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FREQUENCY DOMAIN ANALYSIS OF A SUPERCONDUCTING GENERATOR

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ABSTRACT

This paper investigates the stability and performance of a superconducting generator, connected to an infinite bus via a transformer and a double circuit transmission line, using the frequency domain technique. The mathematical equations of the system are obtained and expressed in frequency domain. The model obtained is then used to provide an extensive stability analysis and also as a base for designing a reliable control system. The controller is intended to substitute for the low inherent damping nature of this new machine. The control scheme is also tested using a fairly detailed non-linear model. The results illustrate the effects of various factors on stability and also a significant achievement in adding positive damping so that the overall performance is substantially improved.

1.INTRODUCTION

There has been a continous need for both increasing generation of electrical energy and up-rating the generator sizes over the years. Although there has been a substantial economic advantage in installing large generating units, the continous progress in up-rating the generators and the consequent trend in machine design parameters adversly affect overall system stability[1]. On the other hand, there are practical difficulties in developing conventional generators of rating beyond 2000 MVA. A possible way of overcoming these problems is by developing the promising superconducting generators (SCG), which are expected to have higher efficiency, smaller size and weight, improved system stability and possible generation at bus voltages.

International efforts have been devoted to develop large superconducting generators for commercial power application [2-6]. This new machine have a different construction criterion to that of the conventional synchronous generators. The exciter loop has a very long time constant and the steam turbine should be of fast response [3]. The per-unit reactances are relatively low which certainly improve dynamic and transient stability of the new machine when connected to the grid. However, the new machine has a low inherent damping which makes the machine oscillate with very poor damping characteristics when subjected to a disturbance. Moreover, the excitation loop long time-constant makes this loop ineffective to damp these oscillations in a similar way to that of the conventional synchronous machines.

Problems associated with the stability and control of superconducting generators have been under extensive investigations since the late 80's [3,4,7,8]. The superconducting alternator has almost zero resistance of the field winding coupled with the large number of amper-turns (the field winding time constant is about 750 s). So, excitation control, which is very effective in conventional generators, becomes ineffective in improving the dynamic performance of superconducting alternators. Therefore, the governor control is considered as the only available loop for improving the machine performance. However, due to the nature of this loop [9], very careful attention is required when dealing with governor control. Previous studies concluded that the phase advance network may be used for the governor loop and, if well designed, can give improved performance[3]. However, the design of these controller parameters were based on a trial and error approach without any quantitative measures regarding the improvement achieved in phase and stability margins or any other quantitative measure.

Alternatively, this paper describes the design of a control scheme for the governor/turbine loop, of the superconducting alternator, taking the phase and gain margins as quantitative measures. Sequential procedures have been taken to design the controller at the required frequency , thus prevents any possibility of system failure. The designed controller is implemented and an extensive stability analysis is described. Moreover, to examine the design approach the control system is applied on a fairly detailed non-linear simulation and the system response to a variety of disturbances, with and without the controller, is presented in a comparative form.

2.FREQUENCY DOMAIN MODEL

In this study, the traditional power system model, defined by a conventional synchronous generator connected to a large power system via a transformer and a double circuit transmission line, is used. The synchronous machine is replaced by its superconducting substitute. Description of the individual elements of the system in frequency domain is given subsequently, where the parameters are shown in appendix-I.

2.1. Superconducting Generator

Starting from the well known park's representation and taking into consideration that each of the rotor shielding screens may be represented by one coil of fixed parameters on each axis without loss of accuracy in control studies[5] .

The following linearized equations together with the mechanical equation of motion are used to represent the superconducting generator:

$$p\Delta\psi_f = \omega_o (\Delta V_f - R_f \Delta I_f) \qquad (1)$$

$$\Delta V_d = \frac{p}{\omega_o}\Delta\psi_d - \frac{p}{\omega_o}\psi_{q_o} \Delta\delta - \Delta\psi_q - R_a \Delta I_d \qquad (2)$$

$$P\Delta\psi_{KD_1} = -\omega_o R_{KD_1}\Delta I_{KD_1} \qquad (3)$$

$$P\Delta\psi_{KD_2} = -\omega_o R_{KD_2}\Delta I_{KD_2} \qquad (4)$$

$$\Delta V_q = \frac{P}{\omega_o}\Delta\psi_q + \frac{P}{\omega_o}\psi_{d_o}\,\Delta\delta + \Delta\psi_d - R_a\,\Delta I_q \qquad (5)$$

$$P\Delta\psi_{KQ_1} = -\omega_o R_{KQ_1}\Delta I_{KQ_1} \qquad (6)$$

$$P\Delta\psi_{KQ_2} = -\omega_o R_{KQ_2}\Delta I_{KQ_2} \qquad (7)$$

$$P^2\Delta\delta = \frac{\omega_o}{2H}\left[\Delta T_M - \Delta T_e - K_d\,P\Delta\delta\right] \qquad (8)$$

$$\Delta T_e = I_{d_o}\,\Delta\psi_d + \psi_{d_o}\,\Delta I_d - \psi_{q_o}\,\Delta I_q - I_{q_o}\,\Delta\psi_q \qquad (9)$$

Following the procedures in [10,11], the following relations can be easily obtained:

$$\Delta\psi_d = -X_{dsc}(P)\,\Delta I_d + G_{sc}(P) \qquad \text{(10}$$

$$\Delta\psi_q = -X_{qsc}(P)\,\Delta I_q \qquad \text{(11}$$

where, $X_{dsc}(P)$, $X_{qsc}(P)$: operational impedances in d and q axes .

$G_{sc}(P)$: operational admittance .

Substituting from equations (10, 11) , then the machine equations can be written as follows:

$$\Delta V_d + \left(R_a + \frac{P}{\omega_o}X_{dsc}(P)\right)\Delta I_d - X_{qsc}(P)\Delta I_q + \frac{P}{\omega_o}\psi_{q_o}\,\Delta\delta - \frac{P}{\omega_o}G_{sc}(P)\Delta V_f = 0 \qquad (12)$$

$$\Delta V_q + \left(R_a + \frac{P}{\omega_o}X_{qsc}(P)\right)\Delta I_q + X_{dsc}(P)\Delta I_d - \frac{P}{\omega_o}\psi_{d_o}\,\Delta\delta - G_{sc}(P)\Delta V_f = 0 \qquad (13)$$

$$[Mp^2 + K_d P]\,\Delta\delta - [I_{q_o}X_{dsc}(P) + \psi_{q_o}]\,\Delta I_d + [\psi_{q_o} + I_{d_o}X_{qsc}(P)]\Delta I_q + I_{q_o}G_{sc}(P)\,\Delta V_f - \Delta T_M = 0 \qquad (14)$$

2.2. 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 manner to that described for the generator the transmission system components are solved into the generator d-q axes then the linearized equations are obtained as follows:

$$\Delta V_d - (V_b \cos \delta_o)\, \Delta\delta - (R_e - \frac{p}{\omega_o} X_e)\, \Delta I_d + X_e\, \Delta I_q = 0 \qquad (15)$$

$$\Delta V_q + (V_b \sin \delta_o)\, \Delta\delta - (R_e + \frac{p}{\omega_o} X_e)\, \Delta I_q - X_e\, \Delta I_d = 0 \qquad (16)$$

2.3. Excitation System

A thyristor controlled static excitation system for the use with large superconducting generators has been designed, whose harmonic content is low so as to avoid appreciable heating in the superconductors [6]. The block diagram of a typical excitation system used is shown in Fig.(1) . The excitation system transfer function is:

$$\Delta V_f = \frac{X_{af}}{R_f}\, G_{AVR} \left[\frac{V_{do}}{V_{to}}\, \Delta V_d + \frac{V_{qo}}{V_{to}}\, \Delta V_q \right] \qquad (17)$$

Equation (17) were substituted in Eqns.(12-14).

2.4. Turbine and Governor System

It has been revealed that the turbine system that derives superconducting alternators should be of fast response with fast valving routine [3]. This would certainly may aid to maintain and improve the stability of that low-inertia unit. The block diagram representation of the governing system used is shown in Fig.(2) .

2.5. Open Loop Model

Arranging Eqns.(11-15) in array form, and dividing all system variables by ΔT_M , as the only permissible input, to formulate the transfer function yields :

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} \end{bmatrix} \begin{bmatrix} \Delta V_d/\Delta T_M \\ \Delta V_q/\Delta T_M \\ \Delta\delta/\Delta T_M \\ \Delta I_d/\Delta T_M \\ \Delta I_q/\Delta T_M \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \quad (18)$$

Equation (18) can be expressed as follows;

$$[\ A\ ]\ [\ \Delta X\ ] = [\ b\ ] \quad (19)$$

or,

$$[\ \Delta X\ ] = [\ A\ ]^{-1}\ [\ b\ ] \quad (20)$$

The system will be considered as single-input multi-output as shown in Fig.(3), and equation (20) can be calculated numerically to obtain the frequency response of, for example, $\Delta\delta/\Delta T_M$. These results are shown in Fig.(4). As expected the results illustrate a very poor damping characteristics which coincides with the results presented elsewhere [2,5]. This in the authors opinion, requires a well designed control scheme, which is the object of this work.

3. PHASE ADVANCE NETWORK

The phase advance circuit must be designed to ensure suitable behavior of the machine in both steady state and large disturbance modes. Fig.(5) illustrates the block diagram of the system after incorporation of the phase advance system. Moreover, for seeking accuracy and avoid misleading results, a non-linear function is also incorporated. The characteristic equation of the system is then written as follows (assuming N=1):

$$1 + G_T(P) \left(\frac{1}{\omega_o R} + G_{ph.a.}(P) \right) \frac{P\Delta\delta}{\Delta T_M} = 0 \quad (21)$$

The phase advance network chosen is a lead compensator, whose transfer function is given by :

$$G_{pha}(P) = K_{pha} \left\{ \frac{1 + P\ T_{pha1}}{1 + P\ T_{pha2}} \right\} \qquad (22)$$

where, K_{pha} : phase advance gain ;

$T_{ph1} = \alpha\ T_{pha2}$, $\alpha > 1$

3.1. Boundary Limits of Control Parameters

Now, it is recommended, before preceding 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 [10]has been applied and the results are shown in Fig.(6). This illustrate the limits and possible combination of parameters which give an acceptable and stable operation.

3.2. Design Technique

The objectives of this part is to design an appropriate phase advance network which improve the system stability and ensure good transient response. The design technique was firstly applied on conventional synchronous generator [11]. The advantages of this technique is its capability to introduce the required phase lead at the system resonance frequency. This is a very important and remarkable point as such design prevents sustained oscillations and consequently system failure. 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[11].

The designed circuit must deduce the required phase at the resonance frequency ω_r , and given as :

$$\phi_{max} = \sin^{-1}\left(\frac{\alpha - 1}{\alpha + 1} \right) \qquad (23)$$

The parameter α is chosen by making ϕ_{max} equal to the required phase at the frequency of the electromechanical mode.

$$\omega_{max} = \omega_r = 1 / T \sqrt{\alpha} \tag{24}$$

$$T_{pha2} = T \quad , \quad T_{pha1} = \alpha \, T_{pha2}$$

Figure (8) shows the polar plot of $\Delta\omega/\Delta T_M$. The phase advance circuit should provide around 74° at resonance frequency of 9.6 rad/sec., then $\phi_{max} = 74^o$ and $\omega_{max} = 9.6$ rad/sec, consequently $\alpha \cong 50$ and $T \cong 0.01$ sec. The designed phase advance circuit has the following transfer function

$$G_{pha}(P) = 0.1 \left[\frac{1 + 0.5\,P}{1 + 0.01\,P} \right] \tag{25}$$

The choice of the suitable gain K_{pha} is very important to ensure the required stability specifications.

4. STABILITY ANALYSIS

The describing function analysis has been used to investigate the system stability and to study the possibilities of system failure. Replacing the nonlinear element in Fig.(7) by its describing function N(X) , then we can write :

$$- \frac{1}{N} = \left[\frac{1}{\omega_o R} + G_{ph.a.}(P) \right] G_T(P) . \frac{\Delta X}{\Delta T_M} \tag{26}$$

Figure(9) show that the system with the designed phase advance network is stable with a gain and phase margins of a range which guarantee a satisfactory transient response(phase margin ≥ 30°and gain margin ≥ 6 db.). Also, it might be observed that the possibilities of limit cycle occurrence is denied with the introduction of the proposed control system.

5. TIME-DOMAIN ANALYSIS

A fairly detailed non-linear model for the SCG were obtained including all non-linearities and constraints imposed on control loops. A three-stage steam turbine with reheat and fast acting electro-hydraulic governors is considered [3].

The previously designed controller with the recommended parameters were implemented using the non-linear model. The system equations are solved using the runge-Kutta integration technique. The system response, with and without control, for a symmetrical three-phase short circuit, of 120 ms duration, at the high voltage bus-bars of the generator transformer is shown in Figs.(10, 11), at unity and leading power factor, respectively. It is interesting to note that after fault , the system without any controllers (curves I) swings around the operating point for a long time with a slight decrease in the amplitude of the system oscillations. Moreover, the system with speed governor only (curves II) shows excessive valve movement and an increase in the system oscillations. Also,the results shows that the speed governor has a little effect on the first rotor angle swing, which represent unsatisfactory performance and that the system requires some sort of stabilization. Finally, the results of the system using the phase advance network (curves III) illustrate a significant improvement in the system performance and an appreciable increase in the damping associated with a reduced rotor first swing.

6. CONCLUSIONS

No doubt that damping oscillations of superconducting alternators represent a very difficult task due to the ineffective nature of the excitation loop. The paper introduced a simple and reliable method for designing a control scheme that introduce positive damping to damp the machine oscillations. This represents the first trial to design controller for superconducting alternators, taking the phase and gain margins as quantitative measures. The resulting scheme prevents the excessive movements of the steam valve and substantially reduce the rotor first swing. The results which were presented in a comparative form illustrate well damped response which substantiate the developed technique.

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List Of Symbols

V = voltage, p.u.
i = current, p.u.
R = resistance, p.u.
X = reactance, p.u.
H = inertia constant, KWs/KVA.
p = differential operator.
ω = angular speed, rad/sec.
T = torque .
ψ = flux linkage, p.u.
δ = rotor angle.

Subscripts

a = armature
d,q = d and q components of the stator winding.
e,M = electrical, mechanical.
f = field.
o = steady state.
KD_1, KQ_1 = d and q components of the outer screen .
KD_2, KQ_2 = d and q components of the inner screen .
fKD_1, fKQ_1 = d and q mutual components between outer screen and field winding.
fKD_2, fKQ_2 = d and q mutual components between inner screen and field winding.

APPENDICES

APPENDIX-I

(i) Superconducting Machine Parameters

2000 MVA , 1700 MW, 3000 r.p.m.

$X_d = X_q = 0.5453$ p.u. $\quad X_f = 0.541$ p.u.

$X_{KD_1} = X_{KQ_1} = 0.2567$ p.u. $\quad X_{fKD_2} = 0.3898$ p.u.

$X_{af} = X_{fKD_1} = X_{ad_1} = X_{ad_2} = X_{KD_1KD_2} = 0.237$ p.u.

$X_{aq_1} = X_{aq_2} = X_{KQ_1KQ_2} = 0.237$ p.u.

$R_a = 0.003$ p.u. $\quad R_{KD_1} = R_{KQ_1} = 0.01008$ p.u.

$R_{KD_2} = R_{KQ_2} = 0.00134$ p.u. $\quad H = 3$ KW sec/KVA.

field time constant 750 sec.

(ii) Transmission System Parameters

$X_T = 0.15$ p.u. $\quad R_T = 0.003$ p.u.

$X_L = 0.05$ p.u. $\quad R_L = 0.005$ p.u.

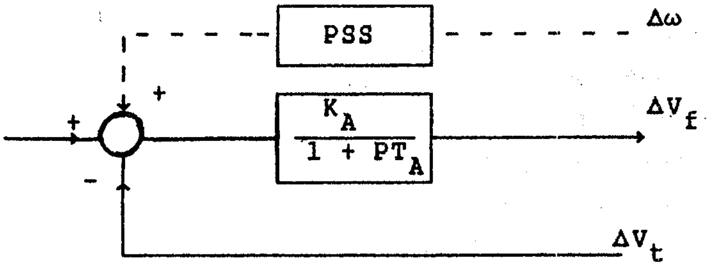


Fig.(1) Block diagram of excitation system

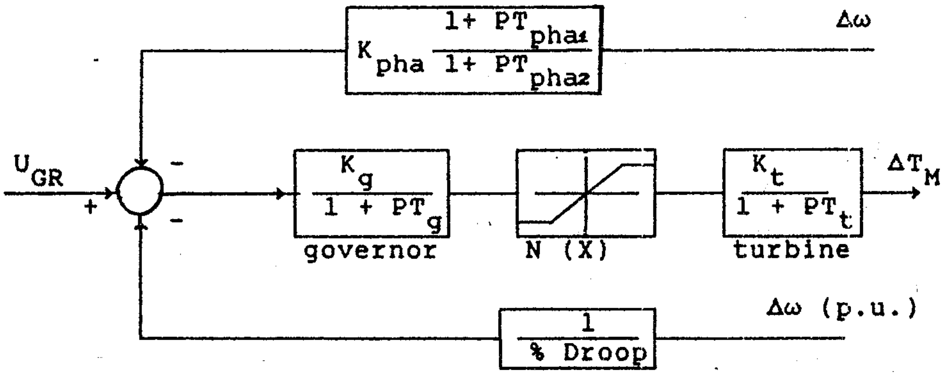


Fig.(2) The governor control system

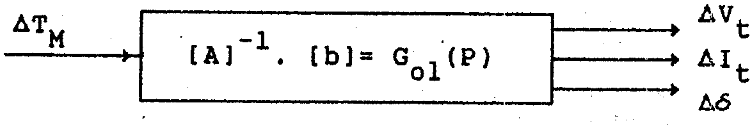


Fig.(3) Single-input/Multi-output System

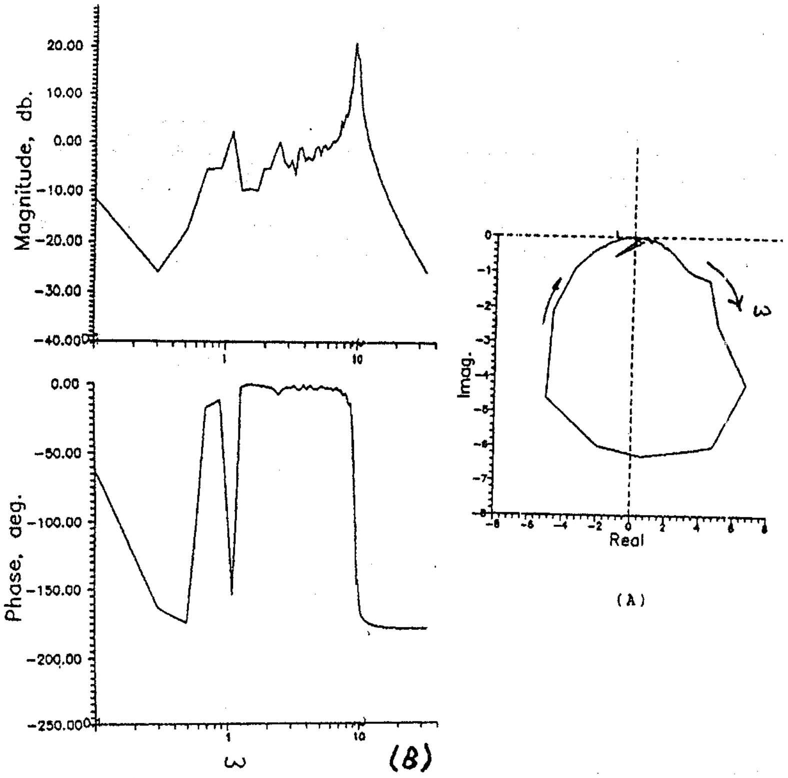


Fig.(4) Frequency response of $\Delta\delta/\Delta T_M$
A- polar plot
B- bode plot

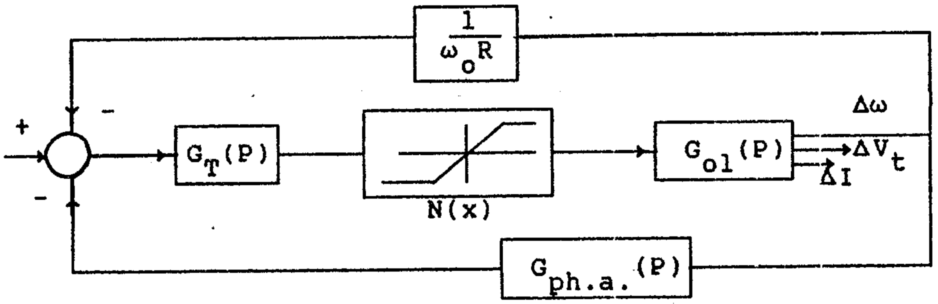
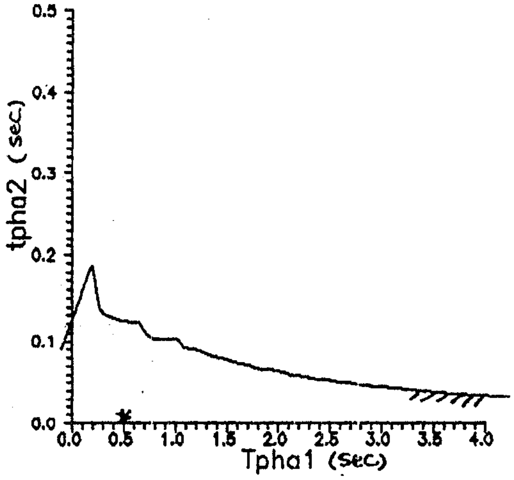


Fig.(5) Block diagram for the system including nonlinearity

Fig.(6) Region of stable operation. ($K_{ph.a.}$=0.1)



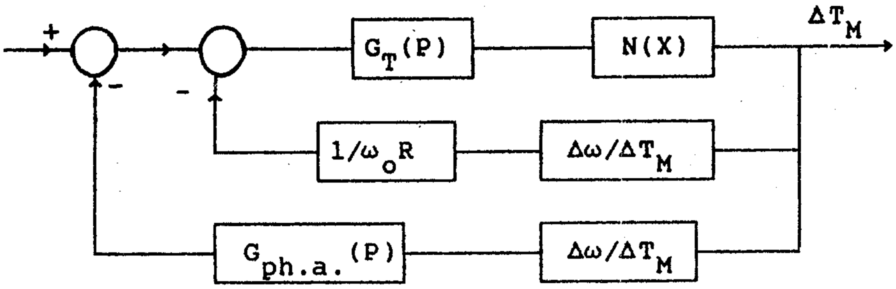


Fig.(7) Block diagram representation used for phase advance design.

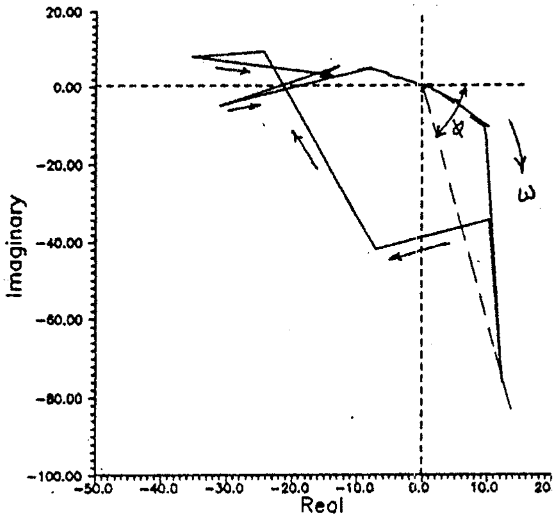


Fig.(8) Polar plot of $\Delta\omega/\Delta T_M$

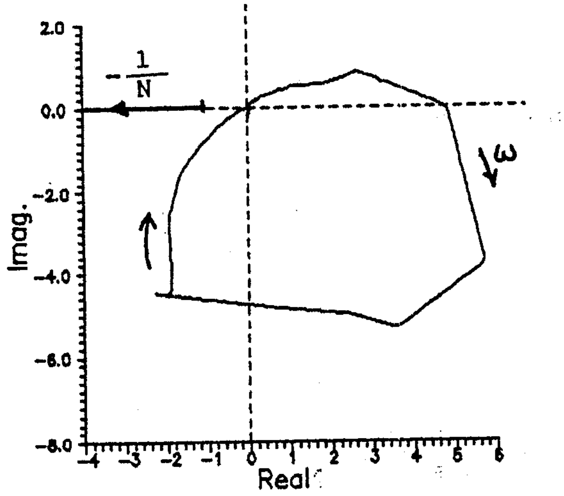


Fig.(9) Stability analysis

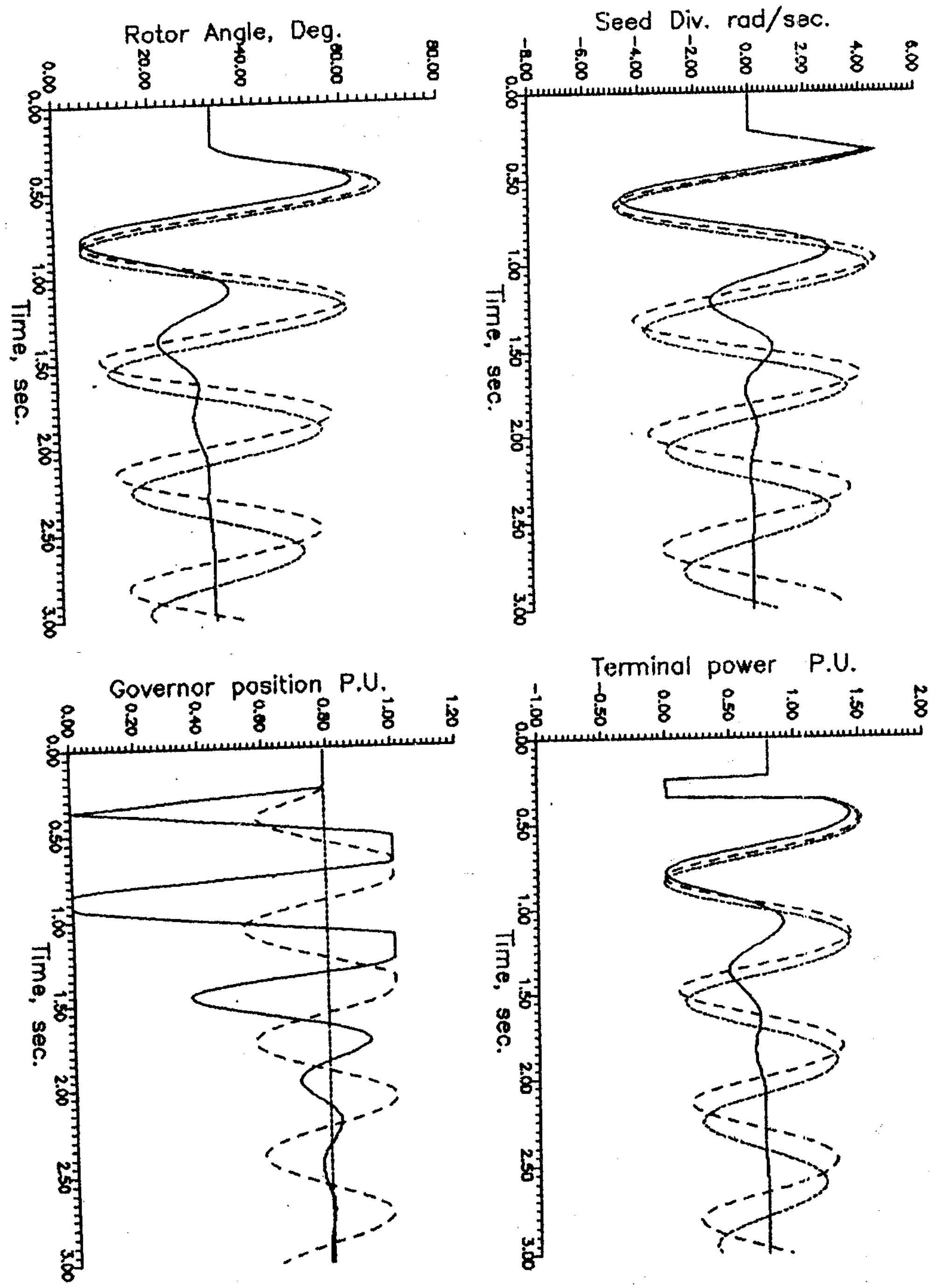


Fig.(10) Transient response of a SCG to 3-phase s.c.
(unity power factor)
----- open loop — — — with SG.
——— with SG. + phase advance

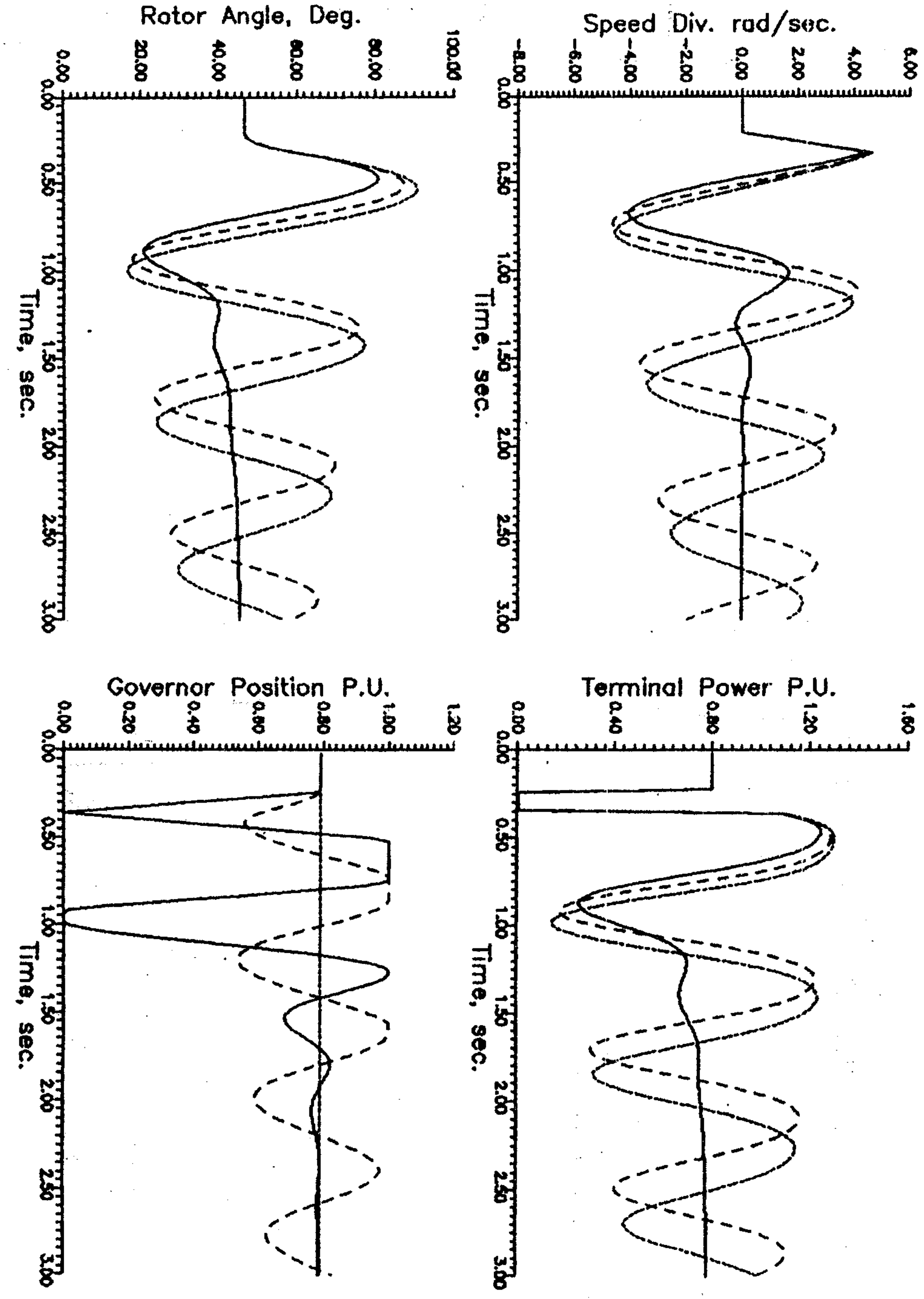


Fig.(11) Transient response of a SCG to 3-phase s.c.
(lead power factor)
----- open loop ---- with SG.
——— with SG. + phase advance

بسم الله الرحمن الرحيم

تحليل أداء المولدات فائقة التوصيل باستخدام طريقة النطاق الترددى

نظرا لزيادة الطلب على الطاقة الكهربية كان الاتجاه الي رفع مقننات وحدات التوليد وتغيير بارامتراتها وبالتالى زيادة احجامها . وبالرغم من الافاده في النواحي الاقتصادية من استخدام تلك الوحدات الكبيرة الا ان تغيير بارامترات تلك الالات يوثر سلبيا على اتزان نظم القوى .

والحل المناسب الان للتغلب على تلك المشاكل هو بادخال المولدات فائقة التوصيل والتى تتميز بكفائتها العالية وحجمها الصغير الى جانب امكانية توليدها للطاقة عند جهود عالية تصل الي جهد الشبكة مباشرة .

هذا البحث يدرس اداء واتزان آله فائقة التوصيل متصلة مع شبكة كبيرة خلال خط نقل وذلك باستخدام طريقة النطاق الترددي . حيث تم إيجاد نموذج للنظام في النطاق الترددي وتم استخدام هذا النموذج لعمل تحليل مكثف لاتزان الاله . كذلك تم استخدامه كأساس لتصميم حاكم ملائم يضيف خمد موجب لعلاج ضعف الخمد المصاحب لطبيعة تلك الاله .

اخيرا تم اختبار الحاكم المصمم بتطبيقه على نموذج غير خطى تفصيلى للنظام وقد اوضحت النتائج مدى التحسن الملموس في أداء النظام وزيادة حدود اتزانه عند تطبيق ذلك الحاكم نظرا لما يضيفه من خمد موجب .