An Indirect Adaptive Fuzzy Power System Stabilizer for a Multi-machine Power System

T. Hussein, A. L. Elshafei, A. Bahgat
Electrical Power and Machines Department
Cairo University
Gama Street, Giza
EGYPT

Abstract: - An indirect adaptive fuzzy power system stabilizer (IDFPSS) is proposed in this paper. It consists of A fuzzy identifier and a feedback linearizing controller. The objective is to damp local and inter-area oscillations that occur following power system disturbance. The effectiveness of the proposed technique is illustrated by applying the IDFPSS to a two-area four-machine system that is typically used in the literature to test the performance of power system stabilizers. A comparison between the proposed IDFPSS and a well-tuned conventional power system stabilizer (CPSS) confirms the superiority of the IDFPSS.

Kew Words: - Fuzzy logic control, Adaptive control, Nonlinear identification, Power system stabilizer.

1. Introduction

Power systems are strongly nonlinear and often have low frequency oscillations, especially in weakly line coupling [1]. To overcome this problem, a power system stabilizer is introduced as supplementary controller to the excitation system to damp this oscillation and to improve power system stability. In many power systems a conventional power system stabilizer is used. The conventional PSS [2] consists of cascade lead-lag compensators that have fixed parameters. They are derived from transfer function and designed at one operating condition. Therefore a CPSS does not provide satisfactory results for a wide range of operating condition.

Due to the nonlinear characteristics, uncertainty in the parameters, wide range of operating conditions, lines switching and unpredictable disturbances in power system, the conventional control with fixed parameters is not given satisfactory results under all operating conditions.

Adaptive control can tune the controller parameters on-line when the power system changes in characteristics or in operating conditions. Therefore adaptive control is expected to give good quality of performance under a wide range of operating conditions.

Adaptive power system stabilizers based on artificial neural networks and fuzzy logic [3-4-5] have been developed to overcome the drawbacks of CPSS.

Unlike classical control design, which requires a plant model for designing the controller, fuzzy logic allows one to design a controller with unknown mathematically model of the dynamic system.

An adaptive power system stabilizer using on-line self learning fuzzy systems is proposed in [6] consisting of an on-line identified plant model to obtain a dynamic equivalent model for the synchronous machine and self-learning fuzzy logic controller. The self learning ability of the fuzzy controller is based on the steepest descent algorithm. An online adaptive neuro-fuzzy power system stabilizer for multimachine systems is derived in [7]. The system is divided into two subsystems, a recursive least square identifier with a variable forgetting factor for the generator and a fuzzy logic based adaptive controller to damping oscillations. Adaptive neural network based power system stabilizer design is suggested in [8]. The author present an indirect adaptive neural network (IDNC) design. The IDNC consists of a neuro-controller to generate a supplementary control signal to the excitation system and a neuro-identifier which is used to model the dynamic of the power system and to adapt the neuro-controller parameters. An artificial intelligence technique applied to adaptive power system stabilizer design [9] gives a number of examples of development and successful implementation of adaptive PSSs based on AI techniques.

The above algorithms rely on the pioneering work of Wang [10] used the Fuzzy Basis Function (FBF) as universal approximator, and proved that the fuzzy identifiers are capable of following the output of a very general nonlinear dynamic system to arbitrary accuracy in any finite time interval.

In this paper, an indirect adaptive fuzzy power system stabilizer is developed. It uses the actual speed and the actual speed deviation as inputs to the fuzzy identifier (obtained online and assumed to be measured from the output of the plant). The output of the fuzzy identifier is the estimates of the unknown nonlinearities of the model. These are used in a feedback linearization algorithm to provide the necessary damping in the power system. The paper organized as follow. Section 2 explains the concepts of the identification algorithm. Section 3 introduce the proposed adaptive control. Sections 4 and 5 give the multimachine system which used in the simulations study. The conclusion of our work is depicted in Section 6.

2. Basic Concepts and Identification Algorithm

Consider the nonlinear system

$$y^r = f(\underline{x}) + g(\underline{x})u \qquad (1)$$

Where f and g are unknown nonlinear function, and suppose that, $g(\underline{x}) \neq 0$ for all value of $\underline{x}$ and must be bounded in the compact set. We need to develop an adaptive law to adjust the free parameters of the fuzzy identifier for the purpose of making the output value y follow the desired output y_m.

From the nonlinear system (1), the control law can be selected as

$$u = \frac{1}{\hat{g}(\underline{x}/\underline{\theta}_g)}\left[-\hat{f}(\underline{x}/\underline{\theta}_f) + y_m^r + \underline{k}^r\,\underline{e}_1\right] \qquad (2)$$

Where

$\underline{e}_1 = [e_1, \dot{e}_1, \ldots, e_1^{(r-1)}]^T \quad = y_m - y$

and $\underline{k} = [k_r, \ldots, k_1]^T$ is such that roots of $s^r + k_1 s^{r-1} + \cdots + k_r = 0$ are stable, $\underline{\theta}_f$ and $\underline{\theta}_g$ are free parameters to be adjusted by the fuzzy identifier.

The goal of this paper is to design an indirect adaptive power system stabilizer based on the actual speed and the deviation of the actual speed measurement such that all variable in the closed loop system are bounded and the output y follow the desired output y_m.

The control law (2) is feedback linearization controller.

First we need to develop an identification model where the f and g are replaced by $\hat{f}(\underline{x}/\underline{\theta}_f)$ and $\hat{g}(\underline{x}/\underline{\theta}_g)$ and the adaptation law to updating parameters $\underline{\theta}_f$ and $\underline{\theta}_g$. The notation $\hat{f}(\underline{x}/\underline{\theta}_f)$ means the estimate of f give measurements of $\underline{x}$ and estimate $\underline{\theta}_f$.

We use the series-parallel identification model [10].

$$\dot{\underline{\hat{x}}} = -\alpha\underline{\hat{x}} + \alpha\underline{x} + \hat{f}(\underline{x}/\underline{\theta}_f) + \hat{g}(\underline{x}/\underline{\theta}_g)u \qquad (3)$$

where α is a positive scalar that determine the error between the actual and it is estimation value and it is designer selected. The goals of identification are following:

Identify the $\hat{f}(\underline{x}/\underline{\theta}_f)$ and $\hat{g}(\underline{x}/\underline{\theta}_g)$ using the fuzzy basis function (FBF) and the adaptive law for the parameters $\underline{\theta}_f$ and $\underline{\theta}_g$. The signals in the identification model must be bounded. The error between the actual output and it is estimation must be as small as possible.

Choose $\hat{f}(\underline{x}/\underline{\theta}_f)$ and $\hat{g}(\underline{x}/\underline{\theta}_g)$

to be fuzzy system characterized by singleton fuzzifier, the center average defuzzification, the product inference and Gaussian membership function. From [10],[11] we have:

$$\hat{f}(\underline{x}/\underline{\theta}_f) = \underline{\theta}_f{}^T\,\underline{p}(\underline{x}) \qquad (4)$$

$$\hat{g}(\underline{x}/\underline{\theta}_g) = \underline{\theta}_g{}^T\,\underline{p}(\underline{x}) \qquad (5)$$

where

$$p_k(\underline{x}) = \frac{\prod_{i=1}^{n} \mu_{F_i^{ji}}(x_i)}{\sum_{j1}^{m1} \cdots \sum_{jn=1}^{mn} \prod_{i=1}^{n} \mu_{F_I^{JI}}(x_i)} \qquad (6)$$

and it is called Fuzzy Basis Function (FBF). $\mu_{F_i^{ji}}(x_i)$ is the membership function assigned to the j^{th} linguistic variable in the i^{th} rule.

Collect the $p_k(\underline{x})$ into vector $\underline{p}(\underline{x})$, θ_{if} and θ_{ig} into vector $\underline{\theta}_{if}$ and vector $\underline{\theta}_{ig}$ and with the same order of $\underline{p}(\underline{x})$.

The error $\underline{e}_2 = \underline{x} - \hat{\underline{x}}$. According to [10],[11] the unknown parameters can updated by

$$\dot{\underline{\theta}}_f = \Gamma_f \, \underline{e}_2^{\,T} \, \underline{p}(\underline{x}) \qquad (7)$$

$$\dot{\underline{\theta}}_g = \Gamma_g \, \underline{e}_2 \, \underline{p}(\underline{x}) u \qquad (8)$$

where Γ_f and Γ_g are diagonal matrices.

3. IDFPSS Design

The procedure for designing the indirect adaptive fuzzy power system stabilizer is as follows

a) Let $x_1 = \omega =$ actual speed

$x_2 = \Delta\omega =$ actual speed deviation

then the state input vector to the fuzzy basis function (FBF) will be

$$\underline{x} = [\omega \quad \Delta\omega]$$

b) Develop fuzzy basis function rule base with two inputs $\omega \; and \; \Delta\omega$ and one output. Set the initial value of θ as initial fuzzy rule base (selected by the designer experience). Apply the adaptation law (7), (8) to compute $\dot{\theta}_f \; and \; \dot{\theta}_g$ online and apply the results to (4) and (5) to identify the unknown nonlinear functions $f(\underline{x}) \quad and \quad g(\underline{x})$.

c) Select $k_1 \quad and \quad k_2$ that make the system stable and the error $e_1 = y_m - y$ as small as possible. Use the identified functions $\hat{f}(\underline{x}/\underline{\theta}_f)$ and $\hat{g}(\underline{x}/\underline{\theta}_g)$ to compute the control law in (2) and apply this control law as power system stabilizer to the synchronous machine to damping the oscillations and improving power system stability.

The inputs states $[\omega \quad \Delta\omega]$ are represented by seven Gaussian membership function as shown in Fig. 1 and Fig. 2, and the range of the membership functions are selected based on simulations with different faults at many operating conditions. The initial conditions for θ are chosen by the designer experience as 49 rule base.

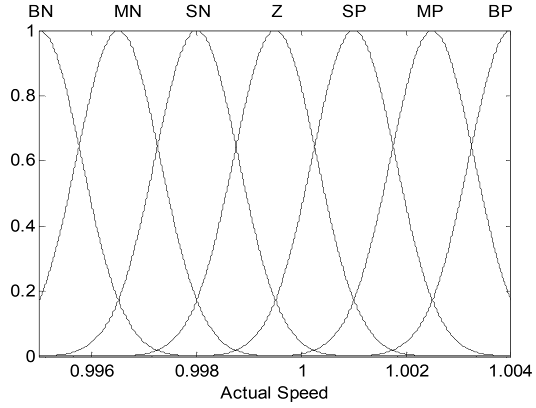


Fig. 1 Membership function for input 1

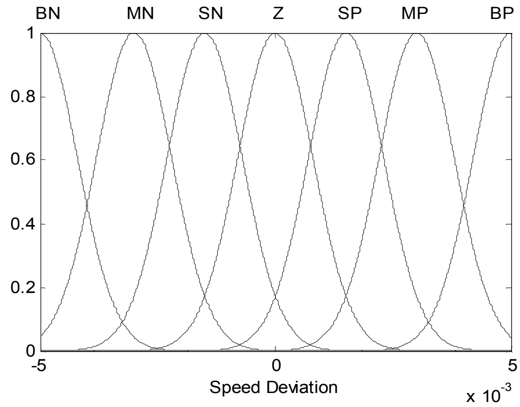


Fig. 1 Membership function for input 2

4. The Four-Machine Two-Area System

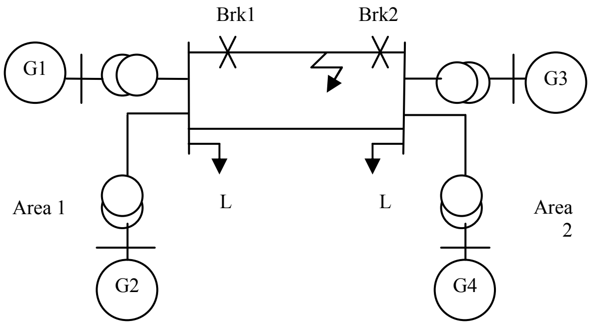
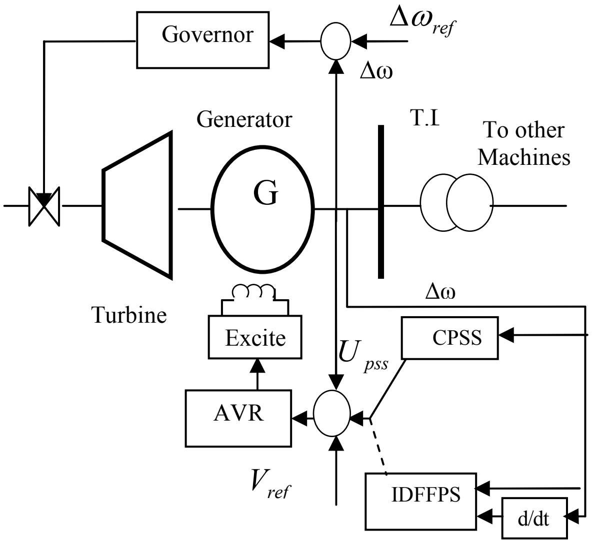


Fig. 3 The multi machine power system configuration

Fig. 3 shows the multimachine system which is used in simulation studies. The test system present in [12] consists of two fully symmetrical areas linked together by two 230 KV lines of 220 Km length. It was specifically designed in [12] to study low frequency electromechanical oscillations in large interconnected power systems. Despite its small size, it mimics very closely the behavior of a typical system in actual operation. Each area is equipped with two identical round rotor generators rated 20 KV/900 MVA. The synchronous machines have identical parameters [12] except for the inertias which are H = 6.5s in area 1 and H is = 6.175s in area 2.

Thermal plants having identical speed regulators are further assumed at all locations, in addition to fast static exciter with a 200 gain. The load is represented as constant impedance and spilt between the areas.

5. Simulation Study



Fig, 4 power system model used in study

The performance of the IDFPSS was evaluated by applying a large disturbance caused by three-phase to ground fault applied at the middle of one tie line at 0.5 sec. and cleared after 0.133 sec by opening the two breakers at two ends of the line fault to isolate it. With one tie-line the system can reach a stable operating point in steady state with good quality of performance. A schematic diagram representation of one generator is shown in Fig. 4, the other three generators are equipped as generator 1.

For comparison purpose, the system is configured to switch between different controls techniques, In order to show the performance improvement of the proposed IDFPSS over CPSS. The optimality is checked by the performance index

$$J_p = \sum \Delta\omega^2 \qquad (9)$$

A conventional power system stabilizer CPSS model that used in comparison with the IDFPSS is represented by the transfer function.

$$G\,(\mathrm{S}) = K\left(\frac{sT_W}{1+sT_W}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right) \qquad (10)$$

Where T_1 *to* T_4 are the controller time constants and T_W is that of a washout filter time constant. CPSS consists of cascade a lag-lead controller with a high pass filter that prevents steady change in speed from modifying the field voltage. The value of the washout time constant T_W should be high enough to allow signals associated with oscillations in rotor speed to pass unchanged. A high value of K_{STAB} is desirable from the viewpoint of transient stability.

For the plant with two types, i.e CPSS and IDFPSS, the actual speed response for various operating conditions have been investigated for all four generators, for brevity only two cases are shown here.

Operating Point 1 (op1)

$P_1 = 0.962pu$ $Q_1 = 0.17pu$
$P_2 = 0.59pu$ $Q_2 = 0.15pu$
$P_3 = 0.8pu$ $Q_3 = 0.1pu$
$P_4 = 0.78pu$ $Q_4 = 0.01pu$

Where P *is the electrical power and* Q *is the reactive power.*

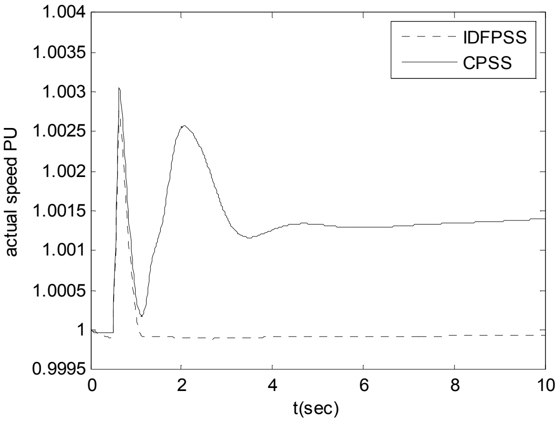


Fig. 5 actual speed for GEN1 op1

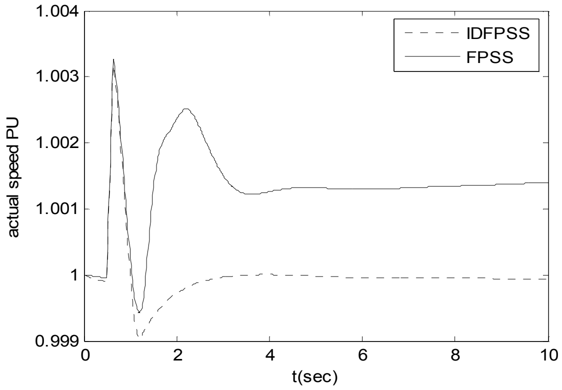


Fig. 6 actual speed for GEN2 op1

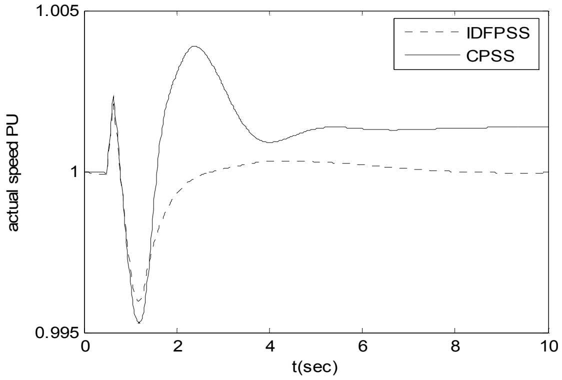


Fig. 7 actual speed for GEN3 op1

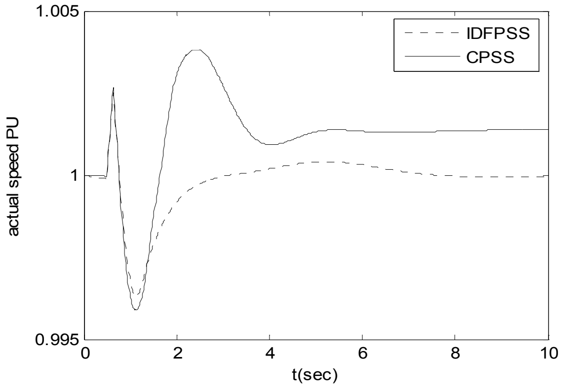


Fig. 8 actual speed for GEN4 op1

Table 1: comparing the performance index op1.

Operating Condition 1	J_p	
	CPSS	IDFPSS
Gen. 1	200	13
Gen. 2	210	23
Gen. 3	360	85
Gen. 4	340	80

Operating Condition (op2)

$P_1 = 0.56pu \qquad Q_1 = 0.0124pu$

$P_2 = 0.93pu \qquad Q_2 = 0.034pu$

$P_3 = 0.56pu \qquad Q_3 = -0.04pu$

$P_4 = 0.61pu \qquad Q_4 = -0.13pu$

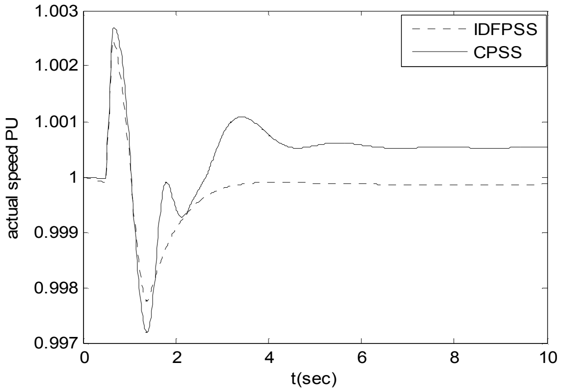


Fig. 9 actual speed for GEN1 op2

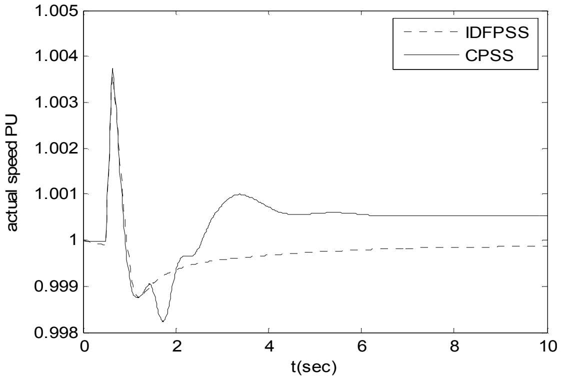


Fig. 10 actual speed for GEN2 op2

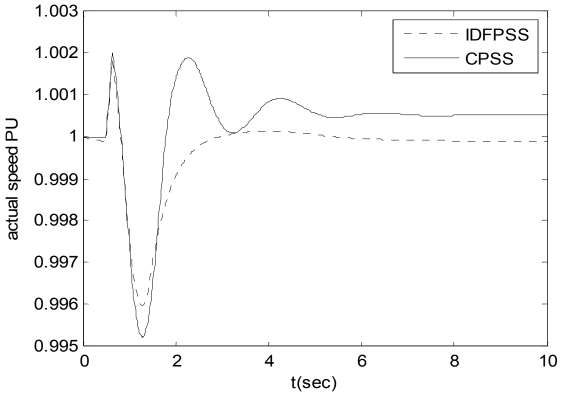


Fig. 11 actual speed for GEN3 op2

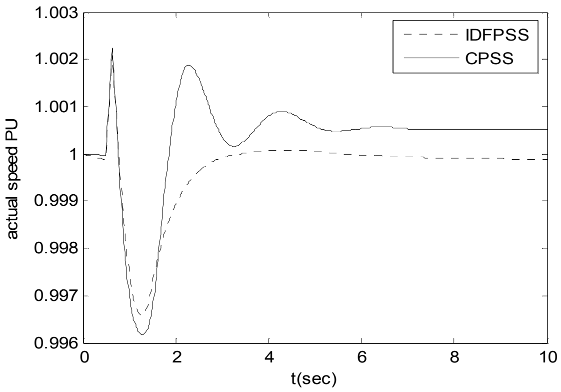


Fig. 12 actual speed for GEN4 op2

Table 2: comparing the performance index

Operating condition 2	J_p	
	CPSS	IDFPSS
Gen. 1	75	42
Gen. 2	65	35
Gen. 3	154	90
Gen. 4	134	79

As shown in the all figures for two operating conditions the one noted that, the damping stability is greatly improvement when used IDFPSS than used CPSS, the steady state error is obvious when CPSS used, this steady state error is decreased when IDFPPS is used and the IDFPSS is less sensitive to change in operating condition than CPSS, the settling time is also less in proposed controller than in conventional.

6. Conclusion

An indirect adaptive fuzzy power system stabilizer is proposed. It consists of nonlinear identifier and a feedback linearizing controller. The fuzzy system has the speed and its derivative as input. Its rule base consists of 49 rules. The identifier tunes the rule consequents on-line.

Comparing the proposed stabilizer to the conventional one, simulation results based on a typical four-machine two-area system have confirmed that the proposed stabilizer has been superior. The proposed stabilizer can cope with large disturbance and has an enhanced capability in damping small disturbance oscillations.

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