Hybrid Fuzzy Logic Control with Global Signals for UPFC to Reduce Control Interactions

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***Abstract*:** In this paper, it is shown that dynamic interactions can occur between multiple UPFCs installed in multimachine power systems. The existence of these dynamic interactions can adversely affect the overall system performance and lead to system instability. To mitigate these adverse interactions, a hybrid fuzzy logic controller for the UPFC is developed. This controller combines the advantages of a fuzzy logic controller and a conventional PI controller. An additional global feedback signal also gives improved performance. The WSCC three-machine system and the IEEE five-machine 14-bus system are used to demonstrate the existence of the control interactions and the efficiency of the proposed approach.

KEYWORDS: Control Interactions, UPFC, Fuzzy Logic

I. INTRODUCTION

The rapid development of the power electronics industry has made FACTS devices attractive for utilities due to their flexibility and capacity of effectively controlling power system dynamics for secure operation. The Unified Power Flow Controller (UPFC) is the most versatile FACTS device, and has the capabilities of controlling power flow in a transmission line, improving transient stability, mitigating system oscillations and providing voltage support [1].

In large interconnected networks, more than one FACTS device in the same region or electrical area will be a natural consequence of the growing use of this technology. However, adverse dynamic interactions can occur not only among the control functions of a single FACTS device but also between different FACTS devices if their controls are not coordinated [2]. The existence of the dynamic interactions among FACTS controls can adversely affect the overall performance and even lead to dynamic instability of the system. Adverse interactions among FACTS controls must be carefully studied and alleviated before multiple FACTS devices can be safely deployed in a system.

Most FACTS device controllers use a conventional proportional-integral (PI) control due to its simplicity. However linear controllers, such as a PI controller, may cause interactions over a wide range of operating conditions or under large disturbances for nonlinear system. To improve the system performance, fuzzy logic theory has been applied to the controller design for FACTS devices. The operation of the fuzzy logic controller does not rely on how accurate the model, parameters, or operating conditions are, but rather, on how effective the linguistic rules of the fuzzy controller are. However, defining membership functions of linguistic variables and formulating fuzzy rules by manual operation are very time consuming. Thus this paper presents a hybrid fuzzy logic controller with global signals for UPFC to minimize the dynamic interactions.

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This controller replaces the proportional term in the conventional PI controller with an incremental fuzzy logic controller while leaving the conventional integral term unchanged. Compared with the existing fuzzy PI controllers, this new hybrid fuzzy proportional plus integral controller keeps the simple structure of the PI controller and can cover a much wider range of operating conditions. To improve the system dynamic stability, additional global control inputs obtained remote from the controller are added into the new hybrid fuzzy controller. Two case studies of the WSCC three-machine system and IEEE five-machine 14-bus system present the efficiency of the proposed hybrid fuzzy logic controller in reducing dynamic control interactions.

II. POWER SYSTEM MODEL

In order to consider the full effects of the generator dynamics including the speed governor and turbine, exciter/AVR and UPFC dynamics, the following dynamic models of the system components were used [3]:

Two-Axis Generator Model:

$$\dot{\delta} = \omega - \omega_s$$

$$M\dot{\omega} = T_M + \frac{V}{x'_d}\left(E'_d \cos(\theta-\delta) + E'_q \sin(\theta-\delta)\right)$$

$$T'_{do}\dot{E}_q = -\frac{x_d}{x'_d}E'_q + \frac{x_d - x'_d}{x'_d}V\cos(\theta-\delta) + E_{fd}$$

$$T'_{qo}\dot{E}_d = -\frac{x_q}{x'_q}E'_d + \frac{x_q - x'_d}{x'_d}V\sin(\theta-\delta)$$

(assumption: $x'_d = x'_q$ and $R_s = 0$)

IEEE Type I Exciter/AVR Model:

$$T_E\dot{E}_{fd} = -K_E E_{fd} - S_E\left(E_{fd}\right)E_{fd} + V_R$$

$$T_A\dot{V}_R = -V_R + K_A\left(R_F - \frac{K_F}{T_F}E_{fd} + V_{ref} - V_T\right)$$

$$T_F\dot{R}_F = -R_F + \frac{K_F}{T_F}E_{fd}$$

Speed Governor Model

$$T_{SV}\dot{P}_{SV} = -P_{SV} + P_C - \frac{1}{R}\frac{\omega}{\omega_s}$$

Turbine Model

$$T_{RH}\dot{T}_M = -T_M + \left(1 - \frac{K_{HP}T_{RH}}{T_{CH}}\right)P_{CH} + \frac{K_{HP}T_{RH}}{T_{CH}}P_{SV}$$

$$T_{CH}\dot{P}_{CH} = -P_{CH} + P_{SV}$$

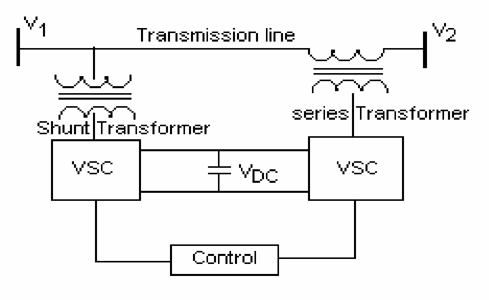

Figure 1: UPFC Schematic diagram

The unified power flow controller, or UPFC, is the most complex voltage-sourced-converter (VSC)–based FACTS device. Figure 1 shows the schematic diagram of a UPFC. It consists of a combination of a shunt and series branches connected through a DC capacitor. The series connected inverter injects a voltage with controllable magnitude and phase angle in series with the transmission line, therefore providing real and reactive power to the transmission line. The shunt-connected inverter provides the real power drawn by the series branch and the losses and can also independently provide reactive compensation to the system by the reactive current [1]. By defining a proper synchronous reference frame, the dynamic model of UPFC can be written as:

$$\frac{1}{\omega}\dot{i}_{d1} = -\frac{R_{s1}}{L_{s1}}i_{d1} + i_{q1} + \frac{k_1}{L_{s1}}\cos(\alpha_1+\theta_1)V_{dc} - \frac{1}{L_{s1}}V_1\cos(\theta_1)$$

$$\frac{1}{\omega}\dot{i}_{q1} = -\frac{R_{s1}}{L_{s1}}i_{q1} - i_{d1} + \frac{k_1}{L_{s1}}\sin(\alpha_1+\theta_1)V_{dc} - \frac{1}{L_{s1}}V_1\sin(\theta_1)$$

$$\frac{1}{\omega}\dot{i}_{d2} = -\frac{R_{s2}}{L_{s2}}i_{d2} + i_{q2} + \frac{k_2}{L_{s2}}\cos(\alpha_2+\theta_1)V_{dc} - \frac{1}{L_{s2}}\left(V_2\cos(\theta_2) - V_1\cos(\theta_1)\right)$$

$$\frac{1}{\omega}\dot{i}_{q2} = -\frac{R_{s2}}{L_{s2}}i_{q2} - i_{d2} + \frac{k_2}{L_{s2}}\sin(\alpha_2+\theta_1)V_{dc} - \frac{1}{L_{s2}}\left(V_2\sin(\theta_2) - V_1\sin(\theta_1)\right)$$

$$\frac{C}{\omega}\dot{V}_{dc} = -k_1\cos(\alpha_1+\theta_1)i_{d1} - k_1\sin(\alpha_1+\theta_1)i_{q1} - k_2\cos(\alpha_2+\theta_1)i_{d2} - k_2\sin(\alpha_2+\theta_1)i_{q2} - \frac{V_{dc}}{R_{dc}}$$

where i_{di} and i_{qi} are the injected dq converter currents, V_{dc} is the voltage across the DC capacitor, R_{dc} represents the switching losses, $V_1\angle\theta_1$ and $V_2\angle\theta_2$ are the terminal voltages of the UPFC.

The power balance equations at bus 1 are given by:

$$0 = V_1\left((i_{d1}-i_{d2})\cos\theta_1 + (i_{q1}-i_{q2})\sin\theta_1\right) - V_1\sum_{j=1}^{n}V_jY_{1j}\cos(\theta_1-\theta_j-\phi_{1j})$$

$$0 = V_1\left((i_{d1}-i_{d2})\sin\theta_1 - (i_{q1}-i_{q2})\cos\theta_1\right) - V_1\sum_{j=1}^{n}V_jY_{1j}\sin(\theta_1-\theta_j-\phi_{1j})$$

and at bus 2:

$$0 = V_2\left((i_{d2})\cos\theta_2 + (i_{q2})\sin\theta_2\right) - V_2\sum_{j=1}^{n}V_jY_{2j}\cos(\theta_2-\theta_j-\phi_{2j})$$

$$0 = V_2\left((i_{d2})\sin\theta_2 - (i_{q2})\cos\theta_2\right) - V_2\sum_{j=1}^{n}V_jY_{2j}\sin(\theta_2-\theta_j-\phi_{2j})$$

III. CONTROL INTERACTION ANALYSIS

The UPFC has three control parameters: the magnitude and angle of the injected voltage and the shunt reactive current. The series output active and reactive power flow control can be controlled independently by injecting a series voltage with an appropriate magnitude and angle. In the synchronous rotating dq reference frame, the series injected voltage can be split into E_d and E_q. By controlling E_d and E_q properly, different active and reactive power flows can be achieved. Similarly by controlling the shunt injected voltage E_d and E_q, the shunt-connected converter can provide independent reactive power support and maintain constant DC capacitor voltage. The conventional PI technique is typically used in UPFC controller design. One straightforward PI-based control is shown in Figure 2 [4].

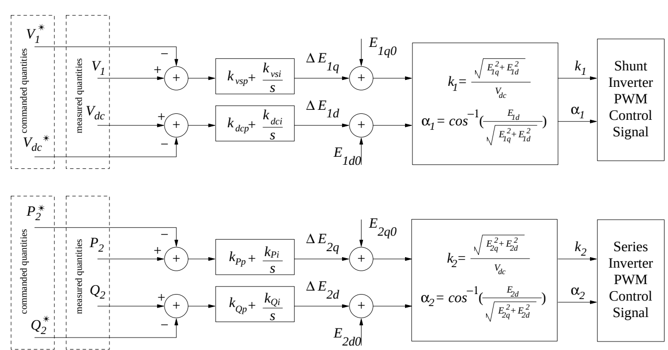

Figure 2: UPFC Control Block Diagram

To investigate the interactions among UPFC controllers, two case studies are presented for the WSCC three-machine nine-bus system and the IEEE five-machine 14-bus system. All the UPFC controllers use the PI-based control approach shown in Figure 2 and each UPFC control is designed and optimized separately without considering the presence of other UPFCs.

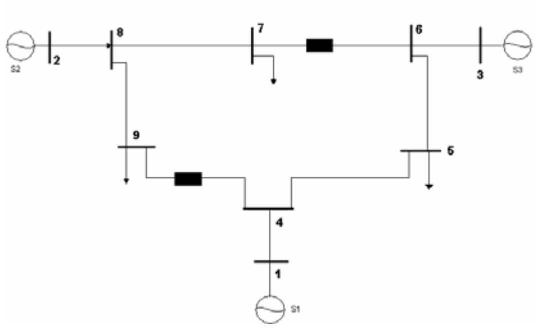

Figure 3: WSCC Three-machine nine-bus System

The WSCC System Example

The WSCC three-machine nine-bus system shown in Figure 3 is adapted to demonstrate the existence of dynamic interactions among UPFC controllers. $UPFC_1$ and $UPFC_2$ are installed in transmission lines 6-7 and 4-9 respectively as shown. A three-phase fault is applied at bus 8 to simulate a transient disturbance. The fault is introduced at 0.02s and cleared after 100ms without a system configuration change. The main control tasks of the UPFC are to maintain the steady-state power flow, DC capacitor voltage, and provide voltage support.

Figures 4 through 6 show the dynamic performance of the system with two UPFCs installed. Figure 4 shows the generator frequencies. Figures 5 and 6 show the active and reactive power flows across their respective lines. All of these responses clearly indicate that an instability occurs, although the system is stable when each UPFC controller is independently installed. This is a clear example that shows the existence of the dynamic interactions between the UPFC controllers, which can lead to potential system instability.

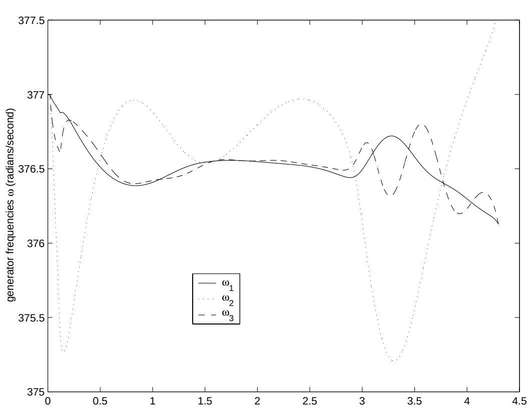

Figure 4: Generator frequencies

To pinpoint which portion of the PI controller is interacting negatively, the simulation of the two UPFC controls with the $UPFC_2$ series reactive power control **disabled** is shown as the dash-dot lines in Figure 7. The solid lines are the results with the $UPFC_2$ series reactive power control enabled. Figure 7 clearly indicates that it is the interaction of the reactive power controls that are causing the instability.

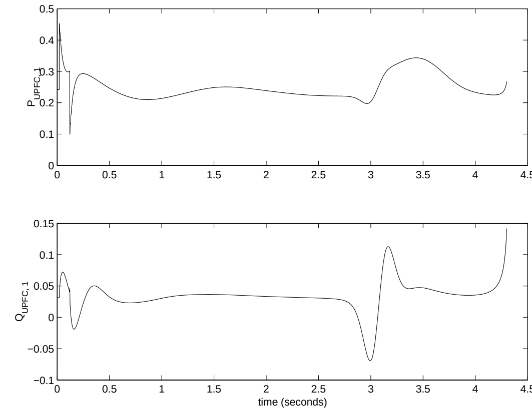

Figure 5: $UPFC_1$ installed in line 6-7

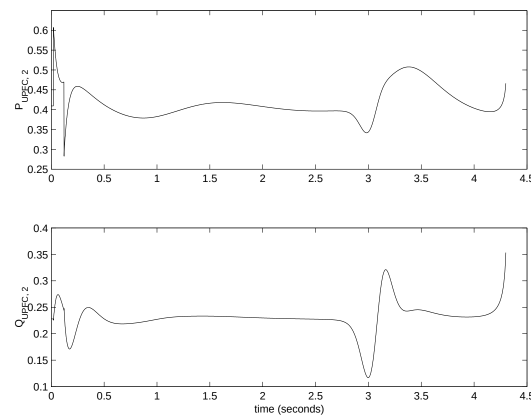

Figure 6: $UPFC_2$ installed in line 4-9

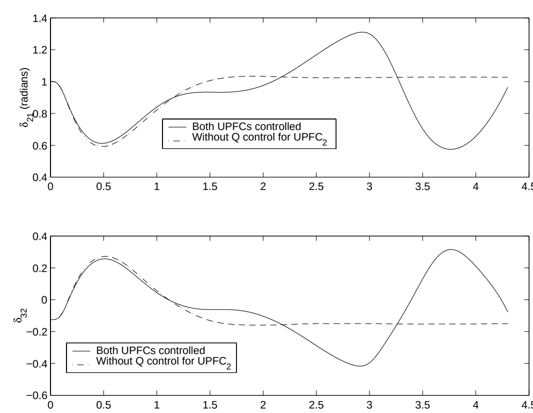

Figure 7: Comparison of the rotor angle differences with and without reactive power controls on $UPFC_2$

The IEEE 14 Bus System Example

This section presents another case study for control interaction analysis. $UPFC_1$ and $UPFC_2$ are installed in transmission line 6-16 and 2-17 respectively of the IEEE 14 bus system as shown in Figure 8. A three-phase fault of 100ms duration is simulated at bus 8.

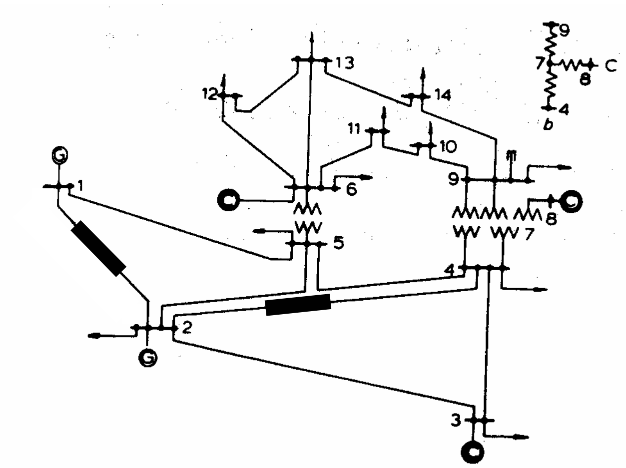

Figure 8: The IEEE five-machine 14-bus System

From Figures 9 and 10, it can be seen that the system exhibits high frequency interactions between these two UPFC controllers. As in the WSCC case, the system is again simulated with the reactive power portion of the $UPFC_2$ PI controller disabled. As before, when the controller is disabled, the interactions cease to exist.

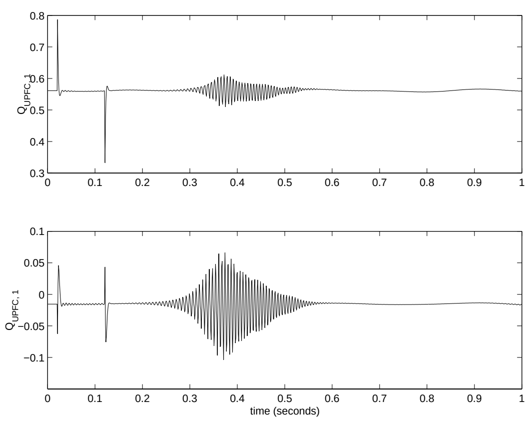

Figure 9: $UPFC_1$ installed in line 6-16

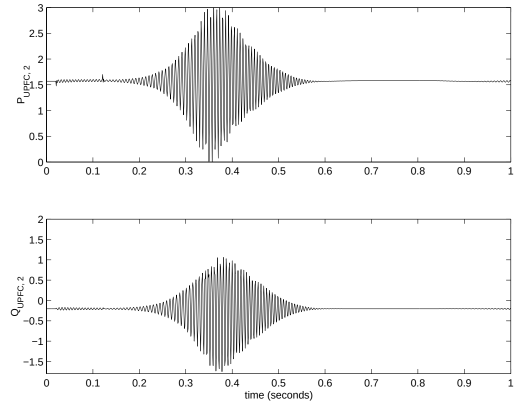

Figure 10: $UPFC_2$ installed in line 2-17

The case studies presented above demonstrate that there dynamic interactions do exist among UPFC controllers and that a purely linear PI control approach may not properly capture the complex dynamics of the system under large disturbances. To deal with the nonlinearity and uncertainty of the system, a nonlinear hybrid fuzzy logic controller with global signals will be developed in the next session to minimize the dynamic interactions.

IV. HYBRID FUZZY CONTROLLER DESIGN

A conventional PI controller uses an analytical expression of the following form to compute the control action:

$$u(t) = K_P \cdot e(t) + K_I \cdot \int e(t)dt .$$

The discrete-time and incremental form is written as

$$\Delta u(k) = K_P \cdot \Delta e(k) + K_I \cdot T \cdot e(k),$$

where

- $\Delta u(k)$ is the change of control output and we have that $\Delta u(k) = u(k) - u(k-1)$,
- $e(k)$ is the error and $e(k) = y_{sp} - y(k)$, where $y(k)$ is the system output and y_{sp} is the desired system output,
- $\Delta e(k)$ is change of error $\Delta e(k) = e(k) - e(k-1)$,
- k is the k-th sampling time and T is the sampling time.

The PI controller has a simple control structure and is easy to design by adjusting the two control parameters K_P and K_I to achieve acceptable performance. The main idea of the hybrid fuzzy controller is to use the fuzzy proportional (P) controller to improve the overshoot and rising time response and a conventional integral (I) controller to reduce the steady-state error [5]. Therefore, combining the advantages of a conventional PI controller and a nonlinear fuzzy logic control technique, this controller is constructed by replacing the proportional term in the conventional PI controller with an incremental fuzzy logic controller.

$$\Delta u(k) = u(k) - u(k-1) = K_P \cdot \Delta u_f(k) + K_I \cdot T \cdot e(k)$$

where $\Delta u_f(k)$ is the output of the incremental fuzzy logic controller. This control scheme is shown in Figure 12.

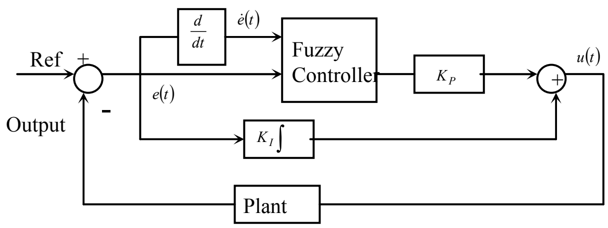

Fig.12 Hybrid Fuzzy control scheme

The main fuzzy logic control procedure is to fuzzify the controller inputs, then infer the proper fuzzy control decision based on defined rules and the fuzzy output is then produced by defuzzifying this inferred control decision.

A. Fuzzification and membership functions

The fuzzification will transfer the crisp control variables to corresponding fuzzy variables. It is common to use the output error and the derivative of the output as controller inputs. Therefore, the incremental fuzzy logic controller selects $e(k)$ and $\dot{e}(k)$ as its inputs in this paper.

Each of the fuzzy logic controller input and output signals is interpreted into a number of linguistic variables and each linguistic variable has its own fuzzy membership function. The membership function maps the crisp values into fuzzy variables. In this hybrid fuzzy controller, membership functions N (negative), Z (zero) and P (positive) assigned with linguistic variables are used to fuzzify the error and its derivative. Inputs $e(k)$ and $\dot{e}(k)$ fuzzify into $(e.n, e.z, e.p)$ and $(\dot{e}.n, \dot{e}.z, \dot{e}.p)$. For the output $\Delta u_f(k)$, $(o.n, o.z, o.p)$ are the fuzzy states. For simplicity, it is assumed that the membership functions are symmetrical and each one overlaps the adjacent functions by 50%. The membership functions for the inputs and the output are shown in Figure 13.

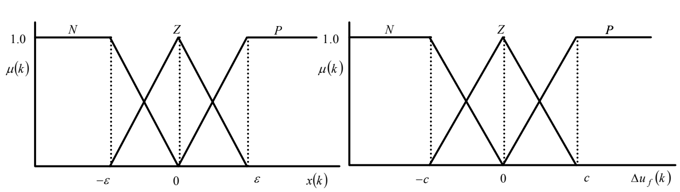

Figure 13: Membership functions for the hybrid fuzzy controller

The membership function of the positive set is

$$\mu_P(x) = \begin{cases} 0 & x < 0 \\ \dfrac{x}{\varepsilon} & 0 \le x \le \varepsilon \\ 1 & x > \varepsilon \end{cases}$$

where $x(k)$ represents the inputs to the fuzzy controller at the kth sampling instant.

The membership function of the negative set is

$$\mu_N(x) = \begin{cases} 1 & x < -\varepsilon \\ -\dfrac{x}{\varepsilon} & -\varepsilon \le x \le 0 \\ 0 & x > 0 \end{cases}.$$

And for the zero set the membership function used is

$$\mu_Z(x) = \begin{cases} 0 & x < -\varepsilon \\ \dfrac{x+\varepsilon}{\varepsilon} & -\varepsilon \le x \le 0 \\ \dfrac{\varepsilon - x}{\varepsilon} & 0 \le x \le \varepsilon \\ 0 & x > \varepsilon \end{cases}.$$

B. Rule base and inference

In general, fuzzy systems map input fuzzy sets to output fuzzy sets. Fuzzy rules are used to characterize the relationship between fuzzy inputs and fuzzy outputs. For a system of two control variables with three linguistic variables in each range, this leads to the following 3×3 rules:

R1: If $e(k)$ is *N* and $\dot{e}(k)$ is *P* then $\Delta u_f(k)$ is *Z*
R2: If $e(k)$ is *Z* and $\dot{e}(k)$ is *P* then $\Delta u_f(k)$ is *P*
R3: If $e(k)$ is *P* and $\dot{e}(k)$ is *P* then $\Delta u_f(k)$ is *P*
R4: If $e(k)$ is *N* and $\dot{e}(k)$ is *Z* then $\Delta u_f(k)$ is *N*
R5: If $e(k)$ is *Z* and $\dot{e}(k)$ is *Z* then $\Delta u_f(k)$ is *Z*
R6: If $e(k)$ is *P* and $\dot{e}(k)$ is *Z* then $\Delta u_f(k)$ is *P*
R7: If $e(k)$ is *N* and $\dot{e}(k)$ is *N* then $\Delta u_f(k)$ is *N*
R8: If $e(k)$ is *Z* and $\dot{e}(k)$ is *N* then $\Delta u_f(k)$ is *N*
R9: If $e(k)$ is *P* and $\dot{e}(k)$ is *N* then $\Delta u_f(k)$ is *Z*

Using the inference engine Max-Min and Zadeh's rules for AND, the activation of the i th rule consequence is a scalar value which equals the minimum of the two antecedent conjuncts' values. A defuzzification method is also required to transform fuzzy control activations into a crisp output value. For the incremental fuzzy logic controller, using center of mass defuzzification method the output $\Delta u_f(k)$ is

$$\Delta u_f(k) = {\sum_{j=1}^{9} \mu_j \cdot c_j(k)} \Big/ {\sum_{j=1}^{9} \mu_j}$$

where $c_j(k)$ is the value of control output corresponding to the membership value of input equal to unity.

C. A Hybrid Fuzzy Controller for UPFC

The conventional PI control approach for UPFC is divided into both shunt and series portions. The shunt PI controller to provide voltage support and maintain the constant DC capacitor voltage is given by:

$$\Delta E_{1q} = K_{vsP}\Delta V_1 + K_{vsI}\int_0^t \Delta V_1(\iota)d\iota$$

$$\Delta E_{1d} = K_{dcP}\Delta V_{dc} + K_{dcI}\int_0^t \Delta V_{dc}(\iota)d\iota$$

The series PI controller to regulate the series output active and reactive power is given by:

$$\Delta E_{2q} = K_{pP}\Delta P_2 + K_{pI}\int_0^t \Delta P_2(\iota)d\iota$$

$$\Delta E_{2d} = K_{qP}\Delta Q_2 + K_{qI}\int_0^t \Delta Q_2(\iota)d\iota$$

To construct the hybrid fuzzy logic controller, the proportional terms in the conventional PI controllers described above are replaced by the output variables of the incremental fuzzy logic controller. Since the series reactive power controller is responsible for the negative interaction in both case studies, the simple conventional PI controller remains for shunt voltage regulation and DC capacitor voltage maintenance. The hybrid fuzzy logic controller is applied for series active and reactive power control only. This reduces the complexity of the control.

D. Additional global signal inputs

The effectiveness in system dynamic stability is limited by using local signals for the controllers. Additional global signal inputs obtained remote from the controller make it possible to get improved performance. From the above case studies, the interactions among UPFC controllers can adversely influence the rotor damping of the generators, thus the difference in speed between two generators are applied as the global signals in this paper. Figure 9 shows the hybrid fuzzy logic control scheme with global signal inputs for the UPFC.

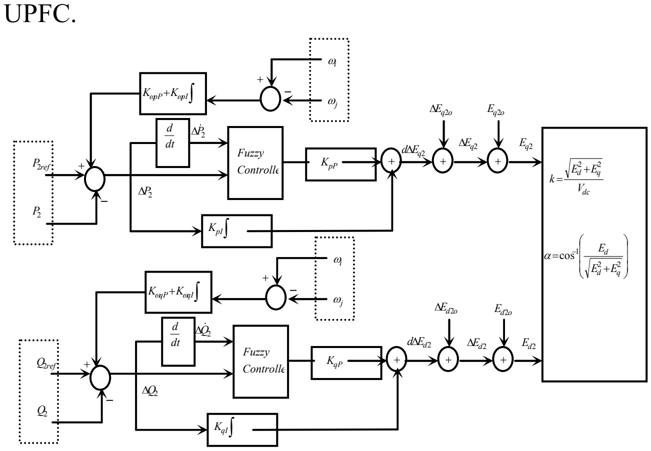

Figure 14: Hybrid Fuzzy Logic Controller with global signal inputs

V. SIMULATION VERIFICATION

The same example systems are used to evaluate the performance of the new hybrid fuzzy logic controller for UPFC in minimizing the dynamic control interactions.

The WSCC Test System

The same three-phase fault with 100ms duration is applied at bus 8 of WSCC three-machine nine-bus system with two UPFCs installed in lines 6-7 and 4-9 respectively.

The speed difference between generators 1and 2, and generators 2 and 3 are chosen to be the global control signal inputs. With the additional global signal inputs, the series hybrid fuzzy logic controller is rewritten as:

$$\Delta E_{2q} = K_{pP}\left(\Delta P_2 + \sum K_{\omega pPk}\left(\omega_i - \omega_j\right) + K_{wpIk}\int_0^t\left(\omega_i - \omega_j\right)\right)$$
$$+ K_{pI}\int_0^t\left(\Delta P_2 + \sum K_{\omega pPk}\left(\omega_i - \omega_j\right) + K_{wpIk}\int_0^t\left(\omega_i - \omega_j\right)\right)d\iota$$

$$\Delta E_{2d} = K_{qP}\left(\Delta Q_2 + \sum K_{\omega qPk}\left(\omega_i - \omega_j\right) + K_{wqk}\int_0^t\left(\omega_i - \omega_j\right)\right)$$
$$+ K_{qI}\int_0^t\left(\Delta Q_2 + \sum K_{\omega qPk}\left(\omega_i - \omega_j\right) + K_{wqk}\int_0^t\left(\omega_i - \omega_j\right)\right)d\iota$$

Figures 15 through 18 show the system dynamic performance comparison by using hybrid fuzzy logic controller with global signals inputs, hybrid fuzzy logic controller only and conventional PI controller respectively. Using a conventional PI controller, the dynamic control interactions occur between the UPFC controllers and lead to the system instability. The adverse interactions cannot be reduced even with the hybrid fuzzy logic controller and the system is still going unstable. By adding the additional global signal inputs, the hybrid fuzzy logic controller minimizes the dynamic interactions and the system returns to a stable state. Therefore, the combination of the hybrid fuzzy logic controller with the additional global signal inputs is the most efficient approach to eliminate the control interactions.

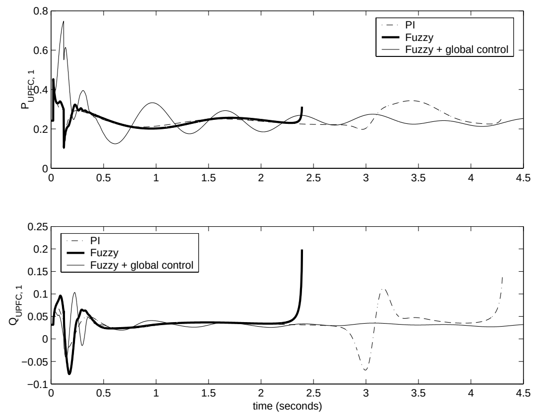

Figure 15: $UPFC_1$ active and reactive power responses

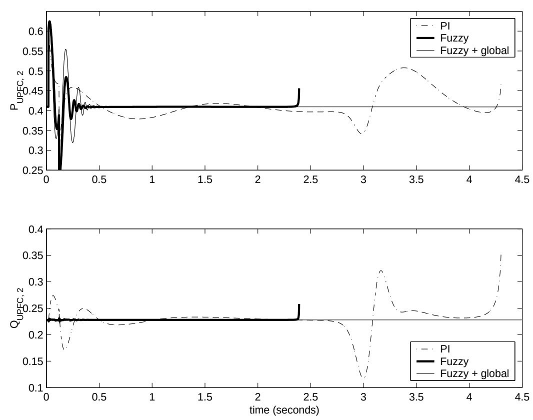

Figure 16: $UPFC_2$ active and reactive power responses

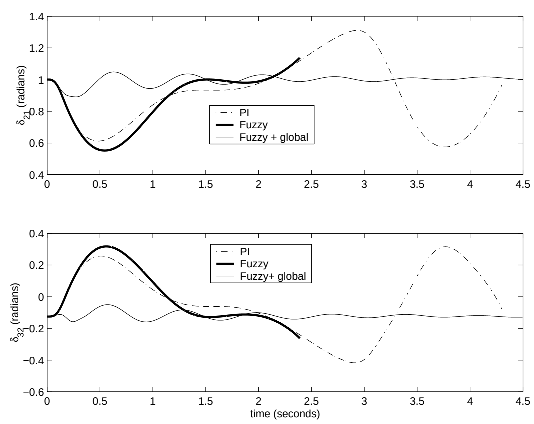

Figure 17: Generator angle differences

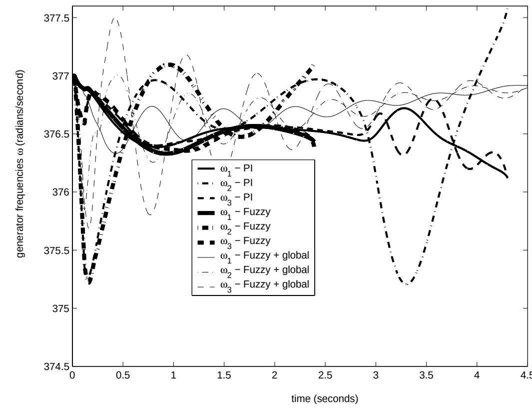

Figure 18: Generator frequencies

The IEEE 14 bus test system

To validate the robustness of the hybrid fuzzy logic controller with global signal inputs, the IEEE five-machine 14-bus system is used with $UPFC_1$ and $UPFC_2$ installed in lines 6-16 and 2-17 respectively. The same three-phase fault of 100ms duration is simulated at bus 8. The results of the global hybrid fuzzy control are shown together with the conventional PI control results in Figure 19 and 20. In this case it can also demonstrate that the new global hybrid fuzzy control approach has a satisfactory performance on the elimination of control interactions.

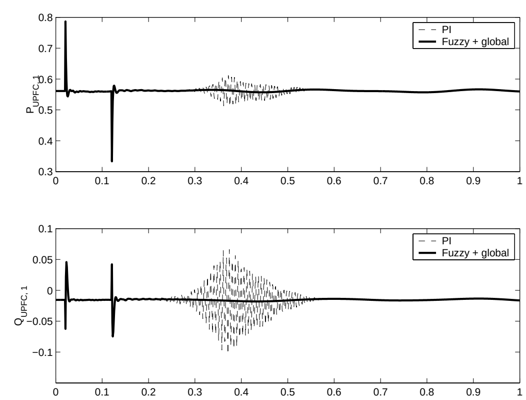

Figure 19: $UPFC_1$ active and reactive power responses

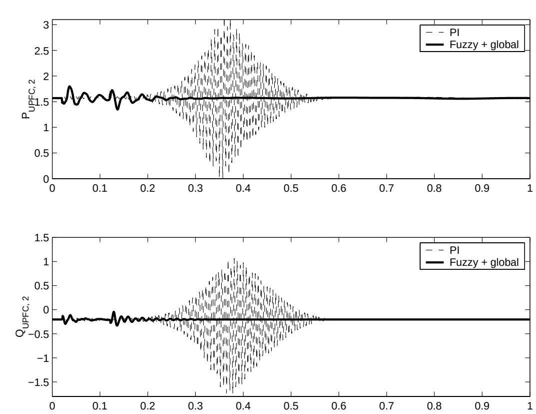

Figure 20: $UPFC_2$ active and reactive power responses

VI. CONCLUSIONS

This paper investigates the existence of dynamic interactions between multiple UPFC controllers. Due to the interactions, the joint operation of the UPFC controllers can result in poor control performance and even a closed-loop system instability. Therefore, a new hybrid fuzzy logic control is presented for UPFC to reduce the dynamic control interactions. The structure of the fuzzy controller is very simple since it only replaces the proportional term of the conventional PI controller in an incremental fuzzy logic controller and remains the conventional integral term. This paper also shows the improved dynamic system stability performance that is achieved by adding additional global control signals to the hybrid fuzzy controller.

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