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STABILIZATION OF A PERMANENT MAGNET SYNCHRONOUS GENERATOR

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ABSTRACT

This paper, presents a new trend to damp the hunting oscillations of a PM synchronous generator connected to an infinite bus , when subjected to a disturbance. A frequency domain model of the PM generator is obtained and used as a base for designing a control scheme, considering the mechanical loop only . Moreover. the controller has been implemented using a detailed non-linear digital simulation of a PM machine connected to a large power system . The performance is demonstrated when a 3-phase short circuit occurs at the generator terminals. The results illustrates that the machine with the designed controller has wide stability limits with well damped response, enabling the direct connection of PM machine into grid . The results and techniques presented promise that, PM generators with their fixed excitation nature could be synchronized directly into power networks and their hunting oscillation can be adequately damped when include the suggested scheme.

1.INTRODUCTION

Permanent magnet excitation of dc motors have been well known for many years. It is only recently, however, that ac permanent magnet (PM) motors and generators with high power rated have appeared due to increasing requirements for high efficiency electric devices, and as a results of the development of high energy magnet materials. With innovative designs of rotors, these machines can be cheap, compact, energy efficient and easy to maintain [1-3]. There has been different configurations of PM machines, depends on the magnet shaping and magnet insertion requirements [3]. Most of these types, have similar construction to synchronous machine but with fixed field strength, which can't be controlled in a way similar to that of the conventional synchronous machine. This, however, present difficulties in damping the hunting oscillations of the PM, when subjected to a disturbance[4]. Therefore, it is not recommended to synchronize this generator into power network, unless the oscillatory response of the PM is improved [5].

This paper presents a new trend to damp the hunting oscillations of a PM synchronous generator, connected to an infinite bus. A frequency domain model of the PM machine is obtained and used as a base for designing a control scheme considering only the mechanical loop as the only available loop due to the constant field nature of this machine. The controller has been implemented using a detailed non-linear digital simulation of a PM machine connected to a large power system. The performance is demonstrated when a 3-phase short circuit occurs at the generator terminals. The results illustrate a well damped response and a substantial reduction in the rotor first swing, which means an extension of machine stability. Also, the terminal voltage recovery is significantly improved. The results indicates that PM generators, with the proposed control strategy, may be connected to the power network without any adverse effect on the inter area oscillations or terminal voltage recovery .

2.PROBLEM FORMULATION

In power systems, the Low frequency hunting oscillations depend largely on the machine parameters, inertia constant and interaction with other generators. This type of oscillations represent a major source of troubles and adversely affect the machine performance. In conventional synchronous generators in which the excitation level can be changed via a control system, these oscillations can be adequately damped via suitable control means. Fig.(1) shows a typical conventional synchronous generator connected to a large power system. The open loop response of this system when subjected to a short circuit is shown in Fig.(2). This oscillatory performance is substantially improved with well damped response following the application of a control system as might be observed from the figure. The controller used is based on feeding back a signal obtained from rotor speed to the reference point of the exciter via lead compensators. This controller has been designed using an eigenvalues shift technique[6]. However in case of PM synchronous generators, this improvements in the performance could not be achieved via the excitation loop due to the fixed excitation nature. This causes problems in synchronizing this machine into power network unless suitable control action is taken. Such control action may consider the mechanical loop only. However, careful attention must be taken in this case due to the very limited range of low frequency oscillations that can be damped via this loop[7]. This is the subject of this paper.

3. MODELING PM GENERATOR IN FREQUENCY DOMAIN

3.1. PM Generator

The d-q axes machine equations are obtained for a fixed rotor reference frame in per unit form. The permanent magnet has been represented by equivalent current source[8]. Assuming balanced operation condition, then perturbing the machine equations about an operating point leads to :

$$\Delta V_d = \frac{P}{\omega_o}\Delta\psi_d - \frac{P}{\omega_o}\psi_{q_o}\,\Delta\delta - \Delta\psi_q - R_a\Delta I_d \qquad (1)$$

$$P\Delta\psi_{KD} = -\,\omega_o\,R_{KD}\,\Delta I_{KD} \qquad (2)$$

$$\Delta V_q = \frac{P}{\omega_o}\Delta\psi_q + \frac{P}{\omega_o}\psi_{d_o}\,\Delta\delta + \Delta\psi_d - R_a\Delta I_q \qquad (3)$$

$$P\Delta\psi_{KQ} = -\omega_o R_{KQ} \Delta I_{KQ} \qquad (4)$$

$$P^2\Delta\delta = \frac{\omega_o}{2H}\left[\Delta T_M - \Delta T_e - K_d P\Delta\delta\right] \qquad (5)$$

$$\Delta T_e = I_{d_o}\Delta\psi_d + \psi_{d_o}\Delta I_d - \psi_{q_o}\Delta I_q - I_{q_o}\Delta\psi_q \qquad (6)$$

Following the procedures described in Ref [9], one may obtain the relation directly between the flux linkages (ψ_d, ψ_q) and the stator current components(i_d, i_q) excluding i_{KD} and i_{KQ} as follows[9]:

$$\Delta\psi_d = -X_{dpm}(P)\ \Delta I_d \qquad (7)$$

$$\Delta\psi_q = -X_{qpm}(P)\ \Delta I_q \qquad (8)$$

where,

$$X_{dpm}(P) = X_d - \frac{P\ X_{ad}^2}{\omega_o R_{KD} + P X_{KD}}$$

$$X_{qpm}(P) = X_q - \frac{P\ X_{ad}^2}{\omega_o R_{KQ} + P X_{KQ}}$$

Substituting from equations (7, 8) in equations (1-6), then the machine equations can be written as follows:

$$\Delta V_d + \left(R_a + \frac{P}{\omega_o} X_{dpm}(P)\right)\Delta I_d - X_{qpm}(P)\ \Delta I_q + \frac{P}{\omega_o}\psi_{q_o}\Delta\delta = 0 \qquad (9)$$

$$\Delta V_q + \left(R_a + \frac{P}{\omega_o} X_{dqm}(P)\right)\Delta I_q + X_{qdm}(P)\ \Delta I_d - \frac{P}{\omega_o}\psi_{d_o}\Delta\delta = 0 \qquad (10)$$

$$[MP^2 + K_d P]\ \Delta\delta - [I_{q_o} X_{dpm}(P) + \psi_{q_o}]\ \Delta I_d + [\psi_{q_o} + I_{d_o} X_{qpm}(P)]\ \Delta I_q - \Delta T_M = 0 \qquad (11)$$

3.2. Transformer and Transmission Line

Lumped series inductance and resistance is used to represent the transformer and the transmission line connecting the generator to the grid. In a similar way the transmission system components are solved into the generator d-q axes and perturbed about the operating point, yielding the following linearized equations :

$$\Delta V_d - (V_b \cos \delta_o)\,\Delta\delta - (R_e + \frac{P}{\omega_o} X_e)\,\Delta I_d + X_e\,\Delta I_q = 0 \qquad (12)$$

$$\Delta V_q + (V_b \sin \delta_o)\,\Delta\delta - (R_e - \frac{P}{\omega_o} X_e)\,\Delta I_q + X_e\,\Delta I_d = 0 \qquad (13)$$

Equations (9-13) are represent the machine and transmission system. Dividing Eqns. (9-13) by ΔT_M, as the single permissible input, the system equations can be written in the following format:

$$\left[\begin{array}{c|c|c|c|c} 1 & 0 & \frac{P}{\omega_o}\psi_{q_o} & R_a + \frac{P}{\omega_o} X_{dpm}(P) & -X_{qpm}(P) \\ \hline 0 & 1 & -\frac{P}{\omega_o}\psi_{d_o} & X_{dpm}(P) & R_a + \frac{P}{\omega_o} X_{qpm}(P) \\ \hline 0 & 0 & Mp^2 + K_d P & -\psi_{q_o} - I_{q_o} X_{dpm}(P) & \psi_{d_o} + I_{d_o} X_{qpm}(P) \\ \hline 1 & 0 & -V_b \cos \delta_o & -R_e + \frac{P}{\omega_o} X_e & X_e \\ \hline 0 & 1 & V_b \sin \delta_o & -X_e & -R_e - \frac{P}{\omega_o} X_e \end{array}\right] \left[\begin{array}{c} \Delta V_d/\Delta T_M \\ \hline \Delta V_q/\Delta T_M \\ \hline \Delta\delta/\Delta T_M \\ \hline \Delta I_d/\Delta T_M \\ \hline \Delta I_q/\Delta T_M \end{array}\right] = \left[\begin{array}{c} 0 \\ \hline 0 \\ \hline 1 \\ \hline 0 \\ \hline 0 \end{array}\right] \qquad (14)$$

Or in compact form :

$$[\ A\ ]\ [\ \Delta X\ ] = [\ b\ ] \qquad (15)$$

The transfer function of the system can be calculated numerically as:.

$$[\ \Delta X\ ] = [\ A\ ]^{-1}\ [\ b\ ] \qquad (16)$$

The system may then be considered as a single-input multi-output system as shown in Fig.(3). Substituting $P=j\omega$ ($\omega = 0 \longrightarrow \infty$) and solving Eqn.(16) numerically using the digital computer give a variety of results regarding system stability, hunting and overall performance. This is a very important results as it indicate the dangers frequency that should be well damped. Otherwise, the generator may, if synchronized into a network, go out of synchronization. The results are plotted in frequency domain as shown in Fig.(4). The resonance frequency is computed from Fig.(4) (ω_r = 11.8 rad/sec.).

4.CONTROLLER DESIGN

As mentioned early, the mechanical input is the only permissible input for control. It has been thought that phase advance control strategy for the mechanical loop could achieve the required control action. The phase advance circuit must be designed to ensure suitable behavior of the machine in both steady state and large disturbance modes of operation. Fig.(5) illustrates the block diagram of the system after incorporating the phase advance system. For seeking accuracy and avoiding misleading results, a non-linear function is also incorporated. The characteristic equation of the system is then written as follows (assuming N=1):

$$1 + G_T(P)\left[\frac{1}{\omega_o R} - G_{ph.a.}(P)\right]\frac{P\Delta\delta}{\Delta T_M} = 0 \qquad (17)$$

Now, it is recommended, before proceeding in the controller design, to illustrate the region of stability for all the phase advance parameters i.e gain $K_{ph.a.}$ and time constants. subsequently, the domain separation technique [9,10] has been applied and the results are shown in Fig.6. This illustrate the limits and all possible combination of parameters which give an acceptable and stable range of operation.

4.1. Controller Design Philosophy

The design approach has been firstly developed and applied to design excitation controller for the synchronous machine in 1992 [9]. In this case, it was decided to use the same approach but for the mechanical loop of the PM generator . The advantages of the technique is its capability to introduce the required phase lead any required frequency which could be the resonance frequency. Therefore, the block diagram ,Fig.(5), is rearranged as shown in Fig.(7), and from polar plot of $\Delta\omega/\Delta T_M$, the resonance frequency and the phase required are calculated[6] . The next step is to add any number of cascade lead networks to obtain the required phase and gain margins. These margins may be specified in a way which ensures good steady state and transient performance (i.e. phase ≥ 30^{o} and gain margin ≥ 6 db.).

Now, considering the following phase advance network structure,

$$G_{ph.a.}(P) = K_{ph.a.}\left\{\frac{P\ T_{wsh}}{1 + P\ T_{wsh}}\right\}\left\{\frac{1 + P\ T_{1}}{1 + P\ T_{2}}\right\}^{n} \quad (18)$$

where,

- $K_{ph.a.}$: phase advance gain;

$T_1 = \alpha\ T_2 \quad ; \quad \alpha > 1$

n : number of cascade circuits required.

T_{wsh} : washout time constant.

The initial procedure is to deduce phase advance circuit requirements in terms of gain and phase requirements at resonance frequency. It is recommended that each network add phase-lead angle (ϕ_{max}) less than 60^{o} otherwise the network becomes sensitive to ensure noise [11], thus;

$$\phi_{max} = \sin^{-1}\left[\frac{\alpha - 1}{\alpha + 1}\right] \quad (19)$$

The parameter α is chosen by making the maximum phase advance equal to the required phase shift at the resonance frequency.

$$\omega_{max} = \omega_{r} = 1 / T \sqrt{\alpha} \quad (20)$$

4.2. Implementation of Design Procedures

Figure (8) shows the polar plot $(\Delta\omega/\Delta T_{M})$. It may be observed that the phase advance network should provide around 55^{o} ($41^{o}+14^{o}$ for lead network) at resonance frequency 13.7 rad/sec. The maximum phase can be obtained by single stage network which has the following transfer function :

$$G_{ph.a.}(P) = 0.007\left\{\frac{2\ P}{1 + 2\ P}\right\}\left\{\frac{1 + 0.13\ P}{1 + 0.013\ P}\right\} \quad (21)$$

From Fig.(7) we can write :

$$-\frac{1}{N} = \left[\frac{1}{\omega_o R} - G_{ph.a.}(P) \right] G_T(P).\ \frac{\Delta X}{\Delta T_M} \qquad (22)$$

Figure(9) show that the machine with the designed phase advance circuit has a significant gain and phase margins. Also, the figure illustrates that there is no possibilities of system failure as there is no limit cycle occurrence. (failure phenomenon occurred if the limit cycle frequency becomes equal the resonance frequency).

5. TIME-DOMAIN PERFORMANCE

The controller designed in section 4 is implemented using a non-linear digital simulation of the system shown in Fig.1, with the conventional synchronous machine replaced by a PM generator. The system is then subjected to a 3-phase short circuit at the generator terminals and the response is shown in Figs.10 and 11 at two different operating conditions. These results illustrates substantial reduction in the rotor first swing and well damping of the subsequent oscillations. The reduction in the rotor first swing indicates an extension of system stability. Moreover, the terminal voltage recovery is significantly improved as might be observed from the results. Also, the valve position of the mechanical loop has two successive closing which indicates that improvements in performance has been achieved with minimum valve movements. This also substantiate the technique applied and implemented in paper.

6. CONCLUSION

A frequency domain model of the PM synchronous generators was introduced and used for designing a phase advance network which applied on the mechanical loop as the only permissible input. The resonance frequency is firstly obtained and the required phase and gain margins are deduced. A sequential design procedure was applied to obtain the values of controller parameters. Extensive stability and performance evaluation of the system with the desired controller, indicated significant achievement in stability, damping of hunting oscillations and overall performance. These results indicate the possibility of synchronizing this machine without any adverse effects on the inter area oscillations and overall damping. These results are of practical importance to power system operators regarding synchronizing such generators into the grid especially at remote ends.

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LIST OF SYMBOLS

i : Current P.U.
V : Voltage P.U.
H : Inertia constant sec.
P : Differential operator
R : Resistance P.U.
T : Torque P.U.
X : Reactance P.U.
δ : Rotor angle
ψ : Axis flux linkage
ω : Angular velocity rad/sec.
X_{ad}, X_{aq} : Mutual direct and quadrature axes reactances.

APPENDIX

PM generator Parameters in per-unit values

$R_a = 0.0173$
$X_d = 0.543$
$X_q = 1.086$
$H = 0.251$
$i_f = 1.817$

$R_{KD} = 0.054$
$R_{KQ} = 0.108$
$X_{ad} = 0.478$
$X_{aq} = 1.021$
$X_{KD} = 0.608$
$X_{KQ} = 1.151$

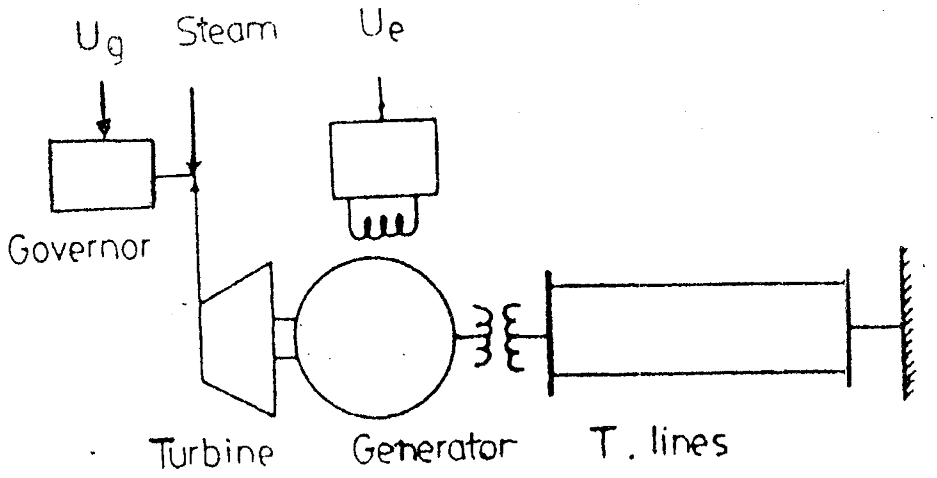

Fig.(1) Schematic diagram of a conventional synchronous generator

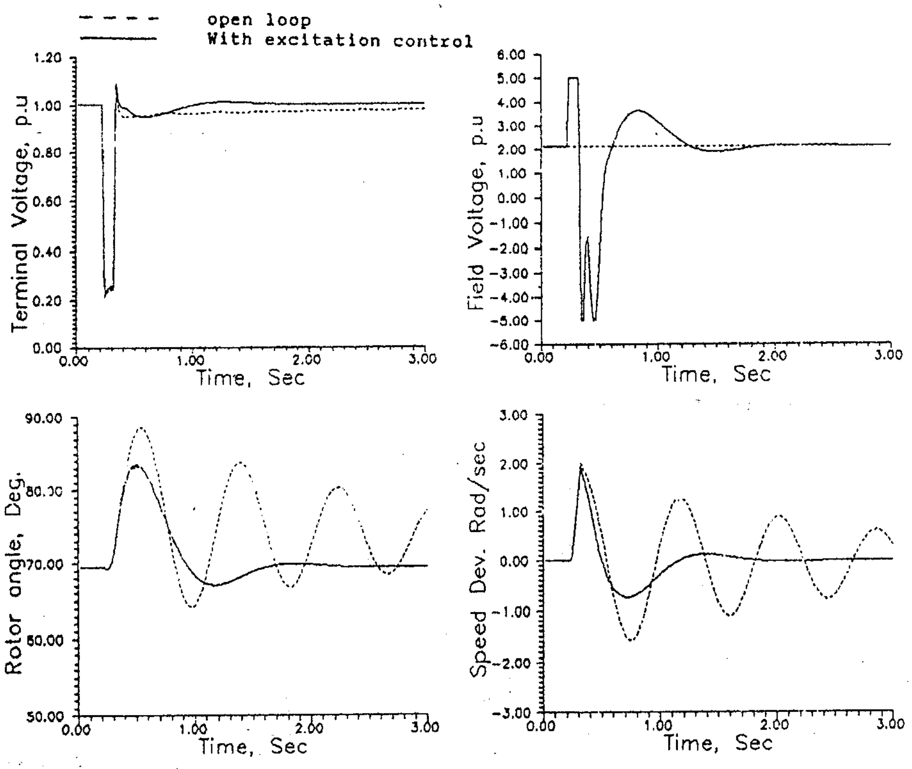

Fig.(2) Typical response of a conventional synchronous generator to a 3-phase S.C.

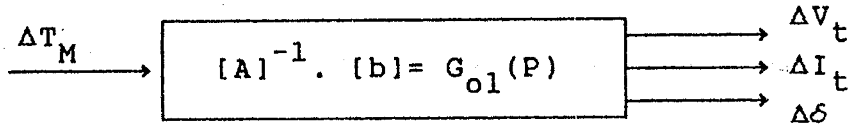

Fig.(3) Single-input/multi-output system

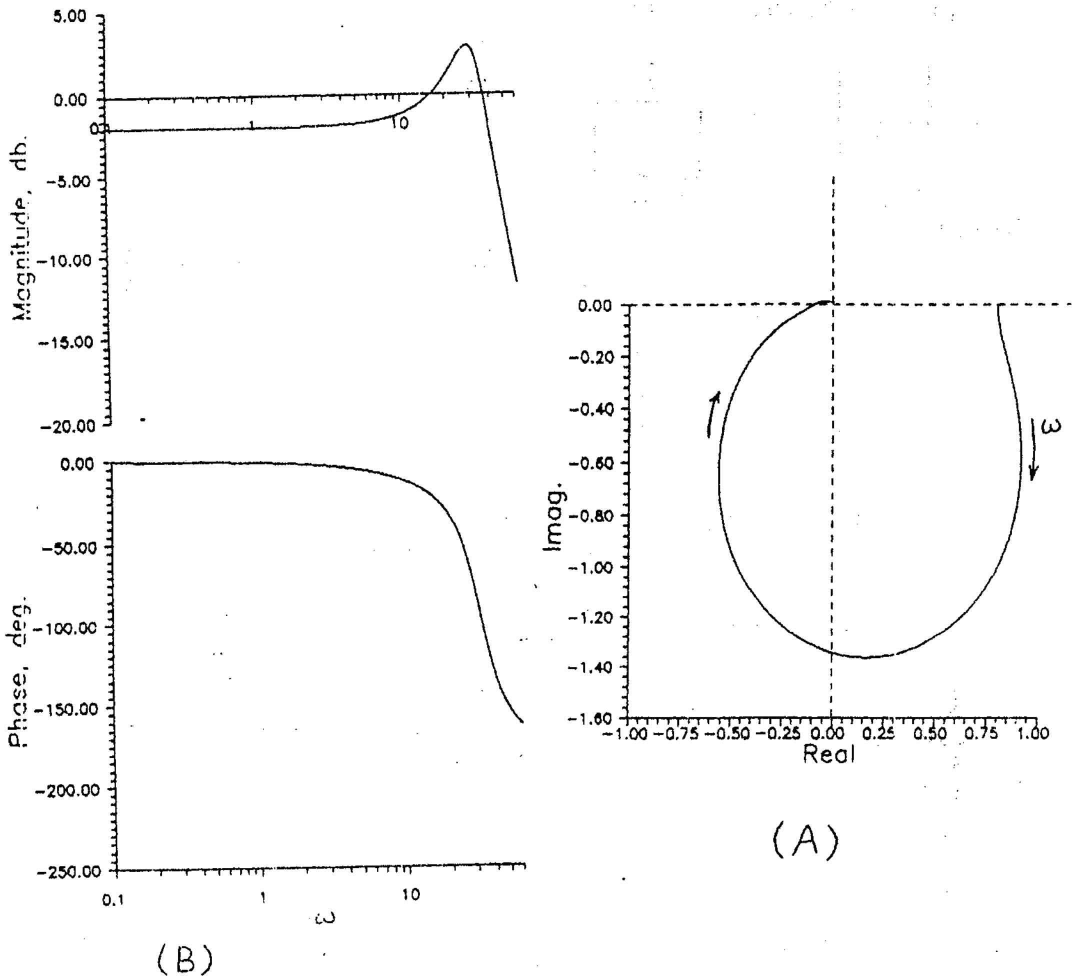

Fig.(4) Frequency response of a PM machine

a. Polar plot of $\Delta\delta/\Delta T_M$

b. Bode plot of $\Delta\delta/\Delta T_M$

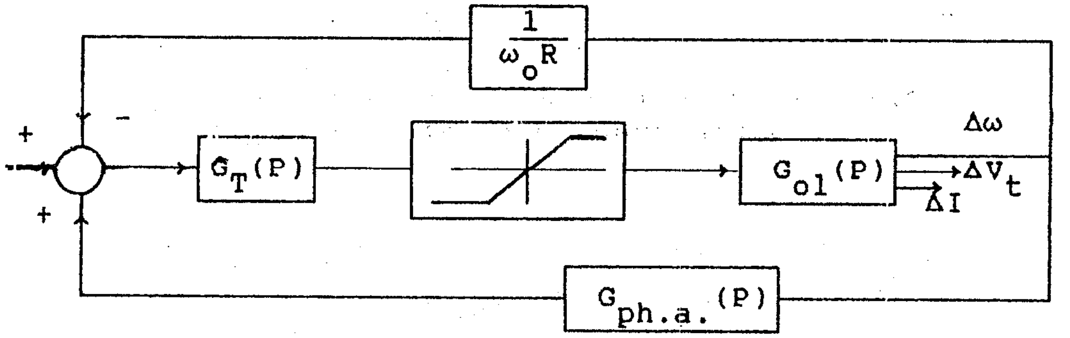

Fig.(5) Block diagram for the system including nonlinearity

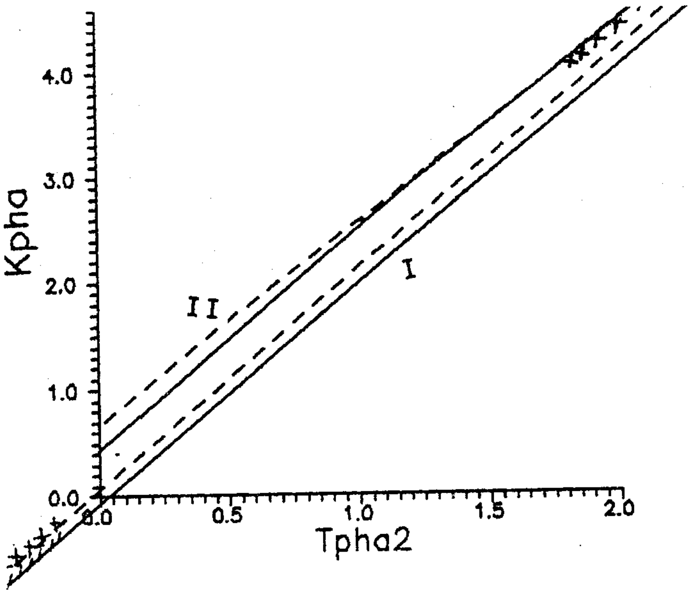

Fig.(6) Regions of stable operations
I- T_{pha1} = 0.15 II- T_{pha1} = 0.1

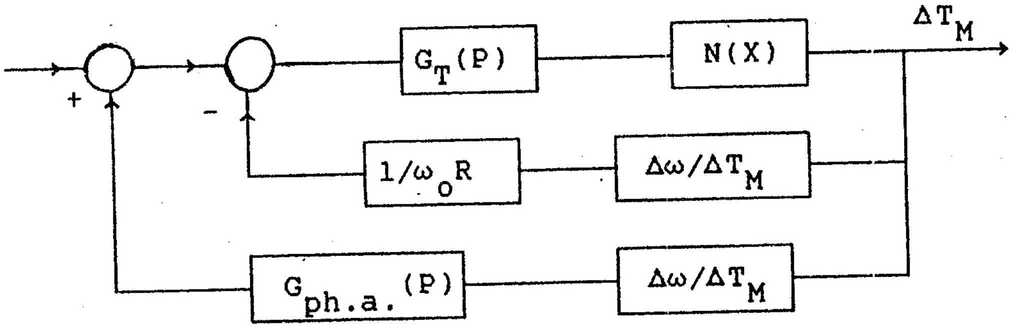

Fig.(7) Block diagram representation used for phase advance design

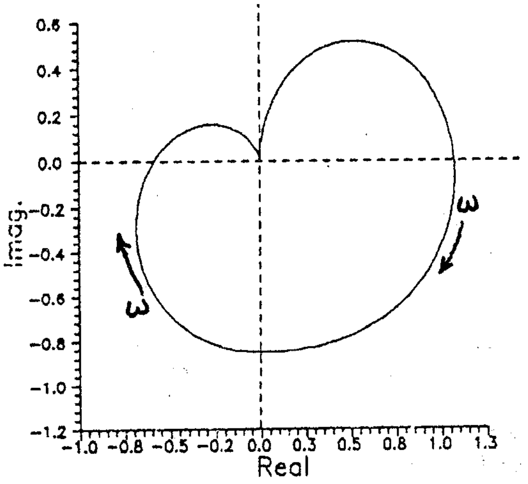

Fig.(8) Polar plot of $\Delta\omega/\Delta T_M$

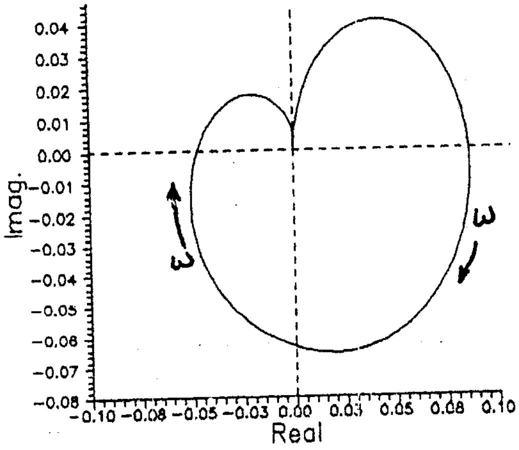

Fig.(9) Stability analysis of a PM generator

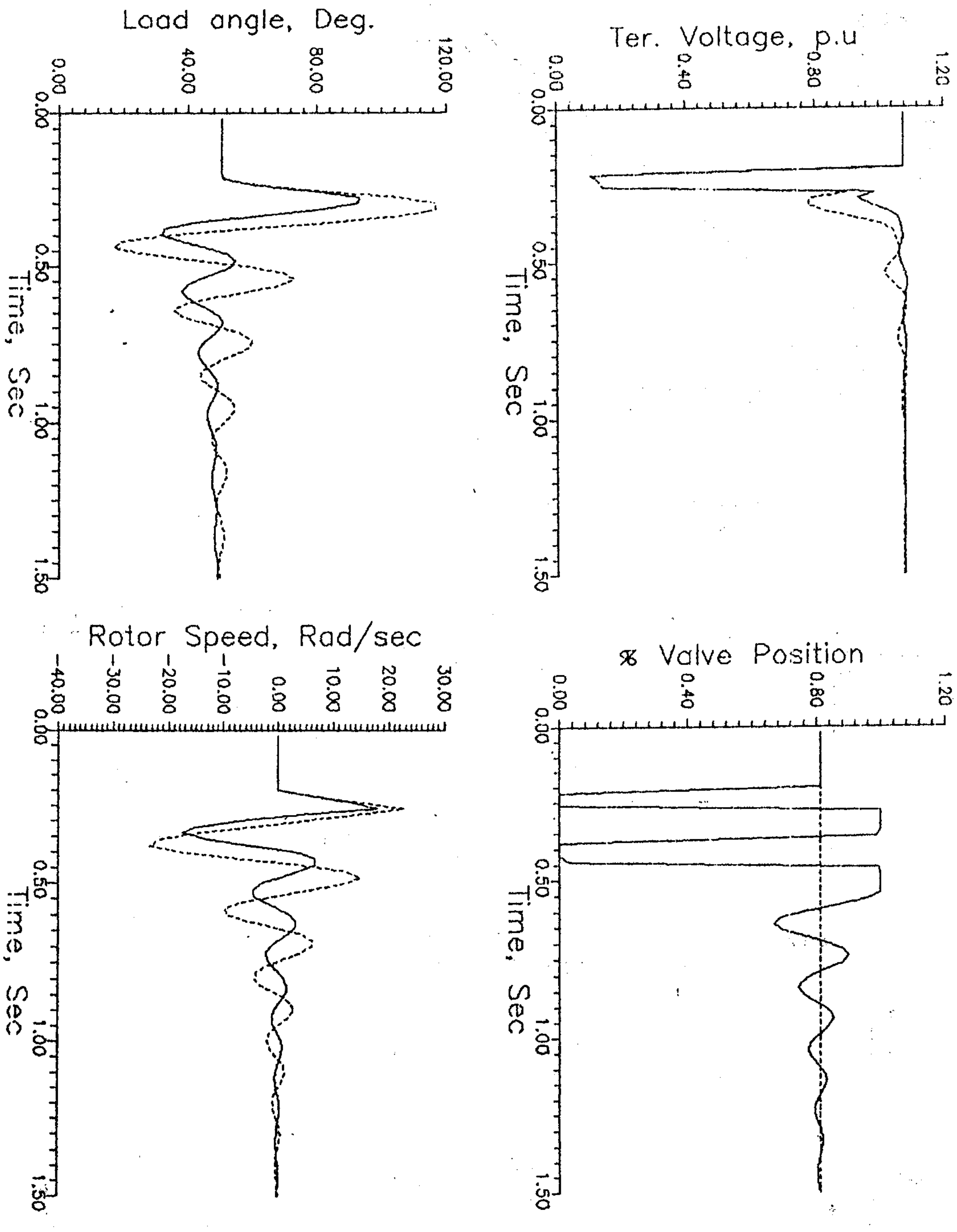

Fig.(10) Response of a PM generator to 3-phase S.C.
(P_t = 0.8 PU. , Q_t= 0.2 PU. , T_f= 50 ms)

- - - - Open loop
——— with phase advance

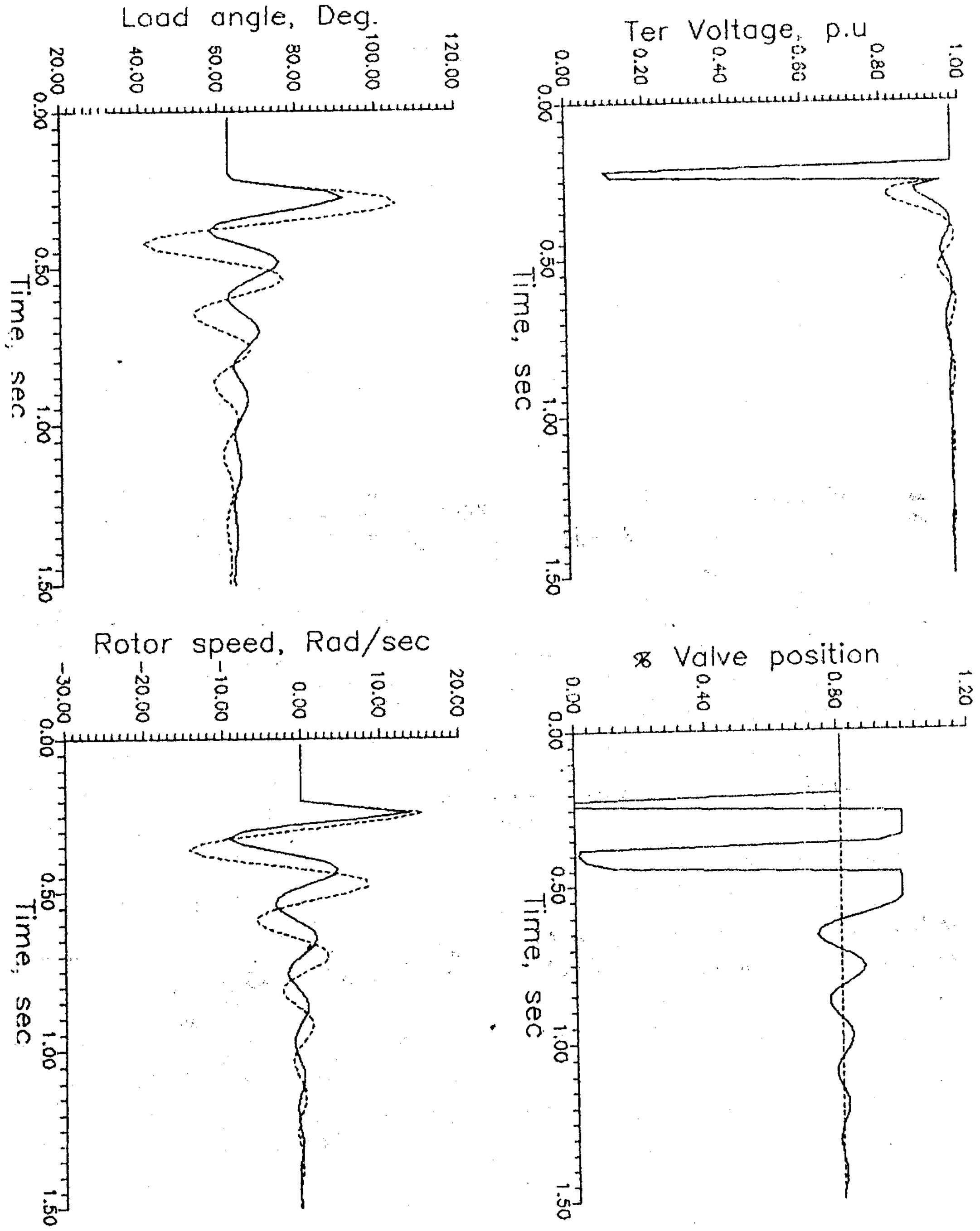

Fig.(11) Response of a PM generator to 3-phase S.C.
(P_t= 0.8 PU. , Q_t= 0.0 PU. , T_f= 40 ms)

- - - Open loop
——— with phase advance

موازنة المولدات المتزامنه ذات المغناطيسيه الدائمه

د/ جمال عبد الوهاب مرسي ؛د/ أحمد حسانين مرسي؛أ.د/ شعبان مبروك عشيبه

كثر استخدام الالات التي عضوها الدوار ذو مغناطيسيه دائمه وذلك نتيجة لمميزاتها العديده . ولكن نظرا لطبيعة مجالها الثابت (المستنتج من عضو ذو مغناطيسيه دائمه) فانه لايمكن استخدام الحاكمات التي تستخدم في الآلات المتزامنه التقليديه والتي كان يسهل التحكم في مغنياتها . وبالتالي يصعب ادماج تلك النوعيه من الآلات مع الشبكات الكهربيه نظرا لصعوبة خمد امتزازاتها . ومن هنا كانت الحاجه ملحه لتصميم حاكمات لتلك النوعيه من الآلات حتي يمكننا دمجها مع الشبكات الكهربيه .

في هذا البحث تم الاتجاه الي الدخل الوحيد لتلك الآلات الذي يمكن استغلاله وهو الدخل الميكانيكي وتم استخدام طريقة النطاق الترددي لتصميم دائرة تحكم تستطيع خمد الامتزازات للآله وبالتالي يسهل ادماجها مع الشبكه .

وللتأكد من كفاءة وموائمة الحاكم الجديد تم تطبيقه في نموزج غير خطي تفصيلي للآله . وتمت دراسة تأثير الاخطاء عليها ونتيجة استخدام الحاكم الجديد .وقد اوضحت الدراسه كفاءة الحاكم الجديد وموائمته لخمد اي امتزازات تحدث وبالتالي اصبح من الممكن ادماج الآلات ذات المغناطيسيه الدائمه (في وجود الحاكم الجديد)مع الشبكه الكهربيه.