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A PI Controller Based on Gain-Scheduling for Synchronous Generator

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Abstract

In this paper a gain- scheduling scheme of a proportional integral (GSPI) controller is proposed for a synchronous generator. In presented scheme, both proportional and integral gains are allowed to vary within a predetermined range. In order to validate the effectiveness of GSPI controller, simulation studies for a single-machine infinite bus power system are used .The results verify improved performance of GSPI controller comparing to conventional AVR under various operating conditions.

Key Words: *Gain-Scheduling PI Controller, Single machine infinite bus, Conventional AVR, Ground fault.*

1. Introduction

Synchronous generator excitation control is one of the most important measures to enhance power system stability and to guarantee the quality of electrical power it provides. The main control function of the excitation system is to regulate the generator terminal voltage which is accomplished by adjusting the field voltage with respect to the variation of the terminal voltage [1,2]. Classical methods that make use of linear models for designing controllers are valid only on small variation around an operating point. A number of new control theories and methods have been introduced to design high performance excitation controllers to deal with the problem of transient stability for nonlinear synchronous generator models. Among them the Lyapunov method [3,4], singular perturbation methods, feedback linearization and sliding mode control [5,6], linear optimal control, the adaptive control method associated with neuro technique [4,7-9], the fuzzy logic control theory [10-12] and the nonlinear controller along with an observer [13-14] are the most commonly used ones.

In the adaptive methods the control laws such as model reference adaptive control and self tuning regulator are nonlinear control laws which are difficult to derive. Furthermore the complexity grows geometrically with the number of unknown parameters. Main drawback of nonlinear control, adaptive or not, is lack of non measurable variable for feedback and are more complicated systems to be implemented. The importance of studying neural network based control methods is revealed in the fundamental difficulties of the current adaptive control technique. Neural network have been applied to the identification and control of nonlinear dynamical systems, but this control approach need state information or plant models. They spent extensive time for online training of neural networks. Fuzzy logic controller has many advantages such as simple in structure and relatively easy to be realized. Mathematical model of the controlled system is not required. Variations of the parameters and operating conditions of the controlled system do not significantly affect the performance of the controller. However the disadvantages such as designing logic controller need expertise of the human expert and determining parameters of controller by trial and error limits its application.

To overcome some drawbacks mentioned above, a continuous gain-schedule rule used to design a simple controller with ease of implementation. In recent years a great deal of research has concerned the gain-scheduling problem both theoretically and practically. The popular engineering method for system controlling concerns a widely varying dynamics domain [15-18]. In this paper, we proposed a gain-scheduling scheme for a proportional-integral controller for voltage control of a synchronous generator modelled by a standard third-order model on the basis of the physically measurements of terminal voltage. Mechanical power is assumed to be constant. For varying operating conditions it is necessary to know the range over which the proportional and integral gain could vary. Actual proportional and integral gains are then allowed to vary within the predetermined range depending on the operation point and hence the error (voltage) signal. When the voltage error is grate, a large proportional gain is used to increase the control effort in order to accelerate or decelerate the voltage to its desired level as quickly as possible. In the other case, when the voltage error is small a large value of the integral gain is used to overcome the steady-state error.

The performance of the proposed scheme is examined for voltage control application of synchronous generator drive through simulation studies using the SLMULINK toolbox of the MATLAB software package. Simulation results show improvement in transient as steady-state performances over the conventional fixed-gain controller.

2. A Power System Dynamic Model

In this paper, a simplified dynamic model of a power system, named a single-machine infinite-bus (SMIB) power system is considered [19-20]. This model is consisted of a single synchronous generator connected through a parallel transmission line to a very large network approximated by an infinite bus. The model is shown in Figure 1. The classic third order single- axis dynamic model of the SMIB power system (Figure 1) can be written as follows [19, 21]:

2.1. Mechanical equations

$$\dot{\delta}\ (t) = \omega\ (t) - \omega_0 \tag{1}$$

$$\dot{\omega}\,(t) = -\frac{D}{2H}\,(\omega\,(t) - \omega_0) - \frac{\omega_0}{2H}\,(P_e\,(t) - P_m) \tag{2}$$

The mechanical input power P_m is treated as a constant in the excitation controller design, i.e., it is assumed that the governor action is slow enough not to have any significant impact on the machine dynamics.

2.2. Electrical generator dynamics

$$E_q'\,(t) = \frac{1}{T_{do}'}\,(E_f\,(t) - E_q\,(t)) \tag{3}$$

2.3. Electrical equations (assumed $x'_d = x_q$)

$$E_q(t) = E'_q(t) + (x_d - x'_d)\ I_d(t) \tag{4}$$

$$E'_f(t) = k_c u_f(t) \tag{5}$$

$$P_e(t) = \frac{E'_q(t)\ V_s}{x'_{ds}} \sin\ \delta\ (t) \tag{6}$$

$$I_d(t) = \frac{E'_q(t) - V_s \cos\ \delta\ (t)}{x'_{ds}} \tag{7}$$

$$I_q(t) = \frac{V_s}{x'_{ds}} \sin\ \delta\ (t) \tag{8}$$

$$Q(t) = \frac{E'_q(t)\ V_s}{x'_{ds}} \cos\ \delta\ (t) - \frac{V_s^2}{x'_{ds}} \tag{9}$$

$$E'_q(t) = x_{ad} I_f(t) \tag{10}$$

$$V_t(t) = \left[\left(E'_q(t) - x'_d I_d(t)\right)^2 + \left(x'_d I_q(t)\right)^2\right]^{\frac{1}{2}} \tag{11}$$

More details about power system modelling can be seen in [15,21]. The definition of the above parameters is as follows:

$\delta\ (t)$ Power angle of the generator, radians

$\omega\ (t)$ Rotor speed of the generator, radian/s

P_m Mechanical power, p. u.

$P_e(t)$ Active electrical power delivered by the generator, p. u.

$E'_q(t)$ Transient EMF in the quadratic axis of the generator, p. u.

$E_f(t)$ Equivalent EMF in the excitation coil, p. u.

$V_t(t)$ Generator terminal voltage, p. u.

$u_f(t)$ Input of the SCR amplifier of the generator

V_s Infinite bus voltage, p. u.

$$x_{ds} = x_d + x_T + x_L\ , \qquad x'_{ds} = x'_d + x_T + x_L\ , \qquad xs = x_T + x_L$$

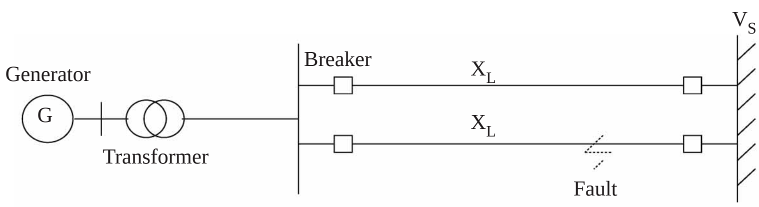


Figure 1. A single machine infinite bus power system.

2.4. Linear model of SMIB

By linearlizing the above equations on at operating point we have the state variable model of a single machine to infinite bus as below:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{12}$$

Where state variable x is defined by:

$$x = [\Delta\delta, \Delta\omega, \Delta E'_q] \tag{13}$$

The control input $u = \Delta u_f$ and the output $y = \Delta V_t$. In the above system matrix A, B, and C are represented by:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{\omega_0}{2H}\frac{V_s}{x'_{ds}}E'_q\cos\delta & -\frac{D}{2H} & -\frac{\omega_0}{2H}\frac{V_s}{x'_{ds}}\sin\delta \\ -\frac{(x_d - x'_d)}{T'_{do}}\frac{V_s}{x'_{ds}}\sin\delta & 0 & -\frac{1}{T'_{do}} - \frac{(x_d - x'_d)}{T'_{do}}\frac{1}{x'_{ds}} \end{bmatrix}_0 \quad B = \begin{bmatrix} 0 \\ 0 \\ \frac{k_c}{T'_{do}} \end{bmatrix}$$

$$C = \left[\frac{(E'_q - x'_d I_d)}{V_t}\left(\frac{-x'_d}{x'_{ds}}\right)V_s\sin\delta + \frac{x'^2_d I_q)}{V_t}\left(\frac{V_s}{x'_{ds}}\right)\cos\delta \quad 0 \quad \frac{(E'_q - x'_d I_d)}{V_t}\left(1 - \frac{x'_d}{x'_{ds}}\right) \right]_0 \tag{14}$$

Where subindex 0 show that matrices are calculated at operating point.

3. Controller Structure

The gain scheduling PI voltage controller that applied in generator is shown in Figure 3 and mathematically can be described by equation (15).

$$\Delta u_f\ (t) = k_p\,(t)\ e\ (t) + k_i\,(t)\int e\ (t)\ dt \tag{15}$$

Where $e\ (t) = V_{ref}\,(t) - V_t\,(t)$ and the proportional gain, $k_p\ (t)$ and integral gain $k_i\ (t)$ are function of the voltage error e(t). The proportional gain $k_p\ (t)$ as the function of the error signal e(t) can be expressed mathematically as follows:

$$k_p\ (t) = k_{p(\max)} - \left(k_{p(\max)} - k_{p(\min)}\right)\ \exp^{-(a|\,e(t)|\,)} \tag{16}$$

Where a is constant, $k_{p(\max)}$ and $k_{p(\min)}$ are the maximum and minimum values of the proportional gain k_p .

From equation (16) it can be seen that when e(t) is large the exponential term approaches zero $\left(\exp^{-(a|\,e\,(t)|)} \to 0\right)$ and therefore $k_p\ (t) = k_{p(\max)}$. Similarly, when error e(t) is small the exponential term approaches 1 $\left(\exp^{-(a|e(t)|)} \to 1\right)$ and hence $k_p\ (t) = k_{p(\min)}$. In this variation k_p is carried out by the voltage controller i.e. when the error e (t) is large we expect a large proportional gain to increase the control signal's voltage up to the transient response and when the error e(t) is small, we expect a minimum proportional gain, $k_{p(\min)}$ to overcome the undesirable problem of overshoot. This variation in the proportional gain is choice of the constant "α" to decide the rate at which $k_p\ (t)$ varies between the maximum and minimum values of the proportional gain.

The integral gain $k_i\ (t)$ in equation (17) as a function of voltage error signal e(t) can be expressed mathematically as follows:

$$k_i\,(t) = (1 - \alpha\,(t))\ k_{i(\max)} \tag{17}$$

Where $0 \leq \alpha\ (t) \leq 1$ and $k_{i(\max)}$ is the maximum value of the integral gain. Depending on the extreme values of $\alpha\ (t)$ the integral gain $k_i\ (t)$ varies in the range of $0 \leq k_i\ (t) \leq k_{i(\max)}$. When the system is in steady-state error and error e(t) is large we need a small integral gain, $k_{i(\min)} = 0$ in order to overcome the undesirable oscillation and overshoot. Instead of a drastic change in $\alpha\ (t)$ from 0 to 1 or vice-versa, it is desirable to have a smooth variation in $\alpha\ (t)$. This can be achieved by using the following equation (18).

$$\alpha\ (t) = \tanh\ (\eta\beta\ (t)) \tag{18}$$

Where

$$\beta\ (t) = \begin{cases} 1 & \text{if} \quad |e\,(t)| \geq \varepsilon > 0 \\ 0 & \text{if} \quad |e\,(t)| \leq \varepsilon \end{cases} \tag{19}$$

Thus, $\alpha\ (t)$ is an increase of $|e\ (t)|$, and converge to either 1 or 0 as $|e\ (t)|$ approaches infinity or enters the range $0 \leq |e\ (t)| \leq \varepsilon$ as shown in Figure 2. Therefore, it can be stated that

$$\alpha\,(t) = \begin{cases} 1 & \text{if} \quad |e\,(t)| >> \varepsilon \\ 0 & \text{if} \quad |e\,(t)| << \varepsilon \end{cases} \tag{20}$$

The value parameter η in equation (18) determines the rate at which $\alpha\ (t)$ changes between zero and one. In this task the values of η and ε are chosen as 0.1 and $0.9\,V_{ref}\,(pu)$ respectively. At the beginning of the parameter transition period a large control signal is required to accelerate or decelerate the voltage generator to the reference value within the shortest possible time. In order to produce a large control signal, the gain-scheduled PI controller should have a large proportional gain, $k_p\,(t)$ which is ensuring with the use of equation (16). During this period the integral gain, $k_i\ (t)$ is reduced to its minimum value.

Alternatively, during steady-state period the integral gain, $k_i\ (t)$ is increase to its maximum value to overcome the steady-state error. Therefore, based on equation (16) and (17) the proportional gain. $k_p\,(t)$ and the integral gain, $k_i\ (t)$ are varied on-line as a function of voltage error e(t). This improves the transient and steady-state performance of the PI voltage controller.

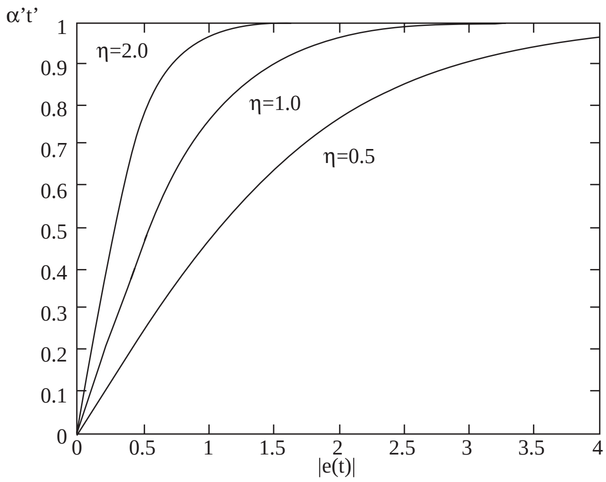


Figure 2. variation of $\alpha\ (t)$ for $\varepsilon = 1$ and for different value of η.

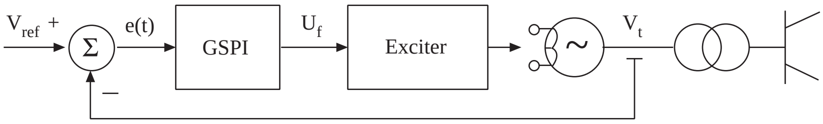


Figure 3. Gain scheduling PI (GSPI) controller for synchronous Generator.

4. Simulation Results

The performance of gain scheduling PI controller is examined trough simulation studies using the SIMULINK toolbox of the MATLAB software package. A generator schematic block diagram of the proposed controller is as shown in Figure 3.

The prefault conditions of the system are:

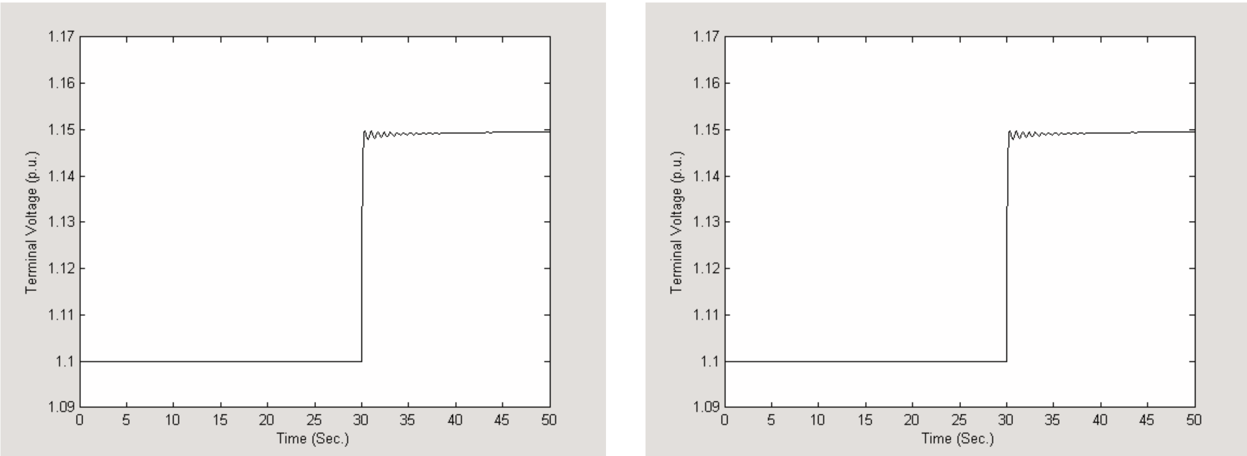
$$\begin{aligned} &x_d = 1.863 \quad x'_d = 0.257 \quad x_T = 0.127 \quad x_L = 0.4853 \\ &x_{ad} = 1.712 \quad H = 4 \quad D = 5 \quad \omega_0 = 314159 \quad k_c = 1 \\ &x_{ds} = 1.7112 \quad x'_{ds} = 0.62665 \quad x_s = 0.36965 \quad T'_{do} = 6.9 \\ &\delta_0 = 29.8^0 \quad P_{mo} = 0.7 \quad V_{to} = 1.1 \end{aligned} \tag{21}$$

4.1. Response of controller for step change in reference voltage

The performance of GSPI controller in step change of voltage is shown in Figure 4. In this case we change reference voltage and consider the performance of proposed controller in this condition. It is clear from this Figure that GSPI controller has good performance in tracking of system and also the power system is stable and has good transient response.

To show the performance clearly for better comparison, the GSPI AVR and conventional AVR are considered in Figure 5.

With the generating unit operating at 0.7 pu power, 0.866 pf lag and terminal voltage of 1.1 p.u., a 0.055 step increase in voltage reference is applied at 15s. At time 30s, the change in input reference voltage is removed and the system returns to its original operating condition.



(a) Terminal voltage (b) Power angle response

Figure 4. performance of gain-scheduling controller (GSPI) as AVR

As shown in Figure 5, the system response with the GSPI-AVR has small effect on the active power while changing the terminal voltage. It is also clear from this figure that the GSPI-AVR presents a good tracking and has a good transient performance.

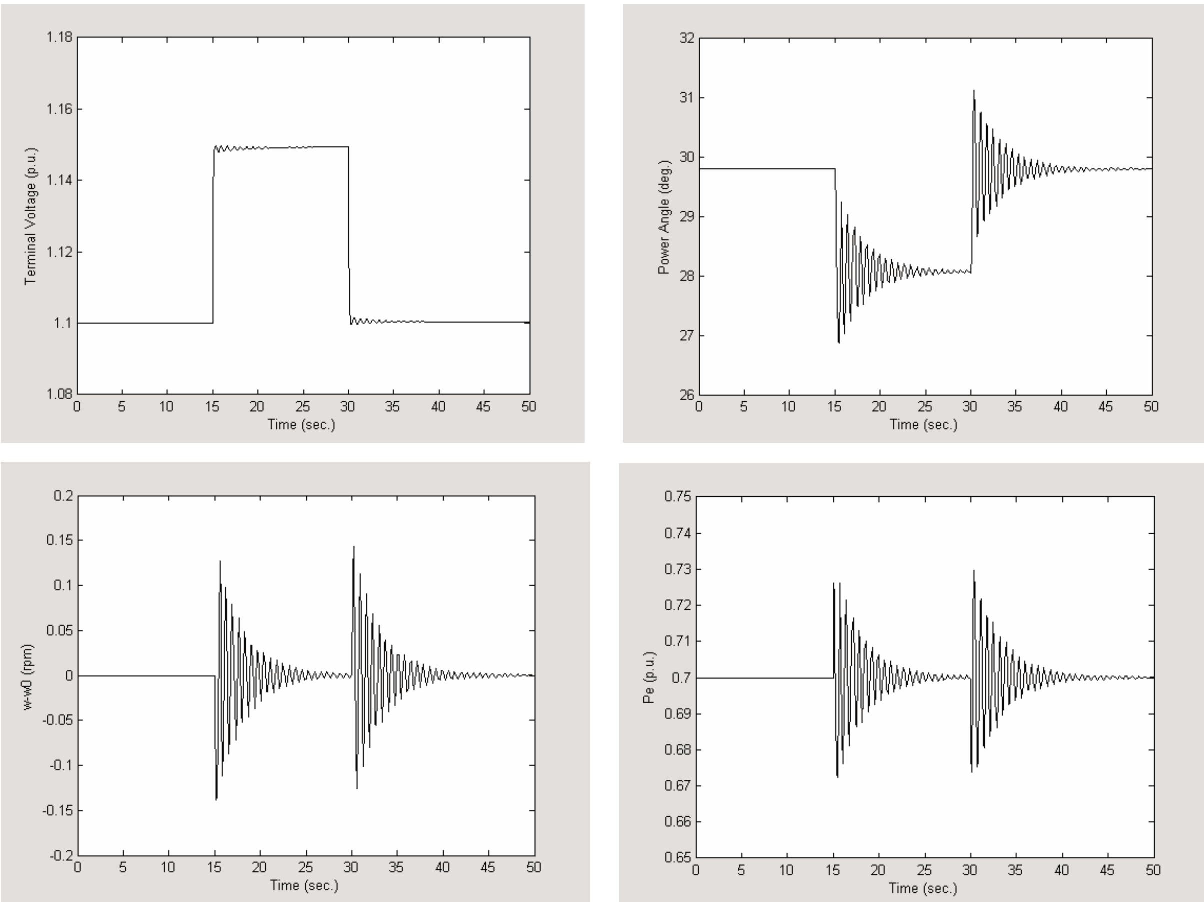


Figure 5. system response to 0.055 pu step disturbance in voltage reference using GSPI controller.

For a better demonstration of performance the response of GSPI-AVR and Conventional AVR are shown in this case (Figure 5 and Figure 6). It is clear that GSPI-AVR has better performance in tracking and better transient performance.

4.2. Three-phase short circuit test

With the generating unit operating at 0.7 pu power, 0.866 pf lag and terminal voltage of 1.1 pu, a transient test was conducted to test the performance of the GSPI controller in response to a disturbance. In this test a three-phase to ground short circuit was applied at half of one transmission line, and the fault was cleared 100 ms later by disconnecting the line. The disconnected line is successfully reconnected after 1 sec.

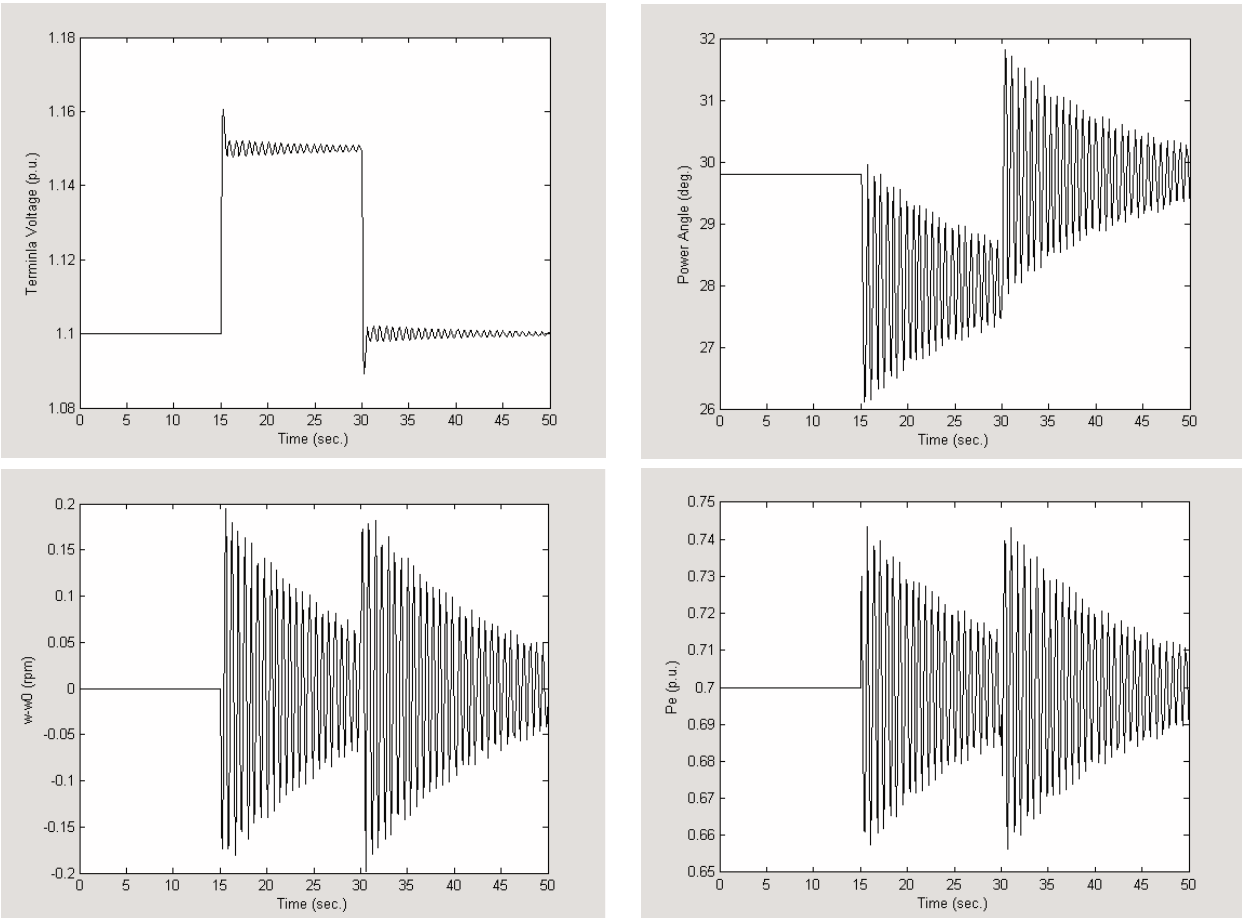


Figure 6. system response to 0.055 pu step disturbance in voltage reference using conventional AVR

In can be seen from Figure 7 that the GSPI-AVR can retain the system stability and keep stable the system operation. For best showing the performance of GSPI controller we consider the performance of conventional AVR in this condition in Figure 8. It is clear that in this condition the GSPI controller has better transient response and system has less oscillation in magnitude and frequency.

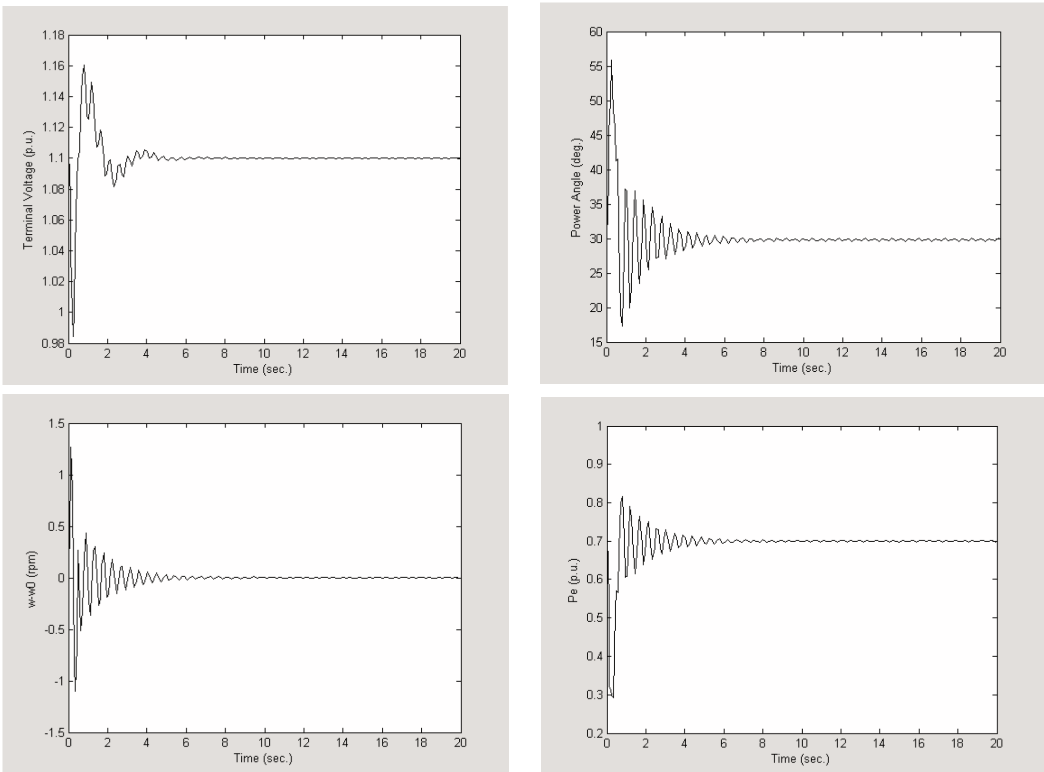


Figure 7. system response to a three-phase to ground fault using GSPI controller.

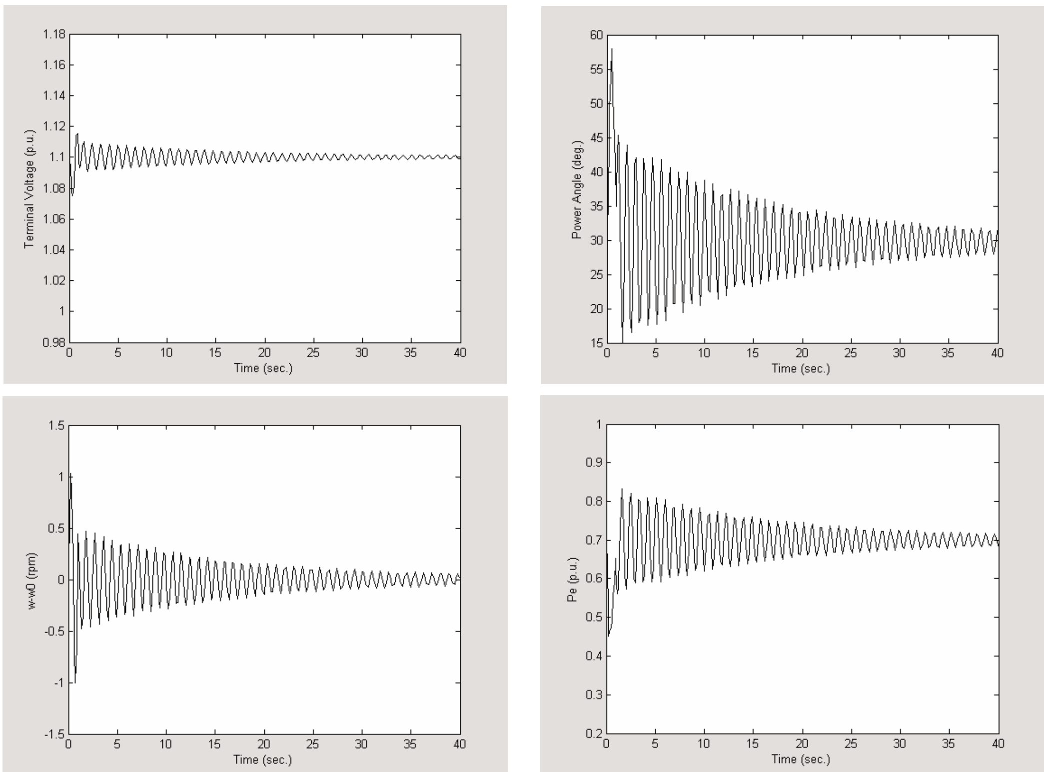


Figure 8. system response to a three-phase to ground fault using conventional AVR.

5. Conclusion

A gain-scheduling PI controller for a synchronous generator is presented in this paper. In this GSPI controller the proportional and integral gains are allowed to vary with in pre-determined range. Simulation studies for a single-machine power system environment are presented to demonstrate the effectiveness of using the GSPI controller. In this case we compared gain-scheduling PI controller with conventional AVR to show the performance of this controller. The two major prevalent faults in a power system we used are change in reference voltage and short circuit.

References

[1] Anderson P. M., A. A. Fouad, "Power System Control and Stability", Iowa State University Press Ames, Iowa, 1977.

[2] B. M. Weedy, B. J. Cory, "Electric Power System", John Wiley & Sons Ltd., Baffins Lane, Chichester, West Sussex, England, Fourth Edition, 1998.

[3] Machowski J, Bialek JW, Robak S, Bumby JR, "Excitation control system for use with synchronous generators", IEE Proceedings- Generation Transmission and Distribution, 145 (5): 537-546 September 1998.

[4] M. M. Salem, O. P. Malik, A. M. Zaki, O. A. Mahgoub, E. A. El-Zahab, "Simple Neuro-Controller with a Modified Error Function for a Synchronous Geberator", Electrical Power and Energy Systems 25, pp. 759-771, 2003.

[5] Loukianov AG, Canedo JM, Utkin VI, Cabrera-Vazquez J, "Discontinuous controller for power systems: Sliding-mode block control approach", IEEE Transactions on Industrial Electronics 51 (2): 340-353 April 2004.

[6] Jiang L, Wu QH, "Nonlinear adaptive control via sliding-mode state and perturbation observer", IEE Proceedings control Theory and Applications 149 (4): 269-277 July 2002.

[7] Shamsollahi P, Malik OP, "Direct neural adaptive control applied to synchronous generator", IEEE Transactions on Energy Conversion 14 (4): 1341-1346 December 1999.

[8] Park JW, Harley RG, Venayagamoorthy GK, "Adaptive-critic-based optimal neurocontrol for synchronous generators in a power system using MLP/RBF neural networks", IEEE Transactions on Industry Applications 39 (5): 1529-1540 September-October 2003.

[9] Herbert Werner, Petr Korba, Tai Chen Yang, "Robust Tuning of Power System stabilizers Using LMI-Techniques", IEEE Trans. on Control System Technology, Vol. 11, No. 1, pp. 147-152, January 2003.

[10] Wen JY, Cheng SJ, Malik OP, "A synchronous generator fuzzy excitation controller optimally designed with a genetic algorithm", IEEE Transactions on Power Systems 13 (3): 884-889 August 1998.

[11] A. R. Hassan, A. H. M. Sadrul Ula, "Design and Implementation of a Fuzzy Controller Based Automatic Voltage Regulator for a Synchronous Generator", IEEE Trans. on Energy Conversion, Vol. 9, No. 3, September 1994.

[12] Ruhua You, Hassan J. Eghbali, M. Hashem Nehur, "An Online Adaptive Neuro-Fuzzy Power System stabilizer for Multimachine Systems", IEEE Transactions on Power System, Vol. 18, No. 1, pp. 128-135, February 2003.

[13] Damm G, Marino R, Lamnabhi-Lagarrigue F , "Adaptive nonlinear output feedback for transient stabilization and voltage regulation of power generators with unknown parameters", International Journal of Robust and Nonlinear Control 14 (9-10): 833-855 Jun-July 2004.

[14] De Leon-Morales J, Busawon K, Acha-Daza S, “A robust observer-based controller for synchronous generators”, International Journal of Electrical Power & Energy Systems 23 (3): 195-211 March 2001.

[15] Ian Fialho and Gary J. Balas, Road Adaptive Active suspension Design Using Linear Parameter-Varying Gain-Scheduling, IEEE Transactions on Control System Technology, vol. 10, No. 1, pp. 43-51, January 2002.

[16] Daniel J. Stilwell and Wilson J. Rugh, “Interpolation of Observer State Feedback Controllers for Gain Scheduling,” IEEE Transactions on Automatic Control, Vol. 44, No. 6, pp. 1225-1229, June 1999.

[17] Pierre Apkarian, Richard J. Adams, “Advanced Gain-Scheduling Techniques for Uncertain Systems, IEEE Transactions on Control System Technology, Vol. 6, No. 1, pp. 21-32, January 1998.

[18] C. H. Lee, M. H. Shin, N. J. Chung, “A Design of Gain-Scheduled Control for a Linear Parameter Varying System: An Application to Flight Control”, Control Engineering Practice 9, pp. 11-21, 2001.

[19] P. Kundur, “Power System Stability and Control”, in the EPRI Power System Engineering Series, New York, Mc Graw Hill, 1994.

[20] Y. Wang, D. J. Hill, R. H. Middleton, L. Gao, “Transient Stability Enhancement and Voltage Regulation for Power Systems”, IEEE Transactions on Power Systems, Vol. 8, pp. 620-627, 1993.

[21] Y. Guo, D. J. Hill, Y. Wang, “Global Transient Stability and Voltage regulation for Power Systems”, IEEE Transactions on Power Systems, Vol. 16, No. 4, pp.678-688, 2001.