Model Predictive Control to Improve Power System Oscillations of SMIB with Fuzzy Logic Controller

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Abstract — In this paper, model predictive control and two methods of fuzzy logic control is used to improve the oscillations of a single machine infinite bus (SMIB) power system, equipped with UPFC. The FLC design by choosing the prepared parameters based on our knowledge of system operation. The MPC has two important functions. First, to predict based on model and second, to assign optimal control inputs for reaching desired control goals.

I. Introduction

Power system oscillations are a characteristic of the system and they are inevitable. However, from an operating point of view, oscillations are acceptable as long as they decay. Power system oscillations are initiated by normal small changes in system loads ,and they become much worse following a large disturbance. The cascading disturbances (faults and protective relaying operation) made the oscillation grow in magnitude, and this growing oscillation caused the final collapse of the whole system. As a result, the system split into disconnected regions and a considerable number of customers lost their power. Different control methods can be applied to the system and different devices, like PSS and Flexible AC Transmission Systems (FACTS) devices can be used in the power system to enhance the damping of power oscillations.

FACTS technology is the newest way to obtain the optimal use of existing equipment by fast control and new abilities. The function of FACTS devise is direct control of power flow in transmission lines by tuning parameters of the system. UPFC is the best and the most useful of them. UPFC is the combination of two other FACTS devices which are called STATCOM (Static Synchronous Compensator) and SSSC (Static Synchronous Series Compensator). Therefore the both advantages of SSSC and STATCOM in steady state and also dynamic operation do exist in UPFC.

Due to ability of MPC to implement constraints in control process systems, MPC has been under consideration in industry. The difference among this method and other control methods is that in MPC, an optimal method based on model uses which predicts system output for obtaining the control rule. However in other control strategies, we decide based on previous duration of the system. The MPC operation is like the decision making process in human beings. People will face the consequences of decisions they make, thus they try to decide in a way to achieve their goals in future [1-5].

Fuzzy Logic is a conventional concept for description and measurement. Most of the fuzzy systems convert the experiment of human beings to computer programs for making decision or control a system. In this paper the classical control and two FLC methods and a MPC method is used to damp oscillations of SMIB power system.

II. System Dynamic Model

The power system that is studied in this paper is shown in Fig. 1. The system consists of a synchronous Generator is connected to transmission lines and an infinite bus via two transformers and an infinite bus [6]. We studied the dynamic model of this system. Nominal parameters of the system presented in Table 1. The SMIB differential equations are presented in Equations (1).

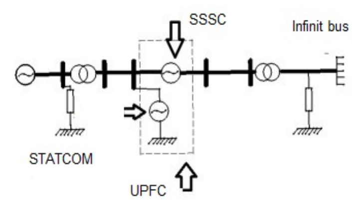

Fig. 1. SMIB with UPFC

Table1: nominal parameteres

Parameter	Value
Generator	T'do=5, Xd=1, H=4, Xq=0.6
Excitation System	K_a=10, T_a=0.05, X_{Te}=0.1, X_e=0.1
Dc link	V_{DC}=1, C_{DC}=3
UPFC	M_b=1.104, d_b=55o, d_e=25o, M_e=1.03

Fig. 2 presents the installation of UPFC in power system. In stability and control studies of power system oscillations, the linearized model can be used. In this paper dynamic model of UPFC for small signal stability improvement is used. Resistance and transient conditions are neglected. The dynamics of UPFC are present in Equations (2) [7, 8].

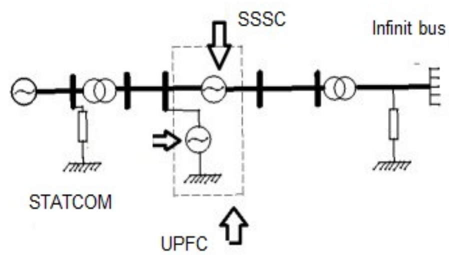

Fig. 2. SMIB with UPFC

$$\begin{cases} \dfrac{d\delta}{dt} = \omega_0 \Delta\omega \\ \dfrac{d\omega}{dt} = \dfrac{1}{2H}(P_m - P_e - D\Delta\omega) \\ \dfrac{dE'_q}{dt} = \dfrac{1}{T'_{do}}(-E_q + E_{qe}) \\ \dfrac{dE'_{qe}}{dt} = \dfrac{k_a}{(1+st_a)}(V_{t0} + V_t) \end{cases} \qquad (1)$$

$$\begin{bmatrix} V_{eTD} \\ V_{eTQ} \end{bmatrix} = \begin{bmatrix} 0 & -x_e \\ x_e & 0 \end{bmatrix} \begin{bmatrix} I_{eD} \\ I_{eQ} \end{bmatrix} + \begin{bmatrix} \dfrac{M_b V_{DC} \cos\delta_e}{2} \\ \dfrac{M_e V_{DC} \sin\delta_e}{2} \end{bmatrix}$$

$$\begin{bmatrix} V_{bTD} \\ V_{bTQ} \end{bmatrix} = \begin{bmatrix} 0 & -x_b \\ x_b & 0 \end{bmatrix} \begin{bmatrix} I_{eD} \\ I_{eQ} \end{bmatrix} + \begin{bmatrix} \dfrac{M_b V_{DC} \cos\delta_b}{2} \\ \dfrac{M_e V_{DC} \sin\delta_b}{2} \end{bmatrix}$$

$$\frac{dV_{DC}}{dt} = \frac{3M_e}{4C_{DC}} \begin{bmatrix} \cos\delta_e & \sin\delta_e \end{bmatrix} \begin{bmatrix} I_{eD} \\ I_{eQ} \end{bmatrix} + \frac{3M_b}{4C_{DC}} \begin{bmatrix} \cos\delta_b & \sin\delta_b \end{bmatrix} \begin{bmatrix} I_{bD} \\ I_{bQ} \end{bmatrix} \qquad (2)$$

By combining and linearizing of equations (1) and (2) state space equations of system will be obtained which are present in equations (3). In this process there are 28 constants denoted by k, which are function of parameters and system initial conditions.

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta W} \\ \dot{\Delta E'_Q} \\ \dot{\Delta E'_{FD}} \\ \dot{\Delta V_{DC}} \end{bmatrix} = \begin{bmatrix} 0 & W_0 & 0 & 0 & 0 \\ \dfrac{-k_1}{2h} & 0 & \dfrac{-k_2}{2h} & 0 & \dfrac{-k_{PD}}{2h} \\ \dfrac{-k_4}{t'_{D0}} & 0 & \dfrac{-k_3}{t'_{D0}} & \dfrac{-1}{t'_{D0}} & \dfrac{-k_{QD}}{t'_{D0}} \\ \dfrac{-k_a k_5}{t_a} & 0 & \dfrac{-k_a k_6}{t_a} & \dfrac{-1}{t_a} & \dfrac{-k_a k_{VD}}{t_a} \\ k_7 & 0 & k_8 & 0 & -k_9 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta W \\ \Delta E'_Q \\ \Delta E'_{FD} \\ \Delta V_{DC} \end{bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ \dfrac{-k_{PE}}{2h} & \dfrac{-k_{P\delta E}}{2h} & \dfrac{-k_{PB}}{2h} & \dfrac{-k_{P\delta E}}{2h} \\ \dfrac{-k_{QE}}{t'_{D0}} & \dfrac{-k_{Q\delta E}}{t'_{D0}} & \dfrac{-k_{QB}}{t'_{D0}} & \dfrac{-k_{Q\delta B}}{t'_{D0}} \\ \dfrac{-k_a k_{VE}}{t_a} & \dfrac{-k_a k_{V\delta E}}{t_a} & \dfrac{-k_a k_{VB}}{t_a} & \dfrac{-k_a k_{V\delta E}}{t_a} \\ k_{CE} & k_{c\delta E} & k_{cB} & k_{c\delta B} \end{bmatrix} \begin{bmatrix} \Delta M_e \\ \Delta\delta_e \\ \Delta M_b \\ \Delta\delta_b \end{bmatrix} \qquad (3)$$

where $\Delta\delta_e$ is deviation in phase angle of shunt inverter voltage, $\Delta\delta_b$ is deviation in Phase angle of series inverter voltage, ΔM_e is deviation in Pulse width modulation index of shunt inverter voltage and ΔM_b is deviation in Pulse width modulation index of series inverter voltage.

III. Damping Control

Two methods of Mamdani fuzzy logic control and a model predictive control compared with classical control. The first FLC has single input and three control rules and the second FLC has two inputs and eight control rules. Scaling factors of FLCs are optimized by gradient descent method. FLC membership function is show in Fig.3. These rules are:

FLC1

$If(\Delta W \to P) \Rightarrow (\Delta M_b \to P)$

$If(\Delta W \to N) \Rightarrow (\Delta M_b \to N)$

$If(\Delta W \to Z) \Rightarrow (\Delta M_b \to Z)$

FLC2

$If(\Delta W \to P),(\Delta\delta \to Z) \Rightarrow (\Delta M_b \to P)$

$If(\Delta W \to Z),(\Delta\delta \to N) \Rightarrow (\Delta M_b \to N)$

$If(\Delta W \to N),(\Delta\delta \to Z) \Rightarrow (\Delta M_b \to N)$

$If(\Delta W \to Z),(\Delta\delta \to P) \Rightarrow (\Delta M_b \to P)$

$If(\Delta W \to Z),(\Delta\delta \to Z) \Rightarrow (\Delta M_b \to Z)$

$If(\Delta W \to P),(\Delta\delta \to N) \Rightarrow (\Delta M_b \to P)$

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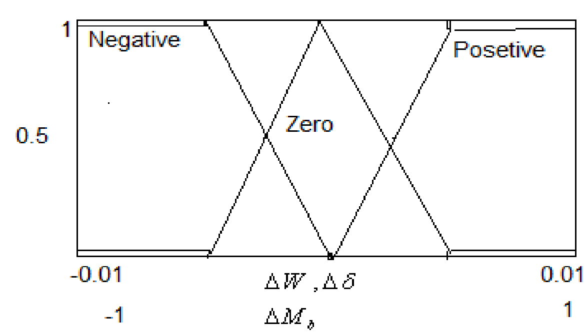

Fig 3. FLC membership functions

Operation of Model predictive control is shown in Fig. 4. Prediction horizon (N_P) is the time range which, future system outputs are predicted in it. Control horizon is the time steps number that input control sequence calculations for the prediction horizon are done. For following the defined reference path by system output in prediction horizon, by attending to information of pervious inputs and outputs the future system output are predicted and due to these new information, reference path, disturbance and control strategy, proper input sequences in control horizon for improvement of system operation can be calculated. In other words in model predictive control, control signal of a few future steps is determined in a way that system output reaches to desired value at future time. In this control method, in the k sampling time base on measuring until this time the controller by use of open loop model of system, N_P sample of the system output is predicted and N_C sample of control input ($N_P \le N_C$) produces in the way that minimize the objective function.

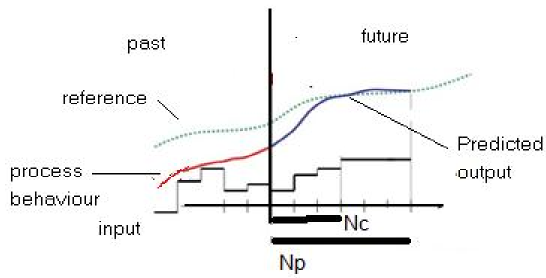

Fig 4: MPC Principals

In order to consider feedback, only the first sequence of control input is applied to the system until next future sampling time. At the next sampling time base on new measuring total process of prediction and optimization repeats. Theoretically, the predictive control algorithm can be express as an optimization problem which is presented in equations (4) and (5).

$$u^* = \arg\min_u (J(k)) \tag{4}$$

$$\begin{aligned} & X(k|K) = x_0 \\ & X(k+j+1|K) = f_d(X(k+j|K), u(k+j|K) \\ & Y(k+j+1|K) = h(X(k+j|K)) \\ & X_{min} \le X(k+j|K) \le X_{max} \\ & u_{min} \le u(k+j|K) \le u_{max} \\ & u(k+j|K)) = u(k+N_C|K)), j \ge N_C \end{aligned} \tag{5}$$

In Equations (4) and (5) $j \in [0, N_P-1]$, X is the state vector of system, Y is the output vector of system and u is the control input of system. $a(m|n)$ represents the value of (a) parameter at the moment m that is predicted at the moment (n) x_o is the initial state of system and f_d, h_d are system models for prediction. $[u_{min}, u_{max}]$, $[x_{min}, x_{max}]$ are up and down bounds of states and system input , the optimization problem of Equations (4) and (5) at the k sampling time solves and the results is $\{u^*(k+1|K), u^*(k+N_C|K)\}$ control sequence then in the next sampling time (k+1) the first sentences of control sequence is obtained $u^*(k+1|K)$ and applied to the system and this process repeats with Matlab optimization toolbox by quadratic optimization method. Different algorithms of MPC introduce various objective functions to obtain control rule. The main objective is that future output (y) follows a defined reference signal on e specific horizon and also we should not use excessive control effort Δu to reach this objective. General expansion for such an objective function is as equation (6).

$$\begin{aligned} J(N_1, N_2, N_u) = & \sum_{i=N_1}^{N_2} \delta(i)[\hat{y}(t+i|t) - w(t+i)]^2 \\ & + \sum_{i=1}^{N_u} \lambda(i)[\Delta u(t+i-1)]^2 \end{aligned} \tag{6}$$

In some methods the second part of equation (6) (which defines the control effort) is skipped in cost function we should pay attention to the following items. N_1 and N_2 are maximum and minimum of cost horizons and N_u is the value of control horizon which should not necessary is equal to maximum range of time in which output follows reference signal.

IV. Simulation Results

The operation of all UPFC controllers including fuzzy, classic and predictive after a sudden disturbance in reference mechanical power is simulated in Fig. 5 the results for $\Delta\delta$ and $\Delta\omega$ are presented in Figs. 6-11.

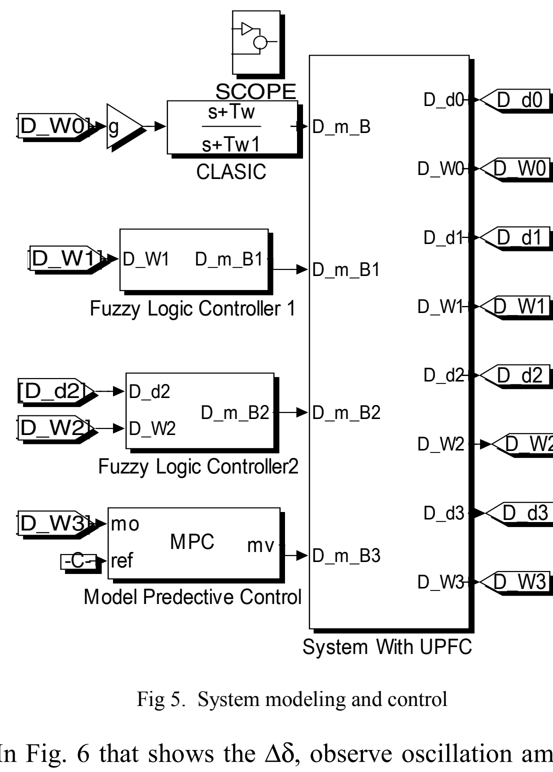

Fig 5. System modeling and control

In Fig. 6 that shows the $\Delta\delta$, observe oscillation amplitude in FLC1 comparing with classical controller is reduced and during 4 seconds is reached to steady state while this time for classical controller is 12 seconds. In Fig. 7 $\Delta\delta$ is compared between classical controller and FLC2,we can see the best performance of controller and damping improvement, undershoot is reduced to 50%, during 3 seconds is reached to steady state while this time for classical controller is 12 seconds. In Fig. 8 we can see that for $\Delta\delta$, control operation of MPC, comparing with FLC1, is more effective but still isn't as effective as FLC2. In Fig. 9 that shows the Δω, observe oscillation amplitude in FLC1 comparing with classical controller is reduced and during 4 seconds is reached to steady state while this time for classical controller is 12 seconds. In Fig. 10 Δω is compared between classical controller and FLC2, we can see the best performance of controller and damping improvement , undershoot is reduced to 20%, during 5 seconds is reached to steady state while this time for classical controller is 9 seconds. In Fig. 11 we can see that for Δω, control operation of MPC, comparing with FLC1, is more effective but still isn't as effective as FLC2.

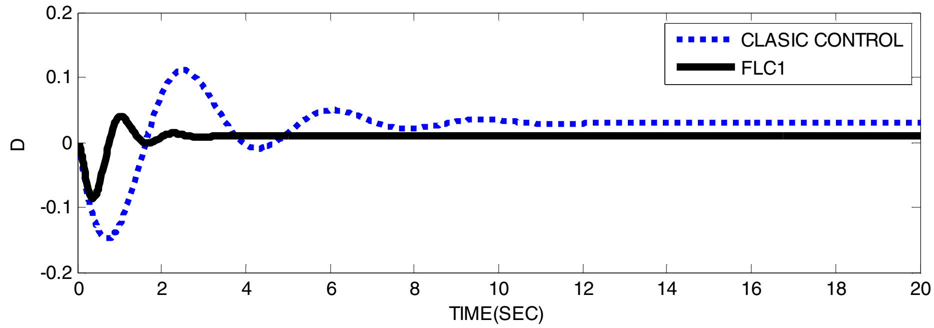

Fig 6. Δδ oscillations of SMIB equipped with UPFC by FLC1

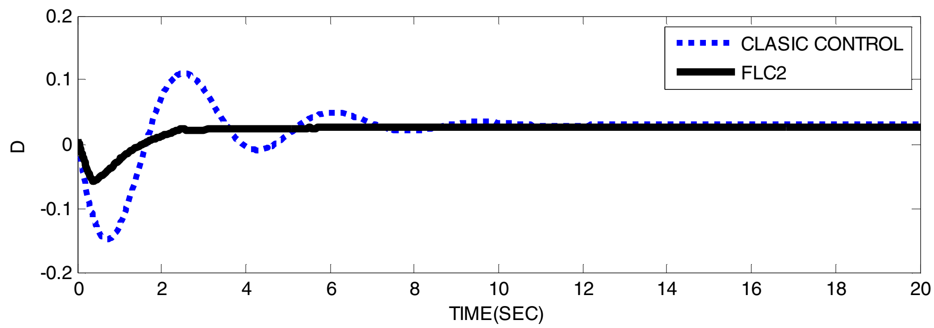

Fig 7. Δδ oscillations of SMIB equipped with UPFC by FLC2

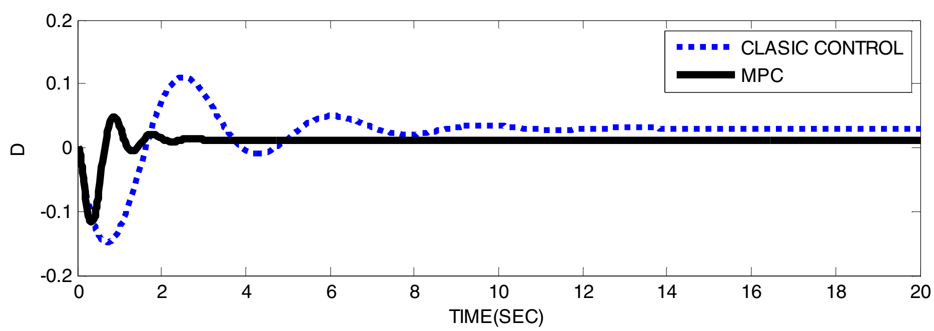

Fig 8. Δδ oscillations of SMIB equipped with UPFC by MPC

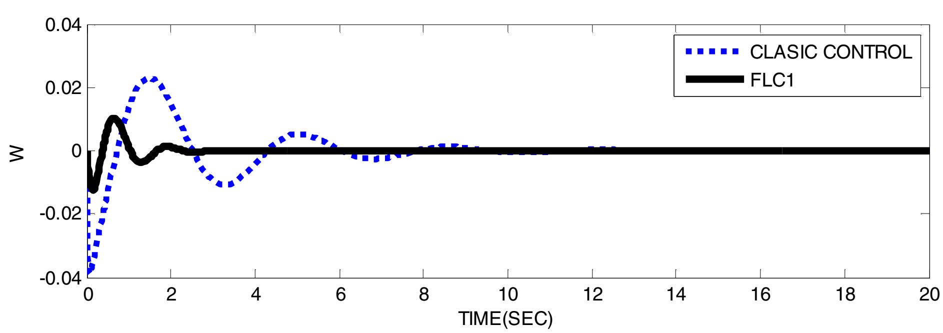

Fig 9. Δω oscillations of SMIB equipped with UPFC by FLC1

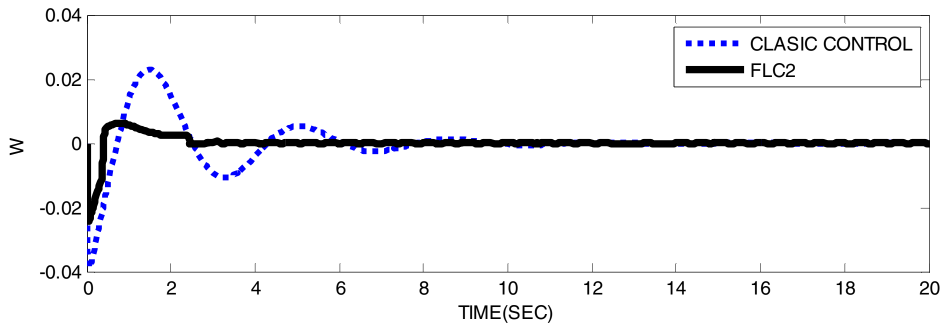

Fig 10. Δω Oscillations of SMIB equipped with UPFC by FLC2

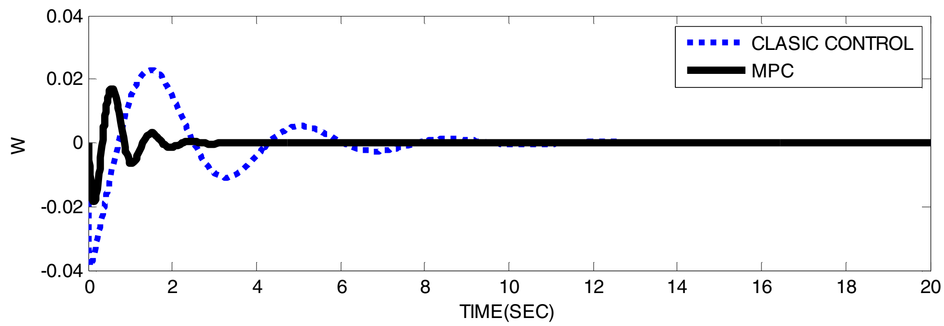

Fig 11. Δω oscillations of SMIB equipped with UPFC by MPC

V. CONCLUSION

In this paper by linearizing and combining the equations of single machine infinite bus power system and unified power flow controller complete state space model of SMIB power system including UPFC was presented for oscillations studding. A classical controller compared with two fuzzy logic controllers and one model predictive controller. The scaling factors in FLC1 and FLC2 were optimized by gradient decent method and MPC was optimized by quadratic programming method. Time domain simulations for power system small signal approved the effectiveness of FLC and specially FLC2 and MPC than classical controller.

REFERENCES

[1] S.J. Gole, A.M. Annakkage, U.D. Jacobson, "Damping performance analysis of IPFC and UPFC controllers using validated small-signal models", IEEE Trans. on Pow. Deli., Vol.26, No.1, pp.446-460, Jan. 2011.

[2] R.H. Adware, P.P. Jagtap, J.B. Helonde, "Power system oscillations damping using UPFC damping controller", IEEE/ICETET, pp.340-344, Nov. 2010.

[3] J. Guo, M.L. Crow, J. Sarangapani, "An improved UPFC control for oscillation damping", IEEE Trans. on Pow. Sys., Vol.24, No.1, Feb. 2009.

[4] S. Bhowmick, B. Das, N. Kumar, "An indirect UPFC model to enhance reusability of newton power-flow codes", IEEE Trans. on Pow. Del., Vol.23, No.4, pp.2079-2088, Oct. 2008.

[5] C.Collins, N.Watson, A.Wood, “UPFC modelimg in the harmonic domain”, IEEE Tran. On Pow. Deli., Vol.21, No.2, pp.933-938, Apri 2006.

[6] B.T. Ooi, M. Kazerani, R. Marceau, Z. Wolanki, F.D. Galiana, D. McGillis, G. Joos, “Mid-point sitting of FACTS devices in transmission lines”, IEEE Trans. on Pow. Del., Vol.12, No.4, pp.1717-1722, Oct. 1997.

[7] H.F. Wang, F.J. Swift, “A unified model for the analysis of FACTS devices in damping power system oscillations part I: Single-machine infinite-bus power systems”, IEEE Trans. on Pow. Del., Vol.12, No.2, pp. 941-946, April 1997.

[8] H.F. Wang, F.J. Swift, “A unified model for the analysis of FACTS devices in damping power system oscillations part II: Multi-machine power systems”, IEEE Trans. on Pow. Del., Vol.13, No.4, pp.1355-1362, Oct. 1998.