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ON-LINE IDENTIFICATION AND CONTROL THROUGH SERIES CONVERTER VOLTAGE OF A UNIFIED POWER FLOW CONTROLLER

A. H. M. A. Rahim *, S. A. Al-Baiyat

Department of Electrical Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

ABSTRACT

The dynamic performance of a power system can be improved by controlling the voltage magnitude and phase angle of the converter voltages in the unified power flow controller (UPFC). Self-tuning adaptive control of the voltage magnitude of the series converter for stabilization of a power system is presented in this paper. The plant parameters are identified through a regressive least square algorithm and the stabilizing control is derived through a pole-shifting technique using the adaptive plant model. The controller has been tested for ranges of operating conditions and for various disturbances. From a number of simulation studies on a single machine infinite bus power system it was observed that the adaptive algorithm converges very quickly and also provides robust damping profiles.

Keywords

Power System Control, UPFC, Damping Enhancement, Adaptive Control, Pole - Shifting Method.

1. INTRODUCTION

The unified power flow controller (UPFC) is normally used for power transmission networks which require reactive power support. The usual form of a UPFC consists of two voltage source converters, which are connected through a common DC link capacitor. The first voltage source converter, known as static synchronous compensator, injects an almost sinusoidal current of variable magnitude at the point of connection. The second voltage source converter, known as static synchronous series compensator, injects a sinusoidal voltage of variable magnitude in series with the transmission line. The real and reactive power exchange between the converters is affected through the common DC link capacitor. UPFC can be used for power flow control, loop flow control, load sharing among parallel corridors, providing voltage support, enhancement of transient stability, mitigation of system oscillations, and others. [1-3]. The stability and damping control aspect of an UPFC has been investigated by a number of researchers [4-7]. Energy function approaches for determining the stability of a multi-machine system with UPFC has been examined recently [8]. Additional damping control circuits can also be installed in normal power flow controllers. Most of the control studies in power systems are based on linearized models of the nonlinear power system dynamics. The methods include exact linearization, linear quadratic regulator theory, direct feedback linearization, etc. Stabilizers based on conventional linear control theory with fixed parameters can be very well tuned to an operating condition and provide excellent damping under that condition. But they cannot provide effective control over a wide operating range for systems that are nonlinear, time varying and subject to uncertainty. In order to yield satisfactory control performance, it is desirable to develop a controller which has the ability to adjust its parameters from on-line determination of system structure or model according to the environment in which it works. Application of adaptive control theory to excitation control problems is well documented in the literature [9, 10]. Adaptive control of static var controller (SVC) systems has also been reported in the literature [11, 12]. UPFC is relatively new power electronics based device, and its control studies have generally been limited in this regard.

This paper considers an on-line adaptive stabilizing control design procedure of the voltage magnitude of the series converter of the UPFC. The design is carried out through a variable pole shifting method employing the identified plant model parameters which are tuned adaptively. Initial results of the study have been presented in [13].

2. SYSTEM MODELWITH UPFC

Fig. 1 shows a generator connected to a large power system bus through a transmission line installed with UPFC. The UPFC is composed of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSC), and a DC link capacitor [1,4]. m and α refer to amplitude modulation index and phase angle of the control signal of the two voltage source converters (E and B), respectively which can be adjusted through their own control loops.

The dynamics of the synchronous generator-exciter system, the series and parallel connected converters including their transformers and the DC link in the UPEC system can be expressed through a 9th order dynamic relationship:

$$\dot{x} = f[x,u] \qquad (1)$$

Here, the state vector $x = [I_{Ed}\ I_{Eq}\ I_{Ld}\ I_{Lq}\ V_c\ \delta\ \ \omega\ e_q'\ E_{fd}]^T$ and $u=[m_E\ \alpha_E\ m_B\ \alpha_B]^T$. The first 4 states are the d-q components of the shunt and series (line) currents respectively; V_c is the DC capacitor voltage, and the last 4 are those for the

*Corresponding author: *E-mail:* ahrahim@kfupm.edu.sa

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generator-exciter system. The control vector comprises of the magnitude and phase angles of the converter voltages.

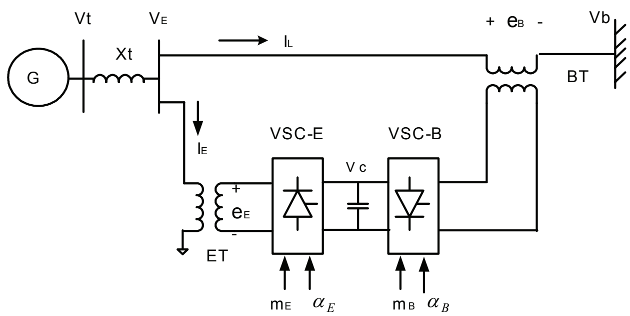

Figure 1. A single machine infinite bus system with UPFC

3. SELF-TUNING ADAPTIVE REGULATOR

Self-tuning control is one form of adaptive control which has the ability of self-adjusting its control parameters according to system conditions. Fig.2 shows the structure of an adaptive regulator. The self-tuning strategy is composed of two processes - the system identifier and the controller. The identifier determines the parameters of the mathematical model of the system from input-output measurement of the plant. The parameters of the identifier are updated at each sampling instant so that it can track the changes in the controlled plant. The control for the plant is then calculated based on this recursively updated system model.

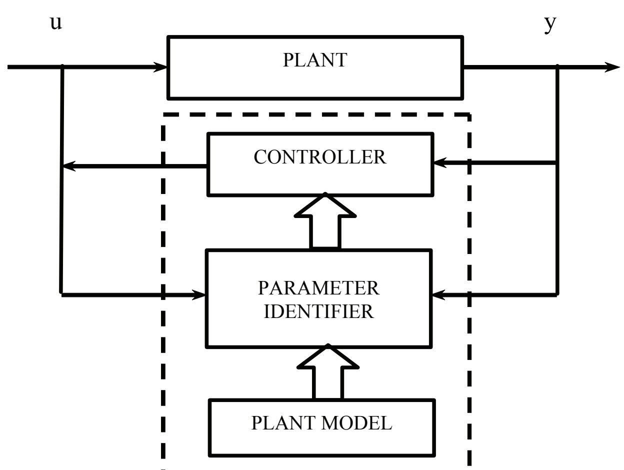

Figure 2. Block diagram of self-tuning controller

The plant model is assumed to be of the form:

$$A(z^{-1})y(t) = B(z^{-1})u(t) + e(t) \tag{2}$$

where, $y(t)$, $u(t)$ and $e(t)$ are system output, input and the white noise, respectively; z^{-1} is the delay operator. The polynomial A and B are defined as:

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + a_4 z^{-4} + ... \tag{3}$$

$$B(z^{-1}) = 1 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} + b_4 z^{-4} + ... \tag{4}$$

The vector of parameters $\theta(t)= [a_1\ a_2........;\ b_1\ b_2.........]^T$ are calculated recursively on-line through the recursive least square [9] technique using:

$$\theta(t+1) = \theta(t) + K(t)\,[y(t) - \theta^T(t)\psi(t)] \tag{5}$$

The measurement vector, modifying gain vector, and the covariance matrix, respectively are:

$$\psi(t) = [-y(t-1)\ y(t-2)......y(t-n_a)\ u(t-1)\ u(t-2).....$$
$$...u(t-n_b)]^T$$

$$K(t) = \frac{P(t)\psi(t)}{\lambda(t) + \psi^T(t)P(t)\psi(t)} \tag{6}$$

$$P(t+1) = \frac{1}{\lambda(t)}[P(t) - K^T(t)P(t)\psi(t)]$$

$\lambda(t)$ is the forgetting factor; n_a and n_b denote the order of the polynomials A and B, respectively. The identified parameters in (5) can be considered as the weighted sum of the previously identified parameters and those derived from the present signals. For systems with constant parameters $\lambda=1$ produces convergence of the algorithm while for systems with time-varying parameter a variable forgetting factor given by [14]:

$$\lambda(t) = \text{trace}[P(t) - K(t)\,\psi^T(t)P(t)]/\text{trace}(P_0) \tag{7}$$

is required to maintain the trace of the error covariance matrix constant. In the above, P_0 is the initial error covariance matrix and P(t) is the matrix at the iteration before discounted by λ. The error covariance matrix is updated at each sampling instant by:

$$P(t) = P(t-1)/\,\lambda\,(t) \tag{8}$$

4. THE POLE-SHIFTING CONTROL

Using the parameters obtained from the real time parameter identification method, a self-tuning controller based on pole assignment is computed on-line and fed to the plant. Under the pole shifting control strategy, the poles of the closed loop system are shifted radially towards the centre of the unit circle in the z-domain by a factor α, which is less than one. The procedure for deriving the pole–shifting algorithm [15] is given below.

Assume that the feedback loop has the form:

$$\frac{u(t)}{y(t)} = -\frac{G(z^{-1})}{F(z^{-1})} \tag{9}$$

where,

$$F(z^{-1}) = 1 + f_1 z^{-1} + f_2 z^{-2} + f_3 z^{-3} + f_4 z^{-4} + ... + f_{nf} z^{-nf}$$

$$G(z^{-1}) = g_0 + g_1 z^{-1} + f_2 z^{-2} + f_3 z^{-3} + f_4 z^{-4} + ... + f_{ng} z^{-ng}$$

$$n_f = n_b - 1, n_g = n_a - 1$$

From (2) and (9) the characteristic polynomial can be derived as:

$$T(z^{-1}) = A(z^{-1})F(z^{-1}) + B(z^{-1})G(z^{-1}) \quad (10)$$

The pole-shifting algorithm makes $T(z^{-1})$ take the form of $A(z^{-1})$ but the pole locations are shifted by a factor α, i.e.

$$A(z^{-1})F(z^{-1}) + B(z^{-1})G(z^{-1}) = A(\alpha\, z^{-1}) \quad (11)$$

Expanding both sides of (11) and comparing the coefficients give,

$$\begin{bmatrix} 1 & 0 & . & 0 & b_1 & 0 & . & 0 \\ a_1 & 1 & . & 0 & b_2 & b_1 & . & 0 \\ . & a_1 & . & . & . & b_2 & . & 0 \\ a_{n_a} & . & . & 1 & b_{n_b} & . & . & b_b \\ 0 & a_{n_a} & . & a_1 & 0 & b_{n_b} & . & b_2 \\ . & 0 & . & . & . & 0 & . & . \\ . & . & . & . & . & . & . & . \\ 0 & 0 & . & a_{n_a} & 0 & 0 & . & b_{n_b} \end{bmatrix} \begin{bmatrix} f_1 \\ . \\ . \\ f_{nf} \\ g_0 \\ . \\ . \\ g_{n_g} \end{bmatrix} = \begin{bmatrix} a_1(\alpha - 1) \\ a_2(\alpha^2 - 1) \\ . \\ . \\ a_{n_a}(\alpha^{n_a} - 1) \\ 0 \\ . \\ 0 \end{bmatrix}$$

The above is written in the form:

$$MZ(\alpha) = L(\alpha) \quad (12)$$

If parameters [$\{a_i\}$, $\{b_i\}$] are identified at every sampling period and pole-shift factor α is known, the control parameters Z= [$\{f_i\}$,$\{g_i\}$}] solved from (12) when substituted in (9) will give:

$$u(t, \alpha) = X^T(t)Z = X^T(t)M^{-1}L(\alpha) \quad (13)$$

Here, $X(t)=[-u(t-1)\ \ -u(t-2).....u(t-n_f)\ \ -y(t)\ \ -y(t-1)\ \ -y(t-2)..........y(t-n_g)]$

The controller objective is to force the system output $y(t)$ to follow the reference output $y_r(t)$. The objective function can then be expressed as:

$$J = \min_{\alpha}[y(t) - y_r(t)]^2 \quad (14)$$

where, $y(t)=b_1u(t) + X^T\beta$; $\beta=[-b_2\ -b_3\ .... \ a_1\ a_2\ ....]$

If the variation of J with respect to α can be made smaller than a predetermined error bound ε_1, it can be shown that a minimum will occur when:

$$\Delta\alpha = \frac{\varepsilon_1 - \frac{\partial J}{\partial \alpha}}{\varepsilon_2 + \frac{1}{2}\frac{\partial^2 J}{\partial \alpha^2}} \quad (15)$$

where, ε_2 is a small number chosen to avoid the singularity in the computation process. This can then be expressed as:

$$\Delta\alpha = \frac{\varepsilon_1 - f_1 f_2}{\varepsilon_2 + \frac{1}{2}[f_1 f_3 + 2b_1^2 f_2^2]} \quad (16)$$

In the above,

$$f_1 = \frac{\partial J}{\partial u};\quad f_2 = \frac{\partial u}{\partial \alpha};\quad f_3 = \frac{\partial^2 u}{\partial \alpha^2}$$

The partial derivatives are evaluated from (13) and (14), and the updates of control is obtained considering first few significant terms of the Taylor series expansion of $u(t, \alpha)$.The algorithm can be started by selecting an initial value of α and updating it at every sample through the relationship,

$$\alpha\,(t) = \alpha(t-1) + \Delta\,\alpha \quad (17)$$

The control function is limited by the upper and lower limits and the pole shift factor should be such that it should be bounded by the reciprocal of the largest value of characteristic root of $A(z^{-1})$. The latter requirement is satisfied by constraining the magnitude of α to unity.

5. CONTROLLER PERFORMANCE

For the power system considered in Fig.1, the input and output of the plant were considered to be the series converter voltage magnitude (m_E) of the UPFC and the generator speed variation ($\Delta\omega$), respectively. In order to excite the plant, a sequence voltage steps and torque pulses in the regulator-exciter and generator shaft, respectively were applied. The diagonal elements of the initial covariance matrix P is assumed be $2x10^5$; the initial pole shift factor 0 and the forgetting factor 1 were used. The starting values of all the parameters were considered to be 0.001 in all the simulations for consistency. The model order to be estimated was assumed to be 3. Fig.3 shows the generator speed deviation with no control when excited by a sequence of voltage steps of +5%, -5%, +5% and -5% in the exciter. The nominal loading is 0.85 pu at 0.9pf lagging. The generator terminal voltage at this load is 1.07 pu and the bus voltage is 1 pu. Fig.4 shows the variation of the generator speed with the pole-shift control applied to the identified process.

The response with and without adaptive pole-shift controller for a sequence of alternate torque pulses are shown in Fig. 5 and 6, respectively. From Figs 3-6, it is apparent that the electromechanical transients are damped very well by the adaptive controller. The plant parameters are unknown at the start of the estimation process giving rise to very large overshoots. However, as the estimation process progresses, the plant parameters are identified more and more accurately to yield better updates of the pole shift factor, and hence providing better damping profiles.

The convergence of the {a} and {b} parameters in the adaptive algorithm are shown in Figs. 7 and 8, respectively. Fig. 9 shows the convergence of the pole shift factor as the estimation process progresses. It can be observed that the estimation algorithm converges to the desired values rapidly. The convergence of the algorithm is independent of the initial choice of the pole shift factor α.

6. TESTING CONTROLLER ROBUSTNESS

A number of case studies were performed with the adapted system model and the pole shift parameters arrived at in the previous section. For a 50% input torque pulse on the generator, the rotor angle variations recorded for 5 operating conditions are shown in Fig.10. These are for generator outputs of a) 1.1 pu, b) 1.02 pu, c) 0.85pu, d)0.78 pu, and e)0.6pu. It can be observed that the damping properties are very good for the whole range of operation considered. Fig. 11 shows the transient angle variations of the generator with the proposed adaptive control strategy for severe three-phase fault of 0.1s duration for the loadings considered in Fig.10. It is to be noted that without control the system is under damped, in general, and unstable in some cases. Fig. 12 shows the response without control (--) and with control (-) for the three phase fault condition at 1.1 pu loading 'a'. Fig.13 shows the variations of the generator terminal voltage for three loading conditions (a) 1.1pu, (b) 1.02 and (c) 0.85 pu. It can be seen that the control strategy restores the voltage very quickly from a total collapse. All these simulation results indicate good dynamic behavior of the power system with the adaptive UPFC controller.

7. CONCLUSIONS

An adaptive control technique has been used to enhance the dynamic performance of a power system installed with unified power flow controller. The control employed is the magnitude of the series converter voltage. The proposed stabilizing technique identifies the plant model and generates a control to stabilize the closed-loop system employing a pole shift technique adaptively. The algorithm has been shown to converge to estimated parameter model rapidly. The on-line controller has demonstrated to provide very good damping to the system transients. The robustness of the control strategy was tested by simulating different types of faults covering a number of operating states. It was observed that the control provides robust performance over the range of power system operation considered.

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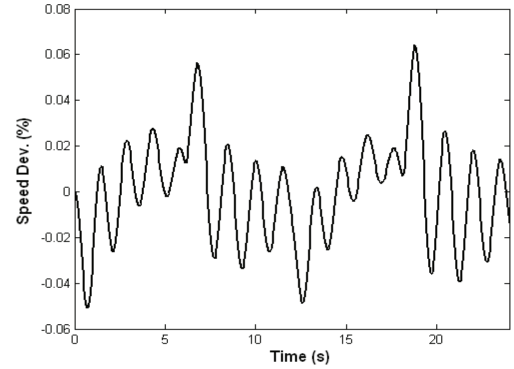

Figure 3. Speed variation of generator in the absence of any control when subjected to sequence of voltage steps at 0,6,12,18s in the exciter-regulator

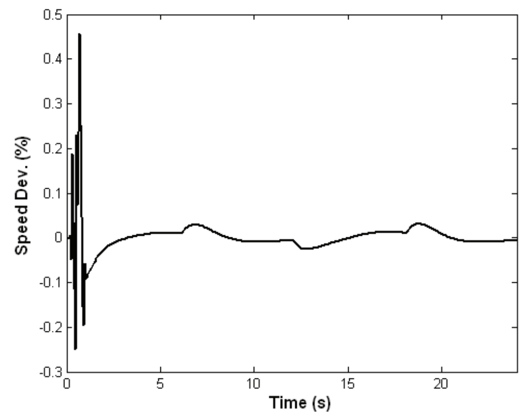

Figure 4. Generator speed variation corresponding to Fig.3 with adaptive pole-shift control

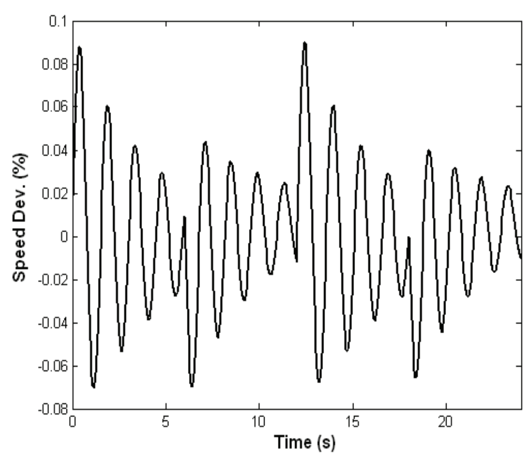

Figure 5. Speed variation of generator in the absence of any control when subjected to sequence of input torque steps at 0,6,12,18s

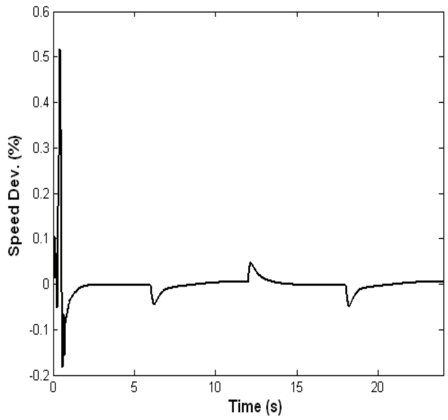

Figure 6. Generator speed variation corresponding to Fig.5 with adaptive pole-shift control

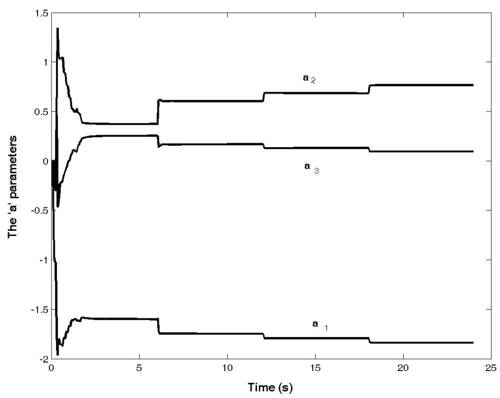

Figure 7. Online adaptations of the ‘a’ parameters in the model function

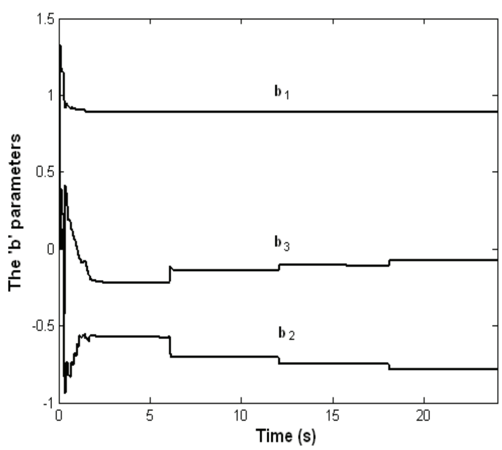

Figure 8. Online adaptations of the ‘b’ parameters

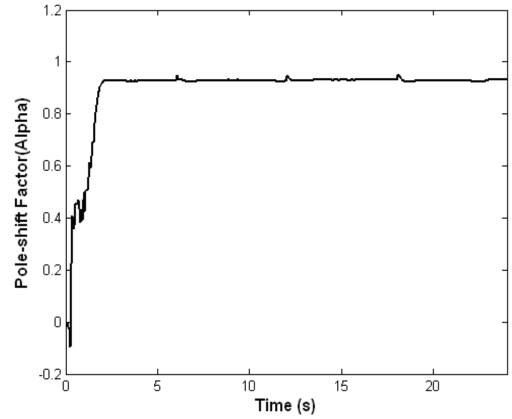

Figure 9. Online adaptation of the pole shift factor

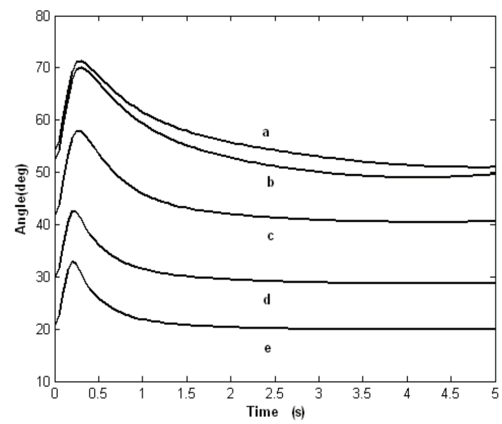

Figure 10. Generator rotor angle variations following 50% torque pulse for 5 loading conditions.

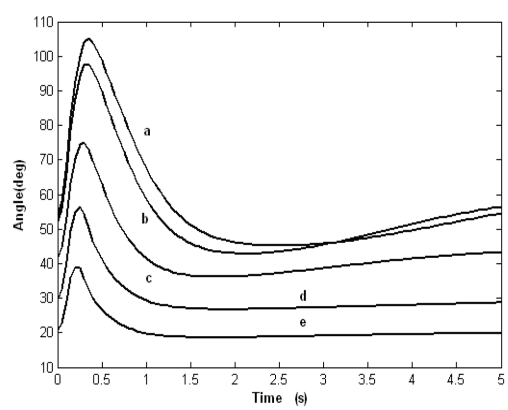

Figure 11. Generator rotor angle following a three-phase fault for the loadings as in Fig. 9

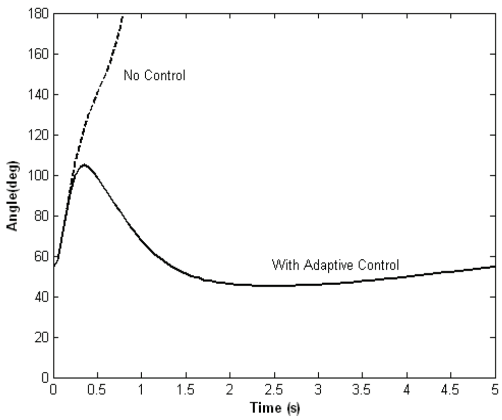

Figure 12. Comparison of response without control and the proposed adaptive control following three-phase fault at 1.1 pu loading 'a'

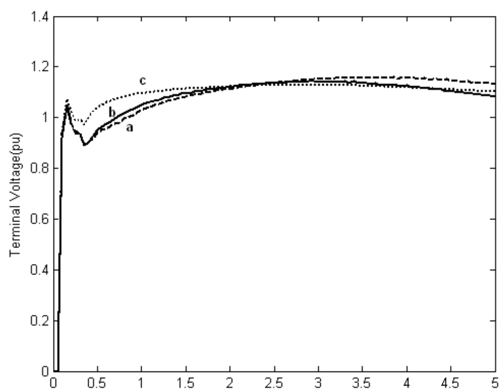

Figure 13. Terminal voltage variation of generator following three-phase fault for different loading conditions

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Biographies

Abu H.M.A. Rahim received his B.Sc. in Electrical Engineering from Bangladesh University of Engineering and Ph.D. from University of Alberta, Edmonton. Since his Ph. D., Dr. Rahim has worked at the University of Alberta, Bangladesh University of Engineering, University of Strathclyde, University of Bahrain, University of Calgary and at the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, where he is a Professor in the Department of Electrical Engineering.

Samir A. Al-Baiyat obtained his B.Sc. and M.Sc. degrees in Electrical Engineering from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia in 1977 and 1980 respectively, and his Ph.D. from the University of Norte Dame, U.S.A. in 1986. Dr. AL-Baiyat joined the KFUPM faculty in 1986, where he is now a Professor and Dean of the College of Engineering.