UNIVERSITY OF NAIROBI

EFFECTIVENESS OF POWER SYSTEM STABILIZERS AND STATIC VAR COMPENSATORS/THYRISTOR CONTROLLED SERIES CAPACITORS IN DAMPING POWER OSCILLATIONS.

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EFFECTIVENESS OF POWER SYSTEM STABILIZERS AND STATIC VAR COMPENSATORS/THYRISTOR CONTROLLED SERIES CAPACITORS IN DAMPING POWER OSCILLATIONS.

A study of Stability in Electric Power Systems
We’ve come so far…
Yet an even longer journey awaits…
Of growing us into true men…
Of honour
Serving
Caring
For the needs of brotherhood

(Starehe School Mantra; My Aspiration)

To Amos
for nurture...

And to the Almighty
for life and His Grace...

my footsteps set to His pace...

Great heights by great men reached and kept: were not attained by sudden flight…
but they, while their companions slept, were toiling upward into the night…

(Dr. Geoffrey W Griffin’s favourite quote; My Inspiration)
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Finally, to my friends and family, thank you for your encouragement and prayers. Your faith in me stands me still.
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<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>AVR</td>
<td>Automatic Voltage Regulator</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<td>FACTS</td>
<td>Flexible AC Transmission System (devices)</td>
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<td>G1</td>
<td>First Generation</td>
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<td>GTO</td>
<td>Gate-Turn-Off</td>
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<td>PLL</td>
<td>Phase Locked Loop</td>
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<td>Particle Swarm Optimisation</td>
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<td>STATCOM</td>
<td>Static Compensator</td>
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<tr>
<td>SVC</td>
<td>Static Var Compensator</td>
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<tr>
<td>TCPST</td>
<td>Thyristor Controlled Phase-Shifting Transformer</td>
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<tr>
<td>TCSC</td>
<td>Thyristor Controlled Series Capacitor</td>
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<tr>
<td>UPFC</td>
<td>Unified Power Flow Controller</td>
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<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
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<td>VSI</td>
<td>Voltage Source Inverter</td>
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ABSTRACT

In recent years, greater demands have been placed on the electric power system generation and transmission network. Increased demands on transmission, absence of long-term planning, and the need to provide open access to generating companies and customers, all together have created tendencies toward less security and reduced quality of supply.

The Power System Stabilizer (PSS) and Flexible AC Transmission System (FACTS) technology is essential to alleviate some but not all of these difficulties by enabling utilities to get the most service from their generation and transmission facilities and enhance grid reliability. While PSS technology provides steadfast ground for managing stability issues at the plant generators, FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines.

The possibility that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors, and use of one of the FACTS Controllers to enable corresponding power to flow through such lines under normal and contingency conditions. It must be stressed, however, that for many of the capacity expansion needs, building of new lines or upgrading current and voltage capability of existing lines and corridors will be necessary.
1. INTRODUCTION

To ensure efficiency in the operation of electric power systems, controllers are oft employed at the generation and/or transmission/distribution stages. Their effectiveness in ensuring stability in the face of perturbation in the system is of utmost importance to the power system engineer. It is this salient aspect of the electric power system that formed the basis of this study; encompassing an investigation of the effectiveness of Power System Stabilizers (PSSs) and Flexible AC Transmission System (FACTS) devices in mitigating power oscillations.

Power system stabilizers (PSSs) have been used in the last few decades to serve the purpose of enhancing power system damping to low frequency oscillations. To this end, PSSs have proved to be efficient in performing their assigned tasks. However, they have been unable to suppress oscillations resulting from severe disturbances, such as three-phase faults at generator terminals.

On the other hand, Flexible AC Transmission System (FACTS) devices have shown very promising results when used to improve power system steady-state performance. In addition, because of the extremely fast control action associated with FACTS-device operations, they have been very promising candidates for utilization in power system damping enhancement. The first generation (G1) FACTS devices include Static Var Compensator (SVC), Thyristor Controlled Phase Shifting Transformer (TCPST), and Thyristor Controlled Series Capacitor (TCSC).

In this paper, a comparison between PSS and G1 FACTS devices (i.e. TCSC, SVC) in damping system low frequency oscillations is carried out. In all controllers, the widely used lead–lag scheme is considered. A test system equipped with the two stabilizers, one per generator, and a Static Var Compensator in its transmission system is simulated. Simulation results are used to compare the effectiveness of the proposed controllers to damp low frequency oscillations of the considered system.
With the view of ensuring this report remained concise, the author avoided delving into the drudgery of presently superfluous theoretical formulations as regards other design approaches of the studied controllers; and optimizations of the discussed design methods. However, references are provided that shall guide the reader into the depths of such scholarly indulgence.
1.1 ELECTRIC POWER SYSTEMS

The generation station, transmission and distribution networks of electric power (usually three phase ac power) constitute the Electric Power System. As it is widely known, electric power is produced, almost entirely, by means of synchronous three-phase generators (i.e., alternators) driven by steam or water turbines [1]. Power is then transported through a three-phase alternating current (ac) system operated by transformers at different voltage levels. Transportation that involves larger amounts of power and/or longer distances is carried out by the transmission system, which consists of a meshed network and operates at a very high voltage level (relative to generator and end-user voltages). This system ensures that at the same transmitted powers the corresponding currents are reduced, thereby reducing voltage dips and power losses. Power transportation that involves shorter distances is accomplished through the distribution system, which also includes small networks of radial configuration and voltages stepped down to end-user levels.

The use of ac, when compared with direct current (dc), offers several advantages, including: use of transformers that permit high-voltage transmission and drastically reduces losses; use of ac electrical machines that do not require rotating commutators; interruption of ac currents that can be accomplished in an easier way. Moreover, the three-phase system is preferable when compared with the single-phase system because of its superior operating characteristics (rotating field) and possible savings of conductive materials at the same power and voltage levels.

For an ac three-phase system, reactive power flows become particularly important. Consequently, it is also important that transmission and distribution networks be equipped with devices to generate or absorb (predominantly) reactive power. These devices enable networks to adequately equalize the reactive power absorbed or generated by lines, transformers, and loads to a larger degree than synchronous machines are able. These devices can be static (e.g., inductive reactors, capacitors, static compensators) or rotating (synchronous compensators, which can be viewed as synchronous generators without their turbines or as
synchronous motors without mechanical loads). Furthermore, interconnection between different systems—each taking advantage of coordinated operation—is another important factor. The electrical network of the resulting system can become very extensive, possibly covering an entire continent.

1.2 Basic Elements of an Electric Power System

The basic elements of a power system are shown in Figure 1.1. Each of the elements is equipped with devices for manoeuvring, measurement, protection, and control. The nominal frequency value is typically 50 Hz (in Kenya) or 60 Hz (in the United States); the maximum nominal voltage ranges, in the case of Kenya, are between 11–15 kV (line-to-line voltage) at synchronous machine terminals; other voltage levels present much larger values (up to 1000 kV) for transmission networks, then decrease for distribution networks as in Figure 1.1.

Generation is predominantly accomplished by thermal power plants equipped with steam turbines using “traditional” fuel (coal, oil, gas, etc.) or nuclear fuel, and/or hydroelectric plants (with reservoir or basin, or fluent-water type). Generation can also be accomplished by thermal plants with gas turbines or diesel engines, geothermal power plants (equipped with steam turbines), and other sources (e.g., wind, solar, tidal, chemical plants, etc.) whose actual capabilities are still under study or experimentation.

The transmission system includes an extensive, relatively meshed network. A single generic line can, for example, carry hundreds or even thousands of megawatts (possibly in both directions, according to its operating conditions), covering a more or less great distance, e.g., from 10 km to 1500 km and over. The long lines might present large values of shunt capacitance and series inductance, which can be, at least partially, compensated by adding respectively shunt (inductive) reactors and series capacitors.

The task of each generic distribution network at high voltage (HV), often called a “subtransmission” network, is to carry power toward a single load area, more or less geographically
extended according to its user density (e.g., a whole region or a large urban and/or industrial area).

Fig1.1: Basic Elements of an Electric Power System (EHV, HV, MV, LV Mean, Respectively, Extra-High, High, Medium, and Low Voltage).

The power transmitted by each line may range from a few megawatts to tens of megawatts. Electric power is then carried to each user by means of medium voltage (MV) distribution networks, each line capable of carrying, for example, about one megawatt of power, and by low voltage (LV) distribution networks. Finally, the interconnections between very large systems (e.g., neighboring countries) are generally developed between their transmission networks. Similar situations involving a smaller amount of power can occur, even at the distribution level, in the case of “self-generating users” (e.g., traction systems, large chemical or steel processing plants, Sugar Millers etc.), which include not only loads in the strict sense but also generators and networks.
1.3 Requirements of a Reliable Electric Power System

The successful operation of a power system largely depends on its ability to provide reliable and uninterrupted service to the loads [2]. Ideally, the loads must be fed at constant voltage and frequency at all times. Practically, this means that both voltage and frequency must be held within close tolerances so that the consumers’ equipment may operate satisfactorily.

The first requirement of a reliable electric power system is to keep the synchronous generators operating in parallel and with adequate capacity to meet the load demand. If a generator loses synchronism with the rest of the system, significant current and voltage fluctuations may occur and transmission lines may be tripped by their relays at undesired locations.

Another requirement of a reliable electrical service is to maintain the integrity of the power network. The high voltage transmission systems connects the generating stations and the load centres. An interruption in this network may hinder the flow of power to the loads.

It is important to note that a ‘steady state’ Power System, in the true sense, never exists. Random changes in the loads take place at all times with subsequent adjustments in the generation. Furthermore, a fault may occur in the system. In the case of a failed generator, synchronism may be lost in the transition from one generator to another; also, growing oscillations may occur on the transmission line, leading to its eventual tripping. This constitutes the Power System Stability Problem.

1.4 The Power System Stability Problem

For the most part, the stability problem is concerned with the behaviour of the synchronous machines after they have been perturbed. The perturbation could be a major disturbance such as the loss of a generator, a fault or the loss of a line, or a combination of such events. It could also be a small load or random load changes occurring under normal operating conditions. If the perturbation does not involve any net change in the power, the machines should return to their original state. If an imbalance is created between the supply and demand by a change in load, in generation, or in network conditions, a new operating state is necessary.
1.4.1 Power Oscillations and the Stability Criterion

The transient following a system perturbation is oscillatory in nature. If the system is stable, these oscillations will be damped toward a new quiescent operating condition. These oscillations, however, are reflected as fluctuations in the power flow over the transmission lines, constituting Power Oscillations.

If a line connecting two groups of machines (usually referred to as the tie-line) undergoes excessive power fluctuations, it may be tripped out by its protective equipment thereby disconnecting the two groups of machines. This problem is termed the stability of the line, even though in reality, it reflects the stability of the two groups of machines.

Adjustment to the new operating condition is called the transient period. The system behavior during this time is called the dynamic system performance, which is of concern in defining system stability. The main criterion for stability being that the synchronous machines maintain synchronism at the end of the transient period.

1.4.2 Classification of Power Oscillations

Oscillations in power systems are classified by the system components that they affect [3]. Some of the major system collapses attributed to oscillations are described, and constitute electro-mechanical phenomena in Electric Power Systems. Electromechanical oscillations are of the following types: Intra-plant mode oscillations; Local plant mode oscillations; Inter-area mode oscillations; Control mode oscillations; Torsional modes between rotating parts.

1.4.2.1 Intra-Plant Mode Oscillations
Machines on the same power generation site oscillate (swing) against each other at 2.0 to 3.0 Hz depending on the unit ratings and the reactance connecting them. This oscillation is termed as intra-plant because the oscillations manifest themselves within the generation plant complex. The rest of the system is unaffected.

1.4.2.2 Local Plant Mode Oscillations
In local mode, one generator swings against the rest of the system at 1.0 to 2.0 Hz. The impact of the oscillation is localized to the generator and the line connecting it to the grid. The rest of
the system is normally modelled as a constant voltage source whose frequency is assumed to remain constant: the *single-machine-infinite-bus* (SMIB) model.

\[ \text{Fig. 1.2: A Typical Example of Local Oscillation} \]

### 1.4.2.3 Inter-Area Mode Oscillations

This phenomenon is observed over a large part of the network. It involves two coherent group groups of generators swinging against each other at 1 Hz or less. The variation in tie-line power can be large as shown in Fig. 1.3. The oscillation frequency is approximately 0.3 Hz. Inter-area Oscillations can severely restrict system operations by requiring curtailment of electric power transfers as an operational measure. These oscillations can also lead to widespread system disturbances if cascading outages of transmission lines occur due to oscillatory power swings.

\[ \text{Fig. 1.3: A Typical Example of Inter-area Oscillation} \]
1.4.2.4 Control Mode Oscillations

These are associated with generators and poorly tuned exciters, governors, HVDC (High Voltage Direct Current) converters and SVC (Static Var Compensator) controls. Loads and excitation systems can interact through control modes [4]. Transformer tap-changing controls can also interact in a complex manner with non-linear loads giving rise to voltage oscillations [5].

1.4.2.5 Torsional Mode Oscillations

These modes are associated with a turbine generator shaft system in the frequency range of 10-46 Hz. A typical oscillation is shown in Fig. 1.4. Usually these modes are excited when a multi-stage turbine generator is connected to the grid system through a series compensated line [6]. A mechanical torsional mode of the shaft system interacts with the series capacitor at the natural frequency of the electrical network. The shaft resonance appears when network natural frequency equals synchronous frequency minus torsional frequency.

![Fig. 1.4: A Typical Example of a Torsional Mode Oscillation](image)

1.4.3 Role of Oscillations in Power Blackouts

Inter-area oscillations have led to many system separations but few wide-scale blackouts [7]. Note worthy incidents include: Detroit Edison (DE)-Ontario Hydro (OH)-Hydro Quebec (HQ) (1960s, 1985), Finland-Sweden-Norway-Denmark (1960s), Saskatchewan-Manitoba Hydro-Western Ontario (1966), Italy-Yugoslavia-Austria (1971-1974), Western Electric Coordinating
2. DAMPING POWER OSCILLATIONS

A continually oscillatory system would be undesirable for both the supplier and the user of electric power. The definition of Stability describes a practical specification for an acceptable operating condition. This definition requires that the system oscillations be damped [Appendix G.6]. Accordingly, a desirable feature in electric power systems, considered necessary for all intents and purposes, is that the system contain inherent features that tend to reduce (or eliminate) power oscillations.

2.1 Power Oscillation Damping Strategies

A number of strategies are available for damping low frequency oscillations in power systems. Of these, the Power System Stabilizer (PSS) is the most commonly used. It operates by generating an electric torque in phase with the rotor speed. In most cases, the PSS works well in damping oscillations. However, because the parameters of PSS are tuned by the original system parameters, its control has less flexibility, which means the control results are far from ideal if the operating conditions and/or structures of the system change.

Modern controllers used to damp power system oscillations include High-Voltage DC (HVDC) Lines, Static Var Compensators (SVCs), Thyristor-Controlled Series Capacitors (TCSCs), Thyristor-Controlled Phase-Shifting Transformers (TCPSTs) and other such Flexible AC Transmission System (FACTS) equipment. FACTS devices provide fast control action and have the advantage of flexibility of being located at the most suitable places to achieve the best control results. As these controllers operate very fast, they enlarge the safe operating limits of a transmission system without risking stability. FACTS devices are oft combined with Energy Storage Systems (ESS) to achieve higher efficiency and greater operational effectiveness. FACTS/ESS technology has the advantages in both energy storage ability and flexibility of its power electronics interface. FACTS/ESS also has capability to work as active and reactive power generation and absorption systems, voltage control systems, and to improve the transmission capability and system stability.
2.2 Power System Stabilizers (PSSs)

These are controllers with the ability to control synchronous machine stability through the excitation system by employing high-speed exciters and continuously acting voltage regulators. The PSS adds damping to the generator unit’s characteristic electromechanical oscillations by modulating the generator excitation so as to develop components of electrical torque in phase with rotor speed deviations. The PSS thus contributes to the enhancement of small-signal stability of power systems. Fixed structure stabilizers generally provide acceptable dynamic performance. The typical ranges of PSS-based controller parameter values are summarized in the Appendix B.1.

2.2.1 Overview of Power System Stabilizer (PSS) Structures

Shaft speed, electrical power and terminal frequency are among the commonly used input signals to the PSS. Different forms of PSS have been developed using these signals. This section describes the advantages and limitations of the different PSS structures.
2.2.1.1 Speed-Based ($\Delta \omega$) Stabilizer

These are stabilizers that employ a direct measurement of shaft speed. Run-out compensation must be inherent to the method of measuring the speed signal to minimize noise caused by shaft run-out (lateral movement) and other sources.

While stabilizers based on direct measurement of shaft speed have been used on many thermal units, this type of stabilizer has several limitations. The primary disadvantage is the need to use a torsional filter to attenuate the torsional components of the stabilizing signal. This filter introduces a phase lag at lower frequencies which has a destabilizing effect on the "exciter mode", thus imposing a maximum limit on the allowable stabilizer gain. In many cases, this is too restrictive and limits the overall effectiveness of the stabilizer in damping system oscillations. In addition, the stabilizer has to be custom-designed for each type of generating unit depending on its torsional characteristics.

2.2.1.2 Frequency-Based ($\Delta f$) Stabilizer

Here, the terminal frequency signal is either used directly or terminal voltage and current inputs are combined to generate a signal that approximates the machine’s rotor speed, often referred to as compensated frequency. The frequency signal is more sensitive to modes of oscillation between large areas than to modes involving only individual units, including those
between units within a power plant. Thus greater damping contributions are obtained to these
*inter-area modes* of oscillation than would be, with the speed input signal.

Frequency signals measured at the terminals of thermal units contain torsional components. Hence, it is necessary to filter torsional modes when used with steam turbine units. In this respect frequency-based stabilizers have the same limitations as the speed-based units. Phase shifts in the ac voltage, resulting from changes in power system configuration, produce large frequency transients that are then transferred to the generator’s field voltage and output quantities. In addition, the frequency signal often contains power system noise caused by large industrial loads such as arc furnaces.

**2.2.1.3 Power-Based (ΔP) Stabilizer**

Due to the simplicity of measuring electrical power and its relationship to shaft speed, it was considered to be a natural candidate as an input signal to early stabilizers. The equation of motion for the rotor can be written as follows:

\[
\frac{\partial}{\partial t} \Delta \omega = \frac{1}{2H} (\Delta P_m - \Delta P_e)
\]

(1)

Where: \(H = \) inertia constant; \(\Delta P_m = \) change in mechanical power input; \(\Delta P_e = \) change in electric power output and \(\Delta \omega = \) speed deviation

If mechanical power variations are ignored, this equation implies that a signal proportional to shaft acceleration (i.e. one that leads speed changes by 90°) is available from a scaled measurement of electrical power. This principle was used as the basis for many early stabilizer designs. In combination with both high-pass and low-pass filtering, the stabilizing signal derived in this manner could provide pure damping torque at exactly one electromechanical frequency.

This design suffers from two major disadvantages. First, it cannot be set to provide a pure damping contribution at more than one frequency and therefore for units affected by both
local and inter-area modes a compromise is required. The second limitation is that an unwanted stabilizer output is produced whenever mechanical power changes occur. This severely limits the gain and output limits that can be used with these units. Even modest loading and unloading rates produce large terminal voltage and reactive power variations unless stabilizer gain is severely limited. Many power-based stabilizers are still in operation although they are rapidly being replaced by units based on the integral-of-accelerating power design.

2.2.1.4 Integral-of-Accelerating Power (ΔPω) Stabilizer

The limitations inherent in the other stabilizer structures led to the development of stabilizers that measure the accelerating power of the generator. Due to the complexity of the design, and the need for customization at each location, a method of indirectly deriving the accelerating power was developed [Figure, Appendix B.2]. The principle of this stabilizer is illustrated by re-writing equation (1) in terms of the integral of power.

\[
\Delta \omega = \frac{1}{2H} \int (\Delta P_m - \Delta P_e) \, dt
\]  

(2)

The integral of mechanical power is related to shaft speed and electrical power as follows:

\[
\int \Delta P_m \, dt = 2H \Delta \omega + \int \Delta P_e \, dt
\]  

(3)

The \(\Delta P_\omega\) stabilizer makes use of the above relationship to simulate a signal proportional to the integral of mechanical power change by adding signals proportional to shaft-speed change and integral of electrical power change. On horizontal shaft units, this signal will contain torsional oscillations unless a filter is used. Because mechanical power changes are relatively slow, the derived integral of mechanical power signal can be conditioned with a low-pass filter to attenuate torsional frequencies. The overall transfer function for deriving the integral-of accelerating power signal from shaft speed and electrical power measurements is given by:
\[
\int \frac{\Delta P_a}{2H} \, dt \rightarrow -\frac{\Delta P_c}{2H_s} + G(s) \left[ \frac{\Delta P_c(s)}{2H_s} + \Delta \omega(s) \right] \quad (4); \text{ where } G(s) \text{ is the transfer function of the low-pass filter.}
\]

The major advantage of a \( \Delta P \omega \) stabilizer is that there is no need for a torsional filter in the main stabilizing path involving the \( \Delta P_c \) signal. This alleviates the exciter mode stability problem, thereby permitting a higher stabilizer gain that results in better damping of system oscillations. A conventional end-of-shaft speed measurement or compensated frequency signal can be used with this structure.

### 2.2.2 Design (Optimization) of Power System Stabilizers

Power System Stabilizer (PSS) controllers, tuned for one nominal operating condition, provide suboptimal performance when there are variations in the system load. There are two main approaches to stabilize a power system over a wide range of operating conditions, namely adaptive control and robust control.

Adaptive controllers have generally poor performance during the learning phase unless they are properly initialized. Robust control provides an effective approach to deal with the uncertainties introduced by variations of operating conditions. Many robust control techniques have been used in the design of PSS such as pole placement, the structured singular value and linear matrix inequality (LMI) [11]. Variable structure control applied to PSS results in high control activity [12].

PSS design based on the \( H_\infty \) approach is applied to the design of PSS for a single machine infinite bus system [13]. The basic idea is to carry out a search over operating points to obtain a frequency bound on the system transfer function. Then, a controller is designed so that the worst-case frequency response lies within pre-specified bounds. It is noted that the \( H_\infty \) design requires an exhaustive search and results in a high order controller.
PSS design based on Kharitonov theorem [14, 15] leads to conservative design [Appendix D.6] as well. The theorem assumes that the parameters of the closed loop characteristic polynomial vary independently. However, in practice, this never happens as these parameters depend on power system loading conditions. Practical operating conditions require the magnitude of the control signal to be within a certain limit. Constraints on rotor angle deviation have also to be considered, otherwise repetitive oscillations with severe overshoots may cause fatigue and damage to the generator shaft. In view of the above, a design technique is developed that obtains the PSS parameters avoiding: the conservatism in robust designs; large overshoots; control signal violation. This is the Particle Swarm Optimisation (PSO) – Based Power System Stabilizer (PSS) design technique.

2.2.2.1 PSO-Based PSS for Minimal Overshoot and Control Constraints.

This is a design technique that obtains the PSS parameters avoiding the conservatism in robust designs, large overshoots and control signal violation. Here, the optimum tuning of fixed structure lead controller to stabilize a single machine infinite bus system [Fig.2.3] is employed. (The lead controllers have found applications in power system control problem for their simplicity and ease of realization).

---

![Diagram: Single-Machine Infinite-Bus System](attachment:diagram.png)

**Fig. 2.3: Single-Machine Infinite-Bus System**
Minimizing the overshoot is equivalent to increasing system damping. A compromise between swiftness of response and allowable overshoot is considered. To achieve robustness and avoiding conservatism in design, the maximum overshoot is selected to be the worst over three operating regimes (heavy, nominal and light loading).

### 2.2.2.1.1 PSS Controller Design

Figure 2.3 shows the system under study, which represents a single machine infinite bus system consisting of a synchronous generator, an exciter and an automatic voltage regulator (AVR), an associated governor, and transmission lines. The infinite bus represents the Thevenin equivalent of a large interconnected power system. The nonlinear equations of the system are:

\[
\dot{\omega} = \omega_0 \omega,  \quad (5.1)
\]

\[
\omega = \frac{T_m - T_e}{M}, \quad (5.2)
\]

\[
E'_q = \frac{1}{T_{do}} \left( E_{fd} - \frac{x_d + x_e}{x_d + x_e} E'_q + \frac{x_d + x'_d}{x_d + x_e} V \cos \vartheta \right) \quad (5.3)
\]

\[
E_{fd}' = \frac{1}{T_E} \left( K_E E_{ref} - K_E V_t - E_{fd} \right) \quad (5.4)
\]

Where all the symbols used are defined in the Appendix B.3. The above equations are linearized for oscillation around an operating point and cast in the block diagram shown in Fig. 2.4.
The parameters of the model are a function of the loading \((P, Q)\). The state and output equations for the system under study are given by:

\[
\dot{x} = Ax + Bu \\
y = Cx 
\]

Where:

\[
x = \begin{bmatrix} \Delta \delta & \Delta \omega & \Delta E'_q & \Delta E_{fd} \end{bmatrix}
\]

\[
A = \begin{bmatrix}
0 & \omega_0 & 0 & 0 \\
-\frac{k_1}{T_E} & 0 & -\frac{k_2}{T_E} & 0 \\
0 & 0 & -1 & -1 \\
-\frac{k_5 k_E}{T_E} & 0 & -\frac{k_6 k_E}{T_E} & -1
\end{bmatrix} \quad B = \begin{bmatrix}
0 \\
0 \\
\frac{k_E}{T_E} \\
\frac{k_E}{T_E}
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
0 & 1 & 0 & 0
\end{bmatrix}, \quad T = k_3 T'_d' 
\]

Constants \(k_2\) to \(k_6\) represent the system parameters at a certain operating condition. Analytical expression of these parameters as a function of the loading \((P, Q)\) are summarized in the Appendix B.4. Typical data for such a system is as follows [11]: For the synchronous machine we have (pu):

\[
\Delta V_{ref} = 0 \\
\frac{k_E}{1+sT_E} \Delta E_f \\
\frac{k_3}{1+k_3 T''} \Delta E_q \\
\Delta T_e \\
\Delta T_m = 0 \\
\Delta \delta \\
\frac{314}{s} \Delta \omega
\]
\[ x_d = 1.6, \quad \dot{x}_d = 0.32, \quad x_q = 1.55 \]
\[ \omega_b = 2\pi \times 50 \text{ rad/sec}, \quad T'_{d0} = 6\text{sec}, \quad M = 10 \tag{8} \]

while for the transmission line (pu): \[ x_e = 0.4. \] To cover wide operating conditions of the machine under study, the following three loading regimes are selected (pu):

<table>
<thead>
<tr>
<th>Load</th>
<th>P</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Normal</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Light</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The selected regimes for designing PSS are chosen to cover heavy, medium and light loading. The proposed controller is designed based on the selected regimes. Testing the obtained controller is checked on the selected ones as well as other operating conditions. The resulting matrices of the state equation are:

1. **Heavy Load Regime**:

   \[
   A = \begin{bmatrix}
   0 & 314 & 0 & 0 \\
   -0.1360 & 0 & -0.1194 & 0 \\
   -0.2547 & 0 & -0.4633 & 0.1667 \\
   -42.1430 & 0 & -2480059 & -20 \\
   \end{bmatrix}
   \]

   \[
   B = \begin{bmatrix}
   0 \\
   0 \\
   0 \\
   500 \\
   \end{bmatrix}
   \]

   \[
   C = \begin{bmatrix}
   0 & 1 & 0 & 0 \\
   \end{bmatrix}
   \tag{9}
   \]

2. **Normal Load Regime**

   \[
   A = \begin{bmatrix}
   0 & 314 & 0 & 0 \\
   -0.1206 & 0 & -0.1236 & 0 \\
   -0.2636 & 0 & -0.4633 & 0.1667 \\
   32.1430 & 0 & -2256232 & -20 \\
   \end{bmatrix}
   \]

   \[
   B = \begin{bmatrix}
   0 \\
   0 \\
   0 \\
   500 \\
   \end{bmatrix}
   \]

   \[
   C = \begin{bmatrix}
   0 & 1 & 0 & 0 \\
   \end{bmatrix}
   \tag{10}
   \]
### 3. Light Load Regime

\[
A = \begin{bmatrix}
0 & 314 & 0 & 0 \\
-0.1186 & 0 & -0.0906 & 0 \\
-0.1934 & 0 & -0.4633 & 0.1667 \\
-5.9319 & 0 & -2257990 & -20
\end{bmatrix}, \quad B = \begin{bmatrix}
0 \\
0 \\
0 \\
500
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
0 & 1 & 0 & 0
\end{bmatrix}
\]

(11)

Given the system (5) we thus seek a lead controller of the form:

\[
u = G_c(s) \Delta \omega, \quad G_c(s) = k \frac{s-Z}{s-P}
\]

(12)

which stabilizes the system while minimizing the maximum overshoot of \(\Delta \delta(t)\) over the operating range. This robust minimal-overshoot controller is obtained by solving the following *mini-max optimization* problem:

\[
\text{minimize } J_1 = \max_{K,Z,P} [\Delta \delta(t)_{\text{max}} - \Delta \delta_{ss}] / \Delta \delta_{ss}
\]

\[\forall \text{ selected regimes}\]

(13)

where \(J_1\) represents the worst overshoot over the selected regimes, \(\Delta \delta_{\text{max}}\) and \(\Delta \delta_{ss}\) represent respectively the maximum and steady state values of *torque angle deviation*.

The control signal should not exceed bounds imposed by practical considerations. This can be cast as a performance index \(J_2\) as follows:

\[
\text{if } u_{\text{min}} < u < u_{\text{max}} \text{ then } J_2 = 0
\]

(14)

Otherwise;
Combining (14) and (15), the overall objective function is:

\[
\minimize_{K, Z, P} J_2 = \max(\abs{u - u_{\text{min}}}, \abs{u - u_{\text{max}}}) \\
\forall \text{selected regimes.} \tag{15}
\]

As \( \beta \to \infty \), control constraints given by (14) are satisfied. However, if (15) includes only \( J_2 \) one of the system constraints is not included in the optimization problem. That is, if the constraints given by (14) are included by clipping the control signal, then in this case the compensator output is no longer active during the clipping period. Accordingly, the values of the design parameters will not take into consideration control constraints. We may get a controller, but it will not be optimal. By injecting \( \beta J_2 \) in the cost function we guarantee that the designed compensator minimizes the overshoot as well as satisfying control constraints (to a certain extent since \( \beta \neq \infty \)). The parameters of the controllers may then be tuned using PSO [11], by minimizing (16).
2.3 Flexible AC Transmission System (FACTS) Devices

*Flexibility of Electric Power Transmission* refers to the ability to accommodate changes in the electric transmission system or operating conditions while maintaining sufficient steady state and transient margins. Wherein, *Flexible AC Transmission Systems (FACTS)* are alternating current transmission systems incorporating power electronic-based and other static controllers (static Controllers not based on power electronics) to enhance controllability and increase power transfer capability. Specifically, *FACTS Controller (device)* refers to a power electronic-based system and other static equipment that provides control of one or more AC transmission system parameters.

It is important to note that FACTS technology refers not to a single high-power Controller, but rather a collection of Controllers, which can be applied individually or in coordination with others to control one or more of the interrelated system parameters which include: *series impedance, shunt impedance, current, voltage* and *phase angle*. The era of the FACTS was triggered by the development of new solid-state electrical switching devices. Gradually, the use of the FACTS has given rise to new controllable systems. The *thyristor* or *high-power transistor* is the basic element for a variety of high-power electronic Controllers (FACTS).

### 2.3.1 Relative Importance of Controllable Parameters

Power flow control presents, among others, the following possibilities:

i. Control of the line impedance $X$ (e.g., with a *thyristor-controlled series capacitor*) can provide a powerful means of current control.

ii. When the phase angle is not large, which is often the case, control of $X$ or the angle, substantially provides the control of active power. Furthermore, Control of the angle (with a Phase Angle Regulator, for example), which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.

iii. Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since the current flow lags the
driving voltage by 90 degrees, this means injection of reactive power in series, (e.g., with *static synchronous series compensation* can provide a powerful means of controlling the line current, and hence the active power when the angle is not large.

iv. Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of precisely controlling the active and reactive power flow. This requires injection of both active and reactive power in series.

v. Because the per unit line impedance is usually a small fraction of the line voltage, the Mega Volt Ampere (MVA) rating of a series Controller will often be a small fraction of the throughput line MVA.

vi. When the angle is not large, controlling the magnitude of one or the other line voltages (e.g., with a thyristor-controlled voltage regulator) can be a very cost-effective means for the control of reactive power flow through the interconnection. Combination of the line impedance control with a series Controller and voltage regulation with a shunt Controller can also provide a cost-effective means to control both the active and reactive power flow between the two systems.

### 2.3.2 Basic Types of FACTS Controllers

In general, FACTS Controllers can be divided into four categories:

i. **Series Controllers**: The series Controller could be a variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, sub-synchronous and harmonic frequencies (or a combination) to serve the desired need (e.g. TCSC). In principle, all series Controllers inject voltage in series with the line. Even a variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.
ii. **Shunt Controllers**: As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these (e.g. SVC). In principle, all shunt Controllers inject current into the system at the point of connection. Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

iii. **Combined series-series Controllers**: This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real-power transfer capability of the unified series-series Controller, referred to as *Interline Power Flow Controller*, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. (The term "unified" here means that the dc terminals of all Controller converters are all connected together for real power transfer).

iv. **Combined series-shunt Controllers**: This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner, or a *Unified Power Flow Controller* with series and shunt elements. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series with the line, with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.

### 2.3.3 Overview of Flexible AC Transmission System (FACTS) Devices

The modification of voltage magnitudes and/or their phase by adding a control voltage is an important concept that forms the basis of some of the first generation (G1) FACTS devices. The injected voltage need not be realized through electromagnetic transformer-winding
arrangements; instead, by using high-speed semiconductor switches such as Gate Turn-Off (GTO) Thyristors and Voltage Source Inverters (VSIs)—synchronized with the system frequency—FACTS devices are developed.

The application of a Voltage Source Inverter (VSI) to compensate the line voltage drop yields a fast, controllable reactive-power compensator: the Static Synchronous Series Compensator (SSSC). The application of a VSI to inject a phase-quadrature voltage in lines yields a fast, controllable phase shifter for active-power control. Once a synchronized VSI is produced, both the magnitude and the phase angle of the injected voltages are regulated, yielding a Unified Power-Flow Controller (UPFC).

A thyristor switch used to turn on or turn off a capacitor, implements a switched capacitor. Parallel combination of switched capacitors and controlled reactors provides a smooth current-control range from capacitive to inductive values by switching the capacitor and controlling the current in the reactor. Shunt combinations of thyristor-controlled reactors (TCRs) and thyristor-switched capacitors (TSCs) yield Static Var Compensators (SVCs). Thyristor switches may be used for shorting capacitors; hence they find application in step changes of series compensation of transmission lines. A blocked thyristor switch connected across a series capacitor introduces the capacitor in line, whereas a fully conducting thyristor switch removes it. This step control can be smoothed by connecting an appropriately dimensioned reactor in series with the thyristor switch—as shown in Fig. 2.6—to yield the Thyristor-Controlled Series Capacitor (TCSC) FACTS controller.

Thyristor switches are used to control the current through circuit elements, such as capacitors and reactors. The switches are also used to perform switching actions in on-load tap changers, which may be employed as Thyristor-Controlled Phase-Shifting Transformers (TCPSTs). An alternative to a thyristor-controlled SVC is a Gate Turn-Off (GTO)-based VSC (Voltage Source Converter) that uses charged capacitors as the input dc source and produces a 3-phase ac voltage output in synchronism and in phase with the ac system. The converter is connected in
shunt to a bus by means of the impedance of a coupling transformer. A control on the output voltage of this converter—lower or higher than the connecting bus voltage—controls the reactive power drawn from or supplied to the connected bus. This FACTS controller is known as a Static Compensator (STATCOM) and is shown symbolically in Fig. 2.7.

![Fig. 2.5: A Thyristor Switch for AC Applications: (a) a switch (b) a controlled reactor current](image)

The use of voltage-source converters (VSCs) to inject a voltage by way of series-connected transformers leads to the Static Synchronous Series Compensators (SSSCs), which inject voltages to compensate for the line-reactance voltage drops. It is easy to visualize that if the reactive drop of a line is partly compensated by an SSSC, it amounts to reducing the line reactance ($X_L$), akin to controlled series compensation. The injected voltage in the line is independent of the line current. Figure 2.8 shows a 1-line diagram of an SSSC, which controls the active-power flow on a line. The functions of an SSSC and a STATCOM, in fact, may be combined to produce a Unified Power-Flow Controller (UPFC). A 1-line diagram of a UPFC is shown in Fig. 2.9. In the UPFC shown, a dc energy source is shared between the STATCOM and SSSC. Normally, no net
energy is drawn from this source, but to compensate for the controller losses, the STATCOM operates so that it draws the compensating active power from the connected ac bus. Thus a UPFC offers a fast, controllable FACTS device for the flow of combined active-reactive power in a line.

Finally, there are FACTS controllers classified as power-conditioning equipment. These controllers are employed as battery-energy-storage systems (BESSs) or superconducting magnetic-energy-storage (SMES) systems. These controllers also use GTO-based converters, which operate in dual roles as rectifiers for energy storage and inverters for energy return.

FACTS devices are increasingly being used as cost effective measures to increase power system transmission capability, to improve first swing margin, to actively damp oscillations and to help stabilize weakly coupled systems in the event of critical faults. The design of Thyristor Controlled Series Capacitors (TCSCs) and Static Var Compensators (SVCs) is discussed in detail.

2.3.4 Design of Static Var Compensators (SVCs)

Static Var compensators (SVCs) rated at 50 ~ 300 MVar, consisting of voltage source inverters using gate-turn-off (GTO) thyristors, are employed in improving power factor and stabilizing transmission systems. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs
reactive power (SVC inductive). The SVC can adjust the amplitude of the ac voltage of the inverters by pulse-width modulation (PWM) or by controlling the dc bus voltage, thus producing either leading or lagging reactive power.

A pulse-width-modulated SVC, in which the dc voltage is controlled to remain at a constant value, responds rapidly to a change in reactive power at the expense of increasing the switching and snubbing losses. High efficiency and high reliability are a priority in practical power system applications of the SVCs. On the other hand, a dc voltage-controlled SVC, which directly controls the dc capacitor voltage by causing a small amount of active power to flow into or out of the voltage-source inverters, results in less switching and snubbing losses because the switching frequency is low. However, the dc voltage-controlled SVC is inferior to the Pulse Width Modulated (PWM) SVC in the transient response of reactive power. A model of the SVC based on the pq theory [17] is developed, and has the ability to deal with the power flow between the ac and dc sides in a transient state.

### 2.3.4.1 Modelling of the SVC

The following assumptions are made in modelling the SVC: first, any harmonic voltage caused by the switching operation of the inverters is excluded from the synthesized ac voltage of the SVC; second, the instantaneous amplitude of the fundamental component of the ac voltage is proportional to the instantaneous voltage of the dc capacitor; third, no power loss occurs in the inverters, therefore the active power on the ac side is equal to the active power on the dc side. The assumptions mean that the harmonic voltage caused by fluctuation of the dc voltage is included in the synthesized ac voltage. Assume an ideal three-phase power supply given by:

\[
\begin{bmatrix}
    v_{Su} \\
    v_{Sv} \\
    v_{Sw}
\end{bmatrix}
= \sqrt{3} V_s \begin{bmatrix}
    \cos \omega_0 t \\
    \cos(\omega_0 t - 2\pi/3) \\
    \cos(\omega_0 t + 2\pi/3)
\end{bmatrix}
\]  

(17)

where \( V_s \) is the rms voltage of the supply and \( \omega_0 \) is its angular frequency. The above assumptions lead to the following ac voltage of the SVC:
\[
\begin{bmatrix}
    v_u \\
    v_v \\
    v_w
\end{bmatrix} = \sqrt{\frac{2}{3}} k v_c \begin{bmatrix}
    \cos(\omega_0 t + \Phi) \\
    \cos(\omega_0 t - 2\pi/3 + \Phi) \\
    \cos(\omega_0 t + 2\pi/3 + \Phi)
\end{bmatrix}
\]

(18)

where \( \phi \) is the angle of the fundamental ac voltage with respect to the supply voltage, and \( K \) is the ac to dc voltage ratio of the SVC.

![Fig. 2.10: Model of the SVC: Single-Phase Equivalent](image)

Using Fig. 2.10, one obtains the following equation:

\[
\begin{bmatrix}
    v_{Su} \\
    v_{Sp} \\
    v_{Sw}
\end{bmatrix} = R + L \frac{d}{dt} \begin{bmatrix}
    i_u \\
    i_v \\
    i_w
\end{bmatrix} + \begin{bmatrix}
    v_u \\
    v_v \\
    v_w
\end{bmatrix}
\]

(19)

Invoking Assumption 3 results in the following equation for active power:

\[
p = v_u i_u + v_v i_v + v_w i_w = \frac{d}{dt} \frac{C}{2} v_c^2 = C v_c \frac{dv_c}{dt}
\]

(20)

The \( pq \) theory can be used to transform (21) ~ (24) to:

\[
\begin{bmatrix}
    L \frac{d}{dt} + R & -\omega_0 L \\
    \omega_0 L & L \frac{d}{dt} + R
\end{bmatrix}\begin{bmatrix}
    i_p \\
    i_q
\end{bmatrix} = \begin{bmatrix}
    V_S - k v_c \cos \Phi \\
    -k v_c \sin \Phi
\end{bmatrix}
\]

(21)

Equation (24) can be represented as a function of \( i_p \) and \( i_q \) as follows:
In (21) and (22), $i_p$ is an instantaneous active current and $i_q$ is an instantaneous reactive current.

The instantaneous reactive power drawn from the supply, $q_s$ is given by:

$$q_s = v_{sp} \cdot i_q - v_{sq} \cdot i_p = V_s \cdot i_q$$ \hspace{1cm} (23)

### 2.3.4.2 Transient Response of Reactive Power

The following analysis assumes a step change in $\phi$ from 0 to $\Phi$ (i.e., $\phi(t) = \Phi \cdot u(t)$, where $u(t)$ is a unit step function). This allows us to deal with the nonlinear functions as constant values which equal $sin \Phi$ and $cos \Phi$, respectively, when $t \geq 0$. This analysis is applicable for a large step change in $\Phi$.

At first, one has to calculate the initial values of $i_p$ and $i_q$ and $v_c$ at time $t = 0$. Such a relationship that the initial values equal their steady-state values at $\phi = 0$ in (21) and (22) gives us their initial values as $i_p(0) = 0$, $i_q(0) = 0$, and $v_c(0) = V_s/K$. Note that the initial value of $v_c$ is not zero. The Laplace transformations of (25) are represented as follows:

$$(sL + R)I_p(s) - \omega_0 L I_q(s) = \frac{V_s}{s} - K \cos \Phi V_c(s) \hspace{1cm} (24)$$

$$\omega_0 L I_p(s) + (sL + R)I_q(s) = -K \sin \Phi V_c(s) \hspace{1cm} (25)$$

Taking into account the initial value of $v_c$, one obtains the Laplace transformation of (22) as follows:

$$sV_c(s) - v_c(0) = \frac{K}{C} \{ \cos \Phi I_p(s) + \sin \Phi I_q(s) \} \hspace{1cm} (26)$$

The Laplace function for the reactive power, $I_q(s)$ is obtained from (24), (25), and (26), as follows:
\[ I_q(s) = \frac{-V_S \left( \frac{A_1}{L} + \left( \frac{R A_1}{L^2} + \omega_0 A_2 \right) + \frac{K^2 A_3}{L^2 C_S} \right)}{s^3 + 2R^L s^2 + \left( \frac{R^2}{L^2} + \frac{K^2}{L C} + \omega_0^2 \right) s + \frac{K^2 R}{L^2 C}} \]  \tag{27}

Where:
\[ A_1 = \sin\Phi, \ A_2 = (1 - \cos\Phi), \ A_3 = \sin\Phi \cos\Phi \]

The following approximation appropriate for the SVC is applied to (31):

\[ R^2/L^2 + K^2/LC \gg \omega_0^2 \]

This allows us to derive the following basic equation:

\[ I_q(s) \approx \left\{ -\frac{B_1}{s} + \frac{B_1 - B_2}{s + R/L} + \frac{s B_2 + B_3}{s^2 + (R/L)s + K^2/LC} \right\} V_S \quad \tag{28} \]

Where: \[ B_1 = (\sin\Phi \cos\Phi)/R, \ B_2 = (1 - \cos\Phi)\omega_0 C/K^2, B_3 = \sin\Phi(1 - \cos\Phi)/L \]

The first and second terms on the right side in (28) are the dominant response of reactive power, while the third term means that an oscillatory component exists. The time constant of the transient response of reactive power, \( T \) is equal to the time constant determined by \( L \) and \( R \) as depicted in Fig. 2.10 and is given as follows:

\[ T = \frac{L}{R} \quad \tag{29} \]

Note that the capacitance of the dc capacitor, \( C \) is excluded from (29). This means that the amount of active power flowing into the SVC is proportional to \( C \) while the dc bus voltage is rising.
2.3.4.3 SVC Control

The SVC can be operated in two different modes: In voltage regulation mode (the voltage is regulated within limits) and in var control mode (the SVC susceptance is kept constant). Fig. 2.11 shows the block diagram of the control circuit. Reactive power feedback using a PI controller makes it possible to improve the transient response of the reactive power. The $pq$ transform circuit calculates the instantaneous reactive power $qs$ from the three-phase supply voltages and the three-phase currents. The calculated reactive power $qs$ and the reference reactive power $q^*$, are applied to the proportional-integral (PI) controller. The output of the PI controller is a reference signal representing the phase angle $\phi^*$.

The counter produces the phase information, $\omega_0t$, from a signal generated by the phase locked loop (PLL) circuit. The phase comparator compares $\Phi$ with $\omega_0t$, and determines the time at which the corresponding switching device is turned on or off. The gate control circuit prevents each switching device from being switched-on more than once in one cycle due to fast changes in $\Phi$.

![Block Diagram of SVC Control Circuit](image)

**Fig. 2.11: Block Diagram of SVC Control Circuit**
2.3.5 Design of Thyristor Controlled Series Capacitor

Among the FACTS devices, the Thyristor Controlled Series Capacitor (TCSC) gives the best results in terms of performance and flexibility. It can have various roles in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; limiting short-circuit currents; mitigating sub-synchronous resonance (SSR); damping power oscillations; and enhancing transient stability. The design objective is to improve the stability of a single-machine infinite-bus (SMIB) power system, subjected to disturbances.

2.3.5.1 Modelling the Power System with TCSC

The basic module of a TCSC is shown in Fig.2.12. It consists of three components: capacitor banks \( C \), bypass inductor \( L \) and bidirectional thyristors \( T_1 \) and \( T_2 \). The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle (\( \alpha \)) or conduction angle (\( \sigma \)), this process can be modelled as a fast switch between corresponding reactance offered to the power system.

Assuming that the total current passing through the TCSC is sinusoidal; the equivalent reactance at the fundamental frequency can be represented as a variable reactance \( X_{TCSC} \). There exists a steady-state relationship between \( \alpha \) and the reactance \( X_{TCSC} \):

\[ Y = G + jB \]

\[ Z = R + jX \]

Fig. 2.12: Basic Module of a TCSC  
Fig. 2.13: The Single Machine Infinite Bus System with TCSC
\[ X_{TCSC}(\alpha) = X_c - \frac{X_c^2(a\sin\alpha)}{(X_c - X_p)\pi} + \frac{4X_c^2 \cos^2(\pi/2) [k\tan(k\pi/2) - \tan(\pi/2)]}{(X_c - X_p)(k^2 - 1)\pi} \] (31)

Where: \( X_c \) = Nominal reactance of the fixed capacitor \( C \); \( X_p \) = Inductive reactance of inductor \( L \) connected in parallel with \( C \); \( \alpha = 2(\pi - \alpha) \), the conduction angle of TCSC controller. 
\( k = \sqrt{X_c/X_p} \), the compensation ratio.

Since the relationship between \( \alpha \) and the equivalent fundamental frequency reactance offered by TCSC, \( X_{TCSC}(\alpha) \) is a unique-valued function, the TCSC is modelled here as a variable capacitive reactance within the operating region defined by the limits imposed by \( \alpha \). Thus \( X_{TCSCmin} \leq X_{TCSC} \leq X_{TCSCmax} \), with \( X_{TCSCmax} = X_{TCSC}(amin) \) and \( X_{TCSCmin} = X_{TCSC}(1800) = X_c \). The controller is assumed to operate only in the capacitive region, i.e., \( \alpha_{min} > \alpha \), where \( \alpha_r \) corresponds to the resonant point, as the inductive region associated with \( 90^0 < \alpha < \alpha_r \) induces high harmonics that cannot be properly modelled in stability studies.

The generator has a local load of admittance \( Y = G + jB \) and the transmission line has impedance of \( Z = R + jX \). In the figure \( V_T \) and \( V_B \) are the generator terminal and infinite bus voltage respectively. The generator is represented by the third-order model comprising of the electromechanical swing equation and the generator internal voltage equation. The state equations may be written as:

\[ \dot{\omega} = P_m - P_e - D(\omega - 1)/M, \quad \dot{\delta} = \omega_b(\omega - 1), \quad V_T = v_d + jv_q, \quad I = i_d + ji_q \] (32)

where, \( P_m \) and \( P_e \) are the input and output powers of the generator respectively; \( M \) and \( D \) are the inertia constant and damping coefficient respectively; \( \omega_b \) is the synchronous speed; \( V_T \) is the terminal voltage; \( I \) is the current, \( \delta \) and \( \omega \) are the rotor angle and speed respectively.

The \( d \)- and \( q \)-axis components of armature current, \( I \) can be calculated as:

\[ \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} Y_d \\ Y_q \end{bmatrix} E' \begin{bmatrix} -v_g \\ Z_e \end{bmatrix} \begin{bmatrix} R_2 & X_1 \\ -X_2 & R_1 \end{bmatrix} \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix} \] (33)
With:

\[ Y_d = (C_1 X_1 - C_2 R_2) / Z_e^2, \quad Y_q = C_1 R_1 + C_2 X_2 / Z_e^2, \quad C_1 = 1 + R G - X B, \quad C_2 = R B + X G \]

\[ Z_e^2 = R_1 R_2 + X_1 X_2, \quad R_1 = R - C_2 X_d', \quad R_2 = R - C_2 X_q, \quad X_1 = X_{Eff} + C_1 X_q \]

\[ X_2 = X_{Eff} + C_1 X_d \quad X_{Eff} = X - X_{TSCS} \alpha \]

The generator power \( P_e \), the internal voltage \( E_q' \) and the terminal voltage \( V_T \) can be expressed as:

\[ P_e = E_q'^* i_q + (X_q - X_d') i_d \]

\[ E_q' = \left[ E_{fd} - E_q' - (X_d' - X_d) i_d \right] / T_{do}' \]

\[ V_T = \sqrt{(X_q i_q)^2 + (E_q' - X_d i_d)^2} \]

Here, \( E_{fd}' \) is the field voltage; \( T_{do}' \) is the open circuit field time constant; \( X_d \) and \( X_d' \) are the \( d \)-axis reactance and the \( d \)-axis transient reactance of the generator respectively. The IEEE Type-\textit{ST1} excitation system is considered in this work. It can be described as:

\[ E_{fd}' = \left[ K_A (V_{ref} - V_T) - E_{fd} \right] / T_A \]

where, \( K_A \) and \( T_A \) are the gain and time constant of the excitation system; \( V_{ref} \) is the reference voltage.
2.3.5.2 Structure of the Lead-Lag Controller

The LL structure of TCSC-based damping controller, to modulate the reactance offered by the TCSC, $X_{TCSC}(\alpha)$ is shown in Fig. 2.14. The input signal of the proposed controllers is the speed deviation ($\Delta \omega$), and the output signal is the reactance offered by the TCSC, $X_{TCSC}(\alpha)$. The Lead Lag (LL) controller consists of a gain block with gain $K_s$, a signal washout block and two-stage phase compensation blocks. The signal washout block serves as a high-pass filter, with the time constant $T_W$, high enough to allow signals associated with oscillations in input signal to pass unchanged. From the viewpoint of the washout function, the value of $T_W$ is not critical and may be in the range of 1 to 20 seconds. The phase compensation block (time constants $T_1$, $T_2$ and $T_3$, $T_4$) provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals.

![Fig. 2.14: Lead-lag structure of TCSC-based controller](image)
3. STABILITY OF AN ELECTRIC POWER SYSTEM EMPLOYING PSS AND SVC

The SimPowerSytems software was used in analyzing a simple transmission system containing two hydraulic power plants [Appendix E]. A static var compensator (SVC) and power system stabilizers (PSSs) were used to improve transient stability and power oscillation damping of the system. The phasor simulation method [Appendix G.17] was employed to demonstrate the effectiveness of either controller.

3.1 Description of the Transmission System

The test system consisted of a 144 MW hydraulic generation plant (machine M1) connected to a load centre through a 132 kV, 300 km transmission line. The load centre was modelled by a 280 MW resistive load. The load was fed by the remote 144 MW plant and a local generation of 144 MW (machine M2). The system had been initialized so that the line carried 182 MW which was its surge impedance loading. In order to maintain system stability after faults, the transmission line was shunt compensated at its centre by a 50-Mvar Static Var Compensator (SVC). The two machines were equipped with a Hydraulic Turbine and Governor (HTG), Excitation system and Power System Stabilizer (PSS). (These blocks are located in the two 'Turbine and Regulator' subsystems of the simulation block diagram [Appendix E]). Two types of stabilizers could be selected: a generic model using the acceleration power (Pa type) [19] and a Multi-band stabilizer (MB PSS) [20, 21] using the speed deviation ($dw$). During the simulation, faults were applied on the system and the impact of the PSS and SVC on system stability observed.

Fig. 3.1: 132 KV Transmission Line
3.2 Single-phase fault: Impact of PSS - No SVC

A single phase fault was applied to the system in the transition time 0.1s to 0.2s. With no application of either PSSs or SVC, the oscillation of the system was as indicated in Fig.: 3.2. Thereafter, with the SVC put out of service (‘Fixed Susceptance’ mode with $\beta_{\text{ref}} = 0$) but with the two PSSs (Pa type) in service, the simulation was started and signals observed on the 'Machines' scope. For this type of fault the system was stable without the SVC. After fault clearing, the 0.8 Hz oscillation was quickly damped, Fig.:3.3. This oscillation mode was typical of inter-area oscillations in a large power system. First trace on the 'Machine' scope showed the rotor angle difference $d_{\text{theta1_2}}$ between the two machines. Power transfer was maximum when this angle reached 90 degrees. This signal was a good indication of system stability. If $d_{\text{theta1_2}}$ exceeded 90 degrees for too long a period of time, the machines would lose synchronism and the system would become unstable. Second trace showed the machine speeds. The machine 1 speed increased during the fault because during that period its electrical power was lower than its mechanical power. By simulating over a long period of time (50 seconds) it was noticed that the machine speeds oscillate together at a low frequency (0.025 Hz) after fault clearing, Fig.3.4. The two PSS (Pa type) succeed to damp the 0.8 Hz mode but they are not efficient for damping the 0.025 Hz mode. Selecting the Multi-band PSS resulted in both the 0.8Hz and 0.025 mode oscillations being damped, Fig.3.5.

3.3 Three-phase fault: Impact of SVC - Two PSSs in Service

A three phase fault was applied in the transition time 0.1s to 0.2s. The effect of this fault on the system was profound, Fig.3.6. The two PSSs (Pa type) and the SVC defined to work in the 'Voltage regulation' mode were then put in service; and the same 3-phase-to-ground fault applied. In the ‘voltage regulation’ mode, the SVC supported the voltage by injecting reactive power on the line when the voltage was lower than the reference voltage. The chosen SVC reference voltage corresponded to the bus voltage with the SVC out of service. On simulation, it was observed that the system was stable with a 3-phase fault, Fig.3.7.
Fig. 3.2: Impact of Single Phase Fault; no PSSs, no SVC
Fig.3.3: Impact of PSSs (Pa-type), no SVC, on Single-Phase Fault
Fig. 3.4: Impact of PSSs (Pa-type), no SVC, for Single-Phase Fault (Longer Simulation)
Fig. 3.5: Impact of Multi-band PSSs, no SVC, for 1-Phase Fault
Fig. 3.6: Three-Phase Fault; No PSSs, No SVC
Fig. 3.7: Impact of PSSs (Pa-Type), and SVC, on 3-Phase Fault
Where:

d_\text{theta1}_2 is the rotor angle difference between the two machines M1 and M2

\omega_1 is the speed of machine M1

\omega_2 is the speed of machine M2

v_{t1} is the terminal voltage of machine M1

v_{t2} is the terminal voltage of machine M2

Where there are two lines on the graph:

Green line represents machine M1

Magenta line represents machine M2
4. CASE STUDY

4.1. The Kenya Power and Lighting Company (KPLC)

Presently, the Kenya Power and Lighting Company does not employ any of the discussed controllers to damp power oscillations in its lines. According to Engineer Peter Mungai, there are a number of good reasons for this:

For a long time, KPLC was the sole generator, transmitter and distributor of Electric Power in Kenya. The best place to obtain reactive Mega Volt Amperes (MVars) to damp the system being the generators, KPLC easily accessed the MVars necessary to damp the system, whenever required. This, in part, explains the non-utilisation of modern sophisticated FACTS on KPLC lines. There was no urgent need at the time. However, with the entry of the Kenya Electricity Generating Company (KENGEN), KPLC no longer has access to unlimited reactive power, whenever required.

KPLC still employs stand-alone capacitors and/or reactors at strategic sections of the line as a means to ensure stability in the lines. This, it is argued, has been producing satisfactory results. As well, these stand alone devices are very flexible; they can easily be shifted along the same line or even to another line should the present line outgrow the device’s capacity; this, unlike many sophisticated Flexible AC Transmission System (FACTS) devices, like the SVC, which are designed to function along a specific line and are usually implemented at substations (Distribution Stations).

With the emergence of Independent Power Producers (IPPs), and the expansive growth of the KPLC grid, introduction of sophisticated Flexible AC Transmission System (FACTS) devices as an effective means to damp oscillations has become an immediate necessity. KPLC has plans to introduce SVCs in the near future. They currently have one of their Chief Engineers, Robert Njoroge, undertaking a Masters program at the Jomo Kenyatta University of Agriculture and Technology, JKUAT, on FACTS devices and their effectiveness in damping Power Oscillations. This same engineer attended a conference (between March 27, 2009 and March 31, 2009) in the United States of America on SVCs. Underscroing the transmission and distribution
company’s resolve to modernize and enhance its efficiency. The rolling out of SVCs is intended to begin in Nairobi; at the major distribution stations such as Juja and Embakasi.

4.2 The Kenya Electricity Generating Company (KenGen)

KenGen is a power producing company with several electric power generating plants in the country. For KenGen, power swings are a particularly undesirable feature and must be damped quickly for the network to remain stable. “If left un-damped, these oscillations could lead to network instability and Grid collapse leading to National blackout,” Engineer Eliud Wamakima, KenGen. “At KenGen we have had no occurrence that led to Grid collapse.” KenGen does employ Power System Stabilizers (PSSs) in some of its generator excitation systems.

4.2.1 Typical Power System Stabilizer employed

As stated above, the PSS [Appendix B.2, Appendix C] is incorporated in the excitation system of the generator. The inputs are Frequency and Power to this function. The output of the PSS controls the field current to the generator, counteracting the power swing in order to damp it. The PSS is sometimes left selectable by the plant operator. When it acts, the operator will get feedback that the PSS is active.

4.2.2 Cost of PSS

For generators, the PSS is an ADD ON function to the excitation system. It is never sold alone. However the cost of an excitation system that is capable of 1500 Amps DC, 300 V DC, excluding the excitation transformer is about KSh. 17 Million. Such excitation systems are imported as they are not locally manufactured, nor are they readily available in the local market.
5. CONCLUSION

A study of Power System Stabilizer (PSS), Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC)-based controllers has been carried out. The design of these controllers was discussed in brief and their effectiveness in enhancing power system stability assessed.

In the PSS design, Particle Swarm Optimisation (PSO) was employed where the search for the optimal controller parameter settings that optimize the objective function was done. To guarantee the robustness of the proposed controller, the design process was carried out considering a wide range of operating conditions: Heavy, normal and light loading. The SVC design process employed gate turn-off thyristors and dc voltage-control. A model of the Power system containing a TCSC was assessed, from which a design of the employed TCSC was derived.

Of the studied controllers, the TCSC is the most versatile FACTS controller finding wide application in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; limiting short-circuit currents; mitigating sub-synchronous resonance (SSR); damping power oscillations; and enhancing transient stability. Meanwhile, the SVC enhances system stability by controlling the amount of reactive power injected into or absorbed from the power system. On the other hand, the PSS has for a long time found application in the exciters of synchronous machines as an effective means of damping the generator unit’s characteristic electromechanical oscillations by modulating the generator excitation.

A simulation was carried out to demonstrate the effectiveness of the PSS and SVC in damping power oscillations. Results obtained clearly highlighted the reasons behind the fast spreading use of Power Oscillation Damping controllers in power systems worldwide: In Kenya, KenGen employs PSSs in its excitation systems while KPLC is due to roll out SVCs in its transmission and distribution systems. Thus, PSSs and FACTS are fast becoming a necessity in power system stability enhancement rather than an option to be considered.
6. FURTHER WORKS

While a study has been done of the PSS and FACTS controllers (SVC and TCSC), in fact many more FACTS are yet to be studied and the full extent of their capabilities assessed. The versatility of FACTS technology means that Power system engineers across the world have leeway to come up with FACTS controllers specific to their needs and systems. An interesting angle to this fast growth in the FACTS area is that the IEEE is at pains to keep up with standardization of new terms and definitions that sprout with the advent of such new (and maybe system-specific) FACTS controllers. Thus the field of FACTS technology is especially dynamic, presenting ample study and research ground.

The study of the PSS with a view to assessing possible improvement areas is also of importance. Equally important is a deeper understanding and comprehension of the technologies discussed in this report. This may be done in the light of the already on-going use of PSSs by KenGen, Kenya; and the soon-to-be implemented SVC technology by the KPLC, Kenya. An important aspect to this particular study would be the cost implications these technologies have or would have to both the generation and transmission/distribution companies, and to the consumer of electric power whose eventual satisfaction is paramount.

With the controller hardware, is software that presents the management aspect of this technology. A study of the various software employed and their role in the monitoring of electric power systems is of great import as well.
APPENDIX A

POWER SYSTEM STABILITY

A.1 System Stability

The stability of a physical system is referred to as its capability to return to the original equilibrium position on the occurrence of a perturbation (disturbance) or to another equilibrium state which is generally in the proximity of the initial equilibrium point. If the state of the system “runs away” so that the physical variables go on increasing as $t \to \infty$, then the system is referred to as unstable. These intuitive ideas are applicable to the electric power system.

A.2 Power System Stability

Every power system has a number of synchronous machines operating in parallel. When applied to electric power systems, stability denotes a condition in which the various synchronous machines in the system remain in synchronism or in step with each other. Conversely, instability denotes a condition involving loss of synchronism or falling out of step. Thus, power system stability is concerned with the conditions necessary for the successful operation of a power system when changing from one stable condition to another due to variations in its operating condition which can be classified as either small and slow or large and sudden; where slow means a long time action compared with the time constants of the field circuits of the machines, of automatic voltage regulators and of the turbine governors.

A.2.1 Types of Stability and Stability Limit

The stability limit is defined as the maximum power which can flow through a point in the system without causing loss of stability. The stability problem can be subdivided into steady stability, transient stability and dynamic stability.

A power system has steady state stability if after a small disturbance it can regain and maintain synchronous speed. The small slow disturbance means normal load variations or changes. The steady state stability limit is the maximum possible flow of power, without loss of stability, when the power is changed very slowly.

A power system has transient stability if, after a large sudden disturbance, it can regain and maintain synchronous speed. A large sudden disturbance is one which is caused by faults and switching. The transient stability limit refers to the maximum possible flow of power without loss of stability when a large sudden disturbance occurs. It is important to note that transient
stability limit is generally less than the steady state stability limit; thus transient stability is oft of greater importance in the analysis of the electric power system [25].

Dynamic stability is sometimes referred to as the case of transient stability when the regulators and governors are fast acting and are taken into account in the analysis. In dynamic stability studies, the system is analysed for 4 to 10 seconds following a large disturbance such as short circuit or loss of generation or loss of load, e.t.c.
APPENDIX B

POWER SYSTEM STABILIZER (PSS)

B.1. Typical values of the parameters of a Power System Stabilizer (PSS)

The lead transfer function of the power system stabilizer is given by:

\[ G_c(s) = K_{PSS} \frac{1 + T_1 s}{1 + T_2 s} \]

Typical values of the parameters are:
- \( K_{PSS} \) is the PSS gain in the range of 0.1 to 50,
- \( T_1 \) is the lead time constant, 0.2 to 1.5 sec,
- \( T_2 \) is the lag time constant, 0.02 to 0.15 sec.

B.2. The IEEE standard model used to represent the Accelerating Power PSS Model

![Accelerating Power PSS Model](image)

Fig. A.1: Accelerating Power PSS Model

B.3. Symbols Used in Problem Formulation of the PSS

All quantities are in p.u. except the time constants and M, which are in seconds.

- \( T_m \) : mechanical torque.
- \( T_e \) : electrical torque.
- \( V_t \) : terminal voltage.
- \( \text{emf} \) : electro motive force.
- \( E_q \) : induced emf proportional to field current.
\( E_{fd} \): generator field voltage.
\( V_{ref} \): reference value of generator field voltage.
\( x_d', x_d, x_q \): generator direct-axis transient reactance, direct and quadrature-axis synchronous reactance respectively.
\( x_e \): external (line) reactance.
\( \delta \): angle between quadrature axis and infinite bus bar.
\( \Delta \omega \): speed deviation.
\( \omega_0 \): \( 2\pi f \), \( f \) = 50 Hz.
\( T'_{do} \): open circuit direct-axis transient time constant.
\( M \): inertia coefficient.
\( k_E, T_E \): exciter gain and time constant.
\( U \): stabilizing signal (PSS output).
\( V \): infinite bus-bar voltage.
\( P, Q \): real and reactive power loading; respectively.
\( k_1, \ldots, k_6 \): the \( k \)-parameters of the synchronous generator block diagram.
\( s \): the Laplace operator.

**B.4. Analytical Expression of the K-Parameters of the Machine in Terms of P and Q (The Loading)**

\[
k_1 = C_3 \frac{P^2}{P^2 + (Q + C_1)^2} + Q + C_1,
\]
\[
k_2 = C_4 \frac{P}{\sqrt{P^2 + (Q + C_1)^2}},
\]
\[
k_3 = \frac{x_d' + x_e}{x_d + x_e},
\]
\[
k_4 = C_5 \frac{P}{\sqrt{P^2 + (Q + C_1)^2}},
\]
\[
k_5 = C_4 x_e \frac{P}{V^2 + Q x_e} \left[ C_6 \frac{C_1 + Q}{p^2 + (C_1 + Q)^2} \right],
\]
\[
k_6 = C_7 \frac{\sqrt{P^2 + (Q + C_1)^2}}{V^2 + Q x_e} \left[ \frac{x_e + C_1 x_q (C_1 + Q)}{p^2 + (C_1 + Q)^2} \right],
\]
\[
C_1 = \frac{V^2}{x_e + x_q}, \quad C_2 = k_3
\]
\[
C_3 = C_1 \frac{x_q - x_d'}{x_e + x_d'}, \quad C_4 = \frac{V}{x_e + x_d'},
\]
\[
C_5 = \frac{x_d - x_d'}{x_e + x_d'}, \quad C_6 = C_1 \frac{x_q (x_q - x_d')}{x_e + x_q},
\]
\[
C_7 = \frac{x_e}{x_e + x_d'}
\]
APPENDIX C

PARAMETER VALUES OF ACCELERATING POWER PSS

C.1. Parameter Values as Employed by KENGEN

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>PARAMETER NO.</th>
<th>RANGE</th>
<th>TYPICAL VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tw1          Frequency Wash-out Time Constant</td>
<td>L650</td>
<td>0 – 20000 ms</td>
<td>3000 ms</td>
</tr>
<tr>
<td>Tw2          Frequency wash-out time constant</td>
<td>L651</td>
<td>0 – 20000 ms</td>
<td>3000 ms</td>
</tr>
<tr>
<td>Tw3          Active power wash-out time constant</td>
<td>L652</td>
<td>0 – 20000 ms</td>
<td>3000 ms</td>
</tr>
<tr>
<td>Tw4          Active power wash-out time constant</td>
<td>L653</td>
<td>0 – 20000 ms</td>
<td>3000 ms</td>
</tr>
<tr>
<td>T6           Frequency filter time constant</td>
<td>L656</td>
<td>0 – 20000 ms</td>
<td>0 ms</td>
</tr>
<tr>
<td>T7           Active power filter time constant</td>
<td>L657</td>
<td>0 – 20000 ms</td>
<td>3000 ms</td>
</tr>
<tr>
<td>Ks2          Proportional gain</td>
<td>L654</td>
<td>0 - +1000</td>
<td>0.6</td>
</tr>
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<td>Ks3          Proportional gain</td>
<td>L655</td>
<td>0 - +1000</td>
<td>1</td>
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<td>T8           Filter time constant</td>
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<td>0 – 20000 ms</td>
<td>400 ms</td>
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<td>T9           Filter time constant</td>
<td>L659</td>
<td>0 – 20000 ms</td>
<td>100 ms</td>
</tr>
<tr>
<td>M            Filter index</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>N            Filter index</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Ks1          Proportional gain</td>
<td>L665</td>
<td>- 1000 - +1000</td>
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<td>180 ms</td>
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<td>PSS_{max}    PSS maximum contribution</td>
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<td>0 – 1</td>
<td>0.1</td>
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<tr>
<td>PSS_{min}    PSS minimum contribution</td>
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C.2. Configuration of M and N Indices

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<th>FILTER INDICES</th>
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<tr>
<td>1      1      0      0      0      0</td>
<td>2    2</td>
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</table>

Source: Courtesy of KenGen; Facilitated by Engineer Eliud Wamakima
APPENDIX D

FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS)

A brief description is given of the various shunt, series and combined controllers in congruence with IEEE terms and definitions [9].

D.1 Shunt Connected Controllers

I. Static Synchronous Compensator (STATCOM): A Static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. It can be based on a voltage sourced or current-sourced converter.

II. Static Synchronous Generator (SSG): A static self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power. SSG is a combination of STATCOM and any energy source to supply or absorb power.

III. Battery Energy Storage System (BESS): A chemical-based energy storage system using shunt connected, voltage-source converters capable of rapidly adjusting the amount of energy which is supplied to or absorbed from an ac system.

IV. Superconducting Magnetic Energy Storage (SMES): A Superconducting electromagnetic energy storage device containing electronic converters that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in an ac system.

V. Static Var Compensator (SVC): A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).

VI. Thyristor Controlled Reactor (TCR): A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve. TCR is a subset of SVC in which conduction time and hence, current in a shunt reactor is controlled by a thyristor-based ac switch with firing angle control.

VII. Thyristor Switched Reactor (TSR): A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve. TSR is another subset of SVC.

VIII. Thyristor Switched Capacitor (TSC): A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.
IX. **Static Var Generator or Absorber (SVG):** A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power. Generally considered to consist of shunt-connected, thyristor-controlled reactor(s) and/or thyristor-switched capacitors.

X. **Static Var System (SVS):** A combination of different static and mechanically-switched var compensators whose outputs are coordinated.

XI. **Thyristor Controlled Braking Resistor (TCBR):** A shunt-connected thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance.

D.2. **Series Connected Controllers**

I. **Static Synchronous Series Compensator (SSSC):** A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power.

II. **Interline Power Flow Controller (IPFC):** The IPFC is a recently introduced Controller and thus has no IEEE definition yet. A possible definition is: The combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines.

III. **Thyristor Controlled Series Capacitor (TCSC):** A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.

IV. **Thyristor-Switched Series Capacitor (TSSC):** A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance.

V. **Thyristor-Controlled Series Reactor (TCSR):** An inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance.

VI. **Thyristor-Switched Series Reactor (TSSR):** An inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance.
D.3 Combined Shunt and Series Connected Controllers

I. **Unified Power Flow Controller (UPFC):** A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source.

II. **Thyristor-Controlled Phase Shifting Transformer (TCPST)/ Thyristor-Controlled Phase Angle Regulator (TCPAR):** A phase-shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle.

III. **Interphase Power Controller (IPC):** A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separate phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches.

D.4 Other Controllers

I. **Thyristor-Controlled Voltage Limiter (TCVL):** A thyristor-switched metal-oxide varistor (MOV) used to limit the voltage across its terminals during transient condition.

II. **Thyristor-Controlled Voltage Regulator (TCVR):** A thyristor-controlled transformer which can provide variable in-phase voltage with continuous control.
APPENDIX E

SIMULATION BLOCK DIAGRAM: STABILITY OF A TWO MACHINE TRANSMISSION SYSTEM WITH PSSs AND SVC

A two-machine transmission system with Power System Stabilizers (PSSs) and Static Var Compensator (SVC)
## APPENDIX F

**KENYA POWER AND LIGHTING COMPANY (KPLC)**

### F.1 LINE DATA

<table>
<thead>
<tr>
<th>External Identity</th>
<th>Ubas (kV)</th>
<th>line length, km</th>
<th>Series resistance p.u./km</th>
<th>Series reactance p.u./km</th>
<th>Shunt susceptance p.u./km</th>
<th>Shunt conductance p.u./km</th>
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<td>0.00025</td>
<td>0.00045</td>
<td>625</td>
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<td>CHEMO-MUHO</td>
<td>KAMB132-KAMB</td>
<td>MASI-KIGA</td>
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Source: KPLC, Juja Control Station, 02.04.2009
# F.2 Transmission Lines Capacity & O/C Settings

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<th>Line (Source-Receiving) / Unit</th>
<th>Voltage</th>
<th>Line Capacity</th>
<th>CT Ratio</th>
<th>O/C setting</th>
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</thead>
<tbody>
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<td>100 800 305</td>
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<td>210 MVA</td>
<td>800 /1</td>
<td>100 800 305</td>
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<td>800 /1</td>
<td>100 800 183</td>
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<td>282 MVA</td>
<td>800 /1</td>
<td>150 1200 457</td>
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</table>

Source: KPLC, Juja Control Station, 02.04.2009
APPENDIX G

DEFINITION OF TERMS

1. **Adaptive control**: involves modifying the control law used by a controller to cope with the fact that the parameters of the system being controlled are slowly time-varying or uncertain. Adaptive control is different from **robust control** in that it does not need a priori information about the bounds on these uncertain or time-varying parameters; robust control guarantees that if the changes are within given bounds the control law need not be changed, while adaptive control is precisely concerned with control law changes.

2. **Alternator**: is an electromechanical device that converts mechanical energy to alternating current electrical energy.

3. **Automatic Voltage Regulator (AVR)**: An excitation-control system employs a voltage controller to control the excitation voltage. This operation is typically recognized as an automatic voltage regulator (AVR).

4. **Commutator**: a common feature of dc rotating machines, it is an **electrical switch** that periodically reverses the **current** direction in an **electric motor** or **electrical generator**. By reversing the current direction in the moving coil of a motor's armature, a steady rotating force (torque) is produced. Similarly, in a generator, reversing of the coil's connection to the external circuit produces unidirectional current in the circuit.

5. **Conservative Design**: Design for which the outcome does not cover a wide range of operating conditions.

6. **Damping** refers to the loss of, or dissipation of, mechanical energy during each cycle of vibration, or oscillation in a power system.

7. **ESS**: stands for **Energy Storage System(s)**. ESS installed in a Power system can rapidly vary real power and reactive power to improve system reliability and power quality. Commonly used ESS is the **Superconducting Magnetic Energy Storage (SMES)**, **Battery Energy Storage System (BESS)**, **Advanced Capacitors (AC)** and **Flywheel Energy Storage (FES)**.

8. **Exciter**: The basic function of an exciter is to provide a dc source for field excitation of a synchronous generator. A control on exciter voltage results in controlling the field current, which, in turn, controls the generated voltage. When a synchronous generator is connected to a large system where the operating frequency and the terminal voltages
are largely unaffected by a generator, its excitation control causes its reactive power output to change.

9. **Gate Turn-Off Thyristor (GTO):** is a special type of thyristor; a high-power semiconductor device. GTOs, as opposed to normal thyristors, are fully controllable switches which can be turned on and off by their third lead, the GATE lead.

10. **Generic Power System Stabilizer (PSS):** PSS that can be used to add damping to the rotor oscillations of the synchronous machine by controlling its excitation. The output signal of the PSS is used as an additional input (V_{stab}) to the Excitation System block.

11. **H\infty control:** Disturbance rejection, input/output decoupling, and general robust stability or performance objectives can all be formulated as gain attenuation problems in the face of dynamical or parametric uncertainty. **H\infty control** is the cornerstone of design techniques for this class of problems.

12. **Hydraulic Power Plant:** Hydro-Electric Power Plant (HEPP)

13. **Infinite bus-bars:** the electrical system to which an alternator is connected, that already has so many other alternators and loads connected to it, such that no matter what power is delivered by the incoming alternator, the voltage and frequency of the system remain the same.

14. **Inverter:** is an electrical or electro-mechanical device that converts direct current (DC) to alternating current (AC); the resulting AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

15. **Particle swarm optimization or PSO:** is a global optimization algorithm for dealing with problems in which a best solution can be represented as a point or surface in an n-dimensional space. Hypotheses are plotted in this space and seeded with an initial velocity, as well as a communication channel between the particles. Particles then move through the solution space, and are evaluated according to some fitness criterion after each time step. Over time, particles are accelerated towards those particles within their communication grouping which have better fitness values. This technique is impressively resilient to the problem of local minima.

16. **Phase-Locked Loop /Phase Lock Loop (PLL):** is a negative feedback control system that generates a signal that has a fixed relation to the phase of a "reference" signal. A phase-locked loop circuit responds to both the frequency and the phase of the input signals,
automatically raising or lowering the frequency of a controlled oscillator until it is matched to the reference in both frequency and phase.

17. **Phasor Solution method**: The phasor solution method is mainly used to study electromechanical oscillations of power systems consisting of large generators and motors. Phasor simulation is the preferred method for simulating power grids when interested in the magnitude and phase of voltages and currents at fundamental frequency (50 Hz or 60 Hz).

18. **Pole Placement**: is a design approach that employs state space techniques to assign closed loop poles, which have a direct impact on time response characteristics such as rise time, settling time and transient oscillations. This method is applicable in the design of dynamic compensators and Multiple Input Multiple Output (MIMO) systems.

19. **Power flow study (Load-flow Study)**: analyses the power system in normal steady-state operation with the principal information obtained being the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line.

20. **Power Swings**: electromechanical oscillations of the electrical generators induced by disturbances occurring in a power system.

21. **PQ Theory**: is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms. The p-q theory consists of an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in the \(a-b-c\) coordinates to the \(\alpha-\beta-0\) coordinates, followed by the calculation of the p-q theory instantaneous power components [17].

22. **Robust control**: Robust methods aim to achieve robust performance and/or stability in the presence of small modeling errors.

23. **Surge Impedance Loading**: In electric power transmission, the characteristic impedance of a transmission line is expressed in terms of the surge impedance loading (SIL), or natural loading, being the MW loading at which reactive power is neither produced nor absorbed.

24. **Swing Bus**: a swing (or slack) bus generates or absorbs the excess power required to balance the active powers throughout the network. The swing bus can be either a voltage source or any other synchronous machine.
25. **Synchronizing Torque**: once properly synchronized, alternators run in synchronism. Any tendency on the part of one to drop out of synchronism is immediately counteracted by the production of a *synchronizing torque* which brings it back to synchronism.

26. **Synchronizing**: the operation of connecting an alternator in parallel with another alternator or with common bus-bars.

27. **Synchronous Machine**: an ac (alternating current) machine whose speed under steady state conditions is proportional to the frequency of the currents in its armature.

28. **Synchronous Speed**: this is the speed at which the rotating field created by the armature current travels, that is the same as the speed created by the field currents; it results in a steady state torque.

29. **Terminal Voltage**: is the Potential difference (pd) or *voltage* across the terminals of a power supply.

30. **Multiband Power System Stabilizer (MB-PSS)**: is based on three separate bands respectively dedicated to the low-, intermediate-, and high-frequency modes of oscillations. The outputs of the three bands are summed and passed through a limiter producing the stabilizer output $V_{\text{stab}}$. This signal then modulates the set point of the generator voltage regulator so as to improve the damping of the electromechanical oscillations.

31. **Thyristor**: is a solid-state semiconductor device with four layers of alternating N and P-type material. Thyristors act as bistable switches, conducting when their gate receives a current pulse, and continue to conduct for as long as they are forward biased (that is, as long as the voltage across the device has not reversed). Normal thyristors (silicon controlled rectifiers) are not fully controllable switches (a "fully controllable switch" can be turned on and off at will).

32. **Turbine**: is a rotary *engine* that extracts *energy* from a *fluid* flow. The simplest turbines have one moving part, a rotor assembly, which is a shaft with blades attached. Moving fluid acts on the blades, or the blades react to the flow, so that they rotate and impart energy to the rotor.
REFERENCES


[21] IEEE recommended practice for excitation system models for power system stability studies: IEEE St. 421.5-2002(Section 9).


