A New Method to Damping of Low Frequency Oscillations

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Abstract: The low frequency oscillations (LFO) usually occur in power systems due to disturbances such as mechanical power variation. The power system stabilizers (PSS) are usually applied to damp these disturbances. Flexible ac transmission systems (FACTS) devices can be used to control power flow in transmission lines. PSS can be replaced by FACTS if it is applied to control the damping. In this paper, the linear model of power system (single machine connected to infinite bus), possessing FACTS devices is investigated. New controllers are designed and simulated for all four FACTS devices inputs. PSS is also designed and simulated for the investigated system assuming the absence of FACTS. The simulation results well shows that these controllers damp the oscillations faster and with better indices in compare with the PID and conventional stabilizers.

Key words: Low frequency oscillations, Flexible ac transmission systems, Damping, Power System Stabilizer

INTRODUCTION

Unified power flow conditioner (UPFC) (Gyugyi 1995) is one of the FACTS devices would have several applications in power system. It is applied to control power flow, to increase the transient stability and to damp the low frequency oscillations (Gyugyi 1995). The precise and mathematical model of UPFC for dynamic and steady state studies is presented in (Ooi *et al.*, 1997; Noroozian *et al.*, 1997; Nabavi-Niaki and Iravani 1996) and (Smith Ran and Penman 1997). The linear model of UPFC is then obtained which can be easily expressed as the state space equations.

Low frequency oscillations in power systems happen because of disturbances occurrence in power system to investigate which the Heffron-Philips model is used. Wang has introduced a linear model for power system containing UPFC, which is a composition of system's Heffron-Philips and Nabavi-Niaki model of UPFC (Wang and Swift 1997). and (Tambey and Kothari 2003). In PSS less systems, the oscillations are damped designing controllers for UPFC, which utilize the phase compensation approach (Leonid Renik 1997).

The Fuzzy controllers operate on the Fuzzy logic basis, which control or describe systems through the lingual variables (Cornelius T. Leondes 1999) and (Yao-Nan Yu 1983). In order to damp low frequency oscillations, in this paper, the Fuzzy controllers are designed and simulated for an infinite bus connected single machine on which the UPFC device is installed. According to the angular speed and load angle variations, the Fuzzy controller lines UPFC input up in a way that the desired damping is achieved. In this investigation, each UPFC input is considered as the control variable and the controller is designed and simulated on this basis. The simulation results well show that the Fuzzy controllers increase the damping rate and decrease the under shoot more in compare with the conventional UPFC controllers.

The comparison of damping results achieved by UPFC and conventional stabilizers also shows that the UPFC shows higher capability in damping low frequency oscillations.

System Model:

An infinite bus connected single machine on which UPFC is installed is considered as Fig. 1.

UPFC is structured by two PWM controlled power electronics converters. Parameters m_E, m_B, δ_E, and δ_B are the modulation indices and reference signals phase angles of each converter, respectively. These parameters are considered as the UPFC inputs.

Conclusions:

In this paper, the state space model of a UPFC installed infinite bus connected single machine system is used to investigate the low frequency oscillations of the power system. Fuzzy and PID controllers are designed and simulated for UPFC inputs. In addition, a PSS is designed and simulated for the considered system assuming the absence of UPFC. The simulation results well show that the Fuzzy controllers are able to damp the low frequency oscillations and can accomplish this mission faster and with lower overshoot in compare with PID controllers and the conventional stabilizers.
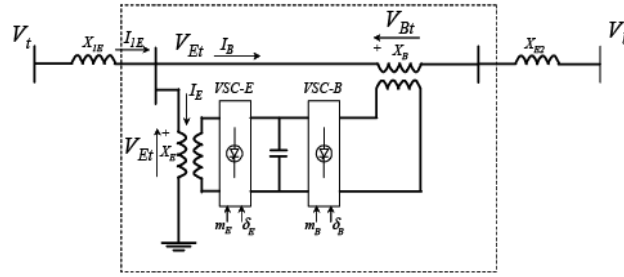

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Fig. 1: Power system of UPFC installed infinite bus connected single machine.

The system's dynamic relations are expressed as follow to investigate the stabilization:

$$\overline{\delta} = \omega_0 \Delta\omega$$
$$\overline{\omega} = (P_m - P_e - D\omega)/M$$
$$\overline{E}_q' = (-E_q + E_{fd})/T_{d0}'$$
$$\overline{E}_{fd} = -\frac{1}{T_A}E_{fd} + \frac{K_A}{T_A}(v_{t0} - v_t)$$

(1)

There exist several models for UPFC depending on several study cases. The equations describe the dynamic behavior of UPFC are as follows:

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

(2)

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

(3)

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

(4)

Combining the linear dynamic equations mentioned as (1) to (4), the state equations could be expressed as follows for the investigated system:

$$\dot{X} = AX + BU$$

(5)

where the following is valid:

$$X = \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_Q \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix}$$

(6)

Parameter U is the input matrix of state space model:

$$U = \begin{bmatrix} \Delta m_E \\ \Delta \delta_E \\ \Delta m_B \\ \Delta \delta_B \end{bmatrix} \tag{7}$$

where Δm_E, $\Delta \delta_E$, Δm_B, and $\Delta \delta_B$, are the variations of UPFC control parameters considered as the inputs of state space model (Wang and Swift 1997).

Matrixes A and B are considered as follows:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\dfrac{k_{pe}}{M} & -\dfrac{k_{p\delta e}}{M} & -\dfrac{k_{pb}}{M} & -\dfrac{k_{p\delta b}}{M} \\ -\dfrac{k_{qe}}{T'_{d0}} & -\dfrac{k_{q\delta e}}{T'_{d0}} & -\dfrac{k_{qb}}{T'_{d0}} & \dfrac{k_{q\delta b}}{T'_{d0}} \\ -\dfrac{k_A k_{ve}}{T_A} & -\dfrac{k_A k_{v\delta e}}{T_A} & -\dfrac{k_A k_{vb}}{T_A} & -\dfrac{k_A k_{v\delta b}}{T_A} \\ k_{ce} & k_{c\delta e} & k_{cb} & k_{c\delta b} \end{bmatrix} \tag{8}$$

$$B = \begin{bmatrix} 0 & \omega_\circ & 0 & 0 & 0 \\ -\dfrac{k_1}{M} & -\dfrac{D}{M} & -\dfrac{k_2}{M} & 0 & -\dfrac{k_{pd}}{M} \\ -\dfrac{k_4}{T'_{d0}} & 0 & -\dfrac{k_3}{T'_{d0}} & \dfrac{1}{T'_{d0}} & -\dfrac{k_{qd}}{T'_{d0}} \\ -\dfrac{k_A k_5}{T_A} & 0 & -\dfrac{k_A k_6}{T_A} & -\dfrac{1}{T_A} & -\dfrac{k_A k_{vd}}{T_A} \\ k_7 & 0 & k_8 & 0 & -k_9 \end{bmatrix} \tag{9}$$

The k coefficients are obtained during the Linearization of (1) and (2) Around the operating point [6].

Power System Stabilizer Designing:
There is a prevalent approach for PSS designing if the system is considered not to possess UPFC [11]. Fig. 2. shows the structure of a PSS.
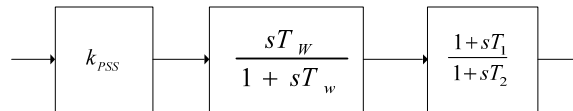

Fig. 2: the structure of a power system stabilizer.

In order to design the stabilizer, the transformation function between PSS output and e'_q state variable is obtained as the following relation:

$$G_E = \frac{k_A k_3}{\left(1 + sT_A\right)\left(1 + sT'_{d0}k_3\right) + k_A k_3 k_6} \tag{10}$$

For $s = j\omega_n$, the lagging property of G_E which is considered as phase angle is calculated (ω_n is the natural frequency of system).
If the following is valid:

$$\angle G_C + \angle G_E = 0$$
$$G_C = \frac{1 + sT_1}{1 + sT_2} \tag{11}$$

the T_1 and T_2 are obtained as follows:

$$\varphi_m = \sqrt{\frac{1}{T_1 T_2}}$$
$$\sin \varphi_m = \frac{\alpha - 1}{\alpha + 1} \tag{12}$$
$$\alpha = \frac{T_1}{T_2}$$

In fact, parameter k_{PSS} is a dc gain obtained as follows or through try and error approach:

$$k_{pss} = \frac{\omega_n M}{k_2 |G_C(j\omega_n)||G_E(j\omega_n)|} \tag{13}$$

The function of $\dfrac{sT_W}{1 + sT_W}$ is a high-pass filter to pass the variations.

Fuzzy Controller Design for UPFC:
If UPFC is installed in system, at the absence of stabilizer, the disturbances caused low frequency oscillations are damped by designing PID regulators for each UPFC input (Leonid Renik 1997).

The Fuzzy controllers are designed for LFO damping. The angular speed variations ($\Delta\omega$) and the load angle variations ($\Delta\delta$) are the Fuzzy controller inputs. The output of the controller regulates one of the UPFC input in a way that the desired damping is achieved. Figure 3. shows the schematic diagram of the Fuzzy controllers.

Since the Mamdani conclusion motor is the most prevalent Fuzzy conclusion approach (Cornelius and Leondes 1999). it is applied in these controllers.

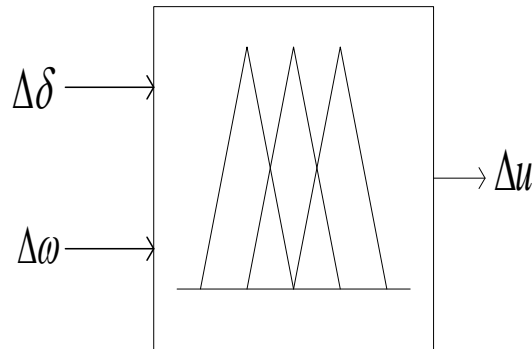$$\Delta u \in \left\{ \Delta m_E, \Delta \delta_E, \Delta m_B, \Delta \delta_B \right\}$$

Fig. 3: the Fuzzy control structure for UPFC.

The dependency functions for inputs and output of the Fuzzy controller, which control the δ_E parameter, are illustrated in Figs. 4 and 5. The difference of Fuzzy controllers dependency functions and other UPFC inputs just fall in their intervals.
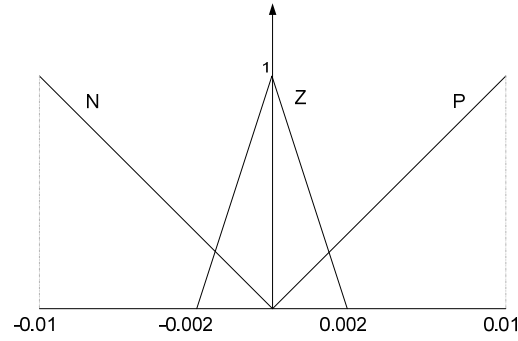
Fig. 4: the dependency functions for Fuzzy controllers (is considered as the control variable).
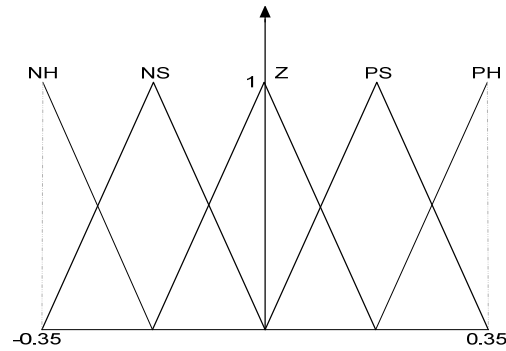

Fig. 5: the dependency functions for Fuzzy controllers (is considered as the control variable).

The variation of Fuzzy controller output in terms of inputs is illustrated in Fig. 6. the smoothness of this surface variations shows the proper design process.
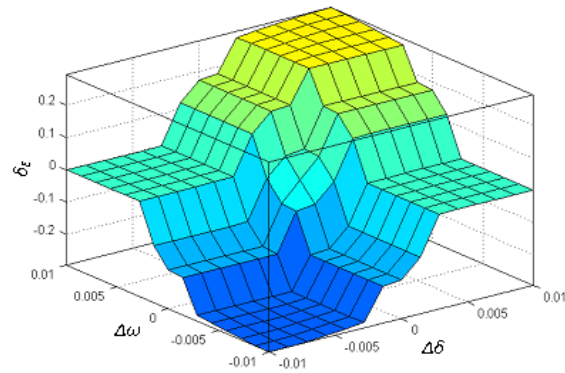

Fig. 6: the controller output variations in terms of inputs.

Table 1. shows the Fuzzy rules of δ_E variable Fuzzy controller. The symmetry exists in the rules table is very important. Other control variables have similar rule tables.

Table 1: The Fuzzy controller's rule table (δ_E is considered as the control variable)

$\Delta\omega$ \ $\Delta\delta$	N	Z	P
N	NH	NS	Z
Z	NS	Z	PS
P	Z	PS	PH

Simulation and comparison Results:

The specifications of simulated system are illustrated in Table 2. If no stabilizer or UPFC is applied in the system, the angular speed variation ($\Delta\omega$) would be as Fig. 7, for the mechanical power step change ($\Delta P_m = 0.01\,pu$).

Assuming the absence of UPFC then, a stabilizer \is designed for the investigated system and the response of system for a step change in mechanical power is simulated.

According to relations presented in section 4, the stabilizer characteristics would be as follows:

Table 2: The parameters of the investigated system.

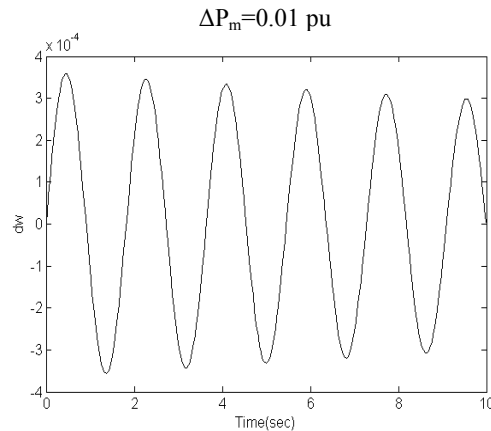|	
Generator	$M = 2H = 8.0\,MJ/MVA, D = 0.0$ $T'_{do} = 5.044\,s$ $X_d = 1.0\,pu, X_q = 0.6\,pu, X'_d = 0.3\,pu$
AVR	$k_A = 100, T_A = 0.01\,s$
Reactance	$X_{lE} = 0.1\,pu, X_E = X_B = 0.1\,pu$ $X_{Bv} = 0.3\,pu, X_e = 0.5\,pu$
Operation points	$P_e = 0.8\,pu, V_t = 1\,pu, V_b = 1\,pu$
UPFC Parameters	$m_E = 0.4013, m_B = 0.0789$ $\delta_E = -85.3478^o, \delta_B = -78.2174^o$
Dc connection	$V_{dc} = 2\,pu, C_{dc} = 1\,pu$

Fig. 7: The angular speed oscillations in PSS and UPFC less system.

Fig.8. shows the effect of applying PSS in the power system on the angular speed variations ($\Delta\omega$) for step change of the mechanical power ($\Delta P_m = 0.01\,pu$). The oscillations are damped by PSS in about 4 seconds with an amplitude of 10^{-3}.

In the next stage, the system is considered to possess no PSS while a UPFC is installed on. Here, the oscillations are damped as disturbances occur by lining up each UPFC input through PID or Fuzzy controllers.

Adjusting δ_E input using PID and Fuzzy controllers after a step change in mechanical power ($\Delta P_m = 0.01\,pu$), the $\Delta\omega$ oscillation is illustrated in Fig. 9.

In Figs. 10-12, the oscillations are damped by designing controllers for m_E, δ_B, and m_B inputs.

The overshoot, undershoot, and the settling time of the responses should be investigated to be able to compare the capability of three simulated approaches in oscillation damping. This is well done as Table 3.
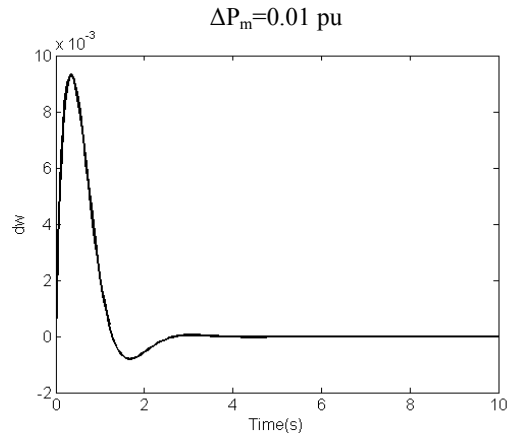
ΔP_m=0.01 pu

Fig. 8: The angular speed oscillations in PSS possessed system.
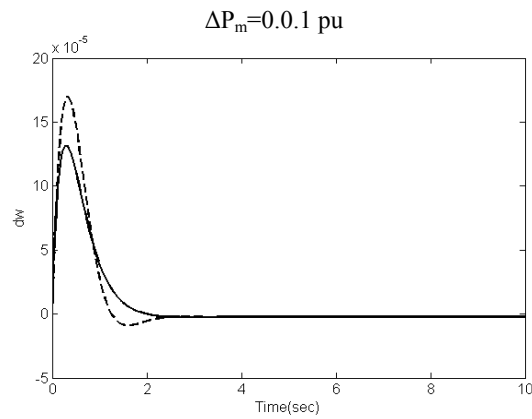
ΔP_m=0.0.1 pu

Fig. 9: The angular speed for step change in mechanical power (dotted: PID controller response. Bald: Fuzzy. controller response (δ_E is the controlling variable))

Table 3: The damping parameters in the simulated approaches

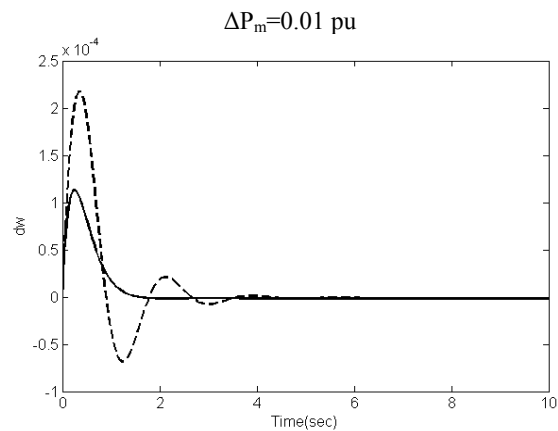|	Settling time (seconds)	Undershoot range	Overshoot range
UPFC with Fuzzy control	2	No undershoot	10^{-5}
UPFC with PID control	2-4	10^{-5}	10^{-5}
Conventional stabilizer	4	10^{-3}	10^{-3}

ΔP_m=0.01 pu

Fig. 10: The angular speed for step change in mechanical power (dotted: PID controller response. Bald: Fuzzy. controller response (m_E is the controlling variable))
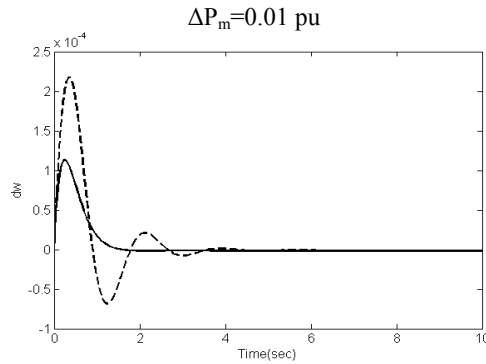
$\Delta P_m=0.01$ pu

Fig. 11: The angular speed for step change in mechanical power (dotted: PID controller response. Bald: Fuzzy. controller response (δ_B is the controlling variable))

The comparison depicts that if damping controllers are designed for UPFC inputs, better damping is achieved in compare with the conventional stabilizers. Higher damping capability is achieved applying Fuzzy controller on UPFC in compare with PID controller.
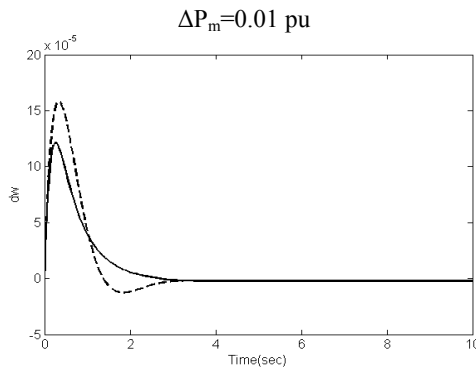
$\Delta P_m=0.01$ pu

Fig. 12: The angular speed for step change in mechanical power (dotted: PID controller response. Bald: Fuzzy. controller response (m_B is the controlling variable))

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