A NOVEL POWER FLOW CONTROLLER FOR CONTROLLED SERIES COMPENSATION


Abstract

The Controlled Series Compensator (CSC) is a second generation FACTS device capable of providing fast, variable on line compensation. The compensation can be varied to meet various objectives such as control of power, damping of oscillations and improvement of stability. This paper presents a novel Constant Angle (CA) controller for power control and the results are presented with a case study.

1 INTRODUCTION

The concept of Flexible AC Transmission Systems (FACTS), was proposed by N.G.Hingorani [1], to overcome the limitations of the present mechanically controlled AC power systems. This is achieved using fast acting and reliable thyristor controllers. The technology offers greater control of power, secure loading of lines nearer to their thermal limits and damping of power system oscillations.

The Controlled Series Compensator is a second generation FACTS device. The CSC is essentially a FC-TCR made up of one or more modules connected in series with the line, capable of providing fast variable compensation. The degree of compensation can be varied by varying the firing angle of the thyristors.

The use of fixed capacitors for increase in power transfer levels has long been in vogue. But capacitors in series with transmission lines may cause subsynchronous resonance (SSR) that can lead to electrical instability at oscillation frequencies lower than the normal system frequency resulting in spontaneous growth of oscillatory response and eventually turbine-generator shaft failure [2]. This aroused the utilities interest to determine the feasibility of the TCSC device [4].

Suitable control strategies are possible to vary the impedance of the CSC to meet various objectives such as power control, damping of oscillations and improvement of stability. Unlike in the case of SVC where the voltage regulation at the SVC bus is universally accepted as the basic control with supplementary control for damping, the strategy for the power control in the lines with CSC is yet to evolve.

This paper presents a detailed dynamic analysis of the CA controller considering various aspects including small signal Stability, transient stability and SSR characteristics. The performance of this novel controller is also compared with that of Constant Current (CC) controller [3]. The analysis is illustrated with the help of case studies employing IEEE second benchmark model-system 1. The results demonstrate the advantages of the CA controller over the CC controller.

2 SYSTEM MODELLING

Generator Model

The generator model considered here includes two circuits on the rotor (i) field winding on the direct axis and (ii) damper winding on the quadrature axis. With this model the differential equations are

\[ E'_q = \frac{1}{T_d} [-E'_q + (X_d - X_q')i_d + E_{FD}] \]  

\[ E'_d = \frac{1}{T_q} [-E'_d - (X_q - X_q')i_q] \]

The stator is represented by the two axis (d and q axes) equivalent of the 3 phase windings. The flux linkages associated with the d and q axes windings are given by

\[ \frac{-1}{\omega_B} \psi_d - (1 + s_g)\psi_q - R_d i_d = V_d \]  

\[ \frac{-1}{\omega_B} \psi_q + (1 + s_g)\psi_d - R_q i_q = V_q \]

where \( s_g \) is the generator slip.

The rotor mechanical dynamics are represented by

\[ M \frac{d^2 \delta}{dt^2} = T_m - T_e \]  

\[ T_e = E'_q i_d + E'_d i_q + (X'_d - X'_q)i_d i_q \]

where \( T_m \) is the mechanical torque and \( T_e \) is the electrical torque. For SSR studies, the mechanical system is described by the multi-resonant model. It is modelled as a linear mass-spring-damper system. A single time constant static exciter with PSS is considered as shown in Figure 1.

Network representation

The AC network consists of the generator transformer and transmission lines. It is represented by
the a-sequence network. The β-sequence network is similar to the a-sequence network. The state and output equations written for a and β sequence networks are transformed to the Kron’s reference frame (D,Q frame). The CSC is represented as consisting of two parts, a fixed capacitor and a TCSC whose reactance is varied by varying the susceptance of the parallel inductor. For transient stability studies where the network transients are neglected, the network is represented by the algebraic equation

\[
[Y][V] = [I]
\]  

(7)

where, [I] is the vector of current injections, [V] is the vector of bus voltages and [Y] is the network bus admittance matrix.

3 CONTROL SCHEMES FOR THE CSC

The CSC is normally operated in the capacitive region. The CSC is operated in the inductive mode when protection of the capacitor is required. Vernier control of the CSC is possible within its reactance limits. Hence the control for the CSC is essentially meant to vary the reactance of the CSC to meet a particular objective. The constant current control reported in the literature [3] aims at regulating the magnitude of the current through the compensated line at a desired value, by suitably varying the reactance. In this paper, constant angle control is proposed which is aimed at regulating the voltage drop (or the phase angle) across the line. The objective is to regulate the power flow in the parallel paths particularly during contingency conditions. If \( V \) is the voltage across the line and \( I_L \) is the current flowing through the line, \( X_L \), the line reactance and \( V_{\text{ref}} \), the voltage across the CSC, then neglecting the line resistance, the control objective is

\[ V = |I_L * X_L + V_{\text{ref}}| = K(\text{constant}) \]

Hence, \( I_L = (K - V_{\text{ref}})/X_L = I_{\text{ref}} \).

\( V_{\text{ref}} \) is assumed to be positive in the inductive region and negative in the capacitive region. Therefore, if we choose a slope \( S_k = -1/X_L \), in the control characteristic then the voltage across the line can be kept a constant. This type of control is expected to reduce the power angle swings. The steady state control characteristics for the CC and CA control can be represented as shown in Figure 2.

4 CONTROLLER

The controller for the CSC is shown in Figure 3. The CSC current, \( I_{\text{ref}} \), and the voltage across the CSC, \( V_{\text{ref}} \), weighted by a factor of \( S_k \) representing the voltage droop are fed to the reference junction. \( T_\varepsilon \) represents the transducer time constant assumed equal for both voltage and current measurements. The error signal \( I_e \) (the difference between the sensed current and the reference current \( I_{\text{ref}} \)) is integrated. This results in a change of the firing angle of the thyristor to appropriately correct the effective reactance of the CSC. The limits \( X_{\text{emin}} \) and \( X_{\text{emax}} \) represent the minimum and maximum values of the CSC reactance. The thyristor controller action is represented by the function \( G_t(s) = \frac{1}{1 + sT_t} \), where \( T_t \) is the delay time.

5 CASE STUDY

The IEEE Second benchmark model [6] shown in Fig. 4 is used for the performance evaluation of the control scheme. It consists of a single machine connected to an infinite bus through two long parallel ac lines, one of which is compensated. System data is given in the appendix.

Eigenvalue analysis is used to determine system stability and to study the effectiveness of CSC controllers on the torsional modes. The method is based on the linearization of the coupled electrical and mechanical equations under small perturbations. Linearized state and output equations are written for each subsystem described above, and then the coupling is established by the use of interface variables to get the total system 'A' matrix.

For the system shown in Fig. 4, Table 1 lists the eigenvalues when the line is 50% compensated i.e., \( X_c = 50\%X_L \), without CSC, with PSS. For this case, modes 1 and 2 are unstable. With the introduction of CSC with \( X_{\text{cl}} = 25\%X_L \), \( X_c = 15\%X_L \) and \( X_{\text{cm}} = 25\%X_L \), which results in total \( X_c = 50\%X_L \), mode 2 is stabilized and the negative damping of mode 1 is reduced as seen from Table 1. Table 1 also lists the eigenvalues for CA and CC controls. For angle control, the gain \( K_I \) of controller is negative. From Fig. 5a which shows the variation of real part of torsional modes with \( K_I \), with CA control, it is seen that damping of modes 2 and 1 increases with gain. Mode 1 is stabilized for gain values beyond -51. However, when the gain is zero, the net damping of mode 1 is negative mainly due to contribution of PSS. Increase in gain causes the damping of mode 0 to first decrease and then increases as seen from Fig. 5b. One of the network modes becomes unstable for gain values beyond -54 as shown in Fig. 5b. Thus, proper choice of controller gain leads to the stable operation of the system.

Fig. 6a shows the variation of real part of torsional modes with \( K_I \) for current control. The gain is positive for current control. The eigenvalues for CC control with \( K_I = 5 \) is given in Table 1. The torsional modes 2 and 3 are stable in the range, but mode 1 is unstable. The damping of mode 1 reduces as the gain is increased. Figure 6b shows the root loci of mode 0 and the network mode with the lowest fre-
frequency. Damping of mode 0 increases first up to a gain of 7, but further increase in gain reduces the damping. The damping of network mode decreases with increase in gain and becomes unstable for gain values beyond 7. Comparison of Figures 5a and 6a show that as the gain magnitude is increased, mode 1 is stabilized for angle control whereas the damping decreases for current control. While the network mode damping puts limits on the gain for both cases, higher gains are feasible for CA control which enables damping of all modes.

Time domain digital simulation is performed to evaluate the transient stability performance of the controller. For the simulation, the CSC is modelled as a variable reactance. The controller dynamic equations are solved to obtain the CSC reactance. The bus admittance matrix is then updated in every time step, and equation (7) is solved for the bus voltages. For the transient stability studies the infinite bus voltage is assumed to be 1.0 p.u. The mechanical torque is assumed to be constant and torsional dynamics is neglected. A three phase fault at the generator terminals, cleared in 3 cycles is considered.

Figure 7 shows the system response at 630 MW. It can be observed that the Constant Angle controller reduces the amplitude of the power angle swings as compared to the Constant Current controller. For this case the system is stable up to a power transfer level of 800 MW for constant reactance control, 730 MW with CC control and 870 MW with CA control. If the excitation control is not considered, then the corresponding maximum power transfer levels are 760 MW with constant reactance control, 700 MW with CC control and 840 MW with CA control.

The CA control is aimed at regulating the power in the parallel lines. Figure 8 shows the power flow in the compensated and the uncompensated lines for a minor disturbance (a small step change in the infinite bus voltage). It can be observed that the power through the uncompensated line is well modulated.

6 CONCLUSIONS

From the results of the case studies, the following conclusions can be drawn.

(i) The introduction of CSC improves the damping of the critical torsional mode as compared to the case without CSC, for the same value of percentage compensation.

(ii) The torsional mode with lowest frequency (mode 1) is most affected as the value of controller gain is varied. For CA control, increase in the controller gain magnitude improves the damping of mode 1 and becomes stable for gain values beyond -51. For CC controller, mode 1 is negatively damped with increase in controller gain. Thus CA control results in damping of the critical torsional mode.

(iii) The CA control improves transient stability limit whereas the application of fast CC control is detrimental to transient stability. This is not surprising as fast CC control prevents the flow of synchronizing power in the line.

Acknowledgement:

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REFERENCES


4. J.Urbanek et al., 1993, ”Thyristor Controlled Series Compensation prototype installation at the Slatt 600kV substation”, IEEE Trans. on PWRD, 8, 1460-1469.

5. S.Nyatí et al., 1994, ”Effectiveness of thyristor controlled series capacitor in enhancing power system dynamics: An analog simulator study”, IEEE Trans. on PWRD, 9, 1018-1027.


APPENDIX

Generator data (600 MVA, 22kV):

- Frequency: 60Hz
- $x_d = 1.65 \text{ p.u.}$, $x'_d = 0.25 \text{ p.u.}$, $T_{de} = 4.5s$
- $x_q = 1.59 \text{ p.u.}$, $x'_q = 0.46 \text{ p.u.}$, $T_{qe} = 0.55s$
- AVR Data: $K_H = 200$, $T_R = 0.025s$
- PSS data: $T_W = 10s$, $K_s = 12$, $T_1 = 0.048s$, $T_2 = 0.032s$. 

Electrical Network (100 MVA):

- $f_0 = 60Hz$
- $x_d = 1.65 \text{ p.u.}$, $x'_d = 0.25 \text{ p.u.}$, $T_{de} = 4.5s$
- $x_q = 1.59 \text{ p.u.}$, $x'_q = 0.46 \text{ p.u.}$, $T_{qe} = 0.55s$
- AVR Data: $K_H = 200$, $T_R = 0.025s$
- PSS data: $T_W = 10s$, $K_s = 12$, $T_1 = 0.048s$, $T_2 = 0.032s$. 

Electrical Network (100 MVA):
\( R_T = 0.0002 \text{ p.u.}, X_T = 0.02 \text{ p.u.}, R_b = 0.0014 \text{ p.u.}, \\
X_b = 0.03 \text{ p.u.}, R_1 = 0.0074 \text{ p.u.}, X_{L1} = 0.08 \text{ p.u.}, \\
X_c = 0.04 \text{ p.u.}, R_2 = 0.0067 \text{ p.u.}, X_{L2} = 0.0739 \text{ p.u.}. \\
\)

CSC data: Fixed compensation in one line of 25%,
CSC capacitive reactance varies from 10% to 45%,
quiescent operating value is 50%.

<table>
<thead>
<tr>
<th>Mass</th>
<th>H (sec.)</th>
<th>D (p.u.)</th>
<th>K (p.u.)</th>
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<tr>
<td>HP</td>
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<tr>
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Figure 1. Block diagram of AVR and PSS

Figure 2. Steady state control characteristics

Figure 3. CSC controller

<table>
<thead>
<tr>
<th>Without CSC</th>
<th>With CSC With fixed reactance</th>
<th>With CSC, ( K_f = -52)</th>
<th>With CSC, ( K_f = 5)</th>
<th>Comments</th>
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<tr>
<td>-0.0479 ± j321.051</td>
<td>-0.0478 ± j321.051</td>
<td>-0.0462 ± j321.051</td>
<td>-0.0478 ± j321.051</td>
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</tr>
<tr>
<td>0.0068 ± j203.3649</td>
<td>-0.0217 ± j203.4282</td>
<td>-0.0048 ± j155.163</td>
<td>-0.0209 ± j203.428</td>
<td>Mode 1</td>
</tr>
<tr>
<td>0.3467 ± j155.4121</td>
<td>0.1998 ± j155.126</td>
<td>-3.076 ± j12.643</td>
<td>-4.199 ± j9.526</td>
<td>Mode 0</td>
</tr>
<tr>
<td>-15.375 ± j185.859</td>
<td>-5.0055 ± j101.0684</td>
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</tr>
</tbody>
</table>

TABLE 1.1 genvalues for system in Fig. 4
Figure 4. System under study

Figure 5a. Variation of real part of torsional modes with $K_I$, (CA)

Figure 5b. Root locus of mode 0 and network mode (CA)

Figure 6a. Variation of real part of torsional modes with $K_I$, (CC)

Figure 6b. Root locus of mode 0 and network mode (CC)
Figure 7. Swing curve

Figure 8. Power flow in the lines