Robust Interline Power Flow Controller with Wind Power Source Using Phase-Plane Fuzzy Logic Control

Komsan Hongesombut[1] and **Thongchart Kerdphol**[2], Members

ABSTRACT

This paper designs the phase-plane fuzzy logic control method of the interline power flow controller (IPFC) in the power system consisting of the single synchronous generator connected to the infinite bus based on the modified Heffron-Phillip's model. The proposed controller is applied to control the frequency robustly and to improve the power system stability due to the uncertainty of power produced from the installed wind turbine in the system. The power from the installed wind turbine is introduced into the system and treated as the uncertainty in the power system. The results reveal that the phase-plane fuzzy logic control can achieve higher performance and more robustness compared with the optimally tuned lead-lag compensator.

Keywords: Phase-Plane Fuzzy Logic Control, Interline Power Flow Controller, Robust Control, Power System Oscillations, Wind Energy

1. INTRODUCTION

With the advent of smart grid technologies, many renewable energy sources can be effectively used for electricity production. Among renewable energy sources, wind energy is fast growing in the electricity markets because it is the sustainable energy and is environmental friendly. However, the electrical power acquired from the wind energy is usually fluctuated resulting in the oscillation of power system frequency [1]. This study focuses on solving the problem of power system frequency oscillation by introducing the Interline Power Flow Controller (IPFC) into the power system [2].

Basically, the power system oscillations between 0.1-1 Hz mostly come from the inadequate power damping in the power system. This problem can be solved by adopting FACTS (Flexible Alternating Current Transmission System) [3]. The IPFC consists of two units of Voltage Source Converters (VSCs) that are used to control the voltage of each power line and to improve the system stability for reliability. The dc linked line is used for exchanging the real power between two power lines. It means that real power is transmitted from the overloaded power line to the under-loaded power line. Moreover, the IPFC can be used to regulate the voltage level in the power lines, to improve the transient response with better damped oscillations and sensitivity.

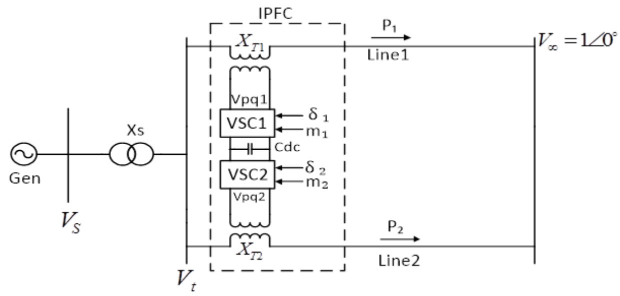

Fig.1: *The generator connected to infinite bus incorporating the IPFC.*

Recently, there are many successful applications of fuzzy logic control to power system problems. The phase-plane fuzzy logic control is one of them that has been proved to work in many power system applications. For example, the implementation of fuzzy logic control based static var compensator is discussed in [4-5]. This paper proposes the phase-plane fuzzy logic control method of the IPFC based on the Heffron-Phillip's model with the addition of wind power source [6]. For the performance verification, the optimally tuned lead-lag controller is selected to be the candidate for comparison against the proposed controller in order to compare the dynamic stability of the power system [7, 8, 9].

2. SYSTEM MODELLING OF IPFC

Fig. 1 shows the generator connected to the infinite bus with the two parallel transmission lines and the IPFC consisting of two VSCs each providing a series compensator for two power lines. The converters are linked together at dc terminals. The equations describing the dynamic performance of the IPFC can

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be expressed as:

$$\begin{bmatrix} V_{pq1d} \\ V_{pq1q} \end{bmatrix} = \begin{bmatrix} 0 & -X_{T1} \\ X_{T1} & 0 \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + \begin{bmatrix} \frac{m_1 cos(\delta_1) V_{dc}}{2} \\ \frac{m_1 sin(\delta_1) V_{dc}}{2} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{pq2d} \\ V_{pq2q} \end{bmatrix} = \begin{bmatrix} 0 & -X_{T2} \\ X_{T2} & 0 \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} \frac{m_2 cos(\delta_2) V_{dc}}{2} \\ \frac{m_2 sin(\delta_2) V_{dc}}{2} \end{bmatrix} \quad (2)$$

The nonlinear dynamic model of the power system of Fig. 1 is as follows:

$$\dot{V}_{dc} = \frac{3m_1}{4Cdc} \left[cos(\delta_1) sin(\delta_1)\right] \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + \frac{3m_2}{4Cdc} \left[cos(\delta_2) sin(\delta_2)\right] \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} \quad (3)$$

$$\dot{\delta} = \omega_0 (\omega - 1) \quad (4)$$

$$\dot{\omega} = \frac{1}{M} (P_m - P_e - D_\omega) \quad (5)$$

$$\dot{E}_q = \frac{1}{T_{do}} (E_{fd} - E_q) \quad (6)$$

$$\dot{E}_{fd} = \frac{1}{T_a} \left[K_a (V_{ref} - V_s) - E_{fd}\right] \quad (7)$$

Where

ω is the rotor angular velocity (rad/s),

V_s is the source voltage (pu.),

V_{ref} is the reference terminal voltage (pu.),

$M = 2H$ is the inertia constant (s),

D is the damping torque coefficient,

C_{dc} is the dc capacitance (pu.),

T_{do} is the longitudinal time constant during open circuit (s),

K_a is the AVR gain,

T_a is the AVR time constant (s),

P_e is the electrical power (pu.),

P_m is the mechanical power (pu.),

$\dot{E}_q$ is the internal voltage of generator (pu.),

$\dot{E}_{fd}$ is the field voltage of generator (pu.),

V_{dc} is the dc voltage (pu.),

δ is the rotor angle (rad),

m_1, m_2 are the adjustable indexes of VSC1 and VSC2 (pu.),

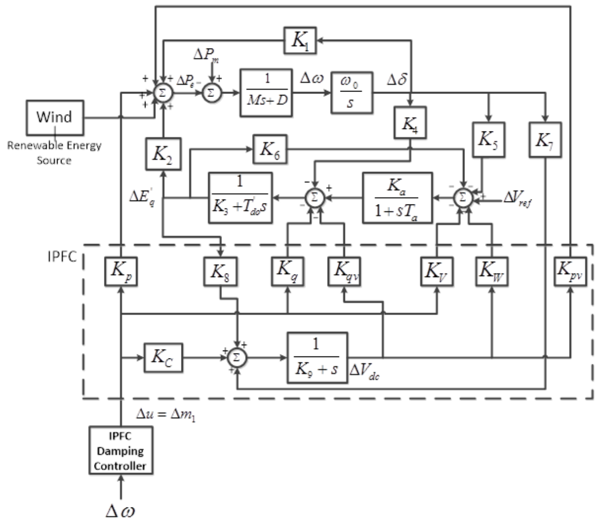

Fig.2: *The Heffron-Phillips model equipped IPFC and wind energy source.*

δ_1, δ_2 are the angles of VSC1 and VSC2 (rad),

i_{1d}, i_{1q} are the d and q currents of 1^{st} line (pu.),

i_{2d}, i_{2q} are the d and q currents of 2^{nd} line (pu.),

$\dot{E}_q$ is the internal voltage of generator (pu.),

Linearizing (3)-(7), the resulting state space equations can be expressed as:

$$\dot{X} = AX + BU \quad (8)$$

Where X and U are

$$X = [\Delta\delta \;\; \Delta\omega \;\; \Delta E_q^{'} \;\; \Delta E_{fd} \;\; \Delta V_{dc}]^T$$
$$U = [\Delta m_1 \;\; \Delta\delta_1 \;\; \Delta m_2 \;\; \Delta\delta_2]^T$$

Where $\Delta m_1, \Delta\delta_1, \Delta m_2$ and $\Delta\delta_2$ are the input signals to the IPFC, respectively.

The modified Heffron-Phillip's model including the IPFC and PSS is linear and can be shown in Fig. 2. The value of K constants can be solved with the initial conditions in [4].

3. THE PROPOSED CONTROL MEDTHOD

A. Phase-Plane Fuzzy Logic Control

The structure of the phase-plane fuzzy logic controller is shown in Fig. 3. The phase-plane fuzzy logic control scheme is applied to the damping control loop of the IPFC. The input signal is the generator speed deviation $\Delta\omega$. The signal Z_s is the measured signal of the generator speed deviation and the signal Z_a is the measured signal of the generator acceleration. The state of generator is represented by the signals Z_s and Z_a on the phase-plane as shown in Fig. 4, where Z_s and Z_a are derived from the generator speed deviation through the washout high-pass filter and the

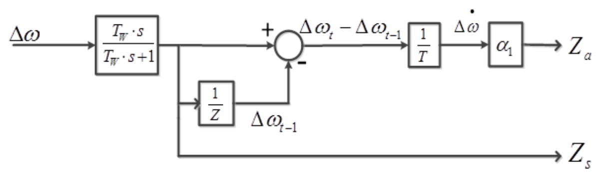

Fig.3: *Phase-plane fuzzy logic controller of IPFC.*

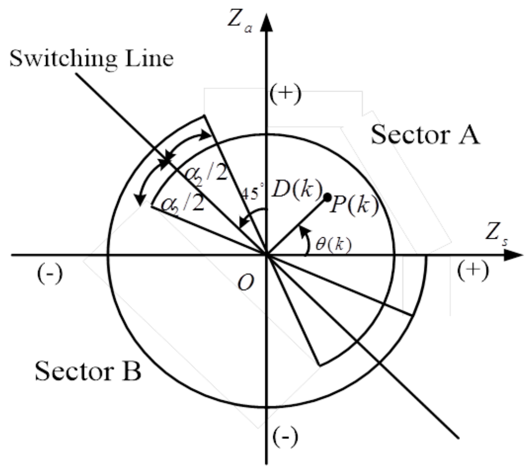

Fig.4: *The phase-plane of fuzzy logic control.*

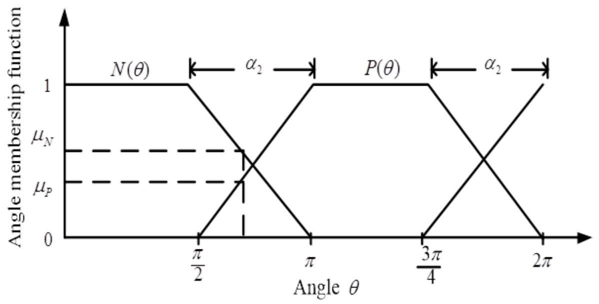

Fig.5: *The angle membership function.*

unit delay. The parameter α_1 is an adjustable scaling factor and T is the sampling time.

From Fig. 4, the state of generator is approximated by the point $P(k)$ in the phase-plane. The phase-plane can be divided into 2 sectors, i.e. sector A and sector B. The parameter α_2 is the overlapping angle between two sectors.

The generator state representing by the polar information is determined by the radius and the phase angle that can be calculated by:

$$D(k) = \sqrt{Z_s^2 + (\alpha_1 Z_a)^2} \tag{9}$$

$$\theta(k) = tan^{-1}\left(\frac{\alpha_1 Z_a}{Z_s}\right) \tag{10}$$

This paper focuses on only the control of because from the parameters study, it turns out that the con-

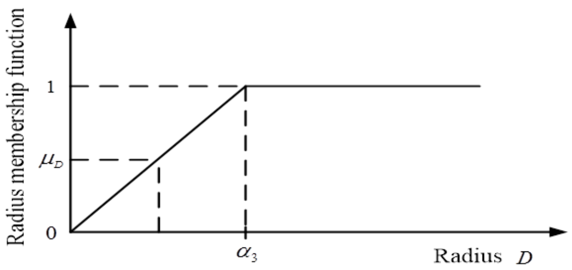

Fig.6: *The radius membership function.*

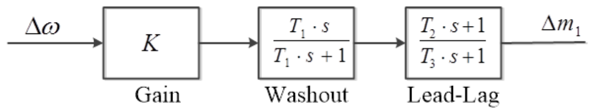

Fig.7: *The structure of the supplementary damping controller.*

trol input yields the best stability. By using the angle and radius membership functions shown in Fig. 5 and Fig. 6 respectively, the output of the proposed controller is given by:

$$\Delta m_1 = (2\mu_N - 1) \cdot \mu_D \cdot U_{max} \tag{11}$$

Where U_{max} is the maximum value of the output signal of the phase-plane fuzzy logic controller.

B. The Lead-Lag Compensator with Parameters Optimally Tuned by GA.

Using GA in the tuning procedure to find the suitable parameters K, T_1, T_2, T_3, the input of controller is $\Delta\omega$ and the output of controller is Δm_1

The structure of block diagram in Fig. 7 consists of the gain block, the filter block and the lead-lag block. The constraints in tuning by GA are as follows:

$$0 \le k \le 50, 0 \le T_1 \le 10, 0 \le T_2 \le 10, 0 \le T_3 \le 10$$

With the cost function of the form:

$$Minimize \;\; j = \frac{1}{\zeta} + \sigma \tag{12}$$

Under the constraints of : $\zeta_{min} \le \zeta \le \zeta_{max}$ and $\sigma_{min} \le \sigma \le_{max}$. Where ζ is the minimum damping , σ is the maximum real part.

4. SIMULATION RESULTS

In order to demonstrate the efficiency of the proposed controller, this paper makes the comparison between the power system without the IPFC and another one equipped the IPFC with the phase-plane fuzzy logic controller. Moreover, the performance verification is done against the optimally tuned lead-lag compensator based on GA under various operating conditions. The disturbance from the wind power source is specified by Fig. 8.

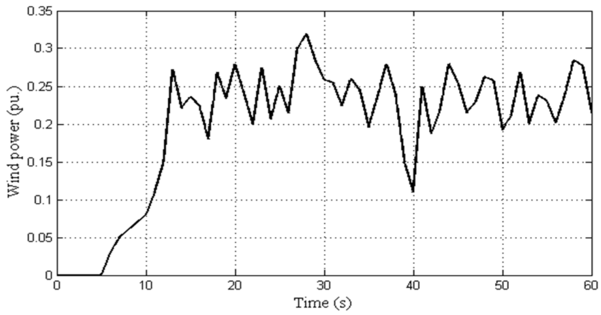

Fig.8: *The disturbance from the wind power source.*

Table 1: *PARAMETERS USED IN THE PHASE-PLANE FUZZY LOGIC CONTROL.*

Input signal to IPFC controller	α_1	α_2	α_3
m_1	0.01	0	0.004

Table 2: *PARAMETERS USED IN THE OPTIMALLY TUNED LEAD-LAG COMPENSATOR.*

Input signal to IPFC controller	K	T_1	T_2	T_3
m_1	16.478	0.774	0.355	0.521

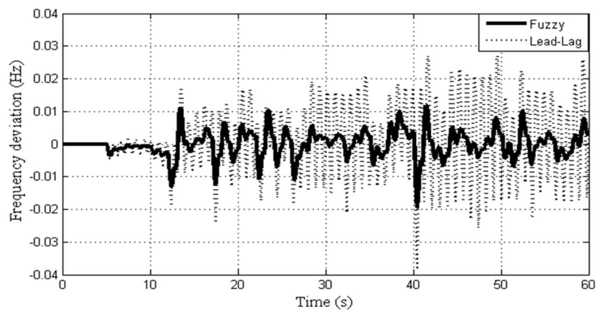

Fig.9: *The frequency deviation of the power system with 30% variation of the wind power.*

Table 1 shows the appropriate values of α_1,α_2 and α_3 of the phase-plane fuzzy logic controller that can be obtained by manual tuning. Table 2 shows the appropriate values of K, T_1, T_2 and T_3 of the optimally tuned lead-lag compensator based on GA.

For the power system without the controller, the oscillation of frequency indefinitely increases and becomes unstable. From the simulation results, the variation of the wind power by the percentage of 30% of the total power generation make the fluctuation of the generated electrical power in the power system. The more percentage of wind integration, the more fluctuation in the system frequency. By introducing the controller using the phase-plane fuzzy logic control, the oscillation is reduced more than when controlling by the optimally tuned lead-lag controller

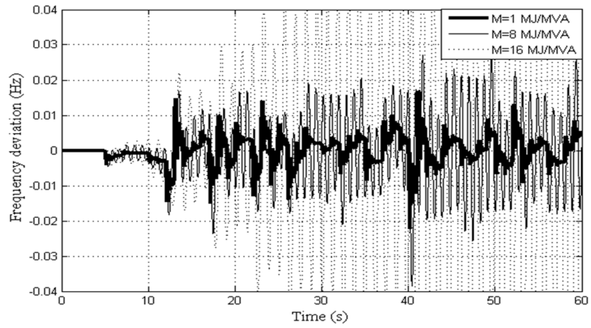

Fig.10: *The frequency deviation when using the optimally tuned lead-lag controller based on GA under the adjustment condition of the inertia.*

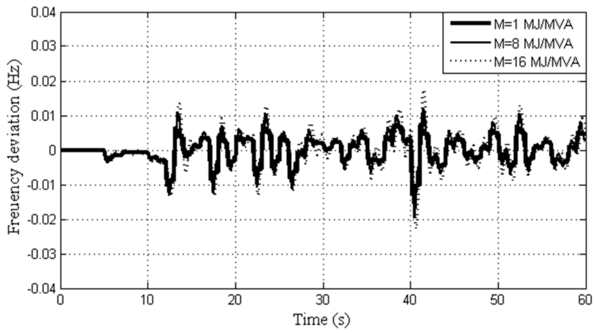

Fig.11: *The frequency deviation when using the proposed phase-plane fuzzy logic controller under the adjustment of the inertia.*

based on GA as in Fig. 9.

The inertia in the power system can be treated as an uncertainty since it is difficult to be measured in real power system. From Fig. 10-11, when the inertia of the system is adjusted in a wide range such that there is 30% variation of the wind power in the power system, the phase-plane fuzzy logic controller can still preserve the stability under the variation of the inertia better than the optimally tuned lead-lag compensator based on GA.

5. CONCLUSIONS

This paper proposes the IPFC robust controller using the phase-plane fuzzy logic control to improve the stability of the power system under the disturbance of the wind power source. The performance of the proposed controller is compared with the optimally tuned lead-lag compensator based on GA. It is obvious that the optimally tuned lead-lag compensator gives poorer stability than the proposed controller by the phase-plane fuzzy logic control. After the power system is adjusted the uncertainty of the inertia, the optimally tuned lead-lag controller is not able to keep the system stability. In contrast, the proposed controller is able to keep the system stability. On other hand, the proposed control method can meet the requirement to include the maximized wind power.

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