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Design and Simulation of a Power Stabilizer System to Mitigate Oscillations of the Industrial Power System

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Abstract: The study presents an approximate solution to the problem of low frequency oscillations of poorly damped power systems which has been a source of concern for engineers, since they limit the transfer of power in the transmission lines and induce tensions in the mechanical axis of the machines in the industrial. Due to small disturbances, power systems experience these poorly damped low frequency oscillations. Dynamic stability of power systems is also affected by these low frequency oscillations. With a suitable design of the Power System Stabilizer (PSS), these oscillations can be well cushioned and therefore, the stability of the system is improved. The basic functions of the PSS are to add a stabilizing signal which compensates for the oscillations of the excitation system voltage error during the dynamic/transient state and to provide a damping component when in phase with the speed deviation of the machine rotor. Studies have shown that PSS are designed to provide additional damping torque for different operating points of normal load, heavy load and leads to improved dynamic stability of the power system. Finally, we discuss some implementation issues, we study an illustrative example using MATLAB simulations and we, also point out possible generalizations of the (PSS) design.

Key words: Protection energy system, power stabilizer system, oscillations, design, industrial power system, damping

INTRODUCTION

In the last decade as interconnected power systems become increasingly complex, the presence of poorly damped low frequency oscillations between networks has hampered their stability limitations, thereby limiting their power transfer capability (Abido, 2002; Azhmyakov *et al*., 2014a, b; Abdel-Magid and Abido, 2003). Likewise, to assure the operation of the system requires an adequate cushioning of the modes between areas to assure the reliability of the system and to increase the overall power (Azhmyakov *et al*., 2014a, b; Slootweg and Kling, 2003; Serrezuela and Chavarro, 2016).

The stability of the power system is defined as “the ability of an electric power system for a given initial operating condition, to recover an operational equilibrium state after being subjected to a physical disturbance” (Mello *et al*., 1980; Serrezuela *et al*., 2016a, b; Wang, 2000). Oscillatory stability is a subcategory of Small Signal Stability (SSS) which is defined as the power system’s ability to maintain synchronous operation under small disturbances. Oscillations usually refer to frequencies between 0.2 and 3 Hz with insufficient damping. There are three types of oscillations that have been observed in the power system which are oscillations between units, typically involves two or more synchronous machines in a power plant or nearby power plants that balance each other with a frequency ranging from 1.5-3 Hz, local mode oscillations generally involve one or more synchronous machines in a power plant which moves together against a comparatively large power system or load center and the oscillation frequency is in the range of 0.7-2 Hz (Serrezuela *et al*., 2016a, b; Chow *et al*., 2000; Carvajal *et al*., 2016). Finally, interarea oscillations involving combinations of many machines in one part of the power system that oscillate against machines in another part of the power system and the frequency range is usually <0.5 Hz (Lerch *et al*., 1991; Montiel *et al*., 2017; Jamal *et al*., 2015).

Controlling these kinds of oscillations is relatively simple task that could be solved by applying Power System Stabilizer (PSS) (Serrezuela *et al*., 2017a, b). By Bidadfar *et al*. (2016) and Serrezuela *et al*. (2017a, b) discussed the phenomena of stability of synchronous machines under small perturbations by examining the case of SMIB through external reactance. The analysis developed insights into the effects of

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thyristor-type excitation systems and established understanding of the stabilizing requirements for such systems.

These stabilizing requirements included the voltage regulator gain parameters as well as the transfer function characteristics for a speed machine derived signal along with the voltage regulator reference for providing damping of machine oscillations (Didier *et al*., 2013; Shahgholian *et al*., 2015). The study had explored a variety of machine loadings, machine inertias and external impedances with a determination of the oscillation and damping characteristics of voltage or speed following a small disturbance in mechanical torque. An attempt has been made to develop some unifying concepts that explain the stability phenomena of concern and to predict desirable phase and magnitude characteristics of stabilizing functions (Shahgholian and Movahedi, 2014; Munz and Metzger, 2014).

Abido (2002) and Azhmyakov *et al*. (2014a, b) provided the analytical work and systematic method to determine PSS parameters for large power generation in a practical power system. The basic PSS design idea based on the stabilizer proposed by Azhmyakov *et al*. (2014a, b), Slootweg and Kling (2003). However, the phase characteristics were obtained using the multi-machine eigenvalue program instead of a single machine model. This research emphasized enhancement of overall system stability and the researchers considered simultaneous damping of inter-area and local modes and the performance of PSS under different system conditions. In addition to small signal stability performance, the researchers also tested the transient stability performance of the PSS and the performance during system is landing. The researchers also demonstrated the importance of the appropriate choice of washout time constant, stabilizer output limits and other excitation system control parameters. The researchers claimed that the frequency response method used to compensate the lag between the excitation input and the electrical torque was fairly robust.

Chow *et al*. (2000) proposed four pole-placement techniques for the design of power system stabilizers with the emphasis on frequency response characteristics of the controller. For controllers to exhibit desirable frequency characteristics, a simple procedure was proposed to obtain controllers suitable for multiple operating conditions.

MATERIALS AND METHODS

Mathematical model: This study 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 frequency 1-3 Hz. The schematic representation of this system is shown in Fig. 1 (Serrezuela and Chavarro, 2016; Chow *et al*., 2000; Jamal *et al*., 2015).

Non-linear equation of SIMB: The non-linear equation of SIMB equipped with SSP:

$$\frac{d\delta}{dt} = \omega_b[\omega-\omega_s] \tag{1}$$

$$\frac{d\omega}{dt} = \frac{1}{M}[T_m-T_e-D(\omega-\omega_s)] \tag{2}$$

Where:

M = The inertia of the rotor
D = The damping coefficient of the rotor motion
δ = The rotor angular position of synchronous generator to a reference axis
T_m, T_e = The mechanical torque and electric torque applied on the rotor of generator, respectively (Carvajal *et al*., 2016):

$$\frac{d\dot{E}_q}{dt} = \frac{1}{T_{d0}}[-E_q-(x_d-\dot{x}_d)i_d+]E_{fd} \tag{3}$$

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A}[-E_{fq}-K_A(V_{ref}-V_t+V_s)] \tag{4}$$

Where:

$\dot{E}_q$ = The q-axis transient excitation voltage
E_q = The q-axis excitation voltage
E_{fd} = The excitation voltage

Power system stabilizer structure: The basic objective of power system stabilizer is to modulate the generator's excitation in order to produce an electrical torque at the generator proportional to the rotor speed (Lerch *et al*., 1991; Montiel *et al*., 2017). In order 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

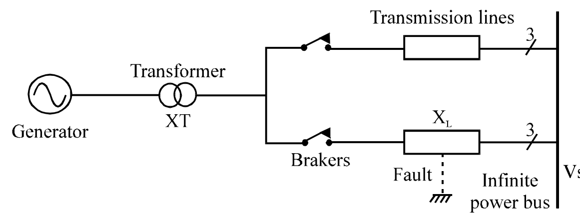

Fig. 1: Schematic diagram of single machine connected infinite bus

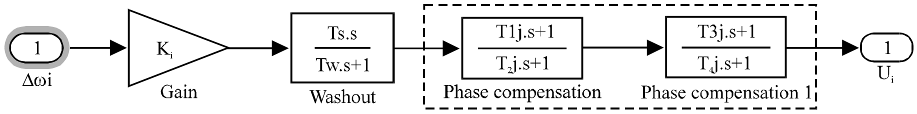

Fig. 2: The block diagram of a typical PSS in MATLAB/Simulink

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 illustrates the block diagram of a typical PSS. The PSS structure generally consists of a washout, lead-lag networks, gain and a limiter stages. Each stage performs a specific function. The differential equations that describe the system are:

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

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

$$\frac{dV_{PSS}}{dt} = \frac{T_3}{T_4}\frac{dV_2}{dt} + \frac{1}{T_4}V_2 - \frac{1}{T_4}V_{PSS} \quad (7)$$

Linearization the system equipped with static excitation system: The general linearized model of the single-machine infinite-bus power system with the PSS installed is:

$$\Delta\delta = \omega_s\Delta\omega \quad (8)$$

$$\Delta\dot{\omega} = -\frac{K_2}{2H}\Delta\dot{E}_q - \frac{K_1}{2H}\Delta\delta + \frac{1}{T_{do}}\Delta E_{fd} \quad (9)$$

$$\Delta\dot{E}_q = \frac{1}{K_3T_{do}}\Delta\dot{E}_q - \frac{K_4}{T_{do}}\Delta\delta + \frac{1}{T_{do}}\Delta E_{fd} \quad (10)$$

$$\Delta E_{fd} = \frac{K_4K_6}{T_4}\Delta\dot{E}_q - \frac{K_4K_5}{T_4}\Delta\delta - \frac{1}{T_4}\Delta E_{fd} + \frac{K_4}{T_4}\Delta V_{ref} \quad (11)$$

Where:

$$K_1 = -\frac{1}{\Delta}[I_qE_b(\dot{X}_d - X_q)\{(X_q+X_e)\text{sen }\delta - R_e\cos\delta\} + E_b\{(\dot{X}_d - X_q)I_d - \dot{E}_q\}\{(\dot{X}_d - X_e)\cos\delta + R_e\text{sen}\delta\}]$$

$$K_2 = \frac{1}{\Delta}[I_q\Delta - I_q(\dot{x}_d + x_q)(x_q + x_\varepsilon) - R_e(\dot{x}_d + x_q)\dot{E}_q$$

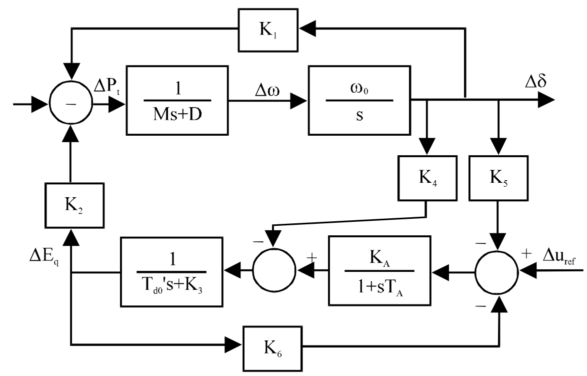

Fig. 3: Heffron Philips Model structure

$$K_3 = \frac{1}{1 + \frac{(\dot{x}_d + x_q)(x_q + x_e)}{\Delta}}$$

$$K_4 = \frac{E_b(\dot{x}_d + x_q)}{\Delta}[(x_q + x_e)\text{sen}\delta - R_e\cos\delta]$$

$$K_5 = \frac{1}{\Delta}\left\{\frac{V_d}{V_t}X_q[R_eE_b\text{sen }\delta + E_b(\dot{x}_d + x_e)\cos\delta] + \frac{V_q}{V_t}X_d[R_eE_b\cos\delta + E_b(\dot{x}_d + x_e)\text{sen}\delta]\right\}$$

$$K_6 = \frac{1}{\Delta}\left\{\frac{V_d}{V_t}X_qR_e - \frac{V_q}{V_t}X_d(x_q + x_e)\right\} + \frac{V_q}{V_t}$$

And:

$$\Delta = R_e^2 + (x_q + x_e)(\dot{x}_d + x_e)$$

Modeling the system in Heffron Philips form: The Heffron-Phillips Model of a synchronous machine has been successfully used for investigating the low frequency oscillations and designing power system stabilizers, Fig. 3 show Heffron Philips structure (Serrezuela *et al*., 2017a, b; Bidadfar *et al*., 2016).

Modeling the system in a state space form without PSS: The state equations of the model are:

$$[\Delta\dot{X}] = [A][\Delta X] + [B][\Delta U] \quad (12)$$

Where:

$$[\Delta X] = [\Delta \dot{E}_q \quad \Delta\delta \quad \Delta\omega \quad \Delta E_{fd}]^T$$

$$[\Delta U] = [\Delta V_{REF}]$$

Where:

$$[A] = \begin{bmatrix} -\frac{1}{K_2 T_{do}} & -\frac{K_4}{T_{do}} & 0 & -\frac{1}{T_{do}} \\ 0 & 0 & \omega_{base} & 0 \\ -\frac{K_2}{M} & -\frac{K_1}{M} & -\frac{\omega_{base} K_d}{M} & 0 \\ -\frac{K_6 K_4}{T_4} & -\frac{K_5 K_4}{T_4} & 0 & -\frac{1}{T_4} \end{bmatrix}$$

$$[B] = \begin{bmatrix} 0 & 0 & 0 & \frac{K_4}{T_4} \end{bmatrix}$$

Modeling the system in a state space form included PSS: Same form in Eq. 12 but different states:

$$[\Delta x_i] = [\Delta \dot{E}_q \quad \Delta\delta \quad \Delta\dot{\omega} \quad \Delta E_{fd} \quad \Delta V_{WF} \quad \Delta V_1 \quad \Delta V_S]^T$$

$$[B_i] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & \frac{K_4}{T_4} \end{bmatrix}^T$$

RESULTS AND DISCUSSION

From the block diagram of SMIB given in Fig. 1, PSS structure in Fig. 2 and the simulation is done in MATLAB/Simulink environment.

Results obtained for variation in speed deviation. The variation in rotor speed is depicted in Fig. 4-7 for different operation points normal load, heavy load, light load and leading power factor.

Simulation is run for 10 sec and non-adaptive algorithm is used for obtaining the characteristics with step function. From the Fig. 4 in case of normal load, it has been observed that the SMIB system without excitation

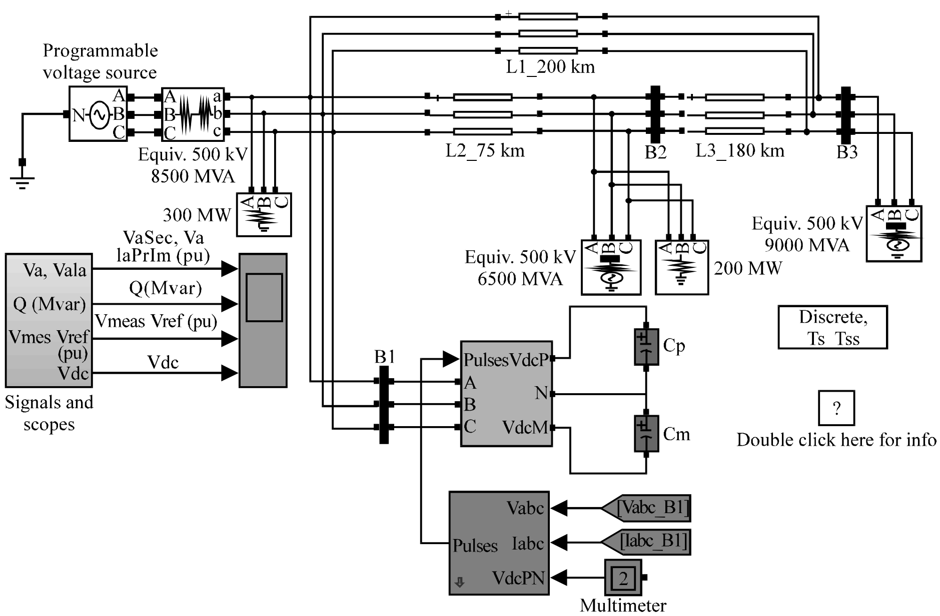

Fig. 4: Simulink diagram of the system P.S.S in MATLAB

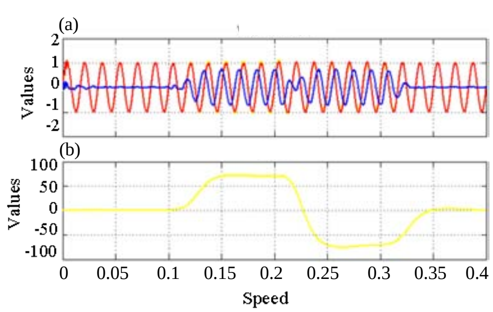

Fig. 5: Variation in speed deviation in MATLAB/Simulink: a) VaSec, ValaPrim (pu) and b) Q(Mvar)

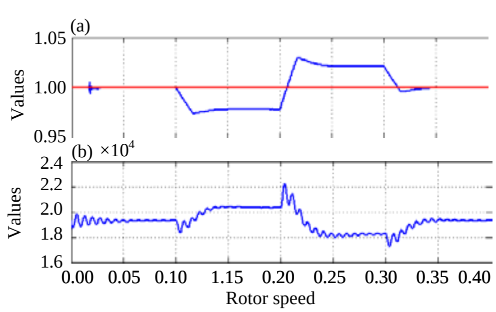

Fig. 6: Variation in rotor speed is depicted in MATLAB/Simulink: a) V_{meas}, V_{ref} (pu); b) V_{dc} (Time of set = 0)

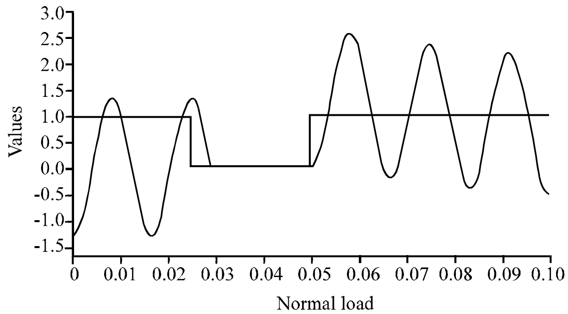

Fig. 7: Different operation points normal load in MATLAB/Simulink (Time of set = 0)

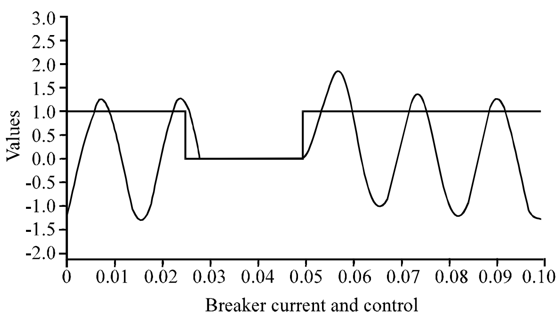

Fig. 8: Different operation points normal heavy load in MATLAB/Simulink (Time of set = 0)

and PSS is unstable. Also in Fig. 5-7 in cases of heavy and leading power the response of speed deviation going a stable and increase in magnitude without PSS but after adding PSS damp out the oscillations during first cycle.

Therefore, the PSS is suitable for damping the oscillations by providing sufficient damping torque to the SMIB System.

CONCLUSION

This study proposes the design of PSS for Single Machine Infinite Bus (SMIB) system by eigenvalues technique to damp out oscillation in the test system described and it returned the system to the stable condition after the disturbance. The performance of PSS evaluated by using time domain analysis and eigenvalue analysis. Time domain analysis graphically shows the oscillations are damped out after the installation of PSS. It is found that designed controller provides good damping enhancement for various operating points of SMIB power system. The proposed PSS is very feasible, applied to multi machine power systems and easy to implement.

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