Mansoura Engineering Journal (MEJ) Vol.13, No.2, December 1988 

# ANALYSIS OF A CO-ORDINATED GOVERNER/EXCITER STABILIZER IN MULTIMACHINE POWER SYSTEMS BASED ON THE TRANSIENT ENERGY FUNCTION

تحليل اتزان نظام نرى كهربى متعدد الالات باشارات اضافية فى دائرتى تغذية المجال ومنظم السرعة ومستنبطة على أساس دالة الطاقة

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الخلاصة — يقدم البحث تحليلا لدالة الطاقة العابرة فى نظام كهربى متعدد الالات . وباستخدام تحليل دالة الطاقة العابرة وبعض النظريات فى الميكانيكا النظرية تم استنباط دوال اشارات اضافية فى دائرتى تغذيه المجال ومنظم السرعة وذلك لتحسين الاتزان الديناميكى لنظام كهربى متعدد الالات وبشرط أن يكون النظام متزنا ( اسميتوتك ) فى دورة التأرجح الأولى بعد حدوث الاضطرابات الكبيرة . تم التأكد حسابيا من فاعلية الاشارات الاضافية على اتزان نظام كهربى ( يكافىء شبكة مصر الموحدة ) مكون من ١٠ محطات مكافئة ، ١٩ نقطة توزيع ١٧ حمل .

ABSTRACT

This paper describes, the application of transient energy function and some laws of theoretical mechanics necessary to the problem of analysing co-ordinated stabilizer in a multimachine power system. The co-ordinated stabilizing inputs for the exciter and governer loops to improve transient stability in the power system are defined. The different energies in the power system are analysed. If the power system is asymptotically stable in the first swing cycle, the rate of change of total transient energy must tend to zero. This constraint is accomplised by the proposed stabilizer. The stabilizer is designed on the base of balancing its forces with the necessary forces to damp swings of generator rotors.

The effectiveness of the proposed stabilizer is demonstrated by applying it to a generating station in a 10-generator and 19-bus power system, which represents the reduced Egyptian Unified Network.

## INTRODUCTION

In modern power systems, improved transient stability is an important consideration in the reliable and efficient operation of the system. The practical approaches to transient stability control can be classified into two types of action:

- methods requiring change in the network
- methods altering the conventional operation of AVR and/or governer

All changes in the network require additional switchgear and timing equipment,which are somewhat expensive and complex.

The implementation of excitation and/or governer control, through a voltage regulator and a turbine governer, d'ont requries such equipment (switchgear and timing equipment) The action of the conventional units, in improving stability, is enhanced by the use of carefully designed supplementary control.

The theory of conventional AVR, on transient stability (1,2) has been will established. Additional signals, other than terminal voltage feedback in the excitation system, have been proposed [3,4].

The use of additional signals in the turbine governer loop has also been studied [4]. A frequency response method [5] was used to examine the effect of the time-integral of speed deviation added to speed deviation.

Most of supplementary excitation control (6,7) and turbine control [6,7] in power systems, are derived on the base of a simple power system (generator connected to an infinite bus through transmission system). They may be effective in case of a power system only, otherwise, their effectiveness in multimachine power systems is not insured.

This paper proposes a design of a co-ordinated exciter/governer stabilizer. The design is based on the transient energy function and some laws of theoretical mechanics. Through analysis of the different energies in the power system, the total energy of the power system is deduced. For asymptotic stability of the system, the rate of change of the total energy must tend to zero. This constraint can be accomplished by the proposed stabilizer. The stabilizer is designed on the base of balancing its forces with the forces, necessary to damp swings of generators rotors. The paper describes theoretical aspects of the design procedure and application to multimachine power system.

ANALYSIS OF TRANSIENT ENERGY FUNCTION

An n-machine system is considered here, as shown in Fig. 1. The dynamics of each generator, without taking the damper winding into consideration, are represented by the following equations:

$$Mi\ dwi/dt-(PTi-Pii)+\sum_{j\neq i}^{n} Pij\ \sin(\delta ij-\alpha ij)=0 \qquad (1)$$

$$d\delta i/dt=wi$$

where

Mi =inertia constant of generator i

$\delta i$ =angle behind Xd of generator i

wi =rotor speed of generator i

PTi=mechanical power input of generator i

Pii=Ei.Ei Yii sin $\alpha ii$

Pij=Ei.Ej Yij

Ei,Ej=voltages behined Xd of generator i and j. They are variables depending on a certain function, as discused below.

Yii=deriving point admittance for internal node of generator i

Yij=transfer admittance between internal nodes i and j

The motion of the center of inertia reference frame, COI, is determined by [8]

$$Me\ dwe/dt-(PTe-PEe)=0 \qquad (2)$$

where

$$Me=\sum_{i=1}^{n} Mi$$

$$we=\sum_{i=1}^{n} Mi\ wi/\sum_{i=1}^{n} Mi$$

$$PTe=\sum_{i=1}^{n} PTi$$

$$PEe=\sum_{i=1}^{n} Pii+\sum_{i=1}^{n}\sum_{j\neq i}^{n} Pij\ \sin(\delta ij-\alpha ij)$$

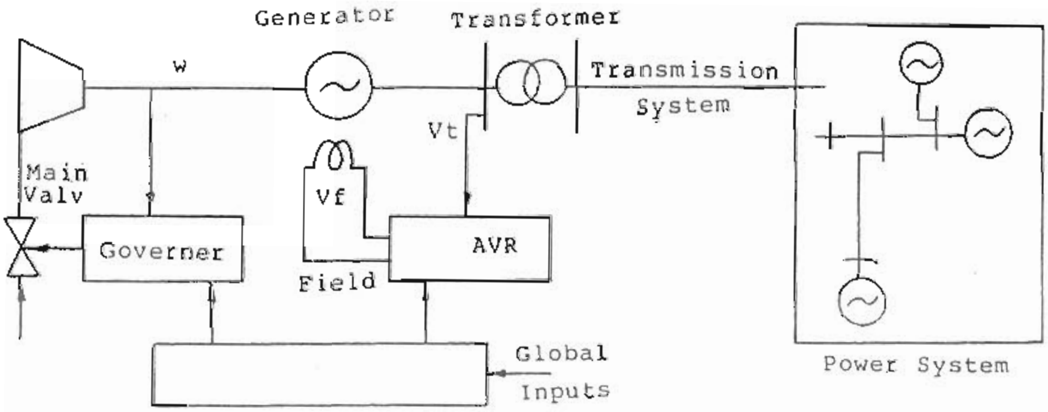



Fig.1 Basic System for Design Co-ordinated Stabilizer

Integrating eq.(1) with respect to rotor angle $\delta i$ and using as a lower limit $\delta i=\delta oi$, where $\delta oi$ is the initial position of rotor i, and summting for n equations, yields

$$\sum_{i=1}^{n} Mi(wi^2-woi^2)/2-\sum_{i=1}^{n}\int_{\delta io}^{\delta i}(PTi-Pii)d\delta i+\int_{\delta io}^{\delta i}\sum_{i=1}^{n}\sum_{j\neq i}^{n} Pij\ \sin(\delta ij-\alpha ij)d\delta i \quad (3)$$

The first term of eq.(3) is the system kinetic energy,VK, with respect to the system initial position. The second and third terms represent the rotor potential energy and the energy stored in the power system, respectivey. As known in the literature, the term "potential energy" is used to indicate the last two terms [8].

If the power network is represented by the so-called classical model [9], where the voltage behined X'd and mechanical input are constant and equal to the corresponding initial values ($PTi=PToi$, $Ei=Eoi$ and $Ej=Eoj$), the potential energy function in eq.(3) becomes (with $d\delta i=wi\ dt$)

$$VPo=-\int_{to}^{t}\sum_{i=1}^{n}(PToi-Poii)wi\,dt+\int_{to}^{t}\sum_{i=1}^{n}\sum_{j\neq i}^{n}Poij\,\sin(\delta ij-\alpha ij)wi\,dt \quad (4)$$

where

$$Poii=Eoi^2\,Yii\,\sin\alpha ii$$

$$Poij=Eoi.Eoj\,Yij$$

The kinetic energy, VK',associated with all generators (internal kinetic energy) is the difference between the total kinetic energy of the power system, VK, and kinetic energy of the COI, VKe [10]

$$VK' = VK - VKe$$

$$=\sum_{i=1}^{n}Mi\,wi^2/2 - Me\,we^2/2$$

$$=\sum_{i=1}^{n}Mi\,wie/2 \quad (5)$$

where

$wie = wi - we$

Integrating eq.(2) with respect to the COI angle $\delta e$, using as a lower limit $\delta e=\delta eo$, where $\delta eo$ is the initial position of COI, yields

$$Me(we^2-weo^2)/2-\sum_{i=1}^{n}\int_{\delta eo}^{\delta e}(PTi-Pii)d\delta e+\int_{\delta eo}^{\delta e}\sum_{i=1}^{n}\sum_{j\neq i}^{n}Pij\,\sin(\delta ij-\alpha ij)d\delta e=0 \quad (6)$$

Equation (6) represents the total transint energy of COI. The first term is the COI kinetic energy, VKe, and the remaining terms represent the potential energy of COI, VPe.

For classical model, the potential energy function of COI in eq.(6) becomes

$$VPeo=-\int_{to}^{t}\sum_{i=1}^{n}(PToi-Poii)we\,dt+\int_{to}^{t}\sum_{i=1}^{n}\sum_{j\neq i}^{n}Poij\,\sin(\delta ij-\alpha ij)we\,dt \quad (7)$$

Subtracting eq.(4) from eq.(3) and substituting by eq.(6) in the obtained equation,yields

$$\sum_{i=1}^{n}Mi(wie^2-wieo^2)/2-\int_{\delta ieo}^{\delta ie}\sum_{i=1}^{n}(PTi-Pii)d\delta ie+\int_{\delta ieo}^{\delta ie}\sum_{i=1}^{n}\sum_{j\neq i}^{n}Pij\,\sin(\delta ij-\alpha ij)d\delta ie \quad (8)$$

Equation (8) represents the total energy of rotors of the synchronous generators with respect to the COI. First term in eq.(8) is the kinetic energy,VK',the other two terms are the potential energy,VP'.

For classical model of the power system, the potential energy in eq.(8) becomes

$$VPo' = -\int_{to}^{t} \sum_{i=1}^{n} (PToi - Poii) wie\, dt + \int_{to}^{t} \sum_{i=1}^{n} \sum_{j\neq i}^{n} Poii \sin(\delta ij - \alpha ij) wie$$

STABILIZER DEFINITION

Now, suppose that the disturbed power system is affected by the supplementary control and becomes dissipated system, i.e the following constraint is fulfilled

$$dV/dt < 0 \qquad (10)$$

where

$V = VK + VPo$

For fulfilling constraint (10), i.e for damping rotor swings, the supplementery control action Ui(t) must be designed on the base of balancing its forces, which are necessary to damp rotor swings, with the forces equivalent to the friction forces. The energy VF, corresponding to the friction forces can be defined as follows [10]

$$VF = \int 2F\, dt \; ; \qquad (11)$$

$$F = \sum_{i=1}^{n} Ki\, wi^2 /2 \qquad (12)$$

where

F =dissipating function, affected by the supplementery control
Ki=generalized friction coefficient

The dissipating function F can be represented by summation of F' and Fe as follows

$$F = F' + Fe \qquad (13)$$

where

$$F' = \sum_{i=1}^{n} Ki\, wie^2 /2 \qquad (14)$$

and

$$Fe = \sum_{i=1}^{n} Ki\, \dot{we}^2 /2 \qquad (15)$$

F' and Fe are the dissipation energy of rotors of system generators and disspation energy of the COI respectively.

If the power system is controlled, the following equation must be governed

$$V + Vf = const \qquad (16)$$

or

$$dV/dt = -2F \qquad (17)$$

Equation (17) shows that the power system is dissipated only in the case of positive values of dissipating function F. Eq.(17) can be subdivided into the following two equations

$$dV'/dt = -\ 2F' \tag{18}$$

$$dVe/dt = -\ 2Fe \tag{19}$$

where

$$V' = VK' + VPo' \tag{20}$$

$$Ve = VKe + VPeo \tag{21}$$

Substituting values of V' and F' in eq.(18), yields

$$\sum_{i=1}^{n}[(PTi-PToi)-(Pii-Poii)]wie-\sum_{i=1}^{n}\sum_{j\neq i}^{n}(Pij-Poij)\ \sin(\delta ij-\alpha ij)wie$$

$$+\sum_{i=1}^{n}Ki\ wie^{2} = 0 \tag{22}$$

Simillarly, substituting the values of Ve and Fe in eq.(18),yields

$$\sum_{i=1}^{n}[(PTi-PToi)-(Pii-Poii)]we-\sum_{i=1}^{n}\sum_{j\neq i}^{n}(Pij-Poij)\ \sin(\delta ij-\alpha ij)we$$

$$+\sum_{i=1}^{n}Ki\ we^{2} = 0 \tag{23}$$

Equations (22) and (23) are not sufficient for determining supplementery controls applied on the excitation system (UEi(t)) of all synchronous generators and supplementery controls applied on all turbine governers (UGi(t). However, this problem can be solved by assuming that the supplementery controls acting only on one turbine-generator unit (unit i) and the remaining units of the power system are uncontrolled, i.e, Ej = Eoj = E'j = E'qj and PTj = Ptoj.

According to the above assumption, eq.(21) and eq.(22) can be used to formulate two equations for UEi(t) and UGi(t), as follows

$$(PTi-PToi)-(Pii-Poii)-\sum_{j\neq i}^{n}(Pij-Poij)\ \sin(\delta ij-\alpha ij)+Ki\ wie = 0 \tag{24}$$

$$(PTi-PToi)-(Pii-Poii)-\sum_{j\neq i}^{n}(Pij-Poij)\ \sin(\delta ij-\alpha ij)+Ki\ we = 0 \tag{25}$$

Each of eq.(24) and eq.(25) can be used for determining the supplementary excitation (SE) control or supplementary governer (SG) control. However, the effectiveness of the SE control is increased, when used for damping rotor swings of generator i with respect to the COI.

Substituting UGi(t) = 0 in eq.(24), yields

$$(Pii-Poii)+\sum_{j\neq i}^{n}(Pij-Poij)\ \sin(\delta ij-\alpha ij) = Ki\ wie \qquad (26)$$

On the other hand, the effectiveness of SG control is increased when used for enhancing damping of oscillations, which occur in the power system as a whole, i.e control of system frequency deviation ($\Delta fav$) from its initial value (fo), where $\Delta fav = we/2\Pi$. Therefore, SG control is obtained from eq.(25), by substituting UEi(t) = 0 :

$$(PTi-PToi)+Ki\ we = 0 \qquad (27)$$

Assuming that the inertia of AVR is neglected. This assumption holds generally, if the electromagnetic inertia of rotor circuit is compensated by: for example, the rotor current as a negative feedback signal [11]. In this case, the forced component of synchronous generator emf (Eqei) is determined by the following equation:

$$Eqei = (1-Kei)\ Eqeyi - Kei\ Eqi \qquad (28)$$

where

Kei = acceleration coefficient

Eqeyi= component of Eqei, which changes corresponding to the change of Eqi

It is known that, the electromagnitic transient in rotor circuit of generator i, is described by

$$Eqei = Eqi + Tdoi\ dEqi'/dt \qquad (29)$$

Substituting eq.(28) in eq.(29), yields

$$Eqi = Eqeyi + [Tdoi/(1+Kei)].dEqi'/dt \qquad (30)$$

If Kei tends to infinity, the last term in eq.(30), consequently, tends to zero and eq.(30) becomes

$$Eqi = Eqeyi = Eqoi + UEi(t) \qquad (31)$$

Substituting eq.(31) in eq.(26), yields

$$(UEi(t)+2Eqoi)\ UEi(t)\ Yii\ \sin(\alpha ii)+\sum_{j\neq i}^{n} UEi(t)\ Eqoj\ Yij\ \sin(\delta ij-\alpha ij)$$

$$= Ki\ wie \qquad (32)$$

For $\alpha ii$ = 0 (in the case of long distance between generator i and the main load centre), the UEi(t) becomes

$$UEi = Ki\ wie/\sum_{j=1}^{n} Eqoj\ Yij\ \sin(\delta ij-\alpha ij) \qquad (33)$$

If generator i at a long distance from the remaninig generators j (j=1˜n, i≠j), the power system can be considered as a generator i is interconnected, through transmission line with no nodes of power take-off, with equivalent bus of constant voltage (Ee) behined equivalent reactance of Xe. Thus,

$$UEi = Ki\ wie /\ Ee\ Yie\ \sin(\delta ie - \alpha ie) \qquad (34)$$

or

$$UEi = Kwi\ wie\ \mathrm{sign}(\delta ie - \alpha ie) \qquad (35)$$

or

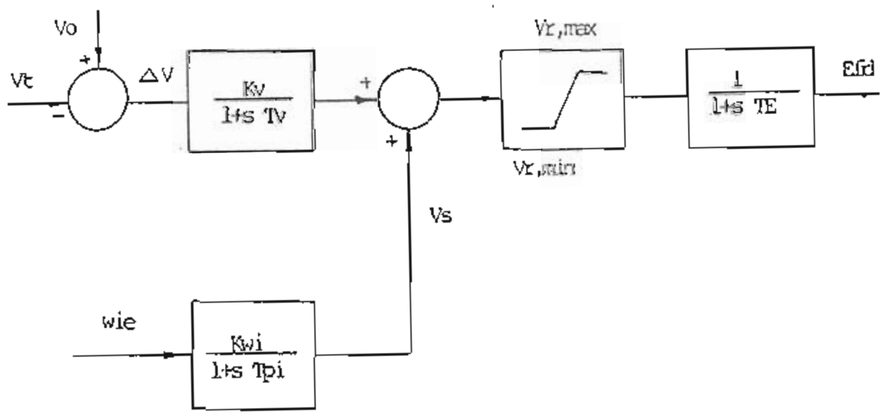
$$UEi = Kwi\ wie \qquad (36)$$

Effectiveness of SE control of eq.(35) is increased with increasing the output of generator i. For heavy loads of generator i, the sign of σie is unchanged.

Similarly, for obtaninig SG control UTi(t), the inertia of governer system is neglected. From eq.(27), the UTi(t) becomes

$$UTi = KTi\ we \qquad (37)$$

Accordingly, a suggested schemes of excitation system with SE control and governor system with SG control are illustrated in Fig.1-a and Fig.1-b respectively.




TE - Exciter time constant
Tv - AVR time constant
Kv - AVR gain
Kwi- Gain of SE control loop
Twi- Time constant of SE control loop

Fig.1-a Excitation System with AVR and SE Contrl

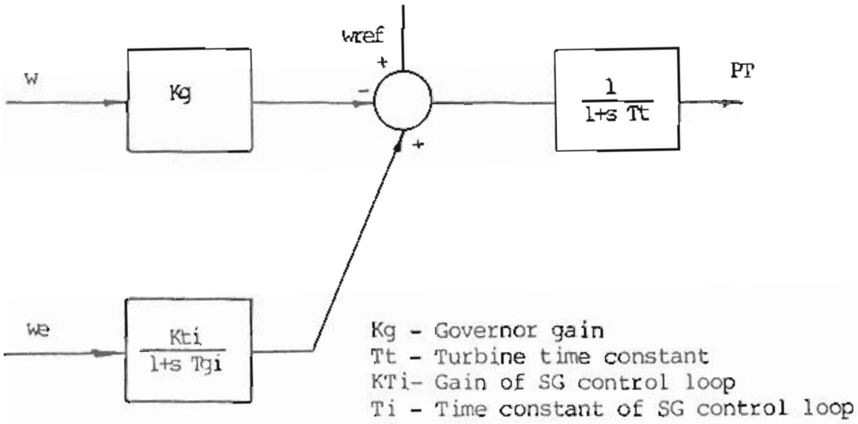



Fig.1-b Governor System with SG Control

SIMULATION STUDIES

Simulation and validation studies are conducted on a 10-generator and 19-bus power system, representing the equivalent of Egyptian Unified Network. Fig.2 shows the outline configuration of the power system. In Fig.2, G1 supplies its power through a long transmission line (900 km) to the main load center, which contains the remaining generators of the power system.

Results of load flow calculations of the system and consequently, the initial values of $\delta i$ and $Eqi$ of generators are also indicated in Fig.2.

In order to demonstrate the stabilizing effect of the suggested scheme of SE and SG controls, a computer program is written for transient stability, which is based on the application of the step-by step method of solution [2]. The system non-linear responses are computed for a large disturbance. The disturbance is a three-phase fault occuring near bus 12 at the begining of one of the two lines between buses 12 and 13. The fault is cleared in 0.2 second by opening the faulted line.

Figures 3 through 6 show the rotor angle ($\delta ie$) variations and the frequency deviations ($\Delta fav$), where

$$\delta ie = \delta i - \delta e,$$

$$\delta e = \sum_{i=1}^{10} \delta i \, Mi / \sum_{i=1}^{10} Mi$$

and

$$\Delta fav = \frac{1}{2\Pi} \left( \sum_{i=1}^{10} wi \, Mi / \sum_{i=1}^{10} Mi \right.$$

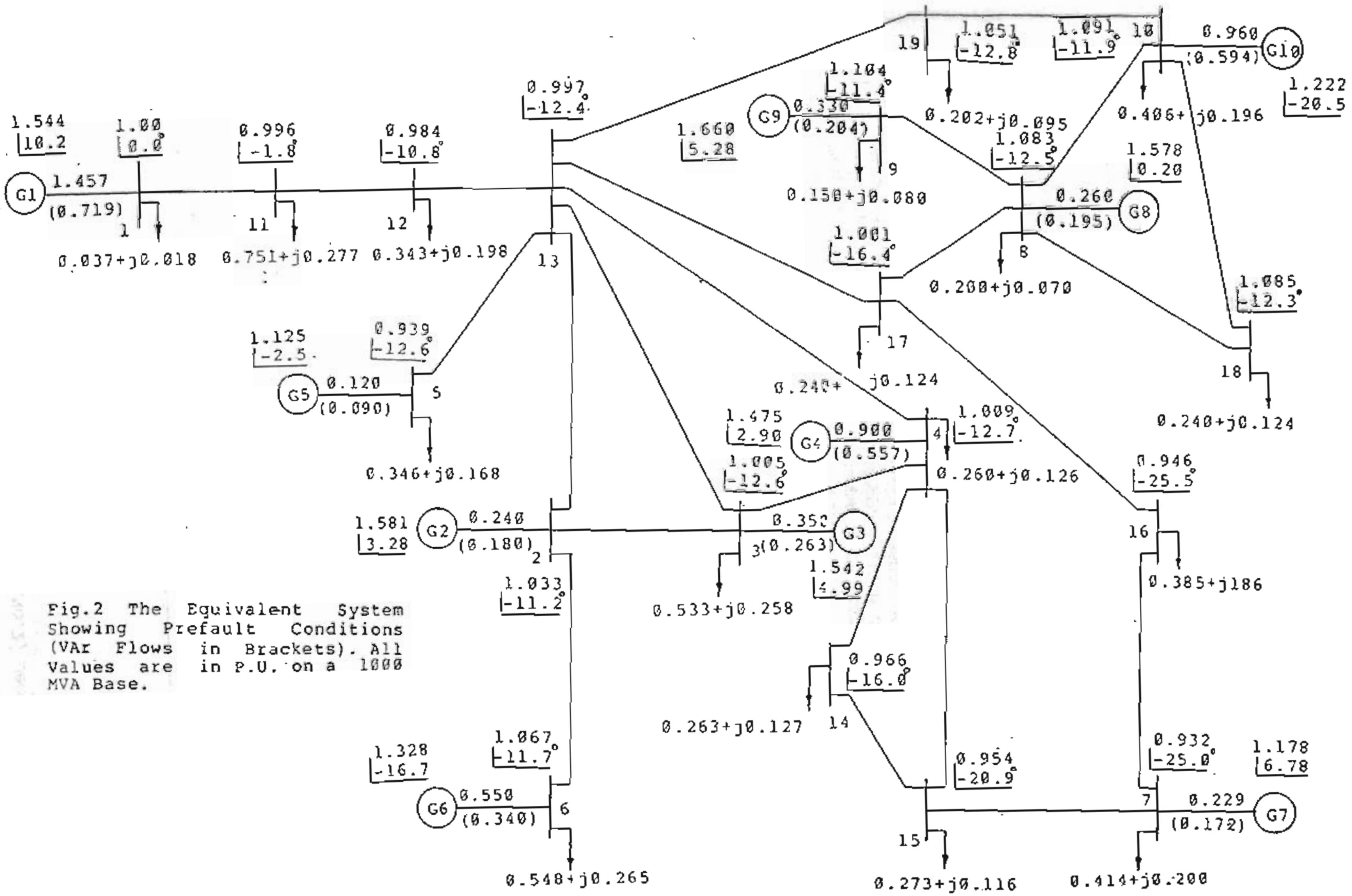



Fig.2 The Equivalent System Showing Prefault Conditions (VAr Flows in Brackets). All Values are in P.U. on a 1000 MVA Base.

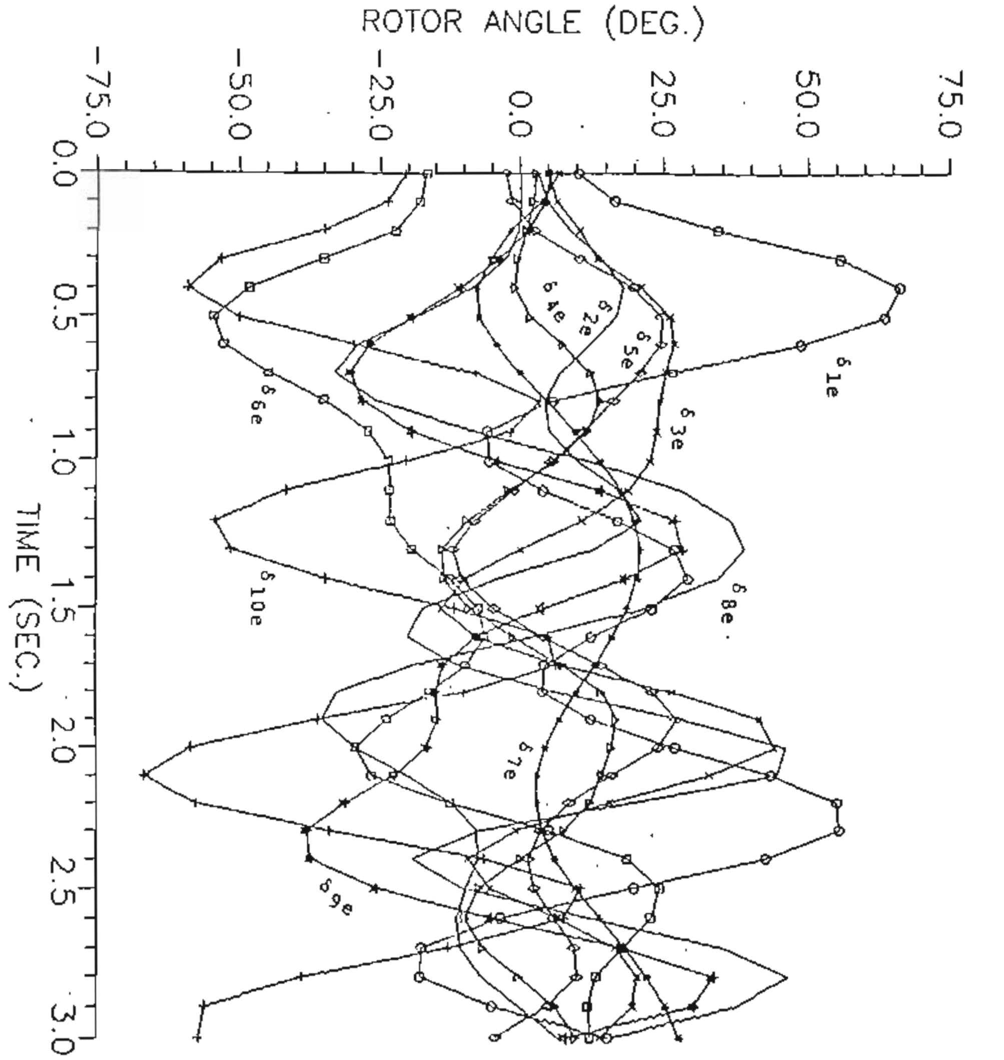



Fig.3 Swing Curves of the System Generators with AVR Control Only.

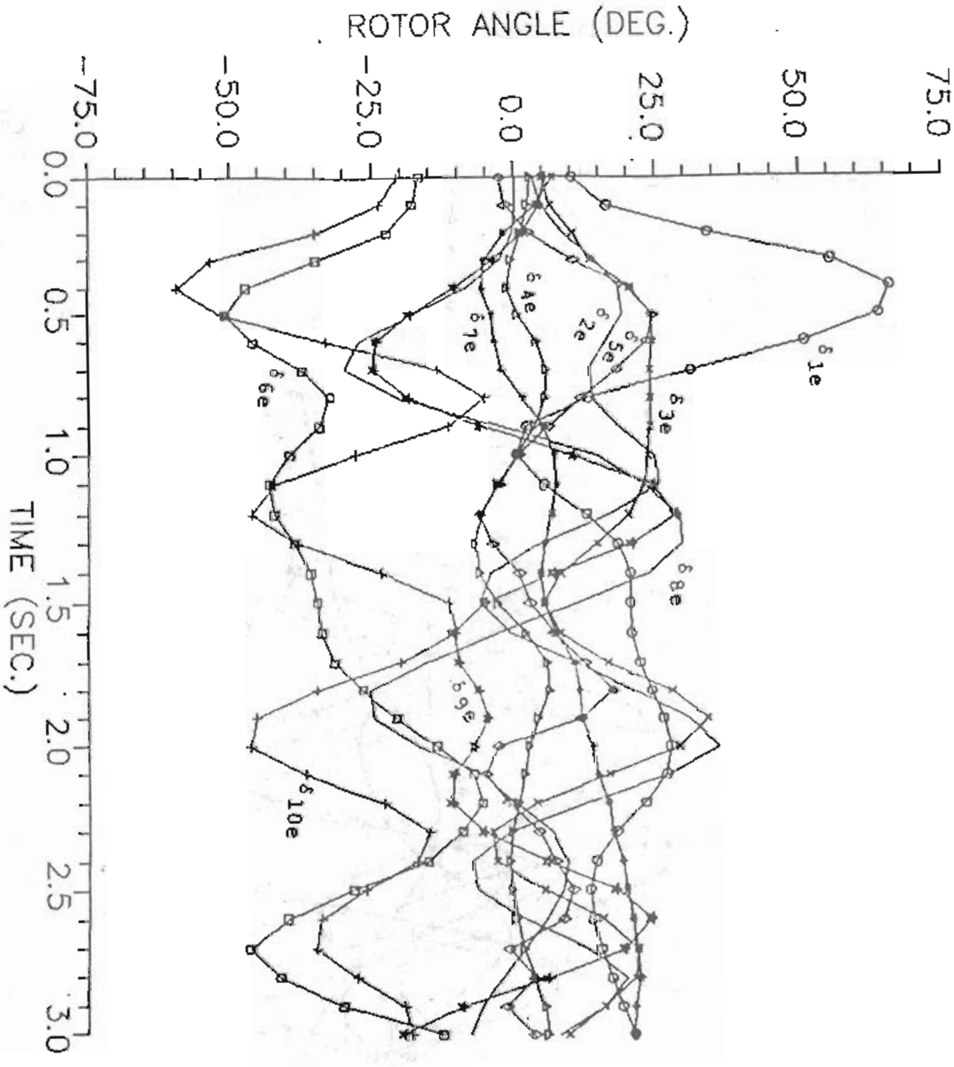



Fig.4 Swing Curves of the System Generators with SE Control.

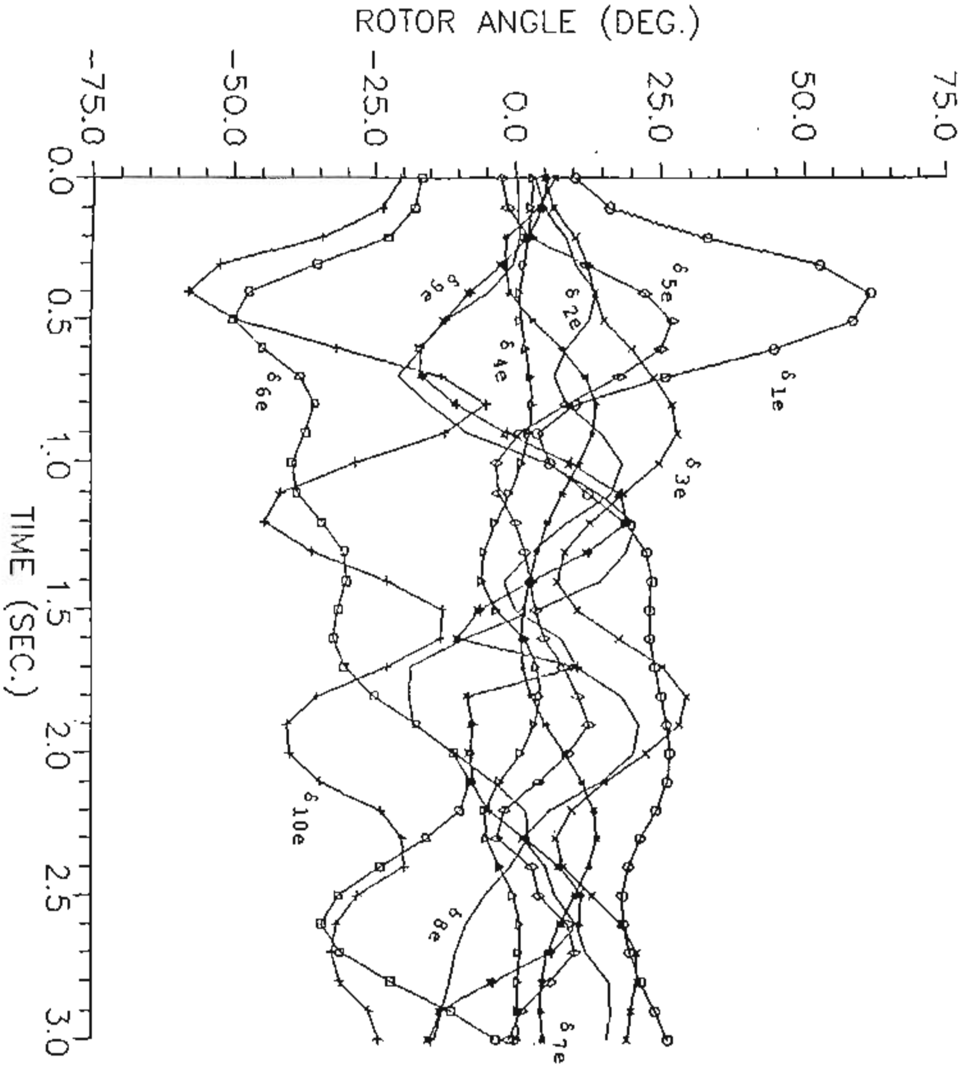



Fig.5 Swing Curves of the System Generatore with SE plus SG Controls.

The responses plotted are with

i) Conventional AVR control. Results are shown in Fig.3 and Fig.6-a. It can be seen that the system is stable but the transient response is poor.

ii) Stabilizing control in the excitation system only. The response of the system is investigated by applying the supplementary excitation controls (eq.36), which are superimposed on the AVR for all synchronous generators of the system. Fig.4 and Fig.6-b show that the excitation control alone is effective in damping out the transients.

iii) A combination of stabilizing controls in the excitation system and governer system. A combination of SE and SG controls as given in eq.36 and eq.37 provided the best transient performance as shown in Fig.5 and Fig.6-c.

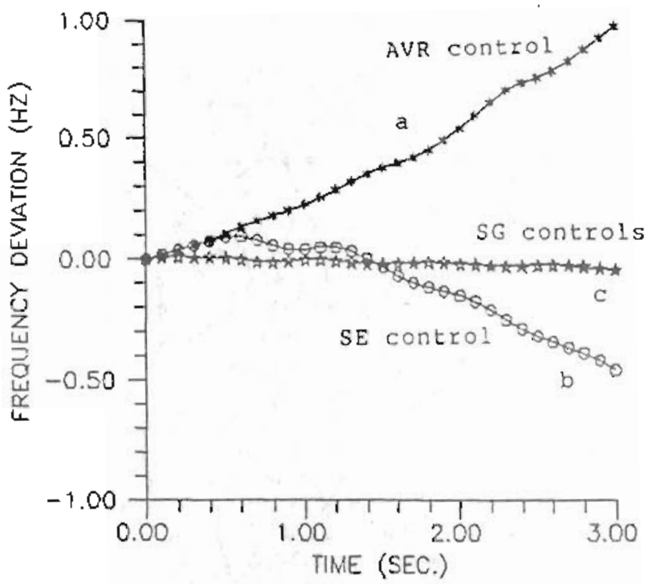



Fig.6 The frequency Deviations in Power System.

CONCLUSIONS

This paper demonstrated the application of a transient energy function and some laws of theoretical mechanics necessary to define the co-ordinated governer/exciter stabilizer in mulltimachine power system. The basic idea is balancing the stabilizer forces with the forces, which are necessary to damp rotor swings. investigations show that the excitation control is effective in improving the transient performance of a multimachine power system. Moreover, when the excitation control as well as govrner control are applied, the best transient response is obtained.

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