CHAPTER – 6

STABILITY ANALYSIS WITH FACTS DEVICES IN PRESENCE OF VOLTAGE DEPENDENT LOADS
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6.1 INTRODUCTION

Electric loads play an important role in the analysis of stability of power systems. The secure operation of power systems with the variation of loads has been a challenge for power system engineers since the 1920s [108, 109]. In last few years, many research studies have been conducted and found that the parameters of the non-linear voltage dependent load model can have a significant effect on the result of dynamic performance and stability of power systems [110-114]. Incorrect parameters of load model could lead to a power system operating in modes that will result in actual system collapse and separation [110, 111, 114]. Accurate load model parameters are, therefore, necessary to allow more exact calculations of power system controls and stability limit which are critical in planning and operation of a power system. The importance of load representation in power system dynamic studies has long been recognized, and it has become clear that assumption regarding load model parameters can impact predicted system performance. Several efforts have been devoted to load modeling and evaluation of load parameters through field measurements. Analytical approaches of constructing accurate load models have also been considered [115-117]. Voltage dependent load models for composite load representation are highly recommended by the IEEE working group [118].

The Static Synchronous Series Compensator (SSSC) is one of the most popular voltage sourced converter based FACTS devices that are used widely by several utilities to support the voltage of power transmission system. SSSC is a variable series compensation base controller and is highly effective in both controlling power flow in the transmission lines and in improving stability [119, 120]. The principle of operation of SSSC controller is to inject the controllable voltage in series with transmission line. The ability of SSSC to operate in capacitive as well as inductive mode makes it very effective in controlling the power flow of the system
SSSC with additional signal injected voltage which improves the damping of power system electromechanical oscillations and to enhance the system stability. The basic limitation of these designs and/or tuning of SSSC based damping controllers presented earlier are that the influence of load model parameters has not been taken into account. Almost all of these SSSC damping controllers are based on a constant impedance load. The constant load representation is not accurate as the parameters of typical loads vary seasonally and in some cases changeover day, consequently, the performance of SSSC stabilizers tuned under fixed load parameters may become unacceptable under other load parameters. Recent studies and experience have shown that incorrect load model parameters could lead to a power system operating in modes that result in actual system collapse and separation [110, 111, 114]. Accurate load models are, therefore, necessary to allow more precise calculations of power system controls and stability limit which are critical in the planning and operation of a power system. The subject of this chapter is to investigate important aspects related to the effect of voltage-dependent loads and their parameters uncertainty on tuning of SSSC damping controllers. In this chapter both lead-lag and proportional-integral (PI) controller structure are considered as supplementary damping controller structures for SSSC to improve the stability.

The main objectives of the research work presented in this chapter are as follows:

1. To investigate the effect of different types of voltage dependent loads on power system stability.
2. To design the FACTS based damping controller in presence of various voltage dependent loads using GSA.
3. To investigate the effectiveness of different FACTS supplementary damping controller structures with different types of loads.
4. To study the effect of variation in load parameters on power system stability.

6.2 SYSTEM UNDER STUDY

6.2.1 SMIB POWER SYSTEM WITH NONLINEAR VOLTAGE DEPENDENT LOAD

The Single-Machine Infinite-Bus (SMIB) power system installed with a SSSC and nonlinear voltage dependent load as shown in Fig. 6.1 is considered in this study.
The system consists of a synchronous generator connected to a large system through a transmission line. The generator is equipped with automatic voltage regulator and governor turbine control systems. The nonlinear voltage dependent load is located at Bus1 as shown in Fig. 6.1. The system data are given in Appendix VI.

6.2.2 CLASSIFICATION OF NONLINEAR VOLTAGE DEPENDENT LOADS

The modeling of loads is often complicated by unpredictability of the compounding of devices (e.g. Fluorescent lamp, compact fluorescent lamps, Refrigerators, Heater, Motor, Oven and Furnace). However, load models are traditionally classified into two broad categories i.e. Static and dynamic. In this research work, the influence of three basic static load models, namely constant impedance, constant current and constant power loads on power system stability has been investigated. The various types of loads considered in this chapter are defined as follows [123]

1. Constant Impedance load model (constant Z): A static load model where real and reactive power varies with the square of the voltage magnitude. It is also referred to as constant admittance load model.

2. Constant current load model (constant I): A static load model where real and reactive power varies directly with voltage magnitude.

3. Constant power load model (constant PQ): A static load model where real and reactive power varies doses not varies with the changes in voltage magnitude. It is also known as constant MVA load model.
6.2.3 MODELING OF NONLINEAR VOLTAGE DEPENDENT LOADS

This chapter follows the recommendation of the IEEE working group [118] and utilities [110, 119] in utilizing the voltage-dependent load model for composite load representation. Utilities normally perform field tests, or in some cases perform regression analysis to establish system load models to be used for power-flow and stability studies, these models are in the form of:

\[
\begin{align*}
P(s) &= P_0 \left( \frac{V}{V_0} \right)^{n_p} \left( \frac{1 + T_{p1}s}{1 + T_{p2}s} \right) \\
Q(s) &= Q_0 \left( \frac{V}{V_0} \right)^{n_q} \left( \frac{1 + T_{q1}s}{1 + T_{q2}s} \right)
\end{align*}
\]  

(6.1)

Where

- \( V_0 \) is the initial positive sequence voltage, ie load bus voltage
- \( P_0 \) and \( Q_0 \) are the initial active and reactive powers at the initial voltage \( V_0 \)
- \( V \) is the positive-sequence voltage
- \( n_p \) and \( n_q \) are exponents (usually between 1 and 3) controlling the nature of the load ie load parameters
- \( T_{p1} \) and \( T_{p2} \) are time constants controlling the dynamics of the active power \( P(s) \)
- \( T_{q1} \) and \( T_{q2} \) are time constants controlling the dynamics of the reactive power

The load representation given in Eq. (6.1) makes possible the modeling of all typical voltage-dependent load models by selecting appropriate values of load parameters \( (n_p \) and \( n_q) \). With load parameters equal to 0, 1 and 2 the load model represents constant power, constant current and constant impedance characteristics respectively. The values of \( n_p \) and \( n_q \) depend on the nature of the load and can vary between 0 to 3 for \( n_p \) and 0 to 4 for \( n_q \). The measurement of typical values of \( n_p \) and \( n_q \) of various kinds of typical power system composite loads are reported in [119]. These measurement values are required for control parameter adaptation.
6.3 THE PROPOSED APPROACH

6.3.1 STRUCTURE OF SSSC-BASED DAMPING CONTROLLER

Here PI and lead–lag structure as shown in Fig.4.4 and Fig.3.5 are considered as SSSC-based damping controllers. In case of lead lag structures controller, the controller gains $K_s$ and the time constants $T_{1s}, T_{2s}, T_{3s}$ and $T_{4s}$ are to be determined. In Proportional Integral (PI) control structure $K_p$ and $K_i$ are to be determined. The remote speed deviation signal is taken as the input signal to the controllers and a time delay of 50 ms (signal transmission delay plus the delay due to sensor time constant) is considered.

6.3.2 OBJECTIVE FUNCTION

In the present study, an integral time absolute error of the speed deviations is taken as the objective function $J$, expressed as:

$$ J = \int_{0}^{t_1} |e(t)| dt $$  \hspace{1cm} (6.2)

Where, ‘$e$’ is the error signal ($\Delta \omega$) and $t_1$ is the time range of simulation. The parameters of the damping controller are obtained using GSA.

For PI-controller

$$ K_p^{\min} \leq K_p \leq K_p^{\max} $$

$$ K_i^{\min} \leq K_i \leq K_i^{\max} $$ \hspace{1cm} (6.3)

For lead-Lag controller

$$ K_s^{\min} \leq K_s \leq K_s^{\max} $$ \hspace{1cm} (6.4)

$$ T_{1s}^{\min} \leq T_{1s} \leq T_{1s}^{\max} $$

$$ T_{2s}^{\min} \leq T_{2s} \leq T_{2s}^{\max} $$

$$ T_{3s}^{\min} \leq T_{3s} \leq T_{3s}^{\max} $$

$$ T_{4s}^{\min} \leq T_{4s} \leq T_{4s}^{\max} $$
Typical ranges of the optimized parameters are [1-100] for $K_s$, $K_p$, $K_i$ and [0.01-2] for $T_{1s}$, $T_{2s}$, $T_{3s}$, $T_{4s}$. GSA is employed to optimize the controller parameters.

6.4 RESULTS AND DISCUSSIONS

6.4.1 APPLICATION OF GSA

The optimization of the proposed SSSC-based supplementary damping controller parameters is carried out by minimizing the fitness given in equation (6.2) employing GSA. The model of the system under study has been developed in MATLAB/SIMULINK environment and GSA programme has been written (in .mfile). For objective function calculation, the developed model is simulated in a separate programme (by .m file using initial population/controller parameters) considering a severe disturbance. Form the SIMULINK model the objective function value is evaluated and moved to workspace. The process is repeated for each individual in the population. For objective function calculation, a 3-phase short-circuit fault in one of the parallel transmission lines is considered. Using the objective function values, the population is modified by GSA for the next generation. The optimization processes is run 20 times for different types of load models and best among the 20 runs for each case are provided in the Table 6.1.

Table 6.1: Optimized SSSC-based damping controller parameters

<table>
<thead>
<tr>
<th>Parameters of the circuit</th>
<th>P-I controller</th>
<th>Lead-Lag controller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_p$</td>
<td>$K_i$</td>
</tr>
<tr>
<td>$n_p = n_q = 0$</td>
<td>30.5880</td>
<td>70.1892</td>
</tr>
<tr>
<td>$n_p = n_q = 1$</td>
<td>56.4415</td>
<td>93.4073</td>
</tr>
<tr>
<td>$n_p = n_q = 2$</td>
<td>84.7951</td>
<td>69.5264</td>
</tr>
</tbody>
</table>

6.4.2 SIMULATION RESULTS

To assess the effectiveness and robustness of the proposed damping controllers various disturbances and load parameter variations are considered. The performance of the PI controllers with different load parameters is compared with
Lead-Lag controller parameters with corresponding load parameters for various systems loading (nominal, light and heavy) condition. The response without controller is shown in dotted lines and the response with PI controller with corresponding load parameters (np, nq) is shown dashed lines. The responses with Lead-Lag controller (LL) with corresponding load parameters (np, nq) are shown in solid lines.

Case I: Nominal loading

The behavior of the proposed controller is verified at nominal loading condition (Pe=0.85 pu, δ₀=38.23°) under severe disturbance condition with different load parameters. A 3-cycle, 3-phase self clearing fault is applied at the middle of one transmission line connecting bus 2 and bus 3, at t = 1.0 s and the system response with different load models (different np, nq values) are is shown in Figs. 6.2-6.4. It can be seen from Fig. 6.2 that for constant power load (np=nq=0), the response with lead lag structures controller is significantly superior to that with PI structured controller. For constant current (np=nq=1) and constant impedance (np=nq=2) loads, the performance of lead lag structured controller is slightly better than that of PI structured controller.

![Chart](image-url)

**Fig. 6.2** The system dynamic response at load parameters at np=nq=0 for 3 cycle 3-phase fault in transmission line
Fig. 6.3 The system dynamic response at load parameters at np=nq=1 for 3-cycle 3-phase fault in transmission line

Fig. 6.4 The system dynamic response at load parameters at np=nq=2 for 3-cycle 3-phase fault in transmission line

Case II: light loading

The performance of the system under is verified with light loading condition (Pe=0.6 pu, δ0=22.71°) with different load parameters (np=nq=0, np=nq=1, np=nq=2). A 3 phase fault is applied at nearest to Bus 3 at time t=1 sec and the fault is clear after 3-cycle and the system response is shown in Figs. 6.5-6.7. It can be observed from Figs. that the performance of the system with lead-lag controller is better than same with PI controller for all types of loads (np=nq=0, np=nq=1, np=nq=2).
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Fig. 6.5 The system dynamic response at load parameters at np=nq=0 for 3-cycle 3-phase fault at Bus-3 in transmission line.

Fig. 6.6 The system dynamic response at load parameters at np=nq=1 for 3-cycle 3-phase fault at Bus-3 in transmission line.

Fig. 6.7 The system dynamic response at load parameters at np=nq=2 for 3-cycle 3-phase fault at Bus-3 in transmission line.
Case III: heavy loading, small disturbance

To test the robustness of the controller to the operating condition and type of disturbance, the generator loading is changed to heavy loading condition ($P_e=1 \text{ pu}$, $\delta_0=47.28^\circ$) under small disturbance by disconnecting the load near bus 1 at $t=1$ sec for 3-cycle. It can be observed from the system response shown in Figs. 6.8-6.10 that the performance of the system with lead-lag controller the stability of the system is maintained with load parameter $np=nq=0$, $np=nq=1$ and $np=nq=2$. The system behaved satisfactorily with both for light and nominal load conditions. However, during heavy load, the settling time and overshoot of the oscillations is considerably shorter and the overall performance is better with the proposed lead-lag structured SSSC based controller.

![Fig. 6.8](image1.png)

**Fig. 6.8** The system dynamic response at load parameters at $np=nq=0$ for 3-cycle 3-phase fault in transmission line

![Fig. 6.9](image2.png)

**Fig. 6.9** The system dynamic response at load parameters at $np=nq=1$ for 3-cycle 3-phase fault in transmission line
**Fig. 6.10** The system dynamic response at load parameters at \( np=\text{nq}=2 \) for 3-cycle 3-phase fault in transmission line

**Case IV: Effect of load parameters in system performance**

In this case, the performances of GSA optimized Lead-lag structured SSSC based damping controller are compared with different load parameters i.e. constant impedance load model \( (np=\text{nq}=2) \), constant current load model \( (np=\text{nq}=1) \) and constant power load model \( (np=\text{nq}=0) \). The three different loading conditions are simulated ie.

- **Case A** \((\text{Pe}=0.85 \text{ pu, } \delta_0=38.23^0, \text{ fault same as case-I})\)
- **Case B** \((\text{Pe}=0.6 \text{ pu, } \delta_0=22.71^0, \text{ fault same as case-II})\)
- **Case C** \((\text{Pe}=1 \text{ pu, } \delta_0=47.28^0, \text{ fault same as case-III})\)

The response of speed deviation for Case A is shown in Fig.6.11. It is clear from Fig. 6.11 that the system with load parameters \( np=\text{nq}=1 \) is poorly damped and become stable in more than \( 2.5 \text{ sec} \). The system become stable with load parameters \( np=\text{nq}=0 \), \( np=\text{nq}=2 \) and settling times are below \( 1.5\text{sec} \). The response of speed deviation for Case B is shown in Fig. 6.12. It can be seen from Fig. 6.12 that the system becomes stable system with load parameters \( np=\text{nq}=0 \), \( np=\text{nq}=2 \) with a settling time of \( 2.5 \text{ sec} \) where as with load parameters \( np=\text{nq}=1 \) the system highly oscillatory. Similarly for
the speed deviation in Case C shown in Fig. 6.13, with load parameters $np=nq=2$, satisfactory damping performance is observed and the system becomes stable at 1.7 sec. From the above three analysis it is concluded that with load parameters $np=nq=2$, the system response is faster than the other two load parameters $np=nq=0$ and $np=nq=1$.

![Graph](image)

**Fig. 6.11** The system dynamic response for nominal condition with load parameters $np=nq=0$, 1 and 2

![Graph](image)

**Fig. 6.12** The system dynamic response for light loading condition with load parameters $np=nq=0$, 1 and 2
6.5 EXTENSION TO MULTI-MACHINE POWER SYSTEM

The study is extended to multi-machine power system with nonlinear voltage dependent load as shown in Fig. 6.14. The system consists of 3 machines (G1, G2, and G3) with 9 bus as shown in the single line diagram in Fig. 6.14. It is assumed that SSSC was located between the Bus5 and Bus6 and the nonlinear voltage dependent load is located at Bus 1. The system data are given in Appendix VII.
6.5.1 OBJECTIVE FUNCTION

A performance index can be defined by the Integral of Time multiply Absolute Error (IATE) of local and inter area modes of oscillations. Accordingly, the objective function $J$ is set to be

$$ J = \int_{t=0}^{t_{sim}} \left( \sum |\Delta \omega_L| + \sum |\Delta \omega_I| \right) \cdot t \cdot dt $$

(6.5)

Where $\Delta \omega_I$ and $\Delta \omega_L$ are the speed deviations of inter-area and local modes of oscillations respectively and $t_{sim}$ is the time range of the simulation. The oscillations between local generators (generators G2 and G3) are local modes of oscillation. The oscillations between generators of each area (between G1 and G2 and between G1 and G3) are inter area modes of oscillation. For the system under study (3 machine 9 bus power system), the local mode of oscillation is given by $\Delta \omega_2 - \Delta \omega_3$ and the inter area modes of oscillations are given by $(\Delta \omega_1 - \Delta \omega_2)$ and $(\Delta \omega_1 - \Delta \omega_3)$ respectively. The same approach as explained for SMIB case is followed to optimize the SSSC-based damping controller parameters for three-machine case. The best among the 20 runs for both the input signals are shown in Table 6.2.

<table>
<thead>
<tr>
<th>Parameters of the circuit</th>
<th>$K_s$</th>
<th>$T_{1S}$</th>
<th>$T_{2S}$</th>
<th>$T_{3S}$</th>
<th>$T_{4S}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_p = n_q = 0$</td>
<td>45.1221</td>
<td>1.2343</td>
<td>1.2316</td>
<td>0.6840</td>
<td>0.8098</td>
</tr>
<tr>
<td>$n_p = n_q = 1$</td>
<td>29.0888</td>
<td>1.5301</td>
<td>1.0771</td>
<td>1.2290</td>
<td>1.0263</td>
</tr>
<tr>
<td>$n_p = n_q = 2$</td>
<td>68.5162</td>
<td>1.5066</td>
<td>0.8935</td>
<td>1.3320</td>
<td>1.2330</td>
</tr>
</tbody>
</table>

6.5.2 SIMULATION RESULTS

Case A: 3-phase fault Disturbance

A self clearing 3-phase fault is applied near bus 1 at $t = 1$ s. The fault is cleared after 3 cycles and the original system is restored after the fault clearance. Figs. 6.15-6.16 show the variations of the inter-area mode of oscillation against time for the control inputs. In these Figs. the response with load parameter $n_p=n_q=0$ is shown with dotted line; and responses with load parameter $n_p=n_q=1$ is shown with dashed
line and the response with load parameter np=nq=2 is shown as solid line. It is clear from Fig. 6.15 that inter-area modes of oscillations with load parameter np=nq=0 and np=nq=1 are highly oscillatory compared to the load parameter np=nq=2. The settling time is less with load parameter np=nq=2 as compared to load parameters np=nq=0 and 1.

**Fig. 6.15** Inter-area mode of oscillation for 3-cycle 3-phase self clearing fault disturbance

**Fig. 6.16** Local mode of oscillation for self clearing 3-phase fault disturbance
Case B: Line outage Disturbance

To show the robustness of the proposed approach, another disturbance is considered. The transmission line between bus 6 and bus 1 is tripped at $t=1.0$ sec and reclosed after 3 cycles. The system response is shown in Figs. 6.17-6.18 from which it is clear that the response with load parameter $np=nq=2$ is better than that with load parameters $np=nq=1$ and 0.

**Fig. 6.17** Inter-area mode of oscillation for line outage disturbance

**Fig. 6.18** Local mode of oscillation for line outage disturbance
Case C: Small Disturbance

For completeness, the load at bus 1 is disconnected for 100 ms and the system response is shown in Figs. 6.19-6.20. It is clear from these Figs. that the proposed controllers are robust and damps power system oscillations even under small disturbance conditions.

**Fig. 6.19** Inter-area mode of oscillation for small disturbance

**Fig. 6.20** Local mode of oscillation for small disturbance
6.6 CONCLUSION

In this chapter, the impact of the parameters of nonlinear voltage dependent load model on power system stability has been investigated. Various load models such as constant power, constant impedance and constant current load are used and different controller structures such as PI and Lead-Lag controller for SSSC are considered. The design problem of the proposed controller is formulated as an optimization problem and GSA is employed to search for optimal controller parameters. The performance of the proposed controller is evaluated under various disturbances for both single machine infinite bus power system and multi machine power system. By the comparative study, it is observed that the performance of power system with lead-lag structured SSSC based damping controller is better than that with PI structured SSSC based damping controller from power system stability point of view. It is also observed that less oscillations and settling times are obtained for constant impedance load (load parameters np=nq=2) compared to constant power load (load parameters np=nq=0) and constant current load (load parameters np=nq=1).