Damping SSR in Power Systems using Double Order SVS Auxiliary Controller with an Induction Machine Damping Unit and Controlled Series Compensation

Sushil K. Gupta, Narendra Kumar and A. K. Gupta

Abstract—This paper presents a new idea for damping subsynchronous resonance in power systems using double order static var system (SVS) auxiliary controller in combination with controlled series compensation (CSC) and an induction machine damping unit (IMDU) coupled with the T-G shaft. A linearized dynamic model of CSC has been developed and incorporated in the system. The eigenvalue analysis using linearized system model has been performed and unstable system modes are investigated. The unstable system modes are stabilized by the proposed combination of controllers. The digital simulation study using nonlinear system model has been carried out under sever fault conditions. The proposed combination shows an effective damping of torsional oscillations, and the system performance is greatly improved at different levels of series compensation.

Keywords: Controlled series compensation (CSC), decremenral factors (DF), double order auxiliary controller (DOAC), induction machine damping unit (IMDU), static var system (SVS)

1. INTRODUCTION

The objective of Flexible AC Transmission Systems (FACTS) is to improve the power system stability and thereby to increase the transmission capability of the existing power system networks. Series compensation of transmission lines may contribute subsynchronous resonance (SSR) in power systems. The SSR introduces torsional oscillations in the power system that may cause the turbine-generator (T-G) shaft failure. A great deal of work has been reported in the literature [1-4] that for enhancing the power system stability using controlled series compensation. A. Hisham Othman and L. Angquist [5] developed an analytical model of a thyristor controlled series compensation to investigate subsynchronous torsional oscillations in the turbine generator shaft, and to evaluate control strategies of the TCSC and other devices in the power systems such as static var system (SVS) excitation systems. J.V. Milanovic and I. A. Hiskens [6] proposed the robust tuning of static var compensator, but the result shows the inter-area modes are less damped when one load had uncertain parameters.

J. F. Hauer et al [7] performed the subsynchronous resonance (SSR) tests on the BPA 500 kV TCSC unit at Slatt Substation. But the security considerations did not permit lightly damped operation of the controlled plant, and therefore, complete demonstration of the TCSC was not feasible.

In this paper, a coordinated approach of CSC with SVS auxiliary controller and induction machine damping unit (IMDU) coupled with the T-G shaft is investigated for damping the SSR oscillations in the power system. A detailed power system model has been developed in section 2, which reflects the power system dynamics with sufficient accuracy. In section 3, the linearized models of the proposed CSC, SVS and IMDU controllers have been developed. In section 4, the application of proposed combination has been demonstrated to IEEE first bench-mark model of power system. In order to demonstrate the effectiveness of the proposed combination, the eigenvalue analysis using linearized system model has been performed. The digital simulation study using non-linear system model under severe fault conditions at different levels of series compensations has been carried out. It is seen from the simulation study that the individual controller or the combination of any two is not able to stabilize all the unstable system modes at different levels of series compensations without considering the natural system damping. Therefore it is essential to combine all the three controllers for damping all the torsional modes under severe fault conditions and at different levels of series compensations. It is to be noted that no natural damping of the system has been considered for evaluating the exclusive effect of the controllers. The results show the very effective damping of torsional oscillations and considerable enhancement of the power system performance.

2. SYSTEM MODEL

The study system consists of a steam turbine synchronous generator set connected to the infinite bus through a long transmission line as shown in figure 1. The mechanical system has been modeled by six-mass representation [8]. A fixed capacitor and thyristor controlled reactor (FC-TCR) type of SVS is considered located at the receiving end of the transmission line. The controlled series compensation is applied at the sending end bus. The IEEE type-1 excitation system [10] is used. The overall interconnection of various subsystems model is presented in figure 2. The elements of various system matrices are given in appendix A. The overall system model after combining the various sub systems is obtained in the form of $X_{p} = A[X] + BU$. Where $A$ is the system matrix of the order of 43. After incorporating the double order SVS auxiliary controller the order of the system becomes 45.

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3. CONTROL SCHEMES

Double order auxiliary controller’s output is used as the auxiliary signal to the input of the static var system. The overall transfer function of the system is modified so as to enhance the dynamic performance of power system. An induction machine damping unit (IMDU) is considered coupled with the high-pressure turbine which acts as a motor or generator depending upon its slip during the disturbances, and hence, increases the mechanical system damping during disturbances conditions. A controlled series compensation scheme is simulated by using the thyristor switched reactors (TSR) and thyristor controlled reactor (TCR) in parallel with fixed series capacitor.

3.1 Auxiliary control of SVS

The auxiliary controller has been assumed to be a double order transfer function as shown in figure 3. Two zeros are added to the system for suppressing the effect of inertial mode. The reactive power deviation at the SVS bus is used as an auxiliary input signal to the controller. The values of various constants, given in appendix, are optimally found from the locus of the results obtained by the digital iterations. The linearized state and output equations are derived as follows:

\[
\begin{align*}
\dot{X}_C &= [A_C] X_C + [B_C] U_C \\
\Delta V_F &= G[1 \quad 1] + G U_C \\
Y_C &= [C_C] X_C + [D_C] U_C
\end{align*}
\]

Where,

\[
U_C = \Delta Q_3 = (V_{1d0}\Delta i_{d0} + i_{d0}\Delta V_{1d} - V_{1q0}\Delta i_{q0} - i_{q0}\Delta V_{1q}) = [F_{CN}] X_N, \quad F_{CN} is (1\times18) matrix.
\]

3.2 IMDU

The property of induction machine to act as a generator or motor is utilized to absorb the mechanical power when there is excess and to generate when there is a deficiency of it. Since the machine comes into operation during transients only, it is designed for very high short-term rating and very small continuous rating. Consequently, the machine has low inertia, low power, small size and low cost. Because of its small mass and tight coupling with the high pressure turbine it has been considered a single mass unit with HP turbine. Since it controls the active power it may be named an active controller. Electrically it is connected to the generator bus. The per unit torque \( T_{in1}(t) \) is given by:

\[
T_{in1} = \frac{3s}{[(\omega_0 - \omega_2)(1 + (s.x_2/r_2)^2)]}
\]

and slip \( s = (\omega_0 - \omega_2)/\omega_0 \)

Hence by considering equation number 3 the mechanical system model is modified as below

\[
M_1.\Delta \omega = -3(D_{11} + D_{12})\omega_1 + D_{12} \omega_2 - K_{12}(\delta_1 - \delta_2) + T_{in1} + T_{in1}
\]

Linearizing equations 3 to 5, we get:

\[
\Delta T_{in1} = \frac{(3/((\omega_0 - \omega_2)^2\{1 + (s.x_2/r_2)^2\}) - s\{(x_2/r_2)^2\})]\Delta s}{[1 + (s.x_2/r_2)^2]^2}
\]

\[
\Delta s = -\Delta \omega_1/\omega_0
\]

At normal operating point \( s = 0 \). Hence \( \Delta T_{in1} = 3. \Delta s/\omega_0 - r_2' = -3\Delta \omega_0/\omega_0 r_2' \)

\[
M_1. \Delta \omega_0 = -(D_{11} + D_{12})\Delta \omega_1 + 3\Delta \omega_0/\omega_0 - r_2' + D_{12} \Delta \omega_2 - K_{12}(\Delta \delta_1 - \Delta \delta_2)
\]

The damping coefficient term \[-(D_{11} + D_{12})\] of high pressure turbine is thus modified to \[-(D_{11} + D_{12} - 3/\omega_0 r_2')\] on application of the IMDU.

3.3 CSC

In order to consider the dynamics of CSC, it is important to consider the deviation in the line reactance as one of the state variables. The appropriate control action in control series compensation is initiated to reduce a function \( P_D \) (defined below) progressively, following the disturbance.

\[
P_D = (P_E - P_M)^2/2
\]

\[
\frac{dP_D}{dt} = \frac{dP_D}{dt} \frac{dP_E}{dx} \frac{dE_s}{dt}
\]

Where \( P_E = (V_e V_i s\delta) \) is electrical output power and \( P_M \) is mechanical input power.

\[
\frac{dX_s}{dt} = (P_M - P_E) X_s^2
\]

For \( P_M > P_E \), \( dP_D/dX_s > 0 \)
It is, therefore, \( \frac{dX}{dt} \) should be less than zero, which means \( X \) should reduce with time and vise versa.

Control of series reactance is simulated by using the thyristor switched reactor (TSR) and thyristor controlled reactors (TCR) in parallel with a fixed series capacitor. A parallel L-C tank is used for controlled series compensation. It has a fixed capacitance, and eleven thyristorised switched inductive reactance and a constant inductive reactance (\( X_{\text{le1}} > X_{\text{base}} \)) to limit the maximum level of series compensation as shown in figure 4(a). Thyristor switched reactor changes the reactance in steps. The required inductive reactors ranging from \( X \) to 1024 \( X \) are switched in or out of the circuit by turning ON or OFF of appropriate group of thyristors. Also an inductance of lowest value is used in the TCR mode to provide fine variation – its detailed circuit is shown in figure 4(b). \( T_c \) conducts from 0\(^{\circ} \) to \( \alpha \) (figure 4.c), as a result, \( X_c \) is connected in series with \( X_{\text{le1}} \). At \( \alpha = \alpha \), \( T_c \) is turned off and \( T_l \) is turned on, consequently, inductive current \( (i_l) \) is diverted to \( T_l \). At the same time \( T_l \) is turned on, which freewheels the current through \( X \) and \( R \), and stored inductive energy is quickly dissipated (in \( R \)). Thus the reactance appears in circuit from 0\(^{\circ} \) to \( \alpha \) and is by passed by \( T_l \) from \( \alpha \) to \( \pi \). Similar operation takes place in negative half cycle.

By varying the conduction period of \( T_l \) (and \( T_c \)), effective value of \( X_{\text{le1}} \) can be controlled. The control of inductive reactance takes place during transients (5-8 s) only and the value of \( X \) is much smaller compared to other series reactances, chopping action will cause negligible distortion of the inductive current \( (i_l) \) of the tank. Hence the line current \( (i_l) \) will be free from harmonics. Another feature of the circuit is that very small variation in the inductive reactance causes large variation in the series compensation.

Value of \( X \) is given in appendix.

\[
-j X_{\text{le1}} = \frac{(-jX_cjX_c)}{(jX_c - jX_c)} = -j (X_c^2/(X_cX_c))
\]

(12)

Hence, reducing \( X_c \) (controlled by TSR and TCR as discussed) increases the level of series compensation. CSC is employed to minimize the deviation of shaft angle, \( \delta_M \) as disturbance occurs, Net level of series compensation is then given by:

\[
X_{\text{le1}} = X_{\text{le1}}0(1+\sin(\delta_M - \delta_{M0}))
\]

(13)

The voltage (\( \alpha \)-axis) across CSC is given by:

\[
\dot{V}_{6a} = V_{x_{le1}}0[1+\sin(\delta_M - \delta_{M0})]i_a
\]

(14)

Linearizing across operating point

\[
\Delta V_{6a} = (i_a/C_{\text{le1}}) \Delta \delta_M + (1/C_{\text{le1}}) \Delta i_a
\]

(15)

Similarly equation can be derived for \( \beta \)-axis.

Converting these equations in D-Q frame of reference.

\[
K = C_{\text{le1}}
\]

4. CASE STUDY

The power system used to study the performance of the proposed control strategies consists two synchronous generators represented by a single equivalent unit of 1110 MVA, at 22 kV and supplying power to an infinite bus through a 400 kV, 600 km long transmission line. The SYS is capable of delivering 650 Mvar reactive power. The natural damping of the system is assumed to be zero so that the effect of controller exclusively can be examined. The main information obtained from the load flow study comprises \( P, V, Q \) and \( \delta \) at operating point on each bus. Although results presented are for 800 MVA load, but the analyses have been performed for wide range of load and the conclusions drawn are general. Initial values of system states, required in the eigenvalues analysis, are calculated from results of load flow studies with the help of the phasor diagram of synchronous generator and transmission line.

4.1 Dynamic Analysis

The dimensions of the system matrix with and without controller are found to be 45 and 43 respectively. The eigenvalues, so obtained from the system matrix, are the familiar modes of response for the system. The real parts of eigenvalues are called decremental factors (DF). They must be in the left half to the complex plane for the system to be stable. The frequencies of modes (imaginary parts of eigenvalues) are found as in [9]. The ‘DF’ for the system at various levels of series compensation are calculated and presented in table 1 and table 3 without and with proposed scheme. The ‘DF’s with double order auxiliary controller in coordination with induction machine only (without CSC) are presented in table 2.

4.2 Time Domain Analysis

Digital time domain analysis, for the system under large disturbances, has been done on the basis of nonlinear differential equations with all non-linearities and limits. A fourth order Runge Kutta method has been used for solving the nonlinear differential equations. Disturbance is simulated by 33\% sudden increase in input torque for 0.6 seconds. The responses of the system without and with the proposed scheme are plotted in figure 6. Further, a three phase open circuit fault has also been considered to occur at point ‘F’ as shown in figure 5. The net level of series compensation considered is 40\% and both the parallel lines are identical. The controller’s performance for this transient fault is demonstrated in figure 7.
5. CONCLUSIONS

A new method for damping the SSR modes of the power system is presented and tested for the system under study. In the paper, it has been seen that the controlled series compensation in combination with SVC auxiliary controller and induction machine damping unit (IMDU) dampens out the torsional oscillations and enhances the dynamic and transient performance of the system. The following conclusion can be drawn from the study performed.

- Damping of mode ‘0’ is excellent which causes the suppression of transmission oscillations. It is verified from the transient analysis.
- All the torsional modes (‘1’ to ‘5’) become stable. This is verified from the transient analysis as shown in figure 6 and 7 for the various shaft torques.
- Damping of SSR is achieved at various levels (10 to 70%) of series compensations over wide range of load variation.
- Effective damping of all SSR modes makes it feasible to increase the power transfer capability of transmission line and control of the power flow.
- Overall performance of the system is improved.
- Transient results show the applicability of proposed controller under sever disturbance and at different levels of series compensation.

References

Discussion

Why we need both series and shunt in a simple radial system.

Comments

The object and application of shunt and series compensation is different. However the question can be under stood as why we need the control of both shunt and series? Answer can be summarize as 1) Different plants connected to the system have different resonant frequencies and therefore tend to damp each others oscillations. Thus the resonant condition become more severe only when a plant ends up in a radial mode through a long series compensation line. In the case of the Mohave plan, the damage occurred when only the high pressure unit was operating and another connection to Eldorado was opened by fault. As a consequence the HP unit was left operating in radial, via 500 kV line with 60% series compensation. 2) Analysis of simple power system using idealized model will help identify the basics of new control techniques. 3) Please refer the section 1, where it is mentioned that from the simulation results, table 1 to 3, it is observed that the individual controller or the combination of any two is not able to stabilize all the unstable system modes at different levels of series compensations. Therefore it is essential to combine all the three controllers for damping all the torsional modes under severe fault conditions without considering the natural damping of the system.
APPENDIX: System Data

a.1 System base quantities:

- Voltage = 400 kV
- MVA = 100
- Frequency = 50 Hz

a.2 Generator data:

- $S_n = 11.1$
- $V_n = \frac{22400}{400}$ pu
- $R_a = 3.243 \times 10^{-4}$
- $X_d^' = 0.042$ pu
- $X_q^' = 0.103$ pu
- $X_d^" = X_q^" = 0.0281$ pu
- $X_l = 0.0189$ pu
- $X_d = 0.174$ pu
- $X_q = 0.157$ pu

a.3 Transformer data:

- $R_T = 0.0$ pu
- $X_T = 0.0135135$ pu

a.4 IEEE type-I Excitation system data:

- $K_A = 400$ pu
- $T_A = 0.02$ s
- $K_E = 1.0$ pu
- $T_E = 1.0$ s
- $K_F = 0.06$
- $T_F = 1.0$ s

a.5 Transmission line data:

- $R = 12.525 \times 10^{-3}$ pu
- $X_L = 119.7 \times 10^{-3}$ pu
- $B_c = 1.784$ pu

a.6 SVS data:

- $Q = 100$
- $K_i = 1200$
- $K_p = -1$
- $K_d = 0.01$ pu
- $T_M = 2.4$ ms
- $T_s = 5$ ms
- $T_i = 1.667$ ms

a.7 Controller’s Data: Auxiliary controller

- $%\text{Compensation}$
- $x$
- $G$
- $\alpha$
- $\omega_d$

<table>
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<td>5.05</td>
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- $y = (\alpha^2 + \omega_d^2)/x$
- $p = ((x-\alpha^2 + \omega_d^2)/(y-x))$
- $q = ((y-\alpha^2 + \omega_d^2)/(y-x)$

Induction m/c controls data

- $r_{i}^' = 3.6x10^{-4}$ pu
- $x_{i} = 0.32646$ pu

Controlled series compensation data

- $D_{ii} = 0$ for $i=1$ to 6
- $D_{ij} = 0$ for $i=1$ to 6, $j=1$ to 6

a.8 Mechanical system data: (at Generator base)

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<th>Inertia (H) (s)</th>
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Fig. 1 Schematic diagram of system under study

Fig. 3 Auxiliary controller’s block diagram

Fig. 2 Interconnection of various subsystems in overall system model
Fig. 4(a) Continuous control series compensation scheme

Fig. 4(b) TCR control of lower part of inductive reactance

Fig. 4(c) Wave forms for the circuit of Fig. 3(b)

Fig. 5 Test power system for 'OC' fault analysis