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**CONFIGURING A POWER SYSTEM STABILIZER FOR  
IMPROVED DYNAMIC PERFORMANCE  
A CASE STUDY FOR LAKVIJAYA POWER STATION**

H. L. L Chandrasena

(198635X)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

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Hitige Lasindu Laknath Chandrasena

(198635X)

Thesis submitted in partial fulfilment of the requirements for the degree  
Master of Science in Electrical Installation

Department of Electrical Engineering

University of Moratuwa  
Sri Lanka

June 2024

## DECLARATION

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**Dr. W. D Prasad**

## ABSTRACT

The concept of Power System Stabilizer (PSS) is widely accepted worldwide as a supplementary excitation control method to improve the dynamic performance of power systems. This work presents the implementation of a PSS by proposing a robust tuning procedure for the inbuilt PSS functions in UNITROL 5000 excitation controllers, focusing on the ST1A type static excitation system. Additionally, this research serves as a case study for the Sri Lankan power system centered around the Lakvijaya Power Station in Sri Lanka, which is the largest coal power plant in the country. The proposed tuning procedure demonstrates how the conventional Frequency Response-Based Method and a Model Based Method incorporated with an optimization technique, can be used in a cascaded format to significantly enhance the dynamic response of the power system. The optimization technique has been completely automated on the Python coding platform, which employs an Eigenvalues-based approach to optimize in the presence of comprehensive dynamic data of the Sri Lankan power system up to the 33kV voltage level.

**Keywords:** *Power System Stabilizer, Simulated Annealing, Frequency Response Based Method, UNITROL 5000, Python*

## **DEDICATION**

I dedicate my M.Sc. research dissertation to my beloved parents and my wife for their support given through thick and thin.

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## LIST OF ABBREVIATIONS

<b>Abbreviation</b>	<b>Description</b>
PSS	Power System Stabilizer
AVR	Automatic Voltage Regulator
LVPS	Lakvijaya Power Station
CEB	Ceylon Electricity Board
RTF	Ramp Tracking Filter
IEEE	Institute of Electrical and Electronics Engineers
WECC	Western Electricity Coordination Council
MOR	Model Order Reduction
BT	Balanced Truncation
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
SA	Simulated Annealing
FACTS	Flexible AC Transmission System
HVDC	High Voltage Direct Current
UFLS	Under Frequency Load Shedding
API	Application Programming Interface
GUI	Graphical User Interface
OPC	Over-Speed Protection Control
FCB	Fast Cut Back
TGR	Transient Gain Reduction

# 1 INTRODUCTION

## 1.1 Power System Stability and Requirement of a Power System Stabilizers

Power system stability is a major concern that determines the level of security of any power system. It involves the study of the behavior of the power system under disturbed conditions. The power system is said to comprise precise stability if it is capable of returning to normal or stable operation after having been subjected to a disturbance and if it is capable of maintaining equilibrium at normal operating conditions. Particularly in some instability conditions, components of a power system may go out of step by losing their synchronism, eventually causing total failures. This is because power systems highly rely on synchronous machines, which need to be maintained at synchronism for smooth operation. But it should be noted that there may be some other reasons for losing the stability of a power system which are irrelevant to synchronism. Stability of voltage and control-related issues can be stated as examples of that. However, this shows the significance of identifying and categorizing stability studies based on the root cause and principles governed by their behavioral properties. Realizing the above requirement, power system stability can be studied under the following three different aspects.

### 1.1.1 Rotor Angle Stability

Rotor angle stability is the capability of synchronous machines of a power system to remain in synchronism with each other. Electromechanical oscillations which appear during a disturbance are studied in this particular subject scope. Additionally, it involves studying the way power outputs of generators oscillate while the rotors are being oscillated.

The electromagnetic torque ( $T_e$ ) of a generator during a disturbance can be resolved into two components. They are the synchronizing and damping torque components. Perturbation of the synchronizing torque component is proportional to the rotor angle perturbation ( $\Delta\delta$ ) and the perturbation of the damping torque is proportional to speed deviation ( $\Delta\omega$ ). Hence the change of electrical torque ( $\Delta T_e$ ) can be expressed as in equation (1) below.

$$\Delta T_e = T_s \Delta\delta + T_D \Delta\omega \quad (1)$$

$T_s$  and  $T_D$  here are constants which depend on the machine and system parameters according to the K constant model explained in reference [1]. Both the components should exist at the required levels for the stability. For the convenience of studies, rotor angle stability can be further divided into two sections as small signal stability and the transient stability.

#### **1.1.1.1 Small Signal Stability**

Ability of a power system to maintain its synchronism during a small disturbance. Linearizing the system equations is accepted in these studies as the disturbance is very small. Instabilities can be seen under two sections.

- Continuous increment of load angle due to lack of synchronizing torque. Hence, aperiodic drifting and pole slipping can occur due to insufficiency of the synchronizing component.
- Loss of control during the mechanical oscillation due to lack of damping torque. Hence, oscillatory instabilities may be caused by insufficiency of the damping torque component.

The responses of the power system to above two sections depend on different reasons such as the initial operating condition, strength of the transmission network, excitation system used in the generators and etc. Oscillations which come under small signal stability can be further examined under different types of oscillations called oscillatory modes.

- **Local Modes / Local Plant Modes**

Local Modes are the localized oscillations in between one power station or a small part of the power system and the rest of the power system [1]. Typically the oscillation frequencies of these modes fall within the range of 0.7-2 Hz [2], [3]

- Inter Area Modes

Inter Area Modes of oscillations occur when one part of the power system oscillates with respect to the rest of the power system. Weak tie-lines in between closely coupled sets of generators can be a major reason behind initiating these modes [1]. Typically, Inter Area Modes fall within the frequency range of 0.1-0.9 Hz [4], [5].

- Inter Machine Modes

Inter Machine Modes show similar behavior to Local Modes. Oscillation occurs in between machines of a power plant showing a power hunting behavior [1]. Typically the oscillation frequencies of these modes fall within the range of 1 – 3Hz [3].

- Control Modes

Control modes can be initiated in generator units and other control systems. Poorly tuned speed governors, excitations systems, HVDC control and static VAR compensators can be the route cause for the initiation of Control Modes [1]. Typically, the oscillation frequencies of these modes are greater than 2Hz [2].

- Torsional Modes

Torsional Modes of oscillations are associated with the mechanical system of a machine. Torsional Modes can be initiated as a result of system compatibility issues of excitation systems, HVDC controls, governor control systems and series capacitor compensated lines [1]. Typically the oscillation frequencies of these modes are greater than 10Hz.

### **1.1.1.2 Transient Stability**

Ability of a power system to withstand by maintaining the synchronism during a severe transient power system disturbance. Nonlinearity of the system becomes prominent in these studies. Large rotor angle excursions may occur in these transient cases which are governed by the non-linear relationships of the power system. The end state of the system after a transient incident could depend on the initial conditions as well as the

severity of the transient. There's a higher possibility that the post - incident steady states of the system differs from the pre- incident steady state point of the system.

Typically, in larger power systems, transient instability does not occur as the first phase or the first swing of the stability. These large oscillations may be formed as a result of overlapping two or more oscillatory modes. Generally, the study period of interest in a transient stability study is 3 -5 seconds [1].

### **1.1.2 Voltage Stability**

Voltage stability is the ability of a power system to maintain voltages of all busses in a disturbance and under the normal operating conditions. It is said that the system is unstable in terms of voltage if it shows a significant voltage drop in the system as a consequent of a disturbance, change in system conditions or increase in demand. Instability of system voltage is mainly caused by the inability of the system to manage the requirement of its reactive power which is consumed by reactive elements in the power system such as long transmission lines and rotary inductive loads [1].

Power system is said to be stable in terms of voltage if all the buses in the system follow a positive Voltage (V)- Reactive Power (Q) sensitivity where the bus voltage shows an increment when reactive power is injected to it. However, if voltage of any bus continues to decrease even when Reactive Power is injected in it then, it's called a negative V-Q sensitivity and that can be identified as symptoms of voltage instability [1].

Additionally, Voltage instability can be caused as a result of out of step condition in synchronous machines. Progressive voltage decrement can be observed in such cases when one generator or a group of generators approach or exceed  $180^0$  in their load angles resulting in significant voltage drops in several intermediate points of a power system [1].

Even though the voltage instability may be initiated as a local phenomenon, it can spread across a part or the entire network resulting in a complete voltage collapse. For purposes of studies, voltage stability can be categorized under following two sections [1].

- Large- Disturbance voltage stability
- Small- Disturbance voltage stability

Further information will not be discussed here under the voltage stability as it is not an interest of this research scope.

### **1.1.3 Mid- Term and Long- Term Stability**

Mid and Long Term stability studies are carried out with the view to analyze dynamic response of the power system due to severe disturbances which, cause to large voltage, frequency and power flow excursions [1]. Additionally, it focuses on of the slow activation and relevant behavior of processes, protections and controls that are initiated after a severe disturbance. More information regarding Mid and Long Term stability studies are not discussed here as it is not an interest of this research scope.

Different techniques and concepts are incorporated to address above discussed stability issues. Insufficiency of damping capability in power system is a common issue which comes under the Rotor angle stability. Power system has its inherent damping capabilities to treat these issues, especially in large synchronous generators. Most of the large synchronous machines have inbuilt damper windings to create a damping torque during a disturbance condition to damp out the mechanical oscillation. Additionally, it can be shown that at a typical generator possesses a positive damping torque as long as constant  $T_D$  in equation (1) holds a positive value. However, it has been identified that some other reasons may cause for negative  $T_D$ , resulting in negative damping torque. One reason is the presence of hydraulic generator units without damper windings operating at light loads and being connected to the grid via a transmission line with higher resistance compared to reactance. Also,  $T_D$  can be negative when a large local load at the generator end is supplied by the generator itself and the remote system at the same time [1].

It's a well-known fact that, once the machine is constructed the damper winding is fixed and is not tangible to control the damping during the operations. Hence, there comes a requirement of manipulating the damping capability of the power system. Power System Stabilizer (PSS) is a well-known supplementary excitation solution for

above purpose. It can be considered as the most convenient and cheapest solution incorporated in most of the power system related applications.

Power system stabilizers have been commercially used since the end of the 20th century with continuous advancements in the technology. Fundamental purpose of the PSS is to create an extra damping torque inside the generator which is in phase with the speed deviation ( $\Delta\omega$ ). This is done by injecting an auxiliary signal at the summing junction of the Automatic Voltage Regulator (AVR). However, the signal added in the summing junction will be modified in phase and magnitude by several transfer functions, such as the exciter and AVR, along the way until it generates the electromagnetic torque ( $T_e$ ). Hence, if the speed deviation signal is directly injected at the AVR summing junction, then the damping torque component created will not be in phase with the speed deviation, which will lead to the damping action behaving improperly. Therefore, PSS function is used to pre – process and condition the speed deviation signal modifying it by relevant compensations.

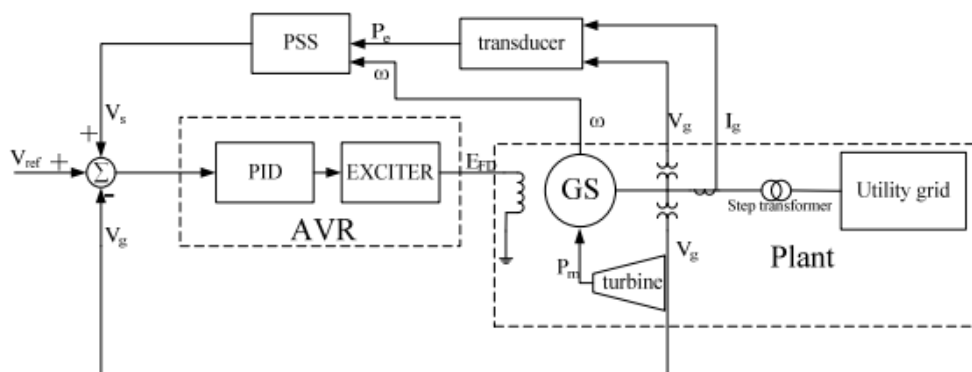


Figure 1-1 Typical Configuration of Delta-P-Omega PSS

With the advancement of the field, PSSs have evolved with different configurations, which will be discussed under Section 2 – Literature Review. Typical arrangement of a Delta-P-Omega ( $\Delta$ -P- $\omega$ ) type PSS is shown in Figure 1-1. Per unit electrical power ( $P_e$ ) and speed ( $\omega$ ) of the machine will be provided as inputs of the PSS. Output signal ( $V_s$ ) of the PSS will be injected to AVR summing junction. As a result of this, a damping torque which is in phase with the speed deviation will be created in the generator to damp out the electromechanical oscillations.

## 1.2 Research Motivation

Sri Lanka is an island located in the Indian Ocean with an approximate population of 21 million and Ceylon Electricity Board (CEB) is the sole licensee for all the three sectors of electricity power generation, transmission and distribution. By the end of 2021, total installed capacity of the country had reached upto 4184 MW including main sources of large hydro, thermal and some non dispatchable power plants such as wind, hydro, solar and biomass [6, 7]. The country is almost 100% electrified and has an islanded grid network which operates at 132kV, 220kV and 33kV voltage levels.

Lakvijaya Power Station (LVPS) owns a prominent place in Sri Lankan power system as it is the largest power plant in this country. It consists of three coal powered units, each of having a rated capacity of 300MW. The generating voltage of each unit is 20kV, which is then stepped up to 220kV by means of 350MVA power transformers. Outgoing power of the plant is connected to the grid via two transmission lines, one to Veyangoda and other to New Anuradhapura grid substations respectively.

All the three units of LVPS consists of UNITROL 5000 type AVR controller units as the main excitation controllers. These controllers consist of ST1A type static excitation system and PSS2A type PSS function conforming to IEEE standards [7]. However, the PSS functions of all the three units are currently not activated as they have not been configured properly during the commissioning phase.

Considering above facts, the importance of having a properly configured PSS units at LVPS can be realized. According to the current configurations and the physical location of the power plant, it can be considered as a comparatively isolated power station in the power system. Additionally, it has been grid connected via comparatively long transmission lines. Both reasons may weaken the transmission line network in between LVPS and the rest of the power system. Hence, it may cause the LVPS to behave erratically during weak system conditions due to local oscillatory modes. Therefore, it's always good to have a localized method of making LVPS more robust for oscillations. With that idea on hand, this research was carried out to propose a methodology to configure existing PSSs of LVPS.

### **1.3 Objectives of the Study**

The main objective of this research was to configure the existing PSS functions of Lakvijaya Power Station. It can be further expanded as follows.

- To demonstrate that the PSS function can improve the transient response of speed oscillations of Lakvijaya power station.
- To design and propose a robust PSS parameter tuning procedure for Lakvijaya Power Station.

### **1.4 Thesis Outline**

The thesis is structured as follows, covering the achievement of the objectives set-out in section 1.3.

A comprehensive literature study will be presented in chapter 2. Chapter 3 will explain the mathematical modeling used in the system study. Especially, the model validation for the complete Sri Lankan power system in PSSE software and model related to LVPS in the MATLAB software will be presented in this section. Additionally it will explain the principles behind the PSS function and its components.

Chapter 4 will provide a comprehensive explanation on the methodology used to configure and tune up the parameters of PSS. The conventional frequency response based method and the selected optimizations technique will be presented here.

Chapter 5 will analyze and compare the results obtained. Performance of the tuned PSS will be evaluated using with and without PSS cases by applying it to several possible contingencies in the previously validated PSSE dynamic model of Sri Lankan Power system. Chapter 6 presents the conclusions and future directions of the study.

### **1.5 Chapter Summary**

The Introduction chapter initiates with a discussion on the critical aspects of Power System Stability, highlighting its significance in ensuring the security and reliability of power grids. It explores various dimensions of stability including rotor angle stability, voltage stability, and mid to long-term stability. Of particular focus are the sub-topics of small signal stability and transient stability, with emphasis on rotor angle stability as the primary research area. Within this frame, the need for enhancing

damping capability within power systems is described, attributing insufficient damping to factors such as long transmission networks and high system impedance conditions. Consequently, the introduction of Power System Stabilizers (PSS) is proposed as a means to augment system damping, thereby mitigating oscillations and enhancing stability.

The subsequent section delves into the motivation behind the research, centering on the Lakvijaya power plant in Sri Lanka. Despite its advanced infrastructure equipped with Unitrol 5000 excitation controllers, the installed PSS functions remain inactive due to lack of configuration, presenting an opportunity for investigation and improvement. Hence, the requirement of having properly configured PSSs in Lakvijaya Power Station is highlighted considering the importance of the role played by it in the Sri Lankan Power system.

Following the elucidation of motivation, the chapter outlines the objectives of the study, aiming to demonstrate the efficacy of PSS functions in improving transient response within the Lakvijaya power station and proposing a robust parameter tuning procedure for optimal performance.

Finally, the chapter concludes with an overview of the thesis structure, delineating the subsequent chapters' content and organization.

## **2 LITERATURE REVIEW**

### **2.1 Different Configurations of Power System Stabilizers**

The rise of Power System Stabilizers related technologies began around the mid of 1960s. Initial configurations used the measured mechanical speed of the machine as the input for the PSS. However, as the PSS is intended to create a damping torque which is in phase with the speed deviation, it is suitable to use any signal which represents the oscillation such as speed, speed deviation, frequency or electrical power for this purpose. Basically, configurations of PSSs can be classified as below considering the technical evolution that has occurred during past few decades.

#### **2.1.1 Delta-Omega Stabilizers**

Delta-Omega Stabilizers use measured speed signal as the input of the PSS. Major disadvantage of this technique is the inherent noise in the mechanical system. Generally, the noises of a generator turbine system may occur due to shaft run outs and other few causes. Further, the noise created by the lateral movement of the shaft near hydro dynamic bearings was unable to be eliminated via typical filter systems. However, it is recommended to have noise percentage less than 0.02% for noise frequencies less than 5Hz [1]. Hence, the solution had to come up with the measuring system of the input signal itself. Therefore, measuring systems with multiple pickups around the shaft were used as a remedy for this in some designs emerged later.

Applying PSS units for thermal units with multi mass shaft systems inherently carried the influence of torsional modes. Especially, torsional modes may be easily instabilized during damping. Therefore, designers were forced to use torsional filters prior to feed the speed input to PSS. One limitation of this solution is the additional phase lag introduced to the network by the filter [1]. Typical arrangement of a Delta-Omega stabilizer is shown in the Figure 2-1

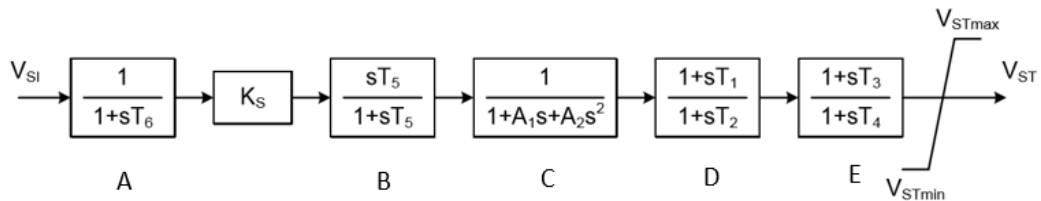


Figure 2-1: Delta-Omega Type PSS

Relevant Parameters are presented in Table 2-1 below.

Table 2-1: Parameter List for Delta - Omega Type PSS

<b>Parameter List for Delta – Omega type PSS</b>	
$V_{SI}$	Input – Speed
$V_{ST}$	PSS Output
$T_6$	Signal Transducer Time Constant
$T_5$	Washout Filter Time Constant
$A_1$	First Parameter Constant of Torsional Filter
$A_2$	Second Parameter Constant of Torsional Filter
$K_s$	Stabilizer Gain
$T_1$	Compensator Block 1 Lead Time Constant
$T_2$	Compensator Block 1 Lag Time Constant
$T_3$	Compensator Block 2 Lead Time Constant
$T_4$	Compensator Block 2 Lag Time Constant
$V_{STmax}$	Stabilizer Output Upper Ceiling Value
$V_{STmin}$	Stabilizer Output Lower Ceiling Value

Commonly used input signals for  $V_{SI}$  are speed of the machine, frequency or electrical power. Two lead – lag compensator blocks and the stabilizer gain ( $K_s$ ) represents the main functions of the PSS. The washout filter, and torsional filter represents the signal processing section. Different components and their functions of Delta-Omega Stabilizer can be identified as follows.

### **2.1.1.1 Lead – Lag Compensator Blocks and Stabilizer Gain ( $K_s$ )**

Time constants ( $T_1, T_2, T_3, T_4$ ) of Lead - Lag blocks as shown in block D and E should be properly configured to compensate the phase lag so that the created torque is in phase with the oscillation. Stabilizer gain ( $K_s$ ) should be determined to ensure that a sufficient stabilizer action is retained while also ensuring that the system's marginal instability is not exceeded.

### **2.1.1.2 Washout Filters**

Both speed and electrical power inputs have a slow increasing and decreasing nature. Hence, a high pass filter is applied to prevent slow changing inputs from affecting the PSS output. Washout filter takes the form of block B as shown in the Figure 2-1. Washout time constant is given by  $T_5$ , which generally takes values in between 2 -10s [2]. The main consideration here is to have washout time constant value so that it is long enough to pass stabilizing signals unchanged in the focused frequency range and not so long that it causes undesirable voltage excursions during a system islanding condition [4].

### **2.1.1.3 Torsional Filters**

Block C of Figure 2-1 represents a second order torsional filter used for some designs based on the requirement in Delta-Omega stabilizers. Lead – Lag blocks may be re-tuned after configuring the filter parameters to compensate the additional phase lag introduced by the torsional filter.

## **2.1.2 Delta-P-Omega Stabilizers**

Delta-P-Omega stabilizers are a solution for addressing torsional mode issues. The idea behind this is to create an equivalent speed deviation input with the help of per unit power and speed measurement signals [1]. Reference [3] in this paper clearly shows the derivation behind the theoretical background of this stabilizer. Following result can be proven starting from the rotor kinetic energy equation as given in equation (2) and (3) below.

$$E_k = \frac{1}{2}J\omega^2 \quad (2)$$

$$\omega = \omega_0 + \Delta\omega \quad (3)$$

Where,

Table 2-2 Parameters for Rotor Kinetic Energy Equation

$E_k$	Rotational Kinetic Energy of the Mechanical Shaft System
$J$	Inertia of the Rotational Mass
$\omega$	Rotor Speed
$\omega_0$	Steady State Rotor Speed
$\Delta\omega$	Rotor Speed Deviation

With above two equations it can be proven that,

$$E_k = \frac{1}{2}J \times (\omega_0 + \Delta\omega)^2 \approx \frac{1}{2}J\omega_0^2 + J\omega_0\Delta\omega \quad (4)$$

It should be noted that higher order terms have been neglected here. Further considering the power balance in the rotating mass system, it can be proven that,

$$E_k = \int (P_m - P_e) dt \quad (5)$$

Additionally,

$$P_m = P_{m0} + \Delta P_m \quad (6)$$

$$P_e = P_{e0} + \Delta P_e \quad (7)$$

$$\int (P_{m0} - P_{e0}) dt = \frac{1}{2}J\omega_0^2 \quad (8)$$

Where,

Table 2-3 Parameters for Power Balance Equations

$P_m$	Mechanical Power Input
$P_{m0}$	Steady State Mechanical Power Input
$P_e$	Generator Electrical Power Output
$P_{e0}$	Steady State Generator Electrical Power Output
$\Delta P_m$	Mechanical Power Change
$\Delta P_e$	Electrical Power Change

By equations (5), (6) and (7)

$$E_k = \int (P_{m0} + \Delta P_m) - (P_{e0} + \Delta P_e) dt = \int (P_{m0} - P_{e0}) dt + \int (\Delta P_m - \Delta P_e) dt \quad (9)$$

From equation (4), (8) and (9) we can reduce above equations as follows

$$\begin{aligned} \frac{1}{2}J\omega_0^2 + J\omega_0\Delta\omega &= \int (P_{m0} - P_{e0}) dt + \int (\Delta P_m - \Delta P_e) dt \\ \frac{1}{2}J\omega_0^2 + J\omega_0\Delta\omega &= \frac{1}{2}J\omega_0^2 + \int (\Delta P_m - \Delta P_e) dt \\ J\omega_0\Delta\omega &= \int (\Delta P_m - \Delta P_e) dt \end{aligned} \quad (10)$$

By taking  $J\omega_0 = 2H$

$$2H\Delta\omega = \int (\Delta P_m dt - \int \Delta P_e dt$$

By Laplace transformation,

$$\Delta\omega(s) = \frac{\Delta P_m(s)}{2Hs} - \frac{\Delta P_e(s)}{2Hs} \quad (11)$$

In the above equation,  $\frac{\Delta P_e(s)}{2Hs}$  term is free from torsional modes [1]. However, estimating  $\frac{\Delta P_m(s)}{2Hs}$  without torsional modes is the next issue. As a solution for this, equation (11) is restructured and repeated in itself with a Ramp Tracking Filter (RTF) function  $G(s)$  as follows. With the new arrangement, equivalent speed deviation free of torsional modes can be obtained as in equation (12).

$$\Delta\omega(s)_{eq} = G(s) \left[ \Delta\omega(s) + \frac{\Delta P_e(s)}{2Hs} \right] - \frac{\Delta P_e(s)}{2Hs} \quad (12)$$

### 2.1.2.1 Ramp Tracking Filter, G(s)

Ramp tracking filter, G(s) takes the form of,

$$G(s) = \left[ \frac{(1+sT_8)}{(1+sT_9)^M} \right]^N \quad (13)$$

The orders of the filter M, N and denominator time constant  $T_9$  are chosen so as to produce required attenuation at high frequency signals and numerator time constant  $T_8$  is selected to provide required ramp tracking behavior conforming to following relationship.

$$T_8 = M \times T_9 \quad (14)$$

Ramp tracking filter is supposed to provide 40dB of attenuation at low torsional frequencies at about 7Hz. Following M, N combinations can be considered so that above requirement is fulfilled.

- M = 5 , N = 1
- M = 2, N = 4
- M = 4 , N = 1

Among the above combinations, M = 5, N = 1 is the commonly used combination in most of the industrial applications as it meets the attenuation requirement better compared to the other two combinations. However, M = 2, N = 4 is the best combination if the application is more concerned about the phase added by the filter [8].

Complete arrangement of a typical dual input Delta- P-Omega stabilizer is shown in the Figure 2-2. Based on the proof of ramp tracking filter values of  $K_{s2}$  and  $K_{s3}$  are typically set to  $T_7/2H$  and 1 respectively [7].

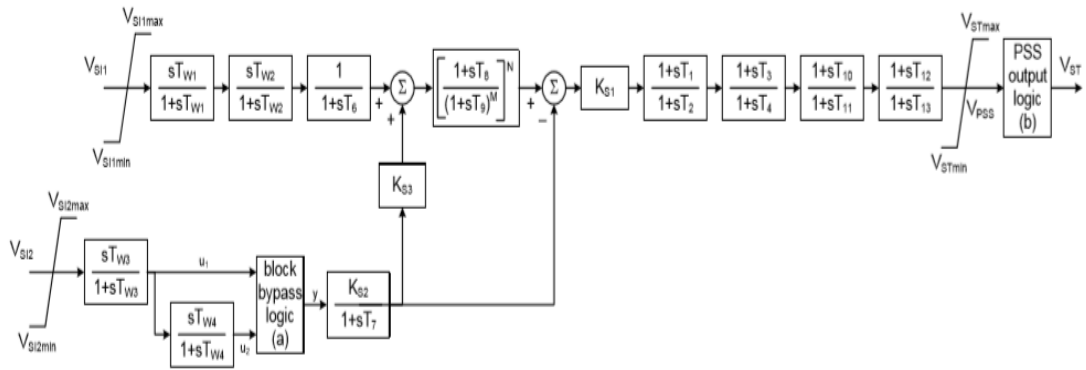


Figure 2-2 Typical Arrangement of a Delta-P-Omega Stabilize

Relevant parameter list is shown in Table 2-4.

Table 2-4 Parameter List for Delta - P - Omega Type PSS

<b>Parameter List for Delta –P – Omega type PSS</b>	
$V_{S11}$	Input 1
$V_{S12}$	Input 2
$V_{ST}$	PSS Output
$T_{w1}, T_{w2}, T_{w3}, T_{w4}$	Washout Filter Time Constants
$T_6$	Signal Transducer Time Constant
$K_{s2}$	Compensation Factor for Calculation of Integral of Electric Power
$T_7$	Time Constant for Calculation of Integral of Electric Power
$K_{s3}$	Signal Matching Factor
$M, N$	Ramp Tracking Filter Orders
$T_8, T_9$	Ramp Tracking Filter Time Constants
$K_{s1}$	Stabilizer Gain
$T_1$	Compensator Block 1 Lead Time Constant
$T_2$	Compensator Block 1 Lag Time Constant
$T_3$	Compensator Block 2 Lead Time Constant
$T_4$	Compensator Block 2 Lag Time Constant
$T_{10}$	Compensator Block 3 Lead Time Constant
$T_{11}$	Compensator Block 3 Lag Time Constant
$T_{12}$	Compensator Block 4 Lead Time Constant
$T_{13}$	Compensator Block 4 Lag Time Constant
$V_{STmax}$	Stabilizer Output Upper Ceiling Value
$V_{STmin}$	Stabilizer Output Lower Ceiling Value

The configurations of Power System Stabilizers (PSSs) have evolved with advancements in PSS-related technologies. According to IEEE standards [7], there are eleven different configurations identified, ranging from PSS1A to PSS7C. There aren't many differences in the filtering section among these PSS configurations. However,

the complexity in the application of the main PSS function has greatly evolved over time based on various theoretical concepts.

## **2.2 Main Tuning Methods of Power System Stabilizers**

Many techniques are incorporated in PSS tuning during last couple of decades. Selection of the method depends on the availability of data and the possibility of going for deeper levels of modeling. Following methods are popular among past applications and researches.

### **2.2.1 Frequency Response Based Method**

As mentioned above under the purpose of a PSS, it is expected to create an auxiliary signal to inject from the AVR summing junction, so that it creates a damping torque, which is in phase with the speed deviation. In this conventional method, the frequency response in between the reference point of AVR and the electromagnetic torque of the generator and the AVR system will be estimated in order to determine the required phase compensation along the path. Thereafter, parameters of lead-lag compensator blocks will be estimated in a heuristic method to compensate above estimated phase lag. Further, some other techniques such as Root Locus technique will be used to estimate the stabilizer gain. In the process of tuning, complete modeling of the respective generator and AVR is required. However, a choice has been provided to represent the rest of the power system as a Thevenin's Equivalent [4]. Hence, this method has been used in most practical applications related to large power systems due to its minimal power system data requirements [1], [8]. One disadvantage of this method is the likelihood of not achieving optimal parameter estimation due to the heuristic nature of estimating Lead-Lag parameters. After the completion of simulation phase, it's required to conduct some field testing to prove the validity of simulated results as well as to fine tune them. A proper guidance for this phase has been given in Institute of Electrical and Electronics Engineers (IEEE) and Western Electricity Coordination Council (WECC) standards [7], [9], [10].

The theoretical background and the effect of system parameters upon the performance of PSS have been presented in the reference [1] of this study. This technique has been followed in some practical scenarios as presented in [4], [11], [2], [12], [13] .

### 2.2.2 Model Based Method

A dynamic model of the power system is developed as the first step of this approach. Then the model is linearized around a certain operating point and the state space model is obtained conforming to following standard equations.

$$\dot{x}(t) = A x(t) + Bu(t) \quad (15)$$

$$y(t) = Cx(t) \quad (16)$$

After having the model, tuning process can be combined with an optimization technique. Related optimization techniques will be discussed under a separate topic in this study. Using a technique such as Model Order Reduction (MOR) is another option to proceed the tuning process, rather than going for direct optimization. This will reduce the computational burden during optimization. Reference [14] of this study uses a Model Based Method correlated with MOR by transforming the system model into new coordinates. This approach is known as Balanced Truncation (BT) as it includes a truncation step, which has a rigorous mathematical acceptance. Thereafter, an optimization technique can be used to estimate the parameters of the PSS.

### 2.2.3 Residue Based Methods

Residue based method can be considered as a variant of Model Based Method as it also deals with mathematical model of the power system. In this method, residue of the critical pole of the transfer function  $G(s)$ , obtained in between AVR reference voltage and the speed output is used to determine parameters of the PSS. Transfer function  $G(s)$  can be stated in the following form.

$$G(s) = \sum_{i=1}^{i=p} \frac{r_i}{s-\lambda_i} \quad (17)$$

If  $\lambda_1$  and  $r_1$  represent the critical pole of transfer function and the residue of  $G(s)$  respectively then, transfer function of the open loop system is given by,

$$G(s) = \frac{r_1}{s-\lambda_1} \quad (18)$$

Subsequently, the closed loop transfer function is obtained for the system by defining the PSS transfer function  $P(s)$  as the feedback path. After closing the feedback path, eigenvalues should be shifted to left. Assuming the new eigenvalue for the

compensated system is  $\lambda_2$ , it can be defined as  $\lambda_2 = \lambda_1 + \Delta\lambda$ . Hence  $\lambda_2$  should satisfy the denominator of the closed loop transfer function as below.

$$1 - G(\lambda_2)P(\lambda_2) = 0$$

$$1 - G(\lambda_1 + \Delta\lambda)P(\lambda_1 + \Delta\lambda) = 0 \quad (19)$$

Having the transfer function of  $P(s)$ , above equations can be further simplified with the help of Taylor series. Thereafter, parameters of the PSS can be calculated considering some constraints [15]. For more details of this technique, reader is encouraged to refer [16] and [17].

### 2.3 Supplementary Techniques Used in PSS Tuning

Supplementary techniques are used to assist main methods in tuning Power System Stabilizers. Some of the identified techniques can be summarized as follows.

#### 2.3.1 Optimization Techniques

Application of optimization for PSS tuning can be implemented as a combination of a selected optimization technique and a selected main method discussed above. Some popular optimization techniques such as Particle Swarm Optimization (PSO) [14], Simulated Annealing (SA) [18], [19], Genetic Algorithm (GA) [20] have been used in past research work for PSS related applications.

In the research work presented in reference [14] of this paper, PSO technique has been combined with a Model Based Method, while references [18], [19] of this paper have been presented as a combination of SA technique with a Model Based Method.

There can be specific pros and cons of selecting a particular optimization technique based on the tuning approach. Hence, a share of consideration should be given to practicability in selecting a suitable optimization for the application based on their own strengths and weaknesses. As an example, in a method like simple hill climbing, only the good moves are accepted. Therefore, there's a higher probability of getting stuck in a local optima. Hence, the user has to make a good initial condition estimation and the step size which is not practical in some optimization problems where the actual behavior of the objective function is unknown.

Genetic Algorithm (GA) is inspired by the selection of natural selection and genetics. It comes as a very versatile technique many search spaces. It maintains a population of candidate solutions and applies operators like selection, crossover, and mutation to evolve better solutions over generations. However, the performance of GA can heavily depend on parameter settings, such as population size, crossover rate, and mutation rate. Additionally, it may encounter structural problems such as premature convergence and duplications within strings during the evolution process.

PSO is inspired by the social behavior of bird flocking or fish schooling. It checks a population of candidate solutions (particles) in the search space. During the searching process, experience of the neighbors and its own experience will be used to adjust the position of trial solutions. PSO is good at quickly converging to solutions, especially in multi objective functions based optimization problems or when the fitness landscape is smooth and continuous. If proper parameter settings were not used, then there's a higher probability of the search process getting stuck in the local optima.

SA is an optimization inspired by 'Annealing' which is a physical process of heating up a solid until it melts, followed by slow cooling it down by decreasing the temperature in steps. Initially it accepts even bad moves with the view to jumping over global highs or lows to achieve better trial solutions. Additionally, SA is effective for finding global optima in complex, multimodal landscapes if the parameters such as cooling schedule and acceptance criterion are carefully tuned. However, it may have a higher computational burden as its need to explore a large portion of the search space. More details on SA technique will be explained in the implementation phase of this study.

### **2.3.2 Online Tuning Techniques**

Online tuning procedures have also been involved in some applications. Technically Online / real time tuning is the most suitable way to address the disturbance as it will pave the way to exactly identify the oscillatory mode and change PSS settings so that an optimum damping is imposed. Performance of the PSS once tuned will not give the optimum damping for any disturbance as the power system is continuously subjected

to changes during operation. Hence, real-time tuning will definitely provide better results rather than going for offline tuning.

However, it may also include some risk in incorporating such a technique as it requires some extra equipment and controllers. Therefore, most of the power system experts still prefer conventional offline tuning methods.

The most popular method for online tuning involves using synchrophasor data available at the generator terminals to determine oscillatory modes. This technique uses ESPRIT method in most of the applications. Hence, as discussed above, reference [15] in this study, which follows the Residue Based Method, utilizes the ESPRIT method to facilitate an online tuning process.

ESPRIT comes as a subspace method which is used to decompose the signal space into signal sub space and noise sub space. It can estimate the modes of oscillation with the help of recorded `space data and the least square sense. For more details of this approach, reader is encouraged to go through reference [15] of this study.

## **2.4 Chapter Summary**

Chapter 2 provides a comprehensive literature review on past techniques and related studies concerning Power System Stabilizers (PSS) and their tuning methodologies. This chapter begins by examining the evolution of PSS configurations, starting from the earliest designs and progressing to contemporary configurations. Further, the emphasis is placed on the fundamental purpose of creating a damping torque in phase with speed deviation, which serves as the primary mechanism for stabilizing power systems. Specifically, the discussion delves into Delta-omega stabilizers and Delta-P-Omega stabilizers, highlighting their constituent (Signal Processing Section and Main PSS function) and their components such as washout filters, torsional filters (only in Delta - Omega stabilizers), Ramp Tracking filter (only in Delta - P - Omega stabilizers only) along with their functional significance.

Subsequently, various tuning methods for PSS are explored, drawing from both theoretical frameworks and practical experience. These methods encompass traditional frequency response-based approaches, model-based techniques, and residue-based methods. Additionally, supplementary control methods are introduced, comprising

Optimization Methods and Online Tuning Techniques. Optimization methods such as Simple Hill Climbing, Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Genetic Algorithms (GA) are evaluated in terms of their applicability, strengths, and limitations. Meanwhile, online tuning techniques, notably employing synchrophasor data and the ESPRIT method, are highlighted for their efficacy in real-time tuning.

Moreover, the chapter underscores the integration of various tuning methodologies in past research and practical applications, emphasizing the effects achieved through combining main and supplementary methods.

In conclusion, the chapter elaborates the purposes and theoretical underpinnings of PSS configurations, discusses different tuning methodologies along with their respective attributes, and justifies the selection of a model-based technique in conjunction with a simulated annealing optimization approach for the proceed the study. The decision to utilize Simulated Annealing can be justified based on its robustness, computational efficiency, and suitability for single-objective function optimization, conforming to the objectives of the research.

### 3 MATHEMATICAL MODELING FOR SYSTEM STUDY

The tuning process presented in this study comes as two phases. A conventional method will be used as the first phase of tuning and secondly a model based technique will be used with an optimization technique. More details about these two phases will be discussed under Section 4 of this dissertation. However, the entire process requires two mathematical models. First model is to replicate the dynamic behavior of the power system upto 33kV voltage level. Most importantly, a model of the Sri Lankan Power System will be involved for this purpose as this research is conducted as a case study for Lakvijaya Power Station and the Sri Lankan power system. This model will be employed in both phases of the tuning process.

The second model will be formed by a portion of the first model, comprehensively representing the LVPS system in detail. The second model will only be used in the first phase of the tuning process. Additionally, the Thevenin's Equivalent circuit derived by means of the first model will be used to represent the rest of the power system in the second model.

However, due to the vast amount of equipment in the system, it's required to use a simulations software considering the convenience of constructing the mathematical model in a physical approach. Additionally, the selected software should be able to facilitate the operations required to be done with relevant model. The expected capabilities of the software package for the first model can be stated as follows.

- Software package should be able to facilitate in modeling the complete Sri Lankan power system up to 33kV voltage level.
- Also, it should be able to accommodate relevant load flow studies and dynamic simulation studies.
- Also, it should be capable of performing linear system conversion studies and eigenvalues estimation.
- Software package should have to provision to be automated in the optimization process

Considering the availability of model and data, PSS/E software was selected for the above task. PSS/E is a versatile software which accommodates all the above

requirements, along with the in-built compatibility to deal with Python programming language. Hence, it fulfills all the expectations for achieving the objectives outlined above. The expected capabilities of the software package for the second model can be stated as follows.

- Software package should be able to facilitate in detailed modeling of generator, turbine and excitation units of LVPS
- Also, it should be able to facilitate some other required analysis tools such as frequency response estimations and Root Locus techniques.

For above requirements, MATLAB Simulink software package is the best match as it consists of all the required tools with flexible system modeling capabilities. Required data collection can be commenced after selecting the software packages. It's important to note the required parameters of relevant models in both the softwares prior to start the data collection as parameter specifications differ from one software to another.

### **3.1 Preparation and Validation of Sri Lankan Power System Model**

#### **3.1.1 Model Preparation for Load Flow Study**

Generally, the power system utilities of any country maintain their power system models in a well-organized manner. This is because of the fact that, a reliable system model is a mandatory requirement of the system's utility. Especially, the planning and forecasting related evaluations and contingency studies are carried out using these type models. Also, a precise simulation of a power grid enhances strategic planning and ensures cost-effectiveness while maintaining operational stability and security. Therefore, these models are updated annually based on the planning requirements and other related routines. Generally, power system modeling software such as PSS/E, PSLF, DigSILENT, ETAP, etc., are used for this purpose all over the world.

To validate a power system model using a dynamic simulation, it involves replicating specific past events such as generator or transmission line failures, bus bar faults, or load rejections within a power flow scenario. This replication requires adjusting various parameters like generation dispatch, load profiles, reactive power compensators, and network configuration to match the conditions observed during the event. Hence, power flow study should be carried out first. The power flow case is

solved using iterative methods such as Newton-Raphson or its variations or Gauss-Seidel, Then results are compared to the actual outcomes.

Steady state models, also known as power flow cases, serve as the cornerstone of system analyses. They comprise a set of models which represent the system topology, load, and dispatch, providing a snapshot of anticipated system behavior under specific operating conditions. The Transmission and Generation Planning division of CEB is responsible for maintaining the power system model for planning purposes which are scheduled biannually. Hence, the Sri Lankan power system model has been created and maintaining in PSS/E software with relevant timely updates. Therefore, creating the model from scratch is not required for ongoing affairs and changes in the power system. The updated system can be obtained by simply adding ongoing changes. After creating the physical connections relevant to timely updates, data will be assigned for model parameters. The single line diagram of the Sri Lankan network is shown in ANNEX B.

Various sources are used in creating a steady state model. The transmission line data is typically derived from line parameter calculations (resistance (R), reactance (X), and susceptance (B)), while transformer data is sourced from manufacturer specifications. FACTS (Flexible AC Transmission Systems) and HVDC (High Voltage Direct Current) models are often developed in collaboration with manufacturers. Generator testing is essential for validating power plant models, typically conducted through staged tests involving deliberate unit maneuvers, including small power rejections. These tests are used to observe dynamic behavior and extract parameters for simulation models of the generator, excitation system, and turbine-governor controls.

Event representation phase comes after the construction phase of the model. A past incident can be selected and the model can be modified so that it exactly represents the pre-fault conditions of selected incident. Following data will be required for this purpose.

- Information regarding any power plant whether it had been dispatched or not.
- Generation of each and every power plant.

- Grid level load conditions for all the grid substations.
- Configuration of the power system at the given time

Above data can be retrieved from the System Control Center of CEB as the online data monitoring and recording system records power system data once in every fifteen minutes. Load flow study can be performed after properly including above data in the model, which will ensure the error freeness. Data inconsistencies of the case could occur due to following reasons.

- Applied values are outside the limits of parameter models.
- Appearance of conflicts in voltages due to multiple voltage regulating devices.
- Resulting in endless hunting in power flow due to less transformer voltage control range.
- Misleading data entry or incorrect data entry.

It's really important to check the results of the load flow study and resolve if there are any issues with it. The dynamic model preparation and validations can be commenced after having satisfactory results from the load flow study.

### **3.1.2 Model Preparation for Dynamic Simulations**

It is really important to ensure that simulations closely reflect actual system dynamics by regular validation against real-world measurements and operational protocols. In a power system simulation software like PSS/E, the model library typically covers a broad range of equipment commonly found in power systems. They can be classified under following sections.

- **Device Models**  
These are the models which represent specific equipment in PSS/E power flow (e.g. models of generators, loads etc.). There may be several other sub section models attached for any given equipment. As an example for any generator unit, there are some other optional models such as for AVR and Turbine.
- **Protection Models** – Protection models are generally used to implement equipment protection schemes or system protection schemes such as Under Frequency Load Shedding (UFLS) criterions.

- Other Models

These custom models, termed as unattached models, are not inherently tied to any specific equipment within the PSS/E power flow environment. They represent a flexible approach that allows engineers to develop custom models tailored to their specific needs, regardless of whether they correspond directly to existing equipment models within the software.

Following models as described in the reference [21] were used to form the dynamic data model. Parameters values employed in these models regarding the LVPS model are shown in ANNEX A.

- Synchronous Generator Models – GENROU ( Cylindrical Rotor Synchronous Generator Model), GENSAL (Salient Pole Synchronous Machine Model)
- Governor – HYGOV (Hydraulic turbine Governor Model), GAST (Gas Turbine Governor Model), TGOV1 ( Tandem Compound Multi Mass Turbine Governor Model)
- AVR/Exciter Models – SEXS (Model SEXS is particularly useful in cases where an excitation system must be represented and its detailed design is not known [21]), EXST1 (This is ST1A model in the standard notation [7]. This is the standard model applied in the UNITROL 5000 controller of LVPS)
- Generic Wind Models – WT4G1, WT4E1, WT3G, WT3E
- Load – CLODAL (This model is designed to simulate a combined load comprising induction motors, lighting, and various other equipment sourced from multiple standard substations. Its purpose is to accurately depict load behavior at a dynamic level, rather than relying solely on algebraic characteristics. This model is particularly useful when detailed dynamic data is unavailable for individual components [21])
- PSS model – UNITROL 5000 controller has its inbuilt PSS2A type PSS function conforming to IEEE standards [7]. Hence it was important to select the same model in simulation software for exact representation. The functional block diagram for model for PSS2A type PSS in the PSS/E software is given in Figure 3-1. All the parameter have usual meanings as explained in the

literature section of Figure 2-2. However, there's no any requirement of adding the PSS function to the model validation phase as it does not exist in the original system. This function should be added to models after tuning only.

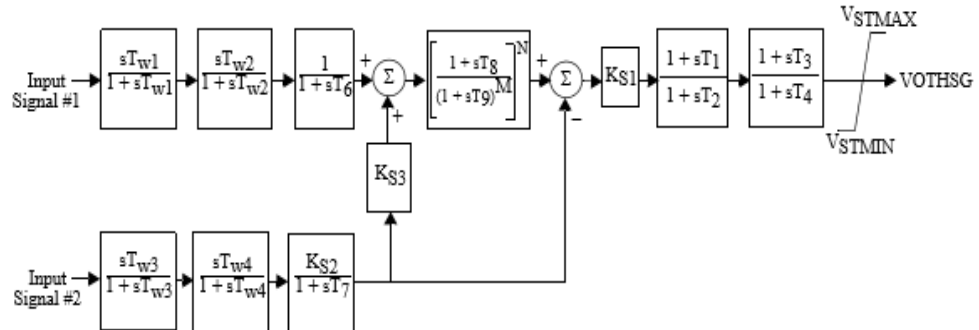


Figure 3-1 PSS2A Type PSS Function in PSS/E Software Package

### 3.1.3 Validating the Sri Lankan Power System Model

The tuning methodology proposed by this research is system independent and can be applied to any power system model given that all the required model data are available. Therefore, 2017 Sri Lankan power system model and a related incident have been used for the validation. Same model after validation will be used for research continuation. First the model will be prepared for the load flow study as described in section 3.1.1. Then it will be validated via a dynamic simulations, which represents the incidents of tripping unit 3 of LVPS. The frequency of the 220kV bus bar of LVPS will be compared in between actual ben records data to justify the validity of the model. Ben records data were retrieved by the Ben record system of LVPS. Details of the event are as follows.

- Incident: Tripping of Unit 03 of Lakvijaya Power Station
- Date: 07/11/2017 at 01.54 am

The extracted ben record of the above incident is shown in Figure 3-2. The frequency variation after the incident can be observed within the red colored box in the figure.

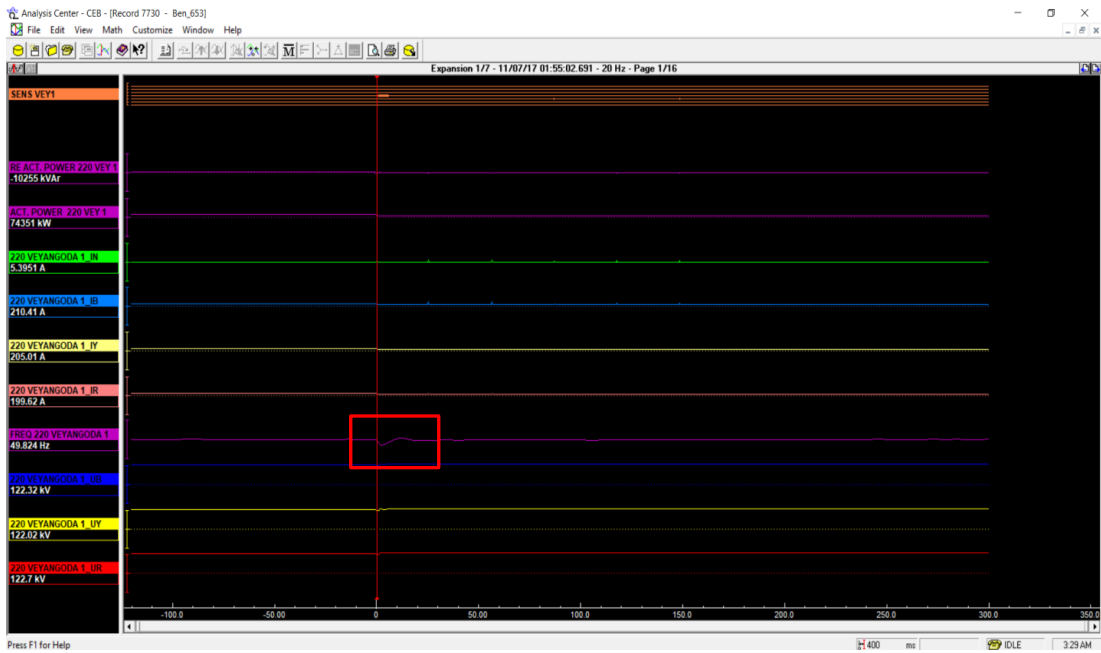


Figure 3-2 Ben Records of the Incident of Tripping LVPS U3

After having the PSSE model, it was further changed according to the pre-fault system configurations of the selected incident. After performing the load flow study for the pre-fault system, dynamic simulation was carried out to replicate the tripping incident. In the simulation, tripping of unit 03 of Lakvijaya Power Station was initialized at 1s and observe the results of the simulation for 40s. Thereafter, actual Ben record results are compared with the simulation results as shown in Figure 3-3.

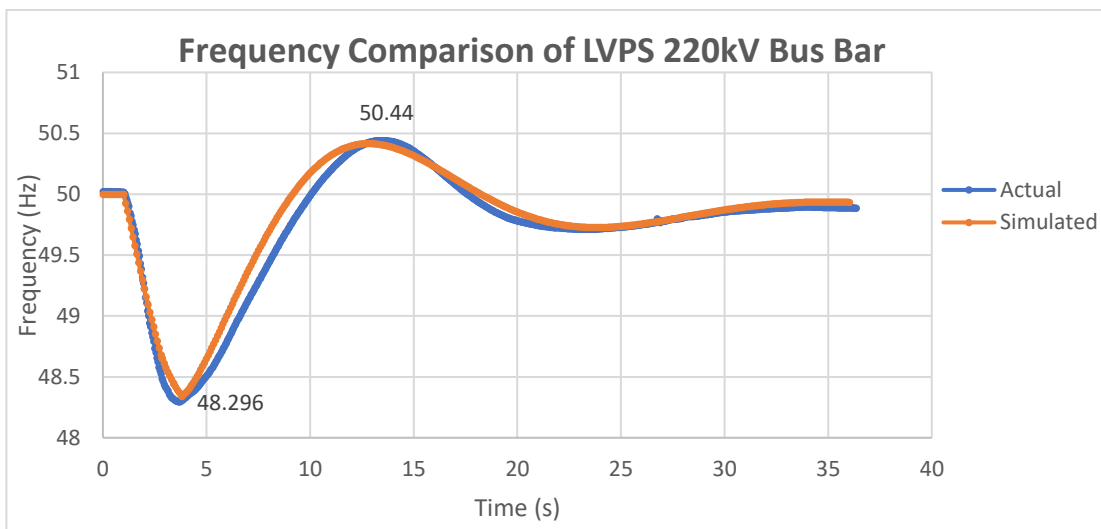


Figure 3-3 Comparison between Actual and Simulated Results

Simulation results have almost similar variation to the actual ben records results. Reasons causing for minor deviations could be.

- Generation dispatch and grid loading data records are done once in every 15 minutes. Exact data cannot be retrieved at the time when the disturbance occurred.
- Standard load models available in the software have been used to model the loads of the system which, may not represent the actual system loads.
- Renewable energy generation and operation (solar and mini hydro) data aren't monitored online.
- Some of the Generator and Governor Data were not available for most of the old plant in the system. Hence typical parameters have been used.

Figure 3-3 demonstrates a close alignment between the simulation outcomes in PSS/E and the real-world scenario, with only a slight variance. Therefore, it can be inferred that the current transmission model of the Sri Lankan power system, as depicted in PSS/E, is confirmed as accurate and reliable for conducting further analyses.

### **3.2 Preparation of MATLAB SIMULINK Model**

This model is prepared with the view to use in the first phase of the tuning procedure, which is the frequency response based method. Model is created via MATLAB Simulink software to represent the complete model of three units of LVPS generator and turbine system. Following blocks were used to represent main components.

- Generator – Synchronous Machine Mask
- AVR – ST1A Excitation Mask
- Tubine – Steam Turbine and Governor Mask (Tandem Compound – Multi Mass)

A Thevenin's equivalent was used to represent the rest of the power system. The Thevenin's equivalent was derived from previously validated PSSE model according to the steps shown below.

## Step 1

- Three generator units of LVPS were removed from the LVPS 220kV bus Bar and the short circuit analysis was done to create a three phase to ground fault at the same bus bar. The 220kV bus bar of LVPS will be finally placed in 1pu, 0 angle voltage as per the settings specified in the fault analysis. Following results were obtained after the simulation.
  - **Voltage = 1 pu, Angle = 0°**
  - **Base Capacity of Bus Bar = 1644.20 MVA**
  - **Fault Current = 4314.9 A , Angle = -77.53°**
  - **Thevenin Impedance (X/R)= 4.52014**

## Step 2

- Based on above results, complete model for the first phase of the research can be derived as shown in Figure 3-4.

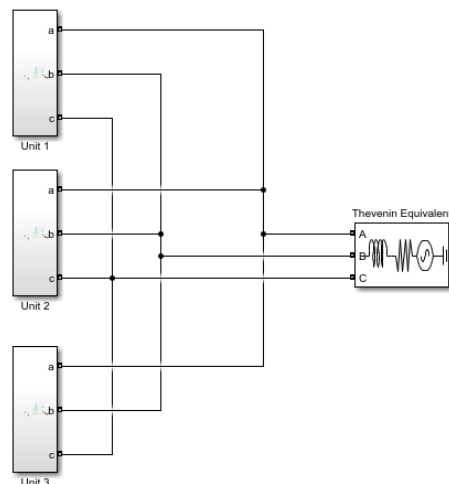


Figure 3-4 Complete Representation of LVPS

In detailed model of one generator turbine unit and the PSS function shown in Figure 3-5 and Figure 3-6 respectively. In the process of selecting a suitable structure for PSS function, it was important to design the PSS function as it is in the UNITROL 5000 controller. The standard configuration of PSS2A has only two lead lag blocks. Hence, it was decided to manually create the PSS function in MATLAB simulink. It should be noted that, washout function of the time constant  $T_{w4}$  and transducer lag time constant  $T_6$  have been bypassed according to IEEE standards [7]. Hence, those two

blocks are not shown in Figure 3-6. There's no any requirement of validating this model in Figure 3-5, as it has employed same parametric data used in validated PSS/E model.

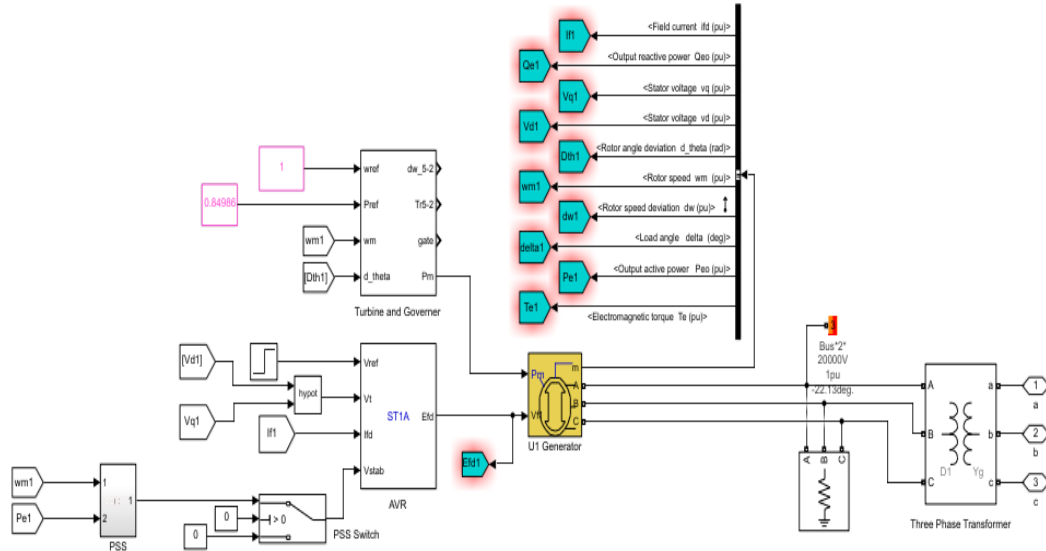


Figure 3-5 Detailed Model of One Generator

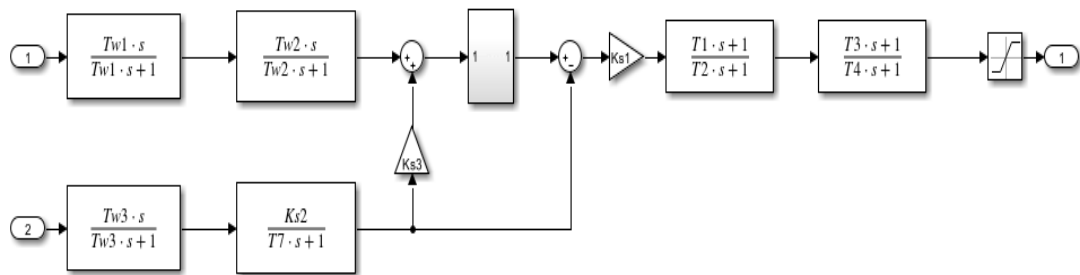


Figure 3-6 PSS Function Created with Functional Block Diagrams

### 3.3 Chapter Summary

Chapter 3 presents the mathematical modelling conducted for the system study, consisting two distinct models aimed at comprehensive analysis and validation. The first model represents model of the Sri Lankan power system, extending up to the 33kV voltage level with complete dynamics. This model, constructed using PSS/E software, draws upon existing data from the Transmission and Generation Planning Division of the Ceylon Electricity Board, Sri Lanka. Further, the chapter elaborates on the validation procedure, detailing the process of comparing simulated results with actual

data obtained from a recorded incident in the BEN recorder, involving the tripping of Unit 3 of LVPS. The validation methodology includes a load flow study followed by dynamic simulation, with results presented to demonstrate the model's accuracy and reliability. Additionally, the chapter provides insights into the different equipment models used within the PSS/E software, enhancing understanding of the modelling framework.

Subsequently, attention shifts to the detailed model of the Lakvijaya Power Station (LVPS) which incorporates all three generators. It was constructed using MATLAB Simulink software. The rest of the power system is represented by Thevenin's equivalent derived from the PSSE model via a short circuit test and related calculations. The chapter explains the construction of this model, highlighting the rationale behind the selection and configuration of model blocks.

In summary, Chapter 3 serves as a pivotal component of the thesis, laying the groundwork for modelling and validation. Through meticulous validation procedures and detailed model construction, the chapter establishes the foundation for accurate system simulations and in-depth explorations of power system dynamics.

## 4 RESEARCH METHODOLOGY

The proposed methodology to configure parameters of the PSS will be discussed in this section under two phases. The conventional frequency response based method will be used to configure parameters in the first phase. An optimization technique will be used as the second phase to improve the results further. The frequency range of interest is 0.1 -2Hz. In other words, the PSS will be focused more for modes of oscillations within that frequency range. It'll provide the capability of the PSS to address inter area modes, local plant modes and, inter machine modes in a more concentrated manner. Configuring procedure of the parameters of the PSS has to deal with evaluating all the parameters of the PSS as discussed under section 2.1.2. Hence, for the convenience of dealing, PSS can be separated in to two sections as *Signal Processing Section* and *Main PSS Function* as shown in Figure 4-1.

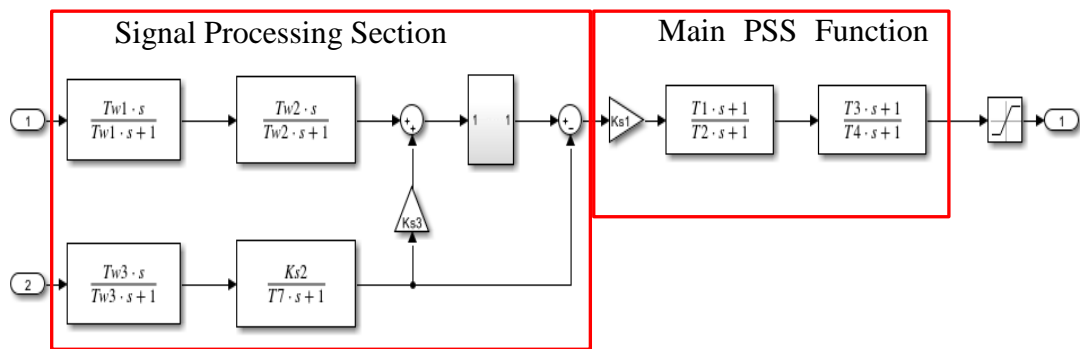


Figure 4-1 Two Sections of a PSS

### 4.1 Estimating Signal Processing Section Parameters

However, the function of the Signal Processing Section parameters does not depend on the system in which the PSS is employed. Therefore, in the ideal case, the performance of the PSS does not depend on these parameters, as the functions of the signal processing section do not introduce any phase or gain to the network within the selected frequency range of operation. However, the quality of PSS function will depend on these parameters, particularly in terms of accuracy, stability and response time, etc. There are well - established values have been proposed for those parameters in literature, based on past research outcomes and experience in practical applications. Therefore, there is no need to propose a tuning methodology for those values.

Following criteria and literature related suggestions have been considered in selecting values for the signal processing section parameters.

- Typically washout function of the time constant  $T_{w4}$  and transducer lag time constant  $T_6$  are bypassed according to IEEE standards [7]. This can be simply done by setting  $T_{w4}$  and  $T_6$  into zero in a software like PSS/E and these blocks were not created in the MATLAB model.
- Values in between 2- 10 are recommended for washout filter time constants  $T_{w1}$ ,  $T_{w2}$ ,  $T_{w3}$  [2], [7]. These are high pass filter that prevents steady changes in the input signal from impacting excitation. Additionally, these filters should be able to admit frequencies as low as 0.1Hz without significant attenuation. The phase shift and gain introduced by the filters should be minimized, and past research recommends a filter cut-off frequency greater than or equal to 0.015Hz [5]. The Bode plot for one washout filter is shown in Figure 4-2. It may be observed that, as the  $T_w$  is increased from 2s to 12s, the phase shift introduced to the network by the washout filter becomes minimum and the gain remains constant throughout the considered frequency range (0.1 -2Hz). Hence, using higher time constant values may be advantageous in terms of the applicability of the washout function. However, it's not recommended to increase  $T_w$  beyond 10 as it may cause to pass very slow ramping signals of speed and power inputs which will unnecessarily manipulate the PSS output. Hence considering all the above facts,  $T_w = 10$ s will be used for all the washout filter time constants.

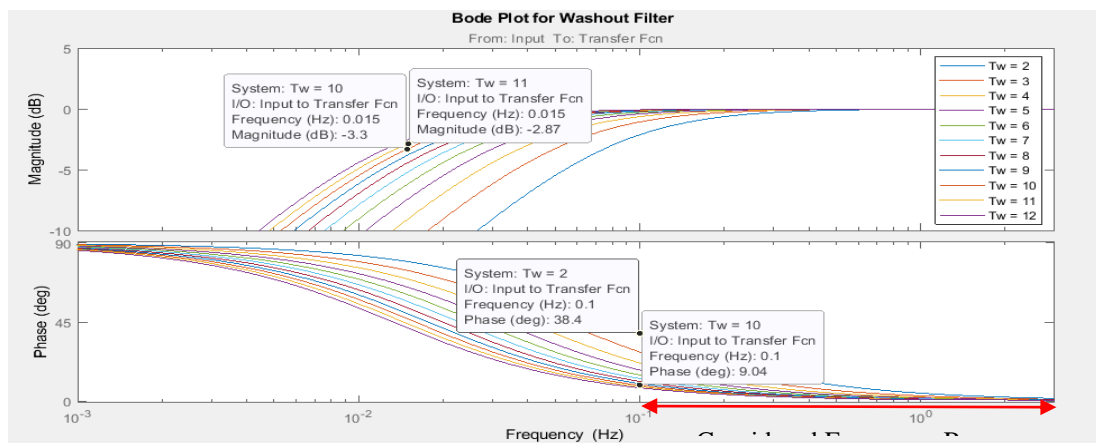


Figure 4-2 Bode Plot for One Washout Filter

- It is recommended to set  $T_{w1} = T_{w3}$ ,  $T_{w2} = T_7$  maintain equal phase shift addition in both the input channels [7]. Therefore,  $T_{w1} = T_{w3} = 10s$ ,  $T_{w2} = T_7 = 10s$ .
- $K_{s2}$  would be normally set to  $T_7/2H$ , Where H is the total inertia constant of the rotating machinery [7]. Further we can calculate the value of H as follows. By commissioning reports of the plant,
  - Inertia constant of the generator = 4.2s
  - Inertia constant of the HP-IP turbine = 0.4264s
  - Inertia constant of the LP turbine = 0.3176s

Hence, the total inertial constant can be calculated as 4.944s

Therefore,  $K_{s2}$  can be calculated as 1.0113

- $K_{s3}$  would be normally set to 1 [7]
- For ramp tracking filter parameters,  $M = 5$ ,  $N = 1$  and  $T_9 = 0.1s$  would be selected as it suits more to the frequency attenuation requirement discussed in section 2.1.2.
- It is recommended to set  $T_9 = 0.1s$  to obtain the required ramp tracking behavior [7], [8]. Hence  $T_8$  can be calculated as  $T_8 = 0.1 \times 5 = 0.5s$  by equation (14) in section 2.1.2. Figure 4-3 shows the phase characteristics of the ramp tracking filter for different recommended M, N combinations. It proves the suitability of  $M = 5$ ,  $N = 1$  combination compared to the other two.

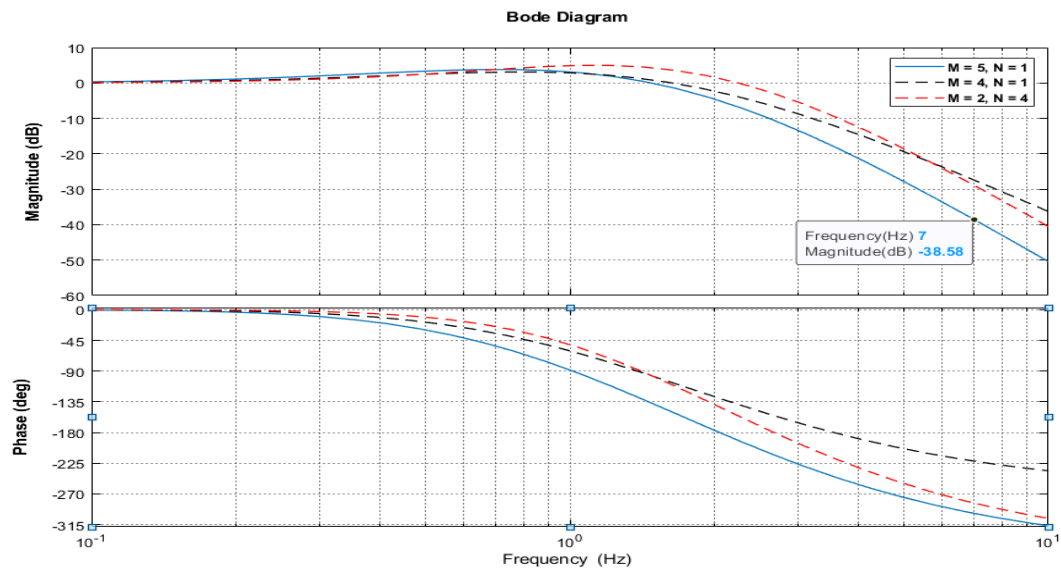


Figure 4-3 Bode Plot for Ramp Tracking Filter

A summary of parameters values of the *Signal Processing Section* can be presented below.

Table 4-1 Summary of Selected Parameters for the Signal Processing Section

<b>Parameter</b>	<b>Value</b>
$T_{w1}$	10s
$T_{w2}$	10s
$T_{w3}$	10s
$T_{w4}$	Block bypassed
$T_7$	Block bypassed
$K_{s2}$	1.0113
$K_{s3}$	1
$M$	5
$N$	1
$T_8$	0.5
$T_9$	0.1

Above values will be used in both models for required simulations. Therefore, the ultimate goal of the study is to estimate values for *Main PSS Function*.

## 4.2 Estimating Main PSS Function Parameters Using Frequency Response

### Base Method

Frequency response method will be used to estimate the PSS parameters as the first phase of the methodology. The purpose of the method is to estimate  $T_1, T_2, T_3, T_4$  time constants and the stabilizer gain  $K_{s1}$ . For the convenience of understanding the methodology, the classical K constant model can be associated with it, as shown in Figure 4-4. All the constants and variables have standard meaning as explained in reference [1] of this research. In the first part of this method, the time constants will be evaluated. Then stabilizer gain will be evaluated using Root Locus method

### 4.2.1 Evaluating Lead - Lag block Time Constants

As it was previously explained in the introduction section, PSS is supposed to feed an auxiliary signal which should alter the damping torque component of the

electromagnetic torque so that it is in phase with the speed deviation. However, the inserted signal has to come from the AVR summing junction all the way up to the point which  $\Delta T_e$  emerges as shown in the highlighted pathway in Figure 4-4. Hence, the signal has to go through AVR and field circuit transfer functions. These transfer functions alter the phase and magnitude of the signal. Therefore, the phase introduced by those transfer functions should be pre-compensated in PSS. Additionally, it should be noted that phase introduced by a transfer function depends on the frequency of input signal. Hence, it's required to configure the PSS so that it compensates the signal within the frequency range of interest (0.1 -2Hz).

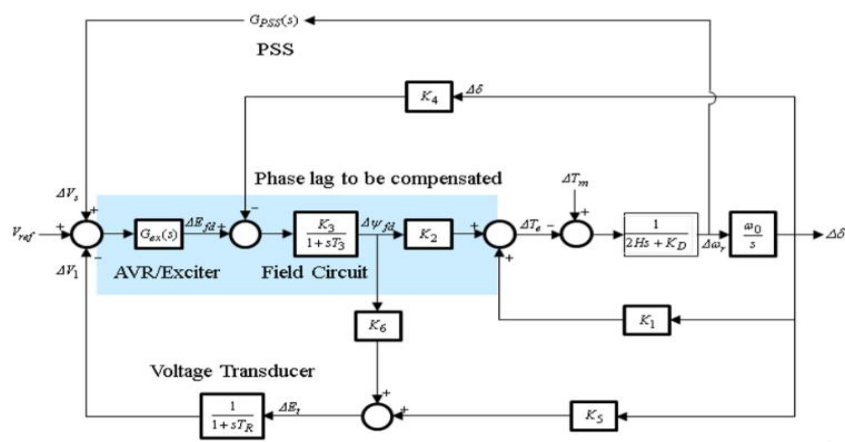


Figure 4-4 Classical K- Constant Model of Generator and Excitations System [1, 7]

It's really convenient to use the *Frequency Response* tool of MATLAB Simulink software to find the phase angle variation to be compensated within the considered frequency range. The second model as described in the previous section will be used to analysis without PSS. As the first step, the model will be verified through a load flow study and results will be applied to the model. Then, a dynamic simulation is conducted to see if the model reaches to a steady state. It's recommended to continue the analysis with the *Frequency Response* tool only if the above results are satisfactory.

There's another consideration that should precede the implementation of frequency analysis. The path in between AVR summing junction and the  $\Delta T_e$  is disturbed by signals routed through  $K_1$  and  $K_4$  constants as shown in Figure 4-4. Further, these signals modify the phase during estimation process causing inaccurate judgements. One solution for this is increasing the value of inertia constant (H) to a large value so

that it keeps the change of delta ( $\delta$ ) at a minimum value, approximating  $\Delta\delta$  into zero. This is called *Large Inertia Constant Method* [2]. The required value of ‘H’ can be determined by observing the frequency response results while increasing the value of H, it until there’s no any visible significant change occurs in phase characteristics. In this research, the value of H had to be increased up to 10000s to obtain satisfactory results.

As the first step of obtaining frequency characteristics, the *linear analysis* tool of *Frequency Response* app creates a liner object at steady state of the model. Thereafter, that liner object could be used to estimate characteristics. The estimated phase characteristics in between  $V_{ref}$  and  $\Delta T_e$  is shown below in Figure 4-5.

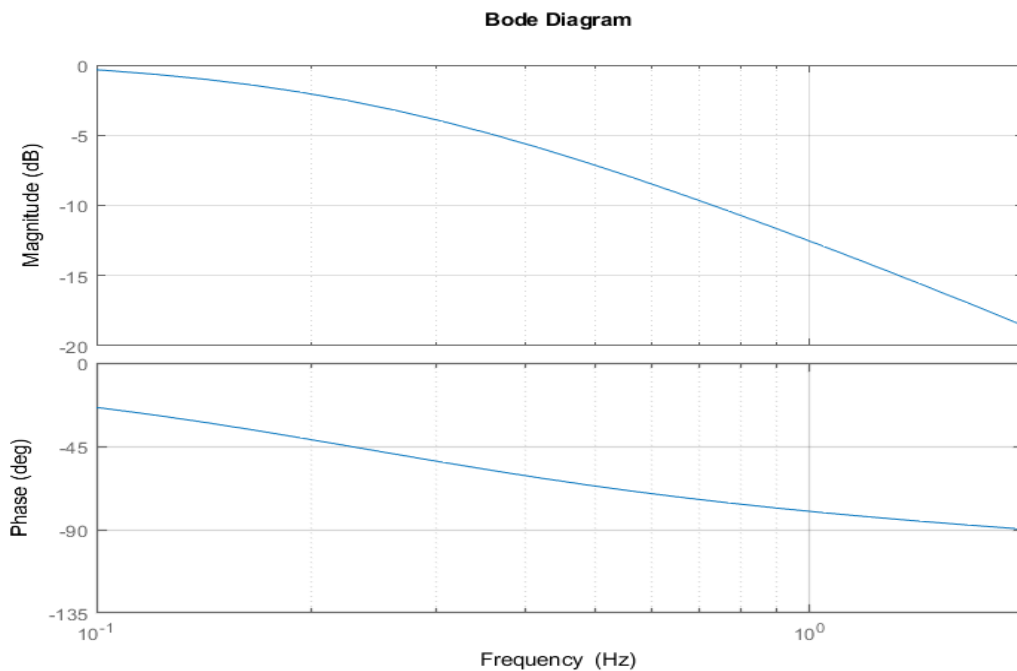


Figure 4-5 Uncompensated Phase- Magnitude Characteristics in Between  $V_{ref}$  and  $T_e$

Thereafter, relevant time constant values of Lead-Lag compensator blocks can be calculated so that above phase lag is compensated. This is done heuristically. Following specifications are proposed by the literature for better performances.

- Phase characteristic should not be less than -30 degrees after compensation [3], [9].
- Full compensation or over compensation is not advised due to the risk of reducing synchronizing torque [2], [3], [9]

Consider the transfer function of the compensator as in equation (20) where  $a_2$  and  $\tau$  constants to be calculated. Best combination for those values was selected after several heuristic trials.

$$\frac{a_2\tau s+1}{\tau s+1}, a_2 > 1 \quad (20)$$

► For 1<sup>st</sup> lead block

► Maximum phase lead 37 degrees occurs at 2Hz

$$a_2 = \frac{1 + \sin(37)}{1 - \sin(37)} = 4.023$$

$$\tau = \frac{1}{2 \times \pi \times f \times \sqrt{a_2}} = 0.0396$$

$$T1 = a_2\tau = 0.16s$$

$$T2 = \tau = 0.04s$$

► For 2<sup>nd</sup> lead block

► Maximum phase lead 45 degrees occurs at 1.6Hz

$$a_2 = \frac{1 + \sin(45)}{1 - \sin(45)} = 5.828$$

$$\tau = \frac{1}{2 \times \pi \times f \times \sqrt{a_2}} = 0.0412$$

$$T3 = a_2\tau = 0.24s$$

$$T4 = \tau = 0.04s$$

Compensated and uncompensated phase characteristics are shown in Figure 4-6. It shows that the compensated curve does not violate specification mentioned above, keeping it above -30 degree level within the considered frequency range. Further, bode plots of tuned lead – lag compensator blocks is shown in the Figure 4-7.

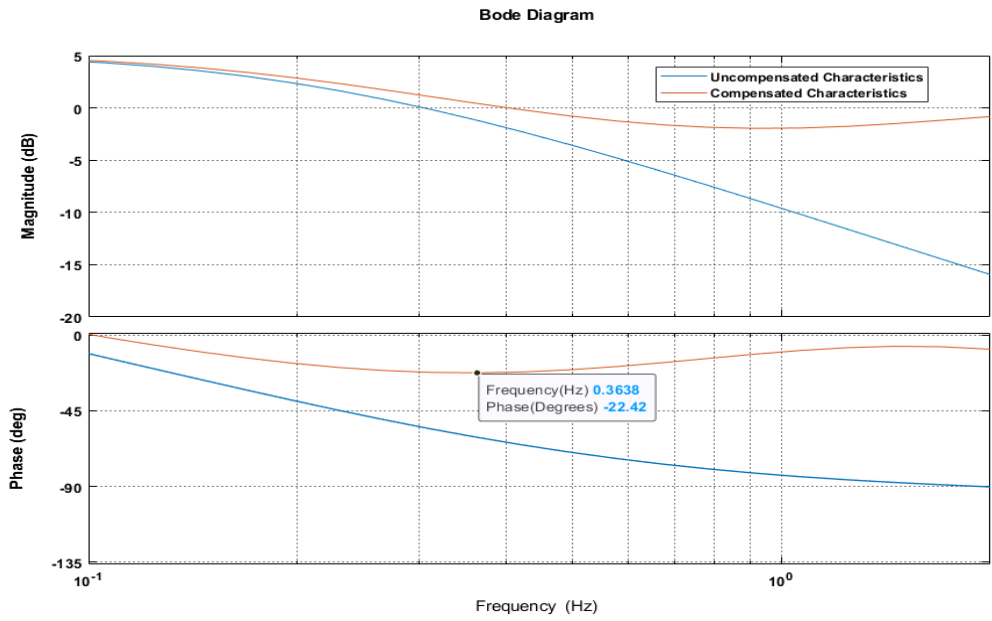


Figure 4-6 Compensated & Uncompensated Characteristics in Between  $V_{ref}$  and  $T_e$

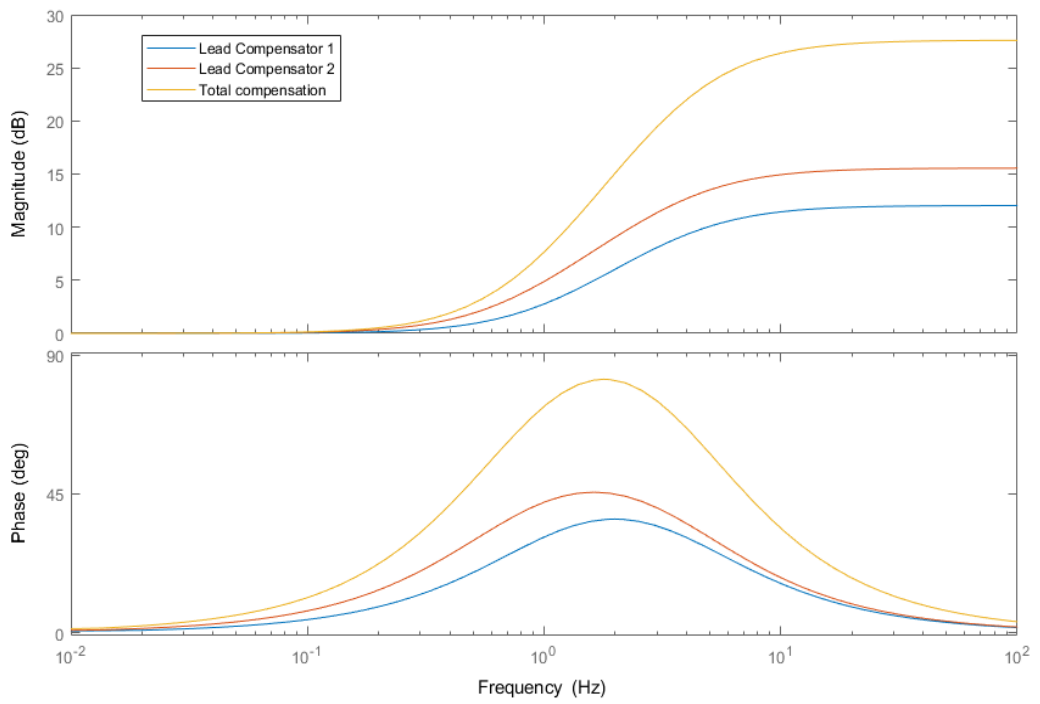


Figure 4-7 Phase and Magnitude Variation of Tuned Lead -Lag Blocks

### 4.2.2 Estimating Stabilizer Gain

With the previously estimated Lead-Lag block time constants at hand, the stabilizer gain will be estimated using the Root Locus technique. This technique can be effectively employed when there's a requirement of observing the behavior of poles, as they represent the dynamic behavior of the system, while one parameter is being changed.

Typically, poles of a system could be either complex or purely real and should lie on the left half plane of the s- plane. In other words real parts of poles should be negative. If that happens only it's said that the system is dynamically stable at that operating point. On the other hand, the stabilizer gain of a PSS should be maximum to obtain the best performance out of it. However, It can be observed that, some poles are shifted to right side when the stabilizer gain is increased making them marginally stable or completely unstable. Therefore, it's required to find the maximum possible value for stabilizer gain  $K_{s1}$  which creates the marginal stability in the system. The SISO tool (Single Input Single Output) of the MATLAB software can facilitate in realizing the above purpose. It accommodates various facilities to obtain real time results such as Bode plots, Root Locus plots etc. for a single input single output system, when one parameter is being changed. The tool has proposed several architectures to model the system using functional block diagrams prior to analysis. Following architecture shown in Figure 4-8 was used in this implementation.

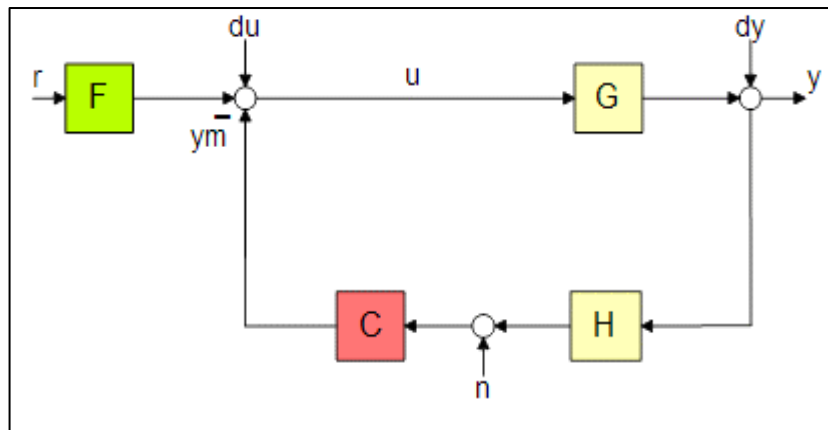


Figure 4-8 System Configuration for Root Locus Study

The subjected system of study should be restructured so that it fits transfer functions represented as F, G and H as shown in Figure 4-8. Input signal 'r' and the output 'y'

should be selected accordingly. Block ‘C’ represents the variable parameter. Hence here we are forced to use  $K_{s1}$  as ‘C’ and the rest of the transfer function of PSS as ‘H’ in the system representation above. Since the PSS is supposed to damp out speed oscillations, it would be an ideal selection to consider any variable that can give an input perturbation as the input ‘r’, and speed as the output ‘y’. However, speed is not the only input for the PSS in this application as discussed. Electrical power also has a share in it. Hence, the only option is to lumps up the signal processing section of PSS to function ‘G’ so that the speed deviation is taken out as output signal ‘y’. Therefore, ‘H’ will represent the transfer function of Lead – Lag compensators only. To match with PSS output after block ‘C’, reference input of AVR ( $V_{ref}$ ) can be selected as the input signal ‘r’. Sign at the summing junction can be corrected by multiplying H function by ‘-1’. It should be noted that selecting speed deviation as the output would not do any harm to the results as it is proportional to speed. Hence the final outcome will be the same. Following is a summary of above functions selection.

Table 4-2 Functions Selected for the Root Locus Study

Transfer Function Block	Description
C	Stabilizer gain $K_{s1}$
G	Transfer function in between $V_{ref}$ and speed deviation signal created by signal processing section of PSS when the speed and power inputs are connected.
H	-(Transfer function of Lead – Lag compensators)
F	Unity gain in the input = 1
r	$V_{ref}$ input signal
y	Equivalent Speed deviation

The transfer function of G can be obtained by the *Model Linearizer* tool of MATLAB Simulink with help of model already been prepared. Transfer function H can be calculated as follows with the help of  $T_1, T_2, T_3, T_4$  time constant values estimated above.

$$H = \frac{1+T_1s}{1+T_2s} \times \frac{1+T_3s}{1+T_4s} = \frac{1+0.16s}{1+0.04s} \times \frac{1+0.24s}{1+0.04s} = \frac{0.0384s^2+0.4s+1}{0.0016s^2+0.08s+1} \quad (21)$$

The Root Locus study can be carried out after acquiring above required functions. The tool has given to the possibility to observe the behavior of poles while increasing the  $K_{s1}$  starting from zero. Figure 4-9 shows the Root Locus plot of the system at  $K_{s1} = 0$ .

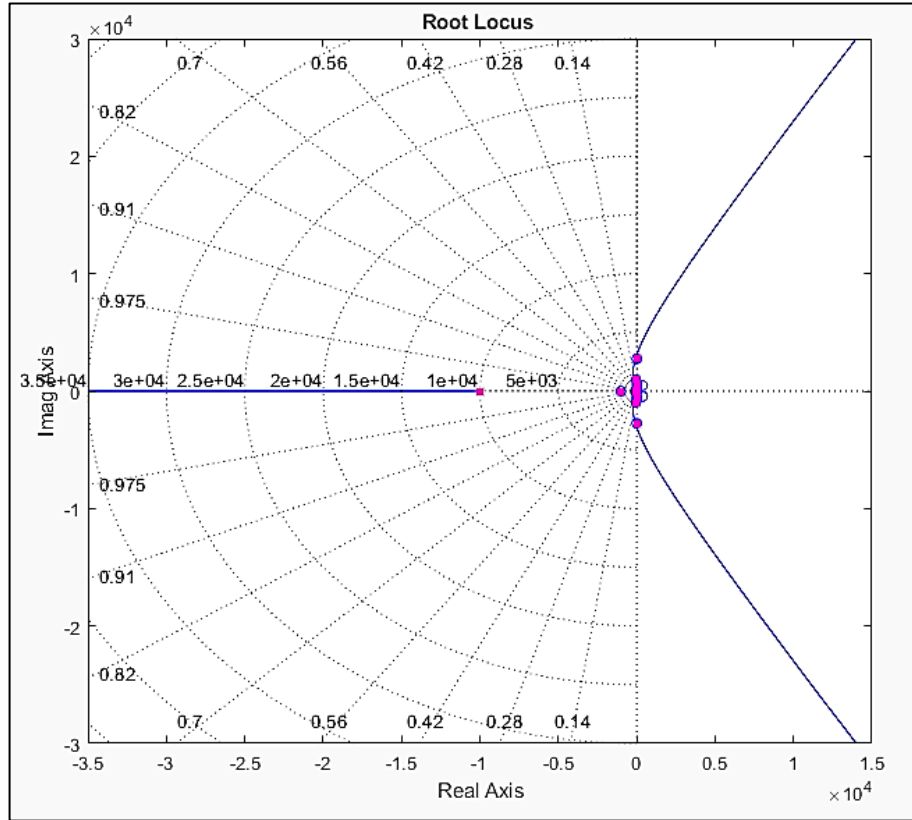


Figure 4-9 Root Locus Plot of the Closed Loop System at  $K_{s1} = 0$

Thereafter, parameter C ( $K_{s1}$ ) is increased and the gain value which causes any pole of the Root Locus plot to cross imaginary axis is obtained. That gain will be considered as the marginal gain ( $K_m$ ) of the system. Figure 4-10 shows the magnified view of a part of the Root Locus plot which represents the marginal stability of the system at  $C=10.864$ . Thereafter, the actual setting for stabilizer gain will be taken as  $K_{s1} = K_m/3$ , as specified by IEEE and WECC standards [7], [9], [10].

$$\text{Hence, } K_{s1} = \frac{K_m}{3} = \frac{10.864}{3} \approx 3.62$$

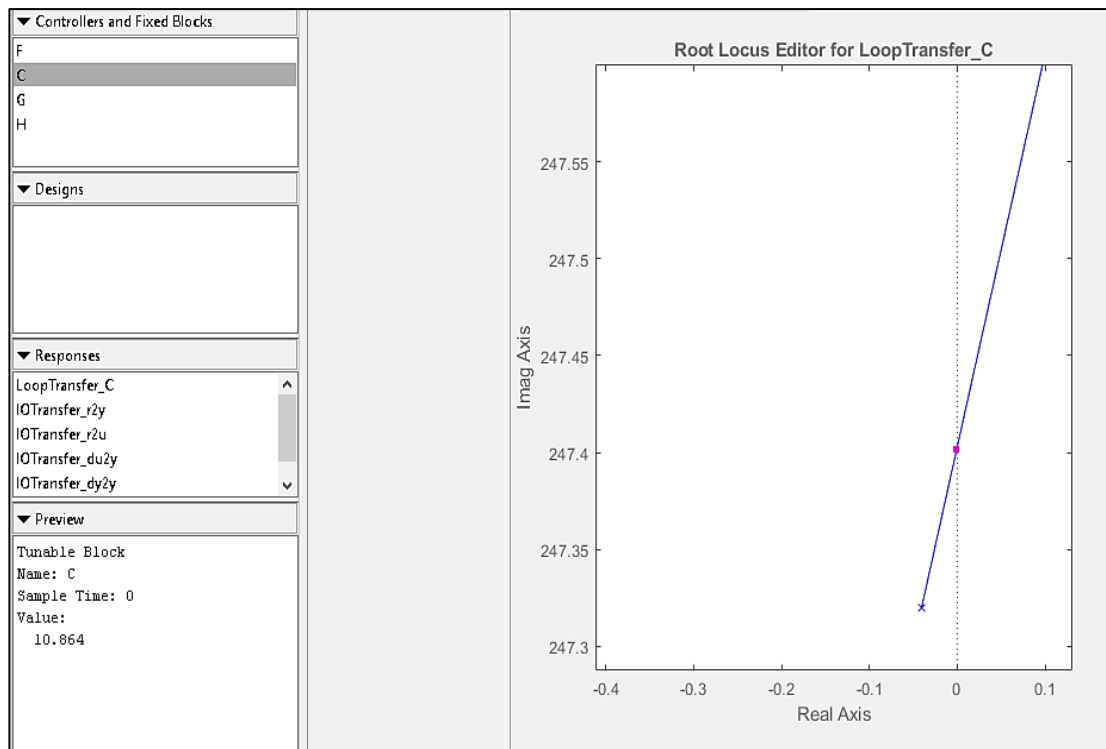


Figure 4-10 Root Locus Plot at the Marginal Gain

### 4.3 Estimating PSS Parameters Using an Optimization Technique – Simulated Annealing (SA)

The second phase of the tuning methodology uses an optimization technique to further enhance the performance of the PSS. Simulated annealing technique has been chosen for implementing the optimization, considering its suitability and convenience of implementation. Simulated Annealing has been proven to have a better convergence rate compared to other popular optimization algorithms such as Simple Hill Climbing and Genetic Algorithm. Additionally, compared to other optimization techniques such as Particle Swarm Optimization (PSO), SA is easy to implement in terms of computational burden, especially for single-objective function-related optimization problems.

#### 4.3.1 Introduction to Simulated Annealing

Annealing is a physical process used in metallurgical industries to improve material properties such as hardness by promoting the formation of more stable atomic structures. The process begins by heating a solid until it melts, followed by gradual cooling through stepwise temperature reduction. During each step, the temperature  $T$

remains constant for a sufficient duration to allow the solid to reach thermal equilibrium, maximizing stability in its atomic structure. At each temperature step  $T$ , the thermal equilibrium state of the system can be described by the Boltzmann distribution, which gives the probability of the solid being in a state  $i$  with energy  $E_i$  as,

$$P_i = ke^{\frac{-E_i}{T}}, \text{ Where } k \text{ is a constant} \quad (22)$$

Simulated Annealing algorithm is a proposed *Monte Carlo* method to simulate the process of reaching thermal equilibrium at a given value of the temperature  $T$ . Hence, at a given temperature step, several trial configurations are checked to select the most stable configuration, in other words, it's the equilibrium at that particular temperature step. The stability of each and every configuration will be evaluated by computing the energy ( $E$ ) of the configuration. As the solid becomes more stable, it releases energy to reach lower energy levels. Hence minimizing energy ( $E$ ) is the purpose of the annealing process. Therefore, when applying SA technique to an actual application, it is required to define an objective function to represent the energy ( $E$ ) at each trial configuration. Definition of objective function will be discussed later in upcoming sections.

In this research application, solutions are checked for  $Ks1, T1, T2, T3, T4$  parameters by creating trial solutions. A pre-defined objective function/cost function ( $J$ ) will be used to evaluate the energy (cost) of each and every trial solution. Ultimate goal is to find  $X$  ( $Ks1, T1, T2, T3, T4$ ) solution set which provides the best damping for the system.

#### **4.3.2 Parameter Analogy**

In the attempt of trying to form a correlation in between the actual annealing process and a practical application of SA technique, it is not an incomprehensible task to identify the analogy in between parameters. Following relationships can be presented with that purpose as shown in Table 4-3.

Table 4-3 Correlation in between the Parameters of Annealing Process and SA Method

<b>Parameter of the Actual Annealing Process</b>	<b>Defined Parameter in SA Application</b>
<b>T</b> (Temperature)	<b>C<sub>p</sub></b> ( Control Parameter)
<b>X<sub>current</sub></b> ( Atom structure of Current configuration)	<b>X<sub>current</sub></b> ( PSS parameters of Current configuration solution)
<b>X<sub>trial</sub></b> ( Atom structure of trial configuration)	<b>X<sub>trial</sub></b> ( PSS parameters of trial configuration solution)
<b>E<sub>current</sub></b> (Energy of current configuration)	<b>J<sub>current</sub></b> (Cost of current configuration)
<b>E<sub>trial</sub></b> (Energy of trial configuration)	<b>J<sub>trial</sub></b> (Cost of trial configuration)

It's required to define the control parameter ( $C_p$ ) in order to represent the behavior of temperature parameter ( $T$ ) of the actual process. As it is done in the actual annealing process,  $C_p$  should start with a very large value and should be decreased in steps. The importance of  $C_p$  and its behavior will be discussed later under *Acceptance criterion* of the objective function. However, a large number of different parameter sets (configurations) are randomly created in each and every cooling step and are defined as  $X_{trial}$ . For each and every  $X_{trial}$ , the value of cost function ( $J_{trial}$ ) can be evaluated. Thereafter, based on the acceptability of a trial solution,  $X_{trial}$  and  $J_{trial}$  will be accepted as a progressive step and will be assigned to  $X_{current}$  and  $J_{current}$ .

### 4.3.3 Defining Objective Function

Every optimization should have an objective function to be optimized. Commonly used technical term for the objective function in SA algorithm is 'Cost Function'. In this application, the cost function will be defined based on eigenvalues approach. Time characteristics of a mode can be explained as  $e^{\lambda_i t}$  where  $\lambda_i$  is the eigenvalue. Hence the stability of the system can be explained as follows based on the nature of eigenvalue. A real eigenvalue signifies a behavior without oscillations. When the real eigenvalue is negative, it indicates a mode that gradually decays over time. The greater its absolute value, the quicker the decrease. Conversely, a positive real eigenvalue signifies a state of gradually increasing instability without periodicity. Complex eigenvalues come in pairs that are conjugate to each other, signifying

oscillatory behavior. Each pair indicates a mode of oscillation. The negative real part of an eigenvalue dictates the damping, indicating how quickly the oscillations diminish. Meanwhile, the imaginary part specifies the frequency of the oscillations. If the real part is positive, it suggests that the oscillations amplify over time. As an example, if a complex pair of eigenvalues  $\sigma \pm j\omega$  then, the frequency of oscillation would be,

$$f = \frac{\omega}{2\pi} \quad (23)$$

The damping ration is given by,

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (24)$$

The damping ration explains the rate of decay of the oscillation. Simply the time constant of the decay can be expressed as  $\frac{1}{|\sigma|}$  which further explains that the oscillation decays to 1/e times of its initial amplitude in  $\frac{1}{|\sigma|}$  seconds. In other words  $\frac{1}{2\pi\zeta}$  cycles of oscillations. Figure 4-11 shows the representation of complex and purely real eigenvalues on the complex plane

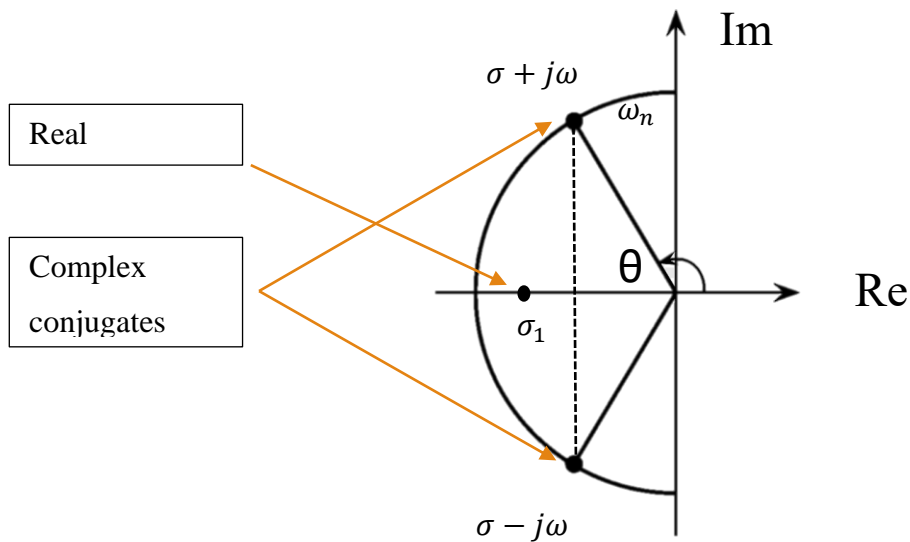


Figure 4-11: Representation of Eigenvalues on the Complex Plane

In Figure 4-11,  $\sigma_1$  represents a purely real eigenvalue while  $\sigma \pm j\omega$  represents complex conjugates, which represents oscillatory modes. In addition to that,

$$\cos \theta = \zeta, \text{ where } \omega_n \text{ is the natural angular velocity in rad/s}$$

$$\text{Therefore, } \sigma = -\zeta\omega_n = -\zeta \times 2\pi \times f_n \quad (25)$$

where  $f_n$  is the natural frequency in Hz

The purpose of defining the objective function is to find a function which can be minimized or maximized when the system damping is increased. Based on the above knowledge, it can be realized that, the real parts of eigenvalues of the system become more negative when the system damping is increased. The objective function for our PSS application could be defined considering that fact as below.

$$J = \sum_{\sigma_i \geq \sigma_0}^{ne} (\sigma_i - \sigma_0)^2$$

$\sigma_i = \text{Real part of the } i^{\text{th}} \text{ eigenvalue}$

$\sigma_0 = \text{Real part threshold}$

$ne = \text{Number of eigenvalues}$

The constant  $\sigma_0$  negative real value that should be calculated to define the real part threshold. It can be observed that as the values of  $\sigma_i$  approach  $\sigma_0$ , the value of the cost function (J) becomes minimum. At the same time, system damping properties will be improved as  $\sigma_i$  values become more negative. In the attempt of calculating  $\sigma_0$ , it should be noted that, a damping ratio of about 0.3 -0.5 is generally recommended for low frequency oscillations for power systems. Hence, the value for  $\sigma_0$  can be calculated considering any value of damping ratio, considering the frequency range of oscillation in interest (0.1 -2 Hz). Following is an example.

Let's consider  $\zeta = 0.5$ . Here, the aim is to calculate the minimum possible value for  $\sigma_0$  so that it reflects above damping ration for frequencies in the considered frequency range. By the relationship in equation (25), it is obvious that for a given damping ratio, the minimum of  $\sigma_0$  occurs in the highest frequency of the considered range (2Hz). Hence, the minimum value for  $\sigma_0$  can be calculated as,

$$\sigma_0 = -0.5 \times 2 \times \pi \times 2 = -6.28$$

Therefore, by setting  $\sigma_0 = -6.28$ , it is expected by the optimization algorithm to minimize the cost function (J) by pushing higher  $\sigma_i$  values towards  $\sigma_0$  which will further enhance the damping capabilities of the power system. Further, it can be shown by a reverse calculation that, frequencies those are less than 2Hz in the range will obtain better damping than 0.5 in this selection. As an example for an oscillation frequency of 0.1Hz,

$$\zeta = \frac{\sigma_0}{-2 \times \pi \times f_n} = \frac{-6.28}{-2 \times \pi \times 0.1} = 9.99$$

Achieving this level of damping in a practical system may not be possible. In other words, there's a higher probability of real parts of oscillations at 0.1Hz not being able to reach -6.28 after the optimization process. However, setting up that threshold would not violate our final expectations.

#### 4.3.4 Elements of Simulated Annealing

Simulated Annealing technique has its own elements which defines the concepts and the process of it. Main elements are explained as follows.

##### 4.3.4.1 Acceptance Criterion

Acceptance criterion defines the conditions to accept or reject trial solution over the current solution. Mainly there are two conditions. The algorithm accepts the trial solution over the current solution if any of the following statements are satisfied.

$$\text{a) } J_{\text{trial}} < J_{\text{current}}$$

$$\text{b) } J_{\text{trial}} > J_{\text{current}}, \text{ only if } e^{\frac{-J_{\text{trial}} - J_{\text{current}}}{c_p}} \geq \text{rand}(0, 1)$$

The algorithm is intended to find the combination for PSS parameters that minimizes the cost function as per the expectation. The condition (a) is obviously suitable for that purpose as  $X_{\text{trial}}$  should be accepted over  $X_{\text{current}}$  if the cost of trial solution ( $J_{\text{trial}}$ ) is less than the cost of current solution ( $J_{\text{current}}$ ), given that this is a minimization problem. Condition (b) above is the exception of SA algorithm compared to other traditional

optimization algorithms such as Simple Hill Climbing. The SA algorithm accepts trial solution over the current solution even if  $J_{\text{trial}} > J_{\text{current}}$ , given that it satisfies following inequality, which may seem counterintuitive. However, there's a special purpose in it.

$$e^{\frac{-J_{\text{trial}}-J_{\text{current}}}{C_p}} \geq \mathit{rand}(0, 1)$$

The left hand side function of the above inequality is called the Sigmoid function which varies in between 0 and 1 for any real value of its parameters given that  $J_{\text{trial}} > J_{\text{current}}$ . The  $\mathit{rand}(0, 1)$  is a random number generator in between 0 and 1. The control parameter will be represented by  $C_p$ .

The algorithm considers this inequality only if the trial and current solutions satisfy  $J_{\text{trial}} > J_{\text{current}}$ . Therefore, the numerator of the power of the Sigmoid function is always negative. Further, total power of the exponential function is negative as  $C_p$  is also positive, which results in decimal values of the function in between 0 and 1. The physical meaning behind this function can be understood with help of equation (22) which describes the Boltzmann behavior of this process. According to equation (22) we may write probability for both trial and current configurations as follows in a particular cooling step.

$$P_{\text{trial}} = k e^{\frac{-J_{\text{trial}}}{C_p}} \quad (26)$$

$$P_{\text{current}} = k e^{\frac{-J_{\text{current}}}{C_p}} \quad (27)$$

By dividing equation (26) by equation (27),

$$\frac{P_{\text{trial}}}{P_{\text{current}}} = e^{\frac{-J_{\text{trial}}+J_{\text{current}}}{C_p}} = e^{\frac{-J_{\text{trial}}-J_{\text{current}}}{C_p}} \quad (28)$$

It is clear that Sigmoid function gives the relative probability of system being in trial and current states at a particular  $C_p$  value. Hence, even if the probability of existence is lower compared to the current solution, if the trial solutions have a significantly higher probability of existence, then the algorithm has a higher chance of accepting that bad move after comparing the value of Sigmoid function with a random number.

There's a special expectation regarding this feature. It can be explained with the help of Figure 4-12.

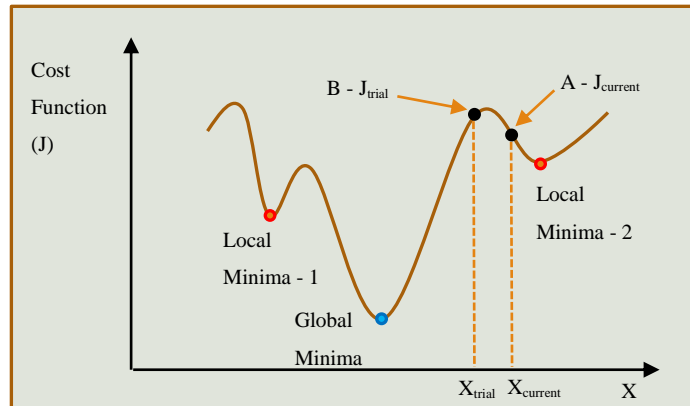


Figure 4-12: Hypothetical Representation of Cost Function

Assume that the curve of Figure 4-12 shows the variation of the cost function  $J$  for different  $X(K_{s1}, T_1, T_2, T_3, T_4)$  values. The local minima of the curve are shown in red while the global minimum is shown in blue, representing the final objective of the optimization process. Assume that,  $X$  is at  $X_{current}$  (Point A) according to the current solution set. If the acceptance criterion accepted good moves only, then the optimization would go towards the Local Minima -2 and become stuck in it. However, accepting the trial solution at point A is a bad move compared to  $X_{current}$  at point B. If this were allowed, then there would be a higher probability of optimization being able to reach to the global minimum by overcoming the energy barrier in between point A and B. Hence, it can be emphasized as a special feature of SA technique, which allows acceptance of even bad moves according to a random probability based manner in the first few phases of the algorithm. Only the good moves are accepted when the algorithm reaches its last few phases. Therefore, if the solution is able to jump from point A to B within first few phases, then reaching the global minima from point B is straightforward in final few phases. However, a parameter will be needed to control this action. This is where the purpose of control parameter ( $C_p$ ) comes into play.

As the  $X_{trial}$  is always generated adjacent to  $X_{current}$ , most probably the value of  $-(J_{trial} - J_{current})$  is trivial. Hence, the sigmoid function will generate values closer to one when

$C_p$  is very large. In other words, there's a higher probability of satisfying the inequality in acceptance criteria (b) above, which results in accepting bad moves. Likewise, the sigmoid function will result in smaller values when  $C_p$  is small, which results a lower probability of accepting bad moves. Therefore, the algorithm will start with a large  $C_p$  value and goes down in cooling steps, forming the required behavior of the sigmoid function. The predefined method of changing  $C_p$  is called 'Cooling schedule' and will be discussed in the next section.

#### 4.3.4.2 Cooling Schedule

As explained by the previous section, a proper schedule is required to define the cooling steps of the control parameter. Cooling schedule can be separated into two phases. The algorithm is supposed to find a suitable value as the starting value of  $C_p$  as the first phase of the cooling schedule. This starting value of  $C_p$  is called  $C_{p0}$ . Then, starting from  $C_{p0}$ ,  $C_p$  will be decreased in steps during the main SA algorithm, which is the second phase of the Cooling schedule.

Cooling schedule specifies a set of parameters that governs the convergence rate of the SA algorithm. In the phase of finding  $C_{p0}$ ,  $\alpha$  is the increment coefficient which governs the equation  $C_{p0} = \alpha C_p$ . Typically,  $\alpha > 1$ . The decrement coefficient of  $C_p$  in the second phase is  $\mu$ , which governs the equation  $C_p = \mu C_p$ . Typically,  $0.8 < \mu < 0.99$ .

#### 4.3.4.3 Acceptance Ratio

Acceptance ratio is the ratio in between the accepted solution count and the total created solution count. This element is used in the determining process of the initial value of the control parameter ( $C_{p0}$ ). Mathematically it can be expressed as follows.

$$\text{Acceptance ratio} = \frac{n_2}{n_1} \quad \text{where,} \quad (29)$$

$n_1$  = Number of trial solutions created at a given  $C_p$  value

$n_2$  = Number of trial solutions accepted at a given  $C_p$  value

#### **4.3.4.4 Equilibrium Condition**

Equilibrium condition occurs when the current solution does not change for a certain number of iterations at a given value of  $C_p$ . In other words, the optimization has found the lowest possible cost and its solution in that particular  $C_p$  value. However, a large number of trial solutions (iterations) should be checked prior to confirming the equilibrium.

#### **4.3.4.5 Stopping Criteria**

Search process will terminate under any of following conditions

- The number of Markov chains (cooling steps) since the last change of the best solution is greater than a specified number. This parameter is defined as ‘Kch\_last\_change’ and it should be manually defined in the algorithm.
- The number of Markov chains reaches the maximum allowable number. This will be monitored by maintain a chain counter parameter ( $K_{ch}$ ). This parameter is defined as ‘Kch\_limit’ and it should be manually defined in the algorithm.

#### **4.3.5 Selecting Initial Conditions - $X_{initial}$**

It is compulsory to define initial conditions for any optimization technique. These conditions determine the effectiveness and efficiency of any algorithm. There is a higher probability for the algorithm to become diverging if the selected initial conditions are out of range or inappropriate. If the initial conditions are far away from the optimum solution, then it takes a large number of iterations to finish up the optimization process increasing the computational burden and the processing time. Hence, the efficiency of the algorithm will be degraded.

For most of the applications, initial conditions are randomly selected and that may cause aforementioned issues. Therefore, the results obtained in the previous phase of frequency response based method will be used as the initial conditions of the optimization phase. It will definitely place the initial conditions of the optimization on a position somewhat closer to the optimum solution rather than going for some randomly generated initial condition. Further, it will cause further improvements and enhancements in the results obtained in the previous phase by cascading the traditional

frequency response based technique with the optimization technique. Therefore, following  $X_{initial}$  parameter values are used in determining phase of  $C_{p0}$  as well as in the main SA algorithm phase.

$$X_{initial} = X(K_{s1}, T_1, T_2, T_3, T_4)_{initial} = X(3.62, 0.16, 0.04, 0.24, 0.04)$$

#### 4.3.6 Determining the Initial Value of Control Parameter $C_{p0}$

Estimating a sufficiently large  $C_p$  value ( $C_{p0}$ ) is the first phase of the algorithm as explained above. A separate algorithm will be executed on this purpose. The steps of the proposed algorithm is shown in ANNEX C as a flow chart.

First  $C_{p0}$  will be set to a small value. After setting  $X_{initial}$ ,  $n_1$  number of trial solutions are created in the neighborhood of  $X_{initial}$ . Then the cost function ( $J$ ) is evaluated for all the trial solutions and the acceptance criteria is checked. If  $n_2$  number of solutions were accepted then,  $n_2/n_1$  can be evaluated as the acceptance ratio. Then a condition will be checked to confirm if the acceptance ratio exceeds a pre-defined limit. Generally, it is recommended to have a value greater than or equal to 0.95. Hence, in this research, the pre-defined limit has been taken as 0.975. However, if the acceptance ratio requirement is satisfied then, that  $C_{p0}$  will be passed to the main SA algorithm. Otherwise, the current  $C_{p0}$  will be multiplied by  $\alpha$  to obtain the next  $C_{p0}$ . This algorithm should be continued until a satisfactory  $C_{p0}$  is found.

#### 4.3.7 Main SA Algorithm

The algorithm is allowed to proceed to the next phase (Main SA algorithm) of the optimization after  $C_{p0}$  is estimated. The block diagram representation of the main algorithm is shown in ANNEX D. After assigning the estimated  $C_{p0}$  value, the chain counter parameter  $K_{ch}$  will be set to 0. This parameter is there to indicate the cooling steps and it should be increased after completing the each and every cooling step. As mentioned above, the  $X_{initial}$  is assigned with the results obtained by the frequency response based method and  $X_{current}$  and  $X_{best}$  parameters will be equalized to  $X_{initial}$ . Then the  $J_{current}$  and  $J_{best}$  can be calculated as the same value. However, evaluating the cost function ( $J$ ) for a given solution of ( $X$ ) is a complex process and that will be discussed in the next section.

Then a trial solution will be created in the neighborhood of  $X_{\text{trial}}$  corresponding  $J_{\text{trial}}$  will be evaluated. However, if  $J_{\text{trial}}$  is less than  $J_{\text{best}}$  in any iteration then, the  $X_{\text{best}}$  and  $J_{\text{best}}$  will be replaced by  $X_{\text{trial}}$  and  $J_{\text{trial}}$  respectively, as it is always required to record the trial solutions which provide the minimum of the objective function. Then acceptance criteria could be checked for each trial solution as  $J_{\text{current}}$  has been already evaluated in the previous step. If the criteria was satisfied then  $X_{\text{current}}$  and  $J_{\text{current}}$  should be set equal to  $X_{\text{trial}}$  and  $J_{\text{trial}}$  respectively. Above step should be bypassed if the acceptance criteria was not satisfied.

The equilibrium conditions are checked as the next step. The algorithm will move back to the step of creating trial solutions if the equilibrium conditions are not satisfied. If the equilibrium conditions are met, then it'd check for the stopping criteria. If the stopping criteria were not satisfied then, the chain counter parameter  $K_{\text{ch}}$  would be increased and the algorithm would go for the next cooling step. If the stopping criteria was satisfied then, optimization will be completed and  $X_{\text{best}}$  will be given as the optimized parameter list.

#### **4.3.8 Actual Implementation**

The implementation of the algorithm is a collaboration in between PSS/E software and the supplementary software package called LSYSON 33. The entire process, starting from loading of relevant system modeling files to obtaining optimized parameter list, has been automated with the help of Python platform version 2.7.18. Python is a popular programming language platform among the computer science communities all over the world and is well known for the compatibility among other software packages and related applications. Python uses various libraries to achieve this task. It includes some common libraries for mathematics and related calculations, as well as some other special purpose libraries for applications handling, file handling and automation. Handling of PSS/E and LSYSON33 software will be discussed in upcoming sections. Following is a list of different library packages used in this automation process.

- numpy as n
- numpy
- subprocess

- time
- Pyautogui
- pygetwindow as gw
- time
- math
- datetime
- psspy

#### **4.3.8.1 Handling PSS/E Software in the Automation Process**

PSS/E is a highly compatible software with the Python platform as there have been provided an impressive accessibility to its features via Python Application Programming Interface (API) [22]. Hence, it has provided the capability to perform some complex analytical operations, simulations and data extractions of PSS/E, even without opening the Graphical User Interface (GUI) of the software. The previously validated PSSE model with dynamic data will be used in the cost function estimation process. The PSS function of the model should be enabled prior to run the algorithm as eigenvalues are calculated with the presence of PSS function while changing the parameters of it.

#### **4.3.8.2 Handling LSYSON 33 Software in the Automation Process**

The LSYSON 33 software comes as an auxiliary software package for PSS/E, which can be used to manipulate linear analysis data. The '.lsa' formatted file can be read by means of the LSYSON 33 and relevant calculations are done to obtain other results, as per the requirement of the user. Some information such as eigenvalues, eigenvectors, time constants of damping oscillations and etc. can be easily derived with the help of this software package. Results of the software can be either displayed in the command window or can be written in a separate text formatted file. More details about this software package can be found in reference [23] of this research.

Generally, the LSYSON33 software is run in a command window itself. Hence, it is necessary to type the required commands, as specified by reference [22], [23] for any task related to linear analysis data to be done. However, this process needs to be

automated in this application, as the cost function should be evaluated every time the PSS parameters are changed by creating trial solutions. Therefore, the 'subprocess' library of Python was used in the automation process to completely automate the operation and commanding of the LSYSON33 software. The final result of the software will be written to a text file so that Python can directly extract it for further calculations of the algorithm.

#### **4.3.8.3 Evaluation of the Cost Function**

Automation process starts by initializing the PSS/E within the Python, it commands PSSE to load relevant files (".sav" file of the system model, ".dyr" of dynamic data) to PSSE. Then the load flow steps followed by model conversion steps are carried out as a preparation for linear analysis. Thereafter, algorithm processes the first phase (determining  $C_{p0}$ ) and the second phase (Main SA algorithm).

Evaluation of the cost function is a critical task of this algorithm as it has to be performed in each iteration step. In the estimation process of the objective function, it's required to estimate all the eigenvalues of the system. As the first step, The PSS/E model will be converted to a linear system with the view to obtain the system matrix. This task is achieved by means of ASTR function of PSS/E software [22], [23]. Python commands to run the ASTR function in the automated process. There are few settings to be made before running the ASTR function. They are,

- Number of state variables – This is important only when some selected states are needed. However, all the available states are requested in this application.
- Input quantity for apply perturbation –  $V_{ref}$  of the machine
- Magnitude of the perturbation in p.u – Default value is used as 0.01

In the automation process, the above settings were used for all the iterations. After executing the ASTR function, PSS/E will convert the system to a linear system, and relevant matrix data will be written to a '.lsa' formatted file in a pre-specified location. Then, Python commands the LSYSON 33 software to access the '.lsa' file and write the calculated eigenvalues to a separate text file in a pre-specified location. Subsequently, the file handling section of Python is executed to extract all the

calculated eigenvalues from the text file and assign the separated real parts to an array variable in the algorithm. Thereafter, the cost function (J) will be calculated according to the definition. The complete flow of calculation of the cost function is shown in ANNEX E for ease of understanding.

The complete code of the above implementations has been attached in ANNEX F. Optimization has been performed as a sensitivity analysis by changing the damping ration. In each and every step the estimated  $C_{p0}$  is inherent to the particular sensitivity step and was calculated by the software itself. Results of these analysis and related discussions are presented in the next chapter.

#### 4.4 Chapter Summary

Chapter 4 presents a comprehensive methodology for tuning Power System Stabilizers (PSS), comprising two phases aimed at optimizing system stability and performance.

The first phase, the Frequency Response based Method employs a MATLAB Simulink model established in Chapter 3 to conduct an in-depth analysis of the frequency response of AVR and generator system. Summary of above steps in estimating PSS parameters with the frequency response based method can be presented as shown in Figure 4-13.

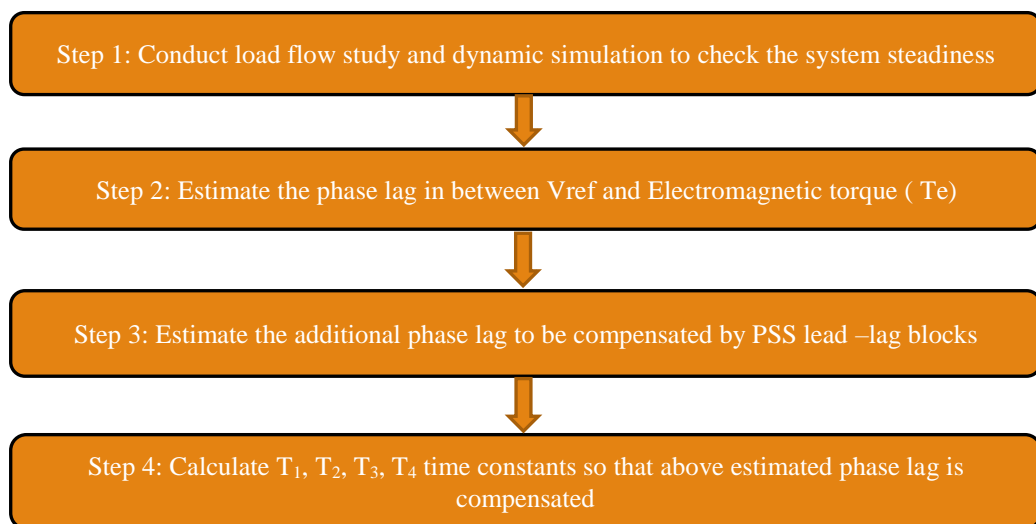


Figure 4-13 Simplified Steps of Estimating Lead - Lag Block Time Constants

Time constants of the lead-lag blocks are calculated utilizing phase characteristics through a heuristic method so that the identified phase lag is compensated, ensuring robustness and accuracy in parameter estimation.

Furthermore, the root locus method is employed to estimate the stabilizer gain, leveraging insights from system dynamics to refine stabilization parameters. Summary of the steps used in estimating  $K_{s1}$  is shown below in Figure 4-14.

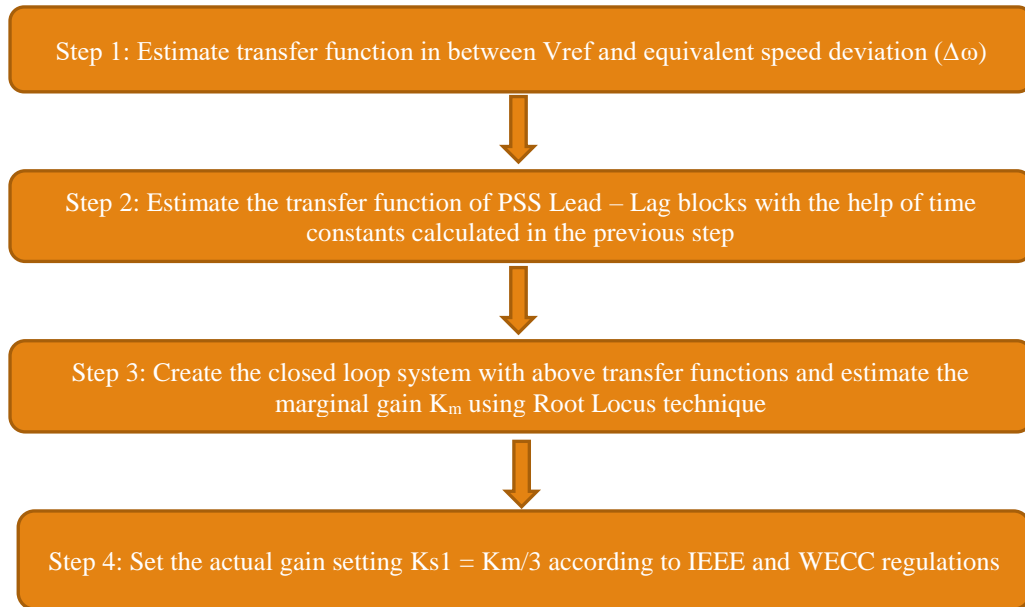


Figure 4-14 Steps of Estimating Stabilizer Gain  $K_{s1}$

The tuned parameter set after the first phase of the tuning procedure is shown in Table 4-4.

Table 4-4 Results of Frequency Response Based Method

<b>Tuned Parameter Set After the First Phase of Tuning</b>	
$K_{s1}$	3.62
$T_1$	0.16s
$T_2$	0.04s
$T_3$	0.24s
$T_4$	0.04s

In the optimization phase, initial conditions were taken as the results of the Frequency Response Based Method. The Simulated Annealing (SA) algorithm is employed as the optimization technique, facilitated through a fully automated program developed using the Python platform. Python interfaces with various tools and software, including

PSS/E models for linear analysis, LSYSON33 software for eigenvalue calculations, and file handling tasks. Through iterative refinement guided by the SA algorithm, the tuning process seeks to optimize PSS parameters for enhanced system damping and stability. Optimization process was repeated for several damping ratio values and the results are shown in Table 4-5.

*Table 4-5 Results of Optimization Based Tuning*

Damping Ratio $\zeta$	Parameters				
	$K_{s1}$	$T_1$	$T_2$	$T_3$	$T_4$
0.3	3.07	1.2	0.04	0.15	0.06
0.4	7.47	0.36	0.06	0.23	0.06
0.5	6.96	0.09	0.01	0.22	0.11
0.6	10.82	0.32	0.03	0.27	0.06
0.7	22.56	0.05	0.04	0.07	0.02
0.8	12.7	0.06	0.05	0.06	0.01

The culmination of both phases yields significant improvements in system damping, establishing the stability and reliability of the power system. By integrating advanced modeling techniques, heuristic methods, and optimization algorithms, Chapter 4 establishes a robust framework for PSS tuning, paving the way for enhanced performance and resilience in electrical grid infrastructure.

## 5 RESULTS AND DISCUSSIONS

Results of the overall research work will be discussed in this section under following sub topics.

### 5.1 Simulation Results – Frequency Response Based Technique

Following results were obtained in the frequency response based method.

$$K_{s1} = 3.62, T_1 = 0.16s, T_2 = 0.04s, T_3 = 0.24s, T_4 = 0.04s$$

The Figure 5-1 shows with PSS and without PSS simulation for the event of tripping U3 of LVPS. Simulation has been performed for 40 seconds.

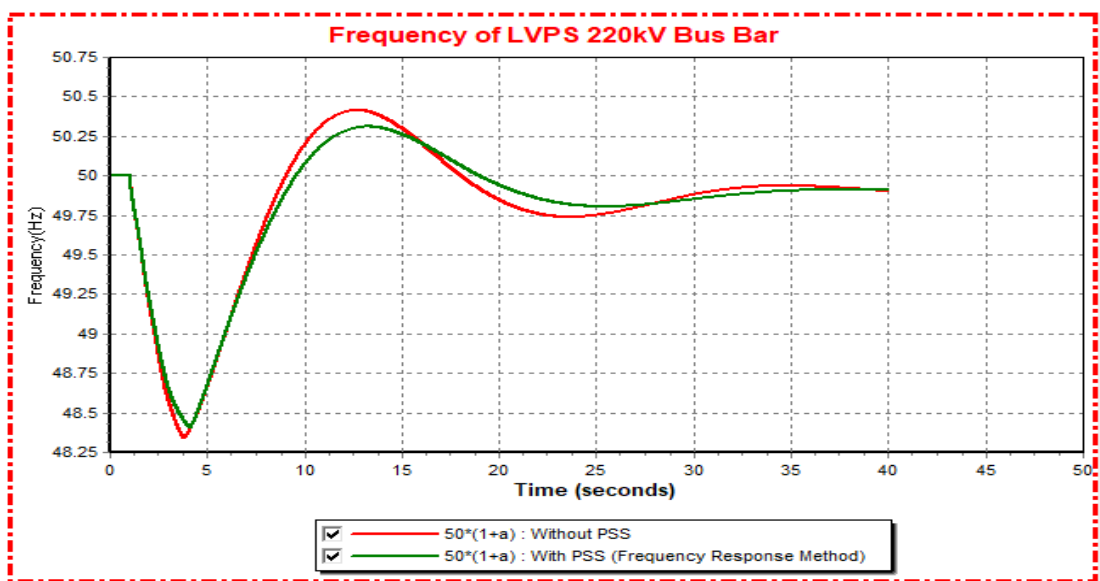


Figure 5-1 With and Without PSS Comparison for Tripping One Unit of LVPS

The figure shows the frequency variation of 220kV bus bar of LVPS switchgear. The red colored curve shows the ‘without PSS’ scenario while the green colored one shows the ‘with PSS’ scenario. It is obvious that the PSS has introduced a significant damping to the system compared to the without PSS case.

### 5.2 Simulation Results – Optimization Based Technique

The results of the optimization based method is presented in Figure 5-2 for tripping of U3 of LVPS. For a better comparison with the frequency response based method, the results of the optimization technique is plotted on the same graph. Following are the special parameter settings used in the optimization algorithm.

$$\zeta = 0.5, \alpha = 1.5, \mu = 0.9, n_1 = 2500, Kch_{limit} = 35, Kch_{last\_change} = 2$$

After the optimization, following results were obtained as the optimized parameter list.

$$K_{s1} = 6.96, T_1 = 0.09s, T_2 = 0.01s, T_3 = 0.22s, T_4 = 0.11s$$

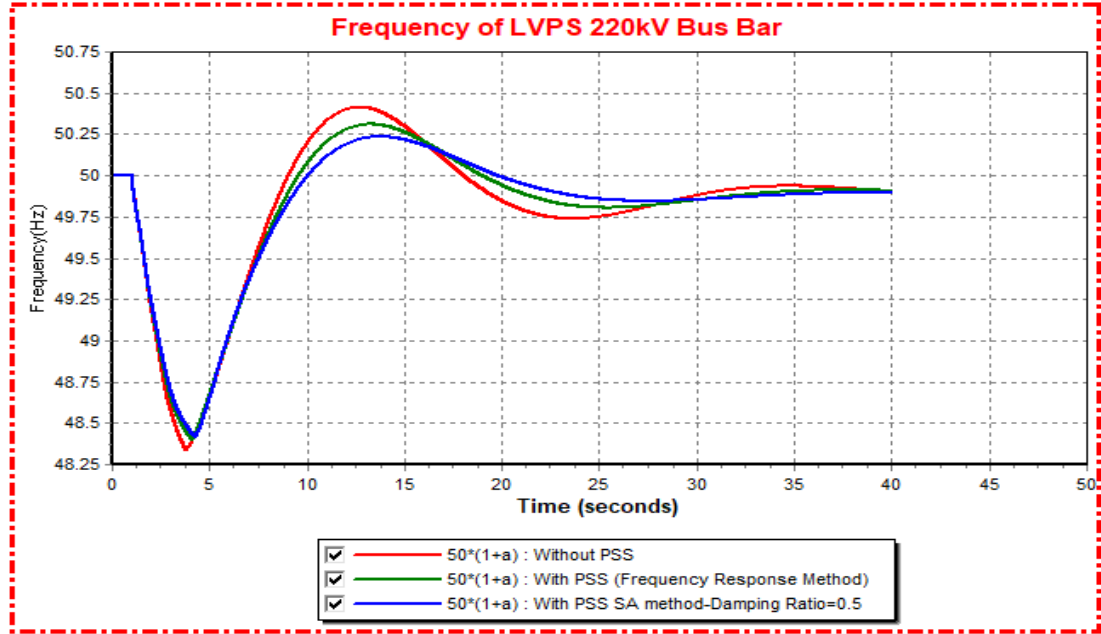


Figure 5-2 Comparison in between Results of Two Tuning Methods

The Figure 5-2 illustrates the frequency variation of the 220kV bus bar of LVPS switchgear under three different cases. The blue curve demonstrates the enhancement achieved by implementing the Power System Stabilizer (PSS) coupled with the Simulated Annealing (SA) optimization technique. It's evident that the damping has significantly improved compared to the frequency response based approach. Additionally, the overshoot of the system has also been reduced up to a considerable level, which can be considered as a side advantage of having the PSS. Therefore, it can be inferred that the combined application of these two methods can notably enhance the power system's damping capability.

### 5.3 Sensitivity Analysis for Different Damping Ratios

The sensitivity analysis for different damping ratios were carried out and the results are presented in this section. In this analysis, the damping ratio ( $\zeta$ ) was changed to 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 in separate cases and final outcomes were compared with separate simulations. Even though the specified damping ratio range for low frequency

oscillation is 0.3 -0.5, above range of the damping ratio was considered just to observe the behavior of the tuning and there's no any strict rule to select the range. The results of above analysis were simulated for a tripping incident of U3 of LVPS and the comparisons are presented in Figure 5-3. Following settings were used in the simulation.

$$\zeta = 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, \alpha = 1.5, \mu = 0.9, n_1 = 2500, Kch_{limit} = 35, Kch_{last\_change} = 2$$

Following results were obtained as optimized parameter lists for different damping ratios.

- For  $\zeta = 0.3$ ;  $K_{s1} = 3.07, T_1 = 1.2, T_2 = 0.04, T_3 = 0.15, T_4 = 0.06$
- For  $\zeta = 0.4$ ;  $K_{s1} = 7.47, T_1 = 0.36, T_2 = 0.06, T_3 = 0.23, T_4 = 0.06$
- For  $\zeta = 0.5$ ;  $K_{s1} = 6.96, T_1 = 0.09, T_2 = 0.01, T_3 = 0.22, T_4 = 0.11$
- For  $\zeta = 0.6$ ;  $K_{s1} = 10.82, T_1 = 0.32, T_2 = 0.03, T_3 = 0.27, T_4 = 0.06$
- For  $\zeta = 0.7$ ;  $K_{s1} = 22.56, T_1 = 0.05, T_2 = 0.04, T_3 = 0.07, T_4 = 0.02$
- For  $\zeta = 0.8$ ;  $K_{s1} = 12.7, T_1 = 0.06, T_2 = 0.05, T_3 = 0.06, T_4 = 0.01$

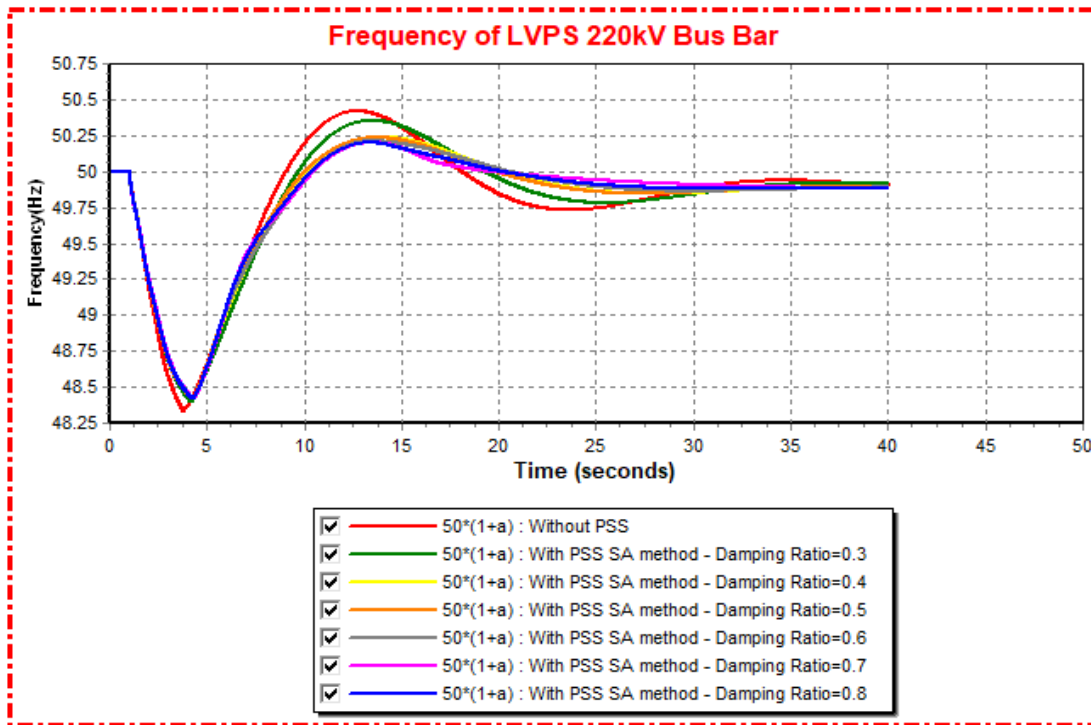


Figure 5-3: Sensitivity Analysis for Different Damping Ratios

The Figure 5-3 shows the frequency variation of the 220kV bus bar of LVPS switchgear for varying damping ratios. It is obvious that the overall damping of the system has been increased when the damping ratio setting of the optimization is increased. The blue curve shows the highest damping relevant to Damping Ratio = 0.7. Additionally, with better dynamic characteristics, the overshoot of the system has also been reduced up to a considerable level, which can be considered as a side advantage of having the PSS.

#### 5.4 Simulations of Possible Contingencies in the Power System

In this section, selected three possible contingencies are simulated to observe the behavior of the power system for with and without PSS cases. For first and second cases, the results obtained with both tuning methods are compared in separate simulation curves. It should be noted that both PSSs use same settings when they are employed together. Following settings were used in the optimization with different damping ratio settings.

$$\zeta = 0.5, 0.7, \alpha = 1.5, \mu = 0.9, n_1 = 2500, Kch_{limit} = 35, Kch_{last\_change} = 2$$

##### 5.4.1 Tripping of Biyagama – Kotmale Transmission Circuit 1

The Biyagama – Kotmale transmission line is considered as a backbone Transmission Line in the Sri Lankan power system 220kV network, as it contributes to transmit a major share of power generated in the Mahaweli complex to Colombo area.

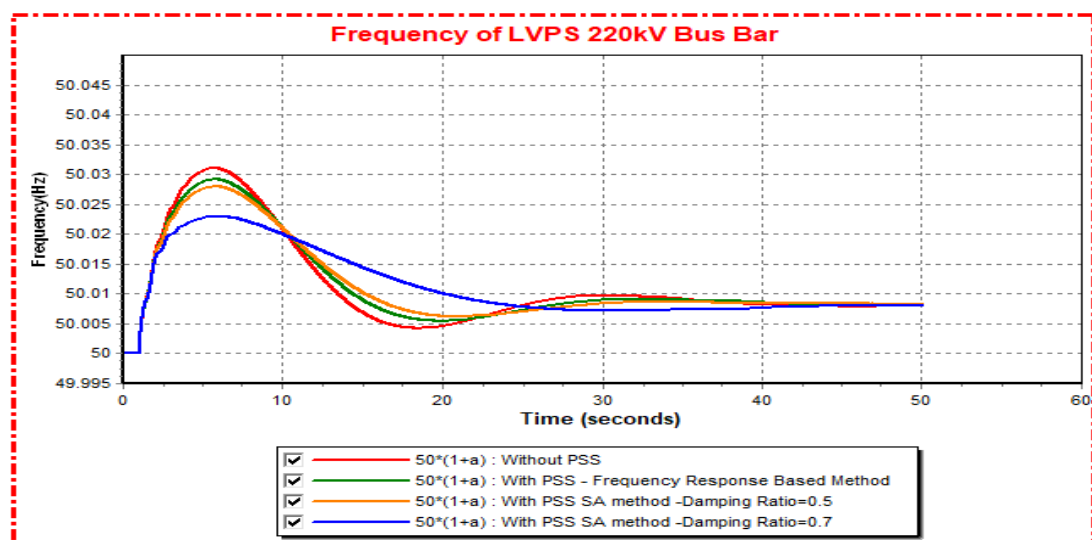


Figure 5-4 Tripping of Biyagam - Kotamale Transmission Line - Circuit 1

This Figure 5-4 of this study emulates the tripping of Biyagama – Kotmale transmission line circuit one. The results illustrates that, adding the PSS function has improved the dynamic characteristics of the system. The PSS tuned with the optimization technique shows the best performance having the damping ratio setting of 0.7.

#### 5.4.2 Tripping of Biyagama – Kotmale transmission circuit 1 & 2

In this simulation, Biyagama – Kotmale circuit 1 trips at  $t = 1s$  and the second circuit goes off after 160ms. The results are shown in Figure 5-5.

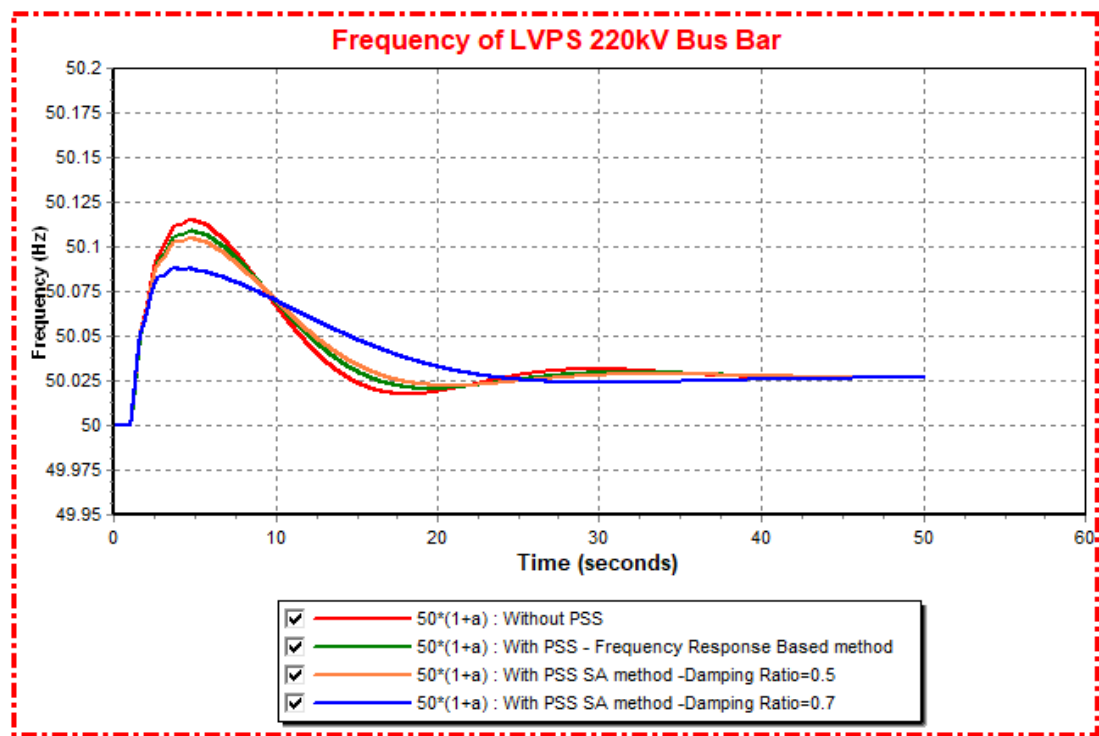


Figure 5-5 Tripping of Biyagama - Kotmale 220kV Transmission Line - Circuit 1&2

A similar variation in results can be observed in this case compared to the previous one. However, the system frequency reaches a higher level due to the significant load rejection resulting from the tripping of both transmission lines. Like in the previous case, the PSS tuned with the SA method, with a damping ratio of 0.7, achieves the best overall performance. Additionally, the overshoot of the system is significantly reduced in both of the aforementioned cases, which can be considered as an additional advantage of having the PSS.

### 5.4.3 Partial Blackout in Colombo Area

This simulation case examines the potential for a partial blackout in the Colombo district, focusing on the Kolonnawa and Kelanithissa 132kV transmission networks. These two primary grid substations were chosen for the study due to their substantial contribution to meeting the demand in the Colombo district area. The total system generation prior to the incident is 914.9MW, while the total demand is 901.6MW. The following loads were disconnected from the system during the partial blackout incident as shown in Table 5-1.

Table 5-1 Loads Rejected During the Partial Blackout Incident

<b>Disconnected Feeder/ Tx Line Name</b>	<b>Load Rejected in MW</b>
COL_I_1 132kV Circuit 1	30.4
KOSGAMA 132kV Circuit 1	0 ( Fed by other direction)
SITHAWAKA-1 132kV Circuit 1	0 ( Fed by other direction)
COL_E-1 132kV Circuit 1	18.1
SUB-C 132kV Circuit1	11.1
KOLONNAWA – 3A 33kV Circuit1	22.1
KOLONNAWA – 3B 33kV Circuit 1	15.4
JAPURA_T1 132kV Circuit 1	12.25
JAPURA_T1 132kV Circuit 2	12.25
COLOMBO_F – 1 132kV Circuit 1	15.94
KELANI – 3A 33kV Circuit 1	13.45
SAPUGASKANDA – 3A 33kV circuit	31
<b>Total Load Rejected</b>	<b>181.99</b>

In the LVPS, there exists a scheme known as Over-Speed Protection Control (OPC), which is activated at certain speed thresholds to swiftly reduce generation when the system frequency is experiencing rapid increment. Upon activation of the OPC scheme in any system, the steam input to both the Intermediate Pressure (IP) and Low Pressure (LP) turbines is promptly cut off. The OPC condition resets once the speed returns to normal.

The second protection scheme is termed Fast Cut Back (FCB), which entirely removes the generator from the system during severe instability in the external power system. However, if the FCB condition is triggered for any machine, neither the boiler nor the turbine is tripped. Consequently, the generator can continue supplying the house load until it is resynchronized with the power system.

According to the current settings, if the system frequency continues to increase, the FCB is activated for unit 2 of LVPS at 3078rpm and OPC is activated for unit 1 and 3 in 3100rpm and 3110rpm respectively. In this case study, we observe that the Fast Cut Back (FCB) is triggered for unit 2 of the LVPS at 3078rpm (51.3Hz), as per the aforementioned protection scheme. Figure 5-6 displays the simulation results for both the 'Without PSS' and 'With PSS' scenarios. In this context, the Power System Stabilizer (PSS), tuned using the SA method with a damping ratio setting of 0.7, has been activated for unit 1 of the LVPS.

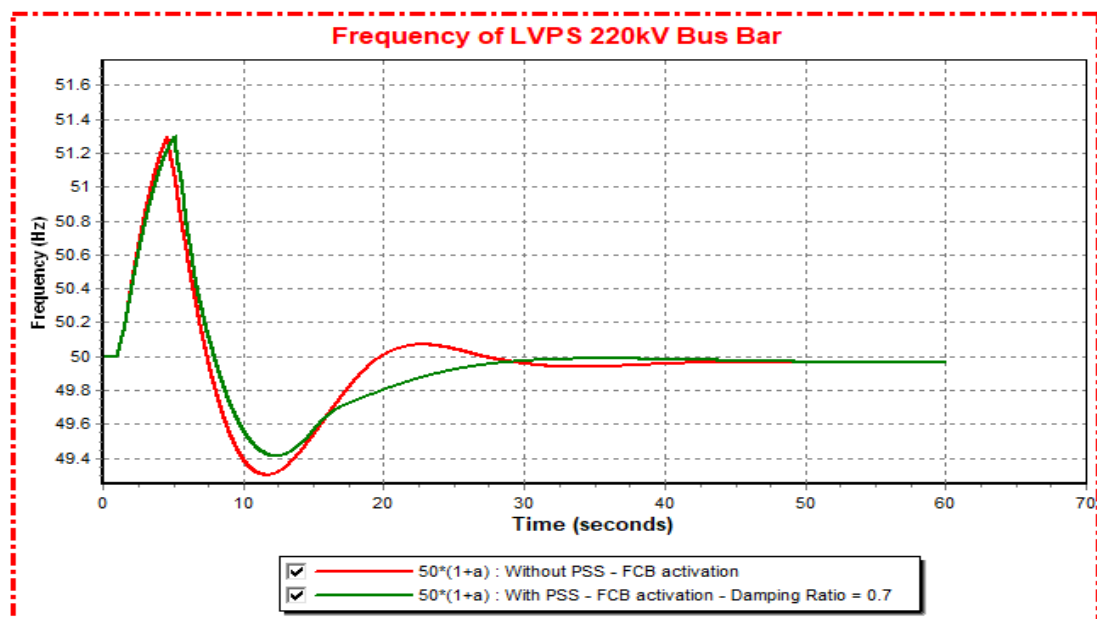


Figure 5-6 Simulation of Partial Blackout for With 1 PSS and Without PSS Cases

The red curve above illustrates the 'Without PSS' operation and the Green curve illustrates the 'With PSS' operation. Even with the presence of single PSS, the power system has not been able to survive the FCB activation of unit 2 of LVPS. However, it is obvious to notice that, PSS has improved the dynamic performance by reducing and damping out the excursions in the fluctuation.

The next simulation in this study will explore the scenario where a second Power System Stabilizer (PSS) had been activated in Unit 2 of the LVPS before the incident. The results are depicted in Figure 5-7.

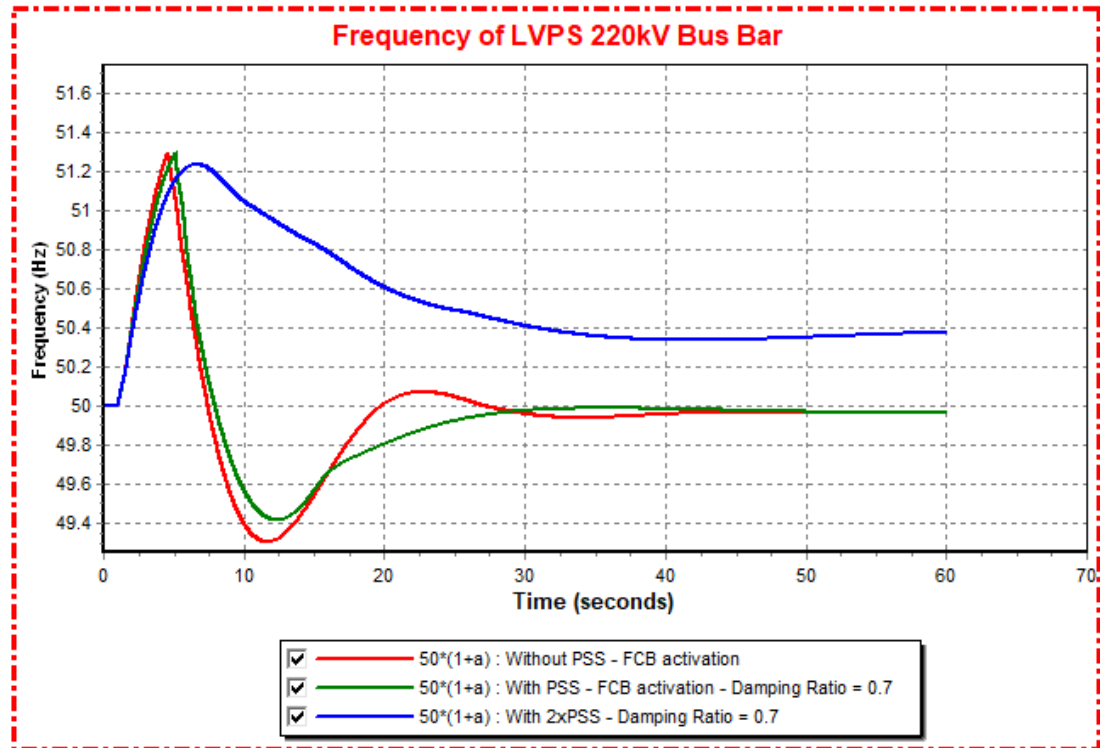


Figure 5-7 Simulation of Partial Blackout in Colombo Area for Second PSS

The blue colored curve which represents the addition of two PSSs in Figure 5-7 yields that, addition of second PSS has been able to avoid the activation of FCB operation in unit 2 of LVPS. This can be attributed to the additional improvement in overshoot reduction achieved by the system, similar to the cases mentioned earlier. Additionally, it is evident that the frequency coasting towards steady state is smoother, without experiencing any further frequency excursions in the system.

From the aforementioned cases, it can be concluded that introducing a PSS has significantly enhanced the damping of the power system. Furthermore, it underscores the importance of having a PSS in larger power plants such as LVPS in securing power system stability in a controlled manner.

## 5.5 Chapter Summary

The results obtained after tuning the PSS according to the above mentioned methodology is discussed in this chapter. As discussed earlier, there are two phases in this research. Hence, first the simulation results of a disturbance after tuning the PSS with the frequency response based method are presented. Then, the simulations results of the same disturbance after tuning the PSS with optimization based method are presented. Additionally, a comparison is done in between two phases to evaluate the improvements introduced to the system damping by the addition of power system stabilizer tuned according to the cascaded methodology. Thereafter, a sensitivity analysis will be presented for the optimization method by changing the damping ratio ( $\zeta$ ) from 0.3 -0.8, and maximum damping has been obtained with the damping ratio setting of 0.7. Finally, simulation examples of possible contingencies in the power system will be presented for both with and without PSS scenarios and the improvement introduced to the system in each and every case was discussed.

## 6 CONCLUSIONS AND FUTURE DIRECTIONS

In conclusion, the research undertaken to configure Power System Stabilizers (PSS) at Lakvijaya Power Station, Sri Lanka has yielded significant insights into enhancing the stability and performance of the power system. Through a methodical approach combining both traditional Frequency Response based method and Simulated Annealing based optimization technique in a cascaded manner, the study aimed to demonstrate the efficiency of PSS in improving transient response and system damping.

The objectives set out at the outset of the research were effectively achieved through a structured methodology. By employing comprehensive modeling of the Sri Lankan power system up to the 33kV voltage level using PSS/E software and the secondary model in MATLAB, the study laid a solid foundation for subsequent analysis. The cascaded approach of integrating Frequency Response based parameter method and automated optimization through Python platform offered superior results compared to individual methodologies. The comparison conducted between the two methods, alongside sensitivity analysis for varying damping ratio settings, provided valuable insights into the robustness of the proposed approach while suggesting the most suitable damping ratio setting of 0.7 for optimizations in the used model. It was evident that the cascaded method not only enhanced system damping but also exhibited versatility and scalability, making it applicable to power systems of diverse scales.

The research outcomes highlight several notable achievements, including the significant enhancement of system damping, development of a versatile implementation platform, and the offloading of computational burden to computer platforms in creating linear systems and related analysis of eigenvalues, which will avoid human errors while maximizing the efficiency. Hence, the implications of this research extend beyond the Lakvijaya Power Station, with the potential for broader applications across different power systems.

For future research endeavors, it is proposed to conduct field testing in alignment with industry standards set forth by the WECC and IEEE. This phase will not only validate the efficacy of the proposed PSS configurations but also provide invaluable insights

into real-world performance and applicability within existing grid configurations. Additionally, further investigation is suggested to assess the impact of the Transient Gain Reduction (TGR) function of the AVR on PSS applicability and effectiveness. Separately studying the influence of TGR on PSS dynamics will facilitate a deeper understanding of their interplay and inform optimized control strategies. Moreover, exploring the feasibility and practicality of online tuning methods for PSS within the operational framework of the Lakvijaya Power Station will be important in ensuring continuous optimization and adaptability to evolving system dynamics.

In light of the findings, it can be concluded that the proposed procedure offers a robust and efficient method for configuring PSS in power systems, leveraging the complete dynamic behavior of the system to enhance stability and productivity. Ultimately, this study contributes valuable insights to the field of power system stability and lays the groundwork for further research and implementation of advanced control strategies to ensure the reliable and efficient operation of power systems in the face of dynamic operational challenges.

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ANNEX A – LIST OF PARAMTERS

**Generator data**

All three generators have almost identical parameters. Generators are two pole, cylindrical rotor type with a stator winding of double circuit Y-Y wave winding. Stator is water cooled and the field winding is hydrogen cooled. Following are the name plate data for rated conditions.

Apparent power = 353 MVA

Maximum continuous output (MCR) = 332 MW

Rated stator voltage = 20 kV

Rated stator current = 10190 A

Exciting current = 2642 A

Exciting voltage = 365 V

Rated power factor = 0.85 lag

Rotate speed = 3000 rpm

Efficiency = 98.9 %

Rotate speed = 3000 rpm

Frequency = 50 Hz

Inertia constant (H) = 4.2 s

Following dynamic data was extracted from commissioning reports.

<b><u>Reactances</u></b>	<b>Direct axis (pu)</b>		<b>Quadrature axis (pu)</b>	
	<b>Saturation</b>	<b>Unsaturation</b>	<b>Saturation</b>	<b>Unsaturation</b>
Sub-transient (X'')	15.5%	16.8%	15.2%	16.57%
Transient (X')	20%	22.75%	33.3%	37.8%
Synchronous (X)	-	183%	-	179%
Negative- phase	15.4%	16.7%	-	-
Zero-phase	7.3%	7.7%	-	-
	<b>Direct axis (s)</b>		<b>Quadrature axis (s)</b>	
Short circuit Sub - transient (T'')	0.035		0.035	
Short Circuit - Transient (T')	0.91		0.17	
	<b>Direct axis (s)</b>		<b>Quadrature axis (s)</b>	
Open Circuit - Transient (T <sub>0</sub> )	8.47		0.94	

Leakage reactance of stator ( $X_{la}$ ) = 12.4% pu

Resistance of stator winding – per phase at 25°C, ( $R_a$ ) = 0.00228Ω

Resistance of field winding at 25°C ( $R_f$ ) = 0.125Ω

### Exciter dynamic data

Parameter	Description	Unit	Value
$K_a$	Voltage regulator gain	pu	400
$T_a$	Excitation time constant	s	0.004
TB	Controller first lag time constant	s	1
TB1	Controller second lag time constant	s	1
TC	Controller first lead time constant	s	0.01
TC1	Controller second lead time constant	s	0.01
$T_r$	Measuring time constant	s	0.02

### Governor with turbine dynamic data

Parameter	Description	Unit	Value
$T_{SR}$	Speed relay time constant	s	0.001
$T_{SM}$	Hydraulic servo time constant	s	0.15
$K_p$	Proportional gain		1
$T_3$	HIP steam chest time constant	s	10
$T_2$	LP crossover time constant	s	negligible

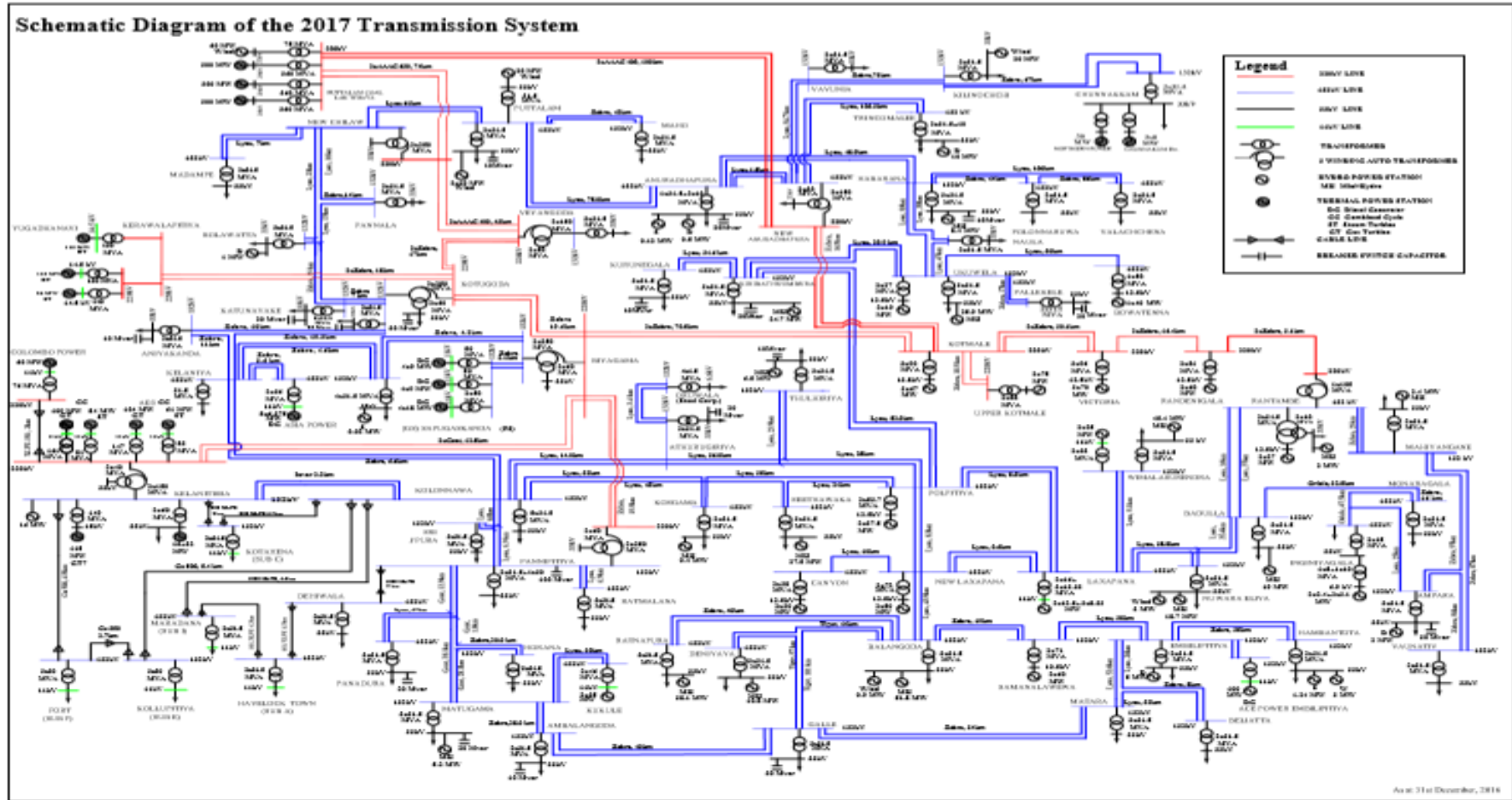
### Multi-mass shaft data

Parameter	Description	Unit	Value
K <sub>12</sub>	Stiffness coefficient	Pu/rad	250.57
H <sub>2</sub>	Coefficient of inertia	s	0.3176
K <sub>23</sub>	Stiffness coefficient	Pu/rad	356.01
H <sub>3</sub>	Coefficient of inertia	s	0.4264

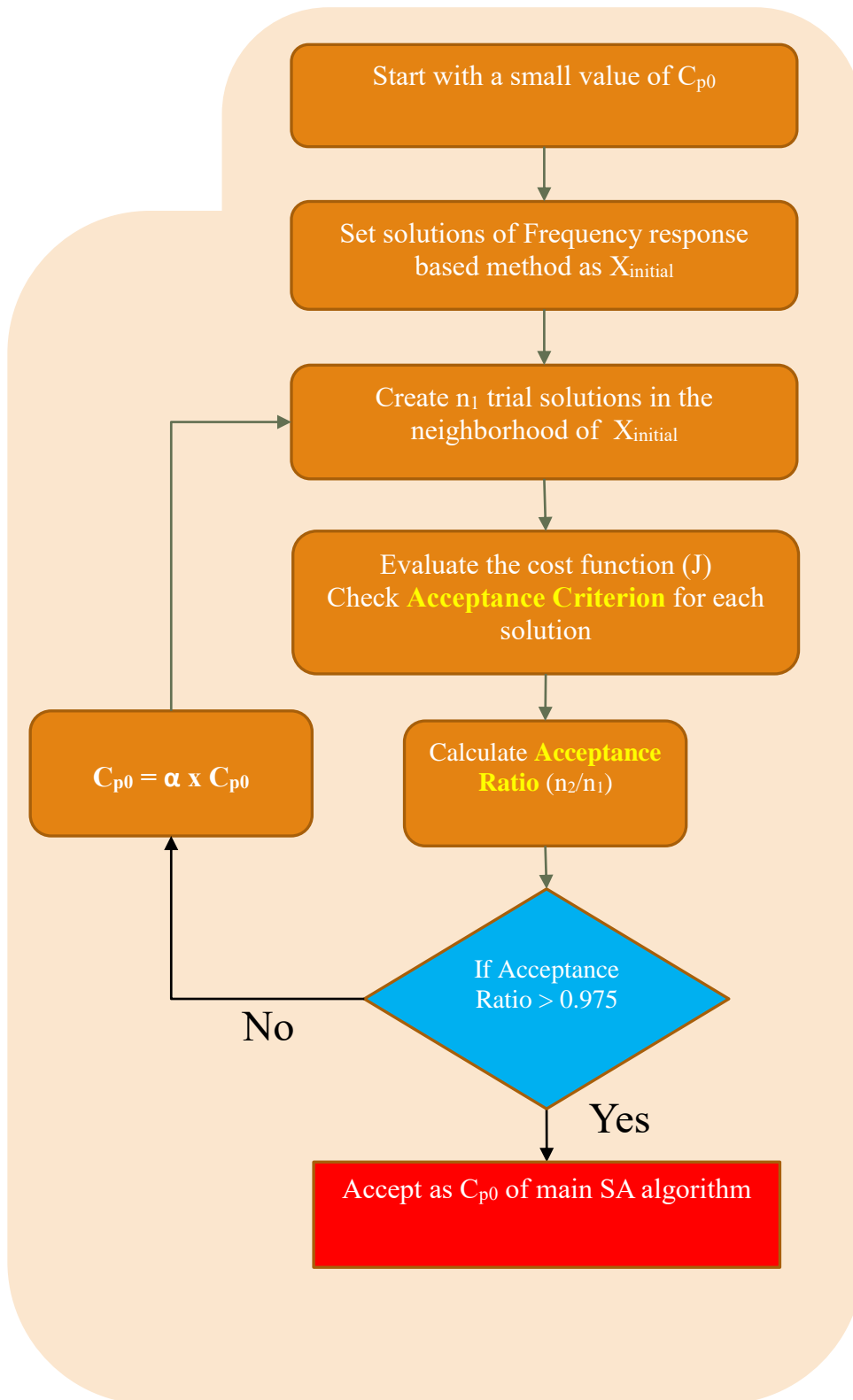
### Main Transformer rated data

Transformer type	= SFPZ-360000/20
No. of Phase	= 3
Rated power	= 360000 kVA
Rated frequency	= 50 Hz
Rated voltage	= (230 ± 8 x 1.25 %) / 20 kV
Connection symbol	= YNd1
Coolinf method	= ONAN / ONAF / ODAF (30/60/100%)
Short-circuit impedance	= 13.98 %
No-load current	= 0.067 %
No-load loss	= 152.17 kW
Load loss	= 727.48

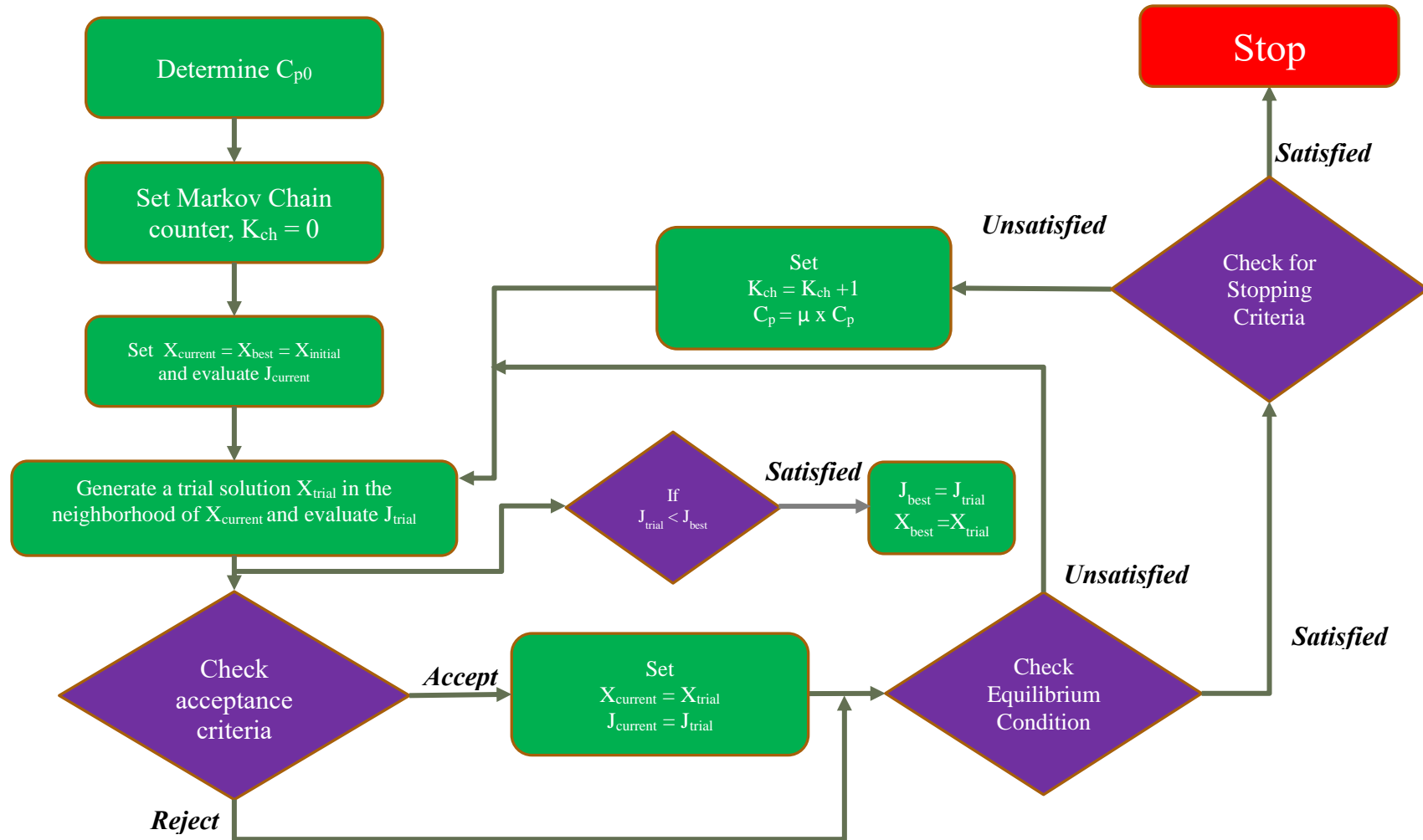
## ANNEX B – SRI LANKAN POWER SYSTEM NETWORK



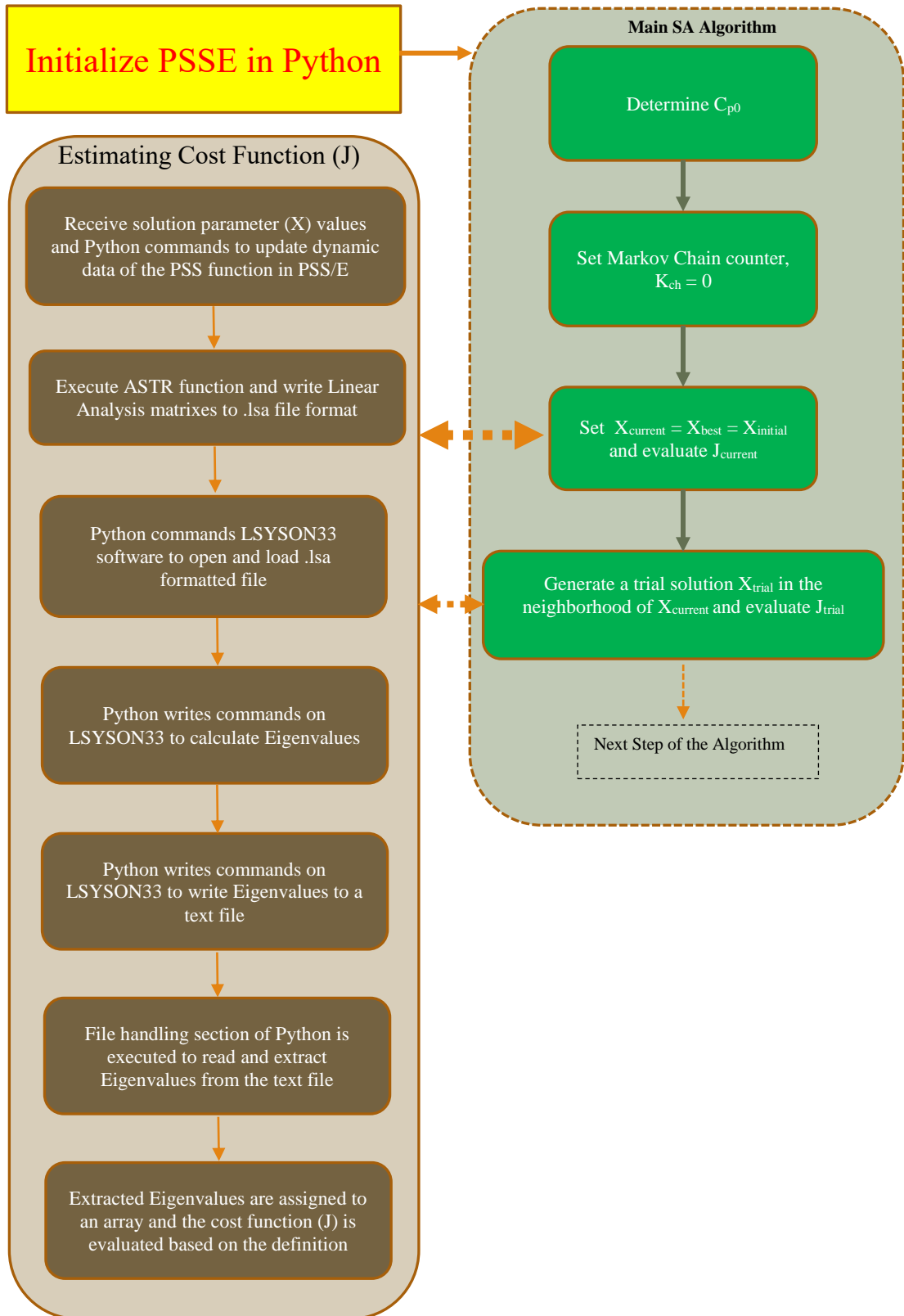
## ANNEX C – ALGORITHM FOR DETERMINING $C_{p0}$



ANNEX D – SIMULATED ANNEALING MAIN ALGORITHM



## ANNEX E – ESTIMATING COST FUNCTION



## ANNEX F – COMPLETE PYTHON CODE FOR OPTIMIZATIO

```
#Required Libraries
import random
import numpy as np
import numpy
import subprocess
import time
import pyautogui
import pygetwindow as gw
import re
import time
import math
from datetime import datetime
#-----
#Variables
#Applications and path related variables
first_open = 0
application_title = 'LSASYN33.exe'
application_path = r'C:\Users\DCS UNIT 03\Desktop\PSSE tests\My tests\Combined\LSYSAN\LSYSAN33.exe'
file_path = 'C:\Users\DCS UNIT 03\Desktop\PSSE tests\My tests\Combined\Matrix.txt'
savfileloc=r"C:\Users\DCS UNIT 03\Desktop\PSSE tests\My tests\Combined"
lastCp0_path = r'C:\Users\DCS UNIT 03\Desktop\PSSE tests\My tests\Combined\LastCp0.txt'
savefile='selectedNotConv.sav'

#Variables for Load Flow Study
LargestMismatch = 100
LarMisTreshold = 0.01
LfilterationFSDNR = 0
LfilterationFNR = 0
AlgoIteration = 1

#Variables for Cost function Evaluation
real_comps =np.array([])
imag_comps =np.array([])
Time_const =np.array([])
num_realparts = 0

#Variables for SA algorithm
#Variables for Determining Cp0
n1 =2000 #Trials Created
n2 =0 #Trials Accepted
Cp0 = 1 #Starting value of Cp0
alpha = 1.5
sample_size = n1
Acc_ratio_lim = 0.95

#Variables for Determining J
damping_ratio = 0.5
zigma_ref = -2*pi*2*damping_ratio
J_cost_func = 0
J_count_cri1 = 0
J_count_cri2 = 0
J_best = 0
J_current = 0
J_trial = 0
J_cost_init = 0
```

```

#Variables for Acceptance Criteria
math_eval = 0
random_prob = 0
x_current = []
x_trial = []
x_best = []
Ksl_init=3.62
T1_init=0.16
T2_init=0.04
T3_init=0.24
T4_init=0.04
x_initial = [Ksl_init,T1_init,T2_init,T3_init,T4_init]

#Other
count_from_Last_acc = 0
count_from_LAmarkos = 0
miu = 0.9
Kch_limit = 35 #important
count_from_last_acc_LIM = 1500 #important
Kch_last_change = 2 #important
Iteration_lim = 5000
unaccepted_count = 0
deltal = 0.5
delta2 = 0.1

#-----
#-----
#Functions

def Change_dyr(Ksl,T1,T2,T3,T4): #This function changes .dyr file of PSS/E for generated trials
    global ierr

    print("Ksl = {}, T1= {}, T2= {}, T3 = {}, T4 = {}".format(Ksl,T1,T2,T3,T4))

    psspy.change_plmod_con(4810,r""1"",r""PSS2A"",11, Ksl)
    psspy.change_plmod_con(4810,r""1"",r""PSS2A"",12, T1)
    psspy.change_plmod_con(4810,r""1"",r""PSS2A"",13, T2)
    psspy.change_plmod_con(4810,r""1"",r""PSS2A"",14, T3)
    psspy.change_plmod_con(4810,r""1"",r""PSS2A"",15, T4)
    psspy.snap([2816,826,345,711,5],r""C:\Users\DCS UNIT 03\Desktop\PSSE tests\My tests\Combined\withPSSdata.snp""")
    ierr = psspy.astr(0, 0.01, 0.01,1,[1],[826],0,[],[1],1,[4],[ 0.01],[4810],[r""1"",[""],r""C:\Users\DCS UNIT 03\
        Desktop\PSSE tests\My tests\Combined\Data.lsa""")

    time.sleep(0.2)

#-----
def last_CP0(): # This function writes a separate text file for recording purposes
    current_datetime = datetime.now()
    formatted_datetime = current_datetime.strftime("%Y-%m-%d %H:%M:%S")

    with open(lastCp0_path, 'a') as file:
        text = 'Last Cp0 is: {}. recorded at {}\n'.format(Cp0,formatted_datetime)
        file.write(text)
        text = 'x_best is: {}. J_best {}\n'.format(x_best,J_best)
        file.write(text)

```

```

#-----
def LSYSAN_run(): # This function runs LSYSAN33 software as a complete automation
    global first_open
    if first_open==0:

        # Use subprocess to open the application in a separate window
        process = subprocess.Popen(['start', 'cmd', '/k', application_path], shell=True)

        first_open = 1

    else:

        # Find the window by title
        app_window = gw.getWindowsWithTitle(application_title)

        # Check if the window is found
        if app_window:
            app_window = app_window[0]

            # Bring the window to the foreground
            app_window.activate()

            # Wait for a moment to ensure the window is active
            time.sleep(1)

            # Replace the coordinates with the actual coordinates of the target window
            window_x, window_y = app_window.left, app_window.top

            # Set focus on the target window
            pyautogui.click(window_x, window_y)
            time.sleep(0.5)

        # Following sections are for keyboard command replication on the LSYSAN33 software
        # Simulate typing a word and pressing 'Enter'
        word_to_type = "BCAS"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        # time.sleep(0.5)
        word_to_type = "Data.lsa"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        # time.sleep(0.5)
        word_to_type = "1"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        # Above command is repeated for 8 times in the actual code.
        # Those additional commands are deleted for the sake of convenience and
        # reduce the length in presenting them in the thesis

        # time.sleep(0.5)
        word_to_type = "EIGN"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        # time.sleep(0.5)
        word_to_type = "EIGP"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        #time.sleep(0.5)
        word_to_type = "1"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        #time.sleep(0.5)
        word_to_type = "2"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        #time.sleep(0.5)
        word_to_type = "Matrix.txt"
        pyautogui.typewrite(word_to_type)
        pyautogui.press('enter')
        #time.sleep(0.5)

```



```

#-----
def Estimate_cost(): # This function estimates the cost function
    global num_realparts,J_cost_func,real_comps, imag_comps, Time_const
    J_cost_func = 0
    for i in range(0,num_realparts):
        if real_comps[i]>=zigma_ref:
            J_cost_func = pow((real_comps[i]-zigma_ref), 2)+J_cost_func

    num_realparts = 0
    real_comps = np.array([])
    imag_comps = np.array([])
    Time_const = np.array([])
#-----
def J_cost_initial(): #This function calculates the cost of initial conditions, So runs only once
    global J_current,J_cost_func,J_cost_init,J_best,x_trial,x_current,x_best
    x_trial[:] = x_initial[:]
    x_current[:] = x_initial[:]
    x_best[:] = x_initial[:]
    Change_dyr(Ksl_init,T1_init,T2_init,T3_init,T4_init)
    LSYSAN_run()
    time.sleep(0.5)
    Readtext_run()
    Estimate_cost()
    J_cost_init = J_cost_func
    J_best = J_cost_func
    J_current = J_cost_func
    J_cost_func = 0
    print("J_current initial:{}".format(J_cost_init))

#-----
def J_accept(): # Algorithm of acceptance criteria
    global J_current,J_trial,J_count_cri1,n2,J_count_cri2,Cp0,random_prob,math_eval
    global unaccepted_count,count_from_Last_acc,count_from_LAmarko,J_best,x_current,x_trial,x_best

    J_trial = J_cost_func
    if J_current > J_trial:
        #accepted directly
        J_current = J_trial
        x_current[:] = x_trial[:]

        J_count_cri1 = J_count_cri1+1
        n2 = n2+1
        count_from_Last_acc = 0
        count_from_LAmarko = 0

    elif J_current < J_trial:
        math_eval = math.exp(-(J_trial-J_current) / Cp0)
        random_prob = random.uniform(0, 1)
        if math_eval >= random_prob:
            J_current = J_trial
            x_current[:] = x_trial[:]

            J_count_cri2 = J_count_cri2+1
            n2 = n2+1
            count_from_Last_acc = 0
            count_from_LAmarko = 0
        else:

            unaccepted_count = unaccepted_count+1
            count_from_Last_acc = count_from_Last_acc + 1

    # To record J_best
    if J_trial< J_best:
        J_best = J_trial
        x_best[:] = x_trial[:]
        last_CP0()

```

```

#-----
def define_random_lim(): # This function defines boundaries around the current solution to generate trial solutions
    if (x_current[0]+delta1)>50:
        Ksl_upper = 50.0001
    else:
        Ksl_upper = x_current[0]+delta1
#-----
    if (x_current[0]-delta1)<0:
        Ksl_lower = 0
    else:
        Ksl_lower = x_current[0]-delta1
#-----
    if (x_current[1]+delta2)>2.5:
        T1_upper = 2.5001
    else:
        T1_upper= x_current[1]+delta2
#-----
    if (x_current[1]-delta2)<0:
        T1_lower = 0
    else:
        T1_lower = x_current[1]-delta2
#-----
    if (x_current[2]+delta2)>2.5:
        T2_upper = 2.5001
    else:
        T2_upper= x_current[2]+delta2
#-----
    if (x_current[2]-delta2)<0:
        T2_lower = 0
    else:
        T2_lower = x_current[2]-delta2
#-----
    if (x_current[3]+delta2)>2.5:
        T3_upper = 2.5001
    else:
        T3_upper= x_current[3]+delta2
#-----
    if (x_current[3]-delta2)<0:
        T3_lower = 0
    else:
        T3_lower = x_current[3]-delta2
#-----
    if (x_current[4]+delta2)>2.5:
        T4_upper = 2.5001
    else:
        T4_upper= x_current[4]+delta2
#-----
    if (x_current[4]-delta2)<0:
        T4_lower = 0
    else:
        T4_lower = x_current[4]-delta2

return Ksl_upper,Ksl_lower,T1_upper,T1_lower,T2_upper,T2_lower,T3_upper,T3_lower,T4_upper,T4_lower

```

```

#-----
def Determine_Cp0(): # This function Determines Cp0

    global n1,n2,Cp0,J_current,J_count_cri1,J_count_cri2,unaccepted_count,acceptance_ratio
    marko_chain_no = 0
    acceptance_ratio = float(n2)/n1
    LB_unacc_count = (1- Acc_ratio_lim)*n1 #Loop break unacceptance count
    J_cost_initial()
    while acceptance_ratio <= Acc_ratio_lim:
        J_current=J_cost_init
        marko_chain_no = marko_chain_no +1
        n2 = 0
        J_count_cri1 = 0
        J_count_cri2 = 0
        unaccepted_count =0
        # write the last value of Cp0 to text file
        last_CP0()

        Ks1_array =np.round(numpy.random.uniform(0.1, 50.0001, size=(1, sample_size)),2)
        T1_array = np.round(numpy.random.uniform(0, 2.5001, size=(1, sample_size)),2)
        T2_array = np.round(numpy.random.uniform(0, 2.5001, size=(1, sample_size)),2)
        T3_array = np.round(numpy.random.uniform(0, 2.5001, size=(1, sample_size)),2)
        T4_array = np.round(numpy.random.uniform(0, 2.5001, size=(1, sample_size)),2)

    for i in range(0,sample_size):

        Change_dyr(Ks1_array[0,i],T1_array[0,i],T2_array[0,i],T3_array[0,i],T4_array[0,i])
        LSYSAN_run()
        time.sleep(0.5)
        Readtext_run()
        Estimate_cost()
        J_accept()
        acceptance_ratio=float(n2)/n1

        if unaccepted_count > LB_unacc_count:
            break

        if acceptance_ratio <= Acc_ratio_lim:
            print("Acceptance ratio:{}".format(acceptance_ratio))
            Cp0 = Cp0*alpha

#-----
def Main_algo(): # This function runs the main SA algorithm
    global n1,n2,Cp0,J_current,J_count_cri1,J_count_cri2,unaccepted_count
    global acceptance_ratio,count_from_Last_acc,count_from_LAmarko,x_trial

    marko_chain_no = 0
    count_from_LAmarko = 0
    LB_unacc_count = (1- Acc_ratio_lim)*n1 #Loop break unacceptance count
    J_cost_initial()

    while 1:

        marko_chain_no = marko_chain_no +1
        count_from_LAmarko = count_from_LAmarko +1

        # write the last value of Cp0 to text file
        last_CP0()

        equilibrium_cond = 0
        J_count_cri1 = 0
        J_count_cri2 = 0
        unaccepted_count =0
        iteration = 0
        n2 = 0
        acceptance_ratio = 0
        count_from_Last_acc = 0

```

```

while 1:
    Ks1_upper,Ks1_lower,T1_upper,T1_lower,T2_upper,T2_lower,T3_upper,T3_lower,T4_upper,T4_lower = define_random_lim()

    Ks1 = np.round(np.random.uniform(Ks1_lower, Ks1_upper), 2)
    T1 = np.round(np.random.uniform(T1_lower, T1_upper),2)
    T2 = np.round(np.random.uniform(T2_lower, T2_upper),2)
    T3 = np.round(np.random.uniform(T3_lower, T3_upper),2)
    T4 = np.round(np.random.uniform(T4_lower, T4_upper),2)

    x_trial = [Ks1,T1,T2,T3,T4]
    Change_dyr(Ks1,T1,T2,T3,T4)

    iteration = iteration + 1

    LSYSAN_run()
    time.sleep(0.5)
    Readtext_run()
    Estimate_cost()
    J_accept()

    acceptance_ratio=float(n2)/iteration

    if (count_from_Last_acc > count_from_last_acc_LIM) or (iteration >Iteration_lim):
        equilibrium_cond = 1
        break

    if (count_from_LAmarko > Kch_last_change) or (marko_chain_no > Kch_limit):
        break
        print("Optimization is completed")

    else:
        Cp0 = miu * Cp0
#-----Function section ends here-----#
#-----#
#Main function
#PSSE Environment Setup
#-----#
import sys,os
PSSE = r"C:\Program Files (x86)\PTI\PSSE33\PSSEBIN"
sys.path.append(PSSE)
os.environ['PATH']=os.environ['PATH']+';'+PSSE
import psspy
#-----#
#PSSE open,Initialize,load save case, Load flow for one time operation
psspy.psseinit()
os.chdir(savfileloc)
psspy.case(savefile) # Case will be opened

#Loadflow,Convert,RSTR function
psspy.fdns([0,0,0,1,1,1,99,0])
LFiterationFSDNR = LFiterationFSDNR + 1
LargestMismatch = psspy.sysmsm() #Largest MVA Mismatch is calculated

if psspy.solved()==0:

    print("Met Convergence Tolerences in algo Iteration: {} and FSDNR Iteration: {}".format(AlgoIteration,LFiterationFSDNR))
    print ('Largest Missmatch is:',LargestMismatch)

else:
    print("Algo Iteration: {} Power flow FSDNR iteration: {} failed".format(AlgoIteration,LFiteration))
    print ('Largest Missmatch is:',LargestMismatch)
    sys.exit()

```

```

while LargestMismatch >= LarMisTreshold:
    psspy.fns1([0,0,0,1,1,0,99,0])
    LfiterationFNR = LfiterationFNR+1
    LargestMismatch = psspy.sysmsm()

if psspy.solved()==0:
    print("Met Convergence Tolerences in algo Iteration: {} and FNR Iteration: {}".format(AlgoIteration,LfiterationFNR))
    print ('Largest Misssmatch is:',LargestMismatch)

else:
    print("Algo Iteration: {} Power flow FSDNR iteration: {} failed".format(AlgoIteration,LfiterationFNR))
    print ('Largest Misssmatch is:',LargestMismatch)
    sys.exit()

#Model conversion and loading the .snp file which contains dynamic data
psspy.cong(0)
psspy.con1(0,1,1,[0,0],[ 100.0,0.0,0.0, 100.0])
psspy.con1(0,1,2,[0,0],[ 100.0,0.0,0.0, 100.0])
psspy.con1(0,1,3,[0,0],[ 100.0,0.0,0.0, 100.0])
psspy.ordr(0)
psspy.fact()
psspy.tysl(0)
psspy.rstr(r"C:\Users\DCS UNIT 03\Desktop\PSSE tests\My tests\Combined\withPSSdata.snp")

#-----
#-----
#Calls Determining_Cp0 Function
Determine_Cp0()
#Calls Main SA algo Function
Main_algo()

#-----End of The Algorithm-----#

```