Design of Variable Structure Fuzzy Power System Stabilizer in Multi-machine System

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Abstract- This paper introduces adaptive variable structure fuzzy controller as a power system stabilizer (AFPSS) used to damp inter-area modes of oscillation following large disturbances in power systems. In contrast to the conventional PSS, fuzzy-based stabilizers are more efficient because they cope with oscillations at different operating points. The proposed controller is a fuzzy-logic-based PSS that has the capability to tune its rule-base on line. The change in the fuzzy rule base is done using a variable-structure algorithm to achieve optimum performance. The adaptive algorithm of the proposed controller significantly reduces the rule base size due to its adaptively and improves its performance. This statement is confirmed by simulation results of a three-machine infinite-bus system under different operating points.

Keywords: Fuzzy Logic Control, Adaptive Control, Power system stabilizer

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1. Introduction

Power system stability is defined as the ability of the system to remain in its equilibrium point that following small and large disturbances. Power system are becoming increasingly stressed because of growing demand and restrictions on building new power plants and lines. One of the consequences of such a stressed system is the threat of losing stability following a disturbance due to poor power system stabilizer (PSS). So, the increasing of power transfer capability and improvement power system stability is necessary to enhancement [1].

Power systems are hardly nonlinear systems that often have low frequency oscillations due to poor damping caused by wide range of operating conditions which can lead to loss of synchronism and cascade blackout [1]. Conventional Power system stabilizers (CPSS) can provide supplementary control signal to excitation system to damp these oscillations [1−4]. The tune of the fixed parameters of these conventional stabilizers are usually based on the linearized model of the power system around a small range of operating points. Operating conditions change as load variations and wide of power generations. These wide range of operating conditions affect power system dynamic behavior which requires fine-designed and tuned PSS [1-4].

Adaptive controller can tune its parameters on-line when the power system changes its operating conditions, line switching and unpredictable fault location in power system. Therefore, adaptive controller is expected to give good quality of performance under a hardly nonlinearity of power system [5-6].

Unlike (CPSS), which requires a linear plant model for its designing, fuzzy logic controller

(FLC) allows to design a controller with unknown or unprecise mathematically model of the nonlinear power system.

This paper proposes adaptive fuzzy-logic PSS (AFPSS) that grasps the advantages of adaptive of nonlinear fuzzy-logic techniques and overcomes FLC drawbacks. The introduced stabilizer is initialized using the rule-base of a standard FLPSS to guarantee an appropriate performance during the learning step. The rule-base is tuned in real time so that the stabilizer can fit to wide range operating conditions. The adaptive feature of the introduced stabilizer results in a satisfactory performance using a significantly small rule base due to its tuned parameters as compared to the standard FLPSS.

2. Adaptive Variable Structure FLPSS:

For singleton fuzzifier, , center average defuzzifier, product inference, and Gaussian membership function, it is easy to shown that [8]

$$v = f(\underline{x}) = \frac{\sum_{l=1}^{M} \theta_i \prod_{i=1}^{p} \mu_{F_i^l}(x_i)}{\sum_{l=1}^{M} \prod_{i=1}^{p} \mu_{F_i^l}(x_i)} \qquad (1)$$

Where M is the number of rules in the FLS and p is the number of inputs to the FLS. θ_l is the centroids of membership functions of the output corresponding to the M rules. Equation (1) can be expressed as

$$v = f(\underline{x}) = \sum_{i=1}^{M} \theta_i \, p_i(\underline{x}) \qquad (2)$$

where $p_i(\underline{x})$ are called fuzzy basis function (FBF) [8] and are given by

$$p_i(\underline{x}) = \frac{\prod_{i=1}^{p} \mu_{F_i^l}(x_i)}{\sum_{l=1}^{M} \prod_{i=1}^{p} \mu_{F_i^l}(x_i)} \qquad (3)$$

Now the FLS can be referred to as a FBF expansion

Consider the nonlinear system

$$y^{(n)} = f(\underline{x}) + bu \qquad (4)$$

Where $f(\cdot)$ is unknown real continuous nonlinear function and b is an unknown constant.

$u \in R$ and $y \in R$ are the input and the output of the system, respectively. $\underline{x} = \left(x, \dot{x}, \ldots, x^{(n-1)}\right)^T \in R^n$ is the system state vector, and $y^{(r)}$ is the rth derivative of y.

The output y is required to follow a reference signal y_m which is selected such that it is derivatives up to the *n*th order exit. Define the tracking error as

$$e = y_m - y, \quad \dot{e} = \dot{y}_m - \dot{y}, \quad e^{(n)} = y_m^{(n)} - y^{(n)}, \qquad (5)$$

Hence, the tracking error state vector, $\underline{e}$, can be selected as

$$\underline{e} = \begin{bmatrix} e & \dot{e} & \cdots & e^{(n-1)} \end{bmatrix}^T$$

If $f(\underline{x})$ *and* b were known, we would choose the feedback control law as

$$u = \frac{1}{b}\left[- f(\underline{x}) + y_m^n + \underline{k}^T \underline{e}\right] \qquad (6)$$

where the design vector $\underline{k}$ is given by $\underline{k}^T = \begin{bmatrix} k_n & k_{n-1} & \cdots & k_1 \end{bmatrix}$. Substituting (6) into (4) leads to

$$y^{(n)} = y_m^{(n)} + \underline{k}^T \underline{e} \qquad (7)$$

Noting the above definition of the tracking error in (5), $\underline{e}$, it is possible to rewrite (7) as

$$e^{(n)} + \underline{k}^T \underline{e} = e^{(n)} + k_1 e^{(n-1)} + \cdots + k_n e = 0 \quad (8)$$

The characteristic equation of the error model (3.8) is

$$s^n + k_1 s^{n-1} + \cdots + k_n = 0 \quad (9)$$

The design parameters $k_1, k_2, \cdots, k_n$ are selected such that the roots of (9) are in the left-hand side of the s-plane to ensure stability. Since $f(\underline{x})$ *and* b are unknown, the control law (3.6) cannot be implemented. Based on the universal approximation theorem [8,9], there is a fuzzy system that can approximate u; i.e. it is possible to write

$$u \approx \underline{\theta}^T \underline{p}(\underline{x}) \quad (10)$$

$\underline{\hat{\theta}}$ is the vector estimated of centeroids of the membership functions assigned to u and $\underline{p}(\underline{x})$ is the vector of fuzzy basis functions. The control law (10) is implemented based on an estimate value $\underline{\hat{\theta}}$ of the true values $\underline{\theta}$. Hence, we can write

$$u = u_c(\underline{\theta}, \underline{x}) = \underline{\hat{\theta}}^T \underline{p}(\underline{x}) \quad (11)$$

Substituting $u_c(\underline{\theta}, \underline{x})$ in (4) leads to

$$y^{(n)} = f(\underline{x}) + b u_c(\underline{\theta}, \underline{x}) \quad (12)$$

Adding and subtracting bu to (3.12) result in

$$y^{(n)} = f(\underline{x}) + bu + b(u_c(\underline{\theta}, \underline{x}) - u) \quad (13)$$

Similar to the derivative of (7), it is possible to show that the error model corresponding to the closed loop system (13) is

$$e^{(n)} = -\underline{k}^T \underline{e} + b(u - u_c(\underline{\theta}, \underline{x})) \quad (14)$$

Eq. (14) can be put in the controllable canonical form by choosing

$$\dot{e}_1 = \dot{e} = e_2,$$

$$\dot{e}_2 = \ddot{e} = e_3,$$

$$\vdots$$

$$\dot{e}_{n-1} = e^{(n-1)} = e_n$$

$$\dot{e}_n = e^{(n)} = -\underline{k}^T \underline{e} + b(u - u_c(\underline{\theta}, \underline{x})) \quad (15)$$

So, the state space model takes the form

$$\underline{\dot{e}} = A_c \underline{e} + \underline{b}_c (u - u_c(\underline{\theta}, \underline{x})) \quad (16)$$

where

$$A_c = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ 0 & 0 & \cdots & 0 & 1 \\ -k_n & -k_{n-1} & \cdots & -k_2 & -k_1 \end{bmatrix},$$

$$\underline{b}_c = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ b \end{bmatrix}$$

The design parameters $k_1, k_2, \cdots, k_n$ are selected such that the eigenvalues of A_c are located in a pre-specified region of the left-hand side of the s-plane.

The estimate value $\underline{\hat{\theta}}$ is typically based on the second method of Lyapunov to ensure the stability of the adaptive system. To illustrate that, consider the following Lyapunov function.

$$V = \frac{1}{2}\underline{e}^T P\underline{e} + \frac{b}{2}\underline{\phi}^T \Gamma^{-1}\underline{\phi} \tag{17}$$

where P *and* Γ are positive definite matrixes and $\phi = \underline{\theta} - \underline{\hat{\theta}}$ is the estimation error. The calculations of P *and* $\underline{\phi}$ are shown below. The designer normally picks up the matrix Γ as diagonal matrix that determine the adaptation rate as shown below. The time derivative of V is

$$\dot{V} = \frac{1}{2}(\underline{e}^T P\underline{\dot{e}} + \underline{\dot{e}}^T P\underline{e}) + b\underline{\phi}^T \Gamma^{-1}\underline{\dot{\phi}} \tag{18}$$

Substituting for $\underline{\dot{e}}$ from (3.16) into (3.18) leads to

$$\dot{V} = \frac{1}{2}(\underline{e}^T PA_c\underline{e} + \underline{e}^T P\underline{b}_c\underline{\varphi}^T\underline{p}(\underline{x}) + \underline{e}^T A_c^T P\underline{e} + \underline{b}^T P\underline{e}\underline{\varphi}^T\underline{p}(\underline{x})) + b\underline{\varphi}^T\Gamma^{-1}\underline{\dot{\varphi}} \tag{19}$$

Eq. (3.19) can be simplified to

$$\dot{V} = \frac{1}{2}\underline{e}^T(PA_c + A_c^T P)\underline{e} + \underline{\phi}^T\,\underline{p}(\underline{x})\underline{b}_c^T P\underline{e} + b\underline{\phi}^T\Gamma^{-1}\underline{\dot{\phi}}$$
(20)

The closed loop system (3.16) is stable if $\dot{V}$ is negative semi-definite. Since A_c has stable eigenvalues, it is true that P is the solution of the algebraic Lyapunov equation

$$PA_c + A_c^T P = -Q \tag{21}$$

where Q is a positive semi-definite matrix that is arbitrarily chosen by the designer. Select the adaptation law as [10, 11]

$$\underline{\dot{\phi}} = -\frac{1}{b}\underline{b}_c^T P_n\underline{e}\Gamma\underline{p}(\underline{x}) \tag{21}$$

Where P_n is the second column of the matrix P.

Hence, it is possible to rewrite (19) as

$$\dot{V} = -\frac{1}{2}\underline{e}^T Qe \tag{22}$$

Eq. (22) clearly shows that the closed-loop system (16) is stable if the adaptation law (21) is employed. To implement (16) and calculate $\underline{\hat{\theta}}$, we assume that the variation of $\underline{\theta}$ is much slower than of $\underline{\hat{\theta}}$ i.e. $\underline{\theta}$ is locally constant [61]. The estimate value $\underline{\hat{\theta}}$ is given by

$$\underline{\dot{\hat{\theta}}} = \frac{1}{b}\underline{b}_c^T P_n\underline{e}\Gamma\underline{p}(\underline{x}) \tag{23}$$

From 23 we have

$$\underline{\dot{\hat{\theta}}} = \frac{1}{b}\underline{b}_c^T P_n\underline{e}\Gamma\underline{p}(\underline{x})$$

The equivalent sigma-modification law is [11]

$$\mu\dot{\theta}_i = \Gamma_i\underline{e}^T\,\underline{p}_n\zeta_i(\underline{x}) - \sigma(\theta_i - \theta_i(0)) \tag{24}$$

The constants μ, Γ_i and σ are design parameters. $\theta_i(0)$ is the initial estimate of θ_i. By selecting $\sigma = 1, \mu \to 0$, and $\Gamma_i = \bar{\theta}_i / \left\|\underline{e}^T\,\underline{p}_n\right\|\zeta_i(x)$, we can rewrite (24) as

$$\theta_i = \bar{\theta}_i\,\mathrm{sgn}(\underline{e}^T\,\underline{p}_n) + \theta_i(0) \tag{25}$$

Where $\bar{\theta}_i$ is a constant set by the designer to specify the possible range of variation of θ_i around $\theta_i(0)$. A smaller $\bar{\theta}_i$ reflect more confidence in the corresponding initial value $\theta_i(0)$. To chattering and ensure smooth variation of θ_i, it is common to replace the sgn(.) function in (25) by the *sat*(.) function. Hence, the estimater is implemented as

$$\theta_i = \bar{\theta}_i\; sat(\underline{e}^T\,\underline{p}_n) + \theta_i(0) \tag{26}$$

The estimates obtained by (25) are used to calculate U_{pss}

Where

$$u = u_c(\underline{\theta}, \underline{x}) = \underline{\hat{\theta}}^T \underline{p}(\underline{x}) \qquad (27)$$

3. Design Procedure Of a Direct Variable-Structure Adaptive Fuzzy PSS

1. Let $x_1 = \Delta\omega$ (speed deviation), $x_2 = \Delta\dot{\omega}$ (speed deviation derivative) be the inputs to the fuzzy basis function (FBF), i.e $\underline{x} = [x_1 \quad x_2]^T = [\Delta\omega \quad \Delta\dot{\omega}]^T$. It is reasonable to choose the generator speed deviation $\Delta\omega$ and its derivative $\Delta\dot{\omega}$ as input signals to the PSS controller, because the aimed is to damping the oscillation of generator speed (system frequency) to zero [11]. Each input is assigned three fuzzy membership functions $N, Z, and\ P$ that stand for the linguistic values negative, Zero, and positive, respectively. Fig. 1 shows the membership functions $N, Z, and\ P$. The membership functions are triangles and equally distributed, the author test unequally distributed membership functions and concentrated within a certain interval as describe in [11], but the author found equally distributed is more effect in our controller specially with triangle shapes. The ranges of membership functions are chosen according to what is expected for maximum and minimum of speed deviation and the derivative of speed deviation

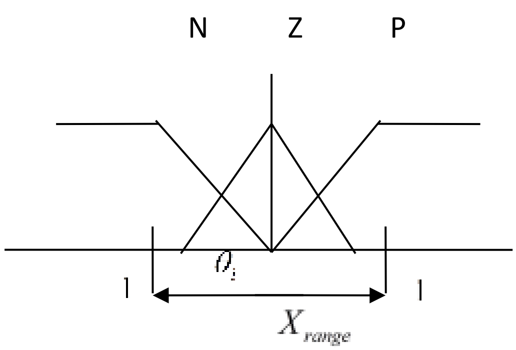

Figure 1: The membership functions used for the AFPSS inputs variables

2. Develop a fuzzy basis function (FBF) rule base with two inputs of speed deviations $\Delta\omega$ and $\Delta\dot{\omega}$, and one output. Set the initial value of $\underline{\theta}$ as initial fuzzy rule base (selected by the designer's experience with help of the table look-up) as in table 1. Apply the adaptation law (26) to compute $\dot{\underline{\hat{\theta}}}$ online in Table 2 and calculate the FBF from (3) and apply the results to (27) to get the PSS output U_{pss}.
3. Use trial and error method to get the gains of controllers $\underline{k}$ and the second columns of P which is of interest in our calculations.

Table: 1 Initial fuzzy rule base of AFPSS

$\Delta\omega$ / $\Delta\dot{\omega}$	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Table 2 Tunable fuzzy rule base of AFPSS

$\Delta\omega$ / $\Delta\dot{\omega}$	N	Z	P
N	$\hat{\theta}_1$	$\hat{\theta}_2$	$\hat{\theta}_3$
Z	$\hat{\theta}_4$	$\hat{\theta}_5$	$\hat{\theta}_6$
P	$\hat{\theta}_7$	$\hat{\theta}_8$	$\hat{\theta}_9$

4. Simulation Results

Nonlinear power system which is used in simulation studies consists of three Generator Multimachine power systems. The performance of proposed (AFPSS) and compared with CPSS as shown in Fig. 2, is evaluated by acting the large disturbance in transmission line at 2 sec and cleared ant 2.133 sec.

The system performance tracking index is characterized by *ISE* as:

$$ISE = \int e^2(t)dt \qquad (28)$$

where e is the out signals deviation

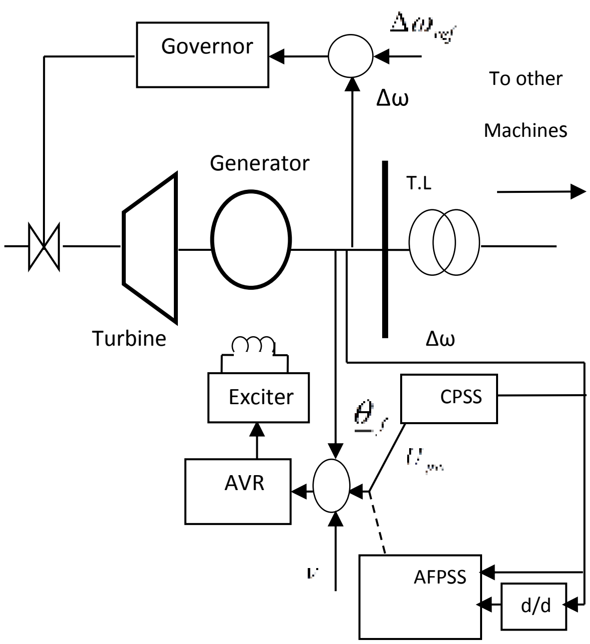

Figure 2: Power system model used in study of one Machine

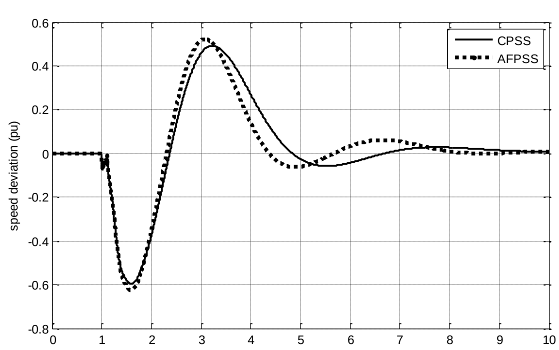

Figure 3: speed deviation response for Gen. (1)

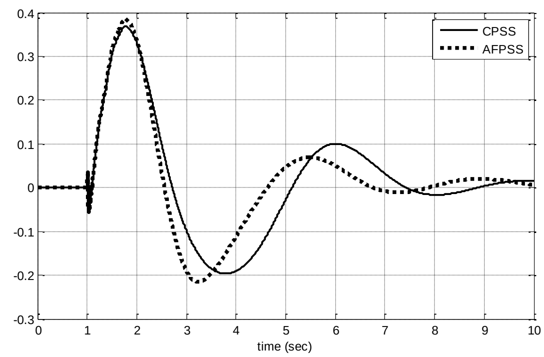

Figure. 4: speed deviation response for Gen. (2)

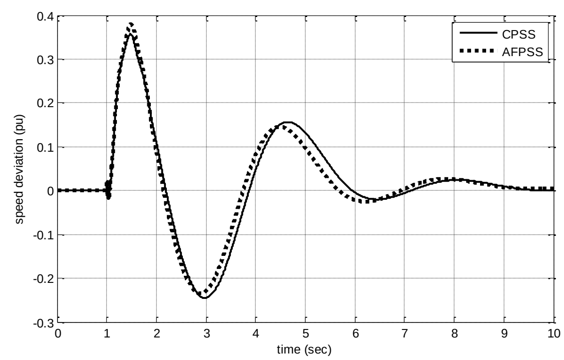

Figure 5: speed deviation response for Gen. (3)

Table 3 Index equation (28)

Speed Deviation	Gen. 1	Gen. 2	Gen. 3
CPSS	0.49	0.16	0.14
AFPSS	0.48	0.15	0.13

5. Conclusion

In this paper, dynamic behavior of three machine systems installed with a conventional power system stabilizer (CPSS) is investigated under 3-phased fault. Proposed variable structure Fuzzy based power are designed to improve damping local and interarea mode of oscillations following three phase faults that occurs at 1 sec. and cleared at 1.1 sec.

The obtained results demonstrate that the proposed AFPSS provides the smallest ISE index in three generators. Therefore, it is recommended to be considered in further and extended studies.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.