Damping of Sub-synchronous Resonance and Power Swing using TCSC and Series capacitor

Durga Prasad Ananthu  
Assistant Professor, EEE dept.  
Guru Nanak Dev Engg College, Bidar  
adp.ananthu@gmail.com

Rami Reddy Mannem  
M.Tech Scholar, EEE Dept.  
SVEC, Suryapet- INDIA  
ramreddy.mannem@gmail.com

Abstract— The proposed series capacitive compensation scheme is effective in damping power swing as well as sub synchronous resonance oscillations. The combination of fixed series capacitor and TCSC is termed as a Hybrid technique. In this paper, the effectiveness of a “hybrid” series capacitive compensation scheme in damping power system oscillations is evaluated. In this scheme, where two phases are compensated by fixed series capacitor (C) and the third phase is compensated by a TCSC in series with a fixed capacitor (Cc). The effectiveness of the scheme in damping power system oscillations for various network conditions, namely different system faults and tie-line power flows is evaluated using the EMTP-RV time simulation program.

Key Words—FACTS Controllers, series compensation, thyristor controlled series capacitor.

1 INTRODUCTION

The transmission network in the INDIA is being wider due to an increasing demand for power transmission combined with the difficulty in approving new lines. Series compensation of transmission lines is a widely-used method to improve the effective capacity of the transmission system, thus avoiding the need to build new lines in many parts of the network. Insertion of capacitive reactance in series with line’s inherent inductive reactance lowers the total effective impedance of the line and thus virtually reduces its length. As a result both angular and voltage stability in the power system gets improved. However, series compensation of lines creates the risk of torsional oscillations between the electrical network and generators. These oscillations are referred to as sub-synchronous resonance (SSR) since they typically occur at sub-synchronous frequencies that means frequencies less than nominal 50Hz or 60 Hz frequency. Because of SSR, generators will get damage.

During the 90’ies the Thyristor Controlled Series Capacitor (TCSC) was being introduced. In this apparatus a thyristor controlled, inductive branch has been connected as an add-on in parallel with the series capacitor bank (Fig. 1.).

When a forward-biased thyristor is fired the capacitor will be partially discharged through the LC circuit constituted by the thyristor controlled inductive branch and the capacitor bank. The circulating current pulse passes through the capacitor in phase with the line current. It creates an additional voltage across the capacitor in excess of the voltage, which is caused by the line current. The increased voltage at a given line current amplitude is perceived by the transmission system as if the inserted capacitive reactance had been increased or “boosted” by the action of the thyristor valves. The generic waveform of the TCSC is shown in Fig. 2.

It was recognized early that the characteristics of the TCSC with respect to SSR differed completely from that of a passive, fixed series capacitor.
Fig. 2. Generic waveforms for the TCSC. From top to bottom: line current, valve current, capacitor voltage, apparent reactance

The latter reveals a capacitive reactance, which is inversely proportional to the frequency. Accordingly it tends towards infinity at zero frequency (DC). The apparent reactance of the TCSC, in contrast, decreases with frequency and gets zero at zero frequency (DC). The reason for this dissimilarity is that the TCSC reacts on an injected sub synchronous line current component by modulating the thyristor current in the inductive branch. This influences the sub synchronous current passing through the capacitor, which determines the sub synchronous voltage across the TCSC.

The algorithm that has been selected for the thyristor triggering control plays the main role in forming the characteristics of the TCSC with respect to SSR behaviour. However, also the regulators executing synchronization and boost control do have an impact on the TCSC’s SSR properties.

The thyristor-controlled series capacitor (TCSC) is one of the most effective countermeasures in practice due to its natural mitigating effect, as well as its ability to damp SSR through a controller. However, the strong dependency between network parameters and generator data plus the complex function of the TCSC require comprehensive studies prior to the installation of a TCSC into the transmission system. Fig. 3 shows the series capacitive compensation scheme. It is a hybrid series compensation scheme, where the series capacitive compensation in one phase is created using a single-phase TCSC in series with a fixed capacitor (C.), and the other two phases are compensated by fixed series capacitors(C). The TCSC control is initially set such that its equivalent compensations at the power frequency combined with the fixed capacitor yield a resultant compensation equal to the other phases. Thus, the phase balance is maintained t the power frequency while at any other frequency, a phase imbalance is created. To further enhance power oscillations damping, the TCSC is equipped with a supplementary controller.

The proposed series compensation scheme can be explained mathematically as:

1) At the power frequency, the series reactances between buses X and Y in Fig. 1, in phase a, b and c are given by

\[ X_a = X_b = \frac{1}{j\omega C} \]  

\[ X_c = \frac{1}{j\omega C} - jX_{TCSC} \]  

Where \(-jX_{TCSC}\) is the effective capacitive reactance of the TCSC at the power frequency such that \(X_a = X_b = X_c\)

2) During any other frequency, \(f\),

\[ X_c = \frac{1}{j\omega C} - jX_{TCSC} - j\Delta X_{TCSC} \]

The first terms in (2) and (3) are different because of the difference in frequency. The third term in (3) represents the change in the effective capacitive reactance of the TCSC due to the action of the TCSC supplementary controller.

This scheme would, definitely, be economically attractive when compared with a full three-phase TCSC which has been used/proposed for power oscillations damping. Furthermore reducing the number of thyristor valves to one third will also have a positive impact on system reliability. The effectiveness of the scheme in damping power swings and sub synchronous resonance oscillations is reported in [2], [3]. This paper evaluates the effectiveness of the scheme in damping power system oscillations. Time domain simulations were conducted on a benchmark network using the EMTP-RV.
II. TEST SCHEME

To demonstrate the effectiveness of the proposed scheme in power system oscillations damping, the system shown in Fig. 4 is adopted as a test scheme. It consists of three large generating stations (G₁, G₂ and G₃) supplying two load centers (S₁ and S₂) through five 500 kV transmission lines. The two double-circuit transmission lines L₁ and L₂ are series compensated with fixed capacitor banks located at the middle of the lines. The compensation degree of L₁ and L₂ is 50%. The compensation degree is defined as the ratio \((X_C/X_L) \times 100\%\) for fixed capacitor compensated phases and \((X_C+X_{TCSC})/X_L \times 100\%\) for the hybrid compensated phase.

The total installed capacity and peak load of the system are 4500 MVA and 3833 MVA respectively. Shunt capacitors are installed at buses 4 and 5 to maintain their voltages within ±0.05 p.u. Two loading profiles designated as Load Profiles A and B are considered in the investigations of this paper. In Load Profile A, \(S_1 = 1400 + j200\) MVA and \(S_2 = 2400 + j300\) MVA while in Load Profile B, \(S_1 = 2000 + j200\) MVA and \(S_2 = 1800 + j300\) MVA. The power flow results for the bus voltages and the line real power flows of the system for these two loading profiles are shown in the Appendix. The EMTPRV is used as the simulation study tool.

III. MODELING OF THE SINGLE-PHASE TCSC

The single-phase TCSC is modeled in the EMTP-RV as a single module using an ideal thyristor pair and an RC snubber circuit as shown in Fig. 5. A Phase Locked Loop (PLL) is used to extract phase information of the fundamental frequency line current, which will be used to synchronize TCSC operation. The thyristor gating control is based on the Synchronous Voltage Reversal (SVR) technique [4]. The TCSC impedance is measured in terms of a boost factor \(k_B\), which is the ratio of the apparent reactance of the TCSC seen from the line to the physical reactance of the TCSC capacitor bank. A positive value of \(k_B\) is considered for capacitive operation. A low-pass filter based estimation algorithm is used to estimate the voltage and the current phasors. A boost measurement block performs complex impedance calculations for the boost factor of the TCSC as \(k_B = \text{Imag}(V_C / \Gamma_C) / X_{TCSC}\), where, \(V_C\) and \(\Gamma_C\) are the estimated phase voltage and current and \(X_{TCSC}\) is the capacitive reactance of the TCSC capacitor branch at the fundamental frequency.

A proportional-integral (PI) control based boost level controller is implemented to control the TCSC boost level to the desired value by adjusting the instant of the expected capacitor voltage zero crossing. The integral part of the controller helps in removing the steady state errors. The controller parameters were determined by performing repeated time domain simulations for the different operating conditions. This algorithm uses the difference between the actual boost level and the reference boost level (err) shown in Fig. 5 as an objective function. The algorithm starts with arbitrary initial values for the control parameters and calculates the values of the objective function each time. The control parameters are incremented for the next iteration and the procedure is repeated until the objective function approaches a minimum value (below a threshold value). The procedure described above is widely used by industry for tuning of controller parameters. The multiple simulations run based tuning procedure similar to the above was reported in [5]-[6].

In Fig. 5, D(t) is a supplemental signal generated from an \(m\)-stage lead-lag compensation based controller. As the real power flow in the transmission line is proportional to the inverse of the total line reactance, the power swing damping can be achieved by properly modulating the apparent TCSC reactance through this controller. The supplemental controller input (stabilizing) signals could be
local (e.g., real power flows) or remote (e.g., load angles or speed deviations of remote generators). If a wide-area network of Synchronized Phasor Measurement (SPM) units is available, then the remote signals can be downloaded at the controller in real time without delay. Local signals are generally preferred over remote signals as they are more reliable since they do not depend on communications.

In Fig. 5, $k_B^{ref}$ is the TCSC boost level set point. The Synchronous Voltage Reversal block solves for angle $\gamma$ from the non-linear relation, $u_{CZ} = X_0 i_{LM} [\lambda \gamma - \tan(\lambda \gamma)]$, where $u_{CZ}$ is the estimated capacitor voltage at the desired instant when the capacitor voltage zero crossing occurs, $i_{LM}$ is the measured value of the line current $i_L$, $X_0$ is the TCSC capacitor reactance at the TCSC resonance frequency, $\lambda$ is the ratio between the TCSC resonance frequency and the system fundamental frequency and $\gamma$ is the angle difference between the firing time and the voltage zero-crossing. The value of $\gamma$ is used to calculate the exact firing instants of the individual thyristors. The non-linear relationship between the boost factor and the thyristor firing angle $\alpha$ is shown in Fig. 6.

IV. TEST SIMULATIONS

This section demonstrates the capability of the proposed hybrid series compensation scheme in power system oscillations damping. For this purpose, the scheme is assumed to be placed in the test scheme replacing the fixed series capacitive compensation in $L_1$ and $L_2$. Moreover, it is assumed that each TCSC provides 50% of the total capacitive compensation and the disturbance is a three-cycle, three-phase fault at bus 4. Furthermore, the performance of the scheme is compared with only fixed capacitor compensation (Fixed C).

TEST CASE 1:

In this test, four different combinations of stabilizing signals (tabulated in Table I) are examined in order to determine the combination that would result in the best system transient time responses. The final results of the time-domain simulation studies (controllers tuning) are shown in Fig. 9 which illustrates the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing.

It can also be seen from Fig. 9 that the best damping of the relative load angle responses are achieved with the $\delta_{21} - \delta_{21}$ combination. The second best damped responses are obtained with the $\delta_{31} - \delta_{21}$ combination. These results should be expected due to the direct relationship between the relative load angles and the generators that yield the problem. It can also be seen from Fig. 9 that the worst damped responses are obtained with $P_{11} - \delta_{21}$ combination which results also in the increase of the first swings.
<table>
<thead>
<tr>
<th>Combination</th>
<th>Each TCSC in L1</th>
<th>Each TCSC in L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\delta_{21}$</td>
<td>$\delta_{21}$</td>
</tr>
<tr>
<td>2</td>
<td>$\delta_{31}$</td>
<td>$\delta_{21}$</td>
</tr>
<tr>
<td>3</td>
<td>$\delta_{31}$</td>
<td>$P_{L2}$</td>
</tr>
<tr>
<td>4</td>
<td>$P_{L1}$</td>
<td>$\delta_{21}$</td>
</tr>
</tbody>
</table>

**Table I**
The Four Examined Combinations Of Stabilizing Signals
For Test Case 1

**TEST CASE 2:**
In this case, $\delta_{21}$ is used as the supplementary controllers stabilizing signal. Fig. 10 illustrates the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing. It can be seen from Fig. 10 that, at this loading profile, the hybrid single-phase-TCSC scheme provides again a better damping performance to system oscillations compared to fixed capacitor compensation. It is observed, however, that there is a slight increase in the first swing of $\delta_{21}$.

**TEST CASE 3:**
In this case, any of the four signals, $\delta_{21}$, $\delta_{31}$, $P_{L1}$ and $P_{L2}$ contains the system’s two natural modes of oscillations and can be used to add damping to these modes as it has been demonstrated in Test Case I. It is a dual channel controller, in this The sum of two properly selected signals, however, should result in a more effective damping. The reason is that the two natural modes of oscillations are, in general, not in phase. A dual-channel controller would adjust separately the gain and phase of each mode of oscillations and, thus, provides a better damping. The results show that the best and second best damped responses are obtained with $\delta_{21}$, $P_{L1}$ and $\delta_{31}$, $P_{L2}$ Fig. 11 illustrates the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing. These results (in red color) are compared to the hybrid case of Fig. 10.
Fig. 11. Generator load angles, measured with respect to generator 1 load angle, during and after clearing a three-phase fault at bus (Test case 3, dual-channel controller).

Fig. 12 illustrates the three-phase voltages, $V_{X,Y}$, across the hybrid single-phase-TCSC compensation scheme (installed in L1 and the controllers are Pair 2) during and after clearing the fault. The system phase imbalance during the disturbance is clearly noticeable especially in phase C.

V. CONCLUSION

The paper presents the application of a new hybrid series capacitive compensation scheme in damping sub synchronous resonance (SSR) and power swing. The hybrid series capacitive compensation scheme is more effective in damping power system oscillations compared to a fixed series capacitor. The effectiveness of the presented scheme in damping power system oscillations is obtained through simulations of case studies on a test scheme.

REFERENCES


BIOGRAPHY

M RAMI REDDY completed B.Tech degree from JNTU Hyderabad and doing his M.Tech in Power Electronics from S.V Engg. College /JNTU Hyderabad. He worked for Sagar Cements as a Sr.Engineer and his area of interests in Power Electronics and Drives, PLC automation.

A DURGA PRASAD, completed B.Tech degree from JNTU Hyderabad And obtained his M.Tech Power Electronics degree from JNTU Hyderabad. Currently he is working for Guru Nanak Dev Engineering College as an Assistant Professor and his area of interest in Renewable energy sources.