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Adaptive Control for Low-Frequency Power Oscillations

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ABSTRACT: *Power system stabilizer (PSS) can increase the system positive damping, improve the steady-state stability limit and suppress the low-frequency oscillations. A conventional PSS (CPSS) is designed by adopting linear control theory, so it has some drawbacks such as the time-consuming tuning and its non-optimal damping in the entire operating range. In this work an adaptive method is presented to design a single machine PSS which has self-tuning structure according to power system operating conditions. This ability of adaptive controller leads to an adaptive performance proportionate with different loading conditions. The nonlinear time domain simulations were done to show effectiveness of the proposed method in comparison with the conventional tuned power system stabilizers.*

Keywords: *Low-frequency oscillations, power system stabilizer, adaptive control.*

I. INTRODUCTION

Low-frequency oscillations in the range of 0.2 to 3 Hz are inherent to power systems. They appear when there are power exchanges between large areas of interconnected power systems or when power is transferred over long distances under medium to heavy conditions. The use of fast acting high gain Automatic Voltage Regulator (AVR), although improves the transient stability, has a detrimental effect on the small-signal stability [1]. For the last four decades, low frequency oscillations arising from the lack of sufficient damping in the system have been frequently encountered in power systems. The recent introduction of the deregulation and the unbundling of generation, transmission and distribution as well as the large amount of Distributed Generation connected to the power system have exacerbated the problem of low-frequency oscillations. For many years, Power System Stabilizers (PSSs) have been used to add damper to the electromechanical oscillations. Conventional Power System Stabilizers (CPSSs) have been widely accepted by the power utilities due to their simplicity. Moreover they have some drawbacks such as the time consuming tuning and its non-optimal damping in the entire operating range [2]. Owing to which the CPSS determined in the nominal operating point does not assure optimal damping in the operating range, the synchronous generator dynamic characteristics also vary when the load increase or decrease. In order to overcome this drawback, numerous advanced techniques have been proposed to design high-performance PSSs such as Klein et al [3] presented the simulation studies into the effects of stabilizers on inter-area and local modes of oscillations in interconnected power systems. It was shown that the PSS location and the voltage characteristics of the system loads are the significant factors in the ability of a PSS to increase the damping of inter-area oscillations. Nowadays, the conventional lead-lag power system stabilizer (CPSS) is widely used by the power system utility [4]. Other types of PSS such as proportional-integral power system stabilizer (PI-PSS) and proportional-integral derivative power system stabilizer (PID-PSS) have also been proposed [5, 6]. However, CPSSs are not able to provide satisfactory results over wider ranges of operating conditions. To overcome this problem, Fuzzy logic based technique is used for designing of PSSs. Fuzzy logic controllers (FLCs) are very useful in the case a good mathematical model for the plant is not available, however, experienced human operators are available for providing qualitative rules to control the system [7]. Also Hybrid PSSs using fuzzy logic and/or neural networks or Genetic Algorithms have been reported in some literature to improve the performance of Fuzzy logic based PSSs [8].

Adaptive control has been used to simplify the CPSS tuning process and to suppress the low-frequency oscillation under various disturbances. The use of adaptive control to design a PSS is possible because of the loading variations, and consequently the variations of the synchronous generator dynamic characteristics, are in most cases considerably slower than the adaptive mechanism.

This work deals with an adaptive design method for the stability enhancement of a single machine infinite bus power system using Model Reference Adaptive System. To show effectiveness of the MRAS, this method is compared with the CPSS. Simulation results show that the proposed method guarantees robust performance under a wide range of operating conditions.

II. MATHEMATICAL MODEL

This section presents the small-signal model for a single machine connected to a large system through a transmission line (infinite bus) to analyze the local mode of oscillations in the range of frequency1-3 Hz. A schematic representation of this system is shown in Figure (1) [9] linearization the system equipped with Static Excitation System and power system stabilizer.

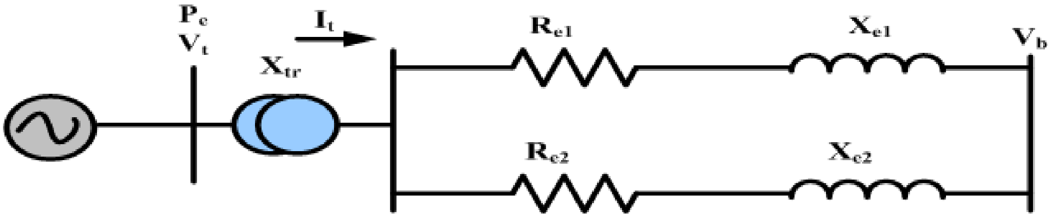

Figure (1) schematic diagram of single machine connected infinite bus

$$\Delta\dot{\delta} = \omega_s \Delta\omega \qquad (1)$$

$$\Delta\dot{\omega} = -\frac{K_2}{2H}\Delta\acute{E}_q - \frac{K_1}{2H}\Delta\delta - \frac{D\omega_s}{2H}\Delta\omega + \frac{1}{2H}\Delta T_M \qquad (2)$$

$$\Delta\dot{\acute{E}}_q = \frac{-1}{K_3 \acute{T}_{do}}\Delta\acute{E}_q - \frac{K_4}{\acute{T}_{do}}\Delta\delta + \frac{1}{\acute{T}_{do}}\Delta E_{fd} \qquad (3)$$

$$\Delta\dot{E}_{fd} = -\frac{K_A K_6}{T_A}\Delta\acute{E}_q - \frac{K_A K_5}{T_A}\Delta\delta - \frac{1}{T_A}\Delta E_{fd} + \frac{K_A}{T_A}\Delta V_{ref} \qquad (4)$$

III. POWER SYSTEM STABILIZER STRUCTURE

The basic objective of power system stabilizer is to modulate the generator's excitation to produce an electrical torque at the generator proportional to the rotor speed [10, 11]. To achieve that, the PSS uses a simple lead-lag compensator circuit to adjust the input signal and correct the phase lag between the exciter input and the electrical torque. The PSS can use various inputs, such as the speed deviation of the generator shaft, the change in electrical power or accelerating power, or even the terminal bus frequency. However in many instances the preferred signal input to the PSS is the speed deviation. Figure (2) below illustrates the block diagram of a typical PSS. The PSS general structure consists of a washout, lead-lag networks, a gain and a limiter stages. Each stage performs a specific function.

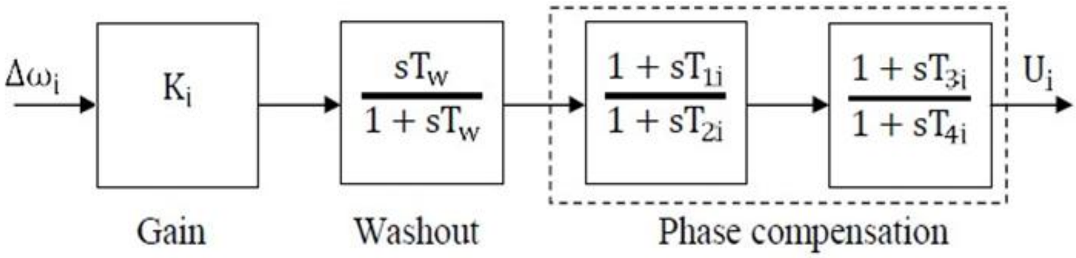

Figure (2) illustrates the block diagram of a typical PSS

$$\frac{dV_1}{dt} = K_{PSS}\frac{d\Delta\dot{\omega}}{dt} - \frac{1}{T_W}V_1 \qquad (5)$$

$$\frac{dV_2}{dt} = \frac{T_1}{T_2}\frac{dV_1}{dt} + \frac{1}{T_2}V_1 - \frac{1}{T_2}V_2 \qquad (6)$$

IV. MODEL REFERENCE ADAPTIVE SYSTEM

The model reference adaptive system (MRAS) is a control method in which the desired performance is defined as a reference model. Then, the system with MRAS controller tracks the reference model following any command in input [12]. In fact, the idea behind MRAS is to create a closed loop controller with parameters that can be updated to change the response of the system to follow the desired model. Figure (3) shows a general block diagram of MRAS method. Two feedback loops are seen, the ordinary feedback loop (inner loop) is used to compose the process and the controller, and another feedback loop (outer loop) are used to adjust the controller parameters. The parameters' adjustment is carried out based on the tracking error which is defined as the difference between the output of the system and the output of the reference model. The methodology of parameters' adjustment in MRAS is obtained by different methods such as gradient method or Lyapunov stability theory.

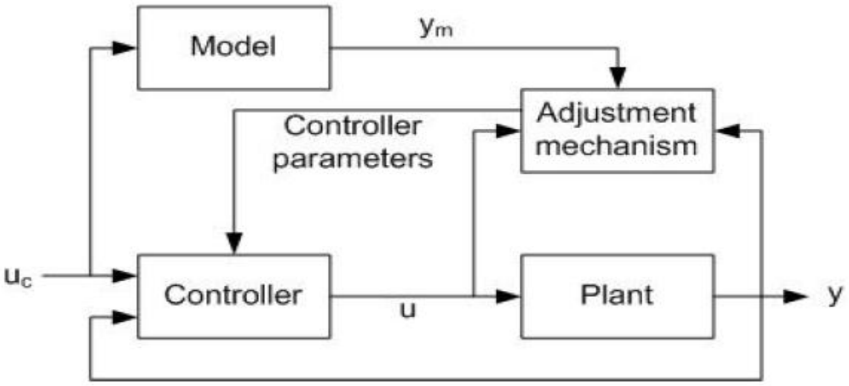

Figure (3) shows a general block diagram

V. MRAC DESIGN USING LYAPUNOV METHOD

The model reference adaptive controller designed using the Gradient method/MIT rule has does not guarantee stability to the resulting closed-loop system. However, MRAC can also be designed such that the globally asymptotic stability of the equilibrium point of the error difference equation is guaranteed. To do this, we use the Lyapunov method [13]. The first requires an appropriate Lyapunov function to be chosen, which could be difficult, whereas the second method is more systematic. This work looks at the MRAC system designed using the Lyapunov method. In designing an MRAC using Lyapunov Method, through the following steps:

i) Derive a differential equation for error, e = y − y_m (i.e. $e^{\bullet}, e^{\bullet\bullet}, ect$) that contains the adjustable parameter θ.
ii) Find a suitable Lyapunov function, V(e,θ) - usually in a quadratic form (to ensure positive definiteness).
iii) Derive an adaptation mechanism based on V(e,θ) such that e goes to zero.

Consider an adaptive control system with the following plant as describe in (6), reference model and controller:

Plant model:

$$\frac{dy}{dt} = -ay(t) + bu(t) \qquad (7)$$

Reference model:

$$\frac{dy_m}{dt} = -ay(t) + b_m r(t) \qquad (8)$$

Controller:

$$u(t) = \theta_1 r(t) - \theta_2 y(t) \qquad (9)$$

It follows from equation (7) and (9), that

$$y = \frac{b}{s + a + b\theta_2}\theta_1 r \qquad (10)$$

$$y_m = \frac{b_m}{s + a_m} r \qquad (11)$$

Step 1: Derive differential equation for e that contains

$$e^{\bullet} = y^{\bullet} - y^{\bullet} \qquad (12)$$

$$y^{\bullet} + (a + b\theta_2)y = b\theta_1 r \qquad (13)$$

$$y^{\bullet} = -(a + b\theta_2)y + b\theta_1 r \qquad (14)$$

$$y_m^{\bullet} + a_m y_m = b_1 r \qquad (15)$$

$$y_m^{\bullet} = -a_m y_m + b_1 r \qquad (16)$$

$$e^{\bullet} = y^{\bullet} - y^{\bullet}$$

$$e^{\bullet} = -(a + b\theta_2)y + b\theta_1 r + a_m y_m - b_1 r \qquad (17)$$

$$e^{\bullet} = -ay - b\theta_2 y + b\theta_1 r + a_m y_m - bmr \qquad (18)$$

$$e^{\bullet} = -ay - b\theta_2 y + b\theta_1 r + a_m (y - e) - bmr \qquad (19)$$

$$e^{\bullet} = -a_m e - (a + b\theta_2 - a_m)y + (b\theta_1 - b_m)r \qquad (20)$$

$$e^{\bullet} = -a_m e - [\frac{a - a_m}{b} + \theta_2]by + [\theta_1 - \frac{b_m}{b}]br \qquad (21)$$

$$e^{\bullet} = -a_m e - [X_1]by + [X_2]br \qquad (22)$$

Step 2: Find the suitable Lyapunov function (usually in quadratic form), The Lyapunov function, $V(e, X_1, X_2)$ is chosen based on (22). Let

$$V(e, X_1, X_2) = [e \quad X_1 \quad X_2] \begin{vmatrix} a_m & 0 & 0 \\ 0 & \lambda_1 & 0 \\ 0 & 0 & \lambda_2 \end{vmatrix} \begin{vmatrix} e \\ X_1 \\ X_2 \end{vmatrix} \qquad (23)$$

$$V(e, X_1, X_2) = a_m e^2 + \lambda_1 X_1{}^2 + \lambda_2 X^2 \qquad (24)$$

Where λ_1, $\lambda_2 > 0$ so that V is positive definite

$$V^{\bullet} = \frac{\partial V}{\partial e}\frac{\partial e}{dt} + \frac{\partial V}{\partial X_1}\frac{\partial X_1}{dt} + \frac{\partial V}{\partial X_2}\frac{\partial X_2}{dt} \qquad (25)$$

$$V^{\bullet} = a_m 2ee^{\bullet} + 2\lambda_1 X_1 X_1^{\bullet} + 2\lambda_2 X_2 X_2^{\bullet} \qquad (26)$$

$$V^{\bullet} = a_m 2e[-a_m e - X_1 by + X_2 br] + 2\lambda_1 X_1 X_1^{\bullet} + 2\lambda_2 X_2 X_2^{\bullet} \qquad (27)$$

$$V^{\bullet} = 2e^2 a_m{}^2 - 2a_m X_1 bye + 2a_m X_2 bre + 2\lambda_1 X_1 X_1^{\bullet} + 2\lambda_2 X_2 X_2^{\bullet} \qquad (28)$$

For stability $V^{\bullet} \prec 0$

$-Y + Z \prec 0 \Rightarrow Z \prec Y$,

Therefore we can take Z=0

$$-2a_m X_1 bye + 2a_m X_2 bre + 2\lambda_1 X_1 X_1^{\bullet} + 2\lambda_2 X_2 X_2^{\bullet} = 0 \qquad (29)$$

For expression

$$X_1 = [\frac{a - a_m}{b} + \theta_2] \Rightarrow X_1^{\bullet} = \theta_1^{\bullet}, X_2 = [\theta_1 - \frac{b_m}{b}] \Rightarrow X_2^{\bullet} = \theta_2^{\bullet}$$

$$-2a_m X_1 bye + 2a_m X_2 bre + 2\lambda_1 X_1 \theta_1^{\bullet} + 2\lambda_2 X_2 \theta_2^{\bullet} = 0 \qquad (30)$$

Derive an adaptation mechanism (for θ_1 and θ_2)

$$-2X_1[-a_m bye + \lambda_1 \theta_2^{\bullet}] + 2X_2[a_m bre + \lambda_2 \theta_1^{\bullet}] = 0 \qquad (31)$$

This is possible if

$$-a_m bye + \lambda_1 \theta_2^{\bullet} = 0 \qquad (32)$$

$$a_m bre + \lambda_2 \theta_1^{\bullet} = 0 \qquad (33)$$

$$\theta_2^{\bullet} = \frac{-a_m bye}{\lambda_1} = \gamma_2 ye \Rightarrow where\, \gamma_2 = \frac{a_m b}{\lambda_1} \qquad (34)$$

$$\theta_1^{\bullet} = \frac{-a_m bre}{\lambda_2} = \gamma_1 ye \Rightarrow where\, \gamma_1 = \frac{a_m b}{\lambda_2} \qquad (35)$$

VI. SIMULATION RESULTS AND DISCUSSION

Following the application of proposed adaptive control to tune the PSS, Figure (4) shows time response of speed deviation of the generator in case of without any controller, conventional PSS and adaptive PSS. The adaptive PSS found to give the best damping for the most dominant poles of the system. Figure (5) shows speed deviation response in different operating points, normal load, heavy load and light load. It's clear from the figure the classic power system stabilizer cannot damp out power system oscillation at different operation points. Figure (6) shows speed deviation response in different operation point, normal load, heavy load and light load. It's clear from the figures that the adaptive power system stabilizer damp out most of the oscillations in different operation points and it shows better performances than the conventional power system stabilizer.

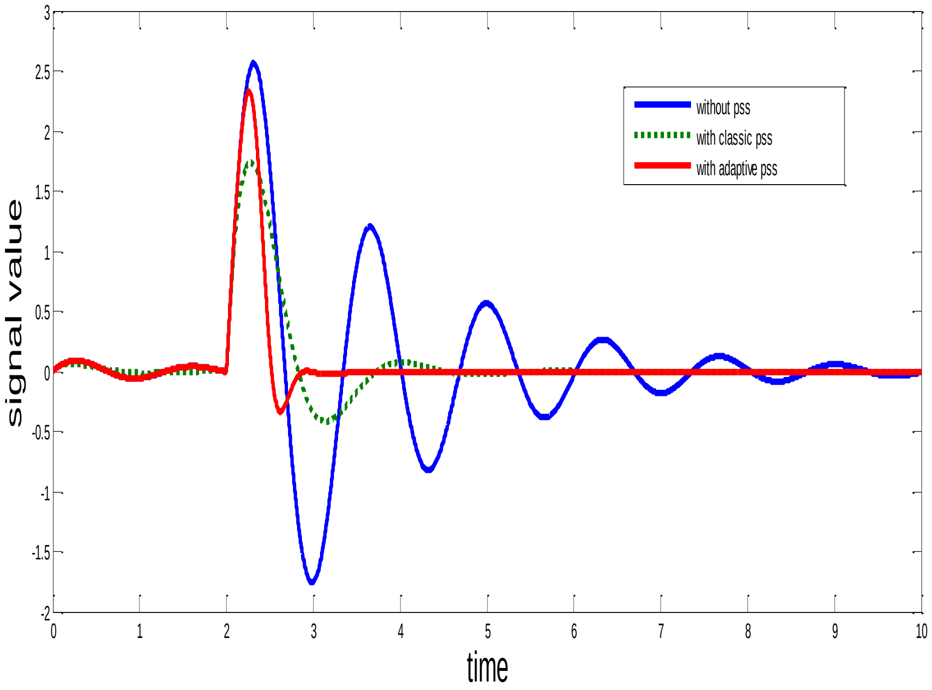

Figure (4) show speed deviation with different type of PSS

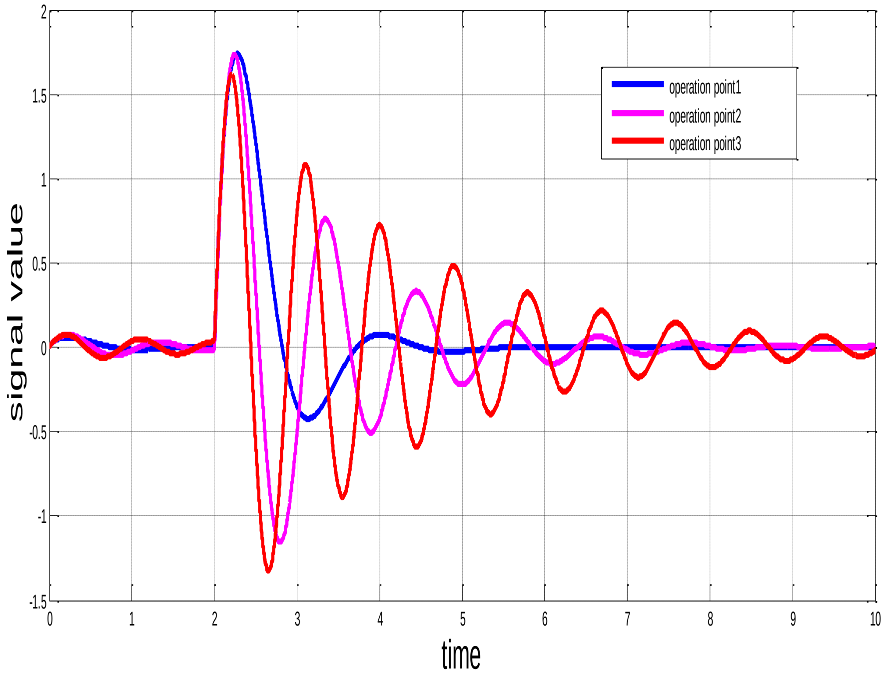

Figure (5) shows speed deviation response in different operation in case of conventional PSS

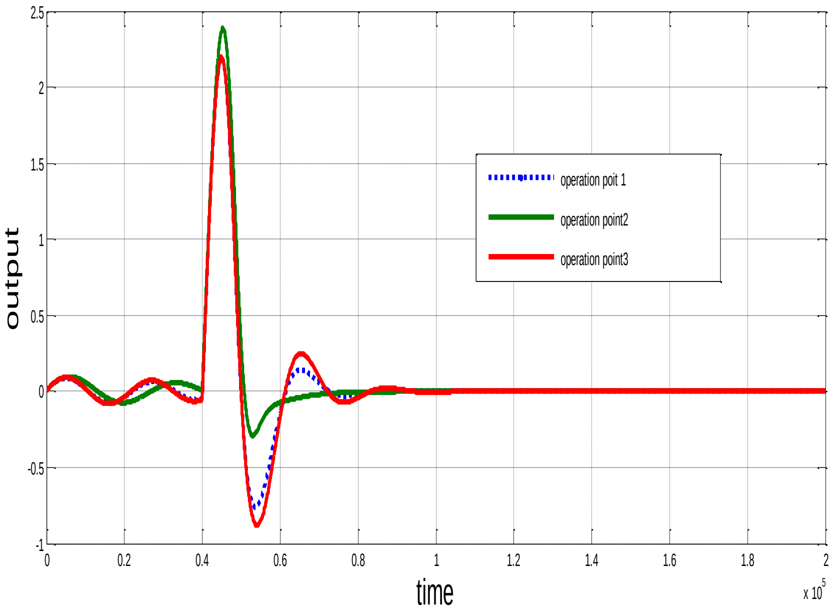

Figure (6) shows speed deviation response in different operation in case of adaptive PSS

VII. CONCLUSION

This work presents an application of MRAS technique to design PSS as a regulator controller in electric power systems. To investigate the performance of the proposed MRAS-PSS under various operating conditions and disturbances are defined and simulated. Furthermore, the proposed MRAS-PSS is evaluated against conventional PSS which is tuned by residue approach. Simulation results emphasize on the viability and robustness of the proposed adaptive method under various operating conditions. The proposed MRAS-PSS systematically tackles the network uncertainties and provides a robust performance following changing parameters. In addition, the results indicate that MRAS-PSS is more effective than CPSS to damp out oscillations and stability enhancement under uncertain conditions.

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