極配置에 의한 同期發電機의 電壓制御器 設計

論 文
34~12~3

Voltage Controller Design of Synchronous Generator by Pole Assignment

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요 약

長距離高力率 運轉되는 發電機는 재래의 電壓調整器(AVR)로서는 動態安定度가 低下하여 定格出力運轉이 不可能한 경우가 있으며 특히 超速應勵磁方式의 AVR에서 이와 같은 現象이 經驗되고 있다.

本研究에서는 이러한 發電機의 動態安定度를 改善하기 위하여 極配置技法에 의하여 電壓 制御器를 設計하고 그 有用性을 보이기 위하여 컴퓨터시뮬레이션한 結果, 動態安定度와 制御性能이 在來式 電壓制御에 비하여 현저히 改善되었음이 確認되었다.

Abstract

A design of robust voltage controller for high speed excitation of synchronous machine was carried out by pole assignment techniques.

An affine map from characteristic polynomial coefficients to feedback parameters is formulated in order to place the system eigenvalues in the desired region.

The feedback parameters determined from linearized model are tested on nonlinear model subjecting it to small disturbances and system faults to show the effectiveness of the controller designed by the proposed technique.

The results obtained indicate that the controller presented improves the dynamic stability and system performances of conventionally controlled synchronous machine significantly.

1. Introduction

Power systems with long transmission lines and fast acting static excitations have made the stability and control problems more difficult than ever.

It is generally observed fact that the conventional feedback control actions of voltage regulators of synchronous machines have the tendency of contributing to negative damping which can cause undamped modes of dynamic oscillations[1].

Thus synchronous machines being transiently stable on the first swing do not always guarantee that they will return to their steady state operations in a well damped manner. New types of controllers are required to increase the damping of machines during transient periods but not affecting the regular functions of voltage control in steady state operation. Since voltage

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control can affect the damping of machine oscillations by sensing machine terminal voltage, it seems possible that supplementary signals to the voltage regulator increase damping.

The general method of studying a synchronous generator and its control has been to consider the generator connected through a transmission line to an infinite bus[2].

Computer simulation of nonlinear system for a large disturbance model of a synchronous machine is one approach, and that of a linearized small disturbance model is another which is particularly suitable for the determination of proper control settings[2].

A great deal of advances has been achieved in this field using excitation control with various stabilizing signals.

Until recently, the design of power system stabilizer (PSS) was based on classical control techniques[3),4)].

Modern control theory provides powerful tools for controller design and has been applied to the power system stabilizer design problems.

Since the design problem is one of system stabilization, pole assignment techniques can be used effectively. Pole assignment method aims at placing the closed-loop poles at specified locations or regions, in order to improve the stability of the system.

For system stabilization, specification of unique closed-loop pole locations is not essential and it is enough if a sector region is specified for the closed loop eigenvalues[5),6)].

Although this idea is important from the practical point of view, it has received very little attention.

The method based on a technique that assigns the closed loop eigenvalues inside a desired sector in the left half complex plane is simple and may be used for the design of voltage controller with feedback from measurable quantities.

In contrast with proposed technique, optimal control techniques often have the drawback that they require trial and error basis. On the other hand, full state feedback is not always practically feasible.

In this paper, a state space model of a synchronous machine is developed, subsequently a systematic procedure of the proposed design method is presented.

Finally, several response tests are conducted using digital simulation.

The objective of this study is to investigate the applicability of pole assignment techniques to the practical problem of robust voltage controller design for the improvement of synchronous machine stability.

2. Methematical Model of the System

2.1 Nonlinear Model

System configuration of synchronous machine with its excitation connected through transmission line to infinite bus is shown in Figure 1.

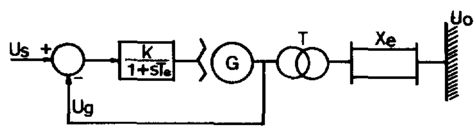

Fig. 1. Single machine-infinite bus system.

The controller is designed for a linearized machine model and subsequently it is tested on nonlinear model.

In order to simplify the analysis, rather simple model of excitation is preferable maintaining the inherent characteristics of it by the time constant and gain[7),8)].

Thus the transfer function of excitation is described as first order system by equation[1)].

$$G_e(s)=\frac{K}{1+sT_e} \qquad (1)$$

For the system stabilization, supplementary signals from rotor angular velocity ω and rotor angle δ are introduced to the exciter, excluding field voltage in the synthesis of voltage control loop because of simplified excitation system. In the modelling, the followings are neglected:

- ohmic resistances

– magnetic saturation
– Speed governor effect

Figure 2 shows vector diagram of a synchronous machine-infinite bus system.

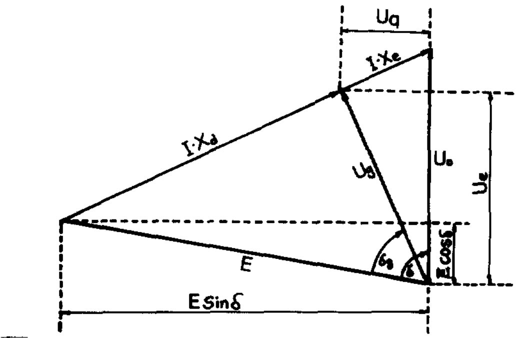

Fig. 2. Vector diagram of the system.

The generator terminal voltage expressed by equation (2) is obtained from this diagram.

$$Ug=\left[\left((E\sin\delta\frac{Xe}{Xd+Xe}\right)^2+\left(U_0-(U_0-E\cos\delta)\frac{Xe}{Xd+Xe}\right)^2\right]^{\frac{1}{2}} \quad (2)$$

For a synchronous machine under constant field excetation, its dynamic system behavior can be described by relating the angular acceleration of the generator rotor to the power imposed on it:

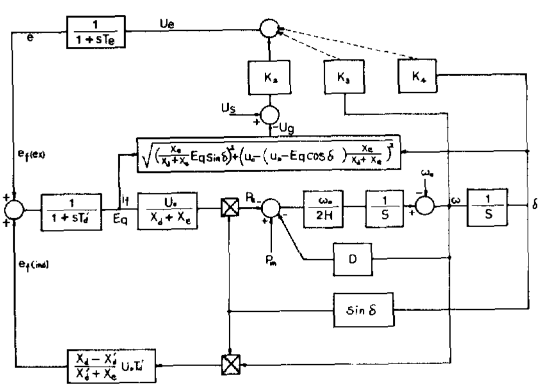

Fig. 3. Nonlinear system block diagram.

$$\frac{2H}{\omega_0}\cdot\frac{d^2\theta}{dt^2}=(P_m-P_e-P_D) \quad (3)$$

$$P_D=D\cdot\frac{d\delta}{dt} \quad (4)$$

Rotor angle disturbances oscillating about the operating point at the angular velocity ω_0 are assumed and hence the relationship in angular velocities is given by

$$\dot{\delta}=\omega=\dot{\theta}-\omega_0 \quad (5)$$

The generator output is represented as

$$P_e=\frac{U_0E}{Xd+Xe}\sin\delta \quad (6)$$

Generator field current is equal to machine internal voltage in per unit and formed from the two parts $e_{f(ex)}$ and $e_{f(ind)}$ [9].

$$i_f=\frac{1}{1+STd'}(e_{f(ex)}+e_{f(ind)}) \quad (7)$$

where

$$Td'=\frac{Xd'+Xe}{Xd+Xe}Td_0'$$

$$e_{f(ex)}=\frac{1}{1+sTe}U_e$$

$$e_{f(ind)}=\frac{Xd-Xd'}{Xd'+Xe}U_0Td'\sin\delta\cdot\omega$$

$$U_e=k_2(U_s-U_g)-k_3\omega-k_4\delta$$

Figure 3 represents equations (1) – (7) in the form of block diagram.

2.2 Linear Model

A linearized generator model of small motion about the operating point is very useful for analyzing oscillatory stability problems. The small perturbation model was suggested already by deMollo, Concordia and others for synchronizing and damping torque analysis[3), 10)]. The system is represented on the common basis with nonlinear model and linearized about the initial operating points.

Referring to equations (1)–(7) and vector diagram, Figure 2, the system equations are represented as

$$\frac{2H}{\omega_0}\cdot\frac{d^2\triangle\theta}{dt^2}=(\triangle P_m-\triangle P_e-\triangle P_D) \quad (8)$$

$$\triangle P_D=D\frac{d\triangle\delta}{dt} \quad (9)$$

$$\triangle P_e=\frac{U_0\sin\delta_0}{Xd+Xe}\triangle E_q+\frac{U_0E_{q0}\cos\delta_0}{Xd+Xe}\triangle\delta \quad (10)$$

$$\triangle\dot{\delta}=\triangle\omega=\triangle\dot{\theta} \quad (11)$$

$$\triangle U_g=\frac{Xe\cos\delta_g}{Xd+Xe}\triangle E_q+\frac{-XeE_{q0}\sin\delta_g}{Xd+Xe}\triangle\delta \quad (12)$$

$$\triangle i_f=\frac{1}{1+sTd'}(\triangle e_{f(ex)}+\triangle e_{f(ind)}) \quad (13)$$

where

$$\triangle e_{f(ex)}=\frac{1}{1+sTe}\triangle U_e$$

$$\triangle e_{f(ind)}=\frac{Xd-Xd'}{Xd'+Xe}U_0Td'\sin\delta_0\triangle\omega$$

$$\triangle U_e=k_2(\triangle U_s-\triangle U_g)-k_3\triangle\omega-k_4\triangle\delta$$

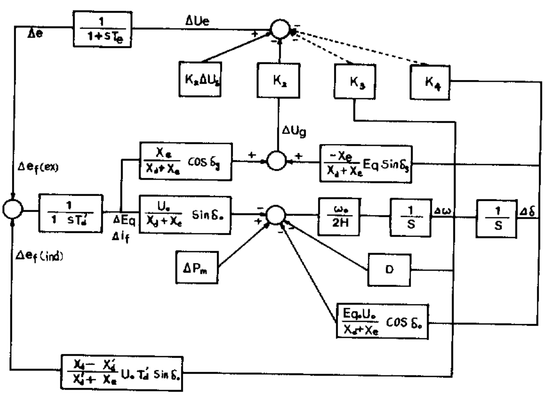

Fig. 4. Linearized system block diagram.

Figure 4 represents equations (8)–(13) in the form of block diagram.

For controller design, two initial operating states (normal and abnormal) and typical system data are selected.

The data given in Appendix 1 are referred to Appendix D, power system control and design by P.M. Anderson and A.A. Foud[1].

2.3 State Space Representation

From the linear model, the system equations for conventional voltage control are described by

$$K_e(\triangle U_s-K_6\triangle E-K_5\triangle\delta)\frac{1}{1+sTe}=\triangle e \quad (14)$$

$$(\triangle e+K_4\triangle\omega)\frac{1}{1+sTd'}=\triangle E \quad (15)$$

$$(-K_2\triangle E-D\triangle\omega-K_1\triangle\delta)K_3=\triangle\dot{\omega} \quad (16)$$

$$\triangle\omega=\triangle\dot{\delta} \quad (17)$$

where

$$K_1=\frac{E\cdot U_0}{Xd+Xe}\cos\delta$$

$$K_2=\frac{U_0}{Xd+Xe}\sin\delta$$

$$K_3=\frac{\omega_0}{2H}$$

$$K_4=\frac{Xd-Xd'}{Xd'+Xe}U_0Td'\sin\delta$$

$$K_5=\frac{-Xe}{Xd+Xe}E\sin\delta_g$$

$$K_6=\frac{Xe}{Xd+Xe}\cos\delta_g$$

The conventional voltage control is pure voltage regulation which derives feedback signal only from machine terminal voltage.

By designating $\triangle e$, $\triangle E$, $\triangle\omega$ and $\triangle\delta$ as state variables, the above equations can be arranged as

$$\triangle\dot{e}=\left[-\frac{1}{Te}\quad 0\quad 0\quad 0\right]\cdot X \quad (18A)$$

$$\triangle\dot{E}=\left[\frac{1}{Td'}\quad -\frac{1}{Td'}\quad \frac{K_4}{Td'}\quad 0\right]\cdot X \quad (18B)$$

$$\triangle\dot{\omega}=\left[0\quad -K_2\cdot K_3\quad -DK_3\quad -K_1K_3\right]\cdot X \quad (18C)$$

$$\triangle\dot{\delta}=\left[0\quad 0\quad 1\quad 0\right]\cdot X \quad (18D)$$

$$U=Ke\left[\triangle U_s-[0\quad K_6\quad 0\quad K_5]\cdot X\right] \quad (18E)$$

$$B=\left[\frac{1}{Te}\quad 0\quad 0\quad 0\right]^T \quad (18F)$$

and in the desired state space form

$$\dot{X}=AX+BU \quad (19)$$

where $X=\left[\triangle e\quad \triangle E\quad \triangle\omega\quad \triangle\delta\right]^T$

$$A=\begin{bmatrix} -\frac{1}{Te} & 0 & 0 & 0 \\ \frac{1}{Td'} & -\frac{1}{Td'} & \frac{K_4}{Td'} & 0 \\ 0 & -K_2\cdot K_3 & -DK_3 & -K_1\cdot K_3 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Selecting $\triangle U_g$, $\triangle\omega$ and $\triangle\delta$ as output, the output vector Y is denoted by

$$Y=\begin{bmatrix}\triangle U_g\\ \triangle\omega\\ \triangle\delta\end{bmatrix}=\begin{bmatrix}0 & K_6 & 0 & K_5\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot X$$
$$=C\cdot X \tag{20}$$

The constant matrices A and C are given in Appendix 2 for the study case.

The effect of governor is neglected in the model because of its large time constant.

This is normal approximation for the representation of synchronous machine with fast acting exciter.

If governor effect is to be considered for instance, the rank of control vector becomes higher.

3. Voltage Controller Design

3.1 Pole Placement Formulation

To investigate the effects of exciter gain for both operating conditions on the system stability of conventional voltage control, the selected initial operating states are applied to represent root locus.

Figure 5 and 6 represent the excursion of system roots as exciter gain is increased from 0 to 150.

The system roots of abnormal operation migrate to the unstable side of S-plane already at the low gain of 45 p.u.. Some measures have to be taken to stabilize this system.

Pole placement formulation of an affinity from the space of characteristic polynomial coefficients to the controller parameter space allows determining controller parameter region which places all eigenvalues in the desired region[11].

Introducing constant state feedback of the form described by the equation (21) to the state equation (19)

$$U=K\left[U_s-kX\right] \tag{21}$$

where K is control gain, k is feedback vector and U_s is reference input, the closed loop system equation is given by

$$\dot{X}=[A-KBk]X+KBU_s \tag{22}$$

Some elements of k may be given, e.g., they may be zero for output feedback.

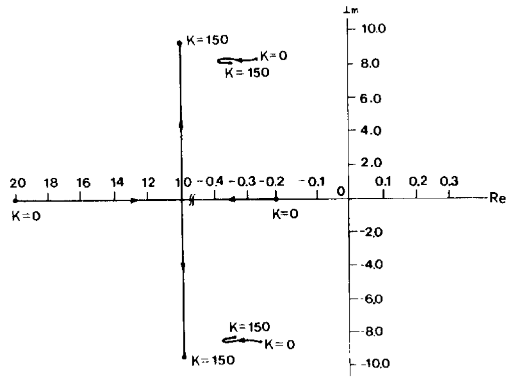

Fig. 5. Root locus of normal operation.

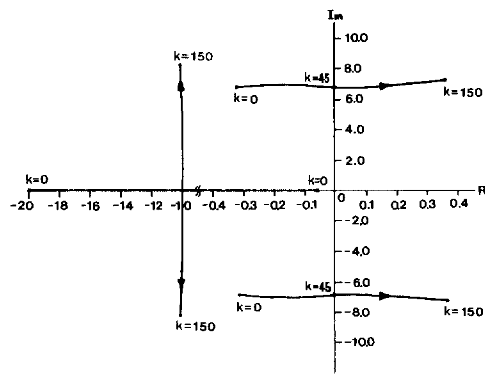

Fig. 6. Root locus of abnormal operation.

The remaining elements constitute the free design parameters. To formulate the relationship between the system eigenvalues and coefficients of characteristic polynomial, the phase variable form of control system is required.

The phase variable representation of the open loop described by the transfer function

$$G(s)=\frac{c_1+c_2s+\cdots\cdots c_m s^{m-1}}{a_1+a_2s+a_3s^2+\cdots\cdots+s^n} \tag{23}$$

takes the form[12]

$$\dot{\bar{X}}=\bar{A}\,\bar{X}+\bar{B}U \qquad (24)$$

$$Y=\bar{C}\,\bar{X} \qquad (25)$$

where

$$\bar{A}=\begin{bmatrix} 0 & 1 & 0 & 0\cdots\cdots\cdots\cdots \\ 0 & 0 & 1 & 0\cdots\cdots\cdots 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0\cdots\cdots\cdots 1 \\ -a_1 & -a_2 & -a_3\cdots\cdots\cdots & -a_n \end{bmatrix}$$

$$\bar{B}=[0 \quad 0 \quad 0\cdots\cdots\cdots 0 \quad 1]^T$$

$$\bar{C}=[C_1 \quad c_2\cdots\cdots c_m \quad 0\cdots\cdots\cdots 0]$$

Thus the system transfer function can be determined from the phase variable representation by simple inspection of above relations.

In terms of the clossed loop, the task may be similarly accomplished. If the closed loop expression for the control is given by

$$U=K[Us-\bar{k}\,\bar{X}] \qquad (26)$$

where $\bar{k}$ is the feedback vector in terms of phase variables, then the system representation becomes

$$\dot{\bar{X}}=\begin{bmatrix} 0 & 1 & 0\cdots\cdots\cdots\cdots 0 \\ 0 & 0 & 1\cdots\cdots\cdots\cdots 0 \\ \cdots & \cdots & \cdots \\ 0 & 0\cdots\cdots\cdots\cdots & 1 \\ -(a_1+K\bar{k}_1) & -(a_2+K\bar{k}_2)\cdots & -(a_n+K\bar{k}_n) \end{bmatrix}\bar{X}+K\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}U_s \qquad (27)$$

$$Y=[c_1 \quad c_2\cdots\cdots c_m \quad 0\cdots\cdots 0]\,\bar{X} \qquad (28)$$

where $\bar{k}_i(i=1,2\cdots n)$ is the element of $\bar{k}$.

Thus the closed loop transfer function is given by

$$\frac{Y(s)}{U_s(s)}=\frac{K(c_1+c_2s+\cdots\cdots+c_ms^{n-1})}{(a_1+K\bar{k}_1)+(a_2+K\bar{k}_2)S+\cdots\cdots+(a_n+K\bar{k}_n)s^{n-1}+s^n} \qquad (29)$$

The denominator is the characteristic polynominal of the closed loop system and its coefficients are represented by the simple equation

$$ak_i=a_i+K\bar{k}_i \quad i=1,2,\cdots\cdots n \qquad (30)$$

The characteristic polynomial of the closed loop system can be related to preassigned eigenvalues Si's:

$$P(s)=a_{k1}+a_{k2}s+a_{k3}s^2+\cdots\cdots+a_{kn}s^{n-1}+s^n=\prod_{i=1}^{n}(s-s_i) \qquad (31)$$

If ai's and *a*ki's are known, then $\bar{k}_i$ for preassigned poles can be determined from equations (30) and (31).

The elements of $\bar{k}_i$ are the coordinates of a parameter space in which the design is performed.

3.2 Phase Variable Representation

It is necessary to transform the system to phase variable form since most systems are not naturally described in phase variables. The feedback parameters determined in phase variables have to be transformed back to the original state variable representation for practical use.

Transforming the system to phase variables is possible if the system is controllable.

Controllability may be determined by the test, which states that the system expressed in equation (32) is controllable if and only if the n by n controllability matrix

$$M_c=[B \;\; AB \;\; A^2B\cdots\cdots A^{n-1}B] \qquad (32)$$

is nonsingular, i.e. Det [Mc] $\neq 0$[13].

The transformation matrix is related to phase variable form as described in equations (33A)–(33E).

$$\bar{X}=T^{-1}X \qquad (33A)$$

$$\bar{A}=T^{-1}AT \qquad (33B)$$

$$\bar{B}=T^{-1}B \qquad (33C)$$

$$\bar{C}=CT \qquad (33D)$$

$$\bar{k}=kT \qquad (33E)$$

The transformation matrix is determined using controllability matrix:

$$T^{-1}=d\begin{bmatrix} Mc^{-1}I \\ Mc^{-1}A \\ Mc^{-1}A^2 \\ \vdots \\ Mc^{-1}A^{n-1} \end{bmatrix} \qquad (34A)$$

$$T = [T^{-1}]^{-1} \tag{34B}$$

where $d = [0 \quad 0 \cdots\cdots 0 \quad 1]$,

I is identity matrix.

For fourth order system, the following equations are obtained from equations (30) and (31).

$$a_{k4} = a_4 + \bar{k}_4 = -(s_1 + s_2 + s_3 + s_4) \tag{35A}$$

$$a_{k3} = a_3 + \bar{k}_3 = (s_1 s_2 + s_3 s_4) + (s_1 + s_2)(s_3 + s_4) \tag{35B}$$

$$a_{k2} = a_2 + \bar{k}_2 = -((s_1 + s_2) s_3 s_4 + (s_3 + s_4)(s_1 s_2) \tag{35C}$$

$$a_{k1} = a_1 + \bar{k}_1 = (s_1 s_2 s_3 s_4) \tag{35D}$$

The exciter gain K is selected as unity and it does not lose generality. Referring to equation (20) and Figure 4, the feedback vector for output feedback is represented by

$$k = [0 \quad K_6 k_2 \quad k_3 \quad K_5 k_2 + k_4] \tag{36}$$

The transformation matrices for the system are given in Appendix 3 and have the general form:

$$T = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & 0 \\ 0 & T_{32} & 0 & 0 \\ T_{41} & 0 & 0 & 0 \end{bmatrix} \tag{37}$$

From equations (33E) and (35A)–(37), the elements of the transformed feedback vector are given by

$$\bar{k}_1 = T_{21} K_6 k_2 + T_{41} K_5 k_2 + T_{41} k_4 = a_{k1} - a_1 \tag{38A}$$

$$\bar{k}_2 = T_{22} K_6 k_2 + T_{32} k_3 = a_{k2} - a_2 \tag{38B}$$

$$\bar{k}_3 = T_{23} K_6 k_2 = a_{k3} - a_3 \tag{38C}$$

$$\bar{k}_4 = 0 = a_{k4} - a_4 \tag{38D}$$

Transformed matrices and veators are given in Appendix 3.

3.3 Feedback Parameter Determination

The design objective is to find feedback parameters which shift the closed loop eigenvalues into a sector defined by sloping line S

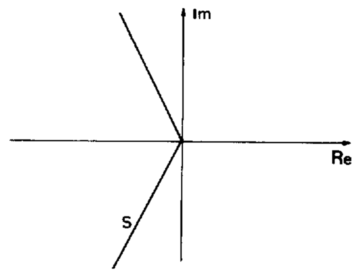

Fig. 7. Sector region for system eigenvalue.

as shown in Figure 7.

Since the control system is not full state feedback, preassignining all eigenvalues is not possible.

If some of eigenvalues are assigned, then the rest of them has to be checked if it lies inside the sector.

Let a conjugate complex pair of eigenvalues be assigned, then the rest may be either complex pair or two real eigenvalues.

Assuming the case of two conjugate complex pairs,

$$s_1 = \alpha_1 + j\beta_1 \tag{39A}$$

$$s_2 = \alpha_2 + j\beta_2 \tag{39B}$$

$$s_3 = \alpha_3 + j\beta_3 \tag{39C}$$

$$s_4 = \alpha_4 + j\beta_4 \tag{39D}$$

where $\alpha_1 = \alpha_2$, $\alpha_3 = \alpha_4$, $\beta_1 = -\beta_2$, $\beta_3 = -\beta_4$, the following relations are obtained by substituting the sector boundary condition $S = \left| \frac{\beta_i}{\alpha_i} \right|$ in equations (35A)–(35D).

$$a_{k1} = \alpha_1^2 (1+s^2) \alpha_3^2 (1+s^2) = d_4 k_2 + d_5 k_4 + a_1 \tag{40A}$$

$$a_{k2} = -(2\alpha_1 \alpha_3^2 (1+s^2) + 2\alpha_3 \alpha_1^2 (1+s^2)) = d_2 k_2 + d_3 k_3 + a_2 \tag{40B}$$

$$a_{k3} = \alpha_1^2 (1+s^2) + \alpha_3^2 (1+s^2) + (2\alpha_1)(2\alpha_3) = d_1 k_2 + a_3 \tag{40C}$$

$$a_{k4} = -(2\alpha_1 + 2\alpha_3) = a_4 \tag{40D}$$

where
$d_1 = T_{23} K_6$
$d_2 = T_{22} K_6$
$d_3 = T_{32}$
$d_4 = T_{21} K_6 + T_{41} K_5$
$d_5 = T_{41}$

From equations (40A)–(40D), the feedback parameters k_2 and k_3 are obtained as functions of α_1 and S.

$$k_2=\frac{\alpha_1(1+s^2)+(d_5k_4+a_1)/\alpha_1^2(1+s^2)-2\alpha_1(2\alpha_1+a_4)-a_3}{d_1-d_4/\alpha_1^2(1+s^2)} \qquad (41)$$

$$k_3=\frac{-2\alpha_1(d_4k_2+d_5k_4+a_1)/\alpha_1^2(1+s^2)+(2\alpha_1+a_4)\alpha_1^2(1+s^2)-d_2k_2-a_2}{d_3} \qquad (42)$$

The pair of real eigenvalue remainders ($S_3=\alpha_3$, $S_4=\alpha_4$) results in the same expressions for k_2 and k_3 as equations (41) and (42).

It is worth noting that the sum of eigenvalues is constant and equal to a_4 as shown in equation (40 D).

Thus the variation of α_1 from zero to $-a_4/2$ is sufficient for pole assignment.

In the procedure of determining k_2 and k_3 regions, k_4 is kept constant so that the eigenvalue locations may not be influenced from it.

The result for the slope $s=3$ is shown in Figure 8. Two dominant regions are available: One of them is the combination of small value feedback parameters, the other is that of large values.

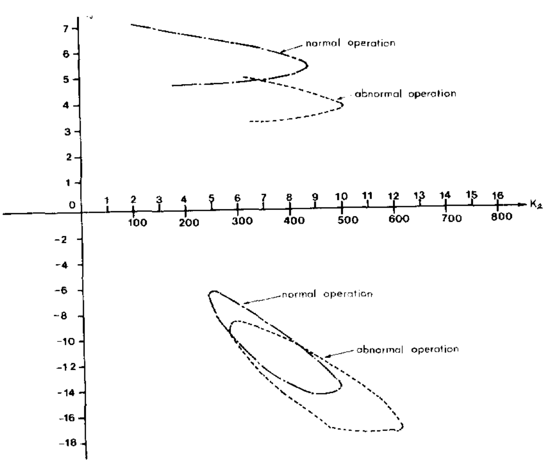

Fig. 8. Feedback parameter regions for S=3.

4. System Performance

4.1 Feedback Parameter Selection

The major function of a voltage regulator is to maintain machine terminal voltage at a pre-set value, regardless of changing requirements of excitation due to changes in load and other system conditions.

Secondly fast response is desirable in compromise with system performances.

To meet these requirements, a high value controller gain is preferable.

The gain values used in actual systems are typically 200-400 per unit[14].

The region of high value feedback parameters agrees with these typical values of controller gain.

Since for low value combination the common region of both initial operating conditions is very small as seen in Figure 8, little flexibility is allowed in choosing parameters.

For performance tests the feedback parameters are chosen from the both regions as

$k_2=6.5$, $k_3=5$ for low value region

$k_2=400$, $k_3=-12$ for high value region

4.2 Steady State Value

It is usually desired to determine the steady state values of system responses.

Assuming the controlled system is stable, the final values can be determined from the relations:

$$\dot{\bar{X}}=\dot{\bar{X}}_\infty=0$$

$$\dot{\bar{X}}_\infty=\bar{A}\,\bar{X}_\infty+\bar{B}\,r=0$$

$$\bar{X}_\infty=-\bar{A}^{-1}\bar{B}\,r$$

$$=\begin{pmatrix}\frac{1}{a_{k1}}\\0\\0\\0\end{pmatrix}r$$

where

$$\bar{A}=\begin{pmatrix}0&1&0&0\\0&0&1&0\\0&0&0&0\\-a_{k1}&-a_{k2}&-a_{k3}&-a_{k4}\end{pmatrix}$$

$$B^T = [0 \quad 0 \quad 0 \quad 1]$$

$$Y_\infty = \bar{C} X_\infty = -\bar{C}\, \bar{A}^{-1}\, \bar{B} r$$

$$= \begin{bmatrix} \triangle u_{g\infty} \\ \triangle \omega_\infty \\ \triangle \delta_\infty \end{bmatrix} = \begin{bmatrix} \frac{\bar{c}_{11}}{a_{k1}} \\ 0 \\ \frac{c_{31}}{a_{k1}} \end{bmatrix} r = \begin{bmatrix} \frac{\bar{c}_{11} \cdot k_2 \cdot \triangle U_s}{a_1 + d_4 k_2 + d_5 k_4} \\ 0 \\ \frac{c_{31} \cdot k_2 \cdot \triangle U_s}{a_1 + d_4 k_2 + d_5 k_4} \end{bmatrix} \quad (43)$$

where

$$\bar{C} = CT = \begin{bmatrix} K_6 T_{21} + K_5 T_{41} & K_6 T_{22} & K_6 T_{23} & 0 \\ 0 & T_{32} & 0 & 0 \\ T_{41} & 0 & 0 & 0 \end{bmatrix}$$

Since the relations $\bar{C}_{11} = K_6 T_{21} + K_5 T_{41}$ and Cu = d4 hold, upon examination of equation (43), one notes that the control system can provides zero steady state terminal voltage error by simply adjusting k_4.

However maintaining zero terminal voltage error is not so important that small value of k_4 is satisfactory in reducing the error.

The calculated steady state values of the system for 0.1 p.u control input are:

$$Y_\infty = \begin{bmatrix} 0.1437 \\ 0 \\ -0.329 \end{bmatrix} \text{normal operation } k_2 = 6.5 \quad k_3 = 5$$

$$Y_\infty = \begin{bmatrix} 0.1005 \\ 0 \\ -0.23 \end{bmatrix} \text{normal operation } k_2 = 400, k_3 = -12$$

$$Y_\infty = \begin{bmatrix} 3.058 \\ 0 \\ -8.69 \end{bmatrix} \text{abnormal operation } k_2 = 6.5, \quad k_3 = 5$$

$$Y_\infty = \begin{bmatrix} 0.1016 \\ 0 \\ -0.289 \end{bmatrix} \text{abnormal operation } k_2 = 400, \quad k_3 = -12$$

From these results, it is clear that the small value combination of feedback parameters is not applicable.

4.3 Performance Tests by Simulation

To investigate the effectiveness of designed controller, simulations are carried out for both sets of feedback parameters by subjecting the nonlinear system model to distinct type of disturbances:

- disturbance A: 0.1 Us step disturbance
- disturbance B: 0.1 Pm step disturbance of 0.1 sec. duration
- disturbance C: interruption of one of double circuits (Xe = 0.35 → 0.55)
- disturbance D: three phase fault of 0.2 sec duration applied on the infinite bus

The parameter k_4 is kept constant as 2.5 for both parameter combination.

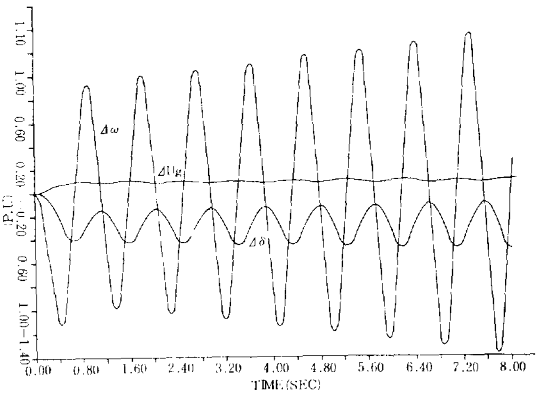

Fig. 9. System response to $\triangle U_s = 0.1$ p.u (Abnormal operation, k_e=50)

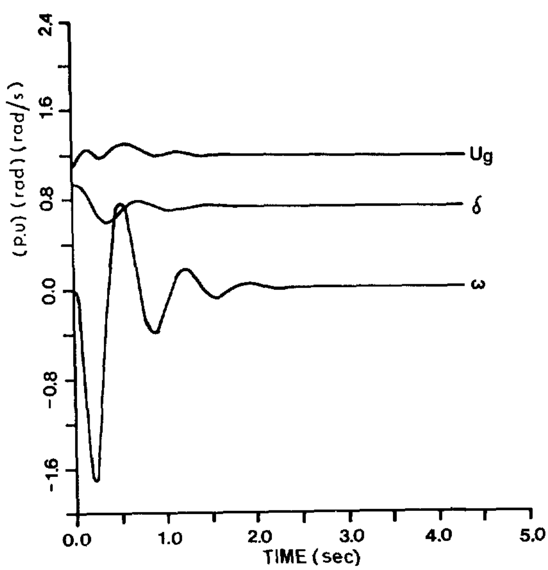

Fig. 10. Disturbance A (normal operation k_2=400, k_3= −12)

The initial machine variables of nonlinear model are determined from the following four equations.

$$(U_s - U_g)\,k_2 - \delta k_4 = e_f = E$$

$$P_e = P_m = \frac{E \cdot U_0}{Xd + Xe}\sin\delta$$

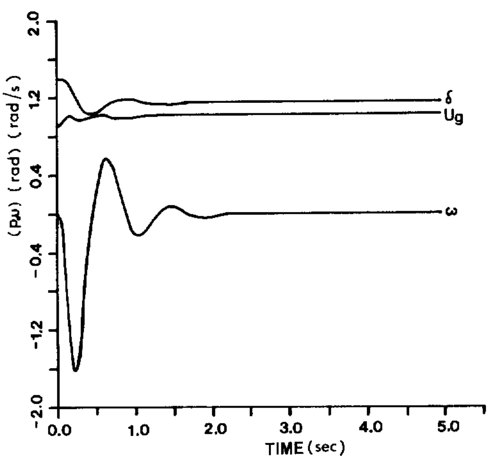

Fig. 11. Disturbance A (abnormal operation k_2=400, k_3= −12)

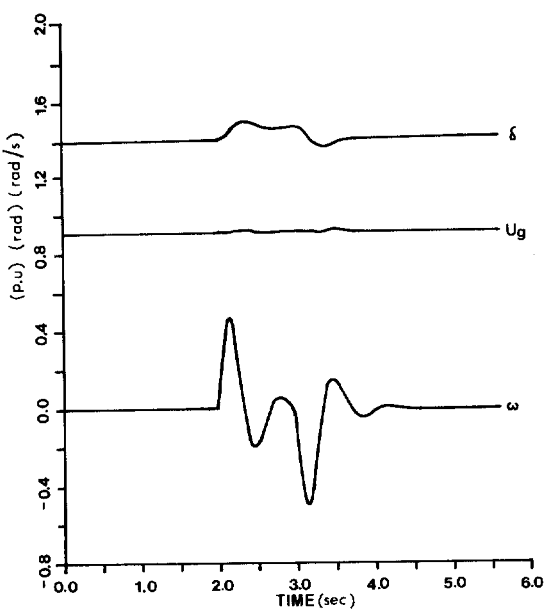

Fig. 12. Disturbance B(abnormal operation k_2=400, k_3= −12)

$$U_g = \left[\left(E\sin\delta\frac{Xe}{Xd+Xe}\right)^2 + \left(U_0 - (U_0 - E\cos\delta)\frac{Xe}{Xd+Xe}\right)^2\right]^{\frac{1}{2}}$$

$$Q = \frac{U_0\,(E\cos\delta - U_0)}{Xd + Xe}$$

The test results are summarized in Figures 9 through 15. The system was oscillatory or unstable without stabilizing signals for both initial operating conditions as shown previously. The low value feedback does not bring the system completely stable for the disturbances.

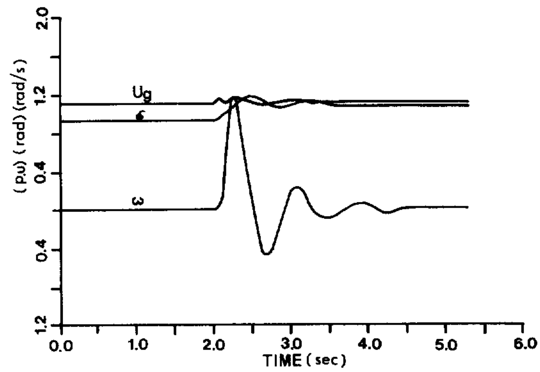

Fig. 13. Disturbance C (normal operation k_2=400, k_3= −12)

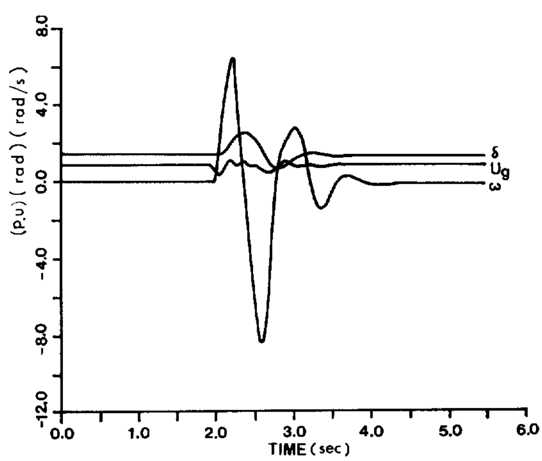

Fig. 14. Disturbance D (abnormal operation k_2=400, k_3= −12)

In particular, this control has no ability to overcome the interruption of one of double circuits and three phase fault as exemplified by Figure 15.

With the high value feedback, the disturbances are damped out very fast and the system is stable with respect to all types of disturbances.

Accordingly the high value feedback parameter combination is the better one of the feedback laws considered.

5. Conclusion

A design of robust voltage controller has been formulated in a procedure of pole assignment techniques using distinct system initial states to provide stabilizing control signals for a fast excitation system of a synchronous machine. Two regions of feedback parameters which shift the system eigenvalues into a specified sector was determined by pole assignment.

The test by simulation proved that stabilization signals are very effective for improving system stability.

The high value set of feedback parameters has shown predominantly better performances than the low value set.

In case with high value feedback, power angle scarcely affects system performances.

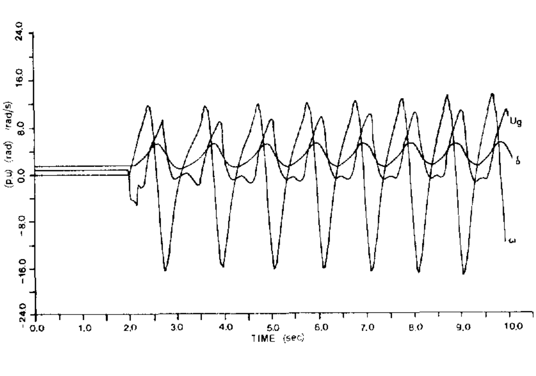

Fig. 15. Disturbance D (abnormal operation k_2=6.5, k_3=5)

Thus the design can be free from the difficulty in access to power angle and feedback from the rotor velocity deviation alone is adequate in stabilizing the system.

Whereas the classical PSS design requires generally a trial and error process or practically not feasible full state feedback, the output feedback design performed in this study provides a definite solution and demonstrated the suitability of the proposed techniques.

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Nomenclature

General	
A	System matrix
B	control vector
C	output matrix
U,r	control input
Us	reference input
X	state vector
Y	output vector
o	subscript denoting initial condition
S	laplace operator
Si	i th system eigenvalue
△	prefix denoting linearized variables.
System parameters (p.u. except as indicated)	
Xe	external reactance
Xd	synchronous reactance
Xd'	transient reactance
Td'o	open circuit field time constant, sec.
Td'	effective transient time constant, sec.
Ke,K	excitation system gain
Te	excitation system time constant, sec.
D	damping coefficient
H	machine inertia constant, sec.
k	feedback parameter

System variables (p.u. except as indicated)

e,ef(ex)	field voltage
ef (ind)	equivalent field voltage induced by speed change
Ue	control signal to exciter
E, Eq	voltage behind synchronous reactance.
Ug	generator terminal voltage
Uo	infinite bus voltage
Pm	mechanical power input
Pe	electric power output
θ	rotor angle, rad
δ	rotor angle with respect to infinite bus
δg	rotor angle with respect to generator terminal voltage

Appendix I

Initial states and system data

Normal operation	Abnormal operation
Pe = 0.85 p.u.	Pe = 0.68 p.u.
Qe = 0.41 p.u.	Qe = 0.0 p.u.
p.f = 0.9	p.f = 1.0
Xe = 0.35 p.u.	Xe = 0.55 p.u.
Te = 0.05 sec.	Te = 0.05 sec.
H = 3.5 sec.	H = 3.5 sec.
Td'o = 7.0 sec.	Td'o = 7.0 sec.
Td' = 2.0512 sec.	Td' = 2.4723 sec.
δo = 0.9436 rad.	δo = 1.3954 rad.
δg = 0.6682 rad.	δg = 0.9730 rad.
Uo = 1.0 p.u.	Uo = 1.0 p.u.
Eqo = 2.2571 p.u.	Eqo = 1.6229 p.u.
Xd = 1.8 p.u.	Xd = 1.8 p.u.
Xd' = 0.28 p.u.	Xd' = 0.28 p.u.
D = 2.0 p.u.	D = 2.0 p.u.

Appendix 2.

Linearized system matrices

Normal operation

$$A=\begin{pmatrix} -20.0 & 0 & 0 & 0 \\ 0.4875 & -0.4875 & 1.9535 & 0 \\ 0 & -20.2818 & -0.2857 & -33.1812 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$B=[20.0 \quad 0 \quad 0 \quad 0]^T$$

$$C=\begin{pmatrix} 0 & 0.1278 & 0 & -0.2277 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Abnormal operation

$$A=\begin{pmatrix} -20.0 & 0 & 0 & 0 \\ 0.4045 & -0.4045 & 1.8032 & 0 \\ 0 & -22.566 & -0.2857 & -6.49 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$B=[20.0 \quad 0 \quad 0 \quad 0]^T$$

$$C=\begin{pmatrix} 0 & 0.1317 & 0 & -0.314 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Appendix 3. Transformation and transformed matrices

Normal operation

$$T=\begin{pmatrix} 323.52 & 1458.82 & 15.46 & 20.0 \\ 323.52 & 2.7856 & 9.75 & 0.0 \\ 0.0 & -197.75 & 0.0 & 0.0 \\ -197.75 & 0.0 & 0.0 & 0.0 \end{pmatrix}$$

$$\bar{A}=\begin{pmatrix} 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 \\ -323.52 & -1475.0 & -88.4 & -20.77 \end{pmatrix}$$

$$\bar{B}=[0.0 \quad 0.0 \quad 0.0 \quad 1.0]^T$$

$$\bar{C}\begin{pmatrix} 86.37 & 0.3560 & 1.2460 & 0.0 \\ 0.0 & -197.75 & 0.0 & 0.0 \\ -197.75 & 0.0 & 0.0 & 0.0 \end{pmatrix}$$

Abnormal opperation

$$T=\begin{pmatrix} 52.50 & 945.1 & 13.80 & 20.0 \\ 52.50 & 2.31 & 8.09 & 0.0 \\ 0.0 & -182.56 & 0.0 & 0.0 \\ -182.56 & 0.0 & 0.0 & 0.0 \end{pmatrix}$$

$$\bar{A}=\begin{pmatrix} 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 \\ -52.5 & -948.6 & -61.1 & -20.7 \end{pmatrix}$$

$$\bar{B}=[0.0 \quad 0.0 \quad 0.0 \quad 1.0]^T$$

$$\bar{C}=\begin{pmatrix} 62.24 & 0.3044 & 1.0655 & 0.0 \\ 0.0 & -182.56 & 0.0 & 0.0 \\ -182.56 & 0.0 & 0.0 & 0.0 \end{pmatrix}$$

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