Interarea Oscillation Damping by Unified Power Flow Controller-Superconducting Magnetic Energystorageintegrated System

Sreelal Elamana, A. Rathinam

Abstract—Interarea oscillations are turned to be a severe problem in large interconnected power systems, hence they cause severe problems like damage to generators, reduce the power transfer capability of transmission lines, increase line losses, increase wear and tear on the network components etc. This paper introduces a new control technique that uses unified power flow controllers (UPFC) with superconducting magnetic energy storage system (SMES) in order to damp the interarea oscillation in an effective manner.

Index Terms—Unified Power Flow Controllers (UPFC), Super Conducting Magnetic Energy Storage Systems (SMES), Inter Area Oscillations

I. INTRODUCTION

Modern power systems are large electromechanically interconnected systems, hence there is a chance for producing electro mechanical oscillations [2, 3] which will cause severe problems like damage to generators, reduce the power transfer ability of transmission lines, increase line losses, increase wear and tear on the network components etc. Electromechanical oscillations occur due to the swinging of synchronizing generators with each other. There will be (n-1) electromechanical modes [3] for an “n” machine system. Such kind of oscillation modes is produced when the rotor of the machines behaves as rigid bodies and oscillation energy will be exchange between the machines through transmission lines. If oscillation occurs between a single machine and a small group of machines with rest of the system then such kind of oscillations are known as local mode oscillations [2, 3]. Typical oscillation frequency ranges from 0.7HZ to 2HZ. If oscillation occurs between a large group of machines and rest of the system then such kind of oscillations are known as interarea mode oscillations [2, 3]. Typical oscillation frequency range from 0.1HZ from 0.8HZ. Typical oscillation frequency ranges from 0.7HZ to 2HZ. If oscillation occurs between a large group of machines and rest of the system then such kind of oscillations are known as interarea mode oscillations [2, 3]. Typical oscillation frequency range from 0.1HZ from 0.8HZ. In order to damp such electromechanical oscillations traditionally we use Power system stabilizers on generator excitation control system. Power system stabilizers are effective but usually they are designed for local modes and in large power systems they will not provide enough damping for interarea modes.

Hence in order to improve the damping of these modes FACTS controllers [6, 7] like Static synchronous compensator (STATCOM) [4, 14], Static series synchronous compensator (SSSC) [11, 13], Unified power flow controllers (UPFC) [1, 8, 9, 10] etc. are used. UPFC is a combination of STATCOM and SSSC or in other words which consist of shunt and series converters connected by a common dc link capacitor. UPFC can simultaneously perform real/reactive power flow in the transmission line and UPFC bus voltage/shunt reactive power control [9]. We have to improve the performance of UPFC during largetransients. Delink capacitor in UPFC is capable of charging or discharging to compensate for converter losses in the UPFC. During large transients, the energy stored in the dc-link capacitor is inadequate to accomplish significant damping without severe dc voltage degradation. For overcome this drawback we use substantial power supplies. The term substantial [6] means enough to deliver active power to the power system over an interval of a few seconds or more. If we use electro chemical battery [6, 12] as substantial power supply, we have to face the problems like high impedance, high cost, chemical reaction occurs on electrodes, higher ageing, high heating levels etc. If we use super capacitor [1, 6, 12] as substantial power supply we have to face the problems like low energy density, low voltage, higher self-discharge and unable to use full energy spectrum etc. so in this paper introducing a new control technique using unified power flow controllers (UPFC) with superconducting magnetic energy storage system (SMES) [11, 12, 15, 6] in order to damp the interarea oscillation in an effective manner. Comparing with other substantial energy supplies SMES having the advantages of high energy density, fast response, high efficiency, minimum energy loss during the conversion etc.

II. UNIFIED POWER FLOW CONTROLLER (UPFC)

The general structure of the UPFC contains two “back to back” voltage source converters using insulated gate bipolar transistor (IGBT) or Integrated Gate Commutated Thyristor (IGCT) with a common DC link. First converter is connected as parallel and another converter as series with transmission line. The shunt converter is used to provide active power demanded by the series converter through a common DC link. The series converter provides the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle.

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The transmission line current flows through series converter and therefore, it exchanges the active and reactive power with the AC system. Since the converters are connected to a common DC link, they exchange only active power and there is no reactive power flow between them. It means that reactive power could be controlled independently at both converters. Generally, this structure (Fig.1) enables voltage control by the shunt inverter and independent active and reactive power flow control by the series inverter. It is normally controlled to balance the real power absorbed from or injected into the power system by the series converter plus the losses by regulating the dc bus voltage at a desired value. Various control strategies to control the series voltage magnitude, angle and the shunt current magnitude have been presented [18-21].

### A. Parallel Branch of UPFC

In the parallel branch of UPFC, from a DC input voltage source, provided by the charged capacitor $C_s$, the converter produces a set of controllable three-phase output voltages with the frequency of the ac system power. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relatively small (0.1-0.15 p.u.) tie reactance. That is, if the amplitude of the converter output voltage is increased above that of the ac system voltage, due to adding load of a systems current will increased and also voltage level decrease, then the current flows through the tie reactance from the converter to the AC system, and the converter generates reactive (capacitive) power for the AC system. If the amplitude of the output voltage is decreased below that of the ac system, then the reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power. If the amplitude of the output voltage is equal to that of the ac system voltage, the reactive power exchange is zero. The reactive current I drawn by the synchronous compensator is determined by

$$I = \frac{V_i - V_c}{X}$$

The corresponding reactive power $Q$ exchanged can be expressed as follows:

$$Q = V_i \left[(i_{d1} - i_{d2}) \cos \theta_1 + (i_{q1} - i_{q2}) \sin \theta_1 \right] - V_i \sum_{j=1}^{n} V_j Y_{ij} \cos(\theta_1 - \theta_j - \phi_{ij})$$

### B. Series Branch of UPFC

In the series branch of UPFC, the series compensator is a reciprocal of the shunt compensator. The series compensator is functionally a controlled voltage source which is connected in series with the transmission line to control its current. This reciprocity suggests that both the admittance and voltage source type shunt compensators have a corresponding series compensator. Indeed, as indicated earlier, the series compensator can be implemented either as a variable reactive impedance or as a controlled voltage source in series with the line. That is, in series compensation the basic reference parameter is line current.

<table>
<thead>
<tr>
<th>(Synchronous) angular frequency</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shunt resistance and inductance</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Rs1 and Ls1</td>
<td></td>
</tr>
<tr>
<td>Series resistance and inductance</td>
<td>$Rs2$</td>
</tr>
<tr>
<td>$Ls2$</td>
<td></td>
</tr>
<tr>
<td>DC-link voltage</td>
<td>$Vdc$</td>
</tr>
<tr>
<td>DC-link capacitance and resistance</td>
<td>$Cdc,Rdc$</td>
</tr>
<tr>
<td>SMES dc voltage</td>
<td>$Vdcsmes$</td>
</tr>
<tr>
<td>SMES capacitance and equivalent resistance</td>
<td>$Csmses$ and $Rsmses$</td>
</tr>
</tbody>
</table>

The UPFC model is a combination of the static synchronous compensator (STATCOM) and static synchronous series compensator (SSSC) models. The currents $I_{d1}$ and $I_{q1}$ are the dq components of the shunt current. The currents are and the components of the series current. The voltage $V_{1-q1}$ and $V_{2-q2}$ are the sending end and receiving end voltage magnitudes and angles, respectively. The UPFC parameters are the following:

The UPFC is controlled by varying the phase angles $\alpha_1$ and $\alpha_2$ magnitudes $K_1$ and $K_2$ of the converter shuntand series output voltages, respectively. The SMES is connected to the dc-link capacitor of the UPFC through a Bidirectional dc-dc converter such as the SEPIC/Zero converter. The steady-state dc-link capacitor voltage and the SMES voltage are related through the duty cycle ratio $D$ as follows:

$$V_{dc} = \frac{D}{(1-D)}V_{dcsmes}$$

The duty cycle is the percent of a switching cycle in which the SMES discharges. For example, if $D=0.5$, then the SMES is in steady state and discharges (and charges) for half of each cycle, and $V_{dc}=V_{dcsmes}$. If $D>0.5$, then the SMES discharges for a greater portion of the switching cycle $V_{dcsmes}$ and drops (and vice versa charges for $D<0.5$).

The power balance equations at bus 1 are given by

$$0 = V_1 \left[(i_{d1} - i_{d2}) \cos \theta_1 + (i_{q1} - i_{q2}) \sin \theta_1 \right] - V_1 \sum_{j=1}^{n} V_j Y_{ij} \cos(\theta_1 - \theta_j - \phi_{ij})$$

$$\frac{1}{\omega_s} \frac{d}{dt} i_{d1} = \frac{R_s}{L_{s1}} \cos(\alpha_1 + \theta_1) + \frac{ω_1}{ω_s} i_{q1} - \frac{R_s}{L_{s1}} i_{d1} - \frac{1}{L_{s1}} \cos \theta_1$$

$$\frac{1}{\omega_s} \frac{d}{dt} i_{q1} = \frac{V_{dc}}{L_{s1}} \sin(\alpha_1 + \theta_1) - \frac{R_s}{L_{s1}} i_{q1} - \frac{ω_1}{ω_s} i_{d1} - \frac{1}{L_{s1}} \sin \theta_1$$

$$\frac{1}{\omega_s} \frac{d}{dt} i_{d2} = \frac{R_s}{L_{s2}} \cos(\alpha_2 + \theta_1) + \frac{ω_1}{ω_s} i_{q2} + \frac{R_s}{L_{s2}} i_{d2} + \frac{1}{L_{s2}} \cos(\alpha_2 + \theta_1) V_{dc} - \frac{1}{L_{s2}} (V_2 \cos \theta_2 - V_1 \cos \theta_1)$$

$$\frac{1}{\omega_s} \frac{d}{dt} i_{q2} = \frac{R_s}{L_{s2}} \sin(\alpha_2 + \theta_1) - \frac{ω_1}{ω_s} i_{d2} + \frac{1}{L_{s2}} \sin(\alpha_2 + \theta_1) V_{dc} - \frac{1}{L_{s2}} (V_2 \sin \theta_2 - V_1 \sin \theta_2)$$
\[
\begin{align*}
\frac{C}{\omega_s} \frac{d}{dt} V_{dc} &= -k_1 \cos(\alpha_1 + \theta_1) i_{d1} - k_1 \sin(\alpha_1 + \theta_1) i_{q1} - k_1 \cos(\alpha_2 + \theta_1) i_{d2} - k_2 \sin(\alpha_2 + \theta_1) i_{q2} - \left( \frac{1}{\alpha_{dc}} + \frac{1}{\alpha_{dmes}} \right) V_{dc} + D1 - DV\text{dmes}\text{Rmes} 
\end{align*}
\]

III. SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

Superconducting Magnetic Energy Storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its temperature. A typical SMES system includes three parts: superconducting coil, power conditioning system and cryogenically cooled refrigerator. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. The power conditioning system uses an inverter/rectifier to transform alternating current (AC) power to direct current or convert DC back to AC power. The inverter/rectifier accounts for about 2-3% energy loss in each direction. SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient; the round-trip efficiency is greater than 95%. Due to the energy requirements of refrigeration and the high cost of superconducting wire, SMES is currently used for short duration energy storage. Therefore, SMES is most commonly devoted to improving power quality.

An electronic interface known as chopper is needed between the energy source and the VSI. For VSI the energy source compensates the capacitor charge through the electronic interface and maintains the required capacitor voltage. Two-quadrant n-phase DC-DC converter as shown in Fig. 3 is adopted as interface. Here ‘n’ is related to the maximum current driven by the superconducting device. The DC-DC chopper solves the problems of the high power rating requirements imposed by the superconducting coil to the UPFC. The DC-DC chopper allows to reduce the ratings of the overall power devices by regulating the current flowing from the superconducting coil to the inverter of the UPFC. The two quadrant single-phase chopper is composed of many shunt connected diode-thyristor legs that permit the driving of the high current ratings stored in the superconducting coil. The chopper has 3 modes of operation to perform the charge, the discharge and the storage in the SMES device. The chopper is operated in step down configuration in the charge mode of the superconducting coil. Here, the IGBT “s1” is operated with the duty cycle “D” while the IGBT “s2” is kept on at all times. The relationship between the coil voltage and the DC bus voltage is given by the equation

\[
V_{\text{SMES}} = D \ast V_{DC}
\]

Once the charging of the superconducting coil is completed, the operating mode of the DC-DC converter is changed to the stand-by mode for which the IGBT “s1” is kept off all the time while the IGBT “s2” is kept on constantly. In the discharge mode, the chopper is operated in a step up configuration. The set of thyristors “b” is operated with duty cycle D while the set of thyristors “a” is kept off at all times. The relationship between the coil voltage and the DC bus voltage is given by the equation

\[
V_{\text{SMES}} = D \ast V_{DC}
\]
\[ V_{SMES} = (1 - D) \cdot V_{DC} \]  
Eq. (15)

The duty cycle ranges from 0 to 1. The relationship between the DC bus voltage and the output voltage of the Inverter is given by the Eq.

\[ V_{DC} = K_a V_{inv} \]  
Eq. (16)

Where,

\[ K_a = k \cdot a \]  
Eq. (17)

where,

\[ k \] = Pulse number

\[ a \] = Ratio of the coupling transformer

### III. TEST SYSTEM SPECIFICATION

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>230000V</td>
</tr>
<tr>
<td>base voltage</td>
<td>230000V</td>
</tr>
<tr>
<td>3 phase short circuit level at base voltage</td>
<td>100000000VA</td>
</tr>
<tr>
<td>Fault resistance</td>
<td>0.01 Ohm</td>
</tr>
<tr>
<td>Transition time</td>
<td>0.0167 Sec, 0.41 Sec</td>
</tr>
</tbody>
</table>

### V. CONTROLLER RESULTS AND COMPARISONS

In the testing system, a solid symmetrical fault has been applied on bus at 0.0167 s and has been cleared in 0.41 s. The location and duration of the fault were chosen to provide a significant disturbance to the interior of the power system and the below comparisons shows how interarea oscillations are damped and how dc link (capacitor) provides compensation

**A. Active Power Comparison with UPFC and UPFC with SMES**

Figure No 4 and Figure No 5 shows that the simulation result for active power (P) for test system with fault and for damping the oscillations in both cases, UPFC alone and UPFC with SMES. A solid symmetrical fault has been applied on bus at 0.0167 s and has been cleared in 0.41 s.

It is clear that before the settling of active power, power oscillations are high in the case of UPFC alone compared with the combination of UPFC and SMES. Also power oscillations are damped quickly when we use the combination of UPFC and SMES

**B. Reactive Power Comparison with UPFC & UPFC with SMES**

Figure No 7 and Figure No 8 shows that the simulation result for reactive power (Q) for test system with fault and for damping the oscillations in both cases, UPFC alone and UPFC with SMES. A solid symmetrical fault has been applied on bus at 0.0167 s and has been cleared in 0.41 s.

It is clear that before the settling of reactive power, power oscillations are high in the case of UPFC alone compared with the combination of UPFC and SMES. Also power oscillations are damped quickly when we use the combination of UPFC and SMES.

**C. DC Link Voltage Comparison with UPFC & UPFC with SMES**

Figure No 9 shows the voltage comparison for the combination of UPFC and SMES.
IV. CONCLUSION

The dynamic performance of the UPFC with and without SMES for the test system, are analysed with Matlab/Simulink. SMES with two quadrature chopper controller plays an important role in real power exchange. In order to improve the performance of the power system UPFC with and without has been developed. It is clear from the results that the UPFC with SMES is very effective in damping power oscillations and to maintain power flow through transmission lines after the disturbances.

REFERENCE


