Faculty of Engineering and the Built Environment
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MSc. Electrical Power Engineering Research Report

Title: Use of Thyristor Controlled Series Capacitors (TCSCs) to enhance power system transient stability and their possible application on the South African Grid

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This research report is submitted as a partial fulfilment of the requirements for a Master of Science degree in Electrical Engineering (Power).

DECLARATION

I declare that this research is my own unaided work except where specifically acknowledged. To my knowledge this specific study to investigate the possible application of TCSCs in the northern part of the South African transmission network has not been conducted before.

Tonderayi Gumunyu

Date

ABSTRACT

Thyristor Controlled Series Capacitors (TCSCs) are FACTS devices which incorporate power-electronic-based and other static controllers to enhance controllability and increase power transfer capability. This research investigated the possibility of applying TCSCs on the South African transmission network, in particular application on long transmission lines connecting bulk thermal generators in the northern part of South Africa to load centres located hundreds of kilometres elsewhere in the country. The investigation, conducted using PSS/E (a power system analysis software) demonstrated that application of TCSCs on this part of South African transmission network results in improved transient stability margins. The resulting improvement in transient stability is comparable to other transient stability enhancement options like addition of transmission lines, thus the use of TCSCs can be considered as an alternative. Further studies would be vital to understand the interaction between Power System Stabilizers (PSSs) and TCSCs in order to ensure proper tuning and interaction amongst the devices.

Key Words – Thyristor Controlled Series Capacitors (TCSCs), Critical Fault Clearing Time (CFCT)

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1. INTRODUCTION

Thyristor Controlled Series Capacitors (TCSCs) are in the family of Flexible Alternating Current Transmission Devices (FACTS). FACTS are defined by the IEEE as "AC transmission systems incorporating power-electronic-based and other static controllers to enhance controllability and increase power transfer capability".

A TCSC consists of a series compensating capacitor shunted by a Thyristor Controlled Reactor (TCR) connected in series with a transmission line. The operation principle is to provide a continuously variable series capacitance [1].

In the event of large disturbances like short circuits (faults) on lines connecting large power stations, power system transient stability can be enhanced by increasing the post-disturbance synchronising torque. One of the ways to increase post-disturbance synchronising torque is by reducing network impedance between the generating sources and the load. A TCSC applied on a transmission line reduces the effective impedance of the line thus increasing the post-disturbance synchronising torque.

1.1. Line Series Reactance Compensating Devices

Fixed Series Capacitors (FSCs), Thyristor Switched Series Capacitors (TSSCs) and GTO Controlled Series Capacitors (GCSCs) can also be applied to alter the line series reactance. Traditionally, FSCs have been applied to increase the power transfer in power systems, especially on long transmission lines that carry power over long distances. However, the use of FSCs as well as TSSCs is inadequate in networks where Sub-synchronous Resonance (SSR) constraints are prevalent whilst GCSCs are still an immature technology [2]. Power systems with TCSC are gaining wide application because introducing control of the series compensation brings additional benefits like dynamic power flow control, power oscillation damping and mitigation of SSR [3].

TCSCs offer a unique possibility to apply higher degrees of series compensation in networks where there is risk of SSR between the transmission system and generators in thermal power stations. Previously, due to SSR risk in such networks, series compensation was avoided or limited to lower compensation levels than required by the system [4].

1.2. Research Questions

The South African transmission network topology is such that the generation stations are situated long distances from the load centres. The generation pool is concentrated in the Limpopo and Mpumalanga provinces in the northern and eastern part of the country and relative to these generation sources, the major load centres are situated several hundreds of kilometres in the central, western and southern parts of the country. This implies that generated power has to be transported over large distances from the generation pools to the load centres. Figure 1.1 shows the topology of the South African transmission network [5].

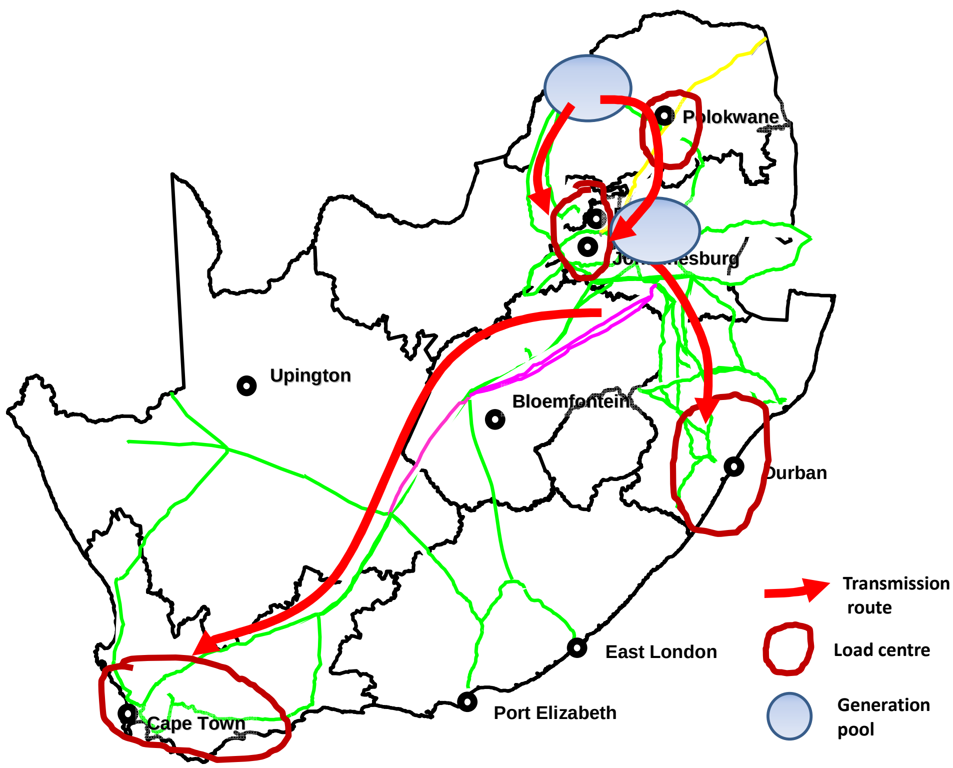

Figure 1.1: South African Grid transmission network topology

Feasibility studies have been conducted for transmission integration of new thermal power generation in the Limpopo province, in the northern part of the country, to the Transmission Grid [6]. Challenges were encountered in ensuring that the network retains transient stability in the event of line faults under light loading conditions. The solutions to transient instability that were investigated include building more transmission lines and implementing operational solutions such as dropping some generators in the event of faults. Building of additional lines was recommended [6].

Obtaining new servitudes to build lines is becoming very difficult in built up load centres and new legislation being enacted to protect the environment renders new servitudes improbable in some areas. In addition to this, building new transmission lines may be too costly especially over long distances. Operational solutions are not preferred because they result in a very tight operating regime which may not allow sufficient network operation flexibility.

This research will focus on the possibility of applying TCSCs on the South African grid to enhance transient stability. The investigation will only focus on TCSCs and no other series compensation devices because SSR risk is of concern in this part of the South African network where thermal generators interact with the transmission system. The research seeks to provide answers to the following questions:

- What is the impact on transient stability of applying Thyristor Controlled Series Capacitors (TCSCs) on long transmission lines connecting thermal generators in the northern part of South Africa to the load centres?
- How significant is the improvement in transient stability margins if any?
- How sensitive are the stability margins to the degree of series compensation?
- In this part of the network, would the application of TCSCs be considered an alternative to conventional solutions like the building of additional lines?

1.3. Research Methodology

The research will entail a review of the theory behind the operation of a TCSC. The review will also encompass transient stability literature and the impact of TCSC action on transient stability. The possible application of a TCSC on the South African Grid will be investigated by conducting simulations on the future South African transmission network (year 2020) post commissioning of the 6 x 846 MW Medupi Power station in the northern part of South Africa [6].

1.4. Research Structure

The following sections summarise the content of each chapter and provide an overview of the structure and flow of the research report.

1.3.1. Review of the TCSC Characteristics

TCSCs are in the family of FACTS devices which are devices employed in power systems to enhance power control. **Chapter 2** discusses the components of a TCSC, how they achieve a variable reactance across the TCSC module and the TCSC operational characteristics relating to dynamic active power control.

1.3.2. Impact of TCSC on Transient Stability

In the event of large disturbances (e.g. line faults) on a power system, connected generators accelerate and absorb kinetic energy. The ability of a power system to retain synchronism amongst all connected generators after a disturbance is called transient stability. Transient stability is dependent on the ability of generators to decelerate by transferring absorbed kinetic energy into the electrical network. A generator strongly connected (implying lower impedance) to the rest of the network will be able to transfer a large amount of electrical power after the disturbance, thus dissipating significant kinetic energy. The post-disturbance power transfer to the network is a function of bus voltage magnitude, load angle and network impedance.

The operation principle of a TCSC is to reduce the network impedance thus increasing the power transfer. In the event of large network disturbances, transient stability can be enhanced by increasing the post-disturbance power transfer. **Chapter 3** discusses the impact on transient stability when TCSCs are connected in series with a transmission line in a power system.

1.3.3. Simulation on the South African Transmission Grid

The South African Transmission Grid will be employed to demonstrate possible application of TCSCs. The focus will be on the lines supplied from the generation pool north of South Africa, which traverse long distances to load centres in the central and south eastern parts of South Africa. Simulations will be based on the future South African transmission network that takes into account large thermal generation in the northern power pool. Large network disturbances in the mould of three-phase line faults will be simulated on selected lines to determine the impact on transient stability of applying TCSCs.

Figure 1.2 depicts the South African transmission network with focus on the research study area enclosed by the dotted red rectangle. The focus area encompasses long lines connecting the northern generation pool to the transmission network.

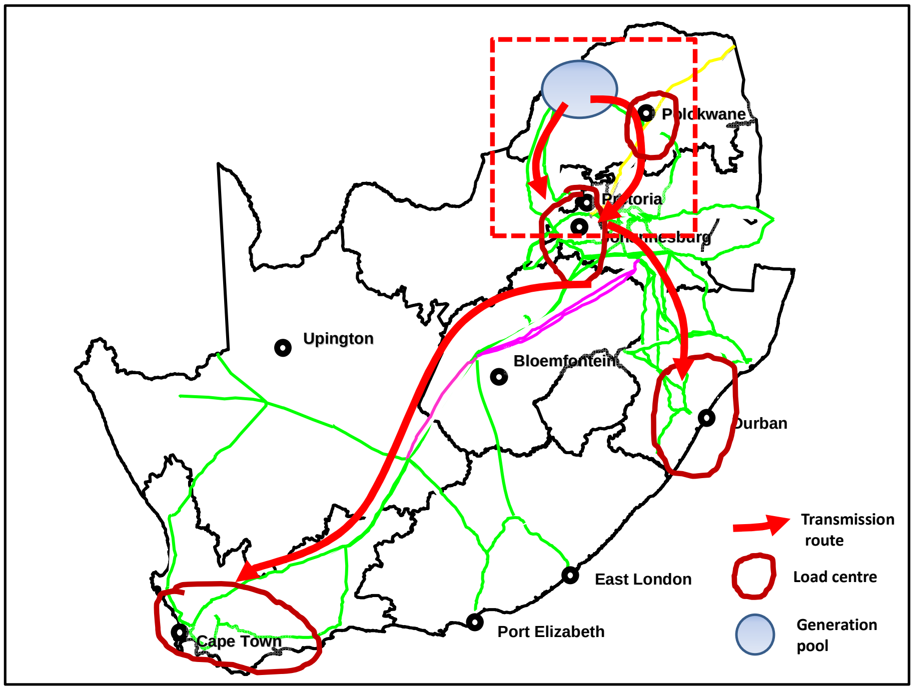

Figure 1.2: Research focus area

Analysis will be conducted using PSS®E, a time domain based software that can be employed to conduct transient stability studies for large power systems. The TCSC will be employed on various lines connected to the northern power pool and three-phase line faults will be simulated to determine the impact of TCSC action.

The simulations will seek to achieve the following three objectives:

- Determine if the introduction of a TCSC results in improved transient stability margins;
- Determine the optimal placing of the TCSC; and
- Determine the impact of varying the degree of compensation.

The impact of introducing a TCSC will be determined by calculating the Critical Fault Clearing Times (CFCTs) *with* and *without* the TCSC. CFCT is defined as the maximum duration within which a fault on a power system should be cleared and beyond this duration the power system becomes transiently unstable. The impact of the TCSC will be simulated on various transmission lines emanating from the Lephalale power pool in order to determine the series compensated line that results in the largest improvement in CFCT. **Chapter 4** discusses the various models that will be employed in the studies as well as presents results of the analysis of the test case study that demonstrates TCSC action.

1.3.4. Results, Analysis and Conclusions

The impact of the TCSC action will be determined based on results obtained from three-phase line faults simulated. Results will be based on time domain graphs that depict network behaviour before, during and after the three-phase line faults. **Chapter 5** discusses the results obtained from the various scenarios studied. Results obtained should give a guide in selection of the compensated line that will result in the greatest benefit from the use of a TCSC. Transient stability trends emerging depending on the compensation level will be determined. The machine signal oscillations will also be plotted to give an indication of network behaviour resulting from the disturbances as well as the impact of the TCSC on CFCTs.

CFCTs will be used as the measure of transient stability margins. Beyond the CFCT, the energy absorbed by the affected generators during the fault would not be transferrable to the connected network without some generators losing synchronism. A higher CFCT indicates a strongly connected transmission network for evacuation of power. The expectation is that the CFCTs (transient stability margins) will increase when TCSCs are applied on transmission lines.

Chapter 6 presents conclusions deduced from the investigations conducted.

2. REVIEW OF THE TCSC CHARACTERISTICS

SSR risk is associated with higher degrees of compensation of transmission lines fed from thermal generators. In such cases, analyses have shown that the complementary series resonance frequency of the compensated line coincides with some poorly damped torsional vibration frequency of the turbo-generator shaft and this could induce increased mechanical stress in the shafts [7].

Two main approaches can be employed to mitigate SSR effects, the first being employing an active filter that monitors the SSR frequencies and controls the series capacitor voltage to introduce an electrical damping torque. The second approach entails making the series capacitor act inductively in the subsynchronous frequency band, thereby preventing subsynchronous torsional interaction between the series capacitor and the shaft of a turbine generator [7]. Due to thermal generation being dominant (SSR concerns become key) in the northern part of South Africa, the application of TCSCs in this part of the network is preferred.

A TCSC consists of a series capacitor connected in parallel with a thyristor controlled reactor. The reactor is controlled by anti-parallel thyristors. Figure 2.1 depicts the basic circuit of a TCSC [1]. When in practical operation a metal oxide varistor (MOV) is installed in parallel with the capacitor to protect the TCSC module from overvoltages.

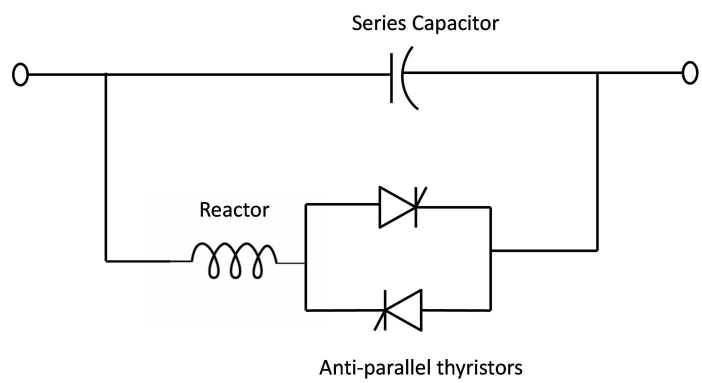

Figure 2.1: Basic circuit of a TCSC

The variable impedance of the TCSC is achieved by changing the inductive reactance of the TCR in parallel with the fixed capacitor. The magnitude of the inductive reactance is determined by the firing angle of the thyristors.

2.1. Operation of a TCSC

In capacitive operation mode (relevant for transient stability studies), the thyristor in the TCR module is triggered once per cycle and has a conduction interval that is shorter than half the rated power frequency cycle. The TCR has a variable reactance that is in parallel with the fixed capacitive reactance as shown in Equation 2.1 on the next page. Figure 2.2 depicts the operation regions of the TCSC [1].

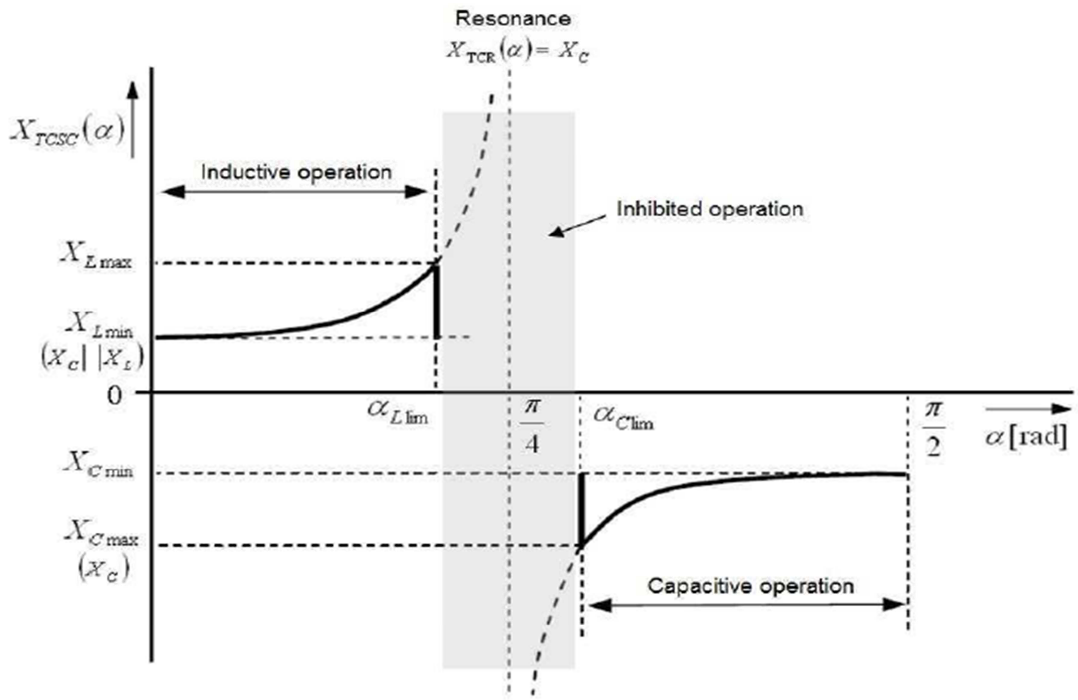

Figure 2.2: TCSC operation diagram

The *magnitude* of the resultant reactance of the TCSC, X_{TCSC} is given by the expression [1]:

$$X_{TCSC}(\alpha) = \frac{X_C X_{TCR}(\alpha)}{X_{TCR}(\alpha) - X_C} \tag{2.1}$$

If the firing angle, α of the thyristors is $0 < \alpha < (\pi/2)$, the magnitude of the TCR reactance is given by the expression [1] below:

$$X_{TCR}(\alpha) = X_L\left(\frac{\pi}{\pi - 2\alpha - \sin 2\alpha}\right) \tag{2.2}$$

Where, $\pi - 2\alpha$ is the conduction angle

Resonance occurs when $X_{TCR}(\alpha) = X_C$ and at resonance, X_{TCR} is infinite. The TCSC must not be operated close to resonance. The shaded operating region in Figure 2.2 is the prohibited resonance region. As shown in Figure 2.2, the TCSC is inductive if the firing angle is smaller than resonance angle and is capacitive for firing angle greater than resonance angle [9].

2.2. TCSC Modes of Operation

The TCSC has four modes of operation namely blocking mode, bypass mode, capacitive mode and inductive mode. The firing angle of the TCR part of the TCSC determines the mode of operation. In order to determine whether the TCSC is capacitive or inductive, a negative sign is introduced to Equation 2.1, to form Equation 2.3 [9].

$$X_{TCSC}(\alpha) = -\frac{X_C X_{TCR}(\alpha)}{X_{TCR}(\alpha) - X_C} \tag{2.3}$$

If X_{TCSC} is positive ($X_{TCR} < X_C$), then the TCSC exhibits an inductive effect and if X_{TCSC} is negative ($X_{TCR} > X_C$), it exhibits a capacitive effect. When, $X_{TCR} = \infty$, the thyristors are blocked.

Blocking Mode of Operation

If the thyristors are not conducting, the TCSC behaves like a fixed series capacitor. In this mode the thyristor firing angle is 90^o and thus the TCR is off. $X_{TCR} = \infty$ when the thyristors are blocked. This operation mode is generally avoided especially if SSR is of concern. Figure 2.3 depicts the TCSC operating in blocking mode [2]. The current through the capacitor is the same as the line current.

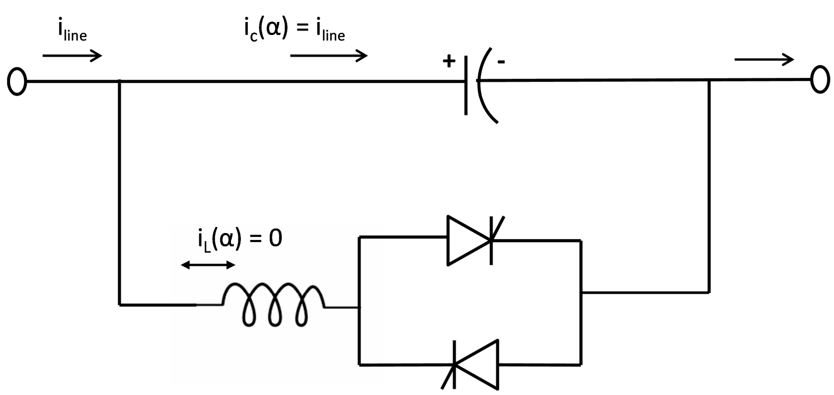

Figure 2.3: Blocking mode of operation

Bypass Mode of Operation

If the anti-parallel thyristors are gated for 180^0 conduction so that they are always conducting, most of the line current will flow through the TCR (full conduction). The series capacitor is essentially bypassed.

Since X_C is much greater than X_{TCR}, the TCSC reactance, X_{TCSC} given by the Equation (2.3) is positive implying that the TCSC will exhibit an inductive effect [9]. Figure 2.4 depicts the TCSC operating in bypassed mode [2].

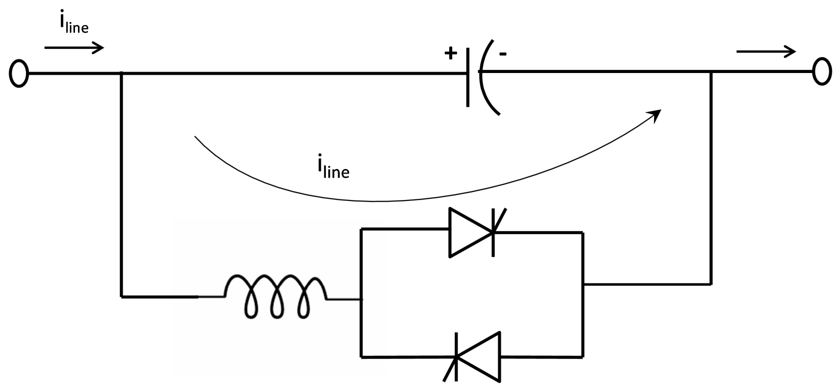

Figure 2.4: Bypassed mode of operation

Capacitive Mode of Operation

In this mode the thyristors are gated in the region where $\alpha_{min} < \alpha < \pi/2$ such that conduction is for part of the cycle (partial conduction).

For this firing angle, $X_{TCR} > X_C$, thus X_{TCSC} as given by the Equation (2.3) is negative and the TCSC exhibits a capacitive effect. Figure 2.5 depicts the TCSC operating in capacitive mode [2].

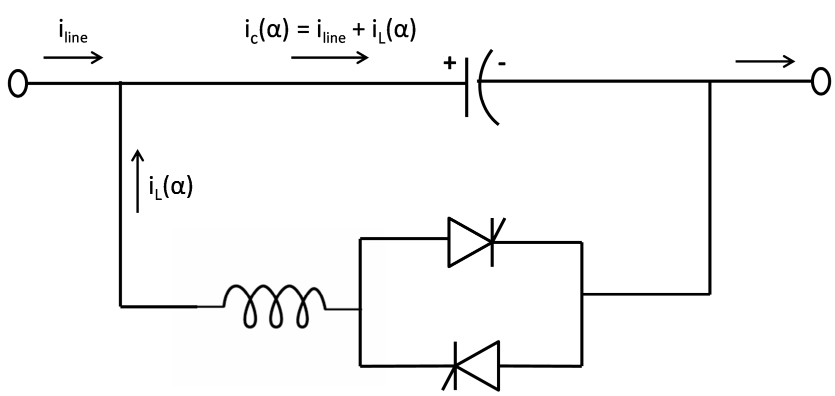

Figure 2.5: Capacitive mode of operation

Inductive Mode of Operation

In this mode the thyristors are gated in the region where $0 < \alpha < \alpha_{lim}$ such that conduction is for part of the cycle (partial conduction).

For this firing angle, $X_{TCR} < X_C$, thus X_{TCSC} as given by the Equation (2.3) is positive and the TCSC exhibits an inductive effect. Figure 2.6 depicts the TCSC operating in inductive mode [2].

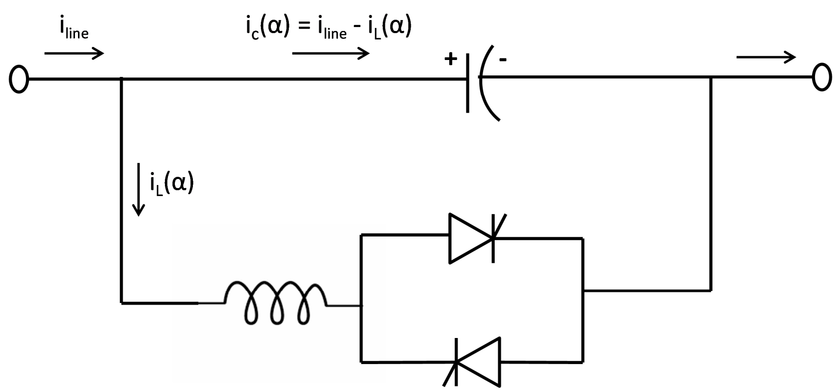

Figure 2.6: Inductive mode of operation

The capacitive and inductive modes of operation enhance the transient stability; other modes of operation are not useful in dynamic system transient stability enhancement.

3. IMPACT OF THE TCSC ON THE TRANSIENT STABILITY

In the event of large disturbances like line faults on an electrical power system, the generators connected will accelerate during the fault and after fault clearance the generators should be able to decelerate by transferring the absorbed kinetic energy into the electrical system in order to maintain synchronism amongst all connected generators. The ability to transfer energy is largely depended upon the impedance of the transmission lines connected to the generators.

Low impedance from a generator to the rest of the network implies strong connection hence greater ability to transfer kinetic energy absorbed. The TCSC‘s ability to dynamically lower the impedance of a line plays a vital role in increasing the post-fault synchronising torque which is important for transient stability.

3.1. Transient Stability Overview

From the swing equation [10]:

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_m - P_{\max}\sin\delta \tag{3.1}$$

where:

P_m	=	mechanical power input (pu)
P_{max}	=	maximum electrical power output (pu)
H	=	inertia constant (MW-sec/MVA)
δ	=	rotor angle (elec. radians)
t	=	time (sec.)

From Equation 3.1, Acceleration Power during the fault, $P_a = P_m - P_{max} \sin \delta$. From the onset of the fault, the generator accelerates because the mechanical power, P_m is much larger that P_e, the electrical power. The magnitude of the electrical power, P_e ($P_e = P_{max} \sin \delta$), depends on the fault type and location. For faults very close to the generator P_e is approximately zero [10].

During a fault, as the machines accelerate they absorb and build up kinetic energy. The kinetic energy stored depends on the generator inertia, fault type and fault duration. After fault clearance the generators start decelerating and the kinetic energy absorbed has to be transferred into the system via a sufficiently strong network to ensure that all the kinetic energy absorbed is expended.

When the kinetic energy transferred during the generators deceleration is equal to the kinetic energy absorbed during acceleration, the generators would maintain synchronism.

The transient stability phenomenon can be illustrated using the classic generator model (represented by a transient voltage, E' behind a transient reactance, X'_d) connected via a step-up transformer to a network of two transmission lines supplying an infinite bus.

Figure 3.1 depicts a simple circuit to illustrate the transient stability phenomenon [5].

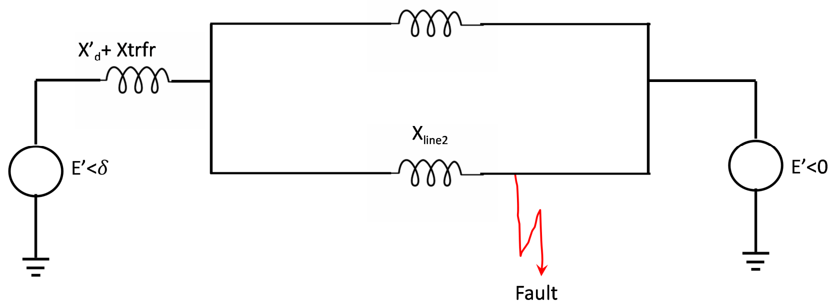

Figure 3.1: Illustration of transient stability

Figure 3.2 depicts the behaviour of the system [10] in the event of a fault on one of the lines as illustrated in Figure 3.1.

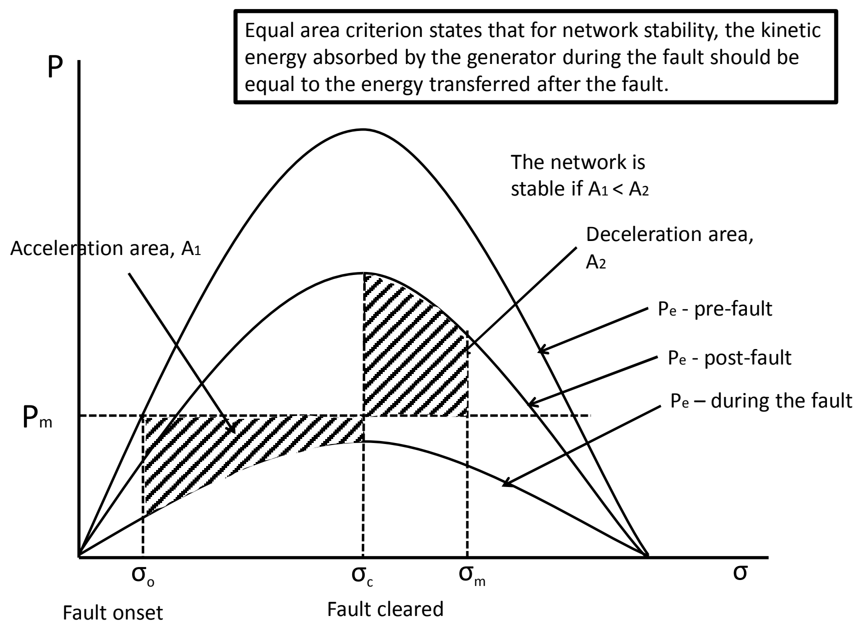

Figure 3.2: Equal angle area criterion

At the fault onset, with the rotor angle equal to σ_o, the machine will accelerate and absorb kinetic energy until the fault is cleared at rotor angle, σ_c. After fault clearance, the machine starts to decelerate and the kinetic energy gained by the machine during the fault is fully transferred to the network when the rotor angle becomes σ_m . The network will return to a stable operating point if the acceleration area (energy), A_1 becomes equal to deceleration area (energy), A_2 (i.e. the equal angle criterion).

3.2. Illustration of TCSC action

The impact of a TCSC on transient stability is illustrated in this section. Figure 3.3 shows a transmission line equipped with a TCSC.

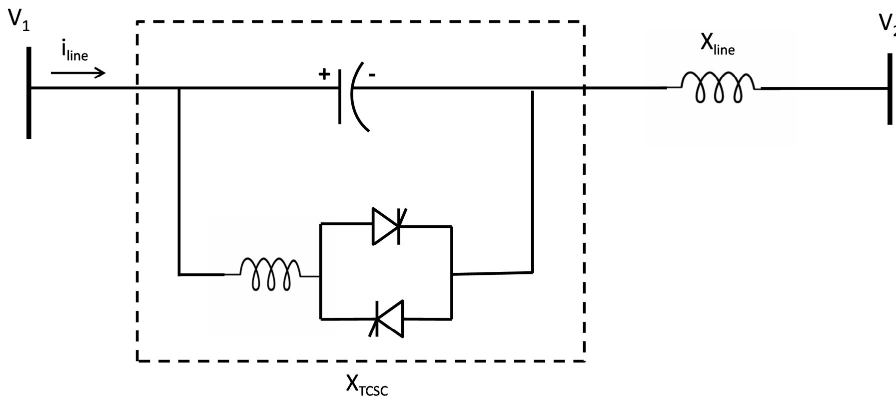

Figure 3.3: Transmission line with a TCSC

In the absence of a TCSC, the active power transferred from node, V_1 to node, V_2 is a function of the sending end voltage, V_1, receiving end voltage, V_2, load angle difference, σ_1 - σ_2 and the effective line impedance, X_{line}.
Active power transferred is given by the expression [1]:

$$P_{12} = \frac{V_1.V_2}{X_{line}}.\ Sin(\sigma_1 - \sigma_2) \qquad (3.2)$$

If a TCSC is installed on the transmission as shown in Figure 3.3, the power transmitted between node, V_1 and node, V_2 becomes:

$$P''_{12} = P_{12} + \Delta P = \frac{V_1.(V_2 + \Delta V)}{X_{line} \pm \Delta X}.\ Sin(\sigma_1 - \sigma_2 \pm \Delta\sigma) \qquad (3.3)$$

Where,

ΔP is the change in power transfer,

ΔV is the voltage change in node, V_2 as result of change in line impedance,

ΔX is the change in line impedance as a result of the resultant reactance, X_{TCSC} via the action of the TCSC,

$\Delta\sigma$ is the change in the load angle caused by the changed reactance of the transmission line.

In order to demonstrate the action of a TCSC, a simple network, shown in Figure 3.4, comprising a generator supplying a load via two connected transmission lines with one of the transmission line series compensated by a TCSC is assumed.

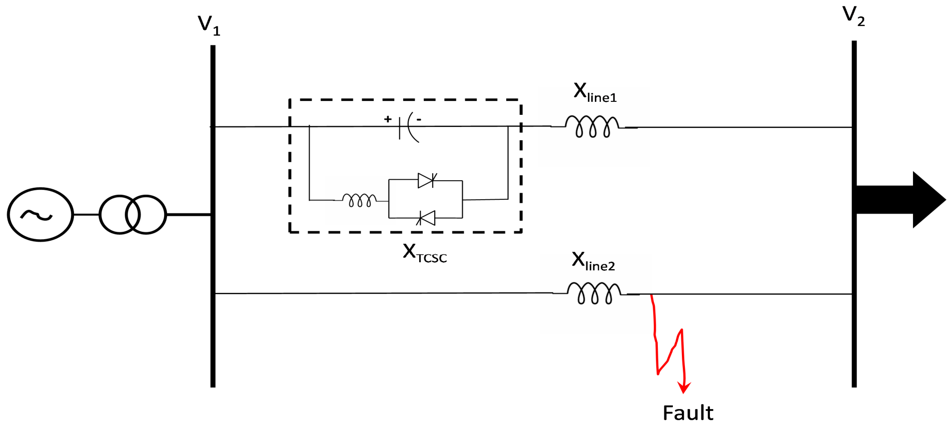

Figure 3.4: Simple network to illustrate TCSC action

The TCSC action is illustrated by a three phase fault simulated on a line without a TCSC and the fault is cleared by switching off the faulted line. The remaining line equipped with a TCSC would be able to evacuate more power from the generator to the load. Figure 3.5 depicts the current pulses injected onto the line current due to TCR action [8].

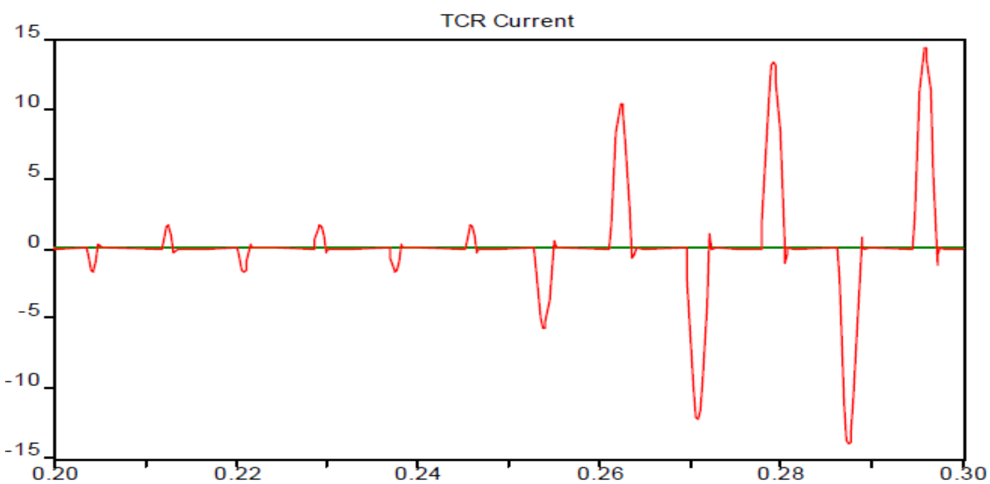

Figure 3.5: Line current pulses due to TCR action

As shown in Figure 3.5, the TCR will conduct during part of the cycle and during the conduction period current pulses are injected onto the line current. Amplitude changes with the firing angle. A larger firing angle results in longer conduction hence larger amplitude. Figure 3.6 depicts the current waveform across the capacitor compensating a line [8].

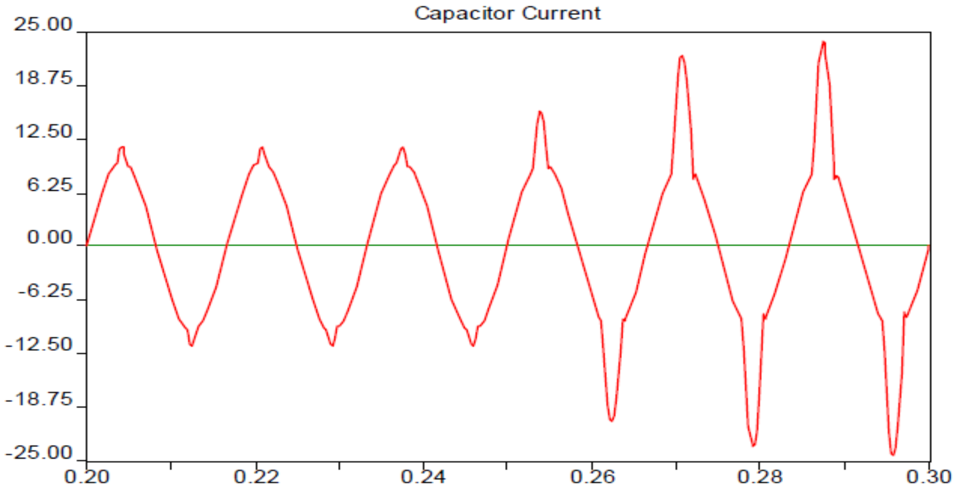

Figure 3.6: Line current (current across the capacitor) with due to TCR action

Figure 3.6 shows the capacitor current due to TCSC action. In capacitive mode of operation the TCR current rides on top of line current in the capacitor [8]. In inductive mode of operation the TCR current is subtracted instead of being added.

Figure 3.7 depicts the impact of TCSC action on the transient stability margin.

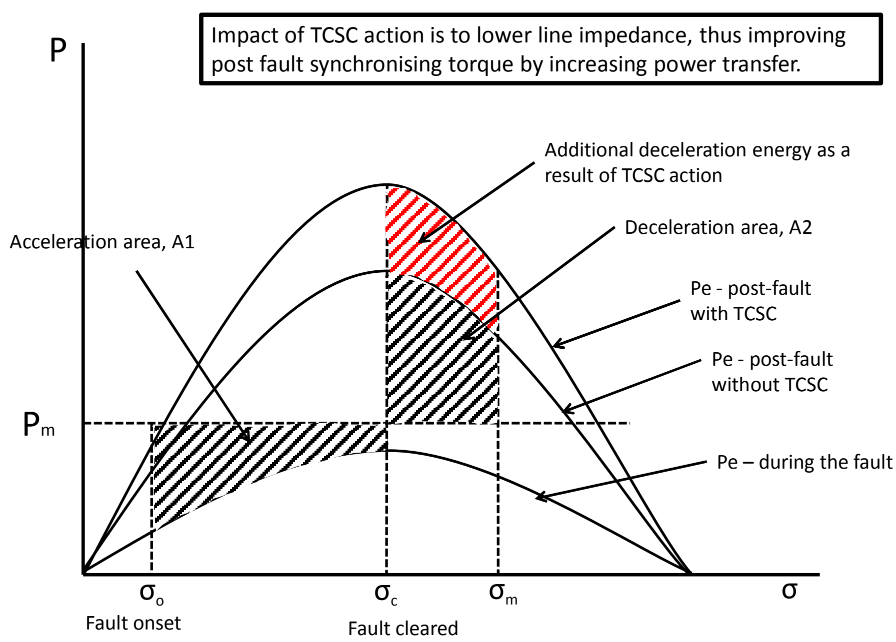

Figure 3.7: Impact of TCSC action on transient stability

As shown in Figure 3.7, when a TCSC is applied, more kinetic energy is transferred due to increased power transfer resulting in increased generator deceleration energy. The transient stability margins are thus improved.

4. INITIAL SIMULATIONS ON THE SOUTH AFRICAN TRANSMISSION GRID

4.1. Network under study

The impact of TCSC action will be demonstrated and simulated through the application of a TCSC transmission lines connected to Medupi, a 6 x 846 MW power station (PS) located in the northern part of South Africa. The planned South African transmission (year 2020) network with all Medupi generators assumed to be in service will be employed in the simulations [11].

There will be seven transmission lines connecting Medupi power station to the rest of the South African Grid. Figure 4.1 show the existing transmission lines connecting existing Matimba 6 x 664 MW PS to the transmission grid and the future transmission lines that will connect Medupi 6 x 846 MW PS. Matimba PS which is about 20km from Medupi PS supplies the same load centre as Medupi PS.

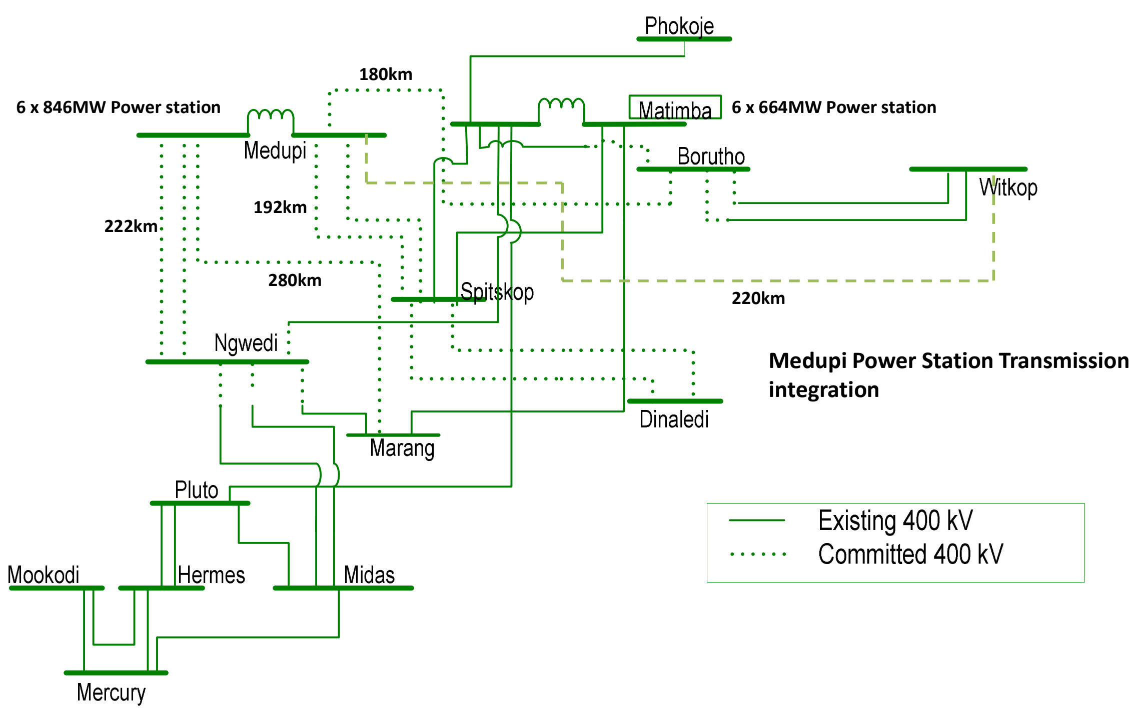

Figure 4.1: Transmission lines connection Medupi and Matimba PS

The research will focus on the lines connected to Medupi PS because the need for a TCSC is greater due to the large size of the Medupi generators compared to the Matimba generators. Studies conducted to integrate future generation have also proposed utilising the lines that will be connected to Medupi for power evacuation [11]. Therefore, simulations of TCSC action will be investigated on these lines only.

4.2. Modelling of the TCSC in PSS®E

The TCSC model as applied in PSS®E ver. 33.4, analysis software will be used. PSS®E uses the CRANIT model to simulate the TCSC action. Figure 4.2 depicts the CRANIT model control function [12].

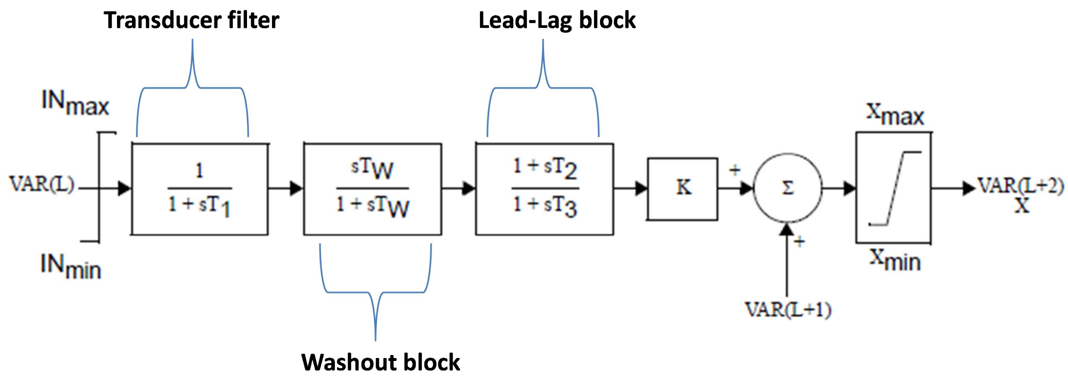

Figure 4.2: Block diagram control function of TCSC Model

The model consists of constants, variables and internal constant inputs that the user can specify.

The **constants** include the following:

- IN_{max} and IN_{min}, maximum and minimum limit (pu) on input signal respectively
- X_{max} and X_{min}, maximum and minimum limit (pu) on output (line reactance) respectively
- K is the gain

T_1, T_w and T_2, T_3 are time constants for the transducer filter, washout block and lead-lag block respectively. The lag block acts as a transducer filter and the lead-lag block (T_1> T_2) compensate for the phase lag between input and the output signals.

The washout block serves as a high pass filter with time constant, T_w sufficiently large to allow signals associated with the fault conditions (high frequency signals) to pass through. The washout block is important in that it inhibits changes to the output due to steady state changes. The washout block will only allow high frequency changes to pass. The **variables** include VAR(L), input variable, VAR(L+1), initial output and VAR(L+2), the desired reactance.

The model **internal inputs** that the user can specify include the following:

CRANIT Input Code:

- pu current on branch (branch between two busbars)
- pu power on branch (branch between two busbars)
- pu frequency difference between two busbars
- pu busbar voltage
- pu frequency deviation on busbar
- machine speed deviation (machine at busbar)

In PSS®E, the branch impedance is adjusted by thyristor control of a reactor in parallel with a series capacitor. The CRANIT model assumes the impedance adjustment to be both continuous and linear.

Compensation limits X_{max} and X_{min} can take any positive (reactor) or negative (capacitor) value, as long as their range includes the initial branch reactance [13]. Upon initialization, model output VAR (L+1) and VAR (L+2) are set equal to the power flow branch reactance. Because of the washout (T_w), controller output is zero in the steady-state. As the simulation progresses, the effective branch reactances are modified in response to changes in controller input VAR (L).

The controls for power system stability in response to large disturbances are generally treated as two separate issues [14]. Transient or first-swing stability deals with the system recovery during the first swing. Damping of subsequent oscillations commonly known as dynamic stability is the second aspect. To improve first-swing stability, it is necessary to increase the system synchronizing power. The TCSC power equipment (i.e., the actual reactance element and firing controls) can be represented relatively simply in the stability program. In this case, the firing control system can be represented by a first-order filter with a time constant (order of 50 ms). Switching could be made on the basis of measured power, line current, or bus voltage.

4.3. Medupi and Matimba Generator Models

Since the Medupi and Matimba power stations are thermal, the round rotor generator models are employed. Table 4.1 and Table 4.2 list values of the Matimba and Medupi generator constants.

Table 4.1 : Matimba Generator Model Parameters

Matimba Generator Constant	Value
T'do	6.38
T"do	0.048
T'qo	1.914
T"qo	0.048
H	2.34
D	0.00
Xd	2.68
Xq	2.49
X'd	0.41
X'q	0.68
X"d = X"d	0.287
X1	0.22
S (1.0)	0.10
S (1.2)	0.40

Table 4.2: Medupi Generator Model Parameters

Medupi Generator Constant	Value
T'do	5.20
T"do	0.021
T'qo	0.690
T"qo	0.032
H	2.07
D	0.00
Xd	2.40
Xq	2.16
X'd	0.34
X'q	0.51
X"d = X"d	0.25
X1	0.22
S (1.0)	0.04
S (1.2)	0.20

The generator model parameters in Table 4.1 are obtained from the Eskom Dynamic Library [15] for existing generators. The model parameters for Medupi generators were obtained from the Eskom Dynamic Library developed from generator manufacturer's data sheets. The machine constants are defined as follows (time constants in seconds and reactances in p.u.):

- T'do – machine d-axis open circuit transient time constant
- T"do – machine d-axis open circuit subtransient time constant
- T'qo – machine q-axis open circuit transient time constant
- T"qo – machine q-axis open circuit subtransient time constant
- H – Machine inertia constant
- Xq – machine q-axis synchronous reactance
- X'd – machine d-axis transient reactance
- X'q – machine q-axis transient reactance
- X"d – machine d-axis subtransient reactance
- X"q – machine q-axis subtransient reactance
- X1 – machine stator leakage inductance
- S(1.0) and S(1.2) are saturation points on the machine open–circuit magnetisation curve
- Xd – machine d-axis synchronous reactance

4.4. Matimba and Medupi Exciter Models

The function of an excitation system is to supply and automatically adjust the field current of a synchronous generator to maintain the terminal voltage as the generator power output varies within the continuous capability of the generator.

Exciters will be required for the Medupi and Matimba for automatic voltage regulation. The machines are large and exciters with a fast response are necessary to enhance transient stability in the event of large disturbances.

As shown in Figure 4.3, Medupi generators will utilise the ESST1A exciter model as represented in the PSS®E standard model library.

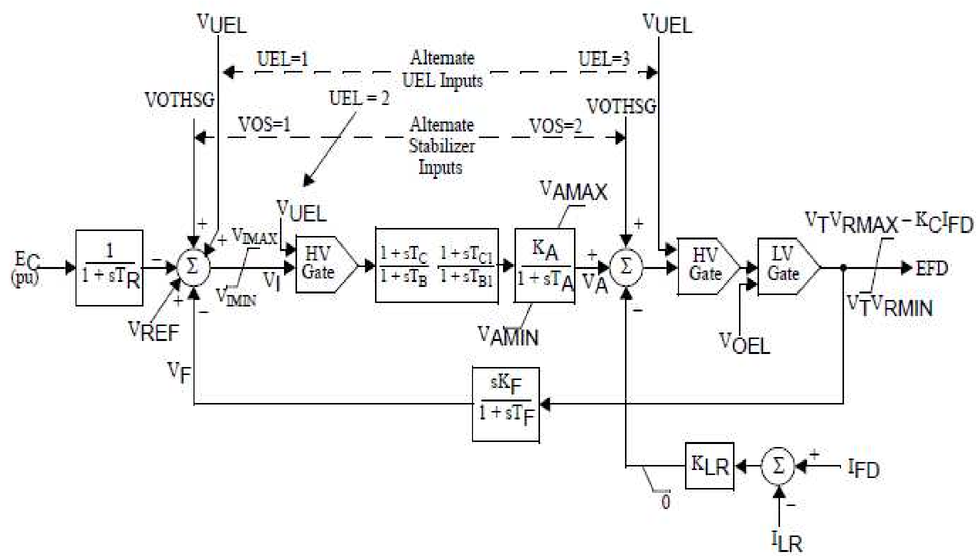

Figure 4.3: ESSTIA Exciter model block diagram

Table 4.3 shows the Medupi generators exciter model parameter values.

Table 4.3: Medupi Exciter model parameter values

Medupi Exciter Constant	Value
TR (sec)	0.020
VI MAX	0.150
VI MIN	-0.150
TB (sec)	4.000
TC (sec)	80.00
TB1 (sec)	1.000
TC1 (sec)	1.000
KA	400.0
TA (sec)	0.010
VA MAX	6.780
VA MIN	-6.780
VR MAX	6.780
VR MIN	-6.780
KC	0.000
KF	0.000
TF>0 (sec)	1.000
KLR	0.000
ILR	0.000

As shown in Figure 4.4, existing Matimba generators utilise the IEEET1 model as represented in the PSS®E standard model library.

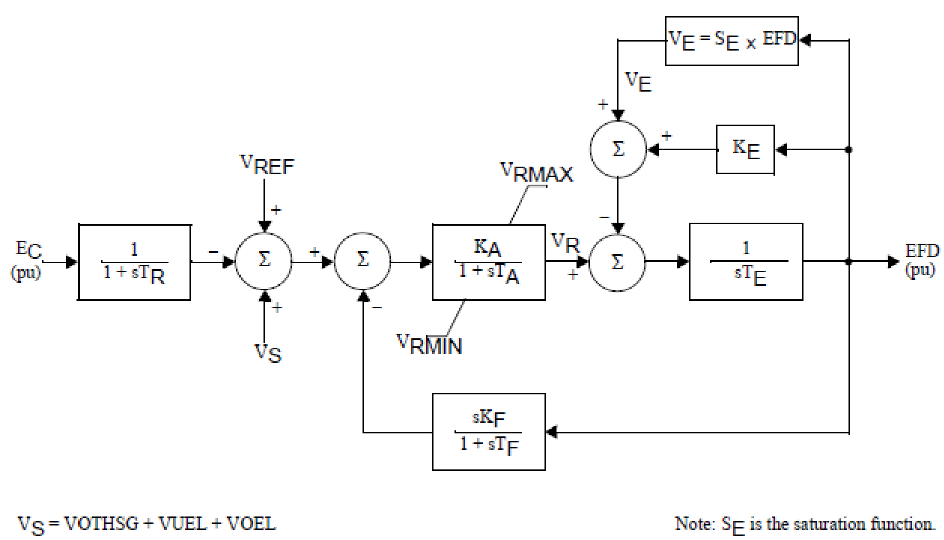

Figure 4.4: IEEET1 Exciter model block diagram

Table 4.4 shows the Matimba generators exciter model parameter values.

Table 4.4: Matimba Exciter model parameter values

Matimba Exciter Constant	Value
TR (sec)	0.028
KA	175.0
TA (sec)	0.030
VR MAX or zero	12.00
VR MIN	-12.00
KE or zero	0.000
TF>0 (sec)	0.266
KF	0.025
TF>0 (sec)	1.500
Switch = 0	0.000
E1	4.500
SE(E1)	1.500
E2	6.000
SE(E2)	2.460

4.5. Matimba and Medupi Stabiliser Models

The purpose of a power system stabiliser is to modulate the generator field current or voltage to inject a torque onto the rotor in phase with any speed variation. This increases the damping of rotor oscillations and the associated power swings. Stabilisers enhance damping in situations where fast acting exciters with large gains are employed. As shown in Figure 4.5, existing Matimba generators utilise the IEE2ST stabiliser model represented in the PSS®E standard model library [15].

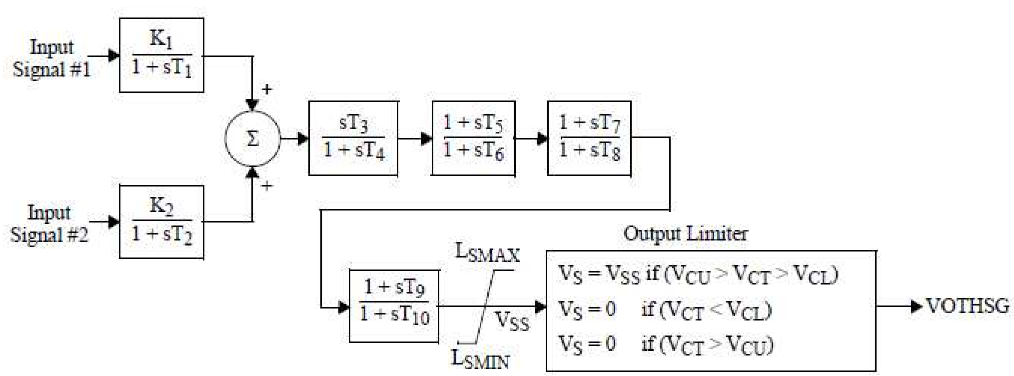

Figure 4.5: IEEET1 Stabiliser model block diagram

Table 4.5 shows the Matimba stabiliser model parameter values.

Table 4.5: Matimba Stabiliser model parameter values

Matimba Stabiliser Constant	Value
K1	-1.000
K2	0.000
T1	0.100
T2	0.000
T3 (if equal 0, sT3 will equal 1)	2.000
T4 (>0)	2.000
T5	0.000
T6	0.000
T7	0.000
T8	0.000
T9	0.000
T10	0.000
LSMAX	0.050
LSMIN	-0.050
VCU (p.u. if equal 0,ignore)	0.000
VCL (p.u. if equal 0,ignore)	0.000

When TCSCs are employed together with power system stabilisers, tuning become necessary because of interaction between the two that may lead to instability. In order to simulate the impact of the TCSC only and reduce the impact of stabilisers in the study area, the stabilisers at Medupi were excluded.

4.6. Case study to demonstrate TCSC action

TCSC action will be demonstrated by simulating a three phase fault on one of the lines (i.e. the Medupi – Burotho 400 kV line) connecting Medupi PS. The TCSC will be installed on one of the unfaulted lines. After fault clearance, it is expected that the series compensated line (i.e. the Medupi – Witkop 400 kV line) will exhibit reduced impedance due to TCSC action, resulting in increased power transfer.

Increased power transfer will result in increased post-fault synchronising torque since more energy can be transferred into the network from the generators. Figure 4.6 depicts the network with the faulted Medupi – Burotho 400 kV line and the series compensated Medupi – Witkop 400 kV line. TCSC action is represented by the variable capacitor symbol.

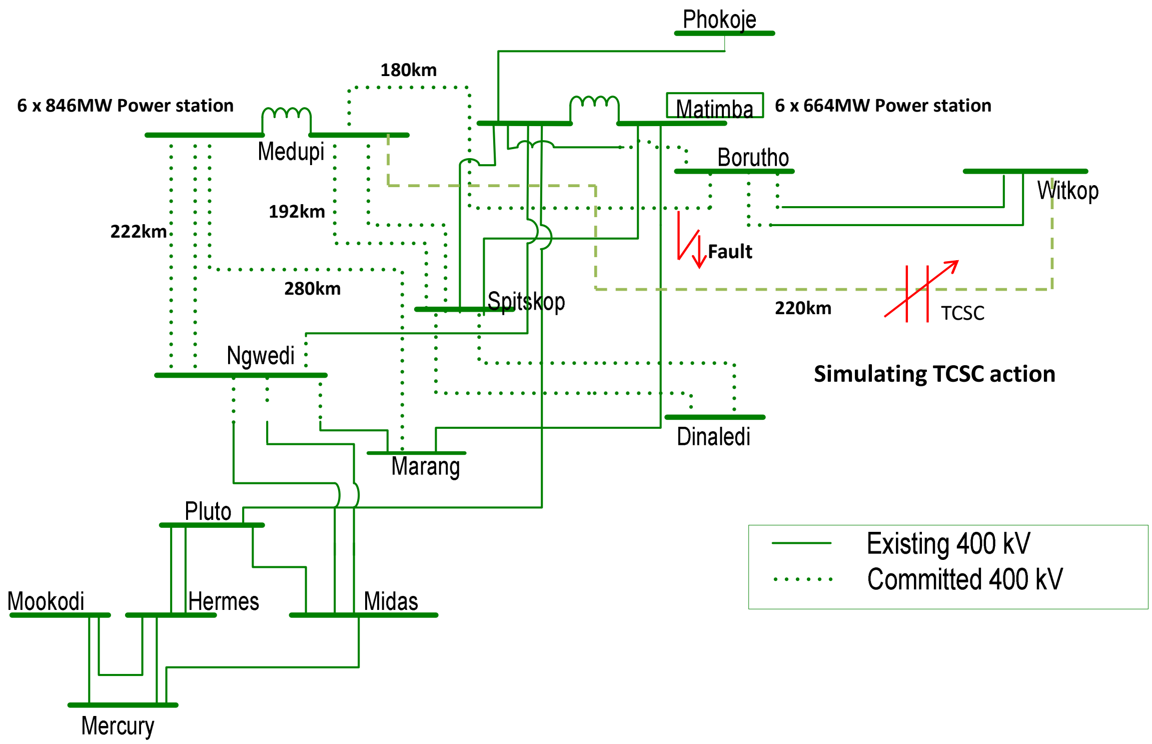

Figure 4.6: Case study network

The sequence of events will be as follows:

- The network behaviour is simulated without the fault (in steady state) for 1 second;
- After 1 second, a three-phase fault is applied on the Medupi – Burotho 400 kV line close to the Medupi PS 400 kV busbar; and
- After 75 ms, the fault is cleared by tripping the faulted Medupi – Burotho 400 kV line.

The following network signals will be observed during the simulation:

- Change in line impedance of the series compensated line;
- Active power flow through the series compensated line;
- Rotor angle deviation of the Medupi generator machines; and
- Voltage recovery at the Medupi 400 kV bus (generator transformers HV bus).

In order to determine the impact of the TCSC, a comparison is made between the scenarios *with* and *without* the TCSC. The aforementioned events are repeated and network signals are plotted on the same scale.

TCSC action on a transmission line compensates the inductive reactance of the line. The inductive reactance of the Medupi – Witkop 400 kV line is 0.03256pu. The Medupi – Witkop line will be series compensated in a range between 40-70 percent, implying that the line inductive reactance can be dynamically controlled between 0.0196pu and 0.0098pu.

4.6.1. Calculation of effective series capacitance

The effective series capacitive reactance that results in a series compensation of 40% is calculated as follows.

Effective series reactance = j (X_L - X_C) where, X_L is the line inductive reactance and X_C is the series capacitor reactance.

Therefore, compensated series reactance =j 0.0196 pu = j (0.03256 - X_C) pu

Effective series capacitive reactance, X_C = 0.013 pu.
Converting to ohms, X_C = 0.013 * Z $_{base}$. On a power base of 100 MVA and voltage base of 400 kV, Z $_{base}$ = 1600

X_C = 0.013 * 1600 = 20.84 Ω

Therefore, effective series capacitive reactance = 20.84 Ω

Since, $\mathrm{X_C} = {}^{1}/_{2\pi \mathrm{fC}}$, Equivalent capacitor size, $C = {}^{1}/_{2\pi 50 * 20.84}$ = 153 $\mu\mathrm{F}$

In the same way the effective capacitance resulting in series compensation of 70 % can be calculated.

The change in bus bar voltage on the high voltage (400 kV) side of the Medupi generator transformer was used as input to the TCSC during the simulation. Table 4.6 shows the TCSC controller parameter values used.

Table 4.6: TCSC controller parameter values

TCSC Model Constant	Value
T1 (sec)	0.050
T2 (sec)	0.100
T3 (>0, sec)	0.020
Tw (>0, sec)	1.900
K	5.000
Xmax (pu) – max. limit on output	0.0196
Xmin (pu) – min. limit on output	0.0098
INmax (pu) – max. limit on input	1.050
INmin (pu) – min. limit on input	0.900

4.6.2. Simulations results of the case study

Figure 4.7 depicts the behaviour of the line impedance of the series compensated line during the simulation. At the onset of a fault, a signal is send to the TCSR module to reduce the line impedance to the minimum value.

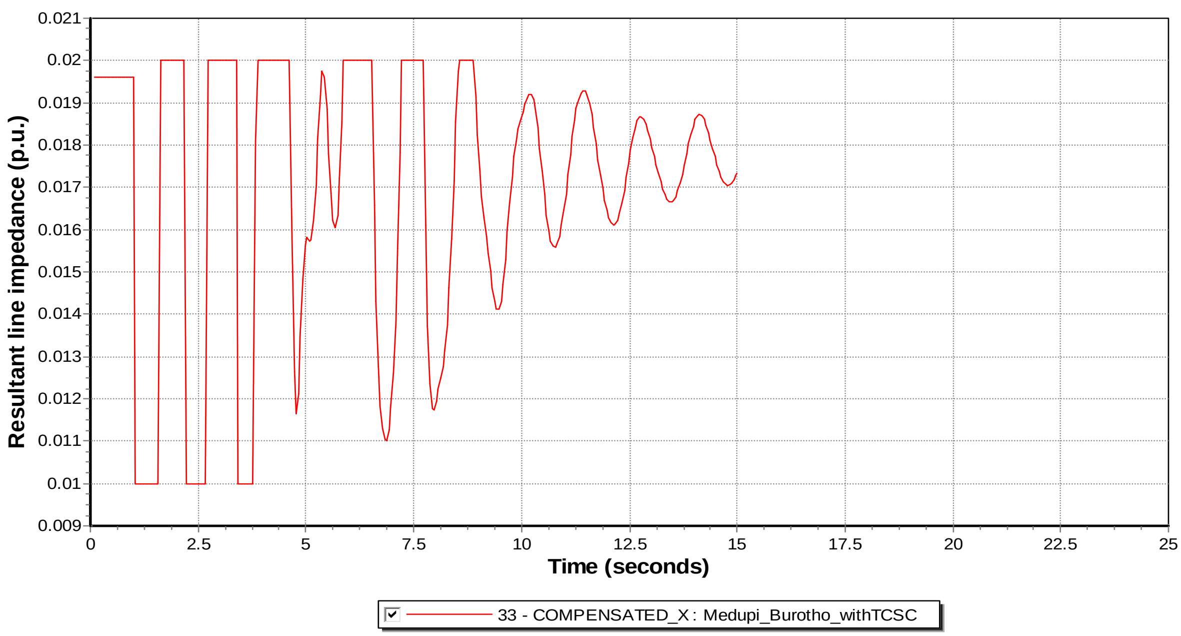

Figure 4.7: Equivalent line impedance (p.u.) of line compensated with a TCSC

As shown in Figure 4.7, the line impedance varies between 0.0196pu to 0.0098pu due to TCSC action. The line impedance gradually settles towards the lowest level of compensation as the system recovers from the fault and returns to a stable operating point.

Practically, the line impedance will settle to a steady value quicker by fine tuning the TCSC control logic. Note: emphasis is not on tuning the TCSC to increase damping but on the TCSC action that results in increased power transfer the first few cycles after the fault (hence increasing post-fault synchronising torque).

Figure 4.8 depicts the active power flow on the Medupi - Witkop 400 kV line with and without the TCSC.

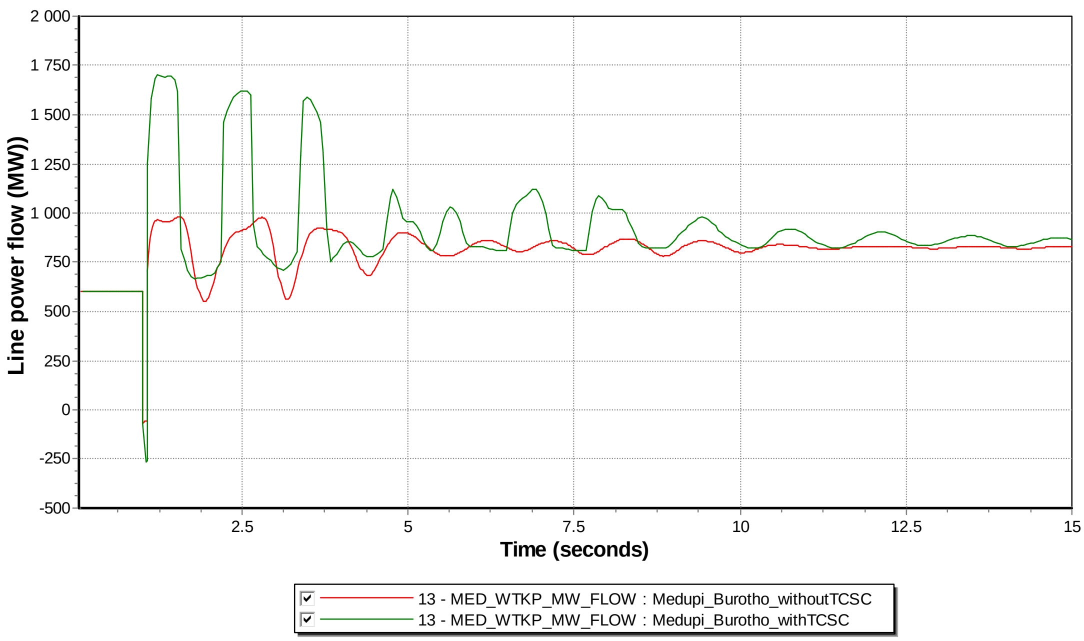

Figure 4.8: Power flow on a line compensated with a TCSC

As shown in Figure 4.8, the introduction of a TCSC results in increased power transfer through the series compensated line. After fault clearance, bulk power (because of very low line impedance) is transferred to the network via the series compensated line. As can be observed in Figure 4.8, power transfer is boosted to about 1750 MW during the first swing after fault clearance in contrast to about 1000 MW transferred without the TCSC.

Figure 4.9 depicts the Medupi rotor angle deviation with and without the TCSC.

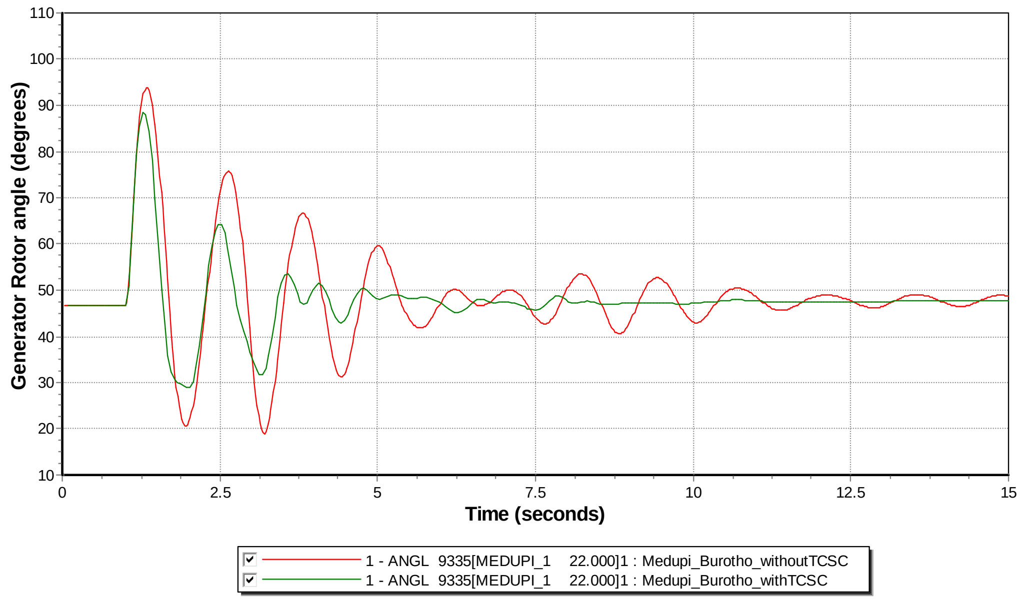

Figure 4.9: Medupi rotor angle separation with and without a TCSC applied

As shown in Figure 4.9, the Medupi machine rotor angle deviation during the first swing is larger without the TCSC. When the TCSC is included, the angle deviations are reduced and the damping of oscillations can be faster with proper tuning.

Figure 4.10 depicts the Medupi high voltage (HV) busbar voltage magnitude *with* and *without* the TCSC.

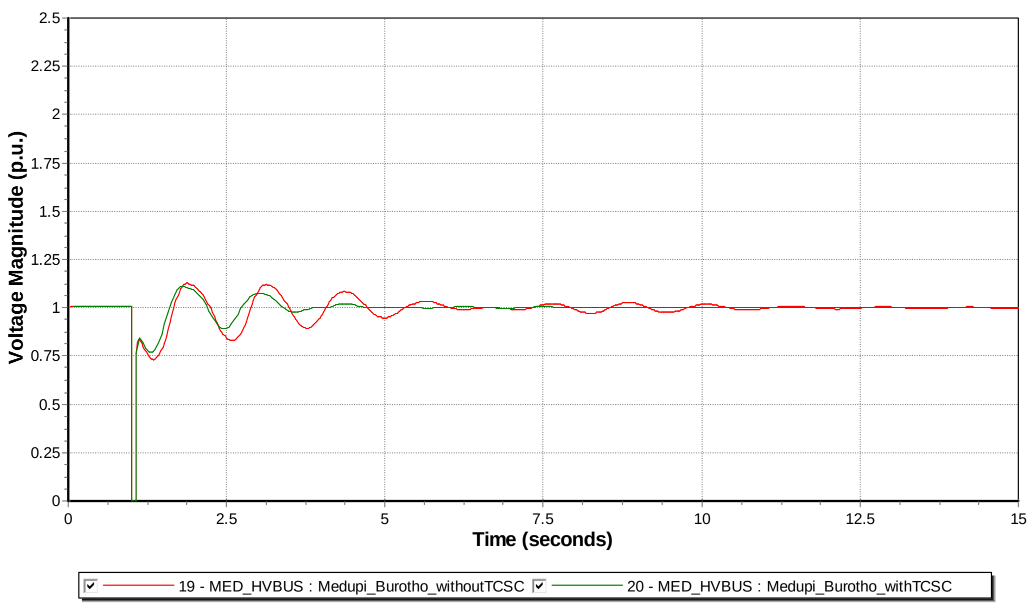

Figure 4.10: Medupi High Voltage (HV) bus with and without a TCSC applied

As shown in Figure 4.10, the Medupi HV busbar voltage exhibits faster recovery with a TCSC introduced.

5. SIMULATIONS ON THE SOUTH AFRICAN TRANSMISSION GRID – CFCT STUDIES

Studies were first conducted to determine the line on which the occurrence of a three-phase line fault would result in the lowest critical fault clearing time. This lowest critical fault clearing time is considered the critical fault clearing time (CFCT) for Medupi PS without the TCSC. Subsequent to identifying the line fault that results in the lowest CFCT, studies were conducted to determine the series compensated line that results in the largest improvement in the CFCT in the event of this line fault. The improvement in CFCT dictates the choice of line where to optimally place the TCSC.

Further simulations were performed on the line selected to install the TCSC employing various degrees (percentages) of series compensation and observing how the CFCT changes in response to changing compensation levels.

5.1. Determining the CFCT without the TCSC

Simulations were conducted to determine the CFCT in the event of a three-phase line fault on any of the transmission lines connected to Medupi PS.

The sequence of events to simulate a three-phase line fault was as follows:

- The network behaviour is simulated in steady state for 1 second;
- After 1 second, a three-phase fault is applied on one of the lines connected to Medupi PS. The fault is applied close to the Medupi PS 400 kV busbar in order to simulate the worst condition; and
- The fault is cleared after a series of fault duration times until the CFCT is determined. Fault duration time is gradually increased until the point of network instability.

A three phase fault was simulated on the Medupi – Witkop 400 kV 220 km line and as shown in Figure 5.1, the CFCT is 78 ms; beyond 78 ms the network becomes unstable.

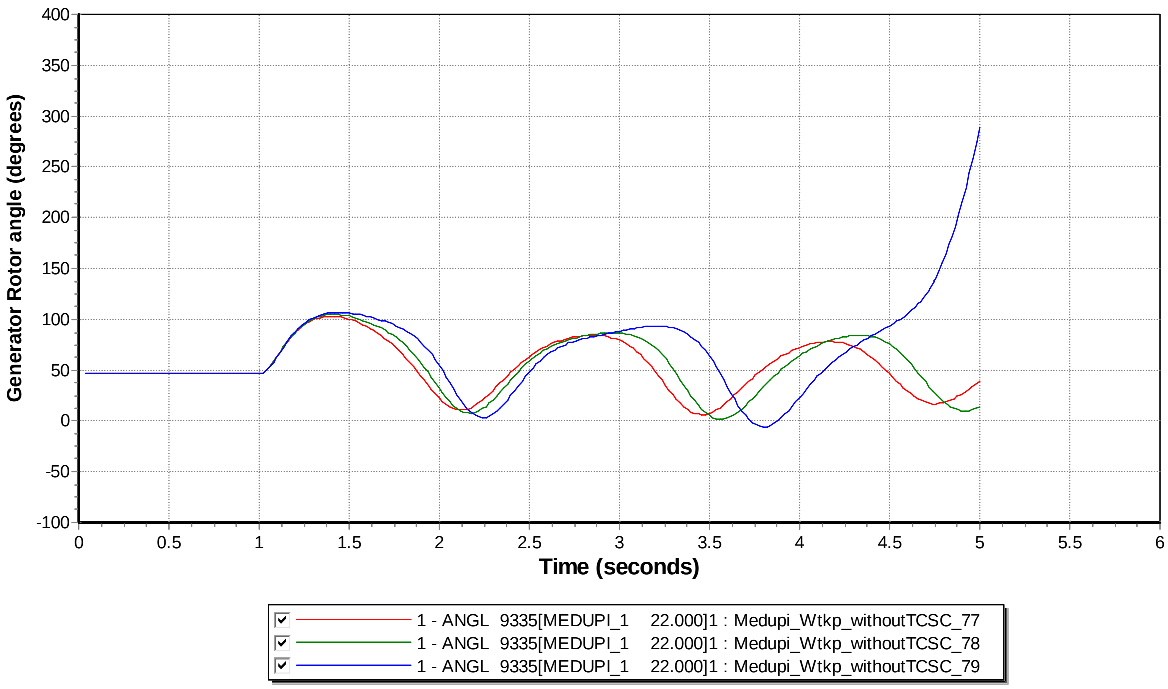

Figure 5.1: CFCT without TCSC with fault applied on Medupi – Witkop 400 kV line

A three-phase fault was simulated on the 192 km Medupi – Spitskop 400 kV line and as shown in Figure 5.2, the CFCT is 81 ms.

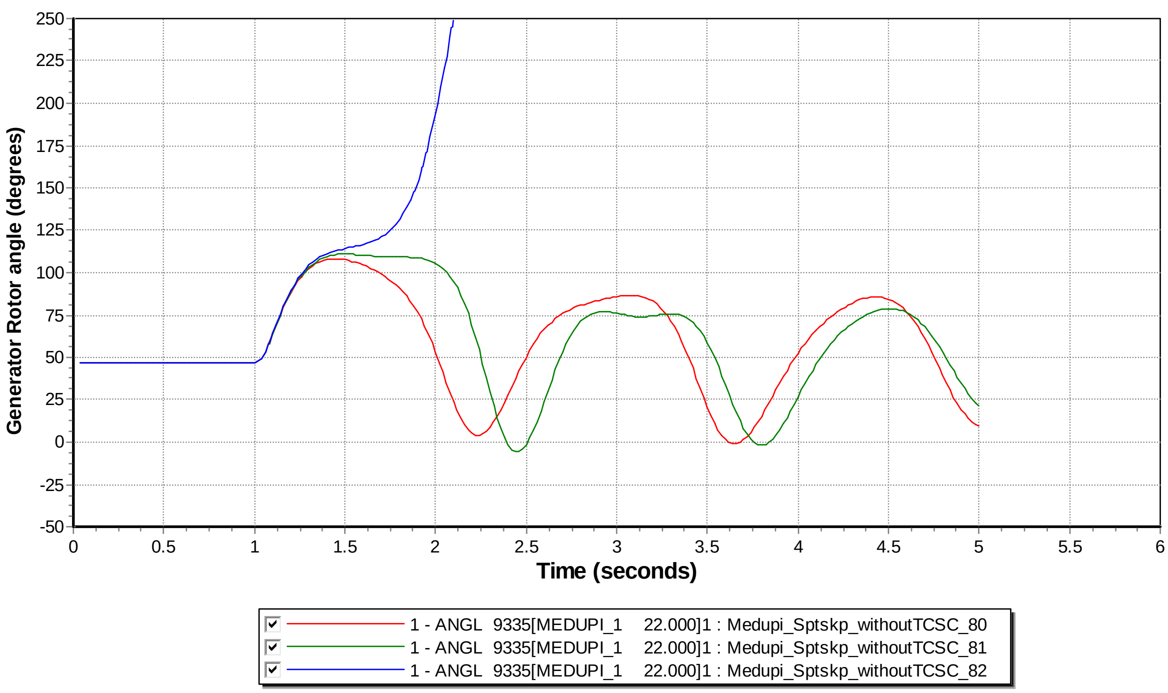

Figure 5.2: CFCT without TCSC with fault applied on Medupi – Spitskop 400 kV line

A three-phase fault was simulated on the 180 km Medupi – Burotho 400 kV line and as shown in Figure 5.3, the CFCT is 78 ms.

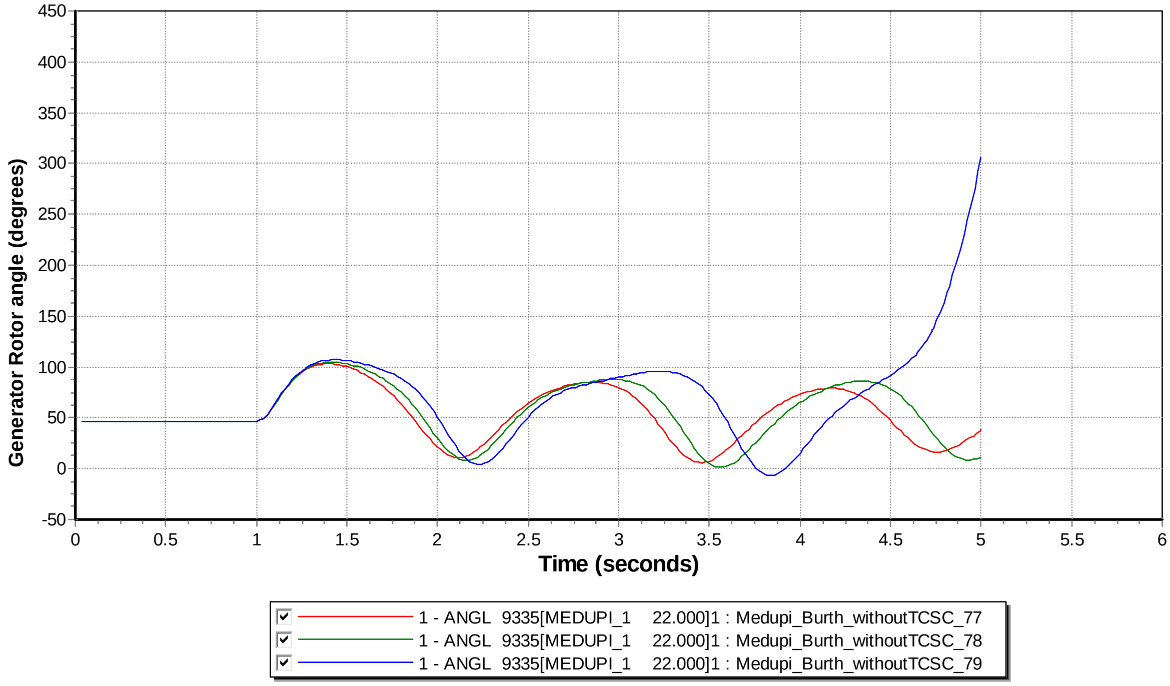

Figure 5.3: CFCT without TCSC with fault applied on Medupi – Burotho 400 kV line

A three-phase fault was simulated on the 222 km Medupi – Ngwedi 400 kV line and as shown in Figure 5.4, the CFCT is 79 ms.

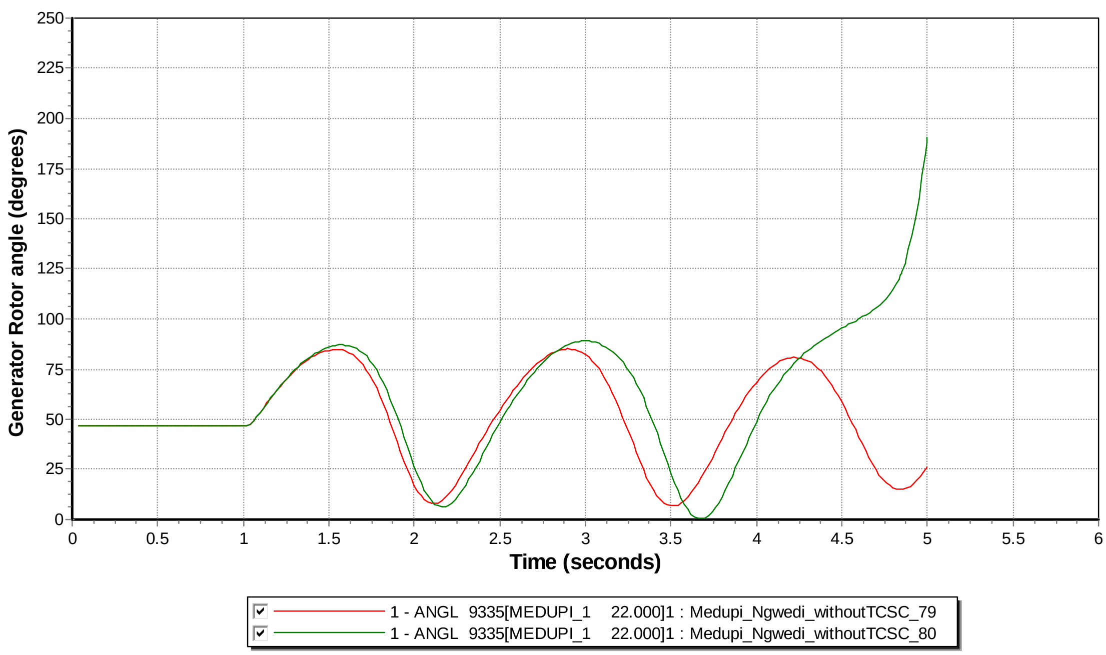

Figure 5.4: CFCT without TCSC with fault applied on Medupi – Ngwedi 400 kV line

A three-phase fault was simulated on the 280 km Medupi – Marang 400 kV line and as shown in Figure 5.5, the CFCT is 81 ms.

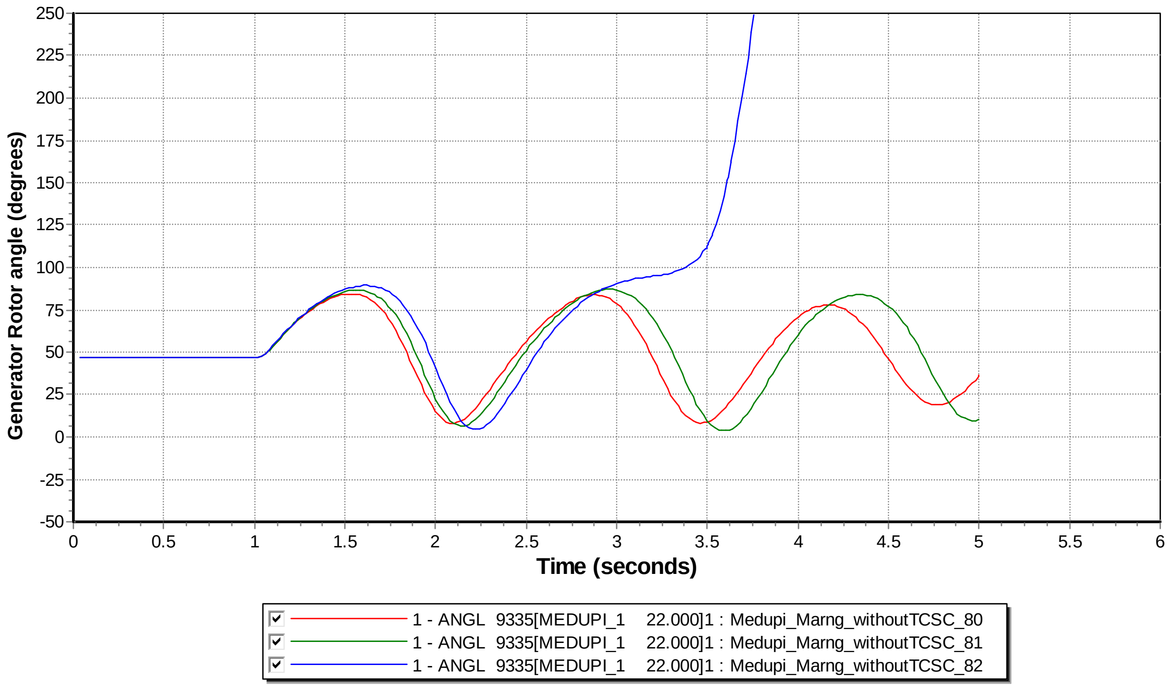

Figure 5.5: CFCT without TCSC with fault applied on Medupi – Marang 400 kV line

5.2. Summary of the results without the TCSC

Figure 5.1 summarises the results of the transient stability analysis conducted without a TCSC.

Table 5.1: Calculated CFCTs without a TCSC applied

Faulted Line	Critical Fault Clearing Time (CFCT) ms
Medupi – Witkop 400 kV line	78
Medupi – Marang 400 kV line	80
Medupi – Spitskop 400 kV line	81
Medupi – Burotho 400 kV line	78
Medupi – Ngwedi 400 kV line	79

As can be observed from Table 5.1, faults simulated on the Medupi – Burotho and Medupi – Witkop lines result in the lowest transient stability margin. The protection equipment recommended in this part of the South African transmission network is able to clear a fault within 80 ms, implying that the Medupi – Witkop, Medupi - Ngwedi and Medupi - Burotho line faults result in transient instability.

5.3. TCSC applied on lines - Impact on transient stability margins

Faults were simulated on one of the lines with the lowest transient stability margin (i.e. the Medupi – Burotho 400 kV line) to determine the improvement in transient stability margin with the other lines connected to Medupi being individually series compensated. The compensation level of between 40-70% is assumed.

With the TCSC applied on the remaining lines (one at a time) connected to Medupi 400 kV busbar, the following sequence of events was simulated:

- The network behaviour is simulated in steady state for 1 second;
- After 1 second, a three-phase fault is applied on the Medupi – Burotho 400 kV line, close to the Medupi PS 400kV busbar; and
- The fault is cleared by tripping the faulted Medupi – Burotho 400 kV line after some fault duration. The CFCT is calculated by gradually increasing the fault duration until the point of transient instability.

5.3.1. Medupi – Ngwedi 400 kV line series compensation

Figure 5.6 depicts the network with the faulted Medupi – Burotho line and the series compensated Medupi – Ngwedi 222 km line. TCSC action is represented by the variable capacitor symbol.

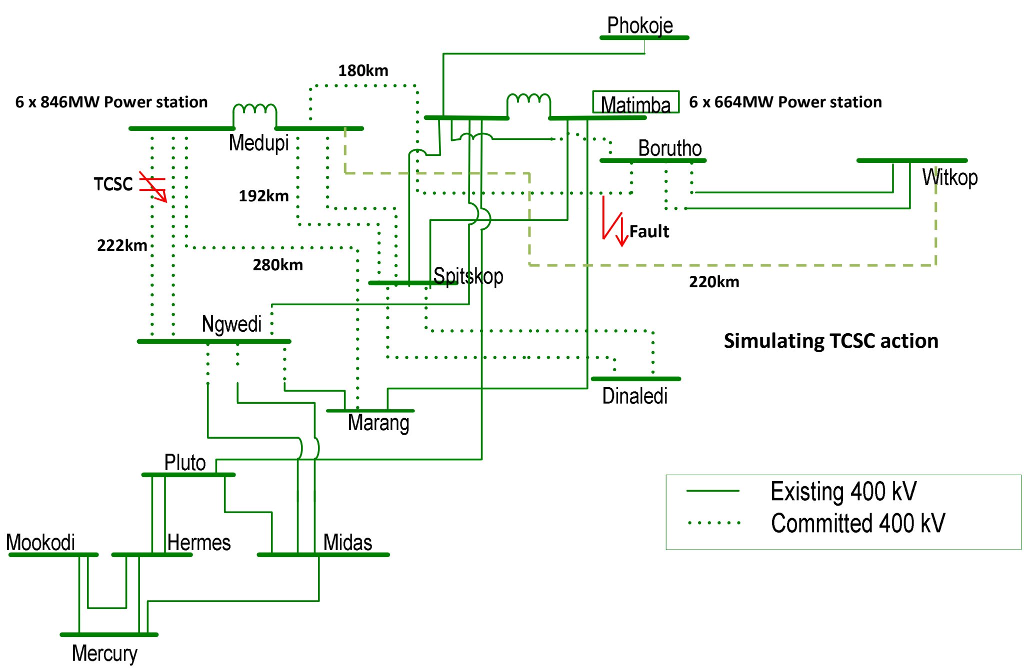

Figure 5.6: TCSC on the Medupi – Ngwedi line

As shown in Figure 5.7, with the Medupi – Ngwedi line series compensated the CFCT increases from 78 ms without TCSC to 88 ms.

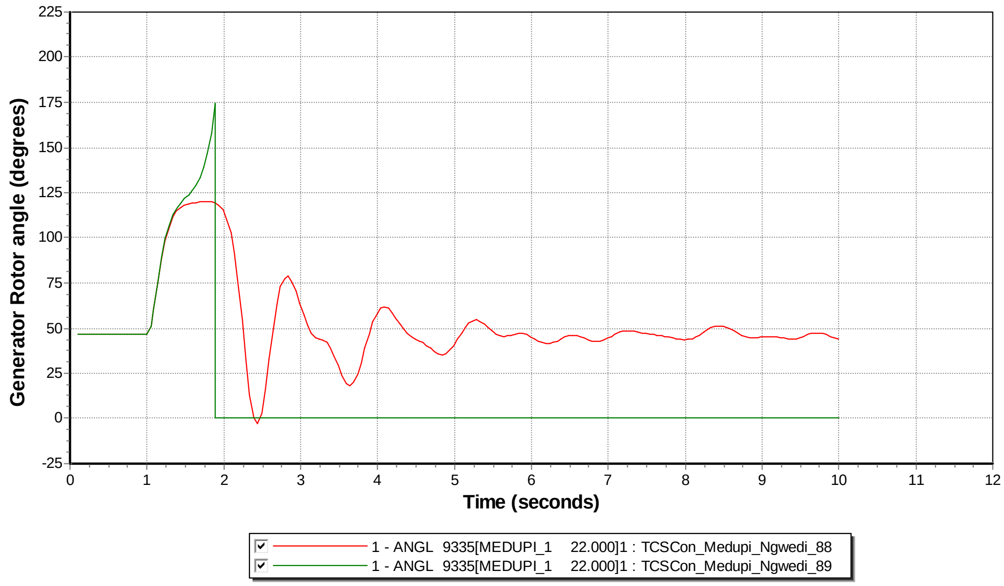

Figure 5.7: CFCT with TCSC on Medupi – Ngwedi line

5.3.2. Medupi – Spitskop 400kV line series compensation

Figure 5.8 depicts the network with the faulted Medupi – Burotho line and the series compensated Medupi – Spitskop 192 km line.

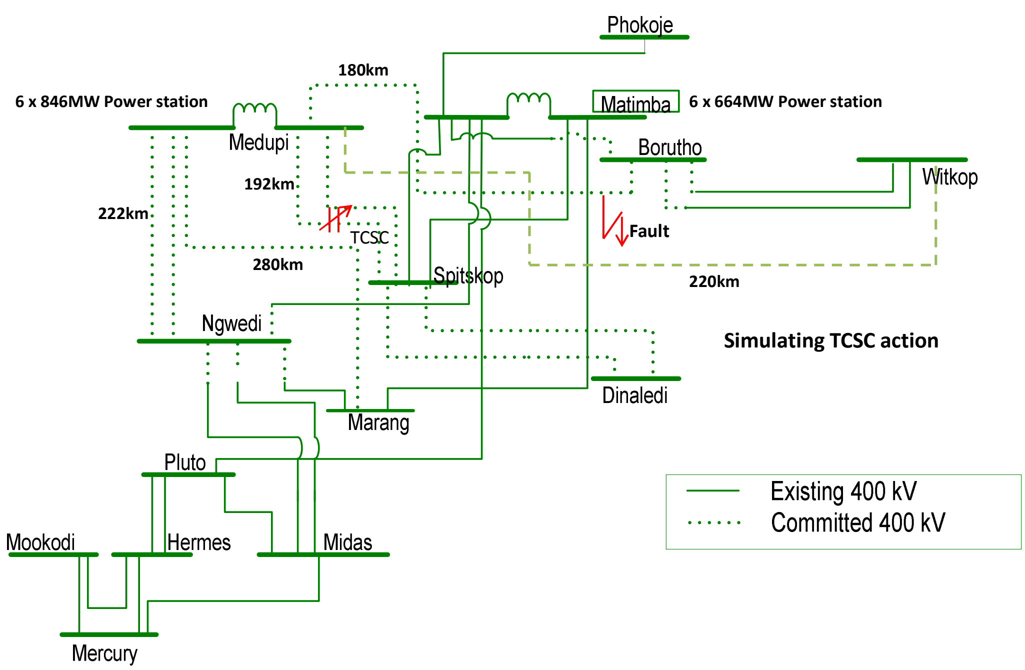

Figure 5.8: TCSC on the Medupi – Spitskop line

As shown in Figure 5.9, with the Medupi – Spitskop line series compensated the CFCT increases from 78 ms without TCSC to 85 ms.

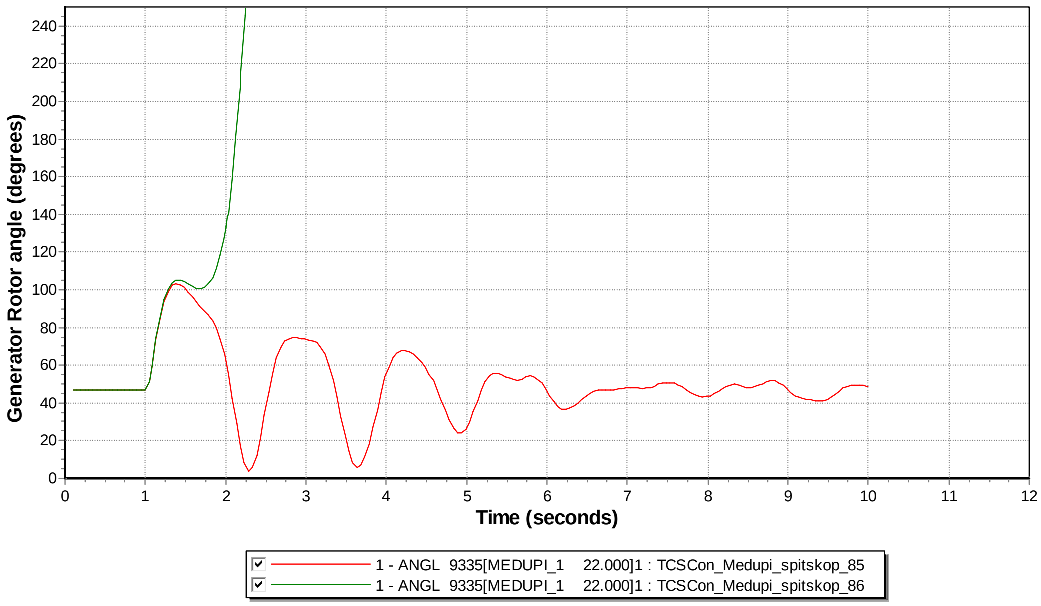

Figure 5.9: CFCT with TCSC on Medupi – Spitskop line

5.3.3. Medupi – Witkop 400kV line series compensation

Figure 5.10 depicts the network with the faulted Medupi – Burotho line and the series compensated Medupi – Witkop 220 km line.

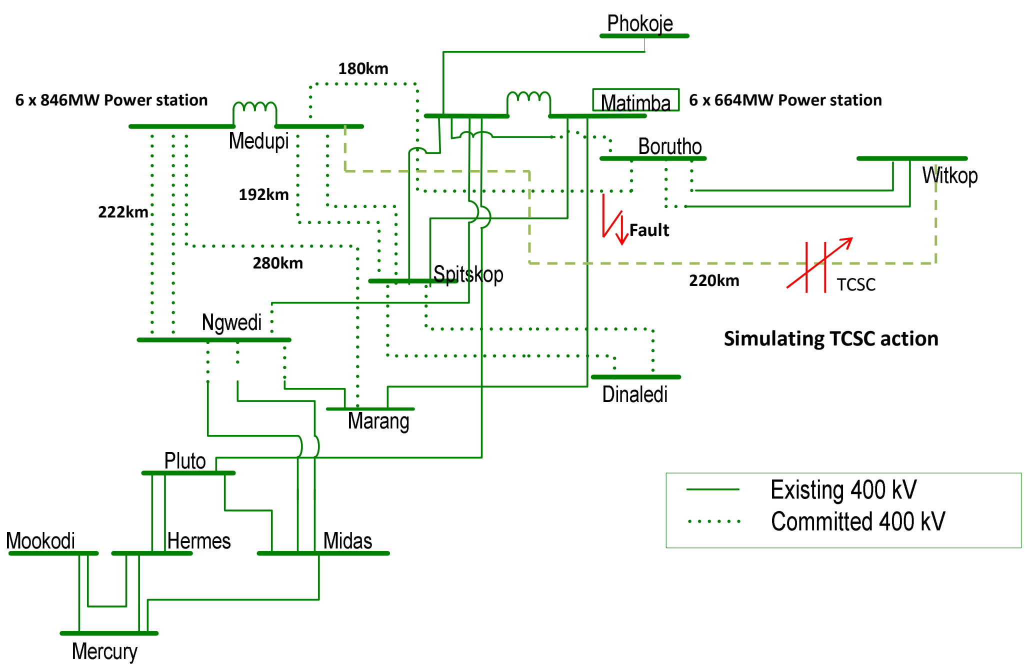

Figure 5.10: TCSC on the Medupi – Witkop line

As shown in Figure 5.11, with the Medupi – Witkop line series compensated the CFCT increases from 78 ms without TCSC to 89 ms.

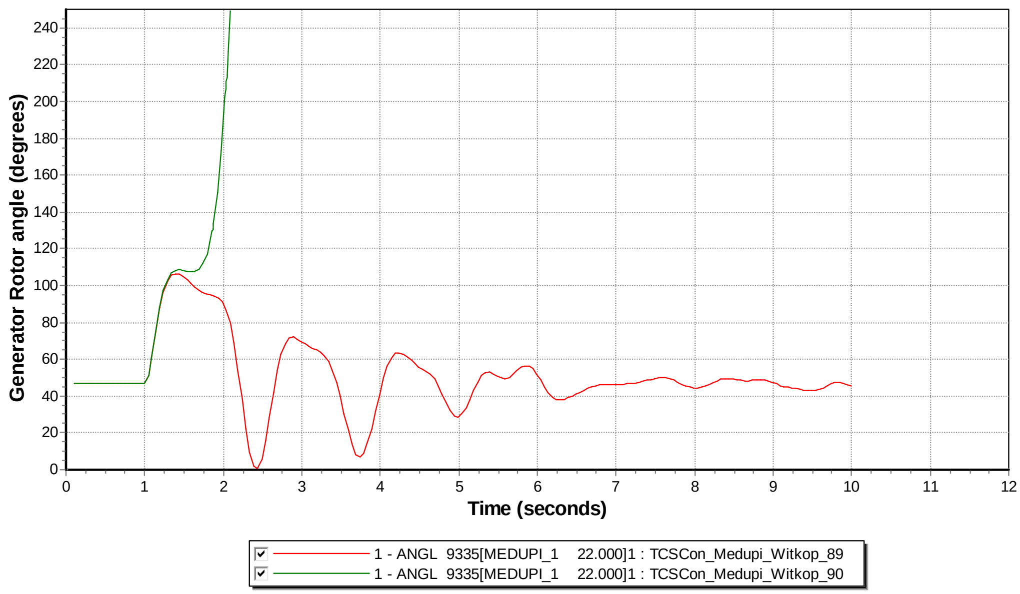

Figure 5.11: CFCT with TCSC on Medupi – Witkop line

5.3.4. Medupi – Marang 400kV line series compensation

Figure 5.12 depicts the network with the faulted Medupi – Burotho line and the series compensated Medupi – Marang 280 km line.

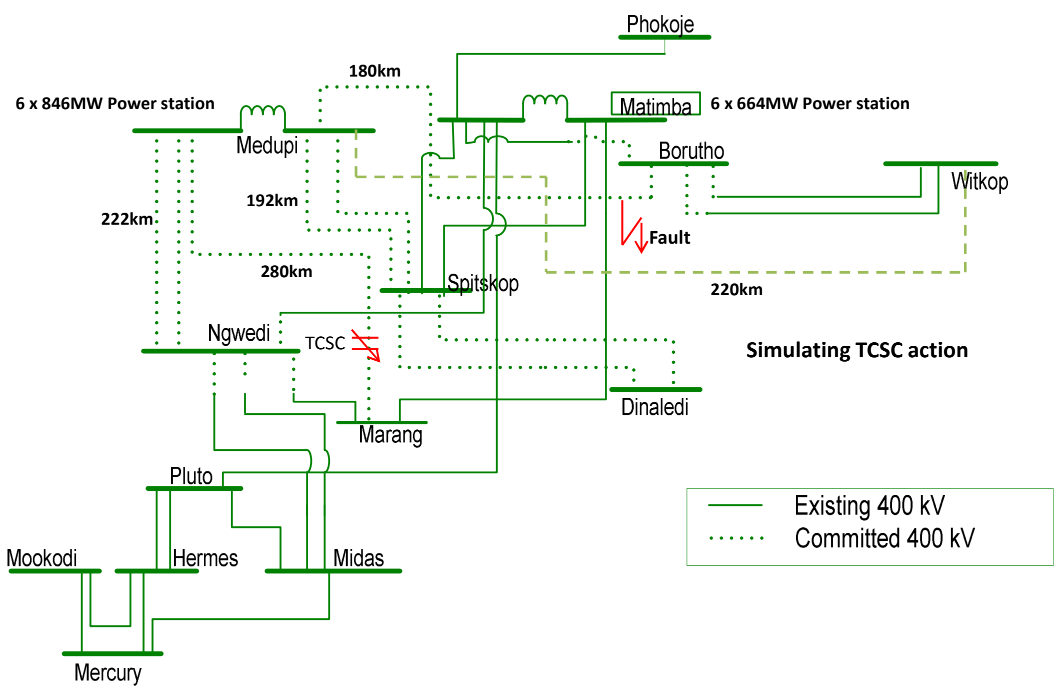

Figure 5.12: TCSC on the Medupi – Marang line

As shown in Figure 5.13, with the Medupi – Marang line series compensated the CFCT increases from 78 ms without TCSC to 87 ms.

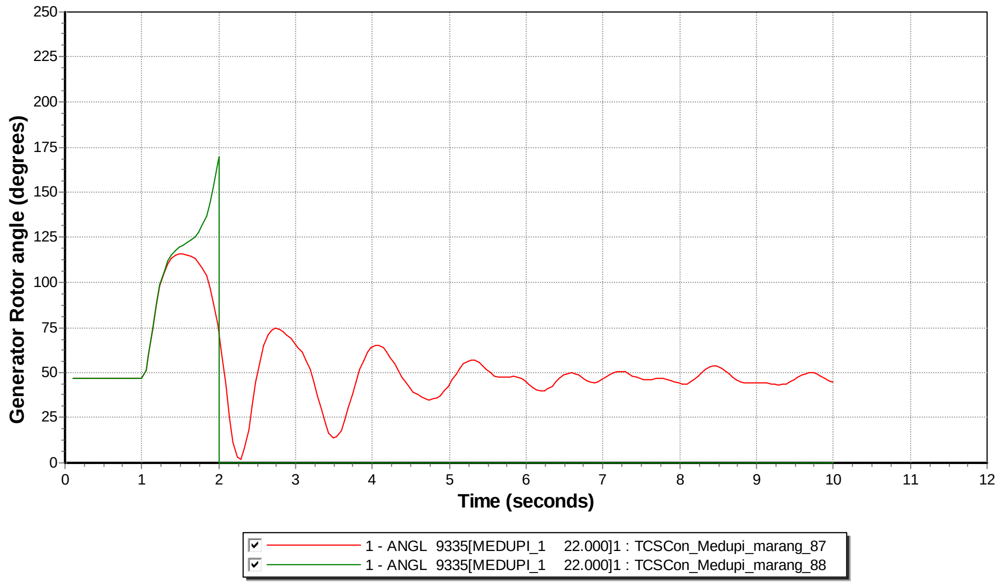

Figure 5.13: CFCT with TCSC on Medupi – Marang line

5.4. Analysis of the Simulation Results

Table 5.2 summarises the results of the analysis conducted with a three-phase fault simulated on the Medupi – Burotho 400 kV line with the TCSC applied on the remaining lines one at a time.

Table 5.2: Calculated CFCTs with TCSC applied in lines

Line compensated with TCSC	Critical Fault Clearing Time (CFCT) ms
Medupi – Witkop 400 kV line	89
Medupi – Marang 400 kV line	87
Medupi – Spitskop 400 kV line	85
Medupi – Ngwedi 400 kV line	88

It can be observed from Table 5.2 that placing the TCSC on the Medupi – Witkop line results in the largest improvement in transient stabilty margin. However, placing the TCSC on this line is unfavourable because a fault on the Medupi – Witkop line will still result in the lowest CFCT (78 ms). The TCSC on the Medupi – Ngwedi line results in the next largest improvement in CFCT, but a fault on the Medupi – Ngwedi line will result in a CFCT of 79 ms.

Additionally, compensating the Medupi - Ngwedi line is unfavourable because there are two lines connecting Medupi to Ngwedi implying that both lines may need to be compensated resulting in increased cost.

Placing the TCSC on the Medupi – Marang line results in an similar increase in CFCT as on the Medupi – Ngwedi line. The advantage with the Medupi – Marang line is that a fault on this line results in a better CFCT (80 ms) compared to a fault on a series compansated Medupi – Ngwedi line. There is a single 280 km line between Medupi and Marang, thus placing a TCSC on this line will result in the most benefit to network stability with least financial cost.

5.5. Impact of varying the degree of Series Compensation

Various degrees of compensation were applied on the Medupi - Marang 400 kV line. The degree of compensation is measured as a function of the percentage reduction in line impedance. In this analysis the line impedance was reduced by 10% intervals up to 80%. At each level of compensation, the resulting critical fault clearing time was calculated. The transient stability margins are expected to increase (increasing CFCTs) as the degree of compensation is increased. Figure 5.14 depicts the network with the faulted Medupi – Burotho line and the TCSC placed on Medupi – Marang line.

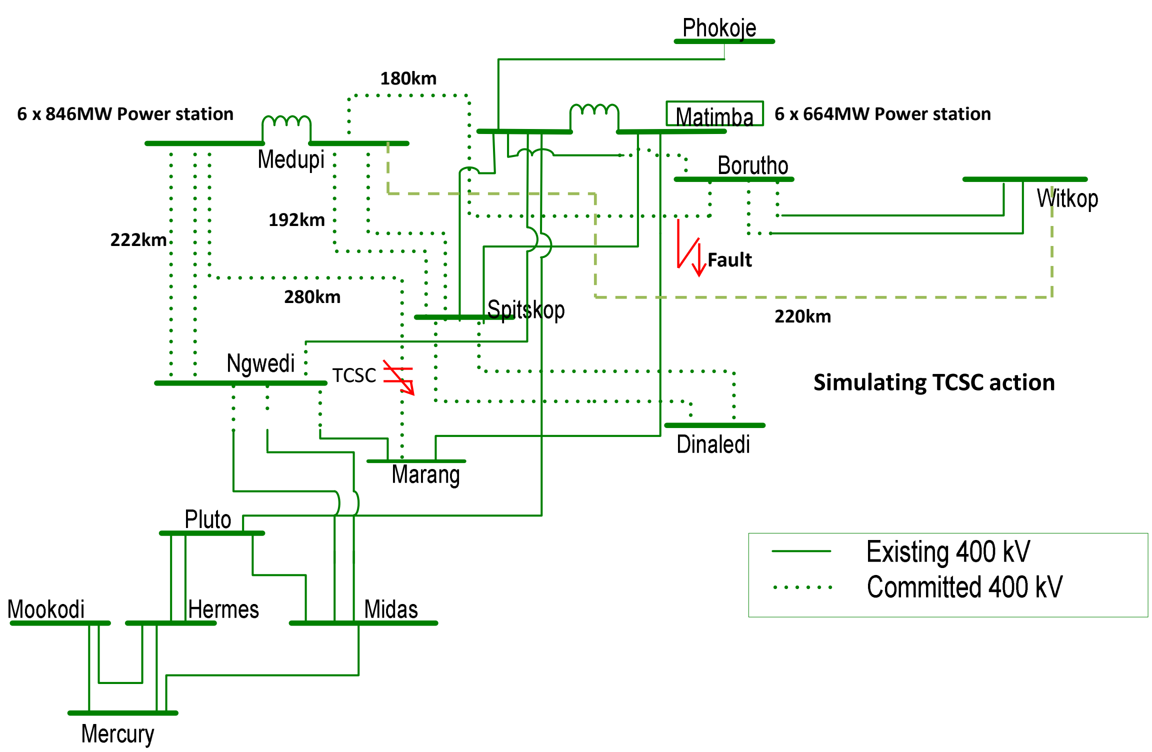

Figure 5.14: Degree of compensation varied on Medupi – Marang line

With the TCSC applied on the Medupi – Marang line the following sequence of events was simulated at each level of compensation:

- The network behaviour is simulated in steady state for 1 second;
- After 1 second, a three-phase fault is applied on the Medupi – Burotho 400 kV line, close to Medupi PS 400kV busbar; and
- The fault is cleared by tripping the faulted Medupi – Burotho 400 kV line after some fault duration. The CFCT is calculated by gradually increasing the fault duration until the point of transient instability.

Figure 5.15 shows the increase in CFCT as the level of compensation is increased. The increase is fairly linear.

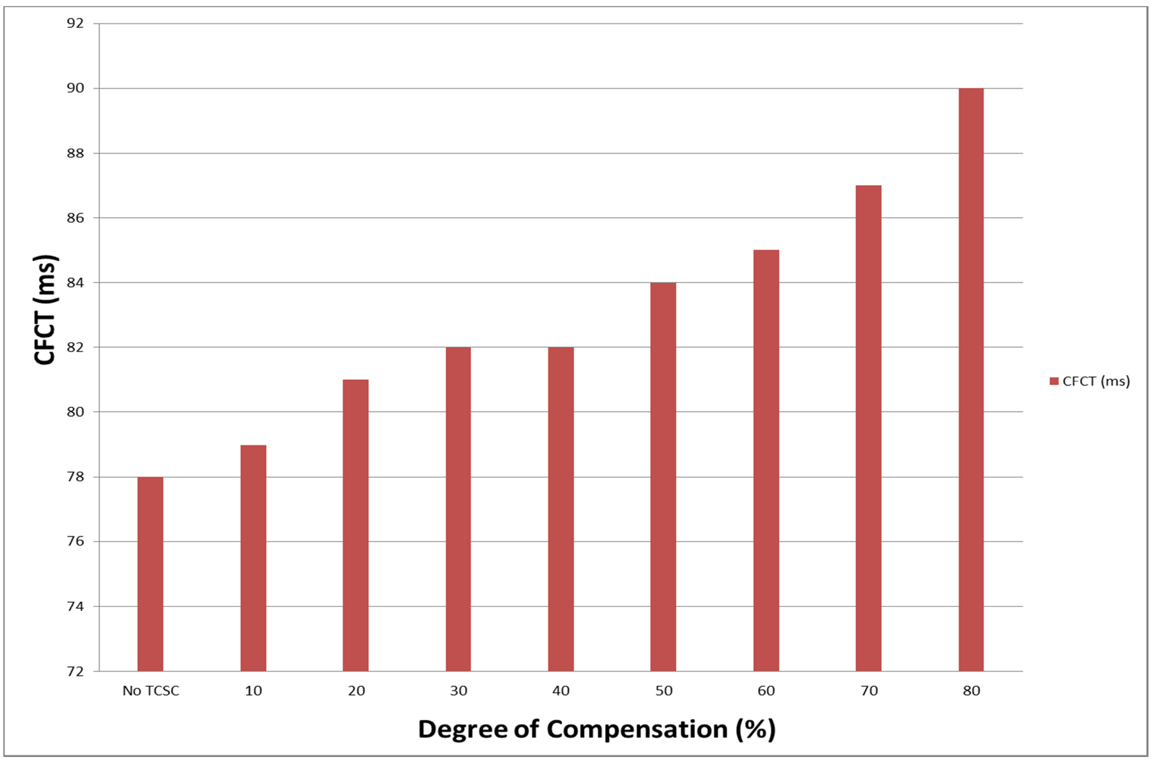

Figure 5.15: Compensation level vs CFCT

The level of compensation to be selected is dependent on the achieved CFCT measure against the fault clearing times of the installed protection equipment. In the South African transmission network, fast protection that has been recommended in this part of the network is able to clear the fault within 80 ms, implying that a compensation level of 20 % is sufficient, however a buffer may be necessary to accommodate future network expansion.

5.6. CFCT with second Medupi – Marang 400 kV line

As an alternative to placing a TCSC on the Medupi – Marang 400 kV line, a second Medupi – Marang 400kV line was added to the network and the resulting CFCT was calculated. A three-phase fault is simulated on the Medupi – Burotho line and the resulting CFCT is calculated. Figure 5.16 depicts the network with the faulted Medupi – Burotho line with a second Medupi – Marang line included.

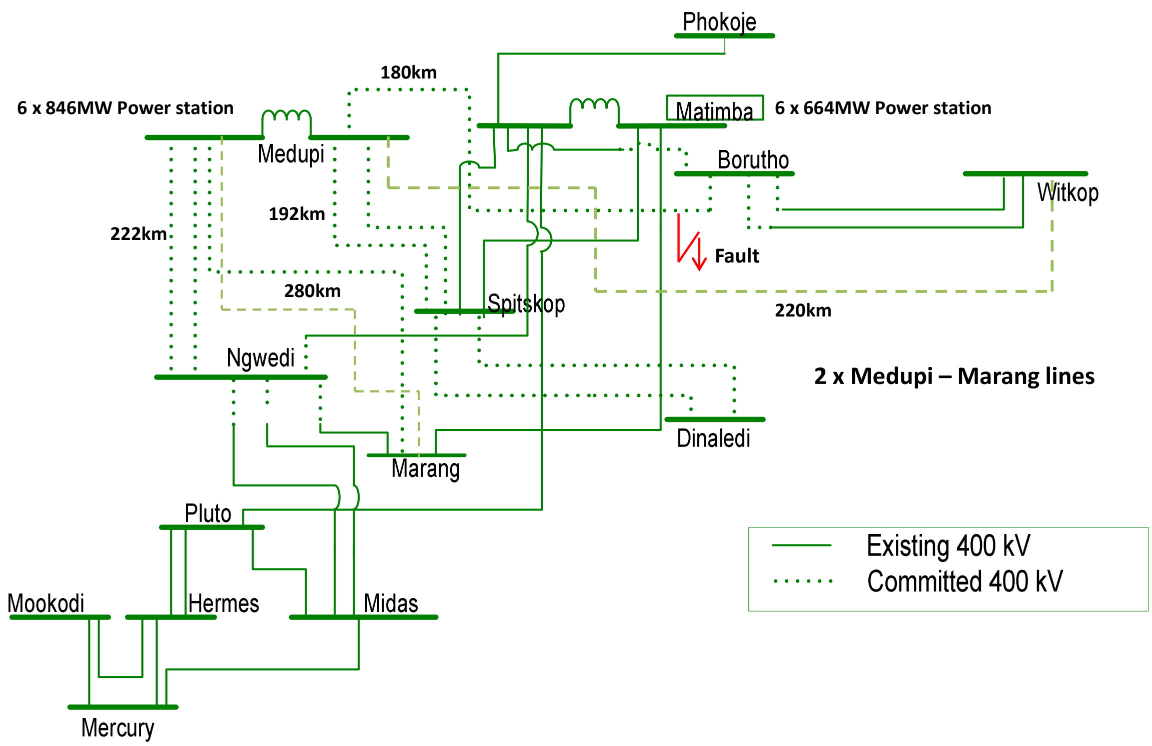

Figure 5.16: Fault simulated with 2 x Medupi – Marang 400 kV lines

Results show that the CFCT will increase from 78 ms to 82 ms. This is equivalent to the increase in CFCT achieved with 30% compensation on a single Medupi – Marang 400 kV line. A cost comparison between the cost of building a new transmission line versus cost of a TCSC with 30% compensation could be conducted and from this comparison the least cost alternative could be recommended.

6. CONCLUSIONS

The research has demonstrated that application of TCSCs on the northern part of the South African Transmission Grid results in improved transient stability margins. The use of TCSCs is preferred ahead of other series compensation devices like FSCs, TSSCs and GCSCs because TCSCs are a proven technology and are effective in mitigating against the SSR effect. Using TCSCs is especially preferred in this part of the South African network where thermal generation is dominant, implying that SSR contraints are expected if a higher degree of compensation is required.

The resulting improvement in transient stability is comparable to some of the conventional solutions like adding more transmission lines. Thus the use of TCSCs can be considered as an alternative. Another advantage of a TCSC is that depending on country, a TCSC could be installed in 12 to 18 months whereas construction of a new line could take 7 to 12 years since obtaining rights-of-way and permits is a time consuming process [11]. Further studies would be vital to understand the interaction between power system stabilizers and TCSCs. This will ensure proper tuning of the respective devices.

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