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Improvement of Dynamic Power System Stability by Installing UPFC Based on Fuzzy Logic Power System Stabilizer (FLPSS)

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Abstract- **Low-frequency oscillation is associated with dynamic power system stability. In this paper, the ability of power system to damp low-frequency oscillation is compared between the conventional system with PSS and system installed with Unified Power Flow Controller (UPFC) based on Fuzzy Logic Power System Stabilizer (FLPSS). Both models are developed using linearized model of Phillips-Heffron Single Machine Infinite Bus (SMIB) and simulated in Matlab Simulink. UPFC controller based on boosting modulation index converter (m_b) and excitation modulation index converter (m_e) have been designed using Single in Single Out (SISO) method. The change of rotor speed, rotor angle and electrical power is investigated when power system is being perturbed by small disturbance. The results of this study shown the improvement of dynamic power system stability using the designed model by damping low-frequency oscillation with less overshoot and shorter settling time.**

I. INTRODUCTION

In today's world, the demand and consumption of electrical energy increased tremendously. To satisfy the increasing demand, a very complex power system has been built. There are interconnected network linking together generators and loads into a large integrated system. Over long distance of transmission the system will experienced instability due to insufficient synchronizing torque where it risen low frequency oscillations. These oscillations may grew in magnitude if not properly damped until loss of synchronism [1]. The existence of these oscillations is traced by fast voltage regulation in generators and can be overcome by supplementary control employing Power System Stabilizer (PSS).

PSS is a device which provides an additional supplementary control to voltage regulator system. Perhaps it is cost efficient and satisfactory solution to the problem of oscillatory instability. In order to provide additional damping, PSS must produce a component of electrical torque in phase with the rotor speed deviations without affecting synchronizing torque at critical oscillation frequencies [2]. The most commonly used structure of PSS consists of three block – a gain block, a phase compensation block and a signal washout block.

Flexible AC Transmission Systems (FACTS) based stabilizers is an alternative choice to PSS to improve power system oscillation damping. UPFC which is proposed by L. Gyugyi in 1992 is the most promising FACTS device that have 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, UPFC can be utilized for damping of power system oscillations by applying a damping controller [3].

II. SYSTEM UNDER STUDY

The power system model installed with UPFC used in this research is based on Fig.1 which consists of two three-phase gate turn-off (GTO) thyristor based voltage sourced converter (VSC), a dc link capacitor, a boosting transformer (BT) and an excitation transformer (ET). The input control signals to the UPFC is m_E, m_B, δ_E and δ_B which are the amplitude modulation ratio and phase angle of each VSC [4].

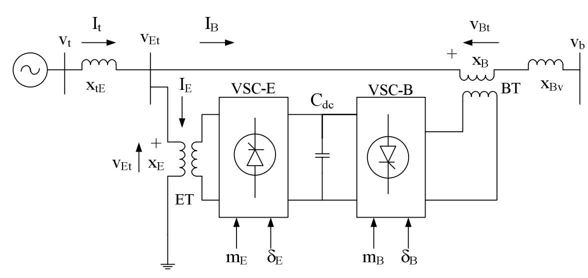


Fig. 1: UPFC installed in SMIB power system

Low frequency oscillation can be analyzed with a linear SMIB [5]. The non-linear differential equation for the Phillips-Heffron model of SMIB power system equipped with UPFC as shown in Fig. 1 is [6]:

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

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

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

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

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:

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

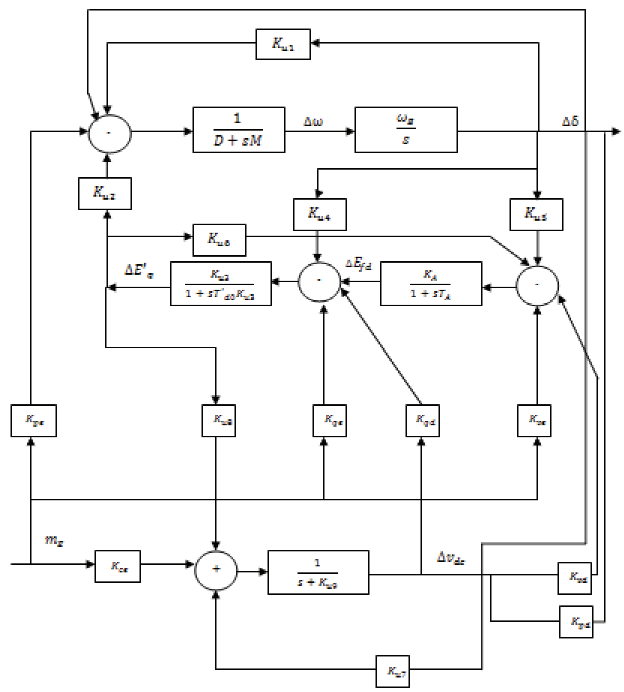
$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \frac{m_B \cos\delta_B v_{dc}}{2} \\ \frac{m_B \cos\delta_B v_{dc}}{2} \end{bmatrix}$$

$$\frac{dv_{dc}}{dt} = \frac{3m_E}{4C_{dc}}\begin{bmatrix} \cos\delta_E & \sin\delta_E \end{bmatrix}\begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}}\begin{bmatrix} \cos\delta_B & \sin\delta_B \end{bmatrix}\begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \qquad (2)$$

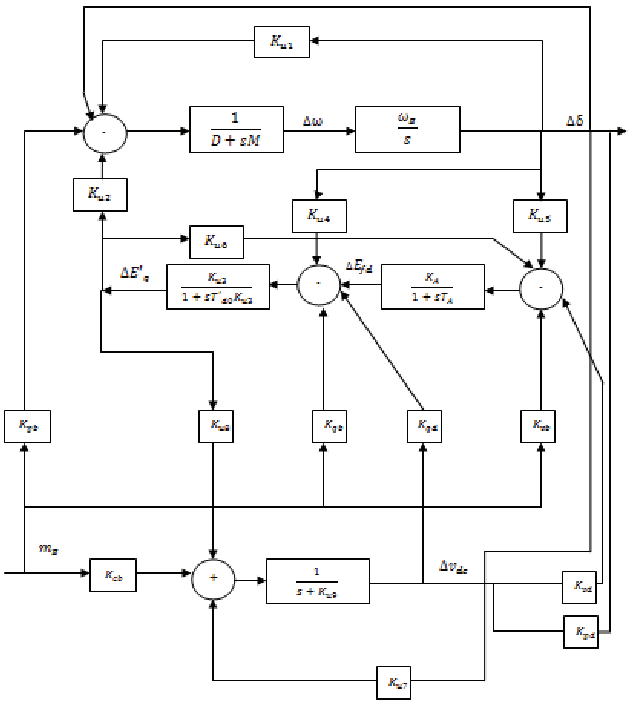
By combining equation (1) and (2), the state variable equations of the power system equipped with UPFC can be represented as:

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

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



(a) using damping controller m_E



(b) using damping controller m_B

Fig. 2: Model of Phillips-Heffron power system equipped with UPFC

where Δm_E, and Δm_B are the damping controller of the UPFC. The model of dynamic linear power system with UPFC for equation (3) is shown in Fig. 2.

In order to monitor and investigated the dynamic power system stability, the analysis started with the mathematical modelling of these power system to derive the equation for the respective parameters followed by designing the power system stabilizer (PSS) for the power system without UPFC and Fuzzy Logic Power System Stabilizer (FLPSS) for the power system with UPFC [7], [8], [9], [10]. Then, after obtaining the initial parameter of the power system, the values of the parameter is calculated using Matlab m-file. Next, with these values the block diagram of the power system is formed using Matlab Simulink and both PSS and FLPSS is added to the particular power system. Both type of power system is then given a small disturbances and the power system characteristics in terms of change of rotor speed, change of rotor angle and change of electrical power is observed.

III. Fuzzy Logic Design

To provide optimum damping to the system low frequency oscillation, fuzzy logic based power system stabilizer has been proposed. Fuzzy logic is logic underlying modes of reasoning which used approximate rather than exact and has no systematic design procedure. One of the advantage applying fuzzy control is it doesn't require mathematical modeling. On the other hand, in contrast to the conventional power system stabilizer which is design in frequency domain, a fuzzy logic power system stabilizer is designed in the time domain. Fuzzy Logic Controller (FLC) is suitable for systems that are structurally difficult to model due to naturally existing nonlinearities or complex in modelling. FLC selects the appropriate control action using the rule base created from the expert knowledge. In this research work, FLC based on mamdani type is used to damp power system oscillations. Mamdani's fuzzy inference method has been chosen because it is the most commonly employed fuzzy methodology and shown a significant excellent result [11].

A. *Identification of input and output variables*

To design a fuzzy controller, the first step is to identify the input signal. FLPSS has two input and a single output. Based on previous study, 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. In practice, only change of rotor speed $\Delta\omega$ is readily available. The rate of change of rotor speed ($\Delta\dot{\omega}$) is derived from $\Delta\omega$ measured at two successive sampling instant,

$$\Delta\dot{\omega}(kT) = \frac{[\Delta\omega(kT) - \Delta\omega(k-1)T]}{T} \qquad (4)$$

where T is the sampling period and k is the sampling count. Fig. 3 shows the input and output of the fuzzy PSS mamdani type used in this research using Matlab Simulink – Fuzzy Inference System (FIS).

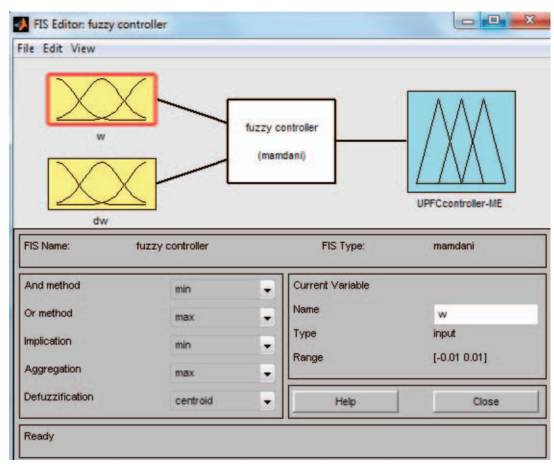


Fig. 3: Input and output signal of FLPSS

B. *Generating Membership Functions*

The measured input variables are converted into suitable linguistic variables known as fuzzy sets. These variables transform the numerical values of the inputs of fuzzy controller to fuzzy quantities. Fuzzy sets consists of members with varying degrees of membership based on the values of the membership function. It can be either linear or nonlinear and it is usually decided from human expertise and observations made. The membership determines all the information contained in fuzzy set thus its choice is critical for the performance of the fuzzy logic system. The number of membership functions influenced the precision of control attainable using fuzzy logic controllers. The precision of control improved when the number of membership function increased. However, the computational time and required memory increased as the number of linguistic variables increased. So, to choose the number of linguistic variables a compromise between computational time and the quality of control is needed.

In this study, seven fuzzy sets for each of the input and the output variables are used to describe them. These are NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). Triangular membership functions are used in this research as shown in Fig. 4. These membership functions are normalized between -0.01 and +0.01 for $\Delta\omega$ while -1 and +1 for $\Delta\dot{\omega}$. These membership functions are symmetrical and each one overlaps with adjacent functions by 50%.

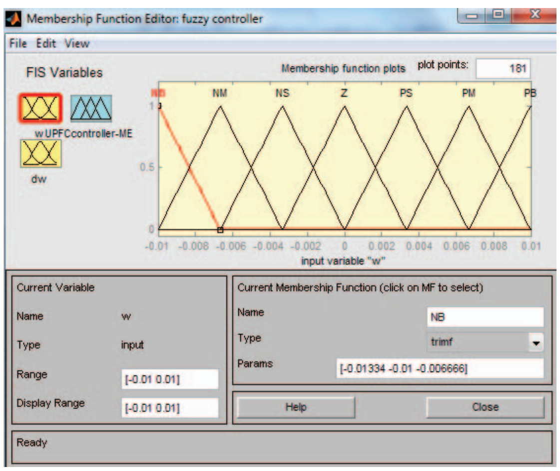


Fig. 4: Membership function of FLPSS

C. *Assigning the membership rules*

In FLC, fuzzy rules plays a major function. These control rules are designed using the knowledge and operating experience with the system or from understanding of the desired effect of the controller. As there are seven linguistics variables assigned for each input, therefore 49 rules are formulated using a simple IF-THEN structure to produce 49 output conditions. Table 1 shows the complete set of control rules.

TABLE I
MEMBERSHIP FUNCTION RULES

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

Example of rules formation can be read as follows:

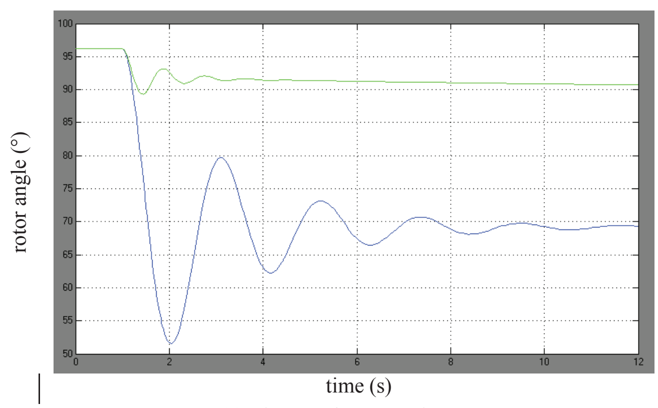
Rule 1: If the change of rotor speed is PS (positive small) and the rate of change of rotor speed is NB (negative big), then the voltage (output of FLPSS) is NS (negative small).

Rule 2: If the change of rotor speed is NM (negative medium) and the rate of change of rotor speed is PB (positive big), then the voltage (output of FLPSS) is ZE (zero).

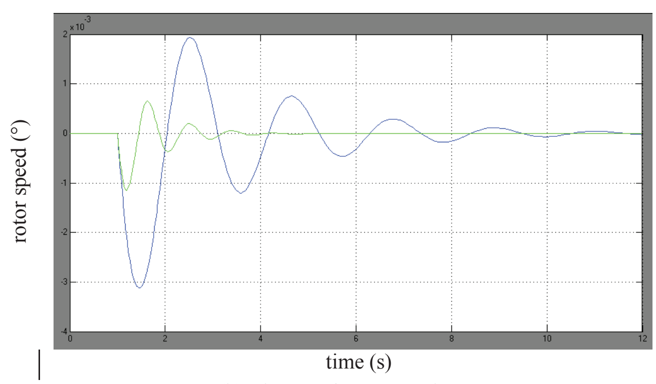
IV. SIMULATION RESULTS

After designing FLPSS in the previous section, the proposed model was validated by simulation. The simulation performed using MATLAB-SIMULINK software. The performance of the designed model without UPFC and with UPFC-FLPSS after being disturbed by a small disturbance in electrical power are shown in Fig. 5 and Fig. 6.

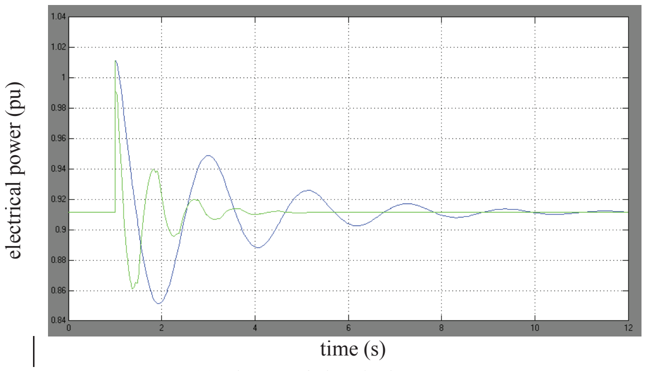
In Fig. 5, UPFC used excitation modulation index converter m_E as its damping controller while in Fig. 6, UPFC used boosting modulation index converter m_B. At $t = 1s$, electrical power disturbances of 0.1 pu was given to the conventional PSS and UPFC based FLPSS power system model. Low frequency oscillations occurred due to the small disturbances is shown in Fig. 5 and Fig. 6 and change of rotor angle, change of rotor speed and change of electrical power is observed in (a), (b) and (c) respectively.



(a) Change of rotor angle

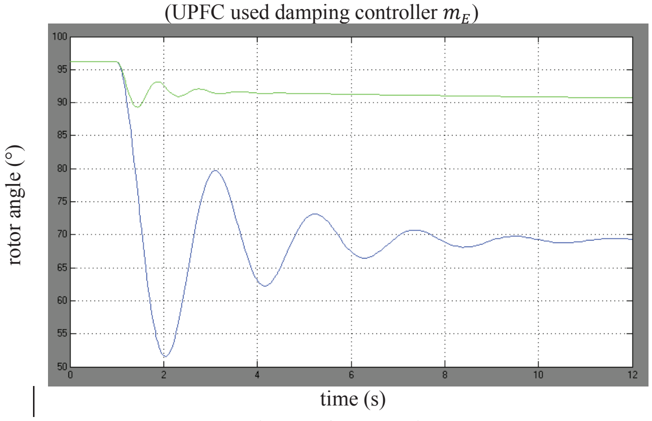


(b) Change of rotor speed

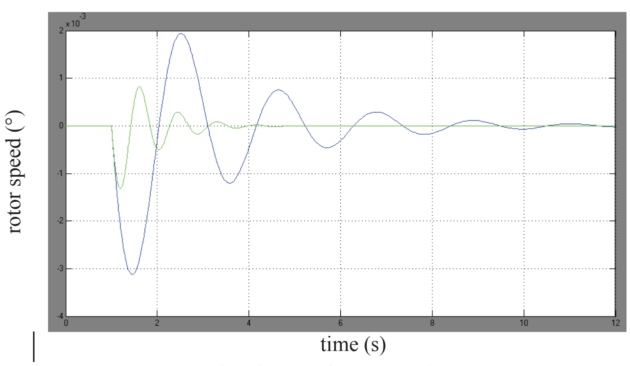


(c) Change of electrical power

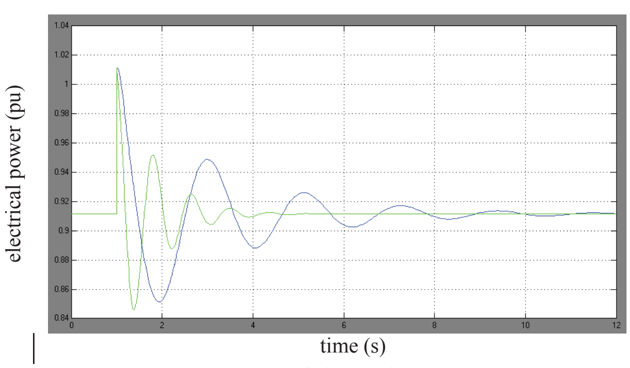
Fig. 5: Oscillation of power system before and after the installation of UPFC (UPFC used damping controller m_E)



(a) Change of rotor angle



(b) Change of rotor speed



(c) Change of electrical power

Fig. 6: Oscillation of power system before and after the installation of UPFC (UPFC used damping controller m_B)

Based on Fig. 5(a), the rotor angle overshoot is seen having a decreased from 44.655° (PSS) to 6.862° (FLPSS) which contributed to a reduction of 84.63%. Meanwhile the settling time also shown a reduction of 80.32% from 6.35s (PSS) to 1.25s (FLPSS).The rotor speed in Fig. 5(b) experienced a decrease of 63.28% in overshoot from -0.003118 pu (PSS) to -0.001145 pu (FLPSS) whereas the settling time is reduced at 61.97% from 10.65s (PSS) to 4.05s (FLPSS). The electrical power in Fig. 5(c) shown a significant reduced in overshoot by 16.31% from 0.0601 pu (PSS) to 0.0503 pu (FLPSS) while the settling time is reduced by 61.80% from 4.45s (PSS) to 1.7s (FLPSS).

Based on Fig. 6(a), the rotor angle overshoot is seen having a decreased from 44.67° (PSS) to 7.651° (FLPSS) which contributed to a reduction of 82.87%. Meanwhile the settling time also shown a reduction of 82.61% from 5.704s (PSS) to 0.992s (FLPSS). The rotor speed in Fig. 6(b) experienced a decreased of 57.55% in overshoot from -0.003121 pu (PSS) to -0.001325 pu (FLPSS) whereas the settling time is reduced at 74.24% from 6.055s (PSS) to 1.56s (FLPSS). The electrical power in Fig. 6(c) shown just a small difference on overshoot compared to PSS. Although the reduction of overshoot by PSS is slightly better than FLPSS by 8.09% (0.0602 pu by PSS and 0.0655 pu by FLPSS), the settling time is reduced by 60.24% from 3.295s (PSS) to 1.31s (FLPSS).

The simulation result depicted in Fig. 5 and Fig. 6 shown that adding UPFC based on FLPSS greatly enhanced the damping of low frequency oscillation. Thus, it proved that fuzzy controller performs better than the conventional stabilizer.

V. Conclusion

In this paper, a linearized model of SMIB power system installed with UPFC is presented to study power system oscillation. Two controllers of UPFC based on FLPSS - m_E and m_B have been selected to improve the dynamic stability of power system. The proposed model is then simulated using MATLAB-SIMULINK and compared with the conventional system with PSS. The simulation results indicated that by incorporating FLPSS with UPFC, the damping of low frequency oscillation shown a better performance than conventional PSS thus improving the dynamic power system stability. Fuzzy logic controller able to decrease the amplitude of low frequency oscillation and increase damping rate successfully. In overall, UPFC based on FLPSS has less settling time and less overshoot.

Appendix

Generator :

M = 2H = 8MJ/MVA $\quad X_d = 1.0$ p.u.

D = 0 $\quad X'_d = 0.3$ p.u.

$T'_{d0} = 5.044s$ $\quad X_q = 0.6$ p.u.

Excitation System:

$K_a = 50$ $\quad T_a = 0.05s$

Transmission lines, infinite bus voltage and step-up transformer:

$R_1 = 0.0$ $\quad X_1 = 1.0$

$V_b = 1.0$ p.u. $X_{tE} = 0.1$

Operating condition:

$P_{e0} = 0.9115$ $V_{dc0} = 2.0$
$V_{t0} = 1.032$ $m_{E0} = 1.0$
$\delta_{E0} = 28.1°$ $m_{B0} = 0.1$
$\delta_{B0} =$ -28.1°

Data for UPFC:

$X_E = 0.1$ $X_B = 0.1$
$X_C = 0.0008842$

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VII. BIOGRAPHIES

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