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UNIFIED POWER FLOW CONTROLLER AS POWER SYSTEM STABILIZER

A dissertation submitted to the
Department of Electrical Engineering, University of Moratuwa
in partial fulfilment of the requirements for the
degree of Master of Science

by

University of Moratuwa, Sri Lanka
WARUSAPPERUMA KANKANAMALAGE MAHESH
www.lib.mrt.ac.lk
PRASANNA WARUSAPPERUMA

Supervised by: Prof. J.R.Lucas
Dr. P.S.N. De Silva

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DECLARATION

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Abstract

The FACTS device - Unified Power Flow Controller (UPFC) and its performance is studied under transient condition in the usage as a power system stabilizer. This device creates an impact on power system stability with its unique capability to control real and reactive power flows simultaneously on a transmission line and regulate voltage at the bus connected. These features become significant as the UPFC can allow loading of the transmission lines up to their thermal limits by regulating the power flow through desired paths. This gives the power system operators the desired flexibility in satisfying the deregulated power system imposed requirements.

The new technology associated with the UPFC and its structure is studied. The theoretical analysis is done in verifying its capability for stability enhancement. A practical system is modelled to verify the theoretical analysis in MATLAB/SIMULINK platform.

Theoretical and practical verification reveals the function of UPFC in power system stabilisation. The parameters associated with the UPFC are studied for optimum stability criterion.



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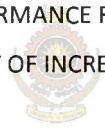
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Chapter 1

Introduction

1.0 Scope of the Project

Today, in the world, reliability of Electrical Power systems is one of the important aspects and numerous researches have been conducting towards this. As far as reliability and stability are concerned, new emerging technology plays vital roles towards achieving these targets.

Flexible AC transmission devices are used to control power flow in power systems. But systems like Unified Power Flow Controllers (UPFC) are very new concepts of flexible AC transmission. It can work in any compensation mode and is the most advanced controller in FACTS devices. And also UPFCs have never been used in Sri Lankan power system as this concept itself is a new system to the world. Study of FACTS devices like UPFC is an objective of this project. And its performance under transient conditions to improve the stability of a power system has been discussed in this thesis. Stability analysis is done with respect to rotor angle stability criterion under transient conditions. And then, Unified Power Flow Controller's capability of standing as a power system stabilizer has been studied. That is, UPFC's capability and how it could introduce dampness to a system is studied theoretically as well as practically for stability enhancement.

A practical power system portion from the Sri Lankan power system is selected for verification of the theoretical development. System selected to carry out the study is Matugama, Kukule, and Horana Pseudo Island of the National Power System. Configuration and the parameters of the Unified Power Flow Controller (UPFC) to be implemented at Matugama, Kukule, and Horana Pseudo Island of the National Power System are studied. Above systems are modelled in the MATLAB/SIMULINK software environment to achieve these results.

1.1 Introduction to stability

Power system stability is analysed when it is subjected to transient disturbance. When subjected to a disturbance, power system parameters would vary depending upon the type of disturbance, for example, Voltage, Frequency, Power flow, etc. This variation could be oscillatory or non – oscillatory depending upon disturbance/ system parameters. In practical power systems, it can be observed that there are mainly two types of disturbances. Severe or large disturbances like Loss of major generating plant, loss of main transmission line, 3 phase – ground fault in a transmission line or faulted circuit breaker, loss of major load etc. Small disturbances are always there in a power system such as small load changes, small load loss, fault through a high impedance, small embedded generator tripping etc.

There are various definitions for stability given in various literatures. But all agree that the stability is in general a state of [1] equilibrium between two opposing forces. Electrical Power System's generation side has been made out mainly from synchronous generators. Therefore, it is a very clear fact that they should remain in synchronism in all of above disturbances. And also there is another instance where instability can be observed without loss of synchronism. In this instant, the system is unable to keep the voltage levels of their buses within acceptable levels but all generators remain intact.

Primitive definition for Stability has been given in the literature [11] as follows:

- If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.

Stability problem could be identified in two different ways, as described in [11].

- Rotor Angle Stability
- Voltage Stability

1.11 Rotor Angle Stability

If we consider a synchronous machine, and from basics of synchronous machines, it's stator electrical quantities are synchronised with the rotor mechanical speed. And also, the machine load is reflected by its rotor load angle (that is the position of the rotor

relative to the rotating magnetic field of the synchronous generator). Therefore, when power system oscillates as a result of a disturbance, the rotor also oscillates with its stator electrical quantities. Therefore, through rotor angle stability analysis, we analyse the behaviour of the rotor angle of the synchronous machines in a power system.

Therefore, Rotor angle stability can be identified as [1] the ability of interconnected synchronous machines of a power system to remain in synchronism. Torque balance of the system is very important for them to remain in synchronism. For this to happen it is necessary that the synchronous generators have to operate in a stable portion of the Power delta curve within which δ varies from 0 to $\pi/2$ as illustrated in the figure 1.0 below.

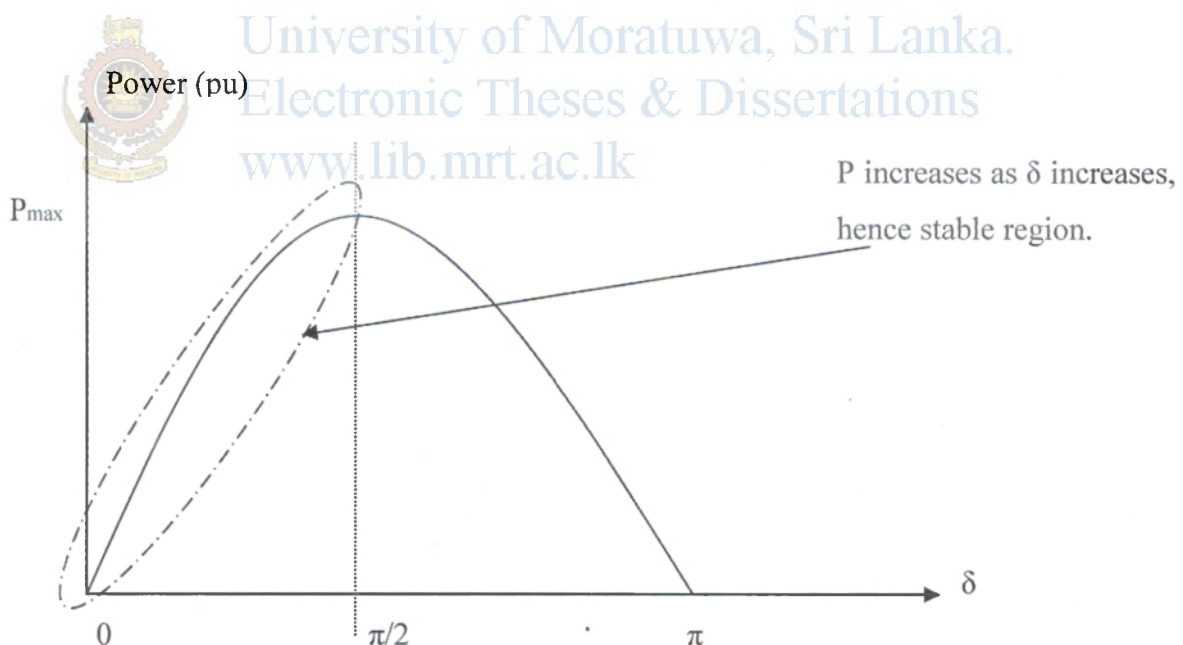


Figure 1.0: Power – delta curve for synchronous machine

Electrical torque variation after a perturbation can be resolved into two components as per the [1].

- Change in Electrical Torque = Synchronising Torque + Damping Torque

In a synchronous machine, electrical torque component is created by interaction between three windings, namely; Stator winding, Field winding and damping winding. And from the above resolved two components, synchronising torque is the most important one. This is the one which continues throughout from steady state to transient condition. The second component is created when the machine is subjected to a transient disturbance. And this damping torque can be resolved further into three different components [11] namely; Positive sequence damping (this is proportional to slip frequency and is beneficial to damp out oscillations), Negative sequence damping (slip frequency in this case is $2-S$, therefore, this is retarding the rotor), DC braking (creates during faults, retard rotor movements).

Depending on the size of the disturbance, Rotor angle stability can be classified into two categories as follows,

- **Small signal stability** – When a system is subjected to small disturbances, system's ability to remain in synchronism is analysed. When subjected to small disturbances, following types of oscillations can be observed in a practical power system[1], such as *Local mode oscillations* (Oscillation of one single machine with respect to the rest of the system), *Inter-area mode oscillations* (Oscillation of many machines in one part of the power system with respect to other parts), *Control mode oscillations* (this is associated with generator units and other controls), *Torsional mode oscillations* (this is associated with turbine shaft rotational components). Automatic Voltage Regulators play a vital role when this type of disturbance occurs. There are AVR based power system stabilizers which provide dampness to active power variation through voltage control.
- **Transient Stability:** When a system is subjected to a large disturbance and system's ability to maintain its synchronism is analysed. This depends upon the initial operating state, location and severity of the disturbance. Thus transient stability of a system has to be defined with these conditions.

In this paper, a case study is carried out with the transient faults on transmission lines. And rotor angle stability enhancement is analysed after adding UPFC to the system.

There can be three possible cases when a system is subjected to a transient disturbance and it is cleared after some time. Those are namely;

- Rotor angle oscillates and stabilises after some time due to system dampness. And this is a stable case.
- Rotor angle increases until synchronism is lost and this is known as first swing instability. This is mainly due to lack of synchronising torque of the system.
- Rotor angle oscillates and grows until synchronism is lost. This is mainly due to lack of damping torque of the system.

1.12 Voltage Stability

Power system might lose its stability without loss of synchronism. That is the case where the voltage instable. This can happen due to increase demand in inductive loads (such as induction motors etc.) in a system. System falls into a situation where, increase in reactive power reduces bus voltage. Therefore, system is instable. In normal circumstances, when we increase the reactive power injection to a bus, the bus voltage increases. This type of instability is out of the scope of my project. Therefore, no detail discussion is carried out.

1.2 Introduction to Flexible AC Transmission Systems

Proper utilization of existing AC transmission systems nowadays is very vital as the power industry is becoming increasingly de-regularised. Transmission system's power transfer capabilities have been restricted by network characteristics such as;

- Stability limits
- Thermal Limits
- Voltage Limits
- Loop Flows

Without adding new generators or transmission lines into the system, its capabilities can be improved by inserting Flexible AC Transmission Systems (FACTS) devices into the system. This is an emerging technology and proved to be very effective systems as well. Role of FACTS devices is to enhance the controllability of AC power transmission and as well as to improve the Power Transfer Capabilities.

FACTS devices use power electronic devices/semiconductors, such as Thyristers, Gate Turn Offs (GTO), Insulated Gate Bipolar Transistors (IGBTs). Since they use these electronic components, they can be controlled very fast as well as with different control algorithms adapted to various situations. There are many different kinds of FACTS devices available, namely;

- Shunt Compensators
- Series Compensators – Series impedance, Phase angle Compensation type
- Shunt – Series Compensators

1.2.1 Shunt Compensation

Shunt compensator is capable of injecting current into a system where it is connected. It should be capable of injecting reactive power into the transmission system in order to increase the transmittable power. Active power transfer capability of a shunt compensator connected to the middle of a transmission line (impedance = X) connected with two voltage sources with equal voltage magnitude (V) and δ phase

difference can be proved to be equal to $P = \frac{2V^2}{X} \sin \frac{\delta}{2}$ value and reactive power

$$Q = \frac{4V^2}{X} \left(1 - \cos \frac{\delta}{2}\right) \text{ as per the literature [12]. Therefore, it is clear that active power}$$

transfer can be improved with an additional injection of reactive power to the system.

There are shunt-compensators available in the world such as:

- TCR – Thyristor – Controlled Reactor
- TSC – Thyristor – Switched Capacitors
- SVC – Static Var Compensators
- STATCOM

1.2.2 Series Compensation

Series compensators are mainly, variable capacitors connected in series with the transmission line. Therefore, they have to be capable of handling the line current. By changing the line impedance variably, power flow through a transmission line can be varied. Detailed analysis can be found on the literature [12]. Active, reactive power flowing through a series compensated transmission line can be proved to be as follows:

$$P = \frac{2V}{(1-r)X} \sin \frac{\delta}{2}$$

$$Q = \frac{2V^2}{X} \times \frac{r}{(1-r)^2} (1 - \cos \delta)$$

Where, $r = \frac{X_{comp}}{X}$ is called the **degree of compensation**.

$$X_{eq} = (X - X_{comp}) = X(1 - r)$$

Following are the typical series compensators available,

- TSSC – Thyristor Switched Series Capacitor
- TCSC – Thyristor Controlled Series Capacitor
- FCSC – Force Commutation Controlled Series Capacitor
- SSTATCOM – Series Static Var Compensator

1.2.3 Series compensation - Phase Angle Compensation

Phase angle compensation is a special case of series compensation where it is required to engage a series voltage source connected in series with the line and with the capability of handling active power as well as reactive power. This enables it to vary its series injected voltage with any phase angle with respect to the line current so that the active power flow can be controlled. All previous compensation modes deal with reactive power sources unlike this one. As this is required to handle active power it has to be installed closer to a voltage source.

Transmittable active power can be controlled in the following manner,

$$P = \frac{V^2}{X} \sin(\delta - \sigma)$$

Where σ is the phase angle of the injected series voltage.

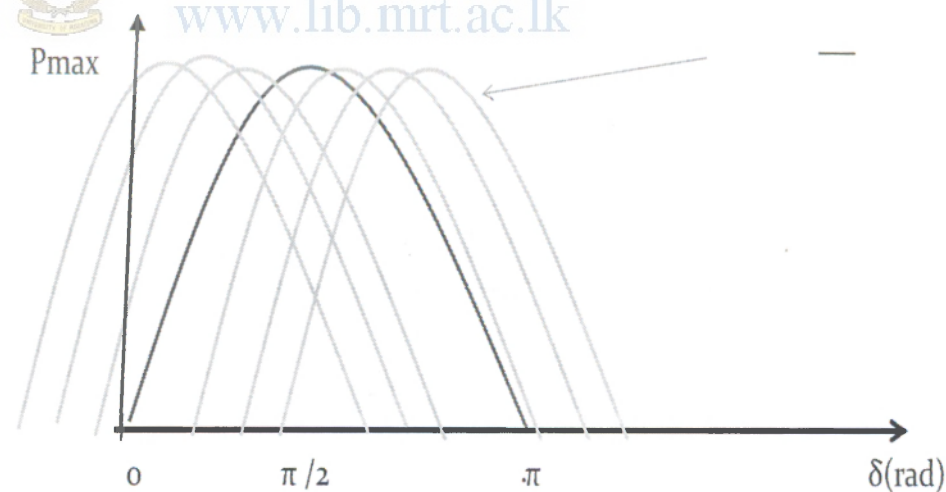


Figure 1.1: Phase-angle compensation

By observing above equation and figure 1.1, we can see that, the power transfer curve can be shifted parallel to the delta axis. Hence, although it doesn't increase the maximum power transfer, maximum power can be obtained with lower delta value by shifting the curve.

Practically, Phase shifter is used as phase angle compensator. It is a shunt connected excitation transformer with secondary connected through thyristors with series transformer. This is worked as a thyristor controlled tap changer which will control the secondary injection voltage to line.

1.2.4 Comparison of FACTS devices

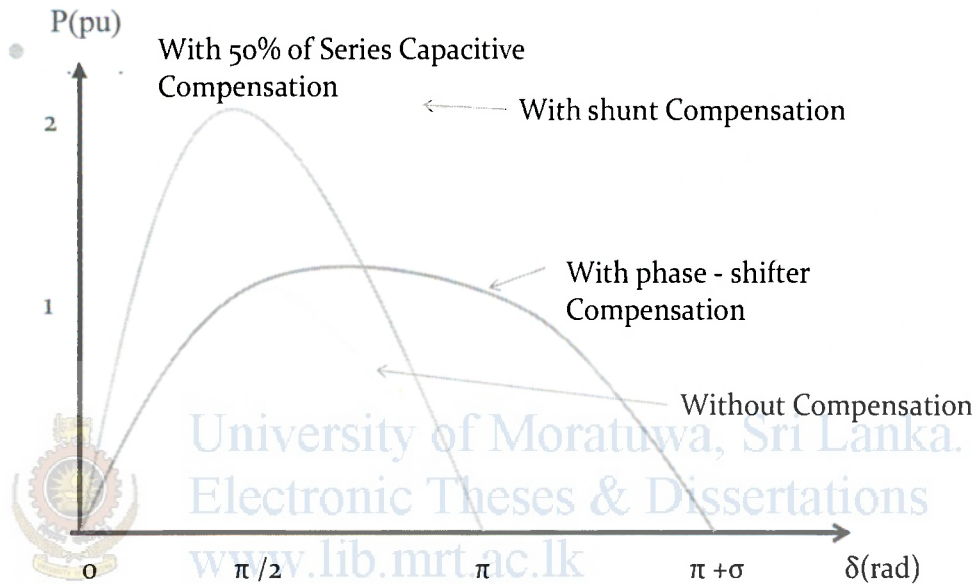


Figure 1.2: Comparison of FACTS devices

Above chart illustrates Active power variation with respect to delta angle for different types of compensation provided by FACTS devices. Shunt controller injects voltage to a point, and it is very effective in controlling bus voltage, therefore it can damp reactive power oscillation (voltage oscillation). And it has increased the stability margin largely, compared to other controllers.

Series controller directly injects line current in series, therefore, it affects power flow directly. Therefore, it is the best option to control and increase power transfer capability. Phase shifter would be connected in the instance where uncontrollable phase differences exist.

1.2.5 Unified Power Flow Controller

Unified Power Flow Controller (UPFC) is the complete compensator with all of above features. Therefore, it can be treated as complete compensator. Block diagram of the UPFC is given in the Figure 1.3 below. It has two Voltage Source Converters

connected to series as well as shunt transformers. These two converters are coupled with a common DC link capacitor.

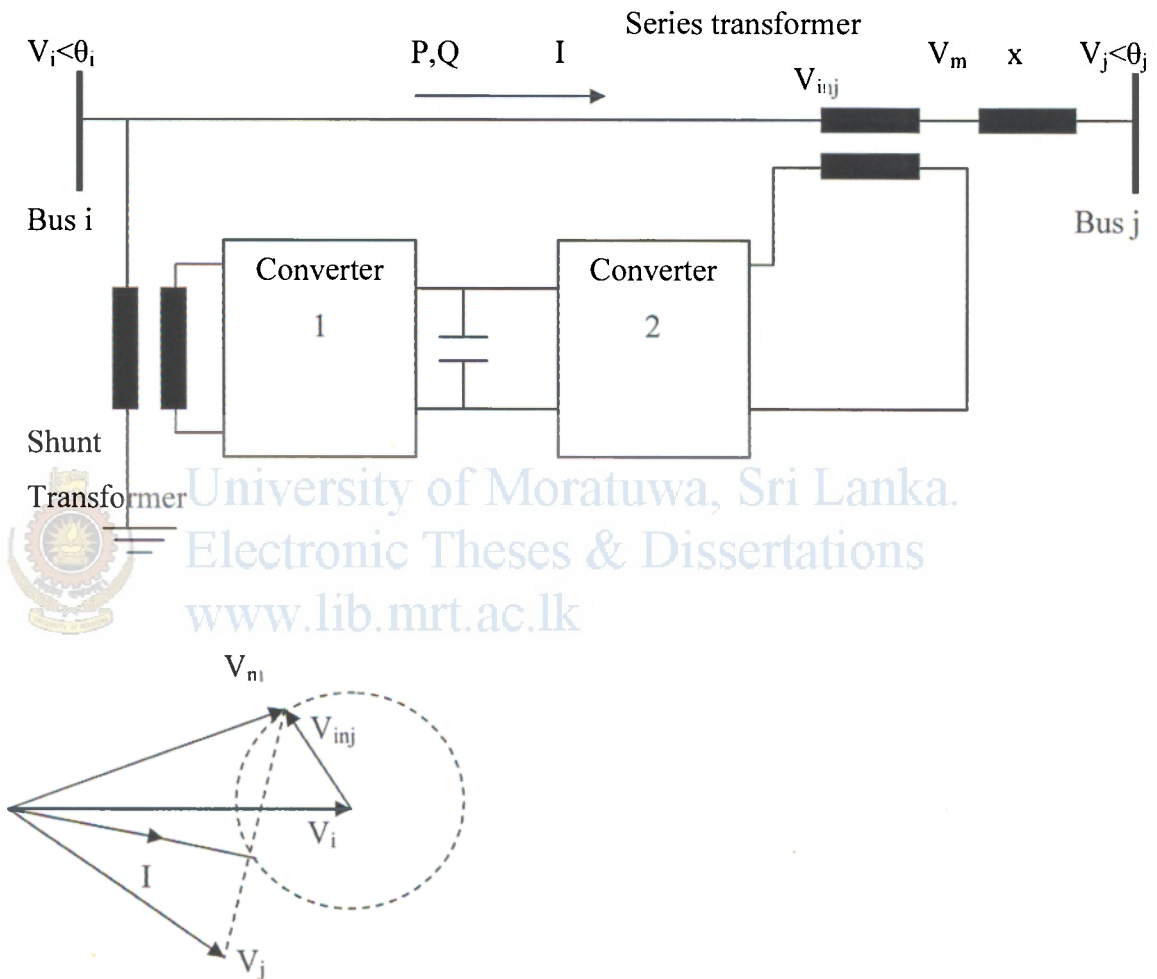


Figure 1.3: UPFC block diagram

Principle of operation

Converter 2 performs the main function of the UPFC by injecting, via a series transformer, an AC voltage with controllable magnitude and phase angle in series with the transmission line. The basic function of converter 1 is to supply or absorb the real power demanded by the converter 2 at the common DC link. It can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. Converter 2 supplies or absorbs the required reactive power locally and exchanges the active power as a result of the series injection of voltage.

Voltage Source Converter

There are two voltage source converters available in the UPFC. Therefore, its operation is discussed here briefly. Following diagram shows basic configuration of Voltage Source Converter.

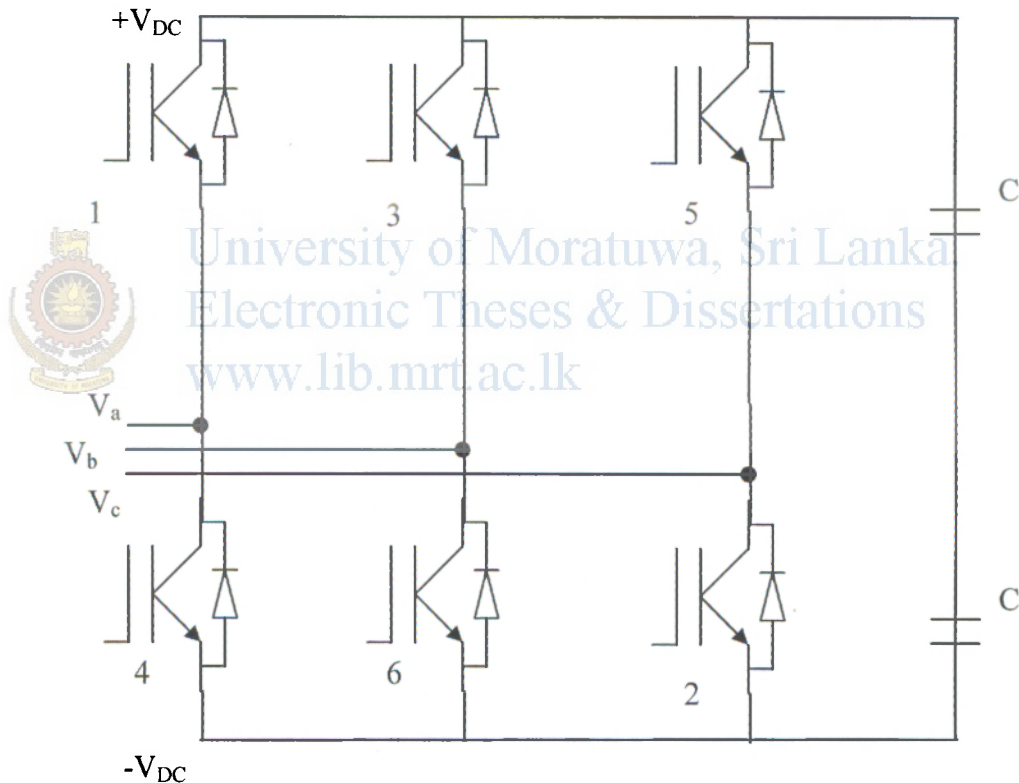


Figure 1.4: VSC simplified diagram

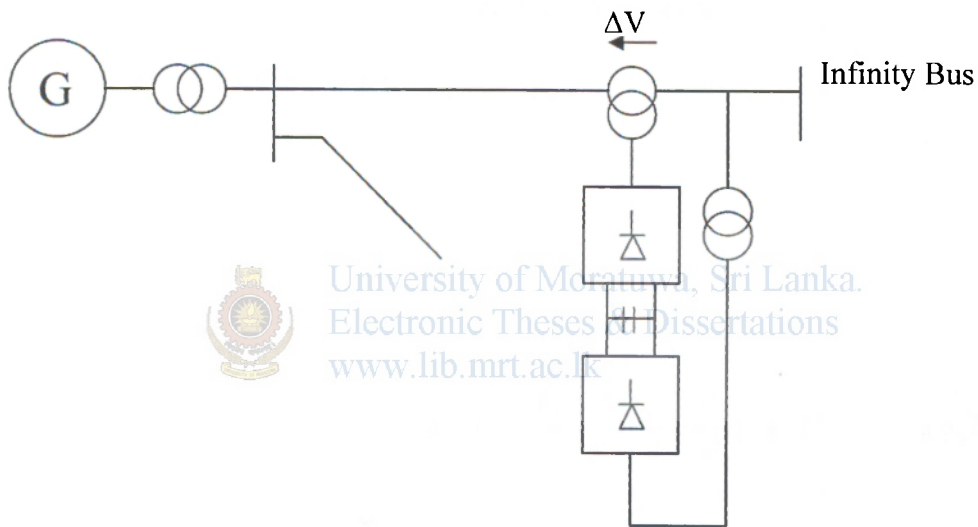
Voltage source converter is made out of 6nos of IGBTs with reverse diode connected each. DC side of the converter is connected to a capacitor. Four quadrant operations are possible for this kind of a converter [14].

Real power exchange between converter DC side and AC side can be performed by controlling output voltage angle [13]. When AC output voltage of the converter leads that of system voltage, then the real power flow from DC side to AC side will happen and vice versa. To exchange reactive power from converter to system, converter voltage magnitude has to be increased, and if the voltage magnitude is decreased with respect to the system voltage then reactive power will be absorbed.

Theoretical Verification

2.0 UPFC as a Power System Stabilizer

The way the UPFC can be used to damp power swing can be explained using the simple generator-infinite bus-bar system [10] shown in the figure below. The system equivalent reactance has been neglected in order to simplify the equation describing the equivalent circuit.



(a) : UPFC with infinity bus system

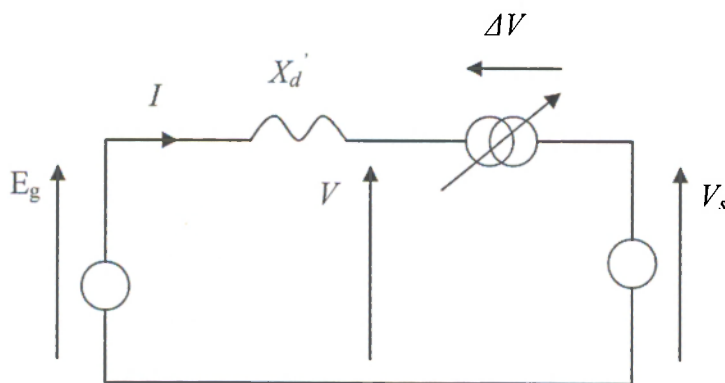


Figure: 2.0

(b): UPFC simplified model

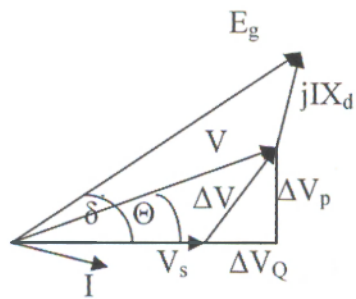


Figure 2.1 : Phasor diagram

The booster voltage ΔV has an in-phase component ΔV_Q and quadrature component ΔV_P . Both components are proportional to the voltage at the point where the UPFC is installed and can be written as,

$$\begin{aligned} \Delta V_Q &= V_s \beta(t), \\ \Delta V_P &= V_s \gamma(t), \end{aligned} \quad (\text{eq2.0})$$

where $\beta(t)$ and $\gamma(t)$ are the control variables.

From figure 2.1 gives,

$$\sin \Theta = \frac{\Delta V_P}{V} = \frac{V_s}{V} \gamma, \quad \cos \Theta = \frac{V_s + \Delta V_Q}{V} = \frac{V_s}{V} (1 + \beta), \quad (\text{eq2.1})$$

Neglecting the network losses, the electrical power can be expressed as,

$$P(\delta') = \frac{E_g V}{X_d} \sin(\delta' - \Theta) = \frac{E_g V}{X_d} (\sin \delta' \cos \Theta - \cos \delta' \sin \Theta) \quad (\text{eq2.2})$$

Where X_d is the equivalent transient reactance which also includes the reactance of the transformer and the transmission line. Substituting for $\sin \Theta$ and $\cos \Theta$ expressions obtained from equation above gives,

$$P(\delta') = \frac{E_g V_s}{X_d} [(\sin \delta')(1 + \beta) - (\cos \delta') \gamma] \quad (\text{eq2.3})$$

$$P(\delta') = b \sin \delta' - (b \cos \delta') \gamma(t) + (b \sin \delta') \beta(t)$$

Where $b = \frac{E_g V_s}{X_d}$ is the amplitude of the power angle characteristic with zero booster voltage. The equation (eq2.3) shows that the control of the in-phase booster voltage (via the control variable $\beta(t)$) increases the amplitude of the power – angle characteristic while control of the quadrature booster voltage (via the control variable $\gamma(t)$) shifts the characteristic horizontally.

From the generator swing equation,

$$M \frac{d^2 \delta}{dt^2} + D \frac{d\delta}{dt} = p_m - p_e$$

from that we can derive,

$$\frac{d\delta'}{dt} = \Delta\omega$$

$$M \frac{d\Delta\omega}{dt} = \tilde{T}_m - (b \sin \delta') - D \frac{d\delta'}{dt} - \tilde{T}_{UPFC} \quad (\text{eq2.4})$$



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Where, $P_{UPFC} = -(b \cos \delta')\gamma(t) + (b \sin \delta')\beta(t)$ is the additional power component enforced by the controller. This component introduces additional damping to the system if it is made positive and proportional to the speed deviation $\Delta\omega$. This can be achieved through the following control strategy:

$$\gamma(t) = -K(\cos \delta')\Delta\omega \quad (\text{eq2.5})$$

$$\beta(t) = K(\sin \delta')\Delta\omega \quad (\text{eq2.6})$$

Substituting equations (eq2.5) and (eq2.6) into the expression for

$$P_{UPFC} = \mathbf{Kb}(\Delta\omega) = \mathbf{D}_{UPFC}(\Delta\omega) \quad (\text{eq2.7})$$

where $D_{UPFC} = K_b$ is the damping coefficient due to the controller. This coefficient is constant for the control strategy defined in equations (eq2.5) and (eq2.6) and does not depend on δ' .

Therefore from equation (eq2.4),

$$M \frac{d\Delta\omega}{dt} = P_m - (b \sin \delta') - D \frac{d\delta'}{dt} - Kb(\Delta\omega)$$

$$M \frac{d\Delta\omega}{dt} = P_m - (b \sin \delta') - D \frac{d\delta'}{dt} - Kb \frac{d\delta'}{dt}$$

$$M \frac{d\Delta\omega}{dt} = P_m - (b \sin \delta') - (D + Kb) \frac{d\delta'}{dt} \quad (\text{eq2.8})$$

Hence from the equation (eq2.7) it is clear that the damping coefficient has increased due to the addition of the UPFC by 'Kb' amount. This definitely supports the improvement of stability of the system. Higher damping level would be added by the UPFC to fadeout the oscillations in the system very quickly.

In the literature [3], it has been explained the way external control may be comprised of different control loops depending on the control objectives. Typically, the principal steady state function of a UPFC is power flow control to a specified set point. Additional functions for stability improvement, such as damping controls, may be included in the external control.

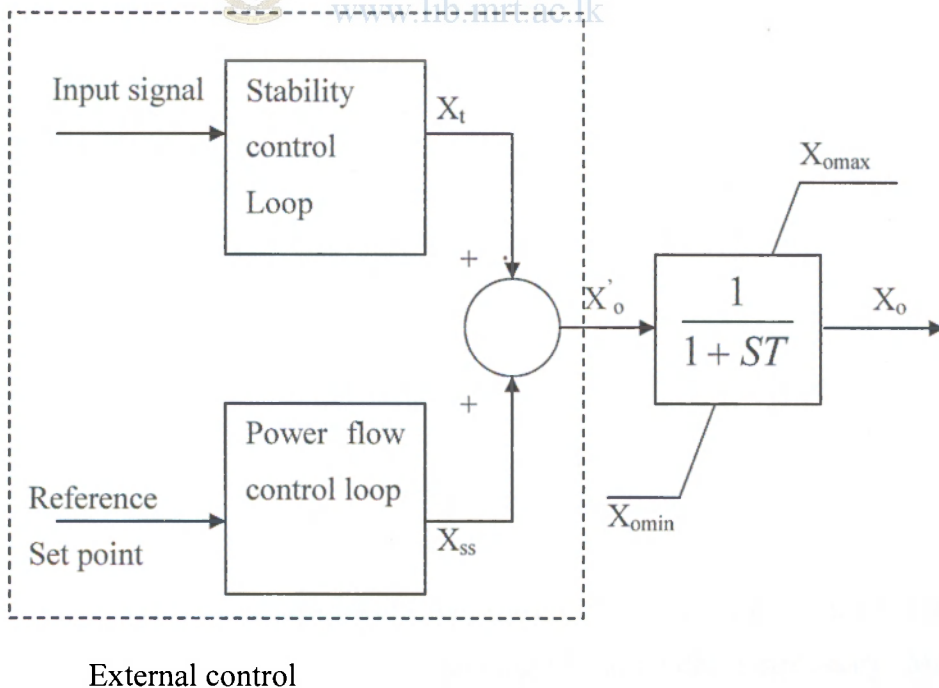


Figure 2.2: Proposed control loop for UPFC

If power flow control loop is “slow”, as is typically the case for a PI controller with a large time constant or for manual control, X_{ss} is assumed here to be constant during large disturbance transient periods. In the particular case of a PI power flow control, a protection logic scheme may be implemented to avoid contradictory control signals that could degrade the overall performance.

When the system is subjected to a severe disturbance, the stability control loop must provide maximum compensation level during the immediate post-fault period, so that synchronizing torque is increased to improve the first – swing stability response of the system, as well as provide proper modulation to damp the subsequent power oscillations.

Two fundamental elements in this controller design process, i.e. input signal and parameter tuning, are discussed below. The effect of set point value on controller performance, and particularly its effect on interactions between the stability control loop (dynamic control) and the power flow control loop (steady state control), is also discussed.

Parameter tuning: a number of alternative methods may be used for selection of control parameters for UPFC. The most popular ones, which are based on linear systems theory, are phase and gain margin techniques, pole placement through root locus analysis, Eigen value placement based on residues, and optimal selection of control parameters based on Eigen value sensitivities. However due to high nonlinearity of UPFC behaviour and major concern is the controller’s performance under severe disturbances, which typically trigger large excursions of generator angles, power flows, bus voltage and other system variables due to non linear characteristics of the power system, parameters were adjusted using full time domain simulation (trial and error method).

2.1 UPFC model in Matlab/Simulink Simulator

UPFC model given in MATLAB/SIMULINK software is used for simulation purposes. Therefore, detail understanding of the model is necessary. Matlab version used for this simulation is R2008a. Following figure shows the basic block given in the simulator. This phasor type block models an IGBT – based UPFC.

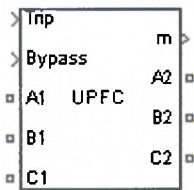


Figure 2.3: UPFC block in Simulink

Parameters can be defined for the UPFC after double clicking it. Detailed analysis of series and shunt controller are given below as per the literature [7],

2.1.1 Series Converter

Control system of series converter is meant to control active power and reactive power. Therefore, it has two degrees of freedom. Simplified block diagram of the UPFC can be drawn as follows,

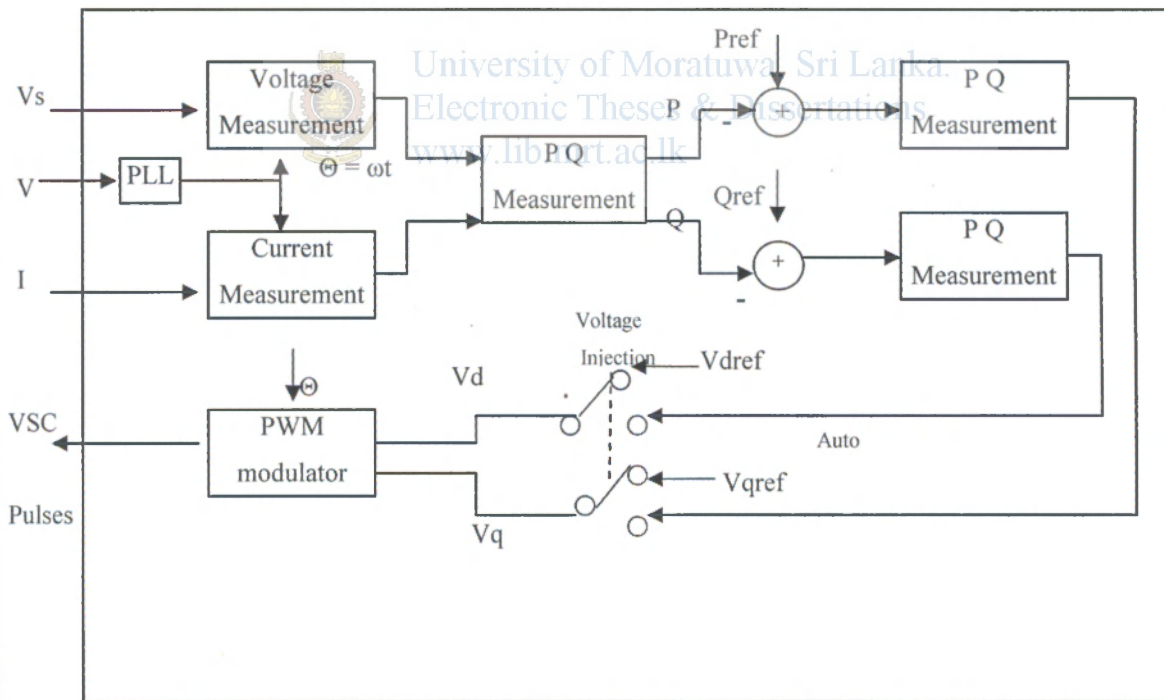


Figure 2.4: Controller - Series compensator

As can be seen from above figure, series converter can be operated on two modes, namely;

- Voltage injection mode
- Auto mode

2.1.2 Voltage Injection Mode

Injected voltage (ΔV) can be resolved into two components as given in the figure 2.1 above. Those are namely; ΔV_p and ΔV_q . These two components can be directly injected to the UPFC model given in the Simulink software. Therefore, by comparing those two systems we can write;

$$\Delta V_p = V_{qref}$$

$$\Delta V_q = V_{dref} \quad \text{Eq - 2.9}$$

The in-phase component with V_s is responsible for reactive power transfer, and the in-phase quadrature component with V_s is responsible for active power transfer. This can be further proved as follows using simple transmission line,

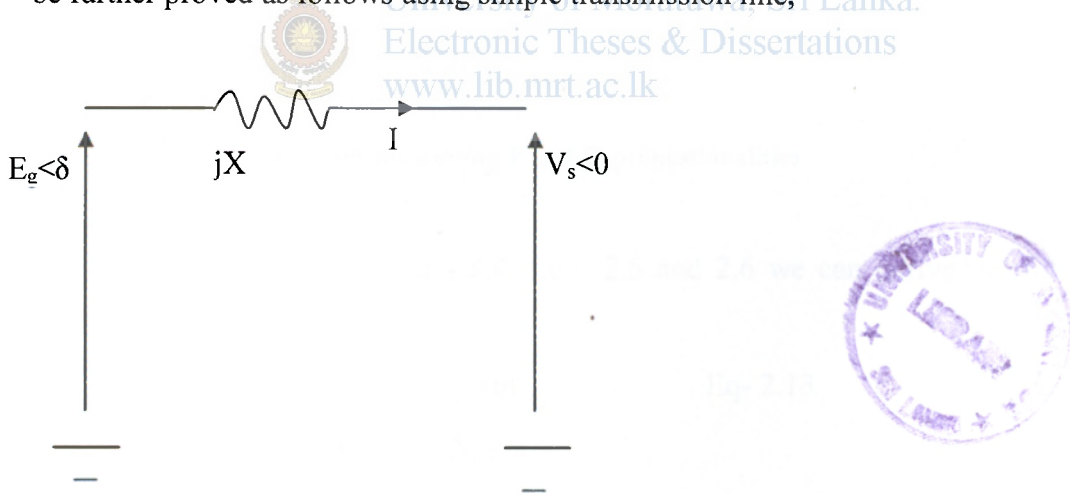


Figure 2.5 Transmission line with voltage sources

From the above figure, we can write KVL as

$$E_g \angle \delta' - V_s \angle 0 = jIX$$

$$E_g \angle \delta' = V_s \angle 0 + jIX \quad \text{Eq - 2.10}$$

But we know that,

$$V^* \times I = P - jQ$$

$$I = \frac{P-jQ}{V_s} \quad \text{Eq - 2.11}$$

Form eq-2.10 & eq 2.11

$$E_g \angle \delta' = V_s \angle 0 + jX \left(\frac{P-jQ}{V_s} \right)$$

$$E_g \angle \delta' = V_s \angle 0 + \frac{jXP}{V_s} + \frac{XQ}{V_s} \quad \text{Eq - 2.12}$$

From eq - 2.12 we can draw the phasor diagram as follows,

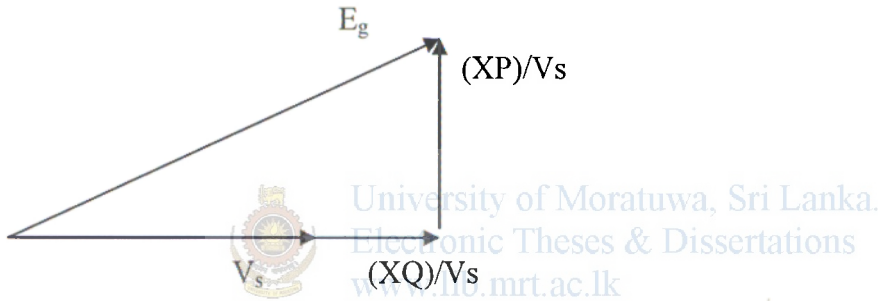


Figure 2.6 : Phasor diagram illustrating P and Q proportionalities

Therefore, from Eq - 2.0, Eq - 2.9, Eq - 2.5 and 2.6 we can derive the following relationship,

$$\Delta V_p = V_{qref} = - V_s K (\cos \delta') \Delta \omega \quad \text{Eq- 2.13}$$

$$\Delta V_q = V_{dref} = V_s K (\sin \delta') \Delta \omega$$

These inputs can be given into the UPFC model in the Simulink to work it as a Power System Stabilizer.

In manual injection mode, inbuilt regulators are bypassed and converter voltage is derived from reference values.

In Automatic mode, power flow control can be done. This is done using sensed voltage and current in the system as illustrated in the block diagram. In this case voltage regulators are used with defined Pref and Qref.

As in this thesis we only do the manual external voltage injection, other parameters associated with the Power flow control (automatic) mode is not discussed in detail.

From the equation 2.7, it is clear that, damping constant of the UPFC can be varied by changing the value of K (since b is a constant).

2.1.3 Shunt Converter

Shunt converter also can be operated on two modes. They are, Voltage Control Mode and Var control Mode. Its block diagram can be drawn as given in the literature [7] as shown below,

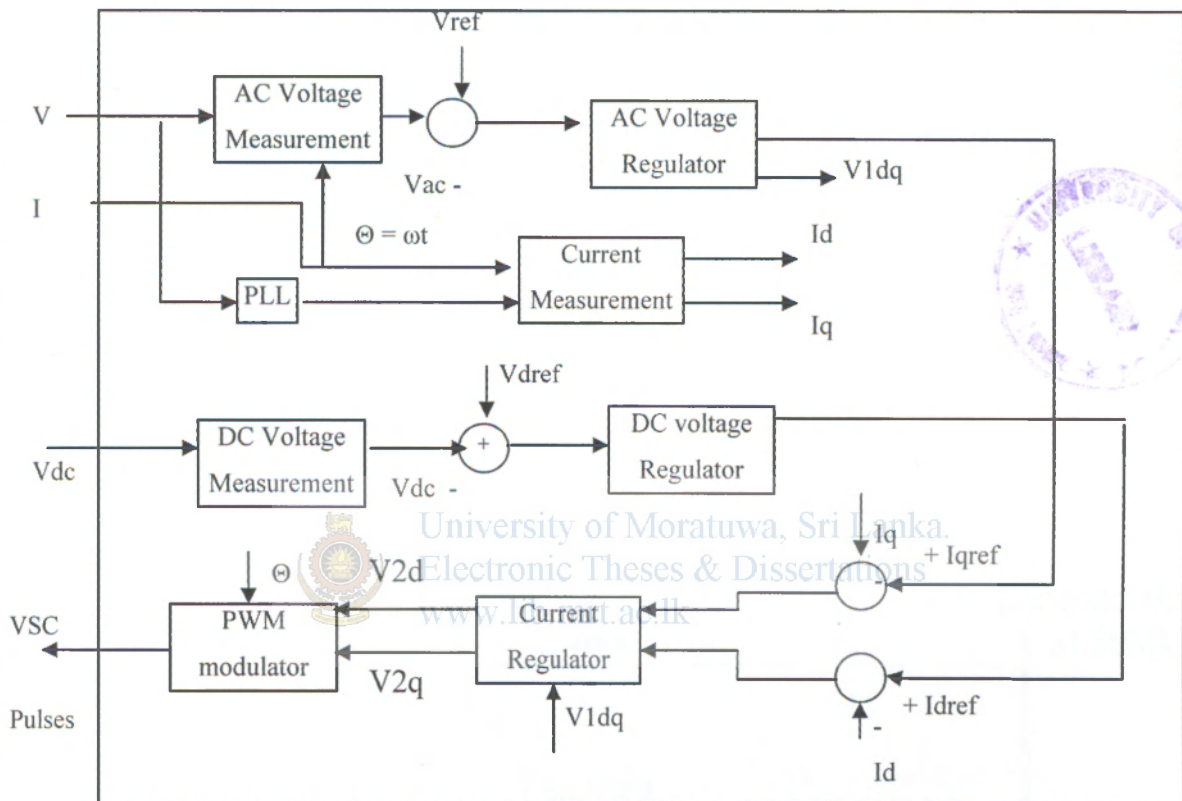


Figure 2.7: Controller – Shunt compensator

The shunt controller can be operated in two different modes:

- Voltage regulation mode: As long as the reactive current stays within the minimum and maximum current values ($-I_{max}$, I_{max}) imposed by the converter rating, the voltage is regulated at the reference voltage V_{ref} .
- Var control mode (reactive power output is kept constant)

In this project the shunt controller is kept in the Voltage control mode.

3.0 Introduction

Performance of the UPFC was monitored with real practical system in Sri Lankan power system. Area selected was Matugama, Kukule, Horana Pseudo Island of the National Power System. System was modelled in the Simulink software, which is a common engineering tool nowadays used by engineers around the world.

Following figure 3.0 illustrates the simplified selected network portion from the Sri Lankan Power system to analyse the theoretical development in the previous chapter. The actual network diagram is given in the Appendix B.

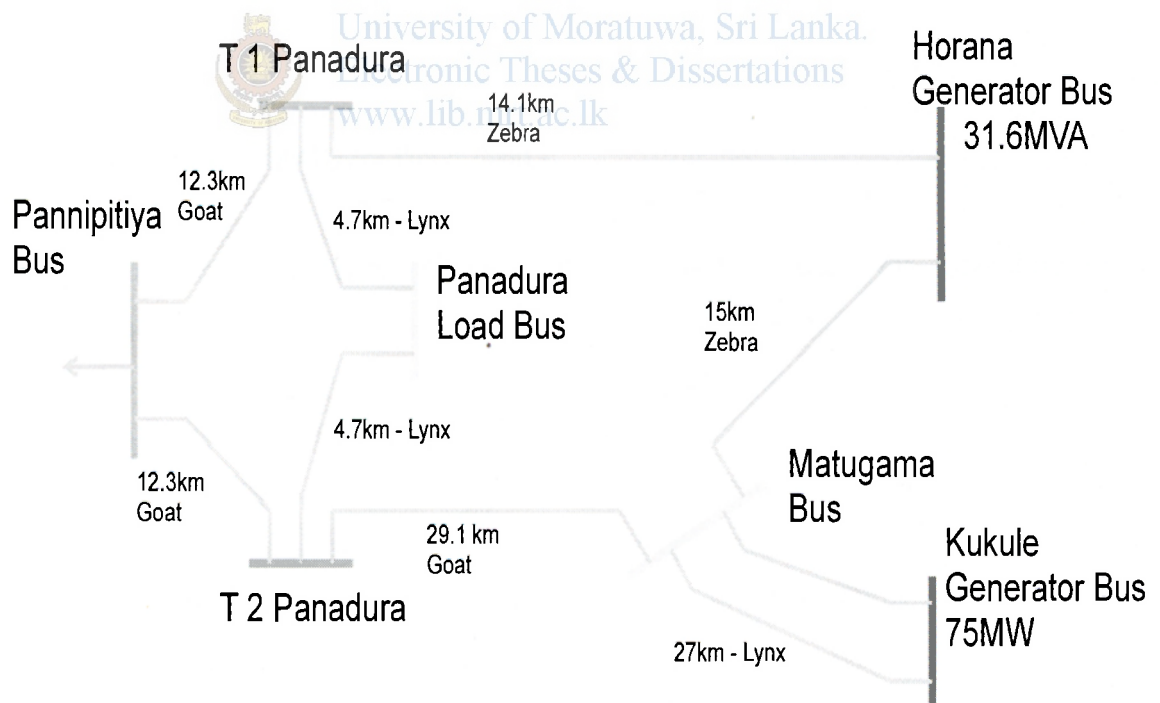
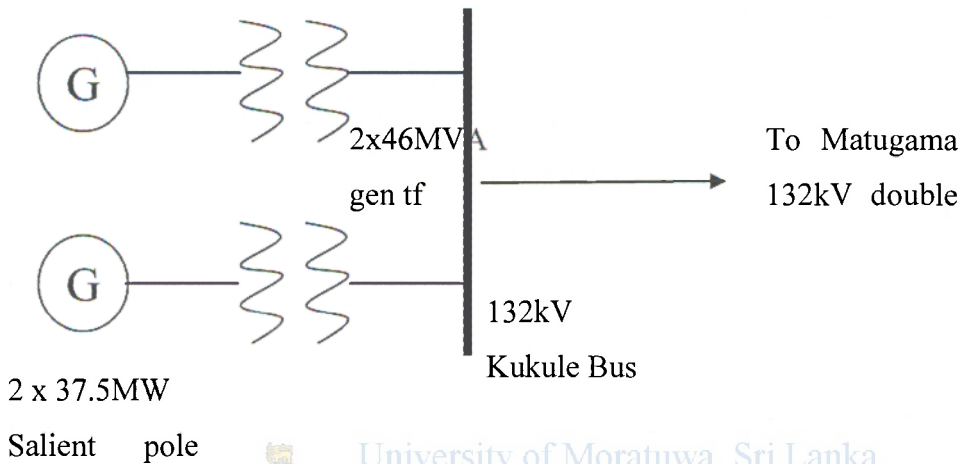


Figure 3.0 : Sub network selected for Case study

All power system components illustrated in the above figure 3.0 are modelled in the Simulink software environment. Detail discussion is given below for each components modelling below.

3.1 Kukule Ganga Hydro Power plant modelling

There are two hydro generators each 37.5MW installed in the Kukule Ganga Power plant, and connected to the 132kV bus through two 46MVA transformers.



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Figure 3.1: Kukule Ganga Hydra Power Plant

Synchronous machine model given in the Simulink is used for modelling of generators. Using this model salient pole 3 phase generator can be modelled. Hydraulic Turbine Governor Model is used to model water turbines of the system. Excitation System Model is used to model excitation system of the generator and to control terminal voltage. The parameters related to those systems are used and combination of above three systems, a complete hydro generator is modelled.

There is a 3phase transformer model given in the Simulink. Simulink implement this using three single-phase transformers.

Generator and Transformer parameters are given below,

3.1.1 Generator Parameters

Parameter	Value
Nominal Power	37.5MW
Line to Line Voltage	13.8kV
Frequency	50Hz
$X_d, X_d', X_d'', X_q, X_q''$	1.305, 0.296, 0.252, 0.474, 0.243, 0.18 (pu)
T_d', T_d'', T_{qo}''	1.01, 0.053, 0.1 (s)
Stator Resistance	0.0028544 (pu)
Inertia Constant - H	3.2 (s)
Pole pairs	32Nos

Table 3.0: Kukule - Generator Parameters



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3.1.2 Hydraulic Turbine Parameters

Parameter	Value
Servo motor K_a, T_a (s)	10/3 , 0.07 s
The speed deviation damping coefficient β	0
Water starting time T_w (s)	2.67s
PID regulator, $K_p, K_i, K_d,$	1.163, 0.105, 0
Permanent droop R_p	0.05
T_d (s)	0.01s

Table 3.1: Kukule - Hydraulic Turbine Parameters

3.1.3 Excitation System Parameters

Parameter	Value
Low Pass Filter Time Constant $T_r(s)$	0.02
Regulator Gain K_a , Time constant $T_a(s)$	300, 0.001
Damping Filter Gain and Time constant $K_f()$, $T_f(s)$	0.001, 0.1

Table 3.2: Kukule - Excitation System Parameters

3.1.4 Unit Transformer Parameters



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Parameter	Value
Nominal Power and frequency	46MVA, 50Hz
Primary winding Voltage, $R(pu)$, $L(pu)$	13.8kV, 0.0027pu, 0.08pu
Secondary winding Voltage, $R(pu)$, $L(pu)$	132kV, 0.0027pu, 0.08pu
Magnetization Resistance pu	500
Magnetization Reactance pu	500
Vector Group	YNd5

Table 3.3: Kukule - Unit Transformer Parameters

In the next page modelled system is shown in figure 3.2,

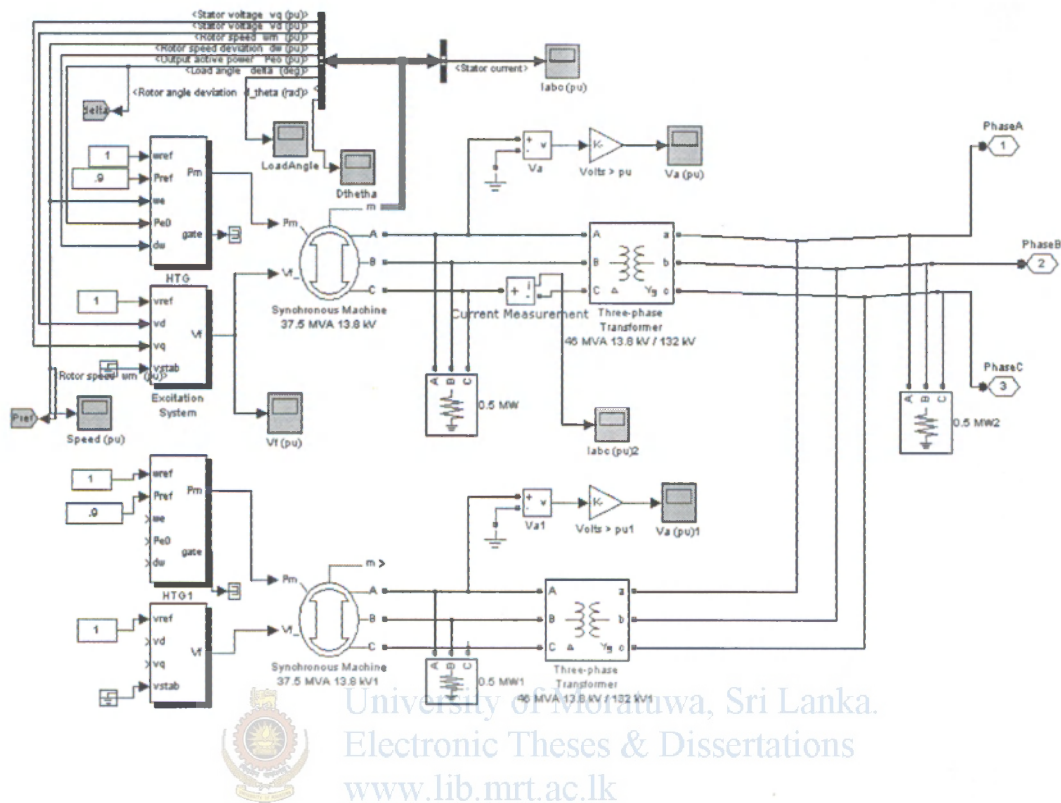


Figure 3.2 Model of Kukule ganga power station in Simulink

3.2 Horana Generators Modelling

Horana power station is a diesel power plant with capacity of 31.6MW. This power plant consists of 4 generators connected parallel with each capacity of 7.9MW. This has been modelled as a single equivalent diesel generator for simplicity. This is also connected through a unit transformer to the 132kV grid at Horana bus.

Equivalent Generator Parameters are given below in the table 3.4,

3.2.1 Equivalent Generator Parameters

Parameter	Value
Nominal Power	31.6MW
Line to Line Voltage	11kV
Frequency	50Hz
$X_d, X_d', X_d'', X_q, X_q''$	1.56, 0.296, 0.177, 1.06, 0.177, 0.052 (pu)
T_d', T_d'', T_{qo}''	3.7, 0.05, 0.05 (s)
Stator Resistance	0.0036 (pu)
Inertia Constant – H	1.7 (s)
Pole pairs	2Nos

Table 3.4: Horana Generator Parameters

3.2.2 Equivalent Governor and Diesel Engine Parameters

Parameter	Value
Regulator Gain	40
Regulator Time constants T_1, T_2, T_3	0.01, 0.02, 0.2(S)
Actuator Time constants T_4, T_5, T_6	0.25, 0.009, 0.0384(S)
Torque Limits	0 to 1.1 (pu)
Engine Time Delay	0.024(S)

Table 3.5: Horana Governor and Diesel Engine Parameters

3.2.3 Excitation system Parameters

Parameter	Value
Low Pass Filter Time Constant $T_r(s)$	0.02
Regulator Gain K_a , Time constant $T_a(s)$	200, 0.02
Damping Filter Gain and Time constant $K_f()$, $T_f(s)$	0.001, 0.1

Table 3.6: Horana Excitation System Parameters

3.2.4 Unit Transformer Parameters

Parameter	Value
Nominal Power and frequency	40MVA, 50Hz
Primary winding Voltage, $R(pu), L(pu)$	11kV, 0.0027pu, 0.08pu
Secondary winding Voltage, $R(pu), L(pu)$	132kV, 0.0027pu, 0.08pu
Magnetization Resistance pu	500
Magnetization Reactance pu	500
Vector Group	YNd5

Table 3.7: Horana - Unit Transformer Parameters

Modelled system is given below,

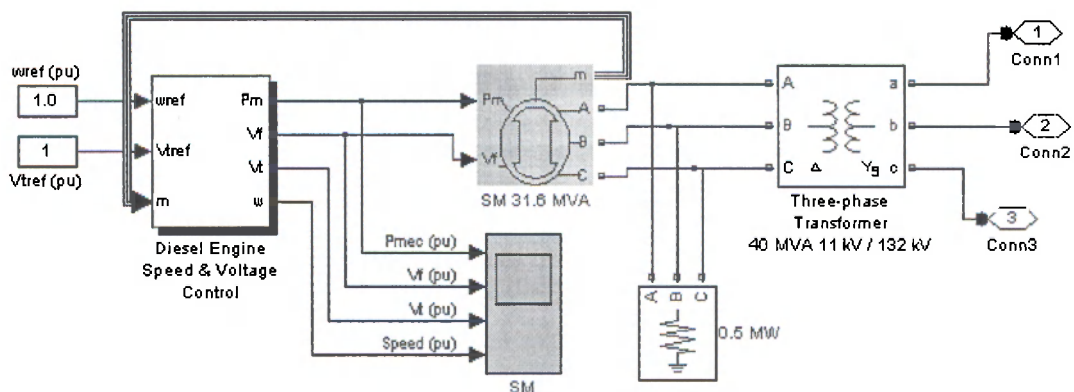


Figure 3.3 Horana diesel power generators

3.3 Transmission Line Modelling

Distributed parameter transmission line model given in the Simulink Library is used for the transmission line modelling of the selected system. As per the literature [7], the Distributed Parameter Line block implements an N-phase distributed parameter line model with lumped losses. The model is based on the Bergeron's travelling wave method used by the Electromagnetic Transient Program (EMTP). In this model, the lossless distributed LC line is characterized by two values (for a single-phase line): the surge impedance and the phase velocity.

There are three main types of 132kV transmission lines in the selected system. Those are Lynx, Zebra and Goat. Those parameters were obtained from the transmission design division of Ceylon Electricity Board. These details are attached in Appendix B. Transmission line parameters of the selected system can be tabulated as follows,

3.4 Transmission Line Data

Line Section	Volt (kV)	Cts.	Conductor	Length (Km)	R/cct In PU	X/cct In PU	Y/cct In PU
Kukule – Mathugama	132	2	Lynx	27.0	0.02758	0.06214	0.01315
Single in and out connection from Horana GS to Panadura T – Mathugama	132	2	Zebra	20.0	0.00872	0.04442	0.01040
Pannipitiya – Panadura (T)	132	2	Goat	12.3	0.00629	0.02734	0.00631
Panadura(T) – Mathugama	132	2	Goat	29.1	0.01488	0.06467	0.01493
Pandura(T) – Panadura Sub Station	132	2	Lynx	4.7	0.00480	0.01082	0.00229

Note : the line parameters are given in pu values wrt $Z_{base} = V_{base}^2 / MVA_{base}$,
($MVA_{base}=100$, V_{base} in kV)

Table 3.8: Horana - Unit Transformer Parameters

UPFC model is inserted near Kukule Generator bus end of the above system. Inputs to the UPFC are given as proved in the Chapter 2.

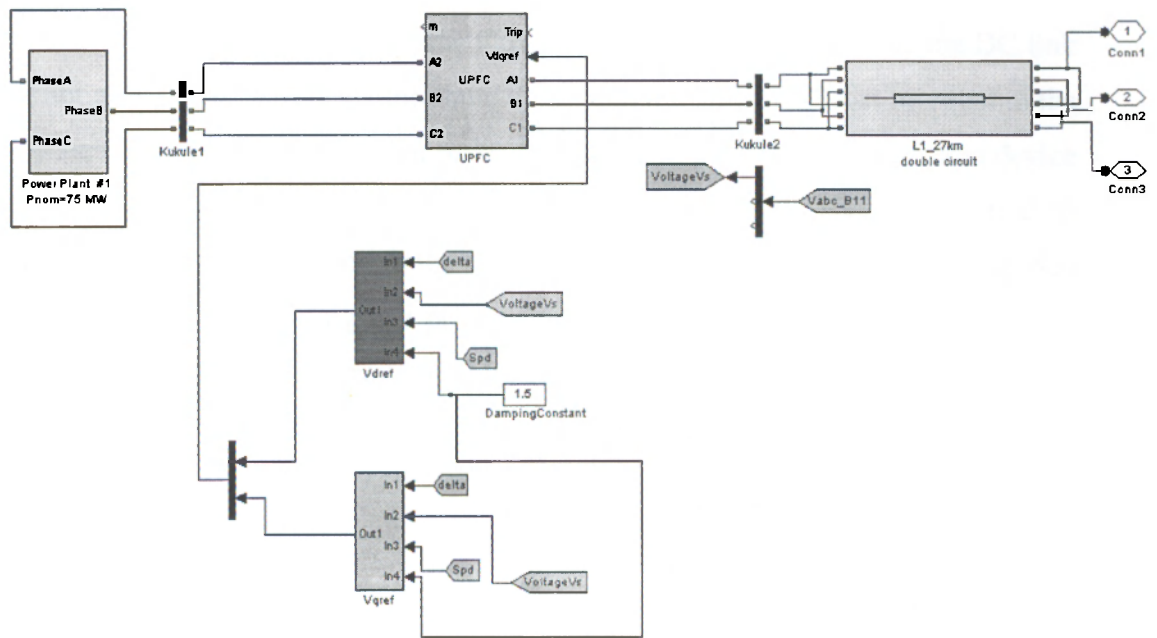


Figure 3.8: Matugama sub system with UPFC

3.7 UPFC modelling

In modelling the UPFC, it is required to identify the capacities and parameters of it. As discussed previously, there are two converters coupled through a common DC link capacitor. Therefore, converter ratings and parameters, capacitor ratings, controller parameters are necessary for modelling purposes.

3.7.1 Series converter of the UPFC

This needs to handle line current as well as its injected voltage to the line in series. Normally, maximum injected voltage is around 0.1pu. Current handling capability of the series transformer should be same as the line current in steady state. Therefore, series converter rating is taken as 0.1xLine rating, it is around 10MVA. Resistance and Inductance of the series converter is taken as 0.00533pu, 0.16pu respectively.

3.7.2 Shunt Converter of the UPFC

As per the literature[15], if we assume the active power to be released by the DC link capacitor at transient state, then the shunt devices rating should at least be equal to the steady state power flow through the series device (i:e about 100MVA). If shunt device is expected to transmit all the transient state power, then, it should be equal to transient state power flow though the series converter. This will be further explained in the simulation by selecting two power values to the shunt converter and how that could affect the transient behaviour. Therefore, for the moment 100MVA value is selected as the shunt converter rating. Shunt converter impedances are taken as typical values, like for resistance 0.00733pu and Inductance 0.22pu.

3.7.3 DC link Capacitor

Details of design aspects of DC link capacitor are given in the literature [15]. According to that, in transient state energy stored in the DC link capacitor is transmitted and stored in the series line inductor as a magnetic energy. This type of situation only happens in the transient state, but not in the steady state. But when DC link capacitor supplies its energy in this transient state, fluctuation of its voltage can be observed. Whereas, if the shunt converter can supply this energy through DC link capacitor, a constant DC link capacitor voltage can be maintained. Value of the DC link capacitor can be obtained from following equation according to [15],

$$C_{dc} = \frac{3L(I_1^2 - I_0^2)}{2\epsilon V_{dc0}^2}$$

Where, C_{dc} = DC link capacitor capacitance in F.

L = Line inductance .

I_1 = value of the current after transient.

I_0 = value of the current at the start of the transient.

V_{dc0} = DC link capacitor voltage – steady state. = 40000V

$$C_{dc} = \frac{3 \times 0.16(720^2 - 200^2)}{2 \times 0.1 \times 40000^2} = 717.6 \mu\text{F} \approx 750 \mu\text{F}$$

Simulation Results and Analysis

4.0 Introduction

In this chapter, the modelled system is analysed with simulation results obtained from the MATLAB/Simulink. Basically, the system is analysed before adding the UPFC to the system and then, the improvement towards the system stability is to be identified after adding the UPFC to the system at Kukule Ganga Generator bus.

The modelled system is simulated before adding the UPFC to the system with various faults created. The aim of this creation of fault is to obtain a situation where system cannot hold its stability. Therefore, three phase line to ground faults have to be created to simulate this situation. Then the critical clearing time was observed to be increasing with the UPFC introduced in the system.

Input K value is changed, in order to observe the effect of the damping coefficient imposed by the UPFC to the system. Results are analysed for various K values. Then effective damping coefficient and damping ratio to the system is calculated using simulation results.

Then UPFC performance is studied by changing parameters of shunt converter, as explained in the previous chapter to find out most suitable parameters for shunt converter for optimum operation. This type of optimisation is normally combined with cost benefit analysis as well.

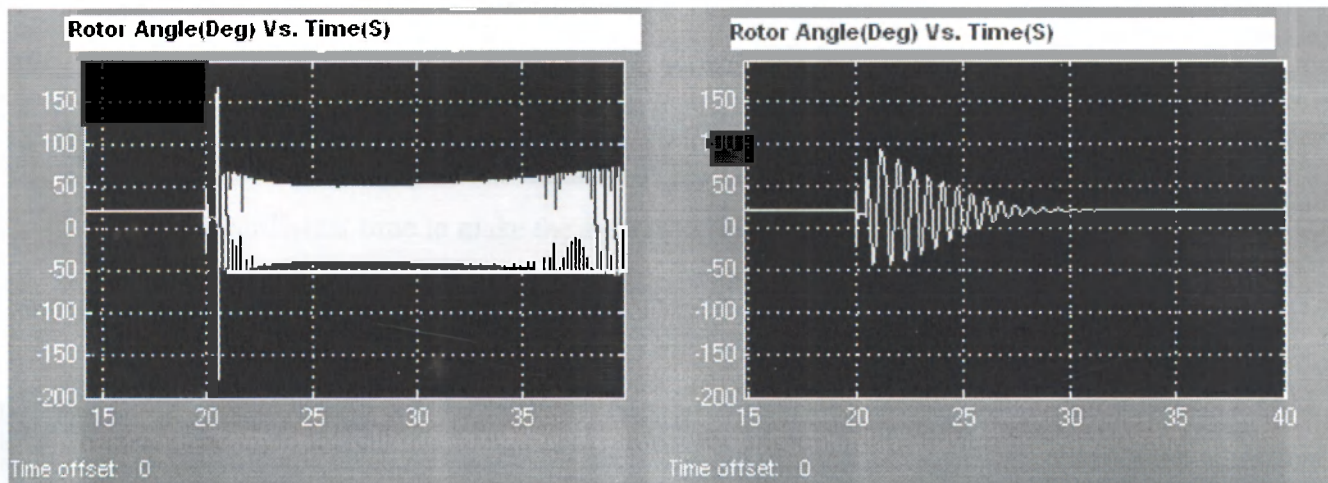
4.1 Analysis of Faults

4.1.1 Fault created on Horana Bus:

A three phase to ground fault is created on Matugama – Horana transmission line towards the Horana end with fault impedance of 0.001Ω . The time duration of the fault is from 20.0s to 20.5s, so that giving sufficient time to make the system to become unstable.

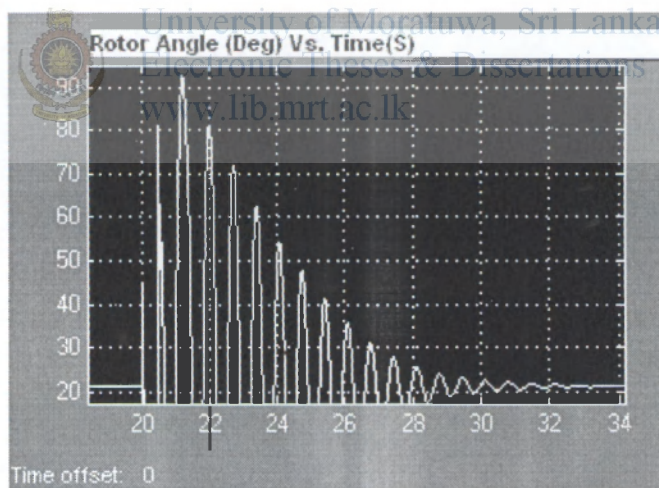
It is observed that with this type of fault in the line, the system is marginally unstable and unable to come back to a stable point after clearing the fault after 500

milliseconds, as system itself does not provide sufficient damping to this type of transient behaviour. Kukul Ganga generator rotor angle variation were observed and results are shown in figures below,



(a) Without UPFC in Operation

(b) With UPFC in Operation



(c) With UPFC in Operation – Zoomed view of (b)

Figure 4.0: Rotor Angle Response to Fault on Horana Bus

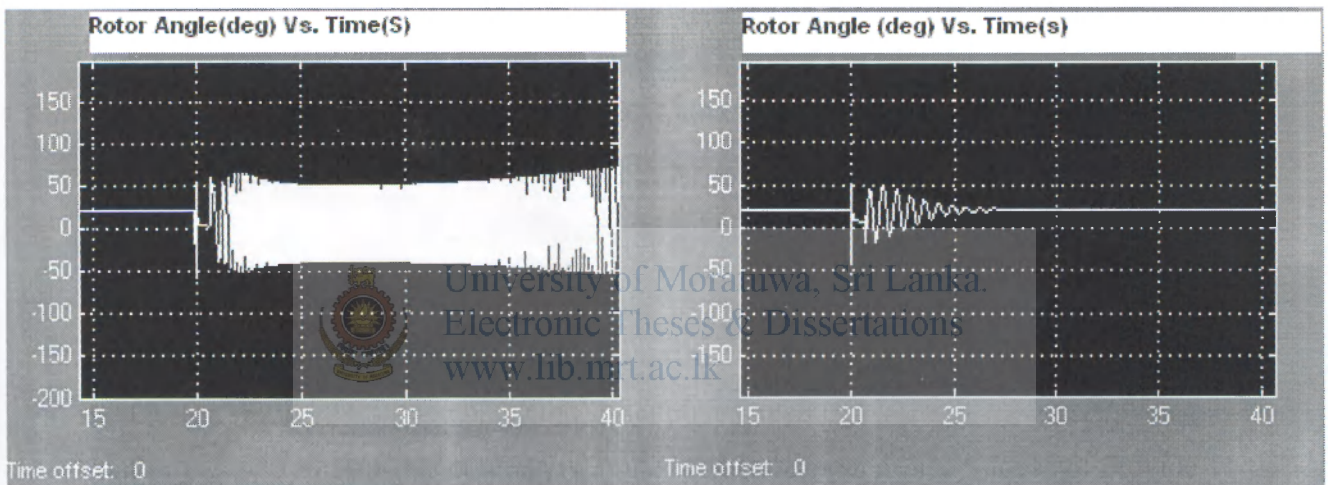
These types of large transient oscillations have been damped by the UPFC as can be seen from the above Figure 4.0. When UPFC is not in operation, huge oscillatory response is observed as shown by Figure 4.0(a). Rotor angle maximum overshoot has been limited to just above 90degrees, when UPFC in operation. Thereafter, oscillation is damped out to zero at around 30s. First swing of rotor angle is a very high value,

when UPFC is not inserted, it goes to above 150 degrees. That behaviour is damped out by DC link capacitor either by absorbing that energy temporary or releasing its stored energy to the series inductor.

4.1.2 Fault created near Pannipitiya Bus:

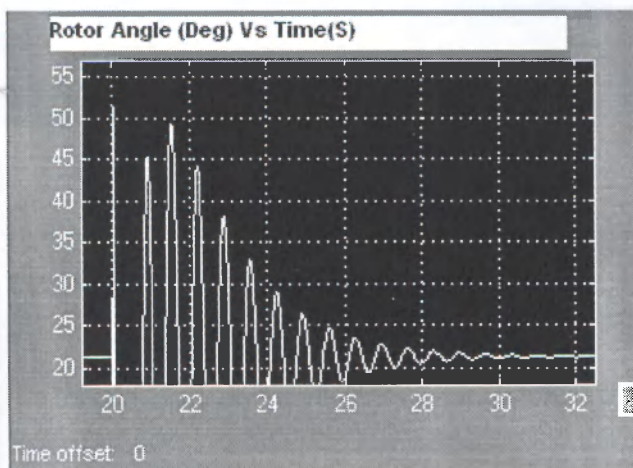
A three phase to ground fault is created on Pannipitiya Bus with fault impedance of 0.001Ω . The critical clearing time of this case before adding the UPFC is 600 milliseconds. Therefore, the time duration of the fault is taken from 20.0s to 20.7s, so that giving sufficient time to make the system to unstable.

Fault time duration for this case is 700 milliseconds, as system itself does not provide sufficient damping to this type of transient behaviour.



(a) Without UPFC in Operation

(b) With UPFC in Operation



(c) With UPFC in Operation – Zoomed view of (b)

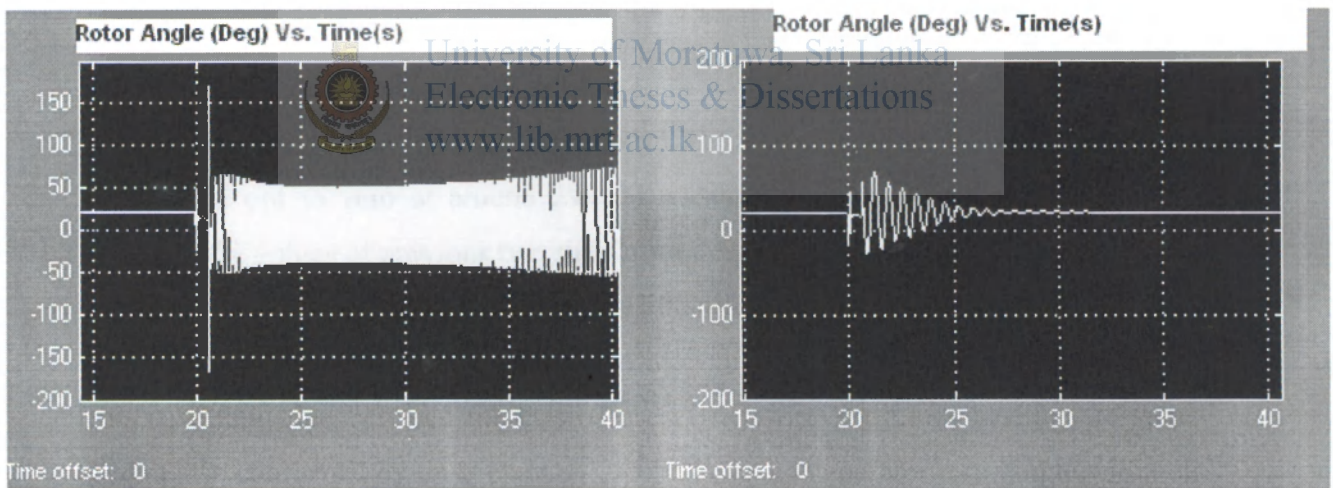
Figure 4.1: Rotor Angle Response to Fault on Pannipitiya Bus

As can be seen from above figure 4.1, rotor angle maximum overshoot has been limited to just below 50degrees, when UPFC in operation. This is because the fault is far away from the Kukule generators and somewhat closer to the infinite bus. Therefore, fault current is largely fed by infinite bus. Thereafter, oscillation is damped out to zero at around 26s.

4.1.3 Fault created near Panadura Load Bus:

A three phase to ground fault is created on Panadura bus with fault impedance of 0.001Ω . The time duration of the fault is from 20.0s to 20.6s, because critical clearing time for this kind of fault is observed to be 500milliseconds.

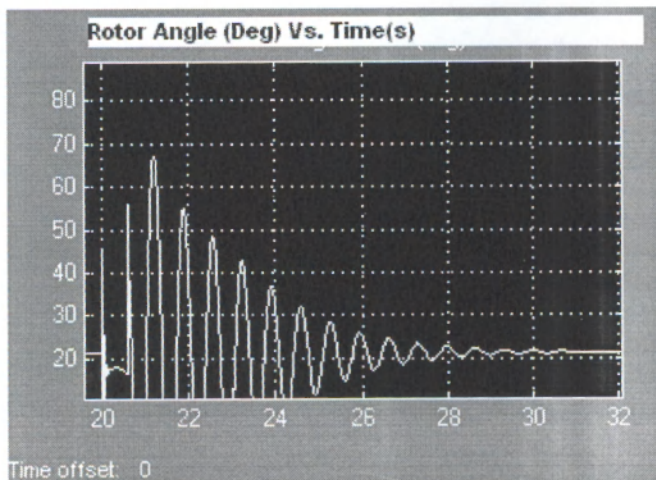
500 milliseconds fault time is in between the values of previous two cases, where in this case fault lied between those two cases. Therefore, the model validity to some extent also confirmed by this behaviour. Kukule Ganga generator rotor angle variation is observed and results are shown in figures below,



(a) Without UPFC in Operation

(b) With UPFC in Operation

Figure 4.2: Rotor Angle Response to Fault on Panadura Bus



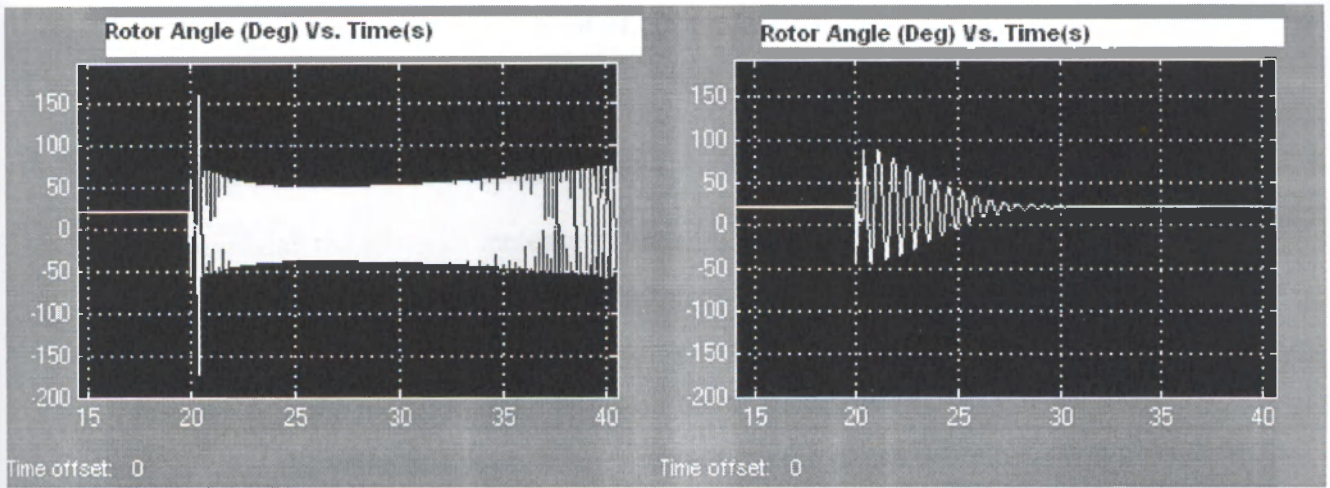
(C) With UPFC in Operation – Zoomed view of (b)

Figure 4.2: Rotor Angle Response to Fault on Panadura Bus

This type of large transient behaviour has been damped out by the UPFC as can be seen from the above Figure 4.2. When UPFC is not in operation huge oscillatory response is observed as shown by Figure 4.2(a). Rotor angle maximum overshoot has been limited to just below 70degrees, when UPFC in operation. Thereafter, oscillation is damped out to zero at around 29s. The maximum overshoot value also lies in between the values of previous two simulations.

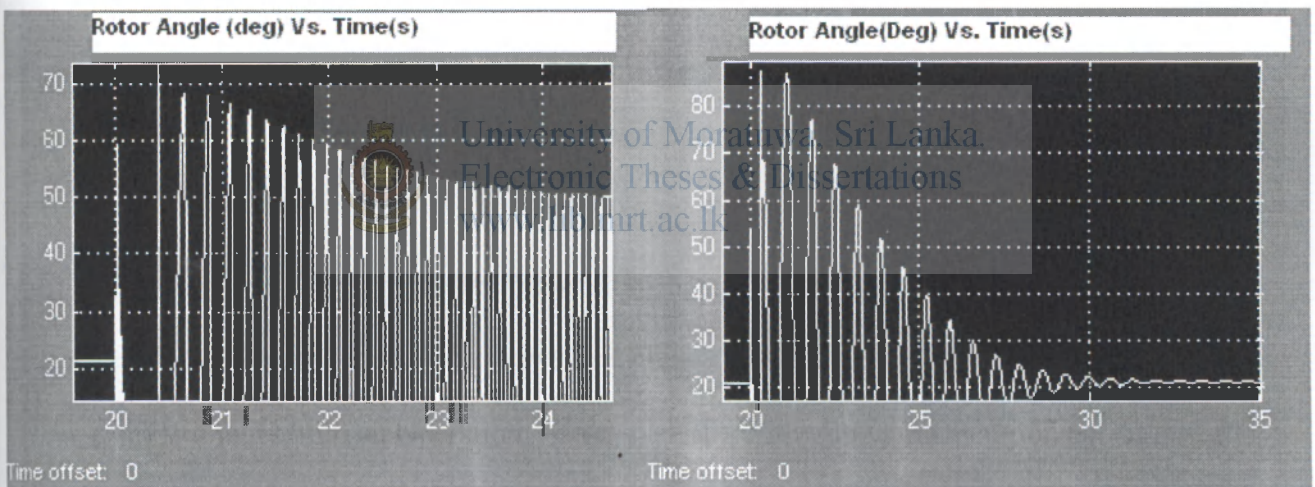
4.1.4 Fault created near Matugama Bus:

A three phase to ground fault is created closer to Kukule generators. That is on Matugama bus with fault impedance of 0.001Ω . The time duration of the fault is from 20.0s to 20.31s, so that giving sufficient time to make the system to become unstable. Critical clearing time for this case is 300 milliseconds, as fault is very closer to the Kukule generators. The fault is allowed to persist 10millisecond more to create an unstable situation. Kukule Ganga generator rotor angle variation were observed and results are shown in figures below,



(a) Without UPFC in Operation

(b) With UPFC in Operation



(c) Without UPFC in Operation – Zoomed (a)

(d) With UPFC in Operation – Zoomed (b)

Figure 4.3: Rotor Angle Response to Fault on Matugama Bus

As can be seen from the above Figure 4.3, UPFC was only able to damp out the oscillation when fault existed 10 milliseconds more unlike in previous cases. When UPFC is not in operation huge oscillatory response is observed as expected, as shown by Figure 4.3(a). Rotor angle maximum overshoot has been limited to just below 90 degrees, when UPFC is in operation. Thereafter, oscillation is damped out to zero at

around 32s. An initial high overshoot of above 150degrees was also observed in this case. And that is due to the closeness of the fault to Kukule bus.

4.2 Effect of increase in damping Coefficient of the UPFC

Let us examine the effect of increase in damping coefficient, as a result of insertion of UPFC to the system practically with the simulation. K_b is the additional damping coefficient provided by the UPFC (according to the equation 2.7). We can increase the value of K_b in the model in order to obtain better results. As b is a constant value, we can increase the value of K . Advantages of by having a larger damping constant to the system can be theoretically explained as follows. Then the system is simulated with different K values and results are shown in Figure 4.5 and Figure 4.6.

Theoretical examination can be shown as follows,

From the generator swing equation,

$$M \frac{d^2 \delta}{dt^2} + \bar{K} \frac{d\delta}{dt} = p_m - p_e$$

For small δ , let it is equal to $\Delta\delta$, then

$$M \frac{d^2 \Delta\delta}{dt^2} + K_d \frac{d\Delta\delta}{dt} - K_e \Delta\delta = p_m$$

As P_e linear for small δ , as shown in the Figure 4.4 below,

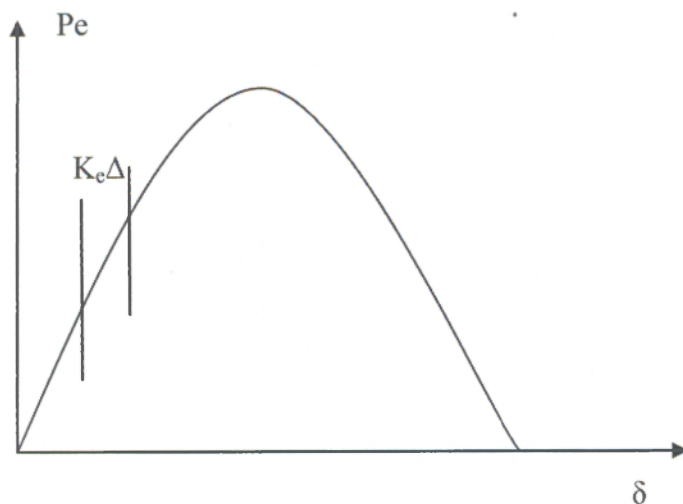


Figure 4.4: Power Vs. Load angle cure for a Synchronous Generator

Taking Laplace Transformation of the above equation,

$$(S^2 + \frac{K_d}{M}S + \frac{K_e}{M})\Delta\delta = P_m$$

Therefore,

$$S = -\frac{K_d}{2M} \pm \sqrt{\frac{K_d^2}{4M} - \frac{K_e}{M}}$$

From above equation, to have real roots,

$$\frac{K_d^2}{4} \geq K_e M$$

When this equation has real roots, that means Eigen values of the system has real negative numbers. When Eigen values are real negative the system damp out without oscillations.

To obtain the point where these two transitions are taking place, the following equality can be written,

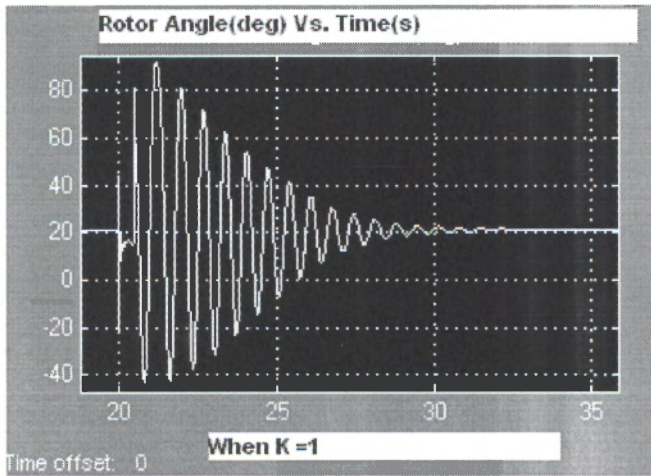
$$\frac{K_d}{\sqrt{K_e}} = 2\sqrt{M}$$



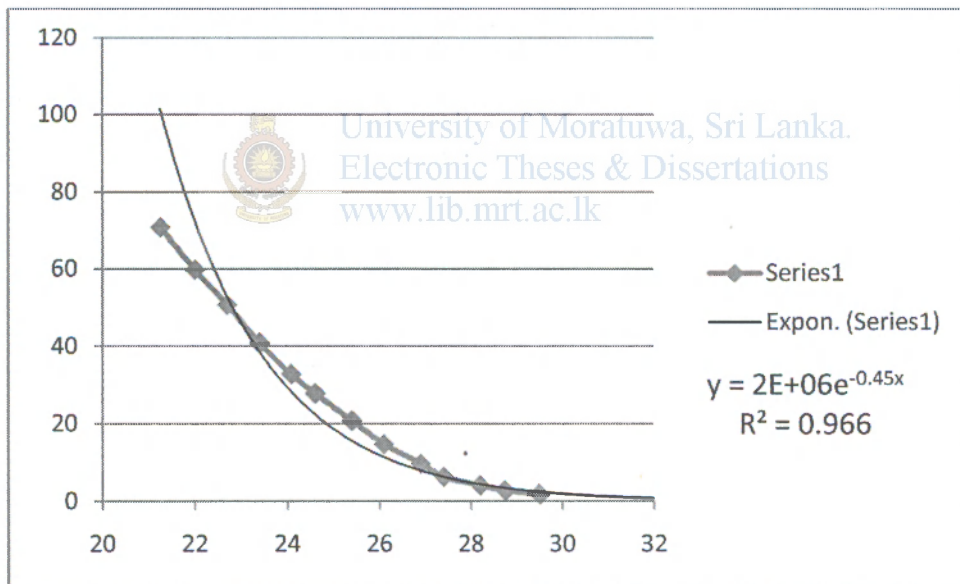
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From the above equation, it can be seen that when K_e has higher values that means when generator is in low load condition, for disturbances in the system creates generator to oscillate more. But, when generator is in higher load condition then generator output oscillations would damp out quickly without much oscillations. But problem with the higher load condition of the generator is that, the chances of getting back to the stability reduce as it operates very closer to the critical clearing angle point. In other words inertia constant can be increased either by reducing K_e , or by increasing K_d . Therefore, by adding UPFC (which will increase the M), we can operate the machine in low load condition so that no oscillations would result due to disturbances in the same time providing enough gap to the critical clearing angle. This will enable the enhancement of stability of a system.

K value (in page 19, Eq – 2.13) of the UPFC input can be increased in this model in order to increase the overall damping coefficient. It is simulated with different K values, and effective increase of dampness is obtained. This simulation is carried out with fault in the Matugama – Horana transmission line towards Horana end.



(a) Simulation Result when K = 1



(b) Simulation Result when K = 1 behaviour of peak values, after adding exponential trend line

Figure 4.5: Simulation results with K = 1

Stability of a system is determined by its Eigen values. Real Eigen values correspond to non-oscillatory mode, complex Eigen values correspond to oscillatory mode response. These complex Eigen values always occur in conjugate pairs.

Typical type of it as follows,

$$\begin{aligned}\lambda &= \sigma \pm j\omega \\ e^{\lambda t} &= e^{(\sigma \pm j\omega)t} \\ &= e^{\sigma t} \cos \omega t \pm j e^{\sigma t} \sin \omega t\end{aligned}$$

If σ is negative, oscillations decay to zero, otherwise it increases. ω is the Angular Velocity of oscillation. Therefore, from the above simulation and from the graph in (b)

Average time between two peaks = 0.6667 s

Damped Frequency of Oscillation = 1.5Hz

Therefore, ω = $2\pi f = 9.4248$ rad/s

From the above graph, σ = -0.45

Lets, find the damping ratio ζ , which determines the rate of decay of the amplitude of the oscillations.

Therefore, damping ratio is $\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$

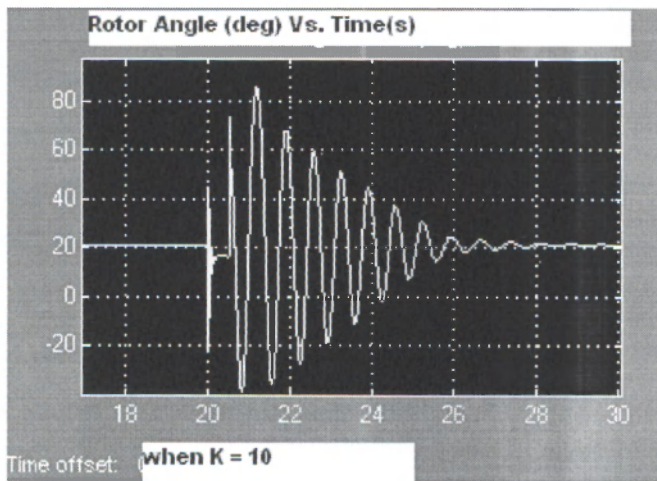
$$\zeta = 0.0477$$

Time constant of amplitude decay is $1/|\sigma|$, which is equal to T_d .

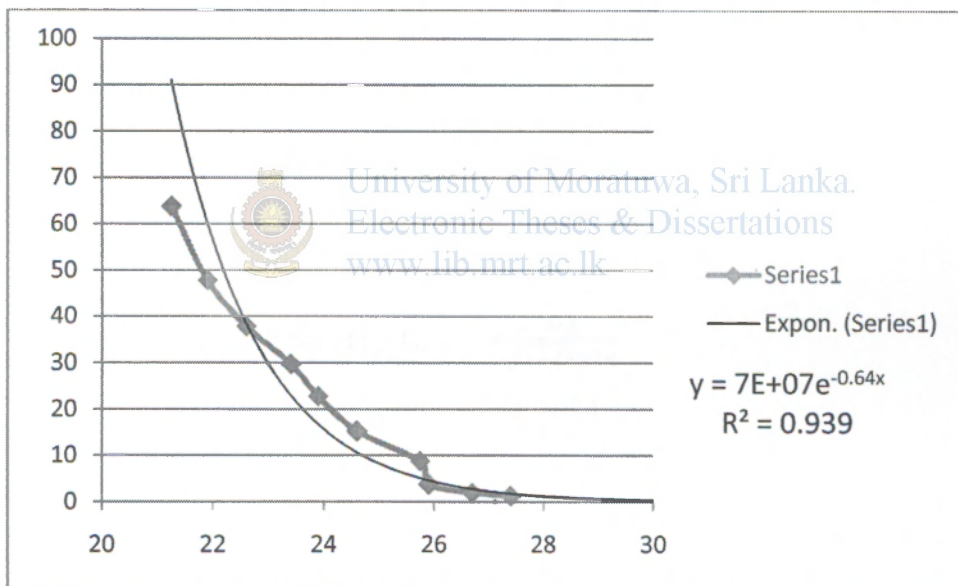
$$T_d = 2.22 \text{ seconds}$$

Un-damped natural frequency $f_n = \frac{\omega_d}{\sqrt{1 - \zeta^2} \times 2\pi}$

$$f_n = 1.5017$$



(a) Simulation Result when K = 10



(a) Simulation Result when K = 10, after adding exponential trend line

Figure 4.6: Simulation results with K = 10

When observing above figures we can see that increase in K has a big effect in damping of oscillation compared to K= 1 case. The most affected parts are when $\Delta\omega$ is high. Similarly, with the above case calculations can be done as follows,

When K= 10 lets calculate above values

$$\begin{aligned} \text{Average time between two peaks} &= 0.6667 \text{ s} \\ \text{Damped Frequency of Oscillation} &= 1.5\text{Hz} \\ \text{Therefore, } \omega &= 2\pi f = 9.4248 \text{ rad/s} \\ \text{From the above graph, } \sigma &= -0.64 \\ \text{Therefore, damping ratio is } \xi &= \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \\ \xi &= 0.0677 \end{aligned}$$

Time constant of amplitude decay is $1/|\sigma|$, which is equal to T_d .



$T_d = 1.5625$ seconds
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$$\begin{aligned} \text{Un-damped natural frequency } f_n &= \frac{\omega_d}{\sqrt{1-\xi^2} \times 2\pi} \\ f_n &= 1.5034 \end{aligned}$$

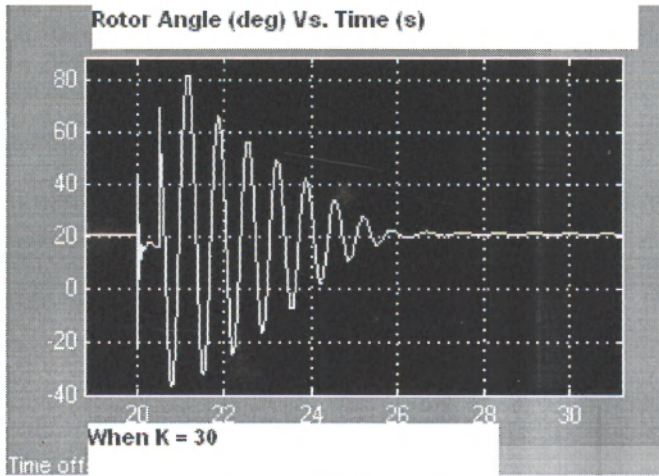
As discussed in the previous chapter UPFC cannot provide damping infinitely. The value of damping that can be provided by the UPFC is mainly determined by the value of the DC link capacitor. At transient state DC link capacitor voltage fluctuates, as active power flows through it and it provides or absorbs active power depending on the condition of the transient. Amount of energy that can be stored/absorbed by DC link capacitor is the decisive factor for this constrain.

$$\begin{aligned} \text{Energy Capacity of a Capacitor is given by } &= \frac{1}{2} CV^2 \\ &= 0.5 \times 750 \times 10^6 \times 40000^2 \\ &= 600000 \text{ J} \end{aligned}$$

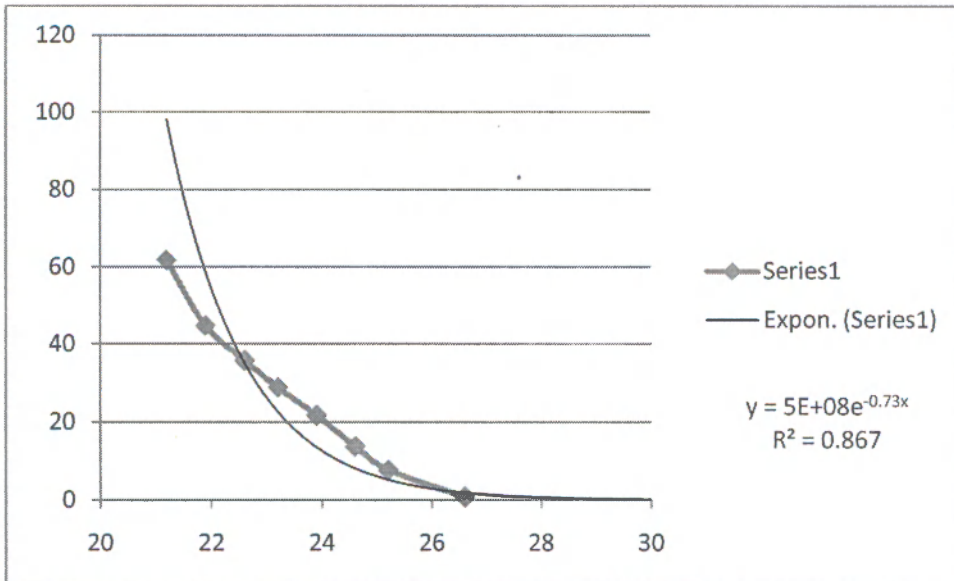
If this amount of energy is increased further, K value also can be increased to get better dampness to the system.

K value is increased, with observing out puts and increase in damping coefficient was observed up to $K = 30$. Thereafter, output rotor angle transient is not damped further with K. Therefore, for $750\mu\text{F}$ capacitance, max K value is 30. At $K = 30$ rotor angle variation is shown below.

$K_{\text{max}} = 30$ for $750\mu\text{F}$ capacitance and shunt converter rating of 100MVA



(a) When $C = 750\mu\text{F}$ and $K_{\text{max}} = 30$



(a) Simulation Result when $K = 30$, after adding exponential trend line

Figure 4.7: Simulation results with $K = 30$

Similarly, with the above case calculations can be done as follows,

When $K=30$ lets calculate above values.

$$\text{Average time between two peaks} = 0.6667 \text{ s}$$

$$\text{Damped Frequency of Oscillation} = 1.5 \text{ Hz}$$

$$\text{Therefore, } \omega = 2\pi f = 9.4248 \text{ rad/s}$$

$$\text{From the above graph, } \sigma = -0.73$$

$$\text{Therefore, damping ratio is } \xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

$$\xi = 0.0772$$

Time constant of amplitude decay is $1/|\sigma|$, which is equal to T_d .



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$$T_d = 1.3699 \text{ seconds}$$

$$\text{Un-damped natural frequency } f_n = \frac{\omega_d}{\sqrt{1-\xi^2} \times 2\pi}$$

$$f_n = 1.5045$$

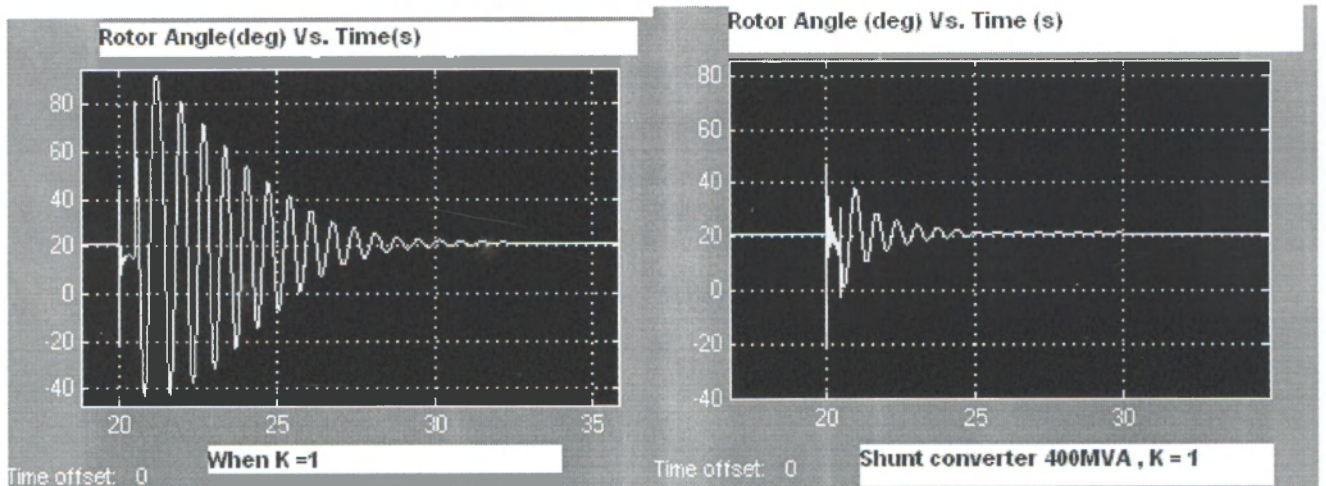
4.3 Effect of increase in shunt converter power rating

Shunt converter performs a major part in transients, as it passes active power requirement to the line inductor through series converter, DC link capacitor. As per the literature [15], if shunt device can handle all active power requirements in transient then, the DC link capacitor voltage will remain unchanged (theoretically). However, to handle transient power, shunt device has to be overrated. This will increase the initial cost investment for the shunt converter as well as its losses.

Transient current through the line is increase to about 750A which is going through the line inductor. Therefore, at transient energy stored in the inductor will be increased $(1/2LI^2)$.

Therefore, transient analysis is done with higher value of shunt converter while keeping the same value for the series converter.

For the same fault with a constant K value (at 1) shunt converter rating is increased to 400MVA. Then obtained results are as follows,



(a) when shunt converter rating 100MVA

(b) when shunt converter rating is 400MVA

Figure 4.8: Simulation results different shunt converter ratings

Transient is damped very quickly with the increase of shunt device rating. This type of behaviour has to be obtained from investing a lot of money and wasting higher losses in the shunt converter. Full economic evaluation has to be carried out in order to decide the size of the shunt converter.

5.0 Conclusion and Results

Power system stability is one of the key issues in today's world. And many different techniques have been used to improve the stability. The FACTS device – Unified Power Flow Controller (UPFC) and its performance has been studied under transient condition to enhance power system stability in the usage as a power system stabiliser.

Contribution of this paper can be summarized as follows,

Theoretical analysis has been carried out of UPFC performance as a power system stabilizer. This analysis is done in chapter 2. It has been identified that by giving proper input to the UPFC as described in Chapter 2, UPFC can be used as a power system stabiliser.

Then a part of Sri Lankan power system is modelled in Simulink as described in Chapter 3. Then the modelled UPFC in the Simulink is used for simulation purposes.

Modelled UPFC parameters can be given as follows for optimum operation.

parameter	Value
Series Converter	
MVA rating	10MVA
Voltage	132kV
Frequency	50Hz
DC link Capacitor	
Capacitance	750 μ F
Vdc	40000V
Shunt Converter	
MVA rating	100MVA
Vac Regulator Gains	Kp = 1, Ki = 100
Vdc Regulator Gains	Kp = 0.0001, Ki = 0.01
Current Regulator Gains	Kp = 0.167, Ki = 6

Table 5.0: UPFC parameters

Above model is simulated in Chapter 4 of this thesis. As discussed in the chapter 3 of this thesis, this device has created an impact on power system stability, with its unique capability to control real and reactive power simultaneously. With addition of UPFC to the system, transient behaviour is analysed. As per the theoretical development, transient behaviour is improved with UPFC in operation. These results for faults created on different locations, can be summarised as follows,

Location of the Fault	Type of Fault	Fault time (ms)	Kukule Generators without UPFC	Kukule Generators with UPFC (s)	
			Maximum Rotor angle variation	Maximum Rotor angle variation	Settling time (s)
Matugama Bus	3 Φ to Ground	310ms	150°, unstable	90°	12
Horana Bus	3 Φ to Ground	500ms	150°, unstable	90°	10
Panadura Bus	3 Φ to Ground	600ms	150°, unstable	70°	9
Pannipitiya Bus	3 Φ to Ground	700ms	60°, unstable	50°	6

Table 5.1: Performance results after adding UPFC to the system

The additional damping added to the system, due to insertion of UPFC has enabled this behaviour as discussed in the chapter 2.

Then, increase of UPFCs damping coefficient is carried out by changing K value. As described in chapter 4 it provides a larger gap to critical clearing angle, hence better performance under transient behaviour. When increasing the K value, effective damping coefficient to the system is also calculated. This is carried out for three different K values, namely 1, 10, 30. Maximum effective K value is limited by the capacitance of the DC link capacitor as explained in chapter 4. These results can be summarized as given in the Table 5.2.

K value	1	10	30
Damped Frequency f_d	1.5000 Hz	1.5000 Hz	1.5000 Hz
Effective Damping Coefficient σ	0.45 s ⁻¹	0.64 s ⁻¹	0.73 s ⁻¹
Damping Ratio ξ	0.0477	0.0677	0.0772
Un-damped Natural Frequency f_n	1.5017 Hz	1.5034 Hz	1.5045 Hz
Time Constant of amplitude of decay T_d	2.22 s	1.5625 s	1.3699 s

Table 5.2: Effect of increase of K values

Then the effect of increase of shunt converter is discussed in Chapter 4. And, it is observed that with shunt converter rating increased to 400MVA, transient performance is increased largely. This type of behaviour has to be obtained from investing a lot of money and allowing higher losses in the shunt converter. Full economic evaluation has to be carried out in order to decide the size of the shunt converter.

Therefore, new technologies are necessary for system's stability improvements apart from the existing technology. Hence, UPFC can be treated as power flow control device as well as with its additional feature of improving stability of the connected system.

5.1 Recommendations for future research

Sri Lankan power system is a small one, where it needs lot of treatments to keep the system in a stable condition. Although in Sri Lanka, FACTS devices have never been used so far, UPFC is one of the key solutions that could be utilized in Sri Lankan context as well. But, one can argue that due to the cost of it and the technology of it, Sri Lankan electricity industry cannot handle it. But, that is one of the recommended future research areas that could be carried out in the future.

With the electricity market being de-regularized, this kind of new technology has to be adopted even by poor countries like Sri Lanka. Therefore, more and more researches

have to be carried out to familiarise this kind of new technology with Sri Lankan context. There are more possible research areas like, special techniques for control coordination when using more than one UPFC, determination of optimum location of FACTS devices for National network, determining the effect of input signal to a stabilizer etc.



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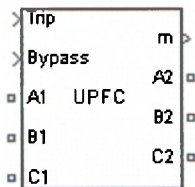
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APPENDIX – A: Unified Power Flow Controller (Phasor Type)

Implement phasor model of three-phase unified power flow controller Library



Parameter data to be entered as follows,

Control Parameters (shunt converter)

Block Parameters: Unified Power Flow Controller (Phasor...)

Unified Power Flow Controller (Phasor Type) (mask)
This block implements a phasor model of an Unified Power Flow Controller (UPFC).
The output (m) is a bus signal. Use the Bus Selector block to extract individual signals.

Parameters

Display: Control parameters (shunt converter)

Mode of operation: Voltage regulation

External control of reference voltage Vref (pu):

Reference voltage Vref (pu): 1.00

Maximum rate of change of reference voltage Vref (pu/s): 0.1

Droop (pu): 0.03

Vac Regulator Gains: [Kp Ki]
[5 1000]

Vdc Regulator Gains: [Kp Ki]
[0.1e-3 20e-3]

Current Regulators Gain: [Kp Ki]
[0.5 25]/3

OK Cancel Help Apply

Power Data Parameters

Block Parameters: Unified Power Flow Controller (Phasor...) [?] [X]

Unified Power Flow Controller (Phasor Type) (mask)
This block implements a phasor model of an Unified Power Flow Controller (UPFC).
The output (m) is a bus signal. Use the Bus Selector block to extract individual signals.

Parameters

Display: [Power data]

System nominal voltage and frequency [Vrms L-L, f(Hz)]:
[500e3, 60]

Shunt converter rating (VA):
[100e6]

Shunt converter impedance [R(pu) L(pu)]:
[0.22/30, 0.22]

Shunt converter initial current [Mag(pu) Pha(deg.)]:
[0, 0]

Series converter rating [Snom(VA) Max. Injected voltage(pu)]:
[100e6, 0.1]

Series converter impedance [R(pu) L(pu)]:
[0.16/30, 0.16]

Series converter initial current [Mag(pu) Pha(deg.)]:
[0, 0]

DC link nominal voltage (V)
[40000]

DC link total equivalent capacitance (F):
[750e-6]

OK Cancel Help Apply



Control Parameters (series converter)

Block Parameters: Unified Power Flow Controller (Phasor...) [?] [X]

Unified Power Flow Controller (Phasor Type) (mask)
This block implements a phasor model of an Unified Power Flow Controller (UPFC).
The output (m) is a bus signal. Use the Bus Selector block to extract individual signals.

Parameters

Display: [Control parameters (series converter)]

Bypass Breaker: [External control]

Mode of operation: [Manual voltage injection]

External control of injected voltage Vdref_Vqref (pu):
Manual voltage injection reference [Vdref Vqref] (pu):
[0.05 0.05]

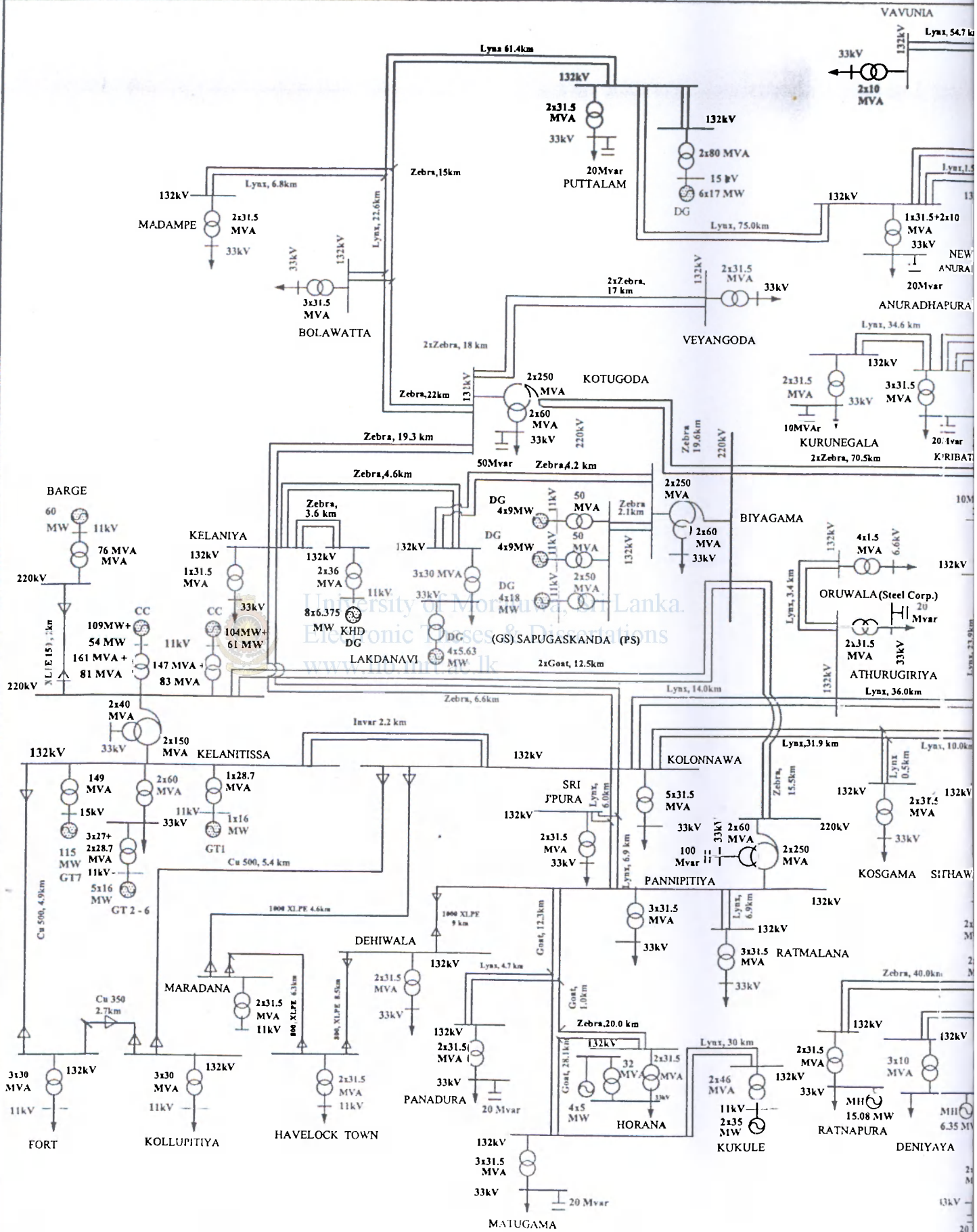
Maximum rate of change for references Vdref_Vqref (pu/s)
[0.2]

OK Cancel Help Apply












APPENDIX – B: Power Grid Data



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Legend

-  220kV LINE
-  132kV LINE
-  33kV LINE
-  11kV LINE
-  TRANSFORMER
-  3 WINDING AUTO TRANSFORMER
-  HYDRO POWER STATION
MH Mini-Hydro
-  THERMAL POWER STATION
DG Diesel Generator
CC Combined Cycle
ST Steam Turbine
GT Gas Turbine
-  CABLE LINE
-  BREAKER SWITCH CAPACITOR
-  Static var compensator

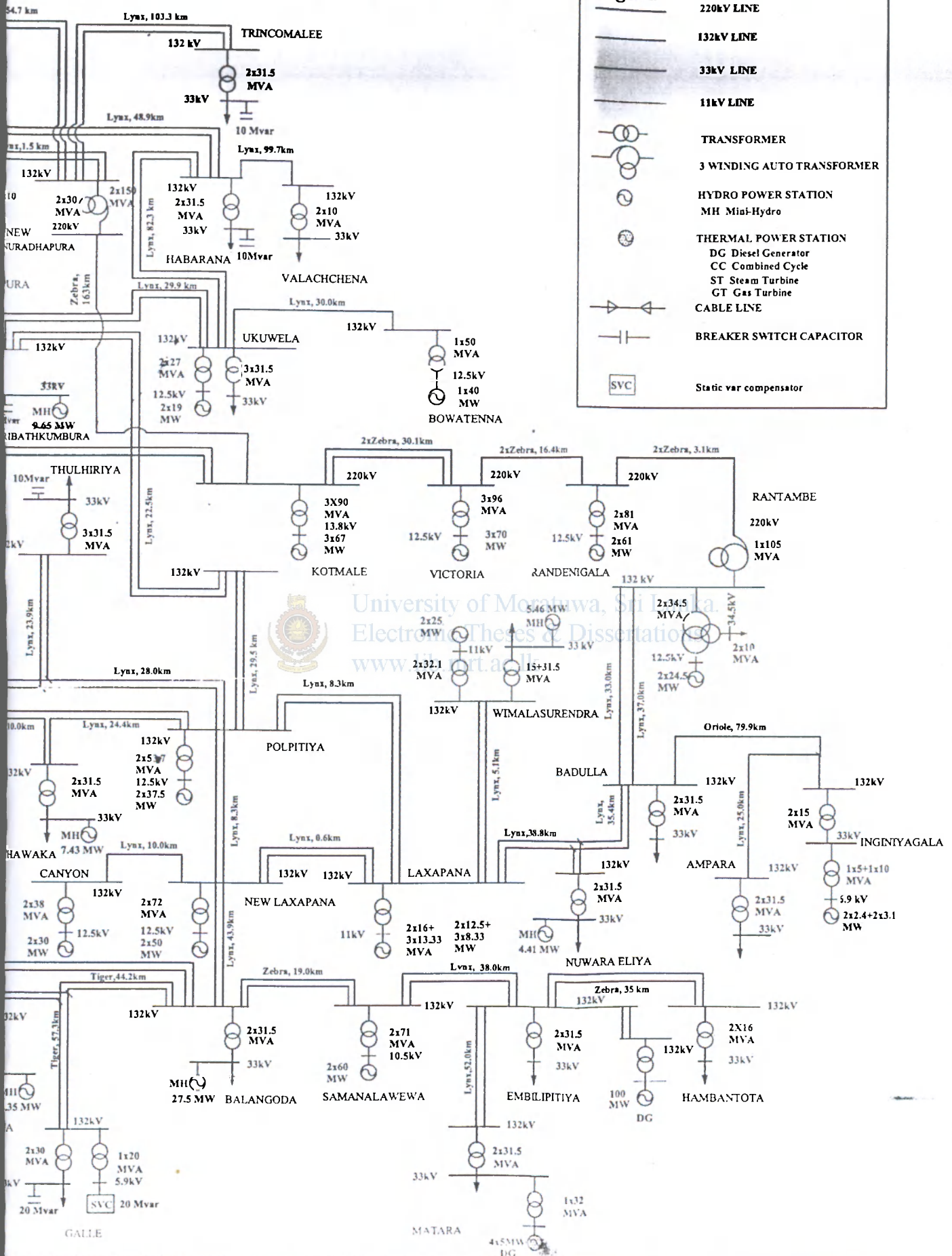


Table 4.11. Maximum three phase fault levels (Continued...)

Grid Substation / Power Station		Voltage (kV)	Existing Switchgear Capacity (kA)	Maximum Three Phase Short Circuit Current (kA)		
				2006	2011	2015
41	Kosgama	132	25	7.6	8.0	8.2
42	Kotmale P/S	220	40	12.4	14.2	17.4
43	Kotugoda	132	31.5	8.7	9.9	10.3
		220		10.8	20.0	24.9
		132	31.5/40	14.7	27.3	23.8
44	Kotugoda New	33	25	9.4	14.2	15.7
		33			10.0	9.9
45	Kukule P/S	132		4.8	6.1	8.0
46	Kurunegala	132	25	4.1	5.0	5.1
47	Laxapana P/S	132	31.5	17.2	19.7	20.3
48	Medagama	132			4.0	4.2
49	Madampe	132		4.2	11.3	12
50	Mahiyangana	132			7.3	8.1
51	Maho	132	25		4.3	4.0
52	Matara	132	31.5	3.5	6.8	7.8
53	Mathugama	220				16.8
		132	40	6.3	9.5	17.4
54	New Chilaw	220				16.8
		132			13.7	14.4
55	Naula	132				8.7
		132			4.7	
56	New Anuradhapura	220		3.1	9.3	13.0
		132		5.4	10.7	12.8
		33		3.4	4.4	4.9
57	New Laxapana	132	31.5/40	17.2	19.7	20.4
58	Nuwara Eliya	132	31.5	7.9	8.9	9.2
59	Oruwala	132		12.4	14.1	14.6
		33		1.1	1.1	1.1
60	Padirippu	132			5.7	6.2
61	Pallekele	132			5.5	6.0
62	Panadura	132	25	10.9	13.2	17.9
63	Pannala	132			8.5	10.4
64	Pannipitiya	220	50	11.6	15.9	20.2
		132	31.5/40	19.2	24.9	27.3
	Tertiary Winding	33		14.1	14.7	14.9
65	Polonnaruwa	132			3.9	4.8
66	Polpitiya P/S	132	17.5	17.4	19.9	20.5
67	Puttalam PS	220			13.5	17.7
68	Puttalam GS	132	25	5.1	8.2	7.1
69	Randenigala	220	31.5	8.5	10.4	11.1
70	Rantembe PS	220	25	8.1	9.9	10.6
		132		6.7	10.2	11.8
		33		9.7	9.7	9.9
71	Ratmalana	132	31.5	14.0	16.8	17.9
72	Ratnapura	132		4.6	5.4	5.6
73	Samanalawewa PS	132	31.5	8.5	10.4	11.7

Table 4.11. Maximum three phase fault levels

Grid Substation / Power Station		Voltage (kV)	Existing Switchgear Capacity (kA)	Maximum Three Phase Short Circuit Current (kA)		
				2006	2011	2015
1	Ambalangoda	132			8.1	10.8
2	Ampara	132	31.5	1.3	5.4	5.8
3	Aniyakanda	132			15.1	15.0
4	Anuradhapura	132	15/11/20/31.5	5.4	10.7	12.8
5	Arangala	220				22
6	Athurugiriya	132		14.1	16.3	17.0
7	Badulla	132	25/31.5	6.5	8.0	8.5
8	Balangoda	132	31.5	8.8	11.4	12.4
9	Barge	220		13.0	18.0	
10	Beliatta	132			4.9	5.6
11	Biyagama	220	40	14.0	21.7	27.4
		132	31.5	18.0	26.1	29.6
		33	25	10.9	16.0	20.8
12	Bolawatta	132	25/17.5/8.8/13.1	6.5	14.0	14.4
13	Bowatenna P/S	132	12.5	3.6	3.9	4.1
14	Canyon P/S	132	25/40	9.5	10.2	10.3
15	Chunnakum	132			2.2	2.3
16	Colombo_A	132		16.8	20.8	22.3
17	Colombo_B	132				10.7
18	Colombo_C	132			26.2	28.4
19	Colombo_E	132	25	19.1	26.2	28.4
20	Colombo_F (Fort)	132	25	18.5	25.9	28.1
21	Colombo_I	132		18.9	24.1	26.0
22	Dehiwala	132		16.6	20.5	22.0
23	Deniyaya	132		4.0	5.9	6.2
24	Embilipitiya	132	31.5	6.1	8.1	11.1
25	Galle	132	10.9/11/40	2.3	8.9	10.4
26	Habarana	220				19.2
		132	20/25/31.5	4.1	7.7	18.7
27	Hambantota GS	220				15.6
		132	31.5	4.1	4.1	12.8
28	Horana	132		6.5	7.5	8.2
29	Inginiyagala	132	12.5	1.5		
		132		18.4	23.4	25.3
31	Kelaniya	132	40	20.3	28.9	31.7
32	Katana	132			17.3	16.9
33	Kegalle	132				5.1
34	Kelanitissa P/S	220	50	13.5	19.0	22.2
		132	25/31.5	21.0	27.7	30.2
	33 - T	33		7.0	7.1	7.1
	33 - A (load bus)	33	25/26.2	11.2	6.6	6.6
	33 - B (load bus)	33	25/26.2	9.8	6.6	6.6
35	Kerawalapitiya P/S	220			17.0	19.6
36	KHD P/S	132	31.5	17.3	23.1	24.8
37	Kilinochchi	132			2.1	2.1
38	Kiribathkumbura	132	25	6.9	8.3	8.9
39	Kirindiwela	220				26.5
40	Kolonnawa	132	40	22.1	29.4	32.2

Table 3.2 Transmission lines/UG cables proposed for the period 2004-2013

Line Section	Volt. / (kV)	Ccts.	Proposed year	Conductor	Length / (km)	R /cct in p.u.	X/cct in p.u.	Y / cct in p.u.
<u>132 kV UG cables</u>								
Pannipitiya - Dehiwala*	132	1	2006	XLPE, 1000	9.0	0.00139	0.00816	0.10346
Colombo I - Kolonnawa*	132	1	2006	XLPE, 1000	4.6	0.00071	0.00417	0.05288
Dehiwala - Havelock Town*	132	1	2006	XLPE, 800	8.5	0.00151	0.00805	0.09073
Colombo A - Colombo I*	132	1	2006	XLPE, 800	6.3	0.00112	0.00597	0.06725
Kelanitissa-Colombo C*	132	1	2008	XLPE, 500	1.6	0.00044	0.00167	0.01401
Colombo C- Kolonnawa*	132	1	2008	XLPE, 500	6.2	0.00171	0.00648	0.05430
Colombo C-Colombo B	132	1	2012	XLPE, 500	2.0	0.00055	0.00209	0.01752
Colombo B-Kolonnawa	132	1	2012	XLPE, 500	4.2	0.00116	0.00439	0.03678
Kolonnawa-Colombo K	132	1	2013	XLPE, 500	5.0	0.00138	0.00522	0.04379
Colombo K-J'Pura	132	1	2013	XLPE, 500	5.0	0.00138	0.00522	0.04379
<u>132kV Overhead lines</u>								
New Galle-Matara	132	1	2007	Zebra	34.0	0.01487	0.07574	0.017733
Ambalangoda-New Galle	132	1	2007	Zebra	36.0	0.01570	0.07996	0.018720
Habarana-Valachchena	132	1	2007	Zebra	99.7	0.04349	0.22144	0.051850
Kelaniya - KHD*- Sapugaskanda GS	132	4	2005	Zebra	3.6	0.00157	0.00800	0.00187
	132	2	2005	Zebra	1.0	0.00044	0.00222	0.00052
Single in out to Horana from Panadura T-Mathugama*	132	2	2005	Zebra	20.0	0.00872	0.04442	0.01040
Mathugama-Ambalangoda*	132	2	2007	Zebra	28.0	0.01221	0.06219	0.01456
Aniyakanda single in out*	132	2	2007	Zebra	5.0	0.00218	0.01111	0.00260
Madampe T- Pannala*	132	2	2007	Zebra	15.0	0.00654	0.03332	0.00780
Ukuwela-Pallekele	132	2	2008	Zebra	18.0	0.00785	0.03998	0.009360
Puttalam-Maho 1cct stringing/double cct	132	2	2007 2012	Zebra	42	0.01832	0.09329	0.02184
Kothmale-Kiribathkumbura	132	2	2007	Zebra	22.5	0.00981	0.04997	0.01170
Rantembe-Ampara	132	2	2007	Zebra	130	0.05670	0.28874	0.0760
Vavuniya-Kilinochchi	132	2	2007	Lynx	74.1	0.07570	0.17054	0.03610
Kilinochchi -Chunnakam	132	2	2007	Zebra	67.2	0.02931	0.14926	0.03495
Ampara-Padirippu	132	2	2009	Zebra	35	0.01527	0.07774	0.018201
Kolonnawa-Pannipitiya	132	2	2009	Zebra	12.9	0.00563	0.02865	0.00671
Kegalle-Thulhiriya	132	2	2010	Zebra	18.7	0.00816	0.04153	0.00972

Note : The line parameters are given in p.u. values w.r.t. $Z_{base} = V_{base}^2 / MVA_{base}$ ($MVA_{base}=100$, V_{base} in kV).

* -committed or under construction

Table 3.1 Existing transmission lines/UG cables cont.

Line Section	Volt. / (kV)	Ccts.	Max. Oper. temp °C	Conductor	Length / (km)	R /cct in p.u.	X/cct in p.u.	Y / cct in p.u.
<i>Double Circuit cont..</i>								
✓ Sapugaskanda GS – Biyagama	132	2	75	Zebra	4.2	0.00183	0.00933	0.00218
✓ Kolonnawa – Kelaniya	132	2	75	Zebra	6.6	0.00288	0.01466	0.00343
✓ Kelaniya – Kotugoda	132	2	75	Zebra	19.3	0.00842	0.04287	0.01004
✓ Kukule-Mathugama	132	2	75	Lynx	27.0	0.02758	0.06214	0.01315
<i>Total 132kV 2 cct route length</i>					1336.3			
<i>Total 132kV 2cct circuit length</i>					2672.6			
<i>220 kV transmission lines</i>								
<i>Single Circuit</i>								
✓ Victoria-Randenigala	220	1	75	2xZebra	16.4	0.00129	0.01037	0.03202
✓ Randenigala-Rantembe	220	1	75	2xZebra	3.1	0.00024	0.00196	0.00605
✓ Kotmale-New Anuradhapura	220	1	75	1xZebra	163	0.02560	0.13033	0.23545
<i>Total 220 kV 1 cct route length</i>					182.5			
<i>Total 220 kV 1cct circuit length</i>					182.5			
<i>Double Circuit</i>								
✓ Biyagama-Kelanitissa	220	2	75	2xGoat	12.5	0.00134	0.00764	0.02361
✓ Biyagama-Kotugoda	220	2	75	Zebra	19.6	0.00308	0.01567	0.02831
✓ Biyagama-Kotmale	220	2	75	2xZebra	70.5	0.00554	0.04457	0.13764
✓ Kotmale-Victoria	220	2	75	2xZebra	30.1	0.00236	0.01903	0.05877
Pannipitiya-Biyagama	220	2	75	Zebra	15.5	0.00243	0.01239	0.02239
<i>Total 220 kV 2 cct route length</i>					148.2			
<i>Total 220 kV 2cct circuit length</i>					296.4			

Note : The line parameters are given in p.u. values w.r.t. $Z_{base} = V_{base}^2 / MVA_{base}$ ($MVA_{base}=100$, V_{base} in kV).
* under construction

57.1

CONDUCTOR	TW	σ Ω/m	E W	Positive Impedance Ω/km	Zero Impedance Ω/km	Mutual Impedance Ω/km
LYRX 1x17.5mm ²	T2	100	1	0.1780 + j 0.4010	0.36278 + j 1.36089	0.20535 + j 0.83694
LYRX 1x17.5mm ²	T2	10	1	0.1780 + j 0.4010	0.32598 + j 1.17140	0.16846 + j 0.64751
* LYRX 1x17.5mm ²	T2	100	2	0.1780 + j 0.4010	0.39735 + j 1.31149	0.25150 + j 0.78757
LYRX 1x17.5mm ²	T2	10	2	0.1780 + j 0.4010	0.35230 + j 1.14242	0.19461 + j 0.61856
ZEBRA 2x40mm ²	T7	100	2	0.0380 + j 0.3060	0.30196 + j 1.07744	0.26575 + j 0.66775
ZEBRA 2x40mm ²	T7	10	2	0.0380 + j 0.3060	0.23918 + j 0.92104	0.20305 + j 0.51121
GOAT 2x30mm ²	T7	100	2	0.0520 + j 0.2960	0.31266 + j 1.07974	0.26575 + j 0.66775
GOAT 2x30mm ²	T7	10	2	0.0520 + j 0.2960	0.24988 + j 0.92334	0.20305 + j 0.51121
ZEBRA 1x10mm ²	T7	100	2	0.0760 + j 0.3870	0.33601 + j 1.18857	0.26577 + j 0.66769
ZEBRA 1x10mm ²	T7	10	2	0.0760 + j 0.3870	0.27323 + j 1.03217	0.20306 + j 0.51117
COYOTE 1x10mm ²	T2	100	2	0.2470 + j 0.4150	0.47054 + j 1.32567	0.25150 + j 0.78757
COYOTE 1x10mm ²	T2	10	2	0.2470 + j 0.4150	0.41153 + j 1.15660	0.19461 + j 0.61856
TIGER 1x10mm ²	T2	100	2	0.2470 + j 0.4150	0.47220 + j 1.32200	0.25150 + j 0.78757
TIGER 1x10mm ²	T2	10	2	0.2470 + j 0.4150	0.41540 + j 1.15298	0.19461 + j 0.61856
ORIOLE 1x10mm ²	T2	100	2	0.1910 + j 0.4360	0.42144 + j 1.31383	0.25150 + j 0.78757
ORIOLE 1x10mm ²	T2	10	2	0.1910 + j 0.4360	0.36464 + j 1.14475	0.19461 + j 0.61856
CABLE 350 Cu	-	-	-	0.0400 + j 0.1510	-	-
CABLE 350 Cu	-	-	-	0.1910 + j 0.4360	-	-
GOAT 1x30mm ²	T2	100	2	0.0897 + j 0.3794	0.36124 + j 1.23669	0.27038 + j 0.75333



Indes - Area line length - 164 km

W:RE2AlljE145-33

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