 | 40.5 | 47 |
| | | | | | | | 545 | OMEGA4 | 400 | -516.4 | -434.6 | 57 |
| | | | | | | | 610 | ANKERLI4 | 400 | -21.9 - | 1070.4 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -15.9 | -999.7 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 50.7 | -0.2 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 51 | -0.2 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2566.1 | 254 |
| | 460 | MULDR4 | 400 | 1.035 | -90.9 | 220.3 | 60 | STIKL4 | 400 | 342.9 | 297.8 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 262 | 309.7 | 33 |
| | | | | | | | 465 | BACCH4 | 400 | -236.9 | -28.9 | 20 |
| | | | | | | | 545 | OMEGA4 | 400 | -345.9 | 304.3 | 38 |
| | | | | | | | 550 | KAPPA4 | 400 | -695.5 | 13.2 | 57 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.3 | 38.1 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.3 | 38.1 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1069.5 | 535 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.5 | 38.7 | 31 |
| 0 | 60 | STIKL4 | 400 | 1.0249 | -91.8 | 150.5 | 1 | | 400 | -173.6 | 137.2 | 18 |
| | | | | 409.94 | | 31.5 | 459 | FGROVE4 | 400 | 22.1 | 31.6 | 3 |
| | | | | | | | 460 | MULDR4 | 400 | -342.4 | -302.6 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 171.7 | 51.1 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 171.7 | 51.1 | 36 |
| | 70 | OMEGA7 | 765 | 1.0175 | -83.5 | 0 | 58 | KAPPA7 | 765 | -819.4 | -235.9 | 15 |
| | | | | 778.4 | | 0 | 90026 | OMEGA_D1 | 400 | 819.4 | 235.9 | 43 |
| | 450 | KOEBG4 | 400 | 1.01 | -90.6 | 83.5 | 1 | | 400 | 174.1 | -166.2 | 20 |
| | | | | 404 | | 25 | 2 | | 400 | 524.2 | 40.7 | 44 |
| | | | | | | | 2 | | 400 | 555.5 | 40.7 | 47 |
| | | | | | | | 545 | OMEGA4 | 400 | -494.1 | -442.2 | 56 |
| | | | | | | | 610 | ANKERLI4 | 400 | -25.4 - | 1070.1 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -19.2 | -999.4 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 50.5 | -0.2 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 50.9 | -0.2 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2572 | 254 |
| | 460 | MULDR4 | 400 | 1.035 | -91.2 | 220.3 | 60 | STIKL4 | 400 | 343 | 298.6 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 268.4 | 309.3 | 34 |
| | | | | | | | 465 | BACCH4 | 400 | -245.9 | -26.7 | 20 |
| | | | | | | | 545 | OMEGA4 | 400 | -323.7 | 300 | 36 |
| | | | | | | | 550 | KAPPA4 | 400 | -715.4 | 17.1 | 59 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.4 | 38.2 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.4 | 38.2 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1072 | 536 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.5 | 38.8 | 31 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 1 | 60 | STIKL4 | 400 | 1.0248 | -92.1 | 150.5 | 1 | | 400 | -166.2 | 136.2 | 18 |
| | | | | 409.93 | | 31.5 | 459 | FGROVE4 | 400 | 15.3 | 33.4 | 3 |
| | | | | | | | 460 | MULDR4 | 400 | -342.5 | -303.4 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 171.5 | 51.2 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 171.5 | 51.2 | 36 |
| | 70 | OMEGA7 | 765 | 1.0183 | -83.3 | 0 | 58 | KAPPA7 | 765 | -774.6 | -236.2 | 14 |
| | | | | 779.02 | | 0 | 90026 | OMEGA_D1 | 400 | 774.6 | 236.2 | 40 |
| | 450 | KOEBG4 | 400 | 1.01 | -91 | 83.5 | 1 | | 400 | 166.7 | -165.5 | 20 |
| | | | | 404 | | 25 | 2 | | 400 | 520.4 | 40.9 | 44 |
| | | | | | | | 2 | | 400 | 551.5 | 41 | 46 |
| | | | | | | | 545 | OMEGA4 | 400 | -471.7 | -449.4 | 55 |
| | | | | | | | 610 | ANKERLI4 | 400 | -28.9 - | 1069.8 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -22.5 | -999.1 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 50.3 | -0.2 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 50.7 | -0.2 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2577.4 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -91.5 | 220.3 | 60 | STIKL4 | 400 | 343 | 299.4 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 274.8 | 308.9 | 34 |
| | | | | | | | 465 | BACCH4 | 400 | -255 | -24.5 | 21 |
| | | | | | | | 545 | OMEGA4 | 400 | -301.4 | 295.9 | 35 |
| | | | | | | | 550 | KAPPA4 | 400 | -735.3 | 21.4 | 60 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.5 | 38.3 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.5 | 38.3 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1075.1 | 538 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.6 | 38.9 | 32 |
| 2 | 60 | STIKL4 | 400 | 1.0248 | -92.4 | 150.5 | 1 | | 400 | -158.8 | 135.2 | 17 |
| | | | | 409.92 | | 31.5 | 459 | FGROVE4 | 400 | 8.4 | 35.2 | 3 |
| | | | | | | | 460 | MULDR4 | 400 | -342.6 | -304.3 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 171.2 | 51.2 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 171.2 | 51.2 | 36 |
| | 70 | OMEGA7 | 765 | 1.0191 | -83.1 | 0 | 58 | KAPPA7 | 765 | -729.9 | -236.4 | 14 |
| | | | | 779.6 | | 0 | 90026 | OMEGA_D1 | 400 | 729.9 | 236.4 | 38 |
| | 450 | KOEBG4 | 400 | 1.01 | -91.4 | 83.5 | 1 | | 400 | 159.3 | -164.8 | 19 |
| | | | | 404 | | 25 | 2 | | 400 | 516.5 | 41.1 | 43 |
| | | | | | | | 2 | | 400 | 547.4 | 41.2 | 46 |
| | | | | | | | 545 | OMEGA4 | 400 | -449.3 | -456.1 | 54 |
| | | | | | | | 610 | ANKERLI4 | 400 | -32.4 - | 1069.5 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -25.8 | -998.9 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 50.2 | -0.1 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 50.5 | -0.1 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2582.3 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -91.9 | 220.3 | 60 | STIKL4 | 400 | 343.1 | 300.3 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 281.3 | 308.5 | 34 |
| | | | | | | | 465 | BACCH4 | 400 | -264.2 | -22.1 | 22 |
| | | | | | | | 545 | OMEGA4 | 400 | -279.1 | 292 | 33 |
| | | | | | | | 550 | KAPPA4 | 400 | -755.2 | 25.9 | 62 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.6 | 38.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.6 | 38.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1078.8 | 539 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.7 | 39 | 32 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 3 | 60 | STIKL4 | 400 | 1.0248 | -92.7 | 150.5 | 1 | | 400 | -151.4 | 134.1 | 17 |
| | | | | 409.91 | | 31.5 | 459 | FGROVE4 | 400 | 1.6 | 37.1 | 3 |
| | | | | | | | 460 | MULDR4 | 400 | -342.6 | -305.2 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 171 | 51.2 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 171 | 51.2 | 36 |
| | 70 | OMEGA7 | 765 | 1.0198 | -82.8 | 0 | 58 | KAPPA7 | 765 | -685 | -236.5 | 13 |
| | | | | 780.14 | | 0 | 90026 | OMEGA_D1 | 400 | 685 | 236.5 | 36 |
| | 450 | KOEBG4 | 400 | 1.01 | -91.7 | 83.5 | 1 | | 400 | 151.8 | -164 | 19 |
| | | | | 404 | | 25 | 2 | | 400 | 512.7 | 41.3 | 43 |
| | | | | | | | 2 | | 400 | 543.4 | 41.5 | 46 |
| | | | | | | | 545 | OMEGA4 | 400 | -426.9 | -462.2 | 53 |
| | | | | | | | 610 | ANKERLI4 | 400 | -35.9 - | 1069.2 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -29 | -998.6 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 50 | -0.1 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 50.4 | -0.1 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900.1 | 2586.5 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -92.2 | 220.3 | 60 | STIKL4 | 400 | 343.1 | 301.3 | 37 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 287.7 | 308.1 | 34 |
| | | | | | | | 465 | BACCH4 | 400 | -273.3 | -19.7 | 22 |
| | | | | | | | 545 | OMEGA4 | 400 | -256.8 | 288.3 | 32 |
| | | | | | | | 550 | KAPPA4 | 400 | -775.1 | 30.7 | 63 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.6 | 38.5 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.6 | 38.5 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1083.2 | 542 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.8 | 39.1 | 32 |
| 4 | 60 | STIKL4 | 400 | 1.0246 | -93.2 | 150.5 | 1 | | 400 | -144.7 | 131.9 | 16 |
| | | | | 409.84 | | 31.5 | 459 | FGROVE4 | 400 | -4.9 | 44.2 | 4 |
| | | | | | | | 460 | MULDR4 | 400 | -342.4 | -310.6 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 170.8 | 51.5 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 170.8 | 51.5 | 36 |
| | 70 | OMEGA7 | 765 | 1.0177 | -82.7 | 0 | 58 | KAPPA7 | 765 | -641.9 | -218.3 | 12 |
| | | | | 778.53 | | 0 | 90026 | OMEGA_D1 | 400 | 641.9 | 218.3 | 34 |
| | 450 | KOEBG4 | 400 | 1.01 | -92.2 | 83.5 | 1 | | 400 | 145.1 | -162 | 18 |
| | | | | 404 | | 25 | 2 | | 400 | 509.3 | 41.7 | 43 |
| | | | | | | | 2 | | 400 | 539.7 | 41.8 | 45 |
| | | | | | | | 545 | OMEGA4 | 400 | -404.7 | -454.9 | 51 |
| | | | | | | | 610 | ANKERLI4 | 400 | -40.2 - | 1068.9 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -33 | -998.3 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 49.9 | -0.1 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 50.2 | -0.1 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2575.9 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -92.6 | 220.3 | 60 | STIKL4 | 400 | 343 | 306.7 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 293.5 | 307.9 | 35 |
| | | | | | | | 465 | BACCH4 | 400 | -282.2 | -9.6 | 23 |
| | | | | | | | 545 | OMEGA4 | 400 | -236 | 289.5 | 31 |
| | | | | | | | 550 | KAPPA4 | 400 | -792.9 | 61.9 | 65 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.7 | 39 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.7 | 39 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1132.3 | 566 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 152.9 | 39.5 | 32 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 5 | 60 | STIKL4 | 400 | 1.0246 | -93.5 | 150.5 | 1 | | 400 | -137.4 | 130.8 | 16 |
| | | | | 409.83 | | 31.5 | 459 | FGROVE4 | 400 | -11.7 | 46.3 | 4 |
| | | | | | | | 460 | MULDR4 | 400 | -342.5 | -311.6 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 170.5 | 51.5 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 170.5 | 51.5 | 36 |
| | 70 | OMEGA7 | 765 | 1.0183 | -82.4 | 0 | 58 | KAPPA7 | 765 | -597.2 | -218.4 | 11 |
| | | | | 778.99 | | 0 | 90026 | OMEGA_D1 | 400 | 597.2 | 218.4 | 32 |
| | 450 | KOEBG4 | 400 | 1.01 | -92.6 | 83.5 | 1 | | 400 | 137.7 | -161.3 | 18 |
| | | | | 404 | | 25 | 2 | | 400 | 505.5 | 41.9 | 43 |
| | | | | | | | 2 | | 400 | 535.7 | 42.1 | 45 |
| | | | | | | | 545 | OMEGA4 | 400 | -382.3 | -460.1 | 50 |
| | | | | | | | 610 | ANKERLI4 | 400 | -43.7 - | 1068.6 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -36.3 | -998 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 49.7 | -0.1 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 50.1 | -0.1 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2579.1 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -93 | 220.3 | 60 | STIKL4 | 400 | 343 | 307.8 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 299.9 | 307.5 | 35 |
| | | | | | | | 465 | BACCH4 | 400 | -291.3 | -7 | 24 |
| | | | | | | | 545 | OMEGA4 | 400 | -213.7 | 286.2 | 29 |
| | | | | | | | 550 | KAPPA4 | 400 | -812.8 | 67.2 | 67 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.8 | 39.1 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.8 | 39.1 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1137.9 | 569 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153 | 39.6 | 32 |
| 6 | 60 | STIKL4 | 400 | 1.0245 | -93.8 | 150.5 | 1 | | 400 | -130 | 129.8 | 15 |
| | | | | 409.81 | | 31.5 | 459 | FGROVE4 | 400 | -18.6 | 48.3 | 4 |
| | | | | | | | 460 | MULDR4 | 400 | -342.5 | -312.7 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 170.3 | 51.5 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 170.3 | 51.5 | 36 |
| | 70 | OMEGA7 | 765 | 1.0188 | -82.2 | 0 | 58 | KAPPA7 | 765 | -552.4 | -218.3 | 10 |
| | | | | 779.4 | | 0 | 90026 | OMEGA_D1 | 400 | 552.4 | 218.3 | 30 |
| | 450 | KOEBG4 | 400 | 1.01 | -93 | 83.5 | 1 | | 400 | 130.3 | -160.4 | 17 |
| | | | | 404 | | 25 | 2 | | 400 | 501.7 | 42.1 | 42 |
| | | | | | | | 2 | | 400 | 531.7 | 42.3 | 45 |
| | | | | | | | 545 | OMEGA4 | 400 | -359.8 | -464.8 | 49 |
| | | | | | | | 610 | ANKERLI4 | 400 | -47.2 - | 1068.3 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -39.6 | -997.8 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 49.6 | 0 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 49.9 | 0 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2581.9 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -93.3 | 220.3 | 60 | STIKL4 | 400 | 343.1 | 308.9 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 306.3 | 307.1 | 35 |
| | | | | | | | 465 | BACCH4 | 400 | -300.4 | -4.3 | 25 |
| | | | | | | | 545 | OMEGA4 | 400 | -191.5 | 283 | 28 |
| | | | | | | | 550 | KAPPA4 | 400 | -832.7 | 72.7 | 68 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 150.9 | 39.2 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 150.9 | 39.2 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1144.1 | 572 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.1 | 39.7 | 32 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 7 | 60 | STIKL4 | 400 | 1.0245 | -94.2 | 150.5 | 1 | | 400 | -122.6 | 128.7 | 15 |
| | | | | 409.8 | | 31.5 | 459 | FGROVE4 | 400 | -25.5 | 50.5 | 4 |
| | | | | | | | 460 | MULDR4 | 400 | -342.6 | -313.9 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 170 | 51.6 | 36 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 170 | 51.6 | 36 |
| | 70 | OMEGA7 | 765 | 1.0193 | -82 | 0 | 58 | KAPPA7 | 765 | -507.6 | -218.3 | 10 |
| | | | | 779.76 | | 0 | 90026 | OMEGA_D1 | 400 | 507.6 | 218.3 | 28 |
| | 450 | KOEBG4 | 400 | 1.01 | -93.4 | 83.5 | 1 | | 400 | 122.9 | -159.6 | 17 |
| | | | | 404 | | 25 | 2 | | 400 | 497.8 | 42.4 | 42 |
| | | | | | | | 2 | | 400 | 527.6 | 42.6 | 44 |
| | | | | | | | 545 | OMEGA4 | 400 | -337.4 | -469.1 | 48 |
| | | | | | | | 610 | ANKERLI4 | 400 | -50.7 - | 1068 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -42.9 | -997.5 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 49.4 | 0 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 49.8 | 0 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2584.3 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -93.6 | 220.3 | 60 | STIKL4 | 400 | 343.1 | 310.1 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 312.7 | 306.8 | 36 |
| | | | | | | | 465 | BACCH4 | 400 | -309.6 | -1.5 | 25 |
| | | | | | | | 545 | OMEGA4 | 400 | -169.1 | 280.1 | 27 |
| | | | | | | | 550 | KAPPA4 | 400 | -852.6 | 78.5 | 70 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151 | 39.3 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151 | 39.3 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1150.9 | 575 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.2 | 39.9 | 32 |
| 8 | 60 | STIKL4 | 400 | 1.0245 | -94.5 | 150.5 | 1 | | 400 | -115.2 | 127.7 | 14 |
| | | | | 409.78 | | 31.5 | 459 | FGROVE4 | 400 | -32.3 | 52.7 | 5 |
| | | | | | | | 460 | MULDR4 | 400 | -342.6 | -315.1 | 38 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 169.8 | 51.6 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 169.8 | 51.6 | 35 |
| | 70 | OMEGA7 | 765 | 1.0197 | -81.8 | 0 | 58 | KAPPA7 | 765 | -462.8 | -218.1 | 9 |
| | | | | 780.09 | | 0 | 90026 | OMEGA_D1 | 400 | 462.8 | 218.1 | 26 |
| | 450 | KOEBG4 | 400 | 1.01 | -93.8 | 83.5 | 1 | | 400 | 115.5 | -158.7 | 16 |
| | | | | 404 | | 25 | 2 | | 400 | 494 | 42.6 | 42 |
| | | | | | | | 2 | | 400 | 523.6 | 42.9 | 44 |
| | | | | | | | 545 | OMEGA4 | 400 | -315 | -472.8 | 48 |
| | | | | | | | 610 | ANKERLI4 | 400 | -54.3 - | 1067.7 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -46.2 | -997.2 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 49.3 | 0 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 49.6 | 0 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2586.1 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -94 | 220.3 | 60 | STIKL4 | 400 | 343.2 | 311.4 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 319.2 | 306.4 | 36 |
| | | | | | | | 465 | BACCH4 | 400 | -318.8 | 1.4 | 26 |
| | | | | | | | 545 | OMEGA4 | 400 | -146.8 | 277.4 | 26 |
| | | | | | | | 550 | KAPPA4 | 400 | -872.4 | 84.6 | 72 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.1 | 39.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.1 | 39.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1158.4 | 579 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.3 | 40 | 32 |

| **LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 9 | 60 | STIKL4 | 400 | 1.0244 | -94.9 | 150.5 | 1 | | 400 | -107.8 | 126.6 | 14 |
| | | | | 409.77 | | 31.5 | 459 | FGROVE4 | 400 | -39.2 | 54.9 | 5 |
| | | | | | | | 460 | MULDR4 | 400 | -342.7 | -316.3 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 169.6 | 51.7 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 169.6 | 51.7 | 35 |
| | 70 | OMEGA7 | 765 | 1.0201 | -81.5 | 0 | 58 | KAPPA7 | 765 | -418 | -218 | 8 |
| | | | | 780.38 | | 0 | 90026 | OMEGA_D1 | 400 | 418 | 218 | 24 |
| | 450 | KOEBG4 | 400 | 1.01 | -94.2 | 83.5 | 1 | | 400 | 108.1 | -157.9 | 16 |
| | | | | 404 | | 25 | 2 | | 400 | 490.2 | 42.8 | 41 |
| | | | | | | | 2 | | 400 | 519.5 | 43.2 | 44 |
| | | | | | | | 545 | OMEGA4 | 400 | -292.6 | -476.1 | 47 |
| | | | | | | | 610 | ANKERLI4 | 400 | -57.8 - | 1067.4 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -49.5 | -997 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 49.1 | 0 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 49.5 | 0 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2587.3 | 256 |
| | 460 | MULDR4 | 400 | 1.035 | -94.3 | 220.3 | 60 | STIKL4 | 400 | 343.2 | 312.7 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 325.6 | 306.1 | 37 |
| | | | | | | | 465 | BACCH4 | 400 | -327.9 | 4.3 | 27 |
| | | | | | | | 545 | OMEGA4 | 400 | -124.5 | 274.8 | 25 |
| | | | | | | | 550 | KAPPA4 | 400 | -892.3 | 90.9 | 73 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.2 | 39.5 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.2 | 39.5 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1166.4 | 583 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.4 | 40.1 | 32 |
| 10 | 60 | STIKL4 | 400 | 1.0244 | -95.2 | 150.5 | 1 | | 400 | -100.4 | 125.5 | 13 |
| | | | | 409.75 | | 31.5 | 459 | FGROVE4 | 400 | -46.1 | 57.2 | 6 |
| | | | | | | | 460 | MULDR4 | 400 | -342.7 | -317.7 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 169.3 | 51.7 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 169.3 | 51.7 | 35 |
| | 70 | OMEGA7 | 765 | 1.0204 | -81.3 | 0 | 58 | KAPPA7 | 765 | -373.2 | -217.7 | 8 |
| | | | | 780.62 | | 0 | 90026 | OMEGA_D1 | 400 | 373.2 | 217.7 | 22 |
| | 450 | KOEBG4 | 400 | 1.01 | -94.6 | 83.5 | 1 | | 400 | 100.7 | -157 | 16 |
| | | | | 404 | | 25 | 2 | | 400 | 486.4 | 43.1 | 41 |
| | | | | | | | 2 | | 400 | 515.5 | 43.4 | 43 |
| | | | | | | | 545 | OMEGA4 | 400 | -270.1 | -478.9 | 46 |
| | | | | | | | 610 | ANKERLI4 | 400 | -61.3 - | 1067.1 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -52.8 | -996.7 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 48.9 | 0 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 49.3 | 0 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2588 | 256 |
| | 460 | MULDR4 | 400 | 1.035 | -94.7 | 220.3 | 60 | STIKL4 | 400 | 343.2 | 314 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 332 | 305.7 | 37 |
| | | | | | | | 465 | BACCH4 | 400 | -337.1 | 7.4 | 28 |
| | | | | | | | 545 | OMEGA4 | 400 | -102.2 | 272.5 | 24 |
| | | | | | | | 550 | KAPPA4 | 400 | -912.2 | 97.5 | 75 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.3 | 39.7 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.3 | 39.7 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1175.1 | 588 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.5 | 40.2 | 32 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 11 | 60 | STIKL4 | 400 | 1.0243 | -95.6 | 150.5 | 1 | | 400 | -93 | 124.4 | 13 |
| | | | | 409.74 | | 31.5 | 459 | FGROVE4 | 400 | -52.9 | 59.6 | 6 |
| | | | | | | | 460 | MULDR4 | 400 | -342.7 | -319 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 169.1 | 51.8 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 169.1 | 51.8 | 35 |
| | 70 | OMEGA7 | 765 | 1.0207 | -81.1 | 0 | 58 | KAPPA7 | 765 | -328.4 | -217.5 | 7 |
| | | | | 780.82 | | 0 | 90026 | OMEGA_D1 | 400 | 328.4 | 217.5 | 20 |
| | 450 | KOEBG4 | 400 | 1.01 | -95 | 83.5 | 1 | | 400 | 93.3 | -156 | 15 |
| | | | | 404 | | 25 | 2 | | 400 | 482.5 | 43.3 | 41 |
| | | | | | | | 2 | | 400 | 511.4 | 43.7 | 43 |
| | | | | | | | 545 | OMEGA4 | 400 | -247.7 | -481.2 | 45 |
| | | | | | | | 610 | ANKERLI4 | 400 | -64.9 - | 1066.8 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -56.1 | -996.4 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 48.8 | 0.1 | 20 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 49.1 | 0.1 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2588.2 | 256 |
| | 460 | MULDR4 | 400 | 1.035 | -95.1 | 220.3 | 60 | STIKL4 | 400 | 343.3 | 315.4 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 338.4 | 305.4 | 37 |
| | | | | | | | 465 | BACCH4 | 400 | -346.3 | 10.5 | 28 |
| | | | | | | | 545 | OMEGA4 | 400 | -79.9 | 270.3 | 23 |
| | | | | | | | 550 | KAPPA4 | 400 | -932.1 | 104.3 | 77 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.4 | 39.8 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.4 | 39.8 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1184.4 | 592 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.5 | 40.4 | 32 |
| 12 | 60 | STIKL4 | 400 | 1.0243 | -96 | 150.5 | 1 | | 400 | -85.6 | 123.3 | 12 |
| | | | | 409.72 | | 31.5 | 459 | FGROVE4 | 400 | -59.8 | 62.1 | 7 |
| | | | | | | | 460 | MULDR4 | 400 | -342.8 | -320.5 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 168.8 | 51.8 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 168.8 | 51.8 | 35 |
| | 70 | OMEGA7 | 765 | 1.0209 | -80.9 | 0 | 58 | KAPPA7 | 765 | -283.7 | -217.1 | 6 |
| | | | | 780.98 | | 0 | 90026 | OMEGA_D1 | 400 | 283.7 | 217.1 | 18 |
| | 450 | KOEBG4 | 400 | 1.01 | -95.4 | 83.5 | 1 | | 400 | 85.9 | -155.1 | 15 |
| | | | | 404 | | 25 | 2 | | 400 | 478.7 | 43.6 | 40 |
| | | | | | | | 2 | | 400 | 507.4 | 44 | 43 |
| | | | | | | | 545 | OMEGA4 | 400 | -225.3 | -483 | 45 |
| | | | | | | | 610 | ANKERLI4 | 400 | -68.4 - | 1066.5 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -59.4 | -996.2 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 48.6 | 0.1 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 49 | 0.1 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2588 | 256 |
| | 460 | MULDR4 | 400 | 1.035 | -95.4 | 220.3 | 60 | STIKL4 | 400 | 343.3 | 316.9 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 344.8 | 305.1 | 38 |
| | | | | | | | 465 | BACCH4 | 400 | -355.5 | 13.8 | 29 |
| | | | | | | | 545 | OMEGA4 | 400 | -57.6 | 268.3 | 22 |
| | | | | | | | 550 | KAPPA4 | 400 | -951.9 | 111.4 | 78 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.5 | 39.9 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.5 | 39.9 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1194.3 | 597 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.6 | 40.5 | 32 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 13 | 60 | STIKL4 | 400 | 1.0242 | -96.3 | 150.5 | 1 | | 400 | -78.2 | 122.1 | 12 |
| | | | | 409.7 | | 31.5 | 459 | FGROVE4 | 400 | -66.7 | 64.6 | 7 |
| | | | | | | | 460 | MULDR4 | 400 | -342.8 | -322 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 168.6 | 51.9 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 168.6 | 51.9 | 35 |
| | 70 | OMEGA7 | 765 | 1.021 | -80.7 | 0 | 58 | KAPPA7 | 765 | -239 | -216.7 | 6 |
| | | | | 781.1 | | 0 | 90026 | OMEGA_D1 | 400 | 239 | 216.7 | 16 |
| | 450 | KOEBG4 | 400 | 1.01 | -95.8 | 83.5 | 1 | | 400 | 78.5 | -154.1 | 15 |
| | | | | 404 | | 25 | 2 | | 400 | 474.9 | 43.9 | 40 |
| | | | | | | | 2 | | 400 | 503.3 | 44.3 | 42 |
| | | | | | | | 545 | OMEGA4 | 400 | -202.9 | -484.4 | 44 |
| | | | | | | | 610 | ANKERLI4 | 400 | -72.0 - | 1066.2 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -62.7 | -995.9 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 48.5 | 0.1 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 48.8 | 0.1 | 20 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2587.2 | 256 |
| | 460 | MULDR4 | 400 | 1.035 | -95.8 | 220.3 | 60 | STIKL4 | 400 | 343.3 | 318.4 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 351.2 | 304.8 | 38 |
| | | | | | | | 465 | BACCH4 | 400 | -364.7 | 17.1 | 30 |
| | | | | | | | 545 | OMEGA4 | 400 | -35.3 | 266.6 | 22 |
| | | | | | | | 550 | KAPPA4 | 400 | -971.7 | 118.7 | 80 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.5 | 40.1 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.5 | 40.1 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1204.9 | 602 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.7 | 40.7 | 32 |
| 14 | 60 | STIKL4 | 400 | 1.0242 | -96.7 | 150.5 | 1 | | 400 | -70.9 | 121 | 12 |
| | | | | 409.68 | | 31.5 | 459 | FGROVE4 | 400 | -73.5 | 67.1 | 8 |
| | | | | | | | 460 | MULDR4 | 400 | -342.8 | -323.5 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 168.4 | 52 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 168.4 | 52 | 35 |
| | 70 | OMEGA7 | 765 | 1.0211 | -80.5 | 0 | 58 | KAPPA7 | 765 | -194.3 | -216.3 | 5 |
| | | | | 781.18 | | 0 | 90026 | OMEGA_D1 | 400 | 194.3 | 216.3 | 15 |
| | 450 | KOEBG4 | 400 | 1.01 | -96.2 | 83.5 | 1 | | 400 | 71.1 | -153.1 | 14 |
| | | | | 404 | | 25 | 2 | | 400 | 471.1 | 44.1 | 40 |
| | | | | | | | 2 | | 400 | 499.3 | 44.6 | 42 |
| | | | | | | | 545 | OMEGA4 | 400 | -180.5 | -485.2 | 43 |
| | | | | | | | 610 | ANKERLI4 | 400 | -75.5 - | 1065.9 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -66 | -995.6 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 48.3 | 0.1 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 48.7 | 0.1 | 19 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2585.9 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -96.2 | 220.3 | 60 | STIKL4 | 400 | 343.4 | 320 | 38 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 357.7 | 304.5 | 38 |
| | | | | | | | 465 | BACCH4 | 400 | -373.8 | 20.5 | 31 |
| | | | | | | | 545 | OMEGA4 | 400 | -13 | 265 | 22 |
| | | | | | | | 550 | KAPPA4 | 400 | -991.6 | 126.3 | 82 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.6 | 40.2 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.6 | 40.2 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1216 | 608 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.8 | 40.8 | 32 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 15 | 60 | STIKL4 | 400 | 1.0241 | -97.1 | 150.5 | 1 | | 400 | -63.5 | 119.8 | 11 |
| | | | | 409.66 | | 31.5 | 459 | FGROVE4 | 400 | -80.4 | 69.7 | 8 |
| | | | | | | | 460 | MULDR4 | 400 | -342.9 | -325.1 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 168.1 | 52 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 168.1 | 52 | 35 |
| | 70 | OMEGA7 | 765 | 1.0212 | -80.3 | 0 | 58 | KAPPA7 | 765 | -149.7 | -215.8 | 5 |
| | | | | 781.22 | | 0 | 90026 | OMEGA_D1 | 400 | 149.7 | 215.8 | 13 |
| | 450 | KOEBG4 | 400 | 1.01 | -96.6 | 83.5 | 1 | | 400 | 63.7 | -152.1 | 14 |
| | | | | 404 | | 25 | 2 | | 400 | 467.3 | 44.4 | 39 |
| | | | | | | | 2 | | 400 | 495.3 | 44.9 | 42 |
| | | | | | | | 545 | OMEGA4 | 400 | -158.2 | -485.6 | 43 |
| | | | | | | | 610 | ANKERLI4 | 400 | -79.0 - | 1065.6 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -69.3 | -995.4 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 48.2 | 0.2 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 48.5 | 0.2 | 19 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2584.1 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -96.5 | 220.3 | 60 | STIKL4 | 400 | 343.4 | 321.6 | 39 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 364.1 | 304.1 | 39 |
| | | | | | | | 465 | BACCH4 | 400 | -383 | 24 | 31 |
| | | | | | | | 545 | OMEGA4 | 400 | 9.2 | 263.6 | 22 |
| | | | | | | | 550 | KAPPA4 | 400 | -1011 | 134.1 | 83 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.7 | 40.4 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.7 | 40.4 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1227.7 | 614 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 153.9 | 41 | 32 |
| 16 | 60 | STIKL4 | 400 | 1.0241 | -97.5 | 150.5 | 1 | | 400 | -56.2 | 118.7 | 11 |
| | | | | 409.64 | | 31.5 | 459 | FGROVE4 | 400 | -87.2 | 72.4 | 9 |
| | | | | | | | 460 | MULDR4 | 400 | -342.9 | -326.8 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 167.9 | 52.1 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 167.9 | 52.1 | 35 |
| | 70 | OMEGA7 | 765 | 1.0212 | -80.1 | 0 | 58 | KAPPA7 | 765 | -105.1 | -215.2 | 4 |
| | | | | 781.21 | | 0 | 90026 | OMEGA_D1 | 400 | 105.1 | 215.2 | 12 |
| | 450 | KOEBG4 | 400 | 1.01 | -97 | 83.5 | 1 | | 400 | 56.3 | -151.1 | 14 |
| | | | | 404 | | 25 | 2 | | 400 | 463.5 | 44.7 | 39 |
| | | | | | | | 2 | | 400 | 491.3 | 45.2 | 41 |
| | | | | | | | 545 | OMEGA4 | 400 | -135.8 | -485.6 | 42 |
| | | | | | | | 610 | ANKERLI4 | 400 | -82.6 - | 1065.3 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -72.6 | -995.1 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 48 | 0.2 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 48.3 | 0.2 | 19 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2581.7 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -96.9 | 220.3 | 60 | STIKL4 | 400 | 343.4 | 323.3 | 39 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 370.4 | 303.8 | 39 |
| | | | | | | | 465 | BACCH4 | 400 | -392.2 | 27.6 | 32 |
| | | | | | | | 545 | OMEGA4 | 400 | 31.5 | 262.4 | 22 |
| | | | | | | | 550 | KAPPA4 | 400 | -1031 | 142.2 | 85 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.8 | 40.5 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.8 | 40.5 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1240.1 | 620 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 154 | 41.1 | 32 |

**LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE**

| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 17 | 60 | STIKL4 | 400 | 1.024 | -97.8 | 150.5 | 1 | | 400 | -48.8 | 117.5 | 11 |
| | | | | 409.62 | | 31.5 | 459 | FGROVE4 | 400 | -94.1 | 75.2 | 10 |
| | | | | | | | 460 | MULDR4 | 400 | -342.9 | -328.5 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 167.6 | 52.1 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 167.6 | 52.1 | 35 |
| | 70 | OMEGA7 | 765 | 1.0211 | -79.9 | 0 | 58 | KAPPA7 | 765 | -60.6 | -214.6 | 4 |
| | | | | 781.17 | | 0 | 90026 | OMEGA_D1 | 400 | 60.6 | 214.6 | 11 |
| | 450 | KOEBG4 | 400 | 1.01 | -97.5 | 83.5 | 1 | | 400 | 49 | -150 | 13 |
| | | | | 404 | | 25 | 2 | | 400 | 459.7 | 45 | 39 |
| | | | | | | | 2 | | 400 | 487.2 | 45.6 | 41 |
| | | | | | | | 545 | OMEGA4 | 400 | -113.5 | -485 | 42 |
| | | | | | | | 610 | ANKERLI4 | 400 | -86.1 - | 1065 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -75.9 | -994.8 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 47.8 | 0.2 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 48.2 | 0.2 | 19 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2578.9 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -97.3 | 220.3 | 60 | STIKL4 | 400 | 343.5 | 325 | 39 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 376.8 | 303.6 | 40 |
| | | | | | | | 465 | BACCH4 | 400 | -401.4 | 31.3 | 33 |
| | | | | | | | 545 | OMEGA4 | 400 | 53.7 | 261.4 | 22 |
| | | | | | | | 550 | KAPPA4 | 400 | -1051 | 150.6 | 87 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 151.9 | 40.7 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 151.9 | 40.7 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1253.1 | 627 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 154.1 | 41.3 | 32 |
| 18 | 60 | STIKL4 | 400 | 1.024 | -98.2 | 150.5 | 1 | | 400 | -41.5 | 116.4 | 10 |
| | | | | 409.59 | | 31.5 | 459 | FGROVE4 | 400 | -100.9 | 78 | 10 |
| | | | | | | | 460 | MULDR4 | 400 | -342.9 | -330.2 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 167.4 | 52.2 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 167.4 | 52.2 | 35 |
| | 70 | OMEGA7 | 765 | 1.021 | -79.7 | 0 | 58 | KAPPA7 | 765 | -16.2 | -213.9 | 4 |
| | | | | 781.08 | | 0 | 90026 | OMEGA_D1 | 400 | 16.2 | 213.9 | 11 |
| | 450 | KOEBG4 | 400 | 1.01 | -97.9 | 83.5 | 1 | | 400 | 41.6 | -149 | 13 |
| | | | | 404 | | 25 | 2 | | 400 | 455.9 | 45.2 | 38 |
| | | | | | | | 2 | | 400 | 483.2 | 45.9 | 41 |
| | | | | | | | 545 | OMEGA4 | 400 | -91.2 | -484 | 41 |
| | | | | | | | 610 | ANKERLI4 | 400 | -89.6 - | 1064.7 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -79.2 | -994.6 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 47.7 | 0.2 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 48 | 0.2 | 19 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2575.6 | 255 |
| | 460 | MULDR4 | 400 | 1.035 | -97.7 | 220.3 | 60 | STIKL4 | 400 | 343.5 | 326.8 | 39 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 383.2 | 303.3 | 40 |
| | | | | | | | 465 | BACCH4 | 400 | -410.5 | 35.1 | 34 |
| | | | | | | | 545 | OMEGA4 | 400 | 75.8 | 260.6 | 22 |
| | | | | | | | 550 | KAPPA4 | 400 | -1070 | 159.2 | 89 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 152 | 40.9 | 31 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 152 | 40.9 | 31 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1266.7 | 633 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 154.2 | 41.5 | 32 |

| LINE LOADINGS FOR DIFFERENT SETTINGS OF PHASE SHIFTING TRANSFORMER ANGLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase shifting transformer angle | FROM | | | | | LOAD | TO | | | POWER FLOW | | |
| | BUS # | NAME | BASE KV | VOLT PU/KV | ANGLE | MW MVAR | BUS# | NAME | BASE KV | MW | MVAR | % loading |
| 19 | 60 | STIKL4 | 400 | 1.0239 | -98.6 | 150.5 | 1 | | 400 | -34.2 | 115.2 | 10 |
| | | | | 409.57 | | 31.5 | 459 | FGROVE4 | 400 | -107.7 | 80.8 | 11 |
| | | | | | | | 460 | MULDR4 | 400 | -342.9 | -332 | 39 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 167.2 | 52.3 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 167.2 | 52.3 | 35 |
| | 70 | OMEGA7 | 765 | 1.0209 | -79.5 | 0 | 58 | KAPPA7 | 765 | 28.2 | -213.2 | 4 |
| | | | | 780.96 | | 0 | 90026 | OMEGA_D1 | 400 | -28.2 | 213.2 | 11 |
| | 450 | KOEBG4 | 400 | 1.01 | -98.3 | 83.5 | 1 | | 400 | 34.3 | -147.9 | 13 |
| | | | | 404 | | 25 | 2 | | 400 | 452.2 | 45.5 | 38 |
| | | | | | | | 2 | | 400 | 479.2 | 46.2 | 40 |
| | | | | | | | 545 | OMEGA4 | 400 | -69 | -482.6 | 41 |
| | | | | | | | 610 | ANKERLI4 | 400 | -93.1 - | 1064.4 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -82.5 | -994.3 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 47.5 | 0.3 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 47.9 | 0.3 | 19 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2571.8 | 254 |
| | 460 | MULDR4 | 400 | 1.035 | -98.1 | 220.3 | 60 | STIKL4 | 400 | 343.5 | 328.7 | 39 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 389.6 | 303 | 40 |
| | | | | | | | 465 | BACCH4 | 400 | -419.7 | 38.9 | 34 |
| | | | | | | | 545 | OMEGA4 | 400 | 97.9 | 260 | 23 |
| | | | | | | | 550 | KAPPA4 | 400 | -1090 | 168.1 | 90 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 152.1 | 41.1 | 32 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 152.1 | 41.1 | 32 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1280.9 | 640 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 154.3 | 41.6 | 32 |
| 20 | 60 | STIKL4 | 400 | 1.0239 | -99 | 150.5 | 1 | | 400 | -26.9 | 114 | 10 |
| | | | | 409.55 | | 31.5 | 459 | FGROVE4 | 400 | -114.5 | 83.7 | 11 |
| | | | | | | | 460 | MULDR4 | 400 | -343 | -333.9 | 40 |
| | | | | | | | 92048 | STIKL_D1 | 132 | 166.9 | 52.3 | 35 |
| | | | | | | | 92049 | STIKL_D2 | 132 | 166.9 | 52.3 | 35 |
| | 70 | OMEGA7 | 765 | 1.0206 | -79.4 | 0 | 58 | KAPPA7 | 765 | 72.4 | -212.4 | 4 |
| | | | | 780.79 | | 0 | 90026 | OMEGA_D1 | 400 | -72.4 | 212.4 | 11 |
| | 450 | KOEBG4 | 400 | 1.01 | -98.8 | 83.5 | 1 | | 400 | 27 | -146.8 | 13 |
| | | | | 404 | | 25 | 2 | | 400 | 448.4 | 45.8 | 38 |
| | | | | | | | 2 | | 400 | 475.3 | 46.5 | 40 |
| | | | | | | | 545 | OMEGA4 | 400 | -46.8 | -480.6 | 40 |
| | | | | | | | 610 | ANKERLI4 | 400 | -96.7 - | 1064.1 | 90 |
| | | | | | | | 610 | ANKERLI4 | 400 | -85.8 | -994 | 84 |
| | | | | | | | 9086 | KOEBG_D1 | 132 | 47.4 | 0.3 | 19 |
| | | | | | | | 9087 | KOEBG_D2 | 132 | 47.7 | 0.3 | 19 |
| | | | | | | | 9875 | KOEBG_1 | 24 | -900 | 2567.5 | 254 |
| | 460 | MULDR4 | 400 | 1.035 | -98.5 | 220.3 | 60 | STIKL4 | 400 | 343.5 | 330.6 | 39 |
| | | | | 414 | | 58.5 | 455 | ACAC4 | 400 | 395.9 | 302.7 | 41 |
| | | | | | | | 465 | BACCH4 | 400 | -428.8 | 42.9 | 35 |
| | | | | | | | 545 | OMEGA4 | 400 | 120 | 259.5 | 23 |
| | | | | | | | 550 | KAPPA4 | 400 | -1110 | 177.2 | 92 |
| | | | | | | | 6001 | MULDR_D1 | 132 | 152.2 | 41.2 | 32 |
| | | | | | | | 6003 | MULDR_D3 | 132 | 152.2 | 41.2 | 32 |
| | | | | | | | 9194 | MULD_SVC | 13.5 | 0 | 1295.7 | 648 |
| | | | | | | | 91553 | MULDR_D4 | 132 | 154.4 | 41.8 | 32 |

## Appendix 3: Voltage Stability Files

### Appendix 3.1: Parameter File

```
        /Action control parameters
CHNGCS    TRUE        /solve with load level increases
CNTGCY    1           /solve first level contingencies
BASDSP    NODISP      /solve basecase with no generation redispatch
CHNDSP    NODISP      /solve change cases with no generation redispatch
CNTDSP    NODISP      /solve contingencies with no generation redispatch
QVCRVS    0           /generate QV curves every 5th load level as well as the last load
level
MRVSTP    0           /perform modal analysis every 5th load level including the last
load level
CNVTLD    FALSE       /use present load models in base powerflow data
CHKVLT    TRUE        /check voltage limits as specified below
CHKFLW    TRUE        /check flow limits as specified below
GNCPCR    FALSE       /use generator capability curves
FLTSTR    FALSE       /use a flat start for the loadflow
TOLBAS    0.19        /voltage deviation tolerance for the basecase.  <0 to bypass
CONTPF    FALSE       /continue the PV curve using continuation power flow
INSTPT    0           /do not compute the NEAREST INSTABILITY POINT
        /Limits and ratings
DVINC1    0.05        /PU voltage increase for class 1 buses (defined by CUTVLM)
DVDEC1    0.1         /PU voltage devrease for class 1 buses
DVINC2    0.05        /PU voltage increase for class 2 buses
DVDEC2    0.1         /PU voltage devrease for class 2 buses
DVINC3    0.05        /PU voltage increase for class 3 buses
DVDEC3    0.1         /PU voltage devrease for class 3 buses
        /CLS3BS       /class 3 busses; either numbers, names or ranges.  can be repeated
CUTVLM    0.00        /buses greater than this and are not class 3 are class 1.  rest are
class 3
LNRATE    2           /use rate 1 - 6.  -1 to use a rating file.  lines to be checked are
specified
                      /by LSBRAR, LSBRNZ and LSBRBS below
TFRATE    2           /same as LNRATE for transformers.
```

```
          /Powerflow solution parameters
QGNLMT    1              /respect gen reactive limits in pre and post contingencies
TAPVAJ    0              /don't adjust TRANSFORMER TAPS for VOLTAGE in pre or post contingency
TAPQAJ    0              /don't adjust TRANSFORMER TAPS for MVAR in pre or post contingency
PHSPAJ    0              /don't adjust phase shifters MW
STCVAJ    0              /don't adjust STC's (static tap changers) for voltage control
STCQAJ    0              /don't adjust STC's (static tap changers) for MVAR control
SPSPAJ    0              /don't adjust static phase shifters for MW control
RANIAJ    0              /don't adjust series compensation for MW control
SVCSAJ    1              /adjust SVC's/CONTINUOUS SHUNTS in pre and post contingency
SWSHAJ    0              /don't adjust switched shunts
AINTAJ    0              /don't adjust area interties
MAXITR    100            /max number of powerflow iterations
TOLRNC    5.0            /powerflow convergence tollerance MVA
ACCFAC    0.9            /powerflow acceloration factor
TOLVLT    1.E-2          /powerflow tollerance for PV bus voltage
BLOWUP    5.0            /blowup voltage for powerflow divergence (PU)
MAXITA    50             /maximum powerflow iterations for adjustments
THRSHA    0.1            /powerflow adjustment threshold
THRSHZ    1.E-5          /zero impedance threshold
METHOD    2              /use BX method of fast decoupled powerflow
          /Solution reporting parameters
PRTBUS    TRUE           /print bus data
PRTGEN    FALSE          /do not print gen data
PRTGLT    FALSE          /do not print MVAr limited gen data
PRTITF    FALSE          /do not print interface flows
PRTCKT    FALSE          /do not print circuit flows
PRTFLW    TRUE           /print rated branch flows
PRTTRV    FALSE          /do not print adjusted ULTC for voltage control
PRTTRF    FALSE          /do not print ULTC/phase shifter for flow control
PRTSTP    FALSE          /do not print static tap changers
PRTSCP    FALSE          /do not print series compensators
```

```
PRTSSH    FALSE       /do not print adjusted switched shunts
PRTDCS    FALSE       /do not print the DC network solution report
PRTAIN    FALSE       /do not print area interchanges
PRTAGC    FALSE       /do not print AGC action results
PRTECD    FALSE       /do not print economic dispatch results
          /LSTSMZ          /list of zone numbers, ranges for zone summaries (can be
repeated)
          /LSTLSZ          /list of zone numbers, ranges for series and shunt losses
          /Miscellaneous
NAMEOP    FALSE       /bus numbers are used instead of names
SELCTG    FALSE        /contingencies are analysed sequentially instead of by user
SELQVC    FALSE        /QV CURVES are generated as in QV curve file instead of by
user
OUTVLM    0            /determines how much detail in output printouts
SHTAPV    FALSE        /print ULTC's that move during powerflow itterations.
(OUTVLM > 0)
MAXVPC    10           /max number of violations to be printed per contingency
          /Report range selection
          /LSTARE          /list of areas for bus data, generation data ior MVAr limited gens
          /LSTZON          /same
LSTBUS  60
LSTBUS  450
LSTBUS  455
LSTBUS  460
LSTBUS  1042           /LSBRAR          /list of lines/transformers for which LIMITS
ARE CHECKED and printed
            /LSBRZN        /list of zones for which branch limits are checked and printed
LSBRBS  60
LSBRBS  450
LSBRBS  455
LSBRBS  460
LSBRBS  1042         /list of bus numbers for which branch limits are checked and
printed
END
```

## Appendix 3.2: Load Level Increase File

```
LDINCR  'Base.psf'      /case name
INISTP  100             /initial step increase
CUTSTP  0.01            /cutoff step increase (will stop at least 10MW from nose)
MAXINC  2000            /stop after 2000MW increase or voltage collapse
        /List of areas to be increased.  One per line
        /LDAREA  1                /Lowveld CLN
        /List of zones to be increased.  One per line
        /LDZONE XX
        /List of buses to be increased.  One per line
LDBUSS  60
LDBUSS  450
LDBUSS  455
LDBUSS  460
LDBUSS  1042
SAVLAS  FALSE /TRUE               /save the last converged loadflow in PSF format
/List of bus voltages to monitor for PV curves.  One per line
LSBSVL 610              /Ankerlig4
LSBSVL 450              /Koeberg
LSBSVL 60               /Stikland4
LSBSVL 460              /Muldersvlei4
LSBSVL 465              /Bacchus4
LSBSVL 550              /Kappa4
LSBSVL 375              /Hydra4
LSBSVL 58               /Kappa7
LSBSVL 55               /Gamma7
LSBSVL 75               /Hydra7

LSCRPF 'ANKERLI-KOEBG-1'
LSCRPF 'KOEBG-ACAC-1'
LSCRPF 'KOEBG-OMEGA'
LSCRPF 'KOEBG-STIKL'
LSCRPF 'KOEBG-STIKL'
```

```
LSCRPF 'OMEGA-MULDR'
LSCRPF 'STIKL-MULDR'
LSCRPF 'STIKL-FGROVE'
LSCRVA 'ANKERLI-KOEBG-1'
LSCRVA 'KOEBG-ACAC-1'
LSCRVA 'KOEBG-OMEGA'
LSCRVA 'KOEBG-STIKL'
LSCRVA 'KOEBG-STIKL'
LSCRVA 'OMEGA-MULDR'
LSCRVA 'STIKL-MULDR'
LSCRVA 'STIKL-FGROVE'
END
```

## Appendix 3.3: Interface File

```
CRCUIT 'ANKERLI-KOEBG-1'
610 450 '1'
CRCUIT 'KOEBG-ACAC-1'
450 2 '1'
2 455 '1'
CRCUIT 'KOEBG-OMEGA'
450 2   '1'
2   545 '1'
CRCUIT 'KOEBG-STIKL'
450 1 '1'
1   60 '1'
CRCUIT 'OMEGA-MULDR'
545 460 '1'
CRCUIT 'OMEGA-KAPPA-1'
70 58 '1'
CRCUIT 'STIKL-MULDR'
60 460 '1'
CRCUIT 'STIKL-FGROVE'
60 459 '1'
```

## Appendix 3.4: Contingency File

```
CNTGCY    'Posdn_Pembr4' 1 1
OUTBRN     1282   1194    '1' /Poseidon-Pembroke 1 400kV Line
CNTGCY    'Grtvl-Lnder4' 1 1
OUTBRN     100    325     '1' /Grootvlei-Leander 1 400kV Line
CNTGCY    'Grtvl_Perss4' 1 1
OUTBRN     100    335 '1' /Grootvlei Perseus 400kV Line
CNTGCY    'Hydra_Beta4' 1 1
OUTBRN     1030   337 '1' /Hydra Beta 400kV Line
CNTGCY    'Lnder_Perss4' 1 1
OUTBRN     325    335 '1' /Leander Perseus 400kV Line
CNTGCY    'Hydra_Posdn4' 1 1
OUTBRN     375    16 '1' /Hydra Poseidon 400kV Line
CNTGCY    'Delphi_Posdn4' 1 1
OUTBRN     375    16 '1' /Delphi Poseidon 400kV Line
CNTGCY    'Beta_Delphi4' 1 1
OUTBRN     337    14 '1' /Beta Delphi 400kV Line
CNTGCY    'Hydra_Droer4' 1 1
OUTBRN     375    23 '1' /Hydra Droer 400kV Line
CNTGCY    'Zeus-Merc7' 1 1
OUTBRN     65     45      '1' /Zeus Mercury 765kV Line
CNTGCY    'Merc-Perss7' 1 1
OUTBRN     45     35      '1' /Mercury Perseus 765kV Line
CNTGCY    'Beta-Perss7' 1 1
OUTBRN     85     35      '1' /Beta Perseus 765kV Line
CNTGCY    'Perss_Hydra7' 1 1
OUTBRN     35     75      '1' /Perseus Hydra 765kV Line
CNTGCY    'Perss_Gamma7' 1 1
OUTBRN     35     55      '1' /Perseus Gamma 765kV Line
CNTGCY    'Gamma_Kappa7' 1 1
OUTBRN     55     58      '1' /Gamma Kappa 765kV 1
CNTGCY    'Hydra_Gamma7' 1 1
```

```
OUTBRN     75    55    '1' /Gamma Kappa 765kV 1
CNTGCY    'Alpha_Beta7' 1 1
OUTBRN     80    19    '1' /Alpha Beta 765kV 1
CNTGCY    'Kappa_Omega7' 1 1
OUTBRN     58    70    '1' /Kapa Omega 765kV 1
CNTGCY    'Apollo_Songo' 1 1
CUTLOD    1676  743.6  -437.9
CNTGCY    'Koeberg_Unit_2' 1 1
CHNGEN    9875  0 '1'
END
```

## Appendix 4: PV Curves for Different Phase Shifting Transformer Angle Settings

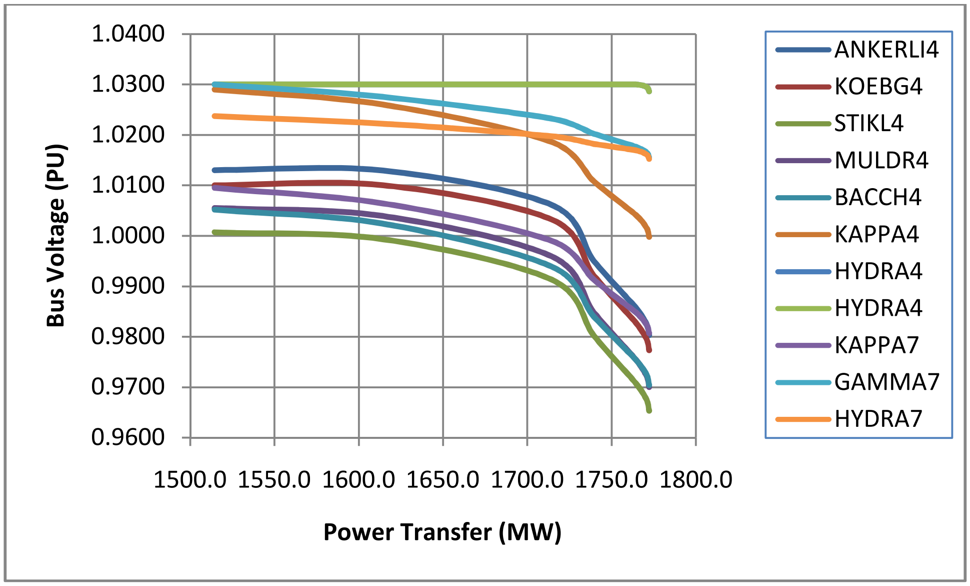


**Figure 16: Phase shifting transformer angle set at -20°**

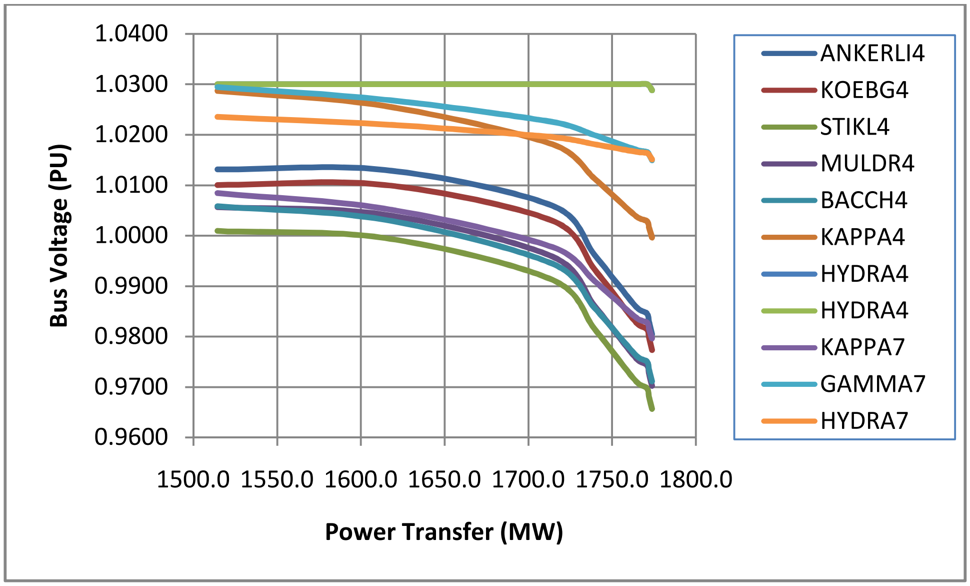


**Figure 17: Angle Phase shifting transformer angle set at -18°**

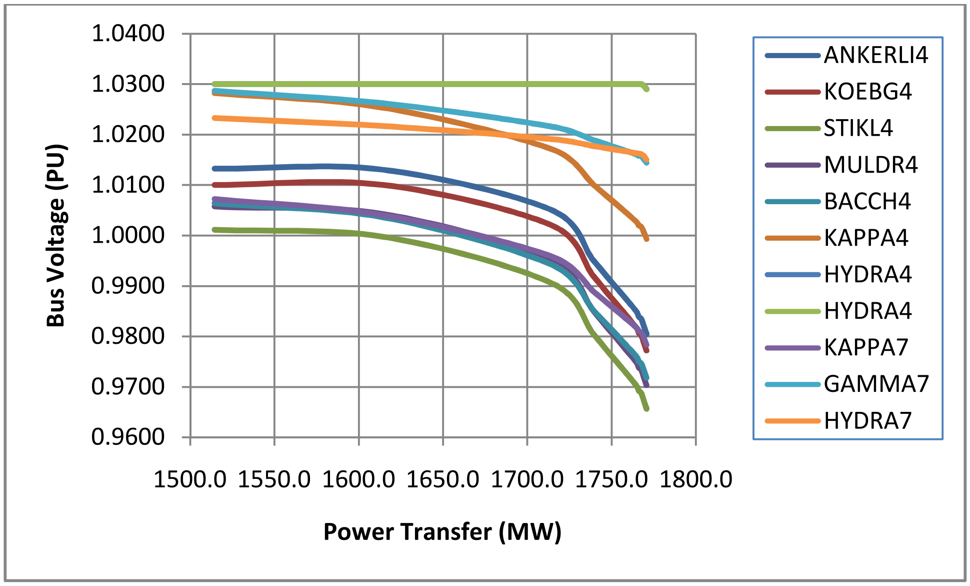


**Figure 18: Phase shifting transformer angle set at -16°**

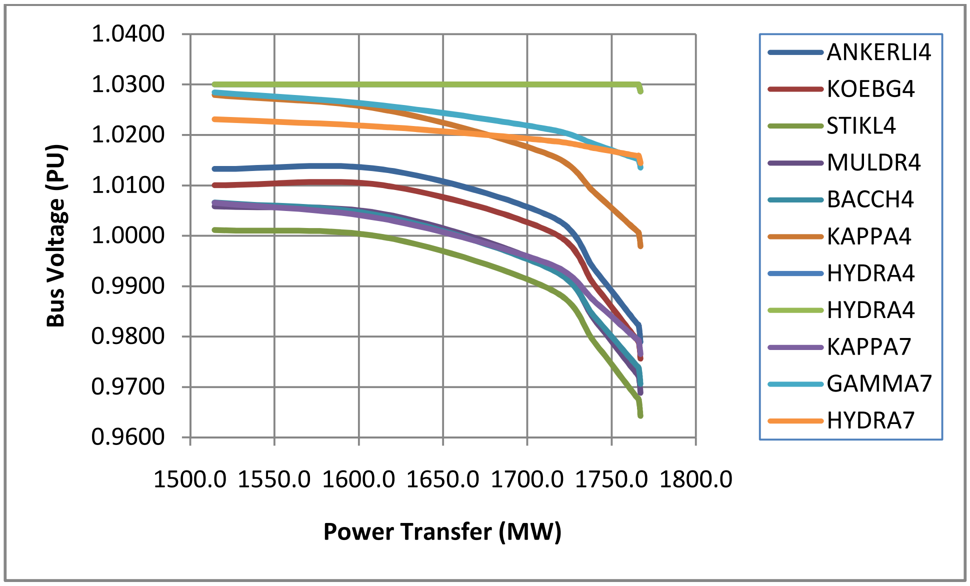


**Figure19: Phase shifting transformer angle set at -14°**

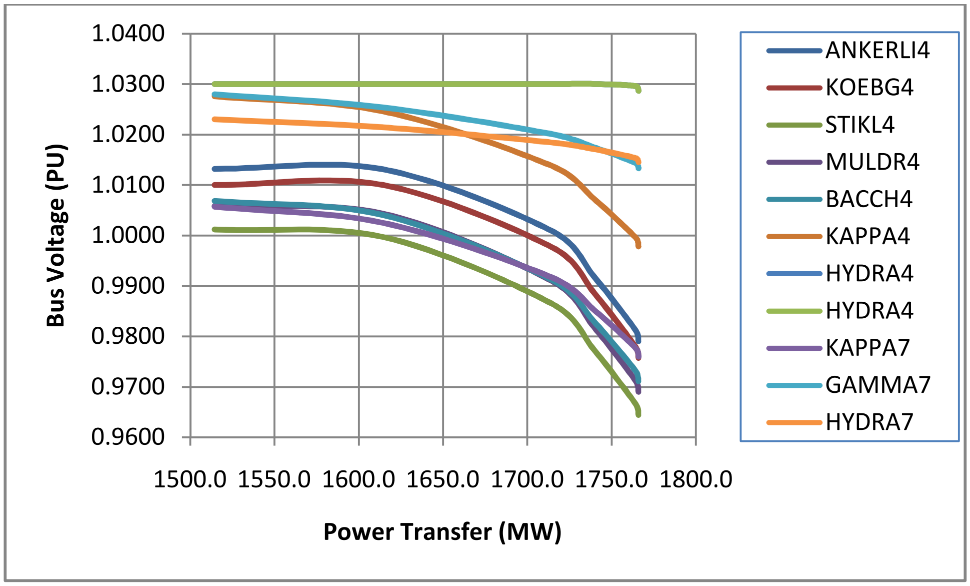


Figure 19: Phase shifting transformer angle set at -12°

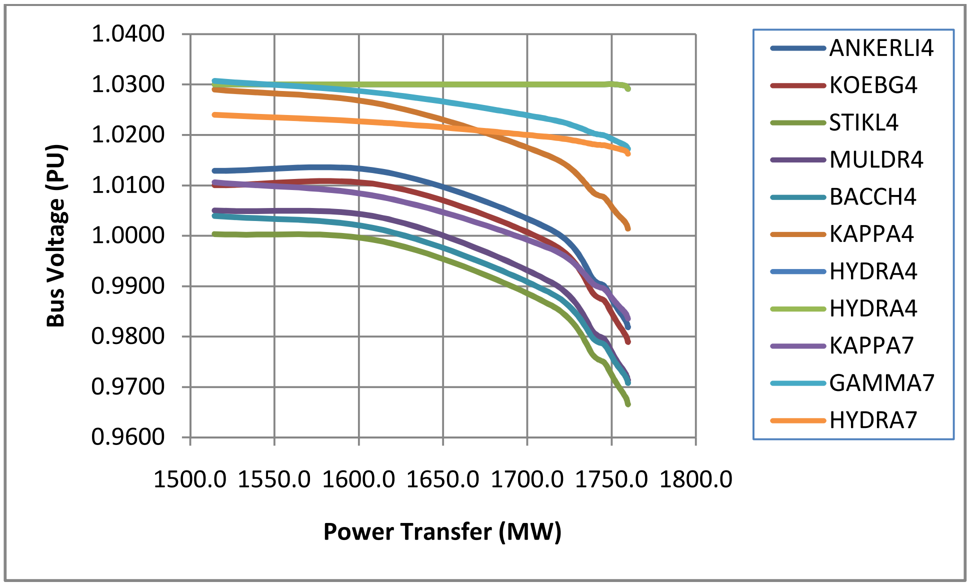


Figure 20:Phase shifting transformer angle set at -10°

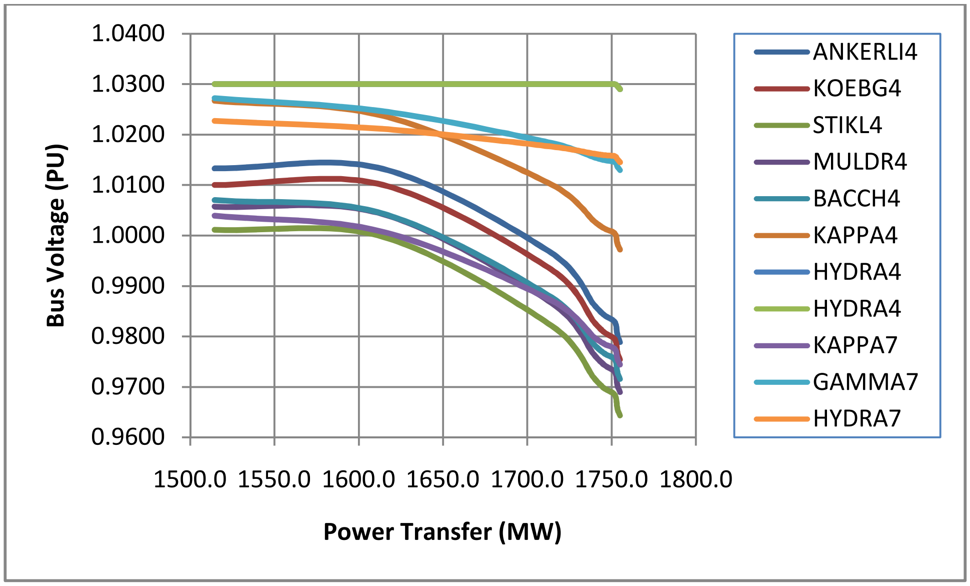


Figure 21:Phase shifting transformer angle set at -8°

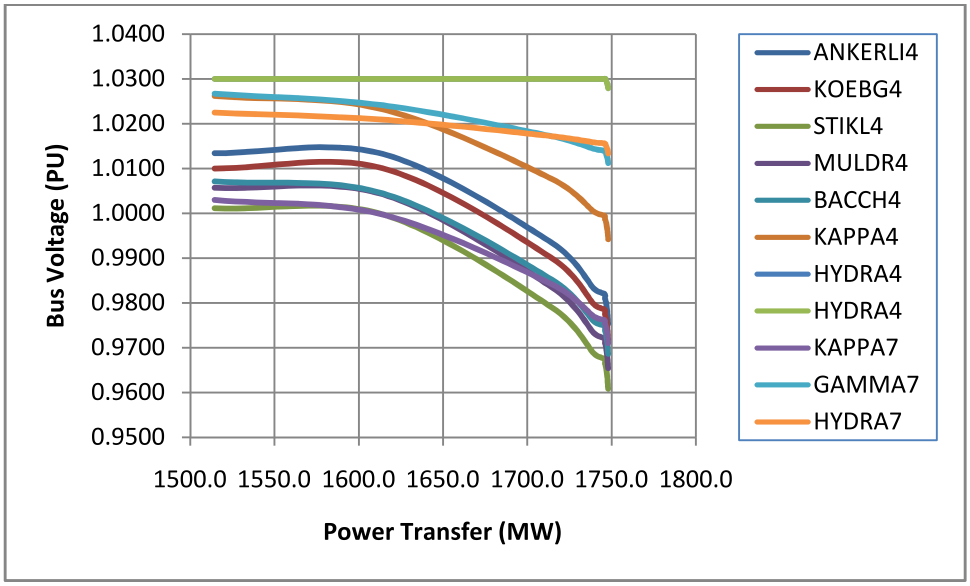


Figure 22:Phase shifting transformer angle set at -6°

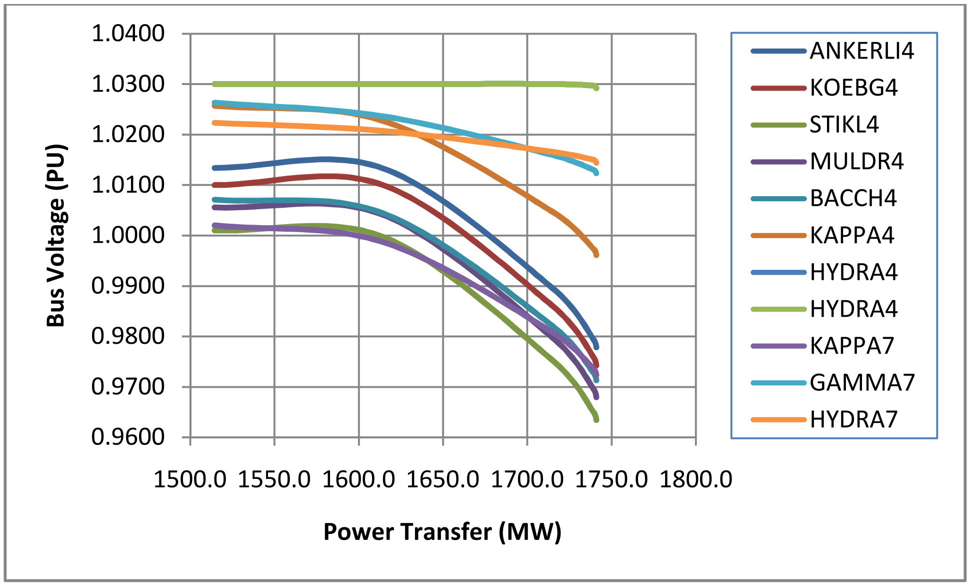


Figure 23:Phase shifting transformer angle set at -4°

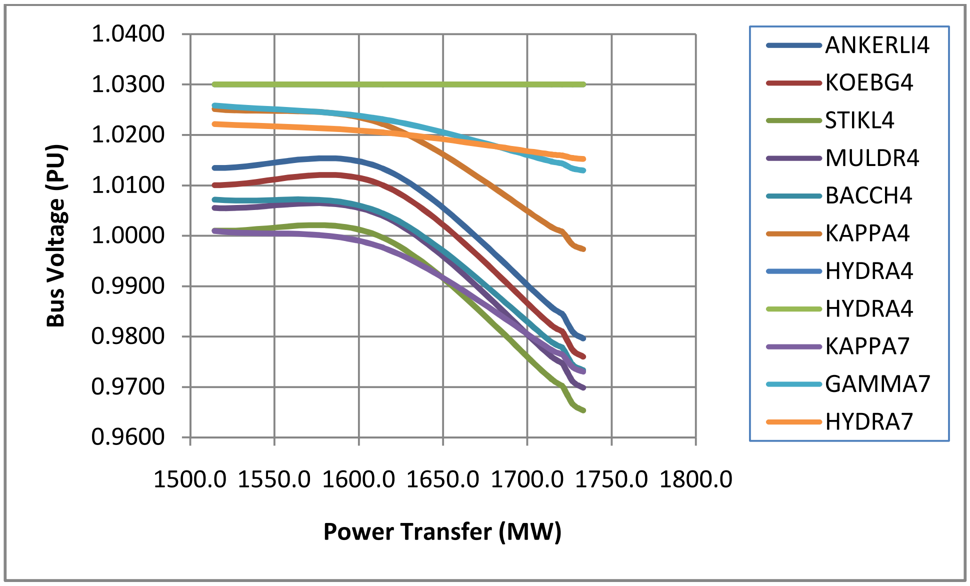


Figure 24:Phase shifting transformer angle set at -2°

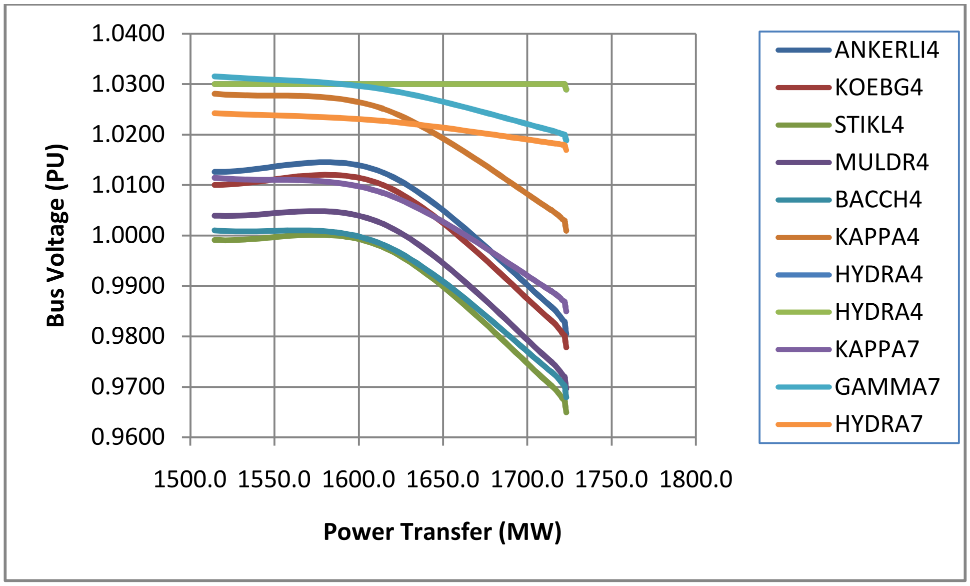


Figure 25: No phase shifting transformer

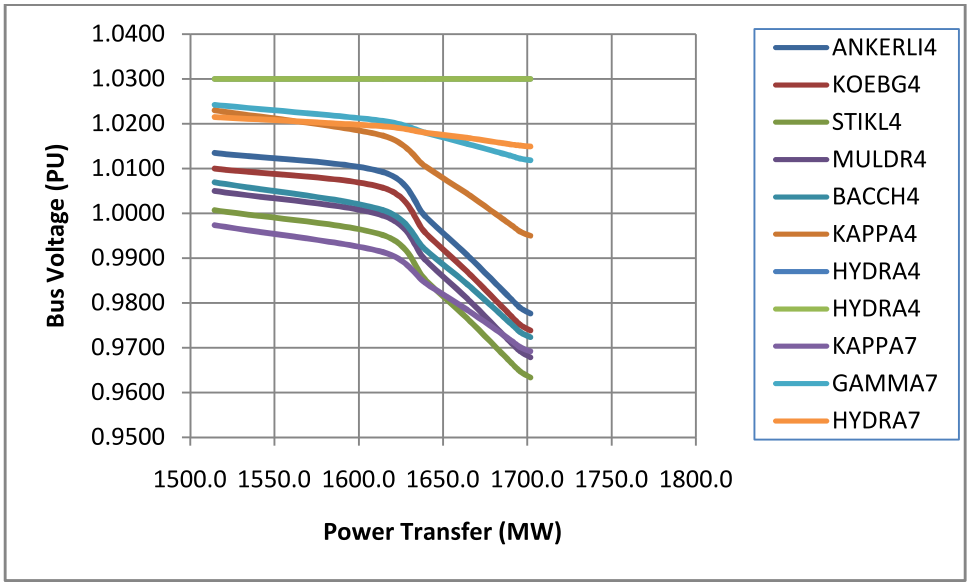


Figure 26: Phase shifting transformer angle set at +2°

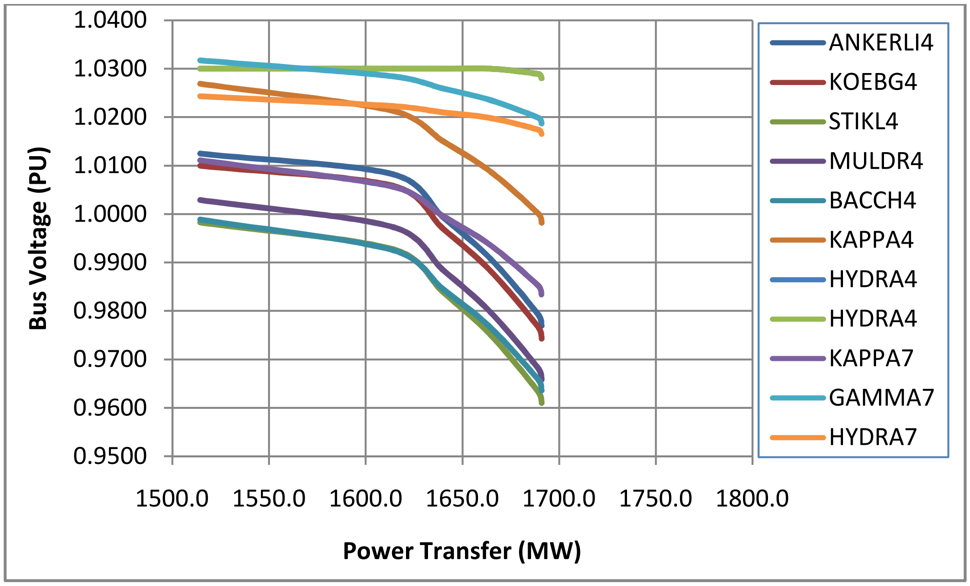


Figure 27:Phase shifting transformer angle set at +4°

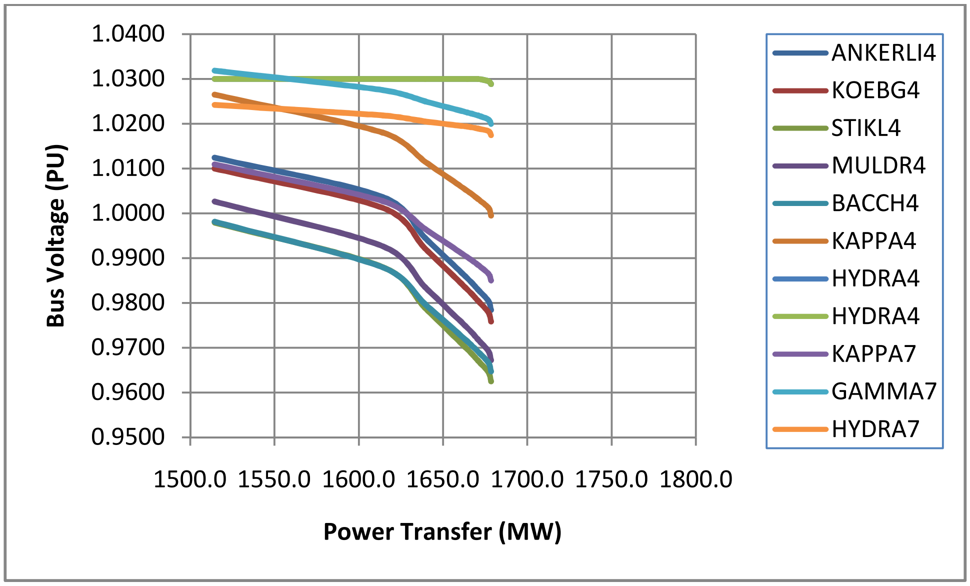


Figure 28: Phase shifting transformer angle set at +6°

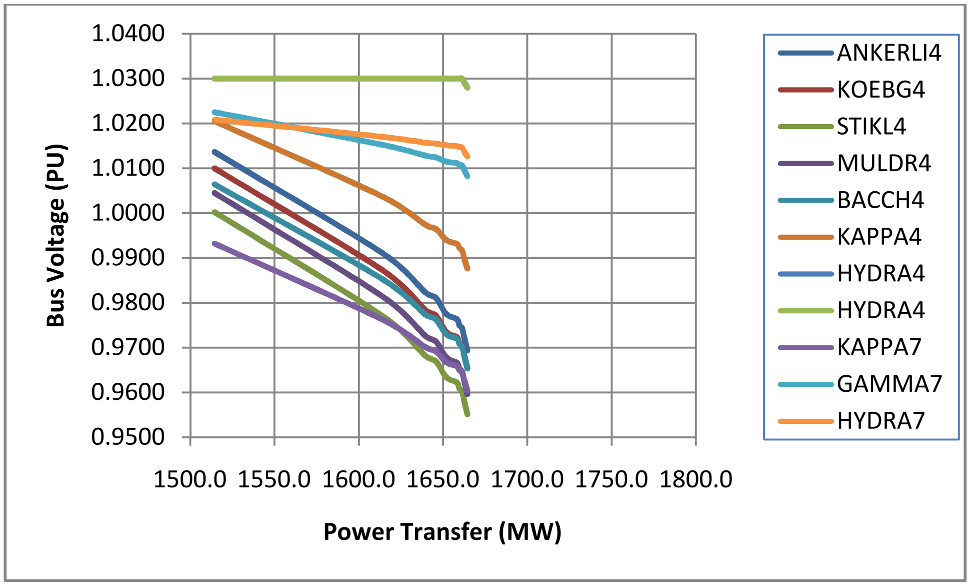


**Figure 29: Phase shifting transformer angle set at +8°**

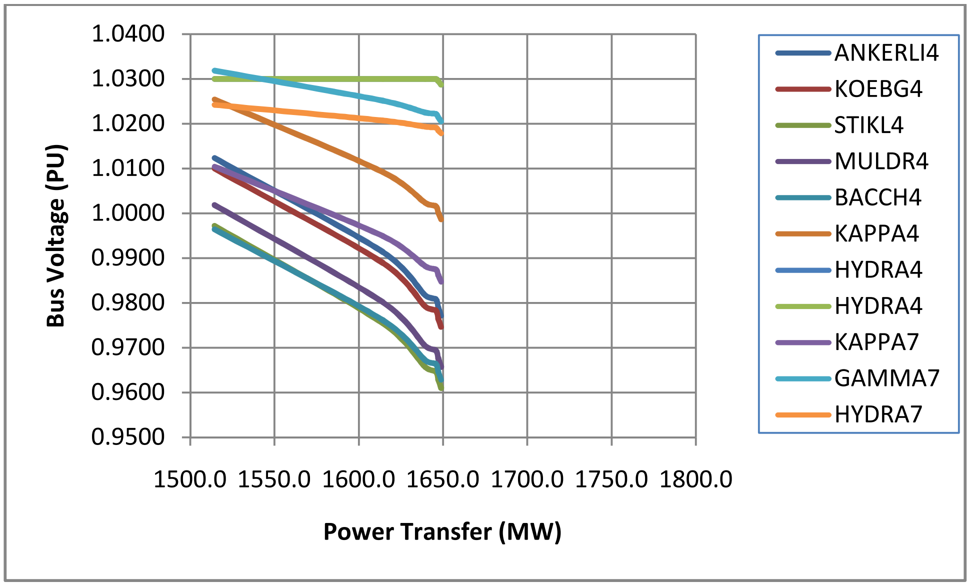


**Figure 30: Phase shifting transformer angle set at +10°**

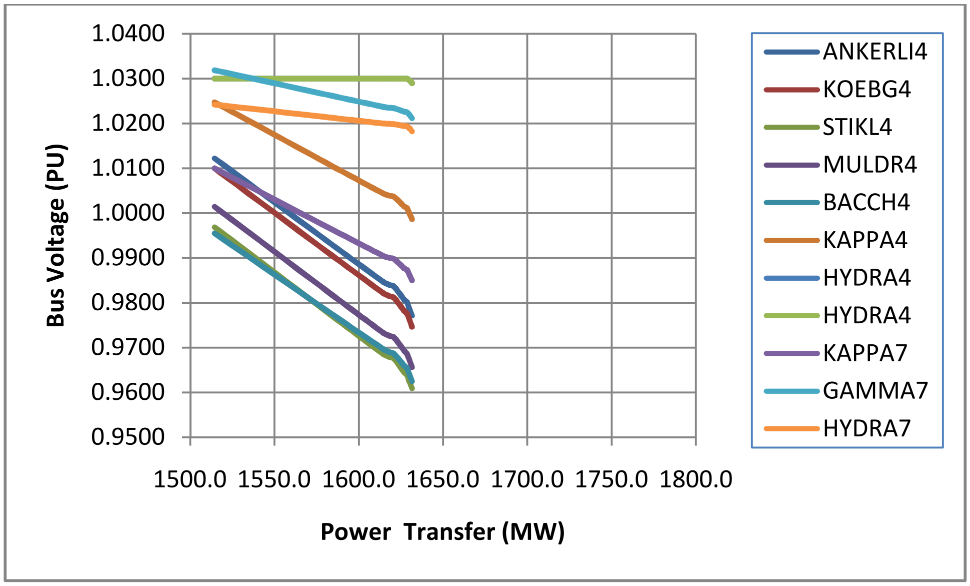


Figure 31: Phase shifting transformer angle set at +12°

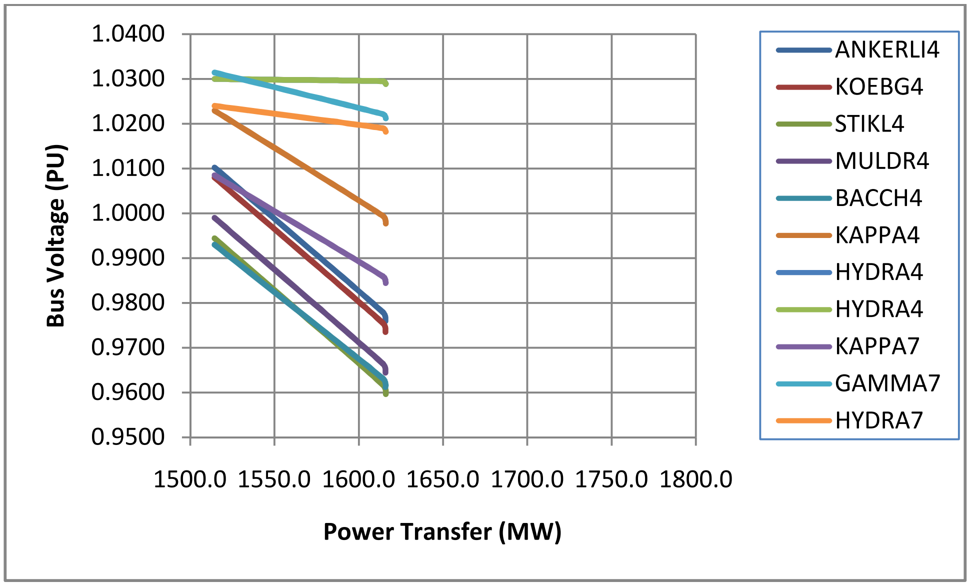


Figure 32: Phase shifting transformer angle set at +14°

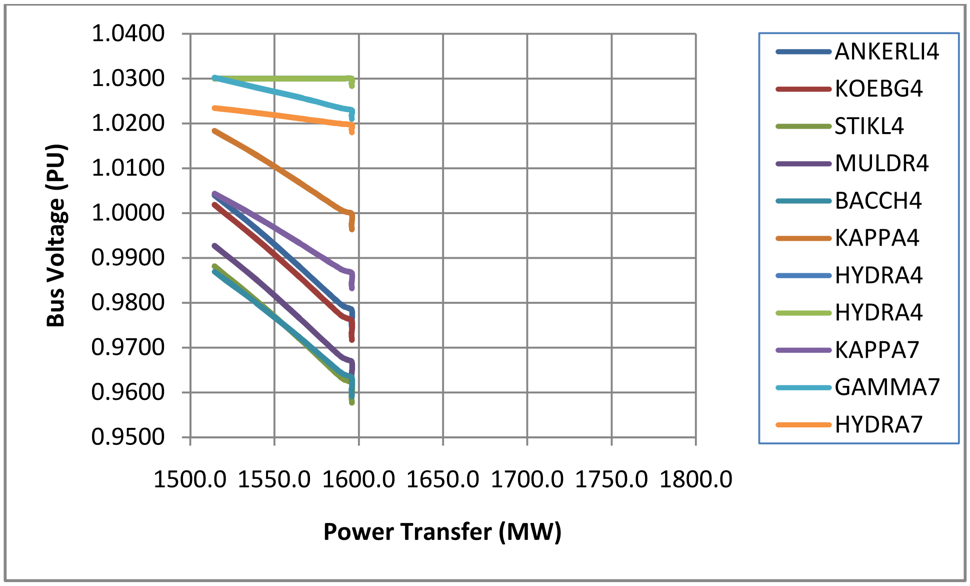


Figure 33: Phase shifting transformer angle set at +16°

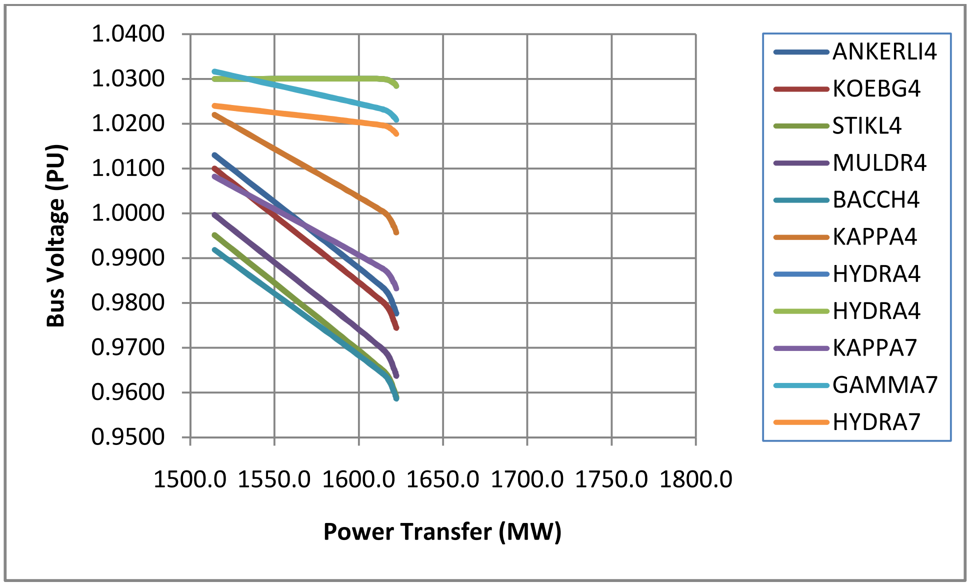
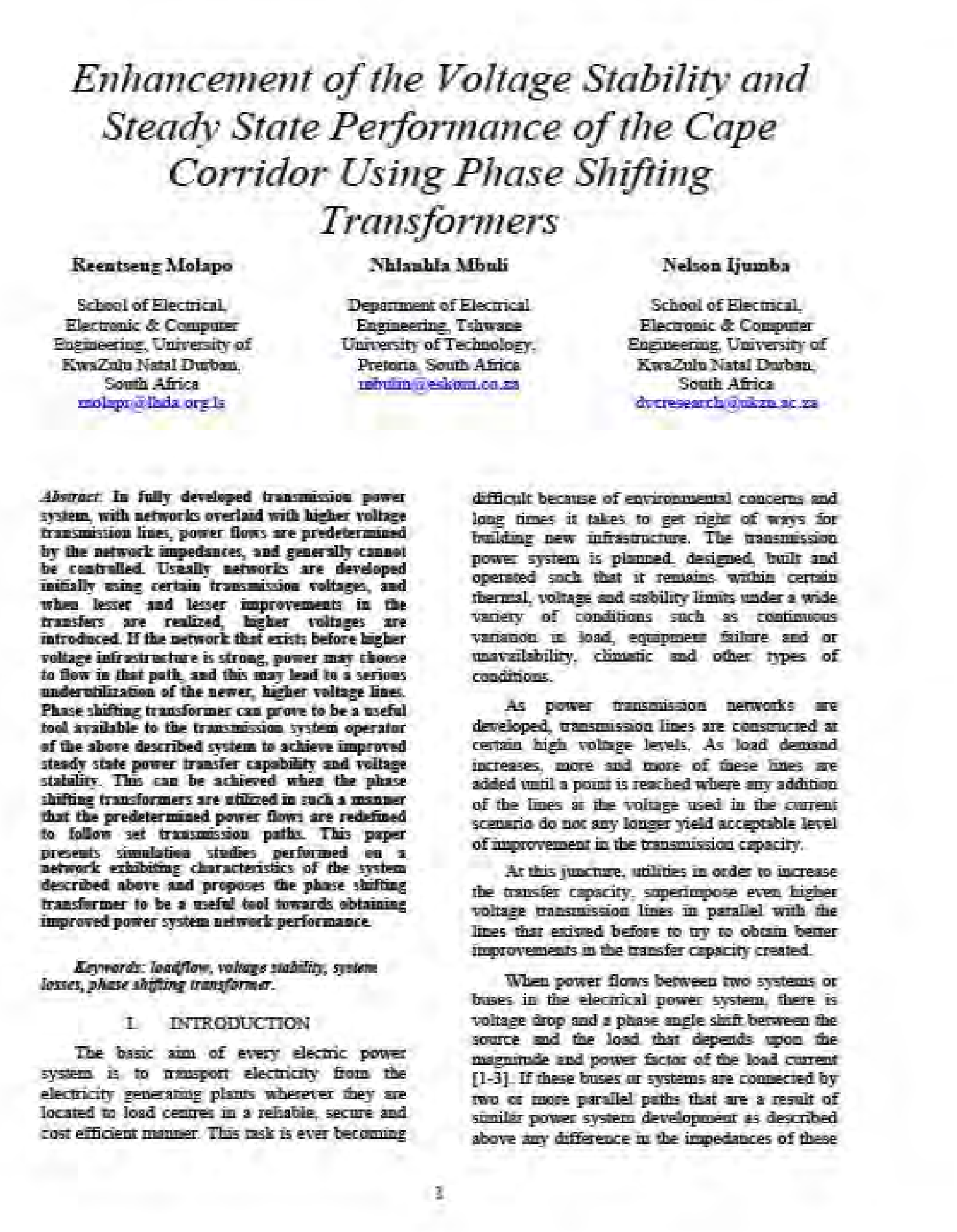


Figure 34: Phase shifting transformer angle set at +18°

# Appendix 5: Paper presented IEEE AFRICON 2011, Conference Proceedings, IEEE AFRICON, Livingstone, Zambia, pp. 1 – 6, Sept. 2011



## *Enhancement of the Voltage Stability and Steady State Performance of the Cape Corridor Using Phase Shifting Transformers*

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*Abstract:* **In fully developed transmission power system, with networks overlaid with higher voltage transmission lines, power flows are predetermined by the network impedances, and generally cannot be controlled. Usually networks are developed initially using certain transmission voltages, and when lesser and lesser improvements in the transfers are realized, higher voltages are introduced. If the network that exists before higher voltage infrastructure is strong, power may choose to flow in that path, and this may lead to a serious underutilization of the newer, higher voltage lines. Phase shifting transformer can prove to be a useful tool available to the transmission system operator of the above described system to achieve improved steady state power transfer capability and voltage stability. This can be achieved when the phase shifting transformers are utilized in such a manner that the predetermined power flows are redefined to follow set transmission paths. This paper presents simulation studies performed on a network exhibiting characteristics of the system described above and proposes the phase shifting transformer to be a useful tool towards obtaining improved power system network performance.**

***Keywords:*** ***loadflow, voltage stability, system losses, phase shifting transformer.***

### I. INTRODUCTION

The basic aim of every electric power system is to transport electricity from the electricity generating plants wherever they are located to load centres in a reliable, secure and cost efficient manner. This task is ever becoming difficult because of environmental concerns and long times it takes to get right of ways for building new infrastructure. The transmission power system is planned, designed, built and operated such that it remains within certain thermal, voltage and stability limits under a wide variety of conditions such as continuous variation in load, equipment failure and or unavailability, climatic and other types of conditions.

As power transmission networks are developed, transmission lines are constructed at certain high voltage levels. As load demand increases, more and more of these lines are added until a point is reached where any addition of the lines at the voltage used in the current scenario do not any longer yield acceptable level of improvement in the transmission capacity.

At this juncture, utilities in order to increase the transfer capacity, superimpose even higher voltage transmission lines in parallel with the lines that existed before to try to obtain better improvements in the transfer capacity created.

When power flows between two systems or buses in the electrical power system, there is voltage drop and a phase angle shift between the source and the load that depends upon the magnitude and power factor of the load current [1-3]. If these buses or systems are connected by two or more parallel paths that are a result of similar power system development as described above any difference in the impedances of these parallel paths will cause loop flows and or unbalanced loading on the system as a result of power flow predominantly flowing in the lower level voltage transmission lines. In fact, if the original system of lines at lower voltages is stronger, disproportionate amount of power may flow through it, leading to complete underutilization of the newer, higher voltage lines.

Furthermore, the unbalanced loading of the different transmission lines results in one of the parallel paths reaching its limits before the others. When this occurs no more additional power can be transferred through the corridor any longer, resulting in the overall capability of the corridor not being fully utilised.

Utilities when faced with situations described above, they employ power flow controlling devices to force power flow as desired to increase the utilization of the power system network and or defer building new infrastructure. As described earlier the power flow in any power system network follows path predetermined by the system's impedance characteristics. But if a power flow controlling such as a phase shifting transformers is utilised a predetermined path, for instance, path 3 which is at higher voltage in Figure 1 below can be made to take the majority of the power flow rather path 1 or 2.

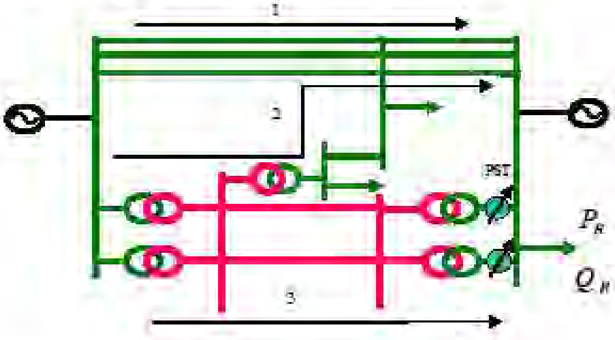


Figure 1 Controlled Power Flow Using PST

In reference[4] it was shown that the use of phase shifting transformers to shift power flow from lower to higher voltage level transmission lines, where they run parallel, could prove to be very useful in improving the voltage stability limit of a corridor as the higher voltage transmission lines possess higher reactive power needed in the transmission of more active power. Furthermore, it was shown that the transfer of power as described above will lead to less system losses as the lower voltage level transmission lines will be transmitting less power thereby reducing current flowing in these transmission lines, and improving the sharing of power between all lines. These improvements are also aided by the fact that higher voltage transmission lines require less current for the same quantity of power transmitted.

This paper aims to present simulation studies that investigated the improvement of power flows and voltage stability of South Africa's Cape corridor by reconfiguring the active power flows at its receiving end using phase shifting transformers. Phase shifting transformers are one of the power flow controlling devices that have existed for a long period of time, and the aim of this paper is to present results of how they can be used to improve transfer capacity of a corridor with lines in parallel and at different voltages.

Section II of this paper describes briefly the South African power system, and particularly the Cape corridor. Section III describes the methodology that was adopted in doing power system analysis to evaluate the impact of the phase shifting transformer in this part of the network. A brief description of how the phase shifting transformers were modelled in the simulation software is made in Section IV. Section V presents the results of the simulations and in Section V conclusions of this study are made.

## II. CAPE CORRIDOR

The South Africa power system is one of the highly developed meshed and intensely utilised power system, it ranks seventh in the world in terms of power sales and generates more than seventy percent of power generated in the Sub-Saharan Africa [5]. It consists of major load centres located in central and coastal areas in the east, south and west of the country. It is because of the existence of these distant regions that it consists of highly developed corridors such as the Cape corridor. See Figure 2 below. The South African Cape corridor consists of parallel 400 and 765 kV system that carry power from the North Eastern part of the country, where most of the power system generators are located [6].

The system was initially developed at lower voltages and as the system load demand increased, the transmission lines were overlaid with the 765 kV lines operating in parallel with the 400 kV transmission lines [6]. The corridor exhibit similar power system network characteristics described above where power flow is predetermined by the characteristics of the power system and the impedances of the transmission lines. The corridor has more power flowing in the 400 kV rather the higher 765 kV voltage transmission lines. This has led to the higher voltage transmission capacity being very much under utilised. The investigation that will be carried out will assess the impact of moving more power from the 400 kV lines to the 765 kV corridor, using phase shifting transformers located on the 400 kV lines at the end of this corridor, as shown Figure 3.

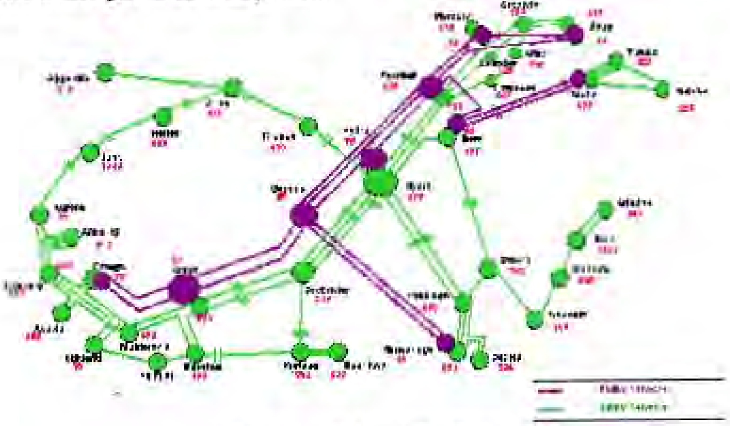


Figure 2: Geographic Layout of Cape Network

## III STUDY METHODOLOGY

The power system simulations were carried out using Power System Simulator for Engineering (PSS/E) Software. The South African power system network data was entered into the software package. The portion showing the Cape corridor, including the network diagram of 400 and 765 kV parallel lines, is shown in Figure 3. The phase shifting transformers are shown in this diagram inserted in the network at the end of the 765 kV corridor, i.e., at Omega substation once the 765 kV is transformed to 400 kV.

### *A. Phase Shifting Transformer Modelling*

The phase shifting transformer in PSS/E is modelled as a two node transformer and its thermal capacity specified only once at the beginning of the network drawing. The impedance of the transformer is also required by the model. There is a field that requires the phase shifter angle, and this can be varied manually by the user of the software or automatically by the software itself. For these studies, certain angles were chosen and varied by the user for various scenarios studied. The location of the phase shifting transformer is shown in Figure 3 below.

### *B. Loadflow Studies*

Loadflow studies were run and power flows at the lower and higher voltage transmission lines were monitored as the phase shifting transformer angle was changed and these were compared with the base case where there was no phase shifting transformer employed in the power system network. To assess the impact of the phase shifting transformers on loadflows, corridors A1, A2, A3 and B, as shown in Figure 3, were monitored. The idea is that by manipulating the phase shifting transformer, the flows in corridor A1, A2 and A3 can be reduced in such a manner that flow in corridor B is increased.

### *C. Voltage Stability Studies*

For voltage stability studies, the entire Cape system load increments were done in steps of 100 MW for different contingencies. Various contingencies involving loss of a single line or a single generator or a single transformer were studied to evaluate the system voltage stability limits for these conditions. The studies were repeated for various settings of the phase shifting transformer angles.

### *D. System Losses*

The system losses were also monitored for the system healthy conditions only for various scenarios studied, i.e., for a case before the use of phase shifting transformers and for cases where they were used (at various angles).

## IV. DISCUSSION OF RESULTS

### *A. Loadflows*

The results of the loadflows are summarised in Table 1 below. It is shown that utilization of the phase shifting transformer resulted in the power flow being moved more and more onto the higher voltage transmission lines as the phase shifting transformer angle was varied. As the angle was varied further the power flow was increasing on the higher voltage transmission corridor it was discovered that the power was further decreased on the 400kV corridor.

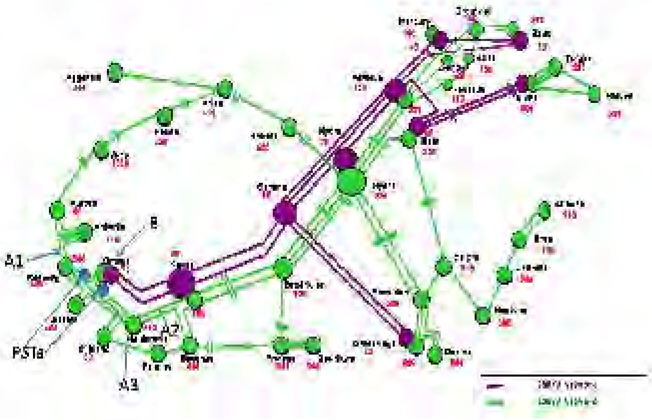


Figure 3: Location of PSTs and Loadflow Monitoring Points

Table 1: Loadflows, System Losses and Voltage Stability at Different PST Angles

| Scenario | 400kV Corridor A1 | 400 kV Corridor A2 | 400 kV Corridor A3 | SUM 400 kV Corridors | 765-400 kV Corridor B | System Losses | Voltage Stability Limit |
|---|---|---|---|---|---|---|---|
| Base Case No PST | 856 | 388 | -188 | 1056 | 1310 | 1346 | 294 |
| 0 | 857 | 415 | -183 | 1089 | 1277 | 1348 | 294 |
| 3 | 866 | 607 | -145 | 1328 | 1040 | 1361 | 275 |
| 6 | 877 | 799 | -107 | 1569 | 803 | 1376 | 256 |
| -3 | 848 | 223 | -220 | 851 | 1514 | 1337 | 306 |
| -6 | 840 | 31 | -256 | 615 | 1751 | 1329 | 313 |
| -9 | 833 | -160 | -293 | 380 | 1987 | 1324 | 325 |
| -12 | 827 | -349 | -330 | 148 | 2222 | 1320 | 325 |
| -15 | 823 | -536 | -367 | -80 | 2453 | 1319 | 331 |
| -17 | 809 | -667 | -397 | -254 | 2631 | 1317 | 331 |

### B. *Voltage stability*

In the simulation of voltage stability studies, the phase shifting transformer angles were varied and the voltage stability limit values obtained at each setting, for various contingencies, with the load increased at all the areas being supplied by the Cape corridor.

The load at the end of the corridor areas was increased in steps of 100 MW to a level where there was system collapse. The voltage stability limit values obtained are as shown in Table 1. The voltage stability limit values decreased as the phase shifting transformer angle was increased positively as more and more power was being transferred through the 400 kV transmission lines. The values increased as power was being transferred through the 765 kV transmission lines

### C. *System losses*

During the above simulation, the power system losses were also noted for the base case as well as for the different angle settings of the phase shifting transformers.

The relationship between the phase shifting transformer angles and the system losses obtained is shown in Table 1. The losses increased as the phase shifting transformer angle was increased positively and decreased as the angle was varied negatively.

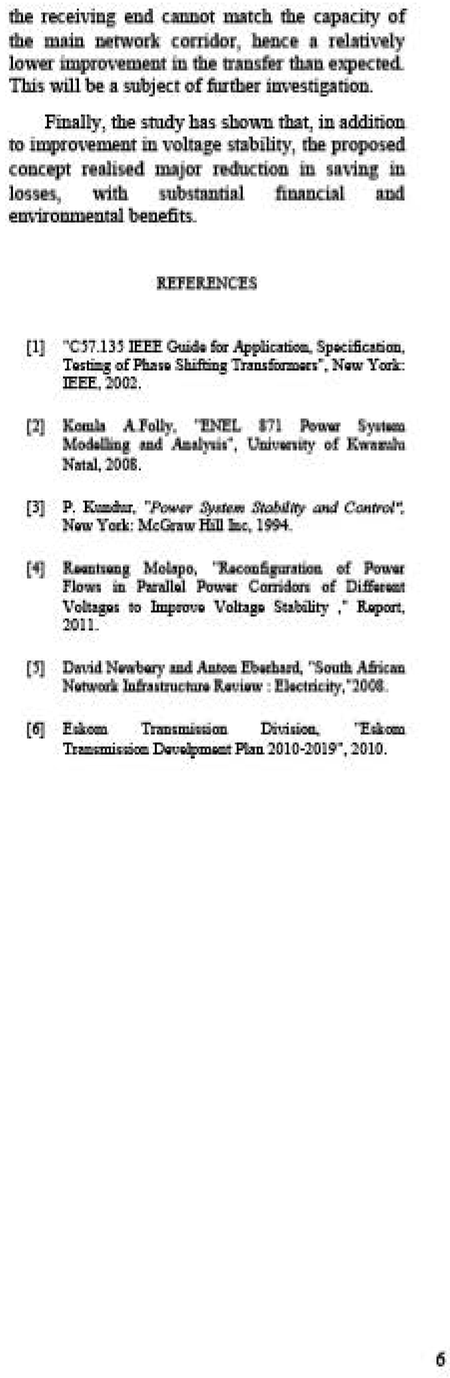
The losses became less as the more power flow was made to flow through the higher voltage transmission lines rather than in the lower voltage transmission lines. In fact, the losses were reduced to about 29 MW as the angle was shifted by 17°. This is worth about R600 million rand in terms of financial worth of losses over 25 years, based on the assumptions used in Eskom.

## V. CONCLUSION

The study has shown that the phase shifting transformer can be used to improve the voltage stability limit of a corridor consisting of a set of many parallel lines overlaid with fewer, higher voltage lines. This is achieved by moving more power to the higher voltage lines through the adjustment of the phase shifter angle.

The calculation of voltage stability limits does show that the total transfer capability of the composite network, i.e., network overlaid with a higher voltage transmission line, can be improved by redirecting of power to the higher voltage transmission line, as initially thought.

In this particular study, the degree of the total improvement is not as high as expected, and based on other work done in this network in the area, it is believed that perhaps the network at



the receiving end cannot match the capacity of the main network corridor, hence a relatively lower improvement in the transfer than expected. This will be a subject of further investigation.

Finally, the study has shown that, in addition to improvement in voltage stability, the proposed concept realised major reduction in saving in losses, with substantial financial and environmental benefits.

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