POWERCON
2010 HANGZHOU

2010 International Conference on Power System Technology

Technological Innovations Making Power Grid Smarter

24-28 October, 2010 Hangzhou, China

PAPER ABSTRACTS

Co-sponsored by

Chinese Society for Electrical Engineering

IEEE PES IEEE Power & Energy Society

Organized by

国家电网
STATE GRID

中国电力科学研究院

Application of Power System Stabilizer in a Combined Model of LFC and AVR Loops to Enhance System Stability

E. Rakhshani, and J. Sadeh, *Member, IEEE*

Abstract— **This paper presents an investigation into the stability enhancement of LFC problem in one area power system using a power system stabilizer. A complete system model for low-frequency oscillation studies should be composed of mechanical and electrical loops. So a new combined model, that is included of LFC and AVR loops to consider the mutual effects between them, is used. The simulation results show that adding a coordinative PSS to this model can improve the dynamic stability of the power system and effectively suppress the low-frequency oscillation.**

***Index Terms*-- Excitation system, Load frequency control, Low-frequency oscillation, Power system stabilizer.**

I. Nomenclature

B	Frequency bias
R	Droop characteristic
ΔP_M	Power generation deviation of unit
ΔP_L	Load deviation
K_P	Power system equivalent gain
T_P	Power system equivalent time constant
T_T	Turbine time constant
T_G	Governor time constant
K_a	Amplifier gain
T_a	Amplifier time constant
K_r	Sensor gain
T_r	Sensor time constant
$\Delta E'_a$	Deviation of transient excitation EMF on stator
T'_{do}	Generator-field transient time constant
ΔV_t	Deviation of terminal voltage
ΔP_e	Deviation of internal electrical power
ΔV_f	Deviation of field winding voltage
$\Delta\delta$	Deviation of torque angle
LFC	Load frequency control
AVR	Automatic voltage regulator
K_{pss}	Power system stabilizer gain
T_w	Washout time constant
T_1-T_4	PSS time constant

Elyas Rakhshani is with Islamic Azad University, Gonabad branch, Iran. (E-mail: elyas.rakhshani@gmail.com).

J. Sadeh is with Electrical Engineering Department, Ferdowsi University of Mashhad, Iran. Fax: (98) 511 8763302, (e-mail: sadeh@um.ac.ir).

II. Introduction

IN power systems, changes of operating conditions will result in small-magnitude low-frequency oscillations that may persist for long periods of time. In some cases, the oscillations will limit the power transfer capability. So power system stabilizer is designed to generate supplementary control signal in the excitation system to enhance system damping [1].

A complete system model for low-frequency oscillation studies must be included of mechanical and electrical loops. It has been recognized that these oscillations can be controlled by adjusting exciter and speed-governor control parameters [2]. Furthermore, it has been shown that the load-voltage characteristic of the power system has a significant effect on its dynamic responses, and suggestions have been made for the proper representation of these characteristics in simulation studies [3]-[5]. The two main control loops of a generation are Load Frequency Controller (LFC) and Automatic Voltage Regulator (AVR) [1]. A lot of studies have been made about LFC over the last decades [6]-[7] but these researches don't have any attention to AVR effects on the results. Infact, in LFC power system control literature, there is a lack of stability analysis for AVR effects or the mutual effects between these loops. Usually, these studies are based on the assumption that there is no interaction between the power/frequency and the reactive-power/voltage control loops. But in practical systems, during dynamic perturbations some interactions between these two control channels are exist [3]. Also, by neglecting the effect of voltage deviation on load demand, an important interaction in LFC systems is ignored. But in [3] a combined model for a power system is proposed and for the first time, interaction between LFC and AVR Loops and their important effects on the steady state response of turbine output power is depicted.

In this paper, a complete research is done for adding a PSS to this combined model for more dynamic improvement. A similar simulations as in [3] are developed to show the performance of this proposed method under practical operating conditions. The results of the proposed method with PSS are compared with a combined model without PSS and also with separate models of LFC and AVR without any interaction. The simulations show that adding a coordinative PSS to a combined model of LFC and AVR can improve the

978-1-4244-5939-1/10/$26.00©2010 IEEE

dynamic stability of the power system and effectively suppress the low-frequency oscillation.

III. Modeling of Power System

For small-signal stability analysis, dynamic modeling is required for the major components of the power system, such as synchronous generator, excitation system, automatic voltage regulator and load frequency control loops as a mechanical part. In this study, the simulation of low-frequency oscillations is based on a single machine connected to infinite bus system [2]. This one machine-infinite bus system with a local load is shown in Fig. 1.

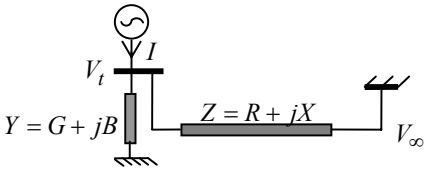

Fig. 1. One machine-infinite bus power system.

Where, Z: series impedance of transmission line and Y: shunt admittance as a local load.

A. Combined LFC- AVR Model for a Power System

The rotational inertia equations describe the effect of unbalance between electromagnetic torque and mechanical torque of individual machines in a LFC system. By having small perturbation and small deviation in speed, the complete swing equation becomes [3]:

$$\Delta f = \frac{K_p}{1+sT_p}[\Delta P_m - (\Delta P_L + \Delta P_e)] \tag{1}$$

Where, ΔP_e is the deviation of internal electrical power that is sensitive to load characteristics. This fact is the basis of developing a new combined model for power system stability studies. Combined model that is used in this paper is shown in Fig. 2. Note that the dashed and dotted lines show the connection between LFC and AVR loops and *PI* block in this figure is a designed PI controller.

The development of used combined model and complete information about K_1-K_6 parameters and related parameters in Fig. 2, are given in [3].

B. Applied PSS for Combined LFC- AVR Model

The PSS transfer function, G_{pss}(s), should have appropriate phase compensation blocks to compensate the phase lag between the exciter input and the electrical torque with using important signal Δf. As shown in Fig.2, this transfer function between the electrical torque and the reference voltage is given by:

$$GEP(s) = \frac{K_3.K_a.K_2}{(1+sT_a).(1+sK_3.T'_{do}) + K_3.K_a.K_6} \tag{2}$$

The considered stabilizer is included of two lead compensators as shown in Fig.3, with a washout filter. The transfer function of PSS is represented as:

$$G_{pss}(s) = \frac{\Delta V_s(s)}{\Delta f(s)} = K_{pss}[\frac{s.T_w}{1+s.T_w}].G_C(s) \tag{3}$$

$$G_C(s) = \frac{(1+s.T_1)}{(1+s.T_2)}.\frac{(1+s.T_3)}{(1+s.T_4)} \tag{4}$$

Where K_{pss} is stabilizer gain, T_w is washout time constant and G_C is transfer function of phase compensator. An optimal stabilizer is obtained by a proper selection of time constants T_1, T_2, T_3, T_4, T_w and K_{pss}.

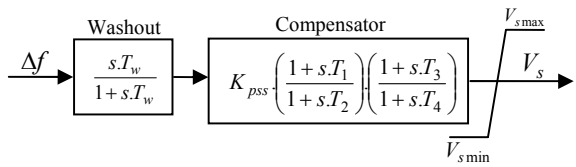

Fig. 3. Structure of PSS.

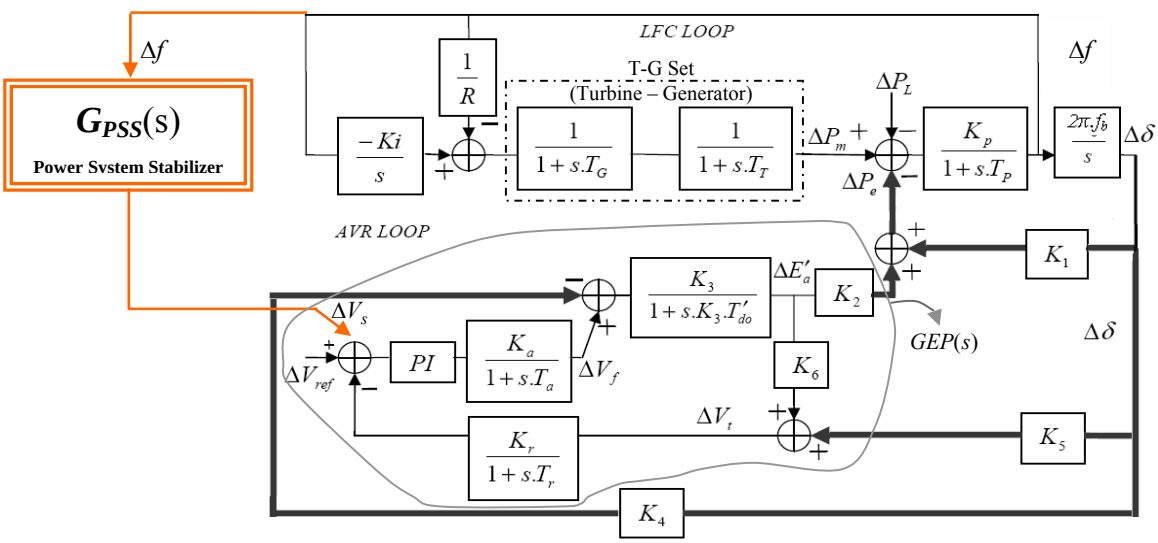

Fig. 2. PSS coordinated with LFC-AVR combined

It is assumed that $T_1 = T_3$ and $T_2 = T_4$. This choice reduces the number of parameters to be optimized. The design consideration and the procedure for selecting the PSS parameters are as follows:

B. 1. Natural frequency of system

Based on the proposed model of synchronous generator model in [2], used mechanical equations for combined model in Fig.2 will be find:

$$M\Delta\dot{\omega} = -\Delta T_D - \Delta T_e + \Delta P_m \tag{5}$$

Assume that:

$$\Delta T_D = D.\Delta\omega \tag{6}$$

$$\Delta T_e = K_1\Delta\delta + D_E\Delta\omega \tag{7}$$

Where $K_1.\Delta\delta$ is a component of torque that is in phase with the rotor angle change. This is known as the "synchronizing torque" and $D_E.\Delta\omega$ is a component of torque that is in phase with the speed change. This is known as the "damping torque". We know that $\Delta\delta=(\omega_b.\Delta\omega)/s$ and $\omega_b=2\pi.f_b$. Therefore:

$$M.s^2/\omega_b + (D + D_E).s/\omega_b + K_1.\Delta\delta = f_{mechanical}(\Delta\delta) \tag{8}$$

Where:

$$\begin{aligned}\Delta P_m = f_{mechanical}(\Delta\delta) &= -\Delta\omega.[(s + R.K_i)/s.R.(1 + sT_{g-t})] \\ &= -\Delta\delta/\omega_b[(s + R.K_i)/R.(1 + s.T_{g-t})]\end{aligned} \tag{9}$$

Where T_{g-t} is the approximated time constant of turbine – generator set in Fig. 2. It is assumed that the value of time constant of turbine – generator set is low and neglected and after linearization:

$$\Delta P_m = -s.\Delta\delta(1/R.\omega_b) - \Delta\delta.(K_i/\omega_b) \tag{10}$$

And by substituting (9)-(10) into (8):

$$[M.s^2 + s.(D + D_E + 1/R) + (K_1.\omega_b + K_i)]\Delta\delta = 0 \tag{11}$$

Where $D=1/K_p$ and $M=T_p/K_p$. Normalization of (11) yields:

$$(s^2 + 2.\zeta.\omega_n.s + \omega_n^2).\Delta\delta = 0 \tag{12}$$

Therefore:

$$s = (-\zeta_n \pm j\sqrt{1-\zeta_n^2}).\omega_n \tag{13}$$

$$\omega_n = \sqrt{(\omega_b K_1 + K_i)/M} \tag{14}$$

$$\zeta_n = (D + D_E + 1/R)/2.\omega_n.M \tag{15}$$

Where ω_n is the natural frequency of system, $\omega_b=2\pi.f_b=377$(rad/s) is the rated speed for a 60 *Hz* system and also ζ_n is desired damping ratio and may be change by selecting of D_E or R. Note that the percent over-shoot and settling time requirements for the closed-loop system responses can be affected by natural frequency and desired damping ratio characteristics for the closed-loop dynamics of systems.

B. 2. Phase lead compensation

To damp rotor oscillations, the PSS should produce a component of electrical torque in phase with the rotor speed deviation. This requires phase-lead circuits to compensate the phase-lag between exciter input (i.e. PSS output) and the resulting electrical torque. The phase characteristic of the system (i.e. *GEP(s)*) depends on the system parameters and the operating condition. The required phase-lead for a given operating condition and system parameters can be achieved by selecting the appropriate value of time constants T_1-T_4.

The time constants of the lead networks are computed so as to compensate the phase angle of the system. Note that $\gamma/2$ as phase angle of the transfer function *GEP(s)* is computed for $s=j\omega_n$. Hence T_1 and T_2 are computed as follows.

$$T_1 = \alpha.T_2 \tag{16}$$

$$T_2 = 1/\omega_n.\sqrt{\alpha} \tag{17}$$

Where:

$$\alpha = \frac{1+\sin(\gamma/2)}{1-\sin(\gamma/2)} \tag{18}$$

$$\gamma/2 = \tan^{-1}\left[\frac{\omega_n(T_a + K_3.T'_{do})}{1 + K_a.K_3.K_6 - \omega^2.T_a.T'_{do}.K_3}\right] \tag{19}$$

B. 3. Stabilizer gain

Stabilizer gain for desired damping ratio ζ_n will be computed by the following equation:

$$K_{PSS} = \frac{2.\zeta.\omega_n.M}{|G_c(j\omega_n).GEP(j\omega_n)|} \tag{20}$$

IV. Simulation Results

In this section to show the dynamic improvement, a power system stabilizer is designed for combined model of LFC and AVR. Simulations are performed for a possible operating condition of power system.

In this simulation the performance of the proposed method is compared with combined LFC-AVR model and also a classic model of a load frequency control system ignoring AVR loop and excitation system. Note that the simulations are done using MATLAB platform. The power system parameters are given in Tables II, III and IV (Appendix).

This simulation is performed assuming that the real power is 0.9 pu, reactive power is 0.6 pu and the machine terminal voltage deviation is 0.091 pu. For the LFC system, the load change in real power is set at 10%. Note that Values of the K_1-K_6 parameters in this condition are presented in Table I. details about calculation of these parameters are given in [3].

TABLE I
K_1-K_6 Parameters in Proposed Combined Model

K_1	K_2	K_3	K_4	K_5	K_6
0.3457	1.8530	0.3794	0.1632	0.0674	1.0304

The frequency deviation, plant power change, deviation of internal electrical power and deviation of terminal voltage are shown in Figs. 4–7, respectively.

Based on Fig. 4 is clear that by using proposed power system stabilizer on this combined model, better dynamic response is accessible. It is clear that frequency oscillations are effectively damped out around 4 s.

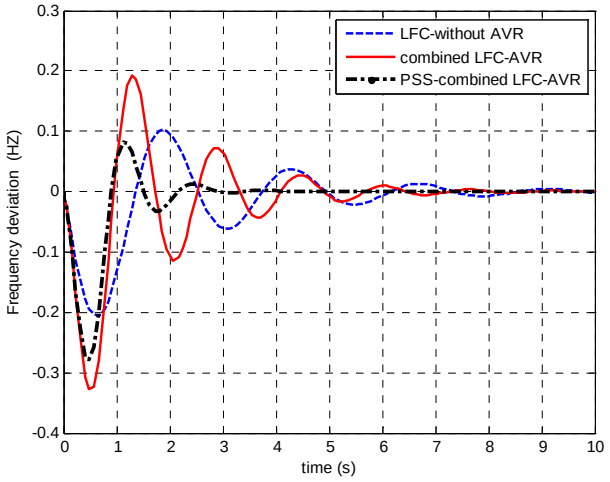

Fig. 4. Frequency deviation (Hz)

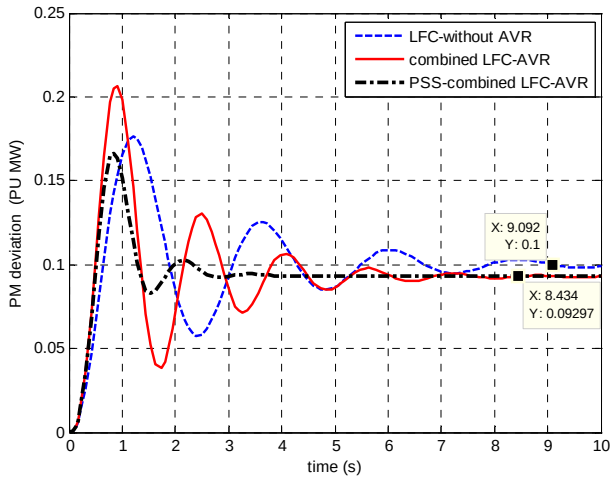

Fig. 5. Turbine output power dynamic response (pu MW).

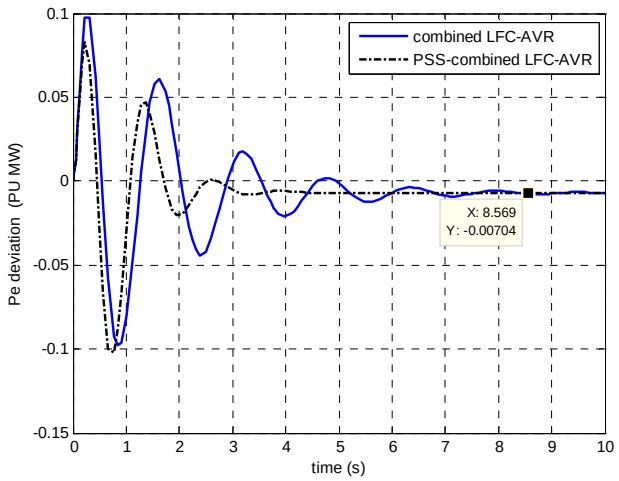

Fig. 6. Internal electrical power deviation (Pu. MW).

From Fig. 5, it should be pointed out that beside of important effects of AVR loop on the steady state output, because of designed PSS, the dynamic responses of this turbine output are improved.

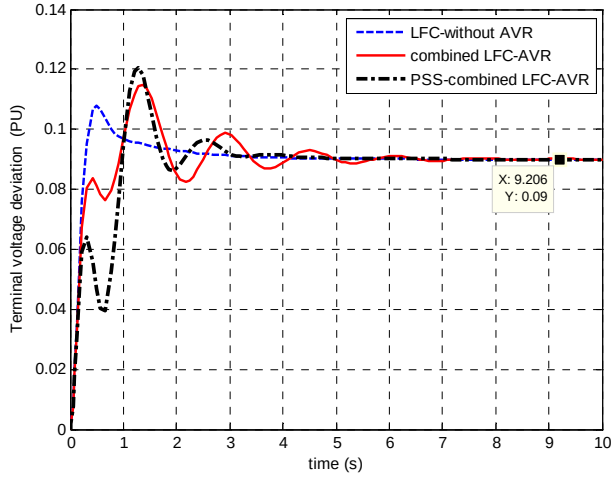

Fig. 7. Terminal voltage deviation (pu).

The load change in real power is set at 0.1 pu and as shown in Fig. 5, the output of turbine decrease to 0.0929 pu. This reduction is about 8% and is supplied from AVR loops. Also as shown in Fig.6, dynamic response of internal electrical power deviation from AVR loop is improved and the steady state value is about 0.007 pu. Also as shown in Fig. 7, with comparing the responses of combined model without PSS and a combined model without PSS, it is clear that a better damping for terminal voltage oscillations is accesible (after 4 s) with using PSS.

V. Conclusion

A power system stabilizer is proposed and carefully redesigned for a combined model of LFC and AVR loops. It is necessary to pay more attention about mutual effects between LFC and AVR loops in power system dynamic stability studies. In this paper, dynamic and also steady state responses of this model are investigated for one-area power system. Based on these simulations it is clear that by using a coordinated PSS to a combined model of LFC and AVR, better dynamic stability is accessible.

VI. Appendix

Complete information about the power system parameters and constants for the LFC system, one machine-infinite bus model and excitation control system are given in Tables II, III and IV, respectively.

TABLE II
Turbine and Governor System Parameters for LFC

K_P (pu/Hz)	T_P (pu/Hz)	T_T (s)	T_G (s)	R (Hz /pu)
102	20	0.32	0.06	1.7

TABLE III
One Machine Infinite Bus Model Parameters (pu)

X_d	X_q	X'_d	r_a	T'_{do}	R_L	X_L
1.973	0.82	0.1	0.003	7.76	0.004	0.74

TABLE IV
EXCITATION CONTROL SYSTEM AND LOCAL LOAD PARAMETERS

Excitation system (pu)				Local load (pu)	
K_a	T_a	K_r	T_r	G	B
20	0.05	1	0.05	0.89	0.862

VII. REFERENCES

[1] P. Kundur, *Power System Stability and Control*, McGraw-Hill Inc., 1994.

[2] Yau-NaN yu, *Electric Power System Dynamics*, London, Academic Press, 1983.

[3] E.Rakhshani, K.Rousbehi and S.Sadeh, "A New Combined Model for Simulation of Mutual Effects between LFC and AVR Loops", in *Proc. Asia-Pacific Power and Energy Engineering Conf.,* vol. 2, pp. 1480-1485, March. 2009.

[4] S. C. Tripathy, N. D. Rao, and L. Roy, "Optimization of exciter and speed governor control parameters in stabilizing intersystem oscillations with voltage dependent load characteristics," *Electric Power and Energy Systems,* vol. 3, pp. 127–133, Jul. 1981.

[5] K. Yamashita and H. Miyagi, "Multivariable self-tuning regulator for load frequency control system with interaction of voltage on load demand," in *Proc. 1991 IEE Control Theory and Applications Conf*., vol.138, pp. 177-183.

[6] E. Rakhshani and J. Sadeh, "A Reduced-Order Control with Prescribed Degree of Stability for Two-Area LFC System in a Deregulated Environment", in *Proc. 2009 IEEE PES Power Systems Conference & Exhibition (PSCE09).*

[7] J. Sadeh and E. Rakhshani, "Multi-area load frequency control in a deregulated power system using optimal output feedback method," *5th International Conf. on European Electricity Market*, pp.1-6, May. 2008.

VIII. BIOGRAPHIES

Elyas Rakhshani was born in Mashhad, Iran in 1982. He received the B.Sc. degree in the power engineering from Islamic Azad University of Iran, Birjand branch, Iran in 2004 and M.Sc. degree in Control Engineering from Islamic Azad University of Iran, Gonabad branch, Iran in 2008. His research interests are Power System Control, Dynamics and Operation, Optimal Control and Neural Computing.

Javad Sadeh was born in Mashhad, IRAN in 1968. He received the B.Sc. and M.Sc. in electrical engineering from Ferdowsi University of Mashhad in 1990 and 1994 respectively and the Ph.D from Sharif University of Technology, Tehran Iran with the collaboration of the electrical engineering laboratory of the National Polytechnic Institute of Grenoble (INPG), France in 2000. Since then he served as an assistant professor at the Ferdowsi University of Mashhad. His research interests are Power System Protection, Electromagnetic Transients in Power System and Restructuring.