Effect of Static Shunt Compensation on Power System Dynamic Performance

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Abstract- **If the reactive power of the load is changing rapidly, then a suitable fast response compensator is needed. Capacitors and inductors are passive devices that generator or absorb reactive power. In this paper the effect of reactive power control equipment, include shunt capacitive compensation and inductive shunt compensation, improve stability is investigate. The proposed model uses the two-port of the line and line parameters. Simulation results show the effect of shunt compensation on damping of power system oscillations.**

I. INTRODUCTION

The power system is a highly complex system. Instability in power system are created due to long length of transmission lines, changing system loads, interconnected grid and line faults in the system. The flows of active and reactive power in the transmission lines are independent of each other as the active power depends on the angle by which the sending end leads the receiving end, while the reactive power depends on the voltage magnitudes. In recent years, they are a very economical means of supplying reactive power for system stability enhancement. Injecting reactive power into the system raise voltages and absorbing reactive power lower voltages. Modern power system comprises long transmission lines and remote sources of generation. Reactive power increases the transmission system losses, reduces the power transmission capability of transmission lines and can cause large amplitude variations in the receiving-end voltage. Reactive power cannot be transmitted over long distance; therefore reactive compensation has to be effected by using various devices [1-3].

Reactive power requirements of industrial loads such as rolling mills, electric arc furnaces, arc welders, traction loads are often unbalanced and could vary in a wide range within short period of time. Reactive power compensation is an important issue in the control of electric energy systems.

Several papers have discussed the configurations and control strategies for the reactive power compensation systems [4, 5]. A method of enhancement of transmission capability limit using system damping resistor and series-shunt capacitors presented in [6]. A computationally efficient methodology for the optimal location and sizing of static and switched shunt capacitors in radial distribution systems proposed in [7]. A method of optimizing real and reactive power in power systems in presented in [8], which for reactive power optimization generator bus voltages, shunt capacitors or reactors, and transformer tap positions are taken as control variables while cost minimization or loss minimization is taken as objective. In [9] shown that the main problem of the electric energy transmission over long line is connected with a compensation of surplus reactive power of line.

Damping the oscillations is not only important in increasing the transmission capability but also for stabilization of power system conditions after critical faults. One of the methods of damping of power system oscillations is control of the transmission line reactance. Reactance control can be achieved by series or shunt compensation.

This propose of this paper is to study shunt compensation in power system to improve steady-state stability and security performance. The transmission line parameters are considered in modeling of the power system. To verify our proposed method, various simulation results using Matlab are provided and discussed under different loading operation.

II. SHUNT COMPENSATION

Many reactive control equipment in a power system can play important roles in maintain desired voltage profiles. The line impedance, the receiving and sending ends, voltages, and phase angle between the voltages determine the transmitted electrical power over a line. Modern power systems have high series impedance which reduces the system stability and deteriorates the voltage control of the load and generation buses. Tasks of dynamic shunt compensation are steady state and dynamic voltage control, reactive power control of dynamic loads, damping of active power oscillations and improvement of system stability. If reactive power is supplied near the load, the line current can be reduced or minimized, reducing power losses and improving voltage regulation at the load terminals [10].

Shunt capacitors and shunt reactors are either permanently connected to the network, or switched on and off according to operative conditions. Shunt reactors and capacitors provide passive compensation. In principle, shunt compensations inject current into the system at the point of connection. The compensation is to modify the network characteristics so as to result in the desired voltage and power transfer.

A. Shunt Capacitor

The basic function of a shunt capacitor is to increase the power system loadability. It is very useful in a steady state operation of power system. The dynamical time response is slow to effectively damp transient oscillations. Use of shunt capacitor reduces the line current necessary to supply reactive power to a load and reduces the voltage drop in the line via power factor improvement. Shunt capacitors are widely used

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to improve voltage, increase power transfer and improve the system stability under heavily load.

B. Shunt Reactor

Shunt reactors are used to compensate for the effects of line capacitance, particularly to limit voltage rise on open line conditions or under light load. A controllable shunt reactor that controls the transmission of power by continuous reactive power compensation will reduce the transmission losses and increase the transmission capacity of active power [11].

III. MATHEMATICAL MODEL

The first step in the analysis and design of control systems is mathematical modeling of the system. In this section the mathematical model for analysis of the SMIB system with shunt compensation is described. It is considered that the transmission line parameters are uniformly distributed and the line can be modeled by a two-port, four-terminal networks. In stability studies, the passive compensating devices are modeled as admittance elements of fixed values [12]. Reactive power affects system voltages, energy loss as well as system security. The sources of reactive power are generators, capacitors and reactors. The generator reactive power is controlled by field excitation. The system model for excitation control design and stability analysis is usually that of a single generator infinite-bus system. Fig 1 shows the power system under study where the shunt compensation is connected in bus M. The rotor angle δ is defined as the angle by which the machine q-axis leads the x-axis, as shown in Fig. 2.

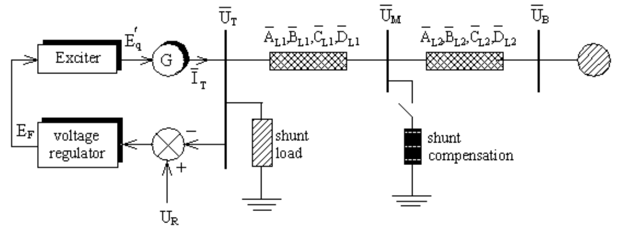

Figure 1. Single-machine infintie-bus installed with chunt compensation

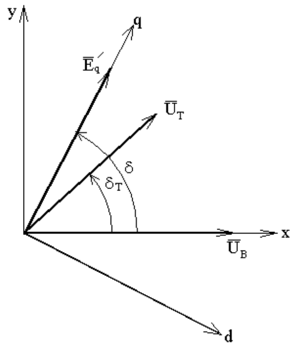

Figure 2. Voltage phsor diagram

The generalized circuit constants (ABCD) of a line of length a, are parameters that depend on the transmission line constants, the characteristic impedance $\overline{Z}_C$ and the electrical length θ. The equal parameters between bus T and bus B are A, B, C and D, so that:

$$\begin{bmatrix} \overline{A} & \overline{B} \\ \overline{C} & \overline{D} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \overline{Y}_L & 1 \end{bmatrix} \begin{bmatrix} \overline{A}_{L1} & \overline{B}_{L1} \\ \overline{C}_{L1} & \overline{D}_{L1} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \overline{Y}_S & 1 \end{bmatrix} \begin{bmatrix} \overline{A}_{L2} & \overline{B}_{L2} \\ \overline{C}_{L2} & \overline{D}_{L2} \end{bmatrix} \tag{1}$$

where $\overline{Y}_L$ is admittance of shunt load in generator bus, $\overline{Y}_S$ is shunt compensation admittance in bus M, and $\overline{A}_{L1}$, $\overline{B}_{L1}$, $\overline{C}_{L1}$, $\overline{D}_{L1}$and $\overline{A}_{L2}$, $\overline{B}_{L2}$, $\overline{C}_{L2}$, $\overline{D}_{L2}$ are line parameters in sections I and II, respectively. Small perturbation transfer function models of the synchronous generator equipped with an exciter and regulator voltage shown in Figure 3. $G_M(s)$, $G_E(s)$ and $G_F(s)$ representing the transfer function of the generator, the field circuit and the exciter, respectively.

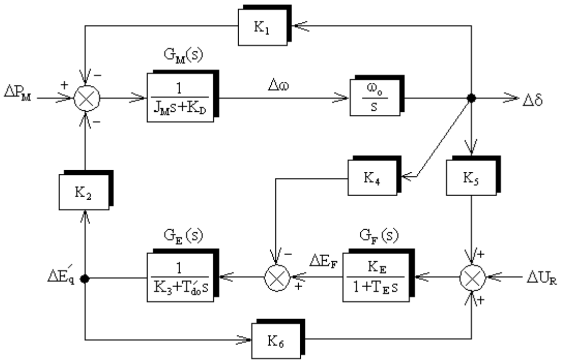

Figure 3. Single-machine infintie-bus installed with chunt compensation

The state variable equations of the power system equipped with shunt compensation can be represented as:

$$\frac{d}{dt}\Delta\delta = \omega_o \Delta\omega \tag{2}$$

$$\frac{d}{dt}\Delta\omega = -\frac{K_D}{J_M}\Delta\omega - \frac{K_1}{J_M}\Delta\delta - \frac{K_2}{J_M}\Delta E_q' + \frac{1}{J_M}\Delta P_M \tag{3}$$

$$\frac{d}{dt}\Delta E_q' = -\frac{K_4}{T_{do}'}\Delta\delta - \frac{1}{K_3 T_{do}'}\Delta E_q' + \frac{1}{T_{do}'}\Delta E_F \tag{4}$$

$$\frac{d}{dt}\Delta E_F = -\frac{K_5 K_E}{T_E}\Delta\delta - \frac{K_6 K_E}{T_E}\Delta E_q' - \frac{1}{T_E}\Delta E_F \tag{5}$$

The effect of shunt compensation is considered in sensitivity constant. The corresponding K constants are [13]:

$$K_1 = F_q[E_{qo}' + I_{do}(X_q - X_d')] + F_d I_{qo}(X_q - X_d') \tag{6}$$

$$K_2 = I_{qo} + Y_q[E_{qo}' + I_{do}(X_q - X_d')] + Y_d I_{qo}(X_q - X_d') \tag{7}$$

$$K_3 = \frac{1}{1 + (X_d - X_d')Y_d} \tag{8}$$

$$K_4 = F_d(X_d - X_d') \tag{9}$$

$$K_5 = \frac{U_{do}}{U_{To}} X_q F_q - \frac{U_{qo}}{U_{To}} X_d' F_d \tag{10}$$

$$K_6 = \frac{U_{do}}{U_{To}} X_q Y_q + \frac{U_{qo}}{U_{To}} (1 - X_d^{'} Y_d) \tag{11}$$

where:

$$R_{E1} = B\cos\beta - X_d^{'} D\sin\gamma + R_A D\cos\gamma \tag{12}$$

$$R_{E2} = B\cos\beta - X_q D\sin\gamma + R_A D\cos\gamma \tag{13}$$

$$X_{E1} = B\sin\beta + X_q D\cos\gamma + R_A D\sin\gamma \tag{14}$$

$$X_{E2} = B\sin\beta + X_d^{'} D\cos\gamma + R_A D\sin\gamma \tag{15}$$

$$Z_E^2 = R_{E1} R_{E2} + X_{E1} X_{E2} \tag{16}$$

$$F_d = -\frac{U_B}{Z_E^2} (R_{E2}\cos\delta_o - X_{E1}\sin\delta_o) \tag{17}$$

$$F_q = \frac{U_B}{Z_E^2} (R_{E1}\sin\delta_o + X_{E2}\cos\delta_o) \tag{18}$$

$$Y_d = \frac{X_{E1}\cos\gamma - R_{E2}\sin\gamma}{Z_E^2} \tag{19}$$

$$Y_q = \frac{X_{E2}\sin\gamma + R_{E1}\cos\gamma}{Z_E^2} \tag{20}$$

The system characteristic equation is given by:

$$\begin{aligned}\Delta(s) = {} & s^4 + \left(\frac{K_3}{T_{do}^{'}} + \frac{1}{T_E} + \frac{K_3}{J}\right)s^3 \\ & + \left(\frac{K_3 + K_E K_6}{T_{do}^{'} T_E} + \frac{K_D (T_{do}^{'} + K_3 T_E)}{J T_{do}^{'} T_E} + \frac{\omega_o K_1}{J}\right)s^2 \\ & + \left[\frac{\omega_o K_1 (T_{do}^{'} + K_3 T_E)}{J T_{do}^{'} T_E} - \frac{K_2 K_4 \omega_o}{J T_{do}^{'}} + \frac{K_D (K_3 + K_E K_6)}{J T_{do}^{'} T_E}\right]s \\ & + \frac{\omega_o}{J T_{do}^{'} T_E}[K_1 (K_3 + K_E K_6) - K_2 (K_4 + K_E K_5)]\end{aligned} \tag{21}$$

The transfer reactance is $X_T = X_H[1-\lambda(1-\lambda)X_H B_C]$, where X_H is the impedance of the whole transmission line, B_C is compensator susceptance and λ is the ratio of the left part of the line to the whole line which varies between 0 and 1. From the equivalent circuit of SMIB, it can be got the bus voltage U_M and phase δ_M:

$$U_M = \frac{1}{1-(1-\lambda)\lambda X_H B_C} \times \sqrt{\lambda^2 U_B^2 + (1-\lambda)^2 U_T^2 + 2\lambda(1-\lambda) U_T U_B \cos\delta_T} \tag{22}$$

The real and the ractive power reseived at the receiving end of the line for the system with controlled shunt compensators are given by:

$$\begin{cases} P_B = \dfrac{U_S U_R}{Z_S \sin\theta - Z_S^2 B_C \sin^2 \dfrac{\theta}{2}} \sin\delta_T \\ Q_B = \dfrac{U_S U_R \cos\delta_T - [\cos\theta - 2 Z_S B_C \sin\theta] U_R^2}{Z_S \sin\theta - Z_S^2 B_C \sin^2 \dfrac{\theta}{2}} \end{cases} \tag{23}$$

When line losses are neglected, the ABCD constant of a short transmission line with shunt compensator are:

$$T = \begin{bmatrix} 1 - \lambda B_C X_H & j X_H (1 - \lambda(1-\lambda) X_H B_C) \\ j B_C & 1 - B_C (1-\lambda) X_H \end{bmatrix} \tag{24}$$

The ABCD constant of a long transmission line with shunt compensator are:

$$T = \begin{bmatrix} \cos\theta - Z_C B_C \sin\lambda\theta\cos(1-\lambda)\theta & j Z_C[\sin\theta - Z_C B_C \sin\lambda\theta\sin(1-\lambda)\theta] \\ j\dfrac{1}{Z_C}\sin\theta + j B_C \cos\lambda\theta\cos(1-\lambda)\theta & \cos\theta - Z_C B_C \cos\lambda\theta\sin(1-\lambda)\theta \end{bmatrix} \tag{25}$$

IV. SIMULATION RESULTS

Loads can also be both real and reactive. The transmission system itself is a nonlinear consumer of reactive power, depending on system loading. At very low levels of system load, transmission lines act as capacitors and increase voltages. Shunt inductive compensation increases Z_C and decreases θ, whereas shunt capacitive compensation in effect decreases Z_C and increases θ. The system parameters are summarized in Table I. The sensitivity constant of mode power system are show in Table II. The system eigenvalues are given in Table III. For system without compensation, the mechanical mode damping is η=0.2651 and the undamped natural mechanical mode frequency is ω_n=2.3241. We can see the frequency change is relatively small. The frequencies of the electrical and mechanical modes have some changes between the system with compensation and system without controller.

The step response of rotor angle and electrical power for change in the in susceptance of the compensation are show in Figures 4 and 5, respectively.

TABLE I
SYSTEM PARAMETERS

Transmission line
$r=0$, $x_L=0.61\Omega/Km$, $x_C= 31.25\times10^4\Omega.Km$, $a=600Km$
Generator synchronous
$J_M=5$, $K_D=0$, $X'_d=0.2$, $X_d=1$, $X_q=0.6$, $T'_{do}=8$, $R_a=0.003$, $f_o=50$
Exciter system
$K_A=50$, $T_A=0.05$
Load normal
$P_{EO}=0.7$, $Q_{EO}=0.1$, $U_{TO}=1$

TABLE II
SENSITIVITY CONSTANT

Constant	B_C=0	B_C=0.0064	B_C=0.0095	B_C=0.0127
K_1	0.2464	0.2532	0.3006	0.2319
K_2	0.6144	0.6132	1.6048	0.6095
K_3	0.9984	1.0023	1.0307	1.0148
K_4	-0.4916	-0.4906	-0.4838	-0.4983
K_5	0.1913	0.1923	0.1995	0.1904
K_6	0.9293	0.9302	0.9366	0.9331

TABLE III
SYSTEM MODE

System mode B_C	Mechanical	Electrical
0	-0.6161±j2.2410 (η=0.2651) (ω_n=2.3241)	-9.6465±j3.7117 (η=0.9333) (ω_n=10.3359)
0.0064	-0.6154±j2.3004 (η=0.2584) (ω_n=2.3813)	-9.6470±j3.7266 (η=0.9328) (ω_n=10.3418)
0.0095	-0.6104±j2.6783 (η=0.2222) (ω_n=2.7470)	-9.6502±j3.8272 (η=0.9296) (ω_n=10.3814)
0.0127	-0.6098±j2.1200 (η=0.2764) (ω_n=2.2060)	-9.6518±j3.7849 (η=0.9310) (ω_n=10.3674)

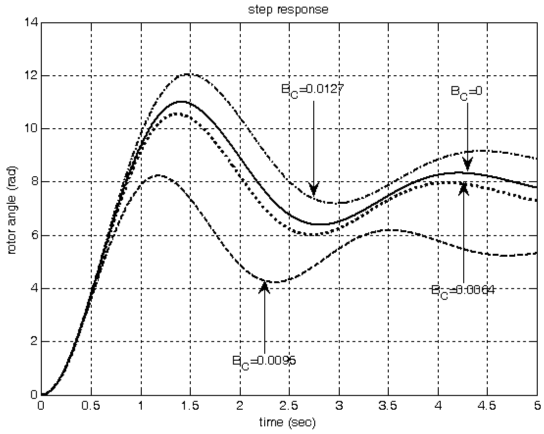

Figure 4. Rotor angle

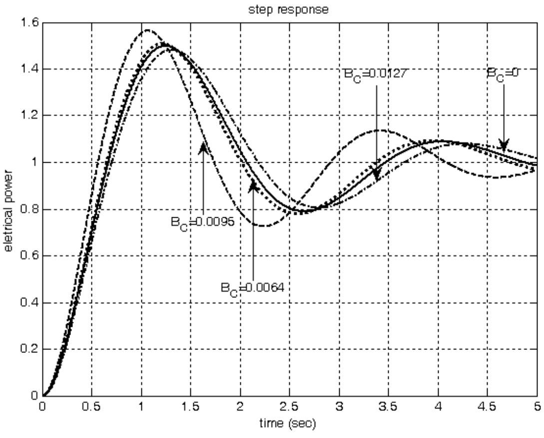

Figure 5. Electrical power

V. CONCLUSION

One of the methods of damping of power system oscillations is control of the line reactance. Reactance control can be achieved by series or shunt compensation. Shunt compensators are primarily used to regulate the voltage in a bus by providing or absorbing reactive power. The dynamic behavior of a SMIB power system installed with shunt compensators has been investigated in this paper. The effect of the compensator in change of the sensitivity constant and system eigenvalue are show.

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