Damping of Oscillations of Multi-machine Power Systems With Multiple UPFC

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Abstract—One of the important function of unified power flow controller (UPFC) is transient stability improvement and damping of oscillations in a power system network. This study examines the impact of multiple UPFC on oscillation damping of a power system. A real based multi machine-65 bus system is modeled and analyzed with Unified Power Flow Controller (UPFC). The placement of the compensators is determined based on the transmission lines with highest voltage drop in the system. Transient stability effects are analyzed for three system cases, one without compensators, one with one compensator at a time and the last one with multiple compensators. Angle, angular speed of rotors is observed. The simulation results showed that the system with multiple compensators can damp oscillations more effectively, which makes the system in a more reliable operation.

Keywords—unified power flow controller, multiple machine, transient stability, damping, voltage drop.

I. INTRODUCTION

Transmission networks of modern power systems have been causing problems because of growing demand and restrictions on building new lines. One of the consequences of such a system is the threat of losing stability following a disturbance. In order to expand or enhance the power transfer capability of existing transmission network the concepts of FACTS (Flexible AC transmission system) is developed by the Electric Power Research Institute (EPRI) in the late 1980s. The main objective of facts devices is to replace the existing slow acting mechanical controls required to react to the changing system conditions by rather fast acting electronic controls. FACTs means alternating current transmissions systems incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability [1]. Flexible AC Transmission System (FACTS) devices are found to be every effective in a transmission network for better utilization of its existing facilities without sacrificing the desired stability margin [2]. There are various forms of FACTS devices, some of which are connected in series with a line and the others are connected in shunt or a combination of series and shunt.

Facts controllers may be series, shunt or combination of both. Shunt controllers inject current into the system and may be variable impedance or variable source or both for ex: Static Synchronous Compensator (STATCOM), static var compensator (SVC) etc. Series controllers inject voltage in series with the line for ex: Static Synchronous Series Compensator (SSSC), Thyristor controlled Series Capacitor (TCSC), Thyristor switched series Capacitor (TSSC), Thyristor Controlled Series Reactor (TCSR), Thyristor Switched Series Reactor (TSSR). A combination of static synchronous compensator (STATCOM) and static series compensator (SSSC) which are coupled via a common dc link to allow bidirectional flow of real power between series o/p terminals of SSSC and shunt o/p terminals of STATCOM is called UPFC (unified Power Flow Controller). A unified power flow controller (UPFC) is a member of FACTS family which is connected to a system in a combination of series and shunt. It has two voltage source converters coupled through a common dc link. Important features is its multiple control function. For example, the series part of the UPFC can be equipped with power flow control function and the shunt part can operate for the AC voltage support [3-4].

A synchronous power system has transient stability if, after a sudden large disturbance, it can regain and maintain synchronism. A sudden large disturbance includes application of faults, clearing of faults, sudden load changes and inadvertent tripping of lines and generators. The maximum power which can be transferred through the system without the loss of stability under sudden disturbances is referred as transient stability limit. Transient stability is the ability to remain in synchronism during the period following a disturbance and prior to the time that the governors can act. Ordinarily the first swing of machine rotors will take place within about 1 second following the disturbance, but the exact time depends up on the characteristics of the machines and the transmission system [5-6].

In a power system network if a single machine is connected to an infinite bus or to other machine then it is called single machine infinite bus (SMIB) system. When
more than two machines are interconnected in a power system network then it is called Multi machine system. In an actual power system, there will be a large no of load buses and generator buses in a multi machine system and it is necessary to maintain synchronous stability of Multi machine system.

In multi machine power system, first swing stability of UPFC power system have been investigated and it is seen its effectiveness in angle stability. In different controller modeling, UPFC provides better results than traditional methods. In the present study, a real based multi-machine 65 bus system is used to evaluate the impact of UPFC under transient conditions. It has been shown that using one UPFC results in late time response. The use of multi UPFC improves the time response and effectively damps oscillations.

II. MULTI MACHINE POWER SYSTEM MODELING

Consider an n bus system with multi machines showed by a classical model. The swing equations are given as \( i = 1,2,\ldots,n \).

\[
\frac{d\Delta w_i}{dt} = w_i \Delta w_i \]  

(1)

\[
2H \frac{d\Delta w_i}{dt} = p m_i - \sum_{j=1}^{n+g} [V_i |V_j||G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\theta_i - \theta_j)]
\]

- KD_{ji} \Delta w_i \]  

(2)

Where, \( \Delta w_i \) is the per unit speed deviation, \( H \) is the inertia constant, \( w_i \) is the synchronous generator speed, \( n_g \) is no of machines, \( P_m \) is the mechanical power input in per unit, \( V_i \) (\( i = 1,2,\ldots,n \)) is the bus voltages in per unit, \( \theta_i \) (\( i = 1,2,\ldots,n \)) is the phase angles in radians, \( \delta_i \) is the angular positions of the rotors.

The power flow equations for a bus in transmission network are given by a set of algebraic equations, \( i = 1,2,\ldots,n \).

\[
PL_i = \sum_{j=1}^{n} [V_i |V_j||Y_{ij} \cos(\delta_i - \delta_j - \theta_j)]
\]

(3)

\[
QL_i = \sum_{j=1}^{n-g} [V_i |V_j||Y_{ij} \sin(\delta_i - \delta_j - \theta_j)]
\]

(4)

Where \( Y_{ij} \) = \( Y_{ij} - \theta \) obtained from the augmented \( Y_{BUS} \) matrix where the admittance corresponding to the transient reactance of the machines are included along with normal. \( PL_i \) and \( QL_i \) are the real and reactive power loads, respectively, at the \( i \)th bus.

III. UNIFIED POWER FLOW CONTROLLER MODELING

Circuit modeling of a UPFC connected transmission line is shown in Fig. 1.

An UPFC consists of a parallel and series branches, each one contain of a transformer, power-electronic converter with turn-off capable semiconductor devices and dc circuit. Converter 2 is connected in series with the transmission line by series transformer. The real and reactive power flows in the transmission line can be quickly regulated by changing the magnitude and phase angle of the injected voltage produced by converter 2. The basic function of converter 1 is to supply the real power demanded by converter 2 through the common dc link \([7]\). converter 1 can also generate or absorb controllable reactive power. The system load flow equations can be rewritten

\[
P_k = P_{k_m} + \sum_{j=1}^{N} [V_k |V_j||Y_{kj} \cos(\delta_k - \delta_j - \theta_j)]
\]

(5)

\[
Q_k = Q_{k_m} + \sum_{j=1}^{N} [V_k |V_j||Y_{kj} \sin(\delta_k - \delta_j - \theta_j)]
\]

(6)

With Facts devices added k bus load flow equations are

\[
P_k = P_{k_m} + \sum_{j=1}^{N} [V_k |V_j||Y_{kj} \cos(\delta_k - \delta_j - \theta_j)] + P_{KUPFC}
\]

(7)

\[
Q_k = Q_{k_m} + \sum_{j=1}^{N} [V_k |V_j||Y_{kj} \sin(\delta_k - \delta_j - \theta_j)] + Q_{KUPFC}
\]

(8)

Load flow equations for the \( m \)th bus with facts devices

\[
P_m = P_{m_k} + \sum_{j=1}^{N} [V_m |V_k||Y_{mk} \cos(\delta_{mk} - \delta_k - \theta_{mk})] + P_{mUPFC}
\]

(9)

\[
Q_m = Q_{m_k} + \sum_{j=1}^{N} [V_m |V_k||Y_{mk} \sin(\delta_{mk} - \delta_k - \theta_{mk})] + Q_{mUPFC}
\]

(10)

Figure 2 shows schematically how multiple UPFCs can be integrated into the system admittance matrix.
By adding multi UPFC into the system, the admittance matrix has been re-established in UPFC 1. Besides this, in UPFC 2 according to the new established admittance matrix, flow value has been re-calculated depending on the converters.

IV. CASE STUDY

A modeling and simulation study has been carried out on a real based multi generator-65 bus system shown in Fig. 3. The system has 35 load buses (buses 2-36) and 29 generator buses (buses 37-65). The system has 35 load buses (buses 2-36) and 29 generator buses (buses 37-65).

A load flow analysis is performed to determine the bus with the lowest voltage and the line with highest voltage drop. While Bus 21 has the lowest voltage, the lines between buses 37-54 and buses 33-59 are found to have the highest two voltage drops. Later, a three phase short circuit between the period of 0.1s and 0.25s is applied to the lowest bus voltage. Circuit breakers located at between buses 21 and 65 has the opening time of 100ms.

Single and multiple shunt and series connections of FACTS devices in the faulted system are simulated and effects are analyzed through observing rotor angle. The following scenarios are simulated.

A series and shunt FACTS, A 100MVA UPFC between bus 18 and 20, Multiple series and shunt FACTS, A 100MVA UPFC between bus 37 and bus 54 and UPFC between bus 33 and bus 59.

V. SIMULATION RESULTS

When the 3 phase fault occurs, it is seen that generator angle speed, angle have been unstable. The results of the 3 phase fault without a UPFC in the system have been given in Figs. 4 & 5.

From Figs. 4 & 5 it shows that generator angular speed and angle variations shows an oscillatory behaviour under transient conditions when there is no UPFC control in the network.
The results of the 21 number bus, 3 phase fault with a single UPFC in the system have been given in Fig.s 6&7. It shows that oscillatory response is slightly reduced with UPFC.

When the 3 phase fault occurs, it is seen that generator angle speed, angle are unstable. For this situation, the results for 21 number bus, 3 phase fault with multi UPFC have been given in Fig.s 8 & 9.

According to the results, the system time responses have been given in table I respectively as without UPFC, with a single UPFC and with multiple UPFC.

If the system parameters in table I are investigated for time response, it is clear that when multiple UPFC is used the system is stable in a short time and oscillations are damped perfectly.
TABLE I
SYSTEM TIME RESPONSE VALUES

<table>
<thead>
<tr>
<th>variables</th>
<th>Without UPFC</th>
<th>With UPFC</th>
<th>With multiple UPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator angular speed</td>
<td>4.4s</td>
<td>3.73s</td>
<td>2.0s</td>
</tr>
<tr>
<td>Generator angle</td>
<td>4.25s</td>
<td>3.50s</td>
<td>1.5s</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

This paper presented successfully the transient stability improvement and damping of oscillations in a power system network using unified power flow controller. The transient stability effects of UPFC in a Multi machine 65 bus system have been investigated in this study. The system with no UPFC shows an oscillatory behaviour under transient conditions. A single UPFC can partly improve the transient stability of the system while multiple UPFC can provide more damping and quick response leading to a more stable and reliable operation of the system.

REFERENCES