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Modeling and Analysis of Power flow controller in the presence of Power system stabilizer for a Multi-machine system

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Abstract

This paper provides an approach for the design of UPFC controllers (STATCOM control SSSC control and power system oscillation damping controller) for a multi-machine system. A case study of a three machine power system to be installed with UPFC is presented. UPFC controllers have been designed in the presence of conventional PSS. The interaction between the UPFC controllers and PSS has been studied. Studies reveal that SSSC control interacts negatively with PSS thereby affecting the damping of the system. It is observed that the UPFC based damping controller is most effective in damping the oscillations.

1. INTRODUCTION

The continuing rapid development of high-power semiconductor technology now makes it possible to control electrical power systems by means of power electronic devices. These devices constitute an emerging technology called FACTS (flexible alternating current transmission systems).FACTS technology has a number of benefits, such as greater power flow control, increased secure loading of existing transmission circuits, damping of power system oscillations, less environmental impact and, potentially, less cost than most alternative techniques of transmission system reinforcement . The UPFC is the most versatile of the FACTS devices. The usual form of this device consists of two voltage source inverters with a common DC link. The UPFC has been devised for real time control and dynamic compensation of the ac transmission systems, providing multifunctional flexibility required for solving many of the complex problems facing the power delivery industry. The ability of the UPFC to control concurrently or selectively, the transmission line voltage, impedance and angle, makes it the most versatile FACTS device. The primary function of UPFC is to control power flow on a given line and voltage at the UPFC bus. The UPFC can also be effectively used for damping power system oscillations by judiciously applying a damping controller. For an UPFC based damping controller, it is desired to extract an input signal to the damping controller from locally measurable quantities at the UPFC location. The power flow on the line can be easily measured at the UPFC location and hence may be used as an input signal to the damping controller.

Recently steady-state and dynamic models of UPFC have been developed by several researchers [1-5]. Nabavi-Niaki and Iravani [1] have presented comprehensive mathematical models of UPFC for steady-state, transient stability and dynamic stability studies. Makombe and Jenkins [2] have derived the mathematical model of a vector controlled UPFC. Morioka et al [3] have described control and protection schemes for UPFC operation. The UPFC miniature model has been developed and verified using a power system simulator. Smith et al [4] have developed decoupled control algorithms of the three independent compensation variables (i.e. real component of series injected voltage, reactive component of series injected voltage and reactive current of shunt converter) of the UPFC. They have developed the analytical models of the system with UPFC for both transient and dynamic performance studies. Papic et al [5] have presented the basic control system, which enables the UPFC to follow the changes in reference values of the active and reactive power supplied from the external system controller. Padiyar and Kulkarni [6] have proposed an UPFC control strategy based on local measurements, in which real power flow through the line is controlled by reactive voltage injection and the reactive power flow is controlled by regulating the magnitude of voltages at the two ports of the UPFC. They have also included an auxiliary controller for improving the transient stability of the system. Wang

[7-9] has developed linearised models of the power system installed with UPFC. These models are known as Modified Heffron-Phillips models. Tambey and Kothari [10] have presented a comprehensive approach for the design of UPFC controllers for a SMIB system.

A brief review of the literature shows that a lot of research work pertaining to the application of UPFC has been reported during a last one decade. The attention of the researchers has been focused on development of dynamic models and control strategies. Hardly any effort seems to have been made to optimize the UPFC controllers for a multi-machine system. Moreover, studies have not been carried out to understand interaction of the UPFC controllers with existing power system stabilizers (PSS). In view of the above, the main objectives of the research work presented in the paper are as follows:

1. To present a comprehensive approach for designing UPFC controllers (i.e. STATCOM control SSSC control and Power system oscillation damping controller) for a multi-machine system in the presence of conventional PSS.
2. To investigate the dynamic interaction between UPFC controllers and PSS.

2. Investigation on Multi-machine system

A 3-machine, 9-bus system [11] has been considered (Fig. 1). The system data as given in ref.[11] have been used. The static excitation system model type IEEE-ST1A has been considered for all the three generators. UPFC is based on pulse width modulation (PWM) voltage-sourced converters The UPFC is installed on line 7-8 for controlling power flow on the line.

3. Mathematical modeling of UPFC

3.1. Nonlinear Dynamic Model

For developing the dynamic model of the system, the network is represented by taking out the buses connecting the line in which UPFC is installed. These buses are numbered as buses 1 and 2 (Fig. 2).

UPFC consists of shunt and series converters connected back to back through a dc link. The two GTO based converters (VSCs) are coupled to the system through excitation and boosting transformers The modulation ratio and phase angle control signals of shunt converter are denoted by m_E and δ_E. Similarly the modulation ratio and phase angle control signals of series converter are denoted as m_B and δ_B. The resistances of the transformers are neglected.While developing the model, the transients associated with the transformers are ignored.

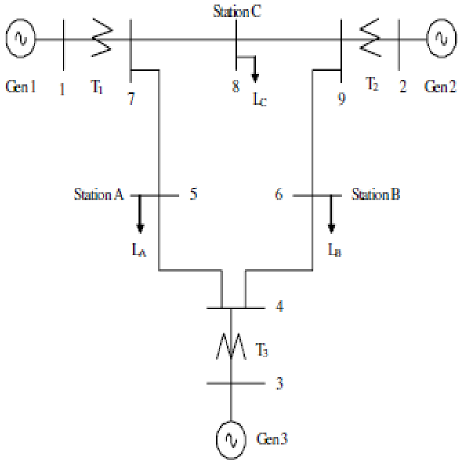

Fig 1: WSSC 3-machine, 9bus system

. The nonlinear model of a multimachine system with UPFC as developed by Wang [9] is given below:

$$\dot{\delta} = \omega_O(\omega - I) \quad \cdots (1)$$

$$\dot{\omega} = M^{-1}(P_M - P_e - D\Delta\omega) \quad \cdots (2)$$

$$\dot{E}'_q = T'^{-1}_{do}\left((X_D - X'_D)I_D - E'_q + E_{fd}\right) \cdots (3)$$

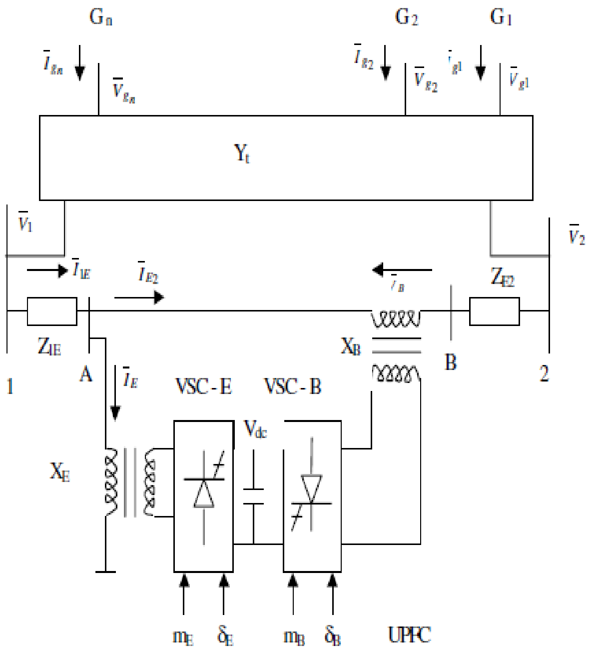

Fig 2: n-machine power system with UPFC installed

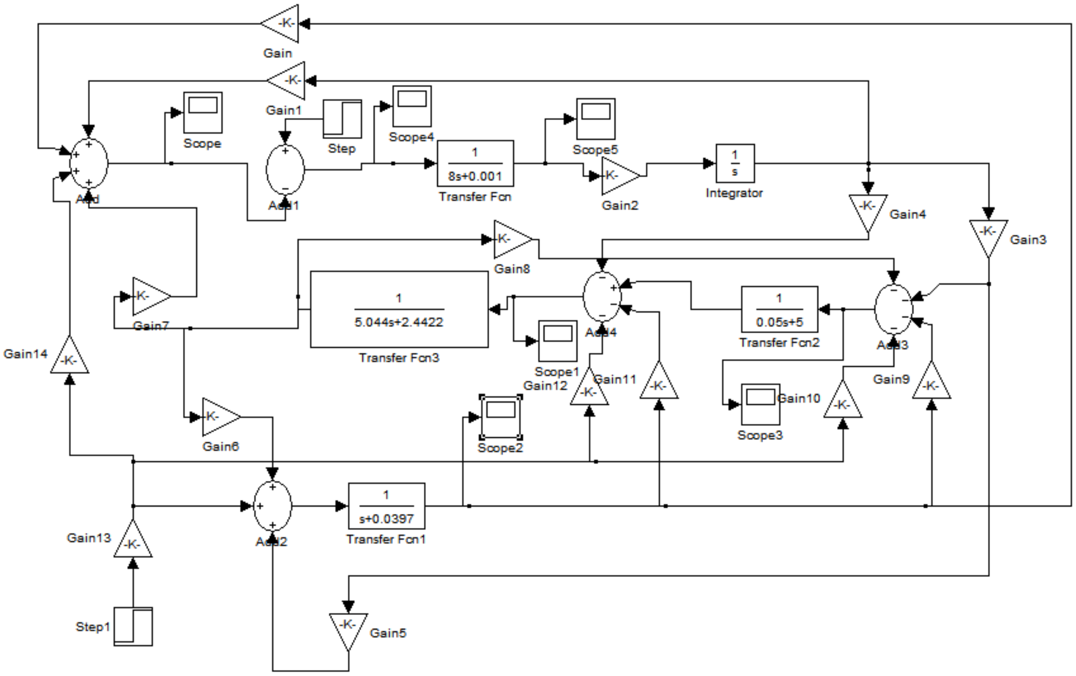

Fig. 3 Linearized Modified Heffron- Phillips transfer function model of Multi-machine system with UPFC installed

$$\dot{E_{fd}} = -T_A^{-1}E_{fd} + T_A^{-1}K_A\left(V_{ref} - V_T\right) \cdots (4)$$

$$\dot{V_{dc}} = \frac{3m_E}{4C_{dc}}(\cos\delta_E\, I_{Ed} + \sin\delta_E I_{Eq})$$

$$+\frac{3m_B}{4C_{dc}}(\cos\delta_B I_{Bd} + \sin\delta_B I_{Bq}) \cdots (5)$$

Where, $P_e = V_{TD}I_d + V_{TQ}I_q$, $V_{TD} = X_Q I_q$

$$V_{TQ} = E'_q - X'_D I_d \quad , \qquad V_{Ti} = \sqrt{V_{TDi}^2 + V_{TQi}^2}$$

$$\omega = [\omega_1\ \ \omega_2 \cdots \omega_n]^T$$

$$E'_q = \left[E'_{q1}\ \ E'_{q2} \cdots E'_{qn}\right]^T$$

$$E_{fd} = [E_{fd1}\ \ E_{fd2} \cdots E_{fdn}]^T$$

$$I_d = [I_{d1}\ \ I_{d2} \cdots I_{dn}]^T \ , \ I_q = \left[I_{q1}\ \ I_{q2} \cdots I_{qn}\right]^T$$

$$V_{TD} = [V_{d1}\ \ V_{d2} \cdots V_{dn}]^T$$

$$V_{TQ} = \left[V_{q1}\ \ V_{q2} \cdots V_{qn}\right]^T$$

$$M = diag(2H_i)\,,\ \ D = diag(D_i)$$

$$T'_{do} = diag(T'_{doi})\,, X_D = diag(X_{di})$$

$$X_Q = diag\left(X_{qi}\right)\ \ ,\ \ X'_D = diag(X'_{di})$$

i = 1, 2, ⋯n, n is number of generators

3.2. Linear Dynamic Model in State Space Form

The linear dynamic model in state space form (Eqn. (6)) is obtained by linearising the non-linear model around a nominal operating condition.

$$\dot{X} = AX + Bu + \Gamma p \ \cdots (6)$$

Where,

$$X = \left[\Delta\delta^T\ \ \Delta\omega^T\ \ \Delta E'^T_q\ \ \Delta E^T_{fd}\ \ \Delta V_{dc}\right]^T$$

$u = [\Delta m_E\ \ \Delta\delta_E\ \ \Delta m_B\ \ \Delta\delta_B]^T$ p is the perturbation vector. A, B and Γ are the compatible matrices and are function of system parameters and operating condition.

3.3.Modified Heffron-Phillips Transfer function Model of a Multimachine system with UPFC

Fig. 3 shows the transfer function model of a multi-machine system including UPFC. In this model, $\Delta\delta$, $\Delta\omega$, $\Delta E'_q$, ΔE_{fd} and ΔV_T are all n dimensional vectors. K_1 - K_6 are n × n matrices. K_{pu}, K_{qu}, K_{vu} and K_{cu} are defined as :

$$K_{pu}=[K_{pe} \quad K_{p\delta e} \quad K_{pb} \quad K_{p\delta b}\ ]$$

$$K_{qu}=[K_{qe} \quad K_{q\delta e} \quad K_{qb} \quad K_{q\delta b}]$$

$$K_{vu}=[K_{ve} \quad K_{v\delta e} \quad K_{vb} \quad K_{v\delta b}]$$

$$K_{cu}=[K_{ce} \quad K_{c\delta e} \quad K_{cb} \quad K_{c\delta b}\ ]$$

Where, $\mathbf{K_{pu}}$, $\mathbf{K_{qu}}$ and $\mathbf{K_{vu}}$ are n×4 matrices. $\mathbf{K_{cu}}$ is a row vector. $\mathbf{K_{pe}}$, $\mathbf{K_{p\delta e}}$, $\mathbf{K_{pb}}$, $\mathbf{K_{p\delta b}}$, $\mathbf{K_{qe}}$, $\mathbf{K_{q\delta e}}$, $\mathbf{K_{qb}}$, $\mathbf{K_{q\delta b}}$, K_{ve}, $\mathbf{K_{v\delta e}}$, $\mathbf{K_{vb}}$ and $\mathbf{K_{v\delta b}}$ are n dimensional column vectors. All the constants of the model are functions of the system parameters and operating condition.

4. Control strategy of UPFC

Fig. 4 shows the schematic diagram of the UPFC control system. It comprises of three types of controllers,

1. STATCOM control
2. SSSC control
3. Power system oscillation damping controller

4.1.STATCOM CONTROL

STATCOM control regulates the power flow on the line in which UPFC is installed. The real power flow is controlled by varying phase angle δB of the series injected voltage, keeping the magnitude of the injected voltage constant. Proportional-Integral (P-I) type power flow controller has been considered (Fig. 5). k_{pp} and k_{pi} are the proportional and integral gain settings of the STATCOM control. u is the stabilizing signal from Power System stabilizer.

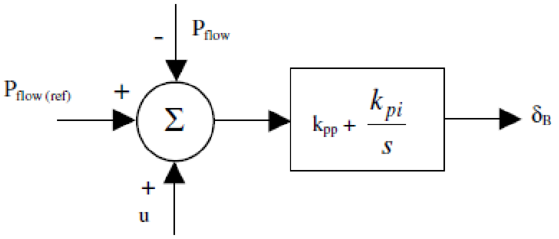

Fig 5: Structure of STATCOM control

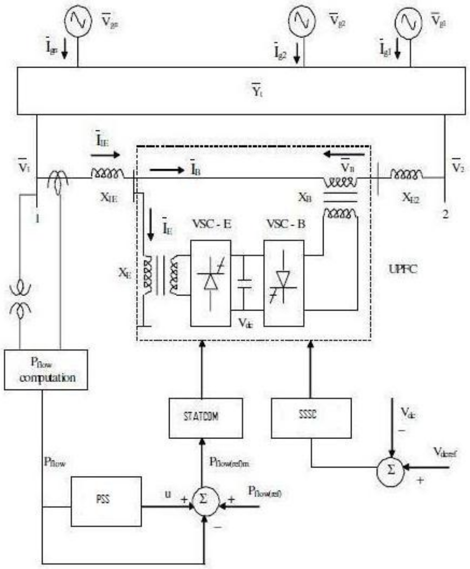

Fig 4: Schematic diagram of an UPFC control system

.4.2. SSSC control

SSSC is used in order to maintain the real power balance between two converters, The DC voltage regulation is achieved by modulating the phase angle of shunt converter voltage. Fig. 6 shows the transfer function of P-I type SSSC control. k_{dp} and k_{di} are the proportional and integral gain settings of the SSSC control .

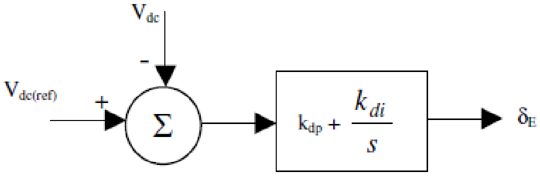

Fig 6: Structure of SSSC control

4.3. Power System oscillation damping controller

Power system oscillations can be damped, by producing a torque in phase with the speed deviation. Choice of easily measurable input signal is the main consideration in the design of any damping controller. In the present work, power flow on the line, which can be locally measured, has been used as an input signal to UPFC based damping controller. Fig. 7 shows the transfer function block diagram of UPFC based damping controller. It comprises of a gain block, signal washout and phase compensator. The parameters of phase compensator are chosen so as to compensate the phase shift provided by the forward path of the closed loop system. The gain setting of the damping controller is chosen such that, the desired damping of the electromechanical mode of concern is obtained, without affecting the damping of the other modes. The output of the damping controller modulates the reference setting of the power flow controller .

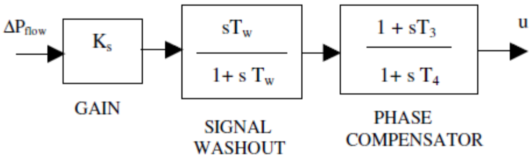

Fig 7: Transfer function block diagram of the Power system stabilizer

5.ANALYSIS

5.1. Load flow analysis of Multi-machine system using Newton-Raphson technique

From the load flow analysis of Multi-machine system it is observed that there is least voltage magnitude at buses 7 and 8. Hence UPFC is installed between buses 7 and 8 for improvement in performance of Multi-machine system

Table 1: Comparison of load flows of Multi-machine system with and without UPFC

Bus No.	Voltage Magnitude Without UPFC	Voltage Magnitude WithUPFC
1	1.140	1.093
2	1.181	1.140
3	0.528	0.501
4	-5.335	0.555
5	0.508	1.589
6	-2.240	0.221
7	**0.086**	**1.106**
8	**-0.625**	**0.007**
9	2.270	-0.391

5.2. Dynamic Performance of the System STATCOM control and SSSC control

The dynamic responses for ΔP_{flow} in line 7-8 (Fig. 9) are obtained with (a) STATCOM control alone and (b) STATCOM control and SSSC control operating simultaneously considering a 5% step increase in STATCOM control reference setting (i.e. ΔPflow(ref) = 0.05 p.u.) It can be clearly seen from Fig. 9 that the power flow on line 7-8 is regulated to the desired value i.e. under steady state condition the power flow on line 7-8 is increased by 5%. However, the response for ΔPflow with STATCOM control alone is somewhat better as compared to the one obtained with STATCOM control and SSSC control operating simultaneously. Fig. 10 shows the dynamic responses for deviation in dc link voltage ΔVdc considering the operation of the system with (a) STATCOM control alone and (b) STATCOM control and SSSC control operating simultaneously. The responses clearly show that the deviation in dc link voltage is regulated to zero when SSSC control is operating along with the STATCOM control. At this stage it is considered necessary to reiterate that the DC voltage must be regulated to maintain the real power balance between shunt and series converters. In order to examine the effect of DC voltage regulator on the dynamic performance of the system, the dynamic responses for $\Delta\omega_{12}$ (Fig. 11) are obtained considering a 5% step increase in P_{flow}(ref) with (a) STATCOM control alone and (b) STATCOM control and SSSC control operating simultaneously.

The above studies clearly show that the damping of the dynamic responses for $\Delta\omega_{12}$ (Fig11) is adversely affected by the incorporation of SSSC cntrol. This may be attributed to adverse interaction between the SSSC control and PSS. The system damping can be improved either by retuning the PSS or by incorporating UPFC based damping controller.

5.3. Design of UPFC based Damping Controller

The UPFC based damping controller is designed to improve the damping of the weakest mode. While optimizing the parameters of UPFC based damping controller, the PSS, STATCOM control and SSSC control are set at their optimum values. The controllable parameters of UPFC (i.e. mB, mE, δB and δE) can be modulated in order to produce the damping torque. The optimum gain and time constants of the UPFC based damping controller obtained are, Ks * = 0.1, T3 * = 0.1885 sec and T4 * = 0.2245 sec.

5.4 Dynamic Performance of the System with Damping Controller

The dynamic performance of the system is now examined considering
(a) PSS, STATCOM control and SSSC control
(b) PSS, STATCOM control and SSSC control and UPFC based damping controller

for $\Delta P_{flow}(ref) = 0.05$ p.u. (Fig. 11). It is evident from Fig. 12 that with the incorporation of UPFC based damping controller the desired damping performance is obtained.

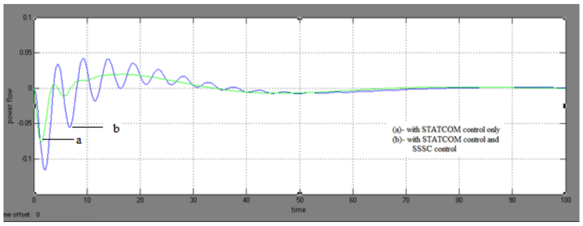

Fig 9: Dynamic responses for ΔP_{flow} considering a 5% step increase in $P_{flow}(ref)$

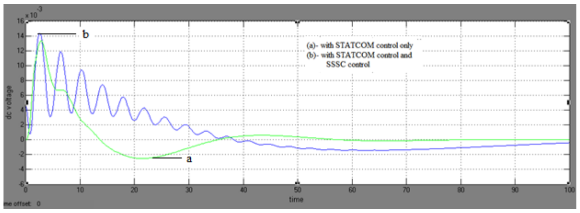

Fig.10 Dynamic resposes for ΔV_{dc} following a 5% step increase in $P_{flow}(ref)$ ($\Delta Pf_{low}(ref)$ = 0.05 p.u.)

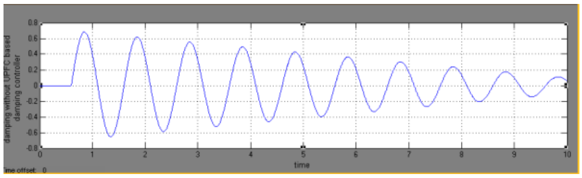

Fig. 11 Dynamic responses for Δω12 without UPFC based damping controller for ΔPflow(ref) = 0.05 p.u.

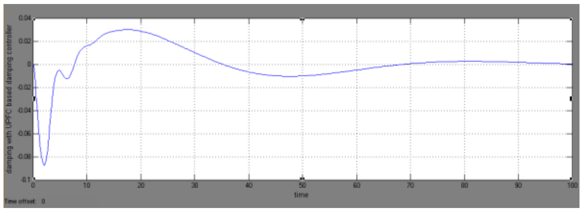

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Fig. 12 Dynamic responses for $\Delta\omega_{12}$ with UPFC based damping controller for $\Delta P_{flow}(ref) = 0.05$ p.u.

6.CONCLUSIONS

The significant contributions of the research work presented in this paper are as follows:

1. A comprehensive approach for optimum design of UPFC controllers (i.e. STATCOM control, SSSC control and power system oscillation damping controller) has been presented for a multimachine system.

2. The interaction between the PSS and UPFC controllers has been studied. The studies reveal that SSSC control interacts negatively with PSS thereby deteriorating the overall damping of the system. The adverse interaction between PSS and SSSC control has been compensated, by providing UPFC based damping controller.

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