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Comparing the performance of UPFC Damping Controller on Damping Low Frequency Oscillations

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Abstract. This paper compares the performance of UPFC damping controller (m_E, m_B, δ_E and δ_B) to damp Low Frequency Oscillations (LFO) in power system equipped with UPFC based on Fuzzy Logic Power System Stabilizer (UPFC based FLPSS). The power system model was developed using linearized model of Phillips-Heffron Single Machine Infinite Bus (SMIB) and simulated in Matlab Simulink. The ability of each controller to damp LFO present in the rotor speed was monitored when the system being perturbed by small disturbances. The results obtained shown that UPFC controller δ_E had better performance to damp LFO compared to the other UPFC damping controllers as it had the lowest overshoot and less settling time.

Introduction

Power system need to provide uninterrupted and a reliable service to the loads where in ideal situation, a constant voltage and frequency must be fed to the loads at all time. In order to have a reliable service, it is required to keep the synchronous generators running in parallel and with adequate capacity to meet the load demand. The stability problem normally take place once the synchronous machines have been disturbed. When there is a change in mechanical power and lack of damping torque, Low Frequency Oscillations (LFO) in power system occur. These oscillations if not well damped may keep growing in magnitude until loss of synchronism [1]. Meanwhile, the power transmission operating capability, power system operating efficiency and power system stability also will be effected by LFO [2]. To damp LFO and ensure system stability, Power System Stabilizer (PSS) has been added to the excitation system. This method was proven to be a simple and cost effective approach.

These days, Flexible AC Transmission Systems (FACTS) are used to control the power flow and enhance system stability. However, the presence of FACTS devices alone does not give so much impact in lowering the oscillations or disturbances. Hence a supplementary control will be added to these FACTS devices to enforce extra damping. This can be overcome by installing Unified Power Flow Controller (UPFC) which is the most versatile FACTS devices based on Fuzzy Logic Power System Stabilizer as its controller in the transmission lines. Fuzzy logic is an artificial intelligence technique that has efficiently been proposed by researchers to design power system stabilizer and reported to outperform the conventional stabilizers.

The UPFC which is proposed by Gyugyi in 1992 is the most promising Flexible AC Transmission System (FACTS) device that has been implemented in power system. It is a FACTS device that combine Static Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) coupled via DC voltage link and has the ability to provide simultaneous and real time control of all or any combination of the basic power system parameters in a transmission line: transmission voltage, line impedance and power angle. Besides, it also capable of controlling both the real and reactive power flow in the line independently. Hence, the UPFC can be utilized for damping of power system oscillations by applying a damping controller [3].

Fig. 1 shown a schematic diagram of a single-phase UPFC power circuit consist of an excitation transformer (ET), a boosting transformer (BT), two three-phase gate turn-off (GTO) thyristor based voltage source converter (VSC) and a dc link capacitor. Exciter voltage source converter (VSC-E) is connected in parallel with the transmission lines while booster voltage source converter (VSC-B) is connected in series with transmission lines. m_E, m_B, δ_E and δ_B are the amplitude modulation ratio and phase angle of the control signal of each VSC respectively, which are the input control signals of the UPFC [4,5].

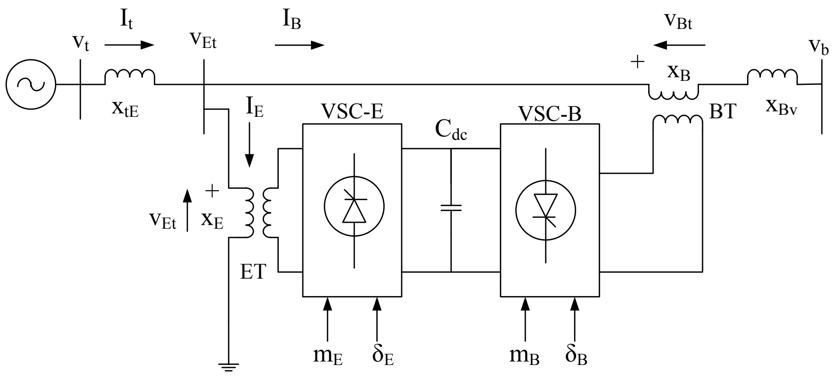

Figure 1: UPFC installed in single machine infinite bus power system

In order to damp the oscillation, UPFC damping controller - m_E (excitation amplitude modulation ratio), m_B (boosting amplitude modulation ratio), δ_E (excitation phase angle) and δ_B (boosting phase angle) are used separately using single-in single-out (SISO) method.

There are numbers of methods used by the researchers as a control strategy for UPFC. In this study, fuzzy logic which based on a set of rules as a control mechanism has been chosen. Fuzzy controller then is added as a power system stabilizer (PSS) to these damping controller to enhance its capability. After given small disturbances to the system, the dynamic stability of both system is observed in terms of change of rotor speed.

Methodology

Mathematical Modelling of power system installed with UPFC. To monitor and investigate power system stability, the analysis started with the mathematical modelling of power system installed with UPFC to derive the equations for the respective parameters. In studying power system oscillation stability and control, a linearized model of power system can be used. The resistance and transients of the transformers of the UPFC can be ignored in the study. The UPFC dynamic equations is [4,6]:

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E \cos\delta_E v_{dc}}{2} \\ \dfrac{m_E \cos\delta_E v_{dc}}{2} \end{bmatrix}$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B \cos\delta_B v_{dc}}{2} \\ \dfrac{m_B \cos\delta_B v_{dc}}{2} \end{bmatrix}$$

$$\frac{dv_{dc}}{dt} = \frac{3m_E}{4C_{dc}} [\cos\delta_E \quad \sin\delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}} [\cos\delta_B \quad \sin\delta_B] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (1)$$

The non-linear dynamic equation for the Phillips-Heffron model of SMIB power system equipped with UPFC as shown in Fig. 1 is:

$$\dot{\delta} = \omega_0 \omega$$

$$\dot{\omega} = (P_m - P_e - D\omega)/M$$

$$\dot{E'}_q = \left(-E_q + E_{fd}\right)/T'_{d0}$$

$$\dot{E}_{fd} = -\frac{1}{T_A} E_{fd} + \frac{K_A}{T_A}(V_{t0} - V_t) \qquad (2)$$

By combining Equation (1) and Equation (2), the state variable equations of the power system equipped with UPFC for each damping controller can be represented as:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E'}_q \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_{u1}}{M} & -\frac{D}{M} & -\frac{K_{u2}}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_{u3}}{T'_{d0}} & \frac{1}{T'_{d0}} & -\frac{K_{qd}}{T'_{d0}} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_A K_{u6}}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_{u7} & 0 & K_{u8} & 0 & K_{u9} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K_{pe}}{M} \\ -\frac{K_{qe}}{T'_{d0}} \\ -\frac{K_A K_{vc}}{T_A} \\ K_{ce} \end{bmatrix} [\Delta m_E]$$

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E'}_q \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_{u1}}{M} & -\frac{D}{M} & -\frac{K_{u2}}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_{u3}}{T'_{d0}} & \frac{1}{T'_{d0}} & -\frac{K_{qd}}{T'_{d0}} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_A K_{u6}}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_{u7} & 0 & K_{u8} & 0 & K_{u9} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K_{pb}}{M} \\ -\frac{K_{qb}}{T'_{d0}} \\ -\frac{K_A K_{vb}}{T_A} \\ K_{cb} \end{bmatrix} [\Delta m_B]$$

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E'}_q \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_{u1}}{M} & -\frac{D}{M} & -\frac{K_{u2}}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_{u3}}{T'_{d0}} & \frac{1}{T'_{d0}} & -\frac{K_{qd}}{T'_{d0}} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_A K_{u6}}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_{u7} & 0 & K_{u8} & 0 & K_{u9} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K_{p\delta e}}{M} \\ -\frac{K_{q\delta e}}{T'_{d0}} \\ -\frac{K_A K_{v\delta e}}{T_A} \\ K_{c\delta e} \end{bmatrix} [\Delta\delta_E]$$

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E'}_q \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_{u1}}{M} & -\frac{D}{M} & -\frac{K_{u2}}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_{u3}}{T'_{d0}} & \frac{1}{T'_{d0}} & -\frac{K_{qd}}{T'_{d0}} \\ -\frac{K_{u4}}{T'_{d0}} & 0 & -\frac{K_A K_{u6}}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_{u7} & 0 & K_{u8} & 0 & K_{u9} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K_{p\delta b}}{M} \\ -\frac{K_{q\delta b}}{T'_{d0}} \\ -\frac{K_A K_{v\delta b}}{T_A} \\ K_{c\delta b} \end{bmatrix} [\Delta\delta_B] \qquad (3)$$

Fuzzy Logic Design. To provide optimum damping to the system low frequency oscillation, fuzzy logic based power system stabilizer has been used. Based on previous study [6,7], the change of rotor speed $(\Delta\omega)$ and the rate of change of rotor speed $(\Delta\dot{\omega})$ are chosen to be the input signals to the FLPSS whereas the voltage signal become the output of FLPSS. The output will be connected to the input of the excitation system. As the precision of control improved when the number of membership function increased, the simulation has been done with 49 rules where seven fuzzy sets for each of the input and the output variables are used to describe them and to produce 49 output condition. Table 1 shows the complete set of control rules.

Table 1: Training data

Change of rotor speed, $(\Delta\omega)$ \ Rate of change of rotor speed, $(\Delta\dot{\omega})$	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NM	NS
NM	NB	NM	NM	NM	NS	NS	ZE
NS	NM	NM	NS	NS	ZE	ZE	PS
SE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	ZE	ZE	PS	PS	PM	PM
PM	ZE	PS	PS	PM	PM	PM	PB
PB	PS	PM	PM	PB	PB	PB	PB

Results

After solving the mathematical modeling, the parameter value for each UPFC controller are:

Table 2: Parameter value for UPFC controller

	m_E	m_B	δ_E	δ_B
K_p	1.3875	0.1830	0.1325	0.0579
K_c	0.2829	-0.1058	0.3753	-0.2794
K_q	-0.6147	0.0427	2.3470e-^{17}	1.0249e-^{17}
K_v	0.6288	0.0233	0.0142	0.0062

At $t = 1s$, electrical power disturbances of 0.1 pu was given to the conventional PSS and UPFC based FLPSS power system model. Low frequency oscillations occurred due to the small disturbances. The ability of UPFC controller to the the oscillations was done one at the time. The performance of UPFC damping controller to damp low frequency oscillation in rotor speed are shown in Fig. 2 to Fig. 5,

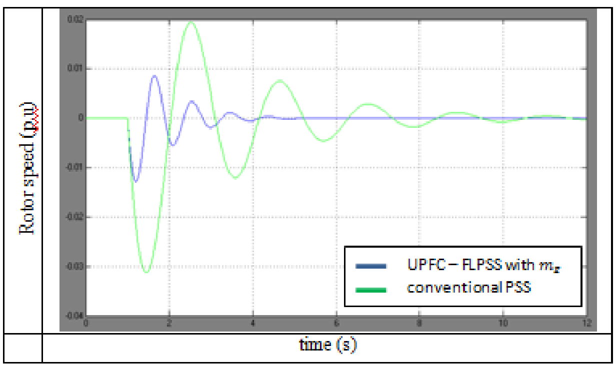

Figure 2: Change of rotor speed using damping controller m_E

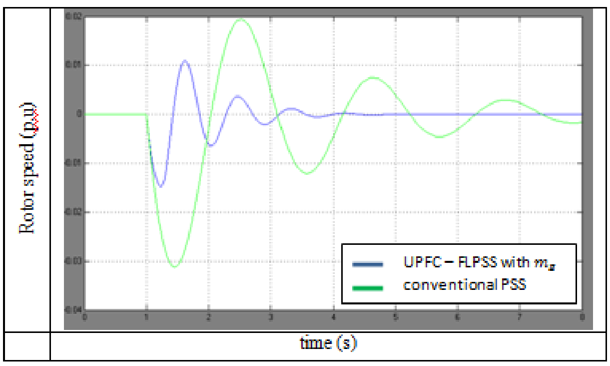

Figure 3: Change of rotor speed using damping controller m_B

In Fig. 2 when the power system was disturbed by small signal disturbance, the rotor speed experienced an overshoot of -0.01284 p.u. and damping controller m_E able to damp the oscillation in 0.8s. Meanwhile in Fig. 3 the rotor speed had an overshoot of -0.01482 p.u and m_B able to damp the oscillation in 0.75s. In Fig. 4 when the power system was disturbed by small signal disturbance, the rotor speed experienced an overshoot of -0.01265 p.u. and damping controller δ_E able to damp the oscillation in 0.68s. Lastly in Fig. 5, there was an overshoot in rotor speed to -0.01458 p.u but damping controller δ_B able to damp the oscillation in 0.77s.

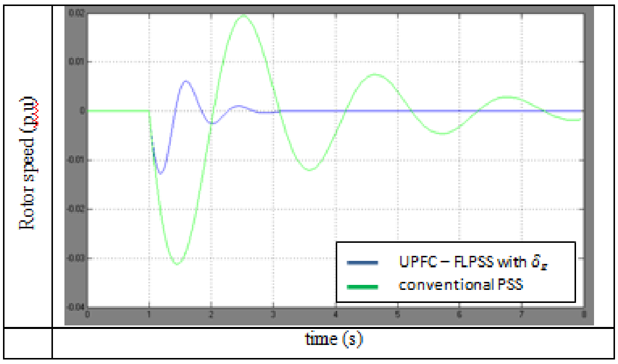

Figure 4: Change of rotor speed using damping controller δ_E

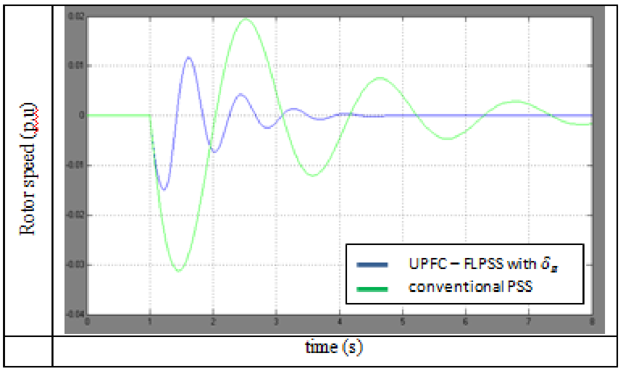

Figure 5: Change of rotor speed using damping controller δ_B

Conclusion

In conclusion, damping controller δ_E shown a better performance in damping low frequency oscillations compared to the other three damping controller due to less overshoot and less settling time.

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