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COMBINED FLC AND TCSR TO ENHANCE THE PERFORMANCE OF POWER SYSTEMS INCLUDING A SUPERCONDUCTING GENERATOR

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ABSTRACT

This paper presents the design and application of a combined fuzzy logic (FL) controller and a thyristor controlled static reactive power compensator (TCSR) to enhance the performance of a multi-machine power system. This is a 12-bus system which includes superconducting generator (SCG) and three conventional machines of different types and ratings. The FL controller is designed and implemented in the governor control loop of the SCG. While, conventional generators are equipped with different excitation systems and their conventional controllers. Also, the TCSR compensator is designed and included at different locations due to its increasing importance in suppressing power system oscillations and improving system damping. A fairly detailed Non-linear model of the whole system is built and computer simulations are used to demonstrate the effectiveness of the combined control scheme in improving the static and dynamic performance of the power system under different disturbances and over a wide range of operating conditions. A comparison is made between these results to select the most effective location of the TCSR. The results are of great interest tp power system utilities, forming a gaint for future applications.

البحث يقدم تصميم وتطبيق حاكم غيمى ومعوض إستاتيكى ذو مكثف ثابت توازى مع ملف محكوم بدائرة ثايرستور ثنائية الاتجاه لنظام قوى كهربية متعدد الألات . يتضمن نظام القوى الكهربية آلة فائقة التوصيل يتم التحكم فى أدائها بالحاكم الغيمى فى دائرة منظم البخار بالإضافة إلى آلات تقليدية مختلفة الأنواع و الأحجام يتم التحكم فى كل منها بحاكمات مصممة بالطرق التقليدية فى دائرة التغذية الكهربية. والمعوض الإستاتيكى يعطى لخطوط النقل مرونة تخفف من زيادة التحميل فى بعض مناطق الشبكة وتزيد من مقدار القدرة الكهربية المنقولة ويحافظ، بما يدفعه من قدرة غير فعالة، على تغير الجهد فى حدود مقبولة بالإضافة إلى دوره فى خمد الاهتزازات وزيادة الاتزان.

باستخدام نموذج غير خطى تفصيلي لكل أجزاء النظام من مولدات ومغذيات وحاكمات ، تم تطبيق المعوض فى مواضع مختلفة . وبدراسة أداء النظام عندما يتعرض لأنواع مختلفة من الأخطاء عند مواضع مختلفة ومقارنته بالأداء فى حالة عدم وجود المعوض المقترح يتبين مدى التحسن في أداء وحدات التوليد المختلفة في النظام من حيث زيادة الاتزان وسرعة عودة المتغيرات إلي قيمها المبدئية إلى جانب انخفاض عدد مرات فتح وغلق صمام البخار للتربينه التى تدير الآلة فائقة التوصيل وما لذلك من قيمة اقتصادية وزيادة العمر الافتراضي لهذا الصمام.

Keywords: Multi-machine power system, Superconducting generator, Fuzzy controller, FACTS.

1. INTRODUCTION

The continuous need for generating more electrical power led to increasing number and rating of generating units with high transmission voltages. However, the continuous progresses in up-rating of the conventional generators are not feasible as the main design features of these large generators are their high p.u. reactance and low inertia constants [2, 3]. The trend of these parameters in design tends to reduce the stability margin and adversely affect system performance [4]. moreover, increasing the number of generating units increases the power system complexity that arise from the high dimensionality of the system, strong interaction among machines, practical constrains on transferring control signals over long distances between power stations [5]. This complexity and the ever increasing size of interconnected power systems have generally reduced the limits of synchronizing power flow and produced low frequency oscillations. This led to a decrease in the overall system stability. Subsequently, a considerable interest is now being placed to synchronize SCGs in multi-machine environments [4].

The SCG has completely different construction criteria than conventional generators and characterized by its lower reactance which allow delivery of higher short-circuit ratios and longer critical fault-clearing times and hence increase system stability. Moreover, the introduction of SCG into the power grid will lead to vastly improved grid operations resulting from the differences in the way this machine respond to transient conditions such as system faults or voltage decay. Also, SCG have additional economic benefits over the conventional units such as increased efficiency, possibility of generation at transmission line voltages, reduced size and weight as well as environmental advantages due to reduced oil consumption and CO_2 emissions [6]. IN addition, SCGs are expected to break through the rating limits and hence replace conventional machines in supplying base loads in large power systems [7,8]. So, research groups are investigating better design criteria of SCGs [9]. However, SCG is also characterized by low inertia constant and low inherent damping, each of which adversely affects the machine stability when connected to the power system. Therefore, SCG require special attention and consideration before being synchronized with the power networks especially the introduction of control signals through their excitation system is not effective due to the very long field winding time constant [10].

Another important area that interests a large number of researchers is that transmission systems are becoming more heavily loaded, being operated in ways not originally envisioned and undergoing continuous changes and restructing. Transmission systems must be flexible to react to more diverse generation and load patterns. In addition, the economical utilization of transmission system assets is of vital importance to enable utilities in industrialized countries to remain competitive and to survive [11]. These circumstances and significant development in the area of power electronics have led to the emergence of a new concept in power transmission, called Flexible AC Transmission Systems (FACTS). FACTs concept provides an alternative for the physical expansion of power transmission systems, by increasing the usable power transmission capacity of the existing systems close to their thermal limits while the focus on the quality of power delivered is greater than ever [12, 13]. They are composed of several electronic controlled devices for the direct control of power flow, voltage, impedance and phase angle of high voltage of AC transmission lines. The potential benefits of FACTS equipment are now widely recognized by the power systems engineers [14]. Also, FACTS devices provide strategic benefits for improved transmission system management through: better utilization of existing transmission assets, increased transmission system reliability and availability, increased dynamic and transient grid stability, increased quality of supply for sensitive industries and enabling environmental benefits [11].

Shunt reactive power compensator with thyristor controlled (TCSR) is one member of shunt connected FACTS controllers that has received much attention by the researchers and utilities in recent years [15]. This is because that TCSR is one of the most important versions of static var compensator which able to minimize the line over voltages under light load conditions, and maintain voltage levels under heavy load conditions [16]. Therefore, TCSR controller is a good way to control the voltage at and around the point of connection.

The objective of this paper is to combine the effect of FLC and a TCSR compensator to enhance the performance of a multi-machine power system including a SCG. The FLC is designed and implemented in the governor control loop of the SCG as the only available loop. The paper describes a technique for designing TCSR compensator for any generating unit in the considered multi-machine power system using local measurements only and taking account of interconnections with other units. The technique is applied and accepts changes in system configuration. The designed compensator is applied at different locations in the tested multi-machine power system. To illustrate the effectiveness of the proposed scheme under transient stability conditions, a detailed nonlinear model simulation is used including all nonlinearities and constrains. The results clearly reveal the superiority of the combined scheme to enhance the overall system performance under different circumstances.

2. POWER SYSTEM STRUCTURE

The multi-machine power system under consideration consists of four generating units of different types and ratings. Three of these generating units are hydro unit, thermal unit and nuclear unit to cover all kinds of conventional units with different ratings. Also, the studied system incorporated SCG. These units are connected to four load areas through proper transmission network. For a high degree of accuracy in the obtained results, detailed representation were made for all system components including the generators regardless of their location relative to disturbances. This is important especially for the SCG which has a rather different construction criterion [4]. The most critical part in the modeling of the SCG is that concerned with rotor screens. The system contains different types of exciters such as slow exciter and fast acting thyristor exciter with different ceiling voltages. All nonlinearities and constrains imposed on valve movements and control loops are taken into consideration. So, this system with the previous conditions is similar to the actual system and, therefore, the obtained results provide a useful guide for the power system engineers. Figure (1) shows the one line diagram of the tested multi-machine power system with different locations of thyristor controlled static reactor compensator at the terminals of generating units. The arrangement of the units is taken as follows: a 590 MVA steam generator which connected to busbar 1 ; a 1300 MVA nuclear unit connected to busbar 2 near loads ; 2000 MVA superconducting generator at busbar 3 and a 615 MVA hydro-electric generator to busbar 4 at remote ends. Loads and network parameters are shown in the figure. All network components are represented by lumped parameters, therefore the transmission lines are represented using π method and the loads are represented by constant impedances.

3. MODELING OF SYSTEM COMPONENTS

This section presents a general view on the modeling of each component in the system as described below:

3.1 Conventional Generating Units

A seventh-order nonlinear mathematical model, based on Park's d-q axes representation, is used to represent each conventional synchronous machine. These equations are arranged in a set of first-order differential equations and the parameters of these generators are listed in the Appendix [3].

3.2 Superconducting Generator

The order of the non-linear mathematical model that describing the SCG based on park's d-q axes is increased to nine to cater the doubly screened rotor. Where, in the case under consideration, each screen is represented by one coil of fixed parameters on each axis [17].

3.3 Excitation System

Various types of exciters have been used with large generator, but recently thyristor exciters become available, which provide very fast response [18]. In this study, the conventional generators are equipped with a fast acting thyristor exciters with negligible time lag and with different ceiling voltages. Also, conventional exciter is also used. A high-gain automatic voltage regulator (AVR) is used with the exciter to control the generator terminal voltage. The block diagram of the excitation system for the conventional generators is shown in Fig. (2). AVR parameters for each conventional machine are listed in Table [1] according to the IEEE standardization. Analysis of modern voltage regulators shows that under heavy load conditions the continuously acting of excitation systems introduces negative damping. To offset this effect and to improve the system damping in general, artificial means of producing torques in phase with the speed are introduced. The means is to introduce a signal at the summing junction where the reference voltage and the signal produced from the terminal voltage are added.

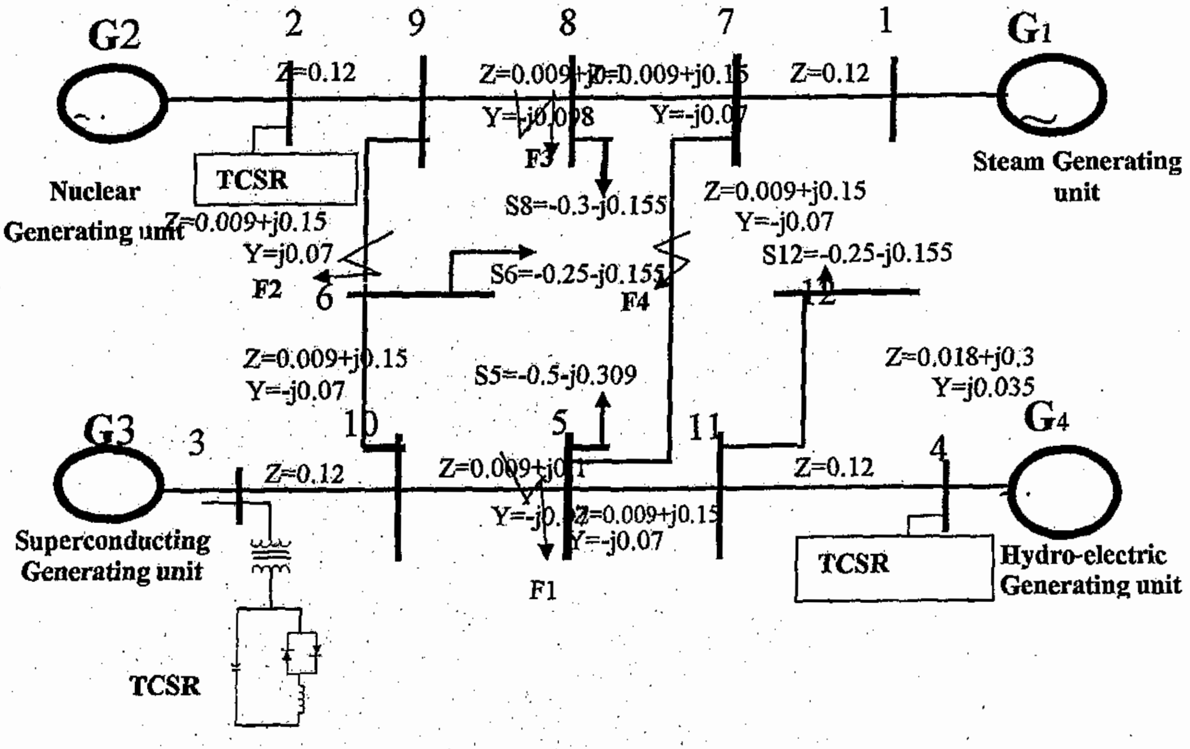

Fig. 1 One-line diagram of the tested multi-machine power system

Table (1) Conventional generators excitation parameters

		K_A	T_A	T_F	K_F	E_{fmin} p.u	E_{fmax} p.u.	Gs
G1	Steam	200	0.3575	1.0	0.0529	-5.73	5.73	0.03
G2	Nuclear	400	0.02	0.04	0.05	0.0	4.46	0.03
G4	Hydro-electric	200	0.02	1.0	0.01	0.0	7.32	0.04

The signal is called supplementary stabilization signal and the network used to generate it is called power system stabilizer (PSS) network [18]. The transfer function of the pss is shown by broken line in Fig.(2). PSS is a lead-lag compensator with two time constants T_{s1} and T_{s2} and a gain G_s[4]. The parameters of the pss should be carefully selected for each machine. For conventional machine the ratio T_{s1}/T_{s2} is 10 [18]. A number of iterations have been considered to obtain the gains of these power system stabilizers and those which gave the best performance were chosen. The gains are listed in Table [1] for each generator. These gains confirm with the IEEE recommendations.

For SCG, excitation control is not effective in improving its transient performance [19]. This is due to the very long time constant of the superconducting field winding and the shielding effects of the two rotor screens, which is designed to protect the superconducting field winding from armature transients, also prevents any events in the field winding to be effective at the stator winding. Moreover, the magnitude and rate of change of the excitation current and field flux must not exceed certain limits, otherwise the superconducting element goes normal (quench) [3]. For these reasons, it has been found that high ceiling voltage has very little effect in improving transient stability [20]. So, this renders the necessity of considering only the governor control loop to enhance the system performance. Adding positive damping via the governor loop is very difficult and requires a great deal of attention [21].

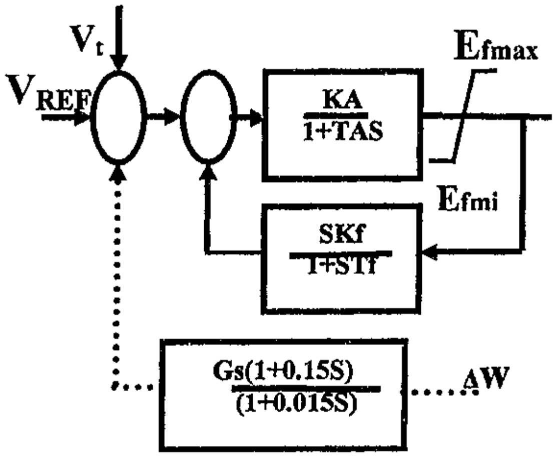

Fig. 2 Excitation system

3.4 Fuzzy Logic Controller for SCG

Fuzzy logic controller (FLC) provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy [22]. The speed error, e (k), and the error change, Δe (k), are chosen as input variables to the FLC where,

$$e(k) = N_d(k) - N(k)$$
$$\Delta e(k) = e(k) - e(k-1)$$

$N_d(k)$ and N(k) are the desired and actual speed of the SCG at the K^{th} sampling interval respectively. The controller inputs e(k) and Δe(k) are normalized into the interval (-1,1) which is called the universe of discourse. Then the normalized input variables are then converted into suitable linguistic variables (fuzzy sets). The ranges of the input variables are converted using seven fuzzy sets. After specifying the fuzzy sets, it is required to determine the membership function of these sets. Each subset is associated with a triangular membership function as shown in Fig. (3) to form a set of seven normalized triangular memberships for each fuzzy variable. The two inputs result in 49 rules to describe the FLC behavior as shown in Table [2]. Each of the 49 control rules represents a desired controller response to a particular situation [23]. Finally, the fuzzy output of the fuzzy controller is converted into a crisp value (numerical output). The fuzzy logic controller is introduced in the governor control loop of the SCG.

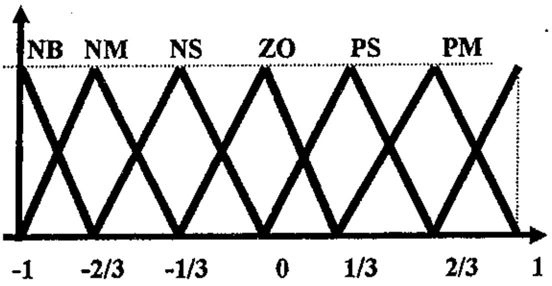

Fig. 3 Membership Function of the input and output

Table (2) Rule Base

Δe(K) e(K)	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

3.5 Equivalent Networks with TCSR Power Compensator

Thyristor controlled static reactive power compensator is assumed to be consists of static var compensator of fixed capacitor connected in parallel with bidirectional thyristor air cored reactor [24]. This compensator is connected at the terminals of the SCG and at the terminals of the other units as shown in Fig (1).

All the interconnections of the ith node to the reminder of the system are expressed in terms of axis current components of the ith generator. These equations describe the axis voltage components of the ith generator driven from the network side are:

$$V_d^i = V_b^i \sin\delta^i - \frac{\omega^i}{\omega_o} X_e^i i_q^i + r_e^i i_d^i \tag{1}$$

$$V_q^i = V_b^i \cos\delta^i + \frac{\omega^i}{\omega_o} X_e^i i_d^i + r_e^i i_q^i \tag{2}$$

When the TCSR is connected at the terminals of ith generator Equations (1) and (2) becomes:

$$V_d^i = V_b^i \sin\delta^i - \frac{\omega^i}{\omega_o} X_e^i i_q^{i\backslash} + r_e^i i_d^{i\backslash} \tag{3}$$

$$V_q^i = V_b^i \cos\delta^i + \frac{\omega^i}{\omega_o} X_e^i i_d^{i\backslash} + r_e^i i_q^{i\backslash} \tag{4}$$

Where,

$$i_d^{i\backslash} = i_d^i - i_{rd}^i - i_{cd}^i \quad , \quad i_q^{i\backslash} = i_q^i - i_{rq}^i - i_{cq}^i \tag{5}$$

$$i_{rd}^{i\backslash} = \frac{\omega_o}{\omega^i}\left(\frac{1}{X_T^i}\right)(V_q^i - E_t^i \cos\delta^i) \tag{6}$$

$$i_{rq}^{i\backslash} = -\frac{\omega_o}{\omega^i}\left(\frac{1}{X_T^i}\right)(V_d^i - E_t^i \sin\delta^i) \tag{7}$$

$$i_{cd}^i = -\left(\frac{\omega_o}{\omega^i X_c^i}\right)V_q^i \quad , \quad i_{cq}^i = \left(\frac{\omega_o}{\omega^i X_c^i}\right)V_d^i \tag{8}$$

$$\delta_t^i = \tan^{-1}(V_d^i / V_q^i) \tag{9}$$

$$E_t^i = V_t^i\left(\frac{2\alpha^i - \sin 2\alpha^i}{2\pi}\right) \tag{10}$$

$0 < \alpha \le \pi$, α: firing angle

The firing angle control range of this scheme is from 0° to 180° With the firing control of the thyristors, it can change its apparent reactance smoothly and rapidly. This characteristic meets the demands of the modern power system that must operate flexibly and react quickly.

$$V_t^i = \sqrt{\left(V_d^i\right)^2 + \left(V_q^i\right)^2} \tag{11}$$

Substituting from Equations (3) to (11) into Equations (1) and (2), the direct and quadrature axis voltages at the ith generator are found as:

$$V_d^i = V_{bd}^{i\backslash} + r_e^{i\backslash} i_d^i - X_e^{i\backslash} i_q^i + c_1^i E_t^i$$

$$V_q^i = V_{bq}^{i\backslash} + r_e^{i\backslash} i_q^i + X_e^{i\backslash} i_d^i + c_2^i E_t^i$$

where,

$$V_{bd}^{i\backslash} = (a_1^i \sin\delta^i - a_2^i \cos\delta^i) V_b^i$$

$$r_e^{i\backslash} = r_e^i a_1^i - a_2^i \frac{\omega^i}{\omega_o} X_e^i$$

$$X_e^{i\backslash} = r_e^i a_2^i + a_1^i \frac{\omega^i}{\omega_o} X_e^i$$

$$c_1^i = \left[\left(\frac{a_1^i r_e^i \omega_o}{\omega^i X_T^i} - \frac{a_2^i X_e^i}{X_T^i}\right)\cos\delta_t^i + \left(\frac{a_1^i x_e^i}{X_T^i} + \frac{r_e^i \omega_o a_2^i}{\omega^i X_T^i}\right)\sin\delta_t^i\right]$$

$$c_2^i = \left[\left(\frac{a_1^i r_e^i \omega_o}{\omega^i X_T^i} - \frac{a_2^i X_e^i}{X_T^i}\right)\sin\delta_t^i + \left(\frac{a_1^i x_e^i}{X_T^i} + \frac{r_e^i \omega_o a_2^i}{\omega^i X_T^i}\right)\cos\delta_t^i\right]$$

$$a_1^i = \{1 + X_e^i(\frac{1}{X_t^i} - \frac{1}{X_c^i})\} / \Delta$$

$$a_2^i = \{r_e^i(\frac{\omega_o}{\omega^i}(\frac{1}{X_t^i} - \frac{1}{X_c^i})\} / \Delta$$

$$\Delta = \{r_e^i \frac{\omega_o}{\omega^i}(\frac{1}{X_T^i} - \frac{1}{X_c^i})\}^2 + \{1 + X_e^i(\frac{1}{X_T^i} - \frac{1}{X_c^i})\}^2$$

4. DIGITAL SIMULATION

A detailed digital computer program has been built which solves the interconnected tested system including all nonlinearities and constrains imposed on valve movements, ceiling voltages and control loops. The digital simulation involves simultaneous solution of the complete non-linear model, together with the solution of the linear voltage and current equations of the network. Each generator is described by the non-linear equations expressed in park's reference frame, which is fixed to the machine rotor. The network is described by lumped impedances and the solution of currents and voltages at specified nodes is with respect to a common reference frame, rotating at synchronous speed. During disturbances, the speeds of machines change and therefore their individual reference frames oscillate with respect to the common reference frame [25]. For high degree of accuracy and stable solution with the detailed models used here the integration step length had to be reduced and therefore the complete solution requires large number of iterations. With the required number of iterations, the iterative solution of the network equations during the integration process was found to be slow, and an alternative method based on matrix manipulation has been used. The simulation is discussed in later sections

5. SIMULATION RESULTS AND DISCUSSION

In order to validate the effectiveness of the designed TCSR controller scheme, several simulations studies are carried out on the multi-machine power system shown in Fig. (1) for different locations of TCSR and different operating conditions. A full order nonlinear model of the multi-machine power system was simulated using a digital simulation program including all nonlinearities and constrains imposed on valve movements, ceiling voltages and control loop under different disturbances.

5.1 Effect of Fault Location

In this case, TCSR compensator is assumed to be installed at the terminals of the superconducting generator (G3) only as shown in Fig.(1). The designed compensator is tested through simulating large system disturbance namely three-phase faults (which are the most severe disturbances in a power system) at different locations. Figure (4) illustrates the time response of the generators (G2, G3 and G4) relative rotor angle , rotor speed and terminal voltage in addition to the valve movement for SCG due to a 3-phase short circuit fault at location F1 with 200ms duration. Also, Fig. (5) show the time response due to 3-phase short circuit fault at location F2. A comparative study is made between the system operates with conventional controllers, the system operates with combined conventional controllers and TCSR at the specified location, the SCG operates with FLC and the other conventional generators operate with power system stabilizers and finally the system operates with combined TCSR at G3 which is controlled with FLC and the other units operate with PSSs with predefined parameters. It can be seen from these figures that the most significant feature of using TCSR is the increase in stability margins, thereby, increasing the loading capacity of exciting transmission systems. This is indicating by the reduction in the rotor first swing for all generators and at all fault locations. So, the fault location does not affect the performance of this compensator which is installed at the terminals of G3 (SCG) which is the most dominant generator in this multi-machine system. Also, the terminal voltage for all generators especially SCG is improved were oscillations are effectively damped, which is the ultimate objective of applying this shunt compensator, and the system variables returns to their original conditions smoothly and quickly.

5.2 Effect of TCSR Location

The most benefit of installation the Facts devices is maintaining the voltage level of that point at and around its nominal value. In this section, the effect of TCSR compensator location's on damping the oscillations is examined. In the previous section the TCSR at terminals of G3 is examined. Two other locations of installation TCSR are selected as shown in Fig. (1) one at the terminals of nuclear unit (G2) only and the other location at the terminals of hydro-electric unit (G4) only. Figures (6) and (7) illustrate the transient response of the relative generators rotor angle, speed deviation and terminal voltage due to a 3-phase short circuit at location F1 when TCSR installed at G2 and at G4 respectively. Examining these figures reveals that the location of the compensator affects its performance. In general, the considered compensator is more effective in damping oscillations and improving terminal voltage in a case of a fault occurring relatively close to it. It is worth noting here, that when TCSR installed at G4 has less effect on system performance but with a slight reduction in the rotor angles for generators and rotor speed of SCG.

5.3 Effect of Adding another TCSR

Multiple TCSR compensators if properly designed will enhance the damping of the system oscillations. This part investigates the effect of improving the performance of the considered multi-machine system by installing two TCSRs. Two cases were taken into consideration. The first case: two compensators are installed at terminals of G2 and G3 and the other case was installed at G3 and G4. Figure (8) concern the first case while Fig. (9) concern the second case for 3-phase short circuit fault at F1. It can observe from these figures that there is no improvement in the system performance when using two compensators than using one compensator. This observation clearly concludes that, for the system under consideration, a single TCSR is sufficient to minimize the voltage deviations due to disturbances on the system, enhance both dynamic and transient stability of the system and effectively damping the system oscillations. So, the application of TCSR improves the power system utilization and performance.

6. CONCLUSION

The paper presented the design and implementation of combination of fuzzy logic controller (FLC) and a thyristor controlled static reactive power compensator scheme (TCSR) to enhance the performance and extend the margin of stability of a multi-machine power system including a superconducting generator (SCG). Detailed representation has made for all system components including generators regardless of their location. This is important especially when a SCG were included. The FLC has been designed and mounted on the governor control loop of the SCG. Also, a technique has described for designing TCSR compensator for any generator in the considered multi-machine power system using local measurements only and taking account of interconnections with other units. The technique is readily applied, regardless of the system configuration or number of units and overcomes the numerical difficulties that arise with other approaches. Extensive nonlinear simulation tests have been made using a detailed digital computer program which solves the interconnected system including all nonlinearities and constrains imposed on valve movements, ceiling voltages and control loops. The compensator has been applied at different locations in the tested multi-machine power system. The decision on where to install this FACTs controller is largely dependent on the desired effect and the characteristics of the specific system. The simulation results illustrate that the introduction of the TCSR compensator at the terminals of the dominant machine (SCG) provides greater improvement of the overall system performance than would be obtained if the compensator were employed at the terminals of any other unit. Moreover, employing two compensators at a time not achieve any additional improvements in the system performance. It can be concluded from the simulation results that combining the FLC and the TCSR compensator significantly improves the overall system performance. This is clarified in terms of system variables fast return to their initial values, reduction in rotor angle's first swing for all generators which mean an increase in stability reserve and the less number of valve movements.

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APPENDIX

SCG parameters in p.u.

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

,X_d= X_q=0.0453 p.u., X_f= 0.541 p.u. ,

X_{KD1}=X_{KQ1}=0.2567p.u., X_{fKD2}=0.3398p.u.

X_{af}=X_{fKD1}=X_{aD1}=X_{aD2}=X_{KD1KD2}=0.237p.u.

X_{aQ1}=X_{aQ2}=X_{KQ1KQ2}=0.237p.u.,

R_{KD2}=R_{KQ2}=0.00134p.u, R_{KD1}=R_{KQ1}=0.01008p.u,

R_a=0.003 p.u.,. H=3.0 KWS/KVA.

Parameters of Governor and Turbine

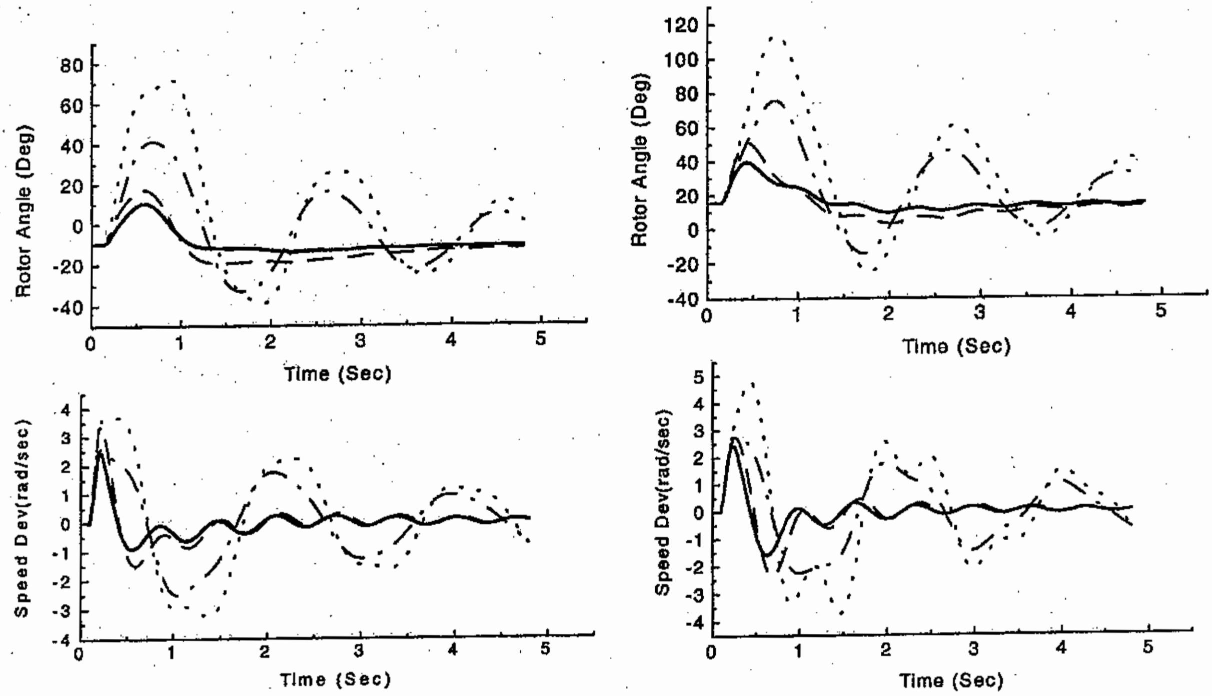
T_{HP}=0.1 sec, F_{HP}=0.26, T_{IP}=0.3 sec, F_{IP}=0.42,

T_{LP}=0.3sec, F_{LP}=0.32,

T_{RH}=10 sec, T_{GM}=T_{GI}=0.1 sec, P_o=1.2 P.U.

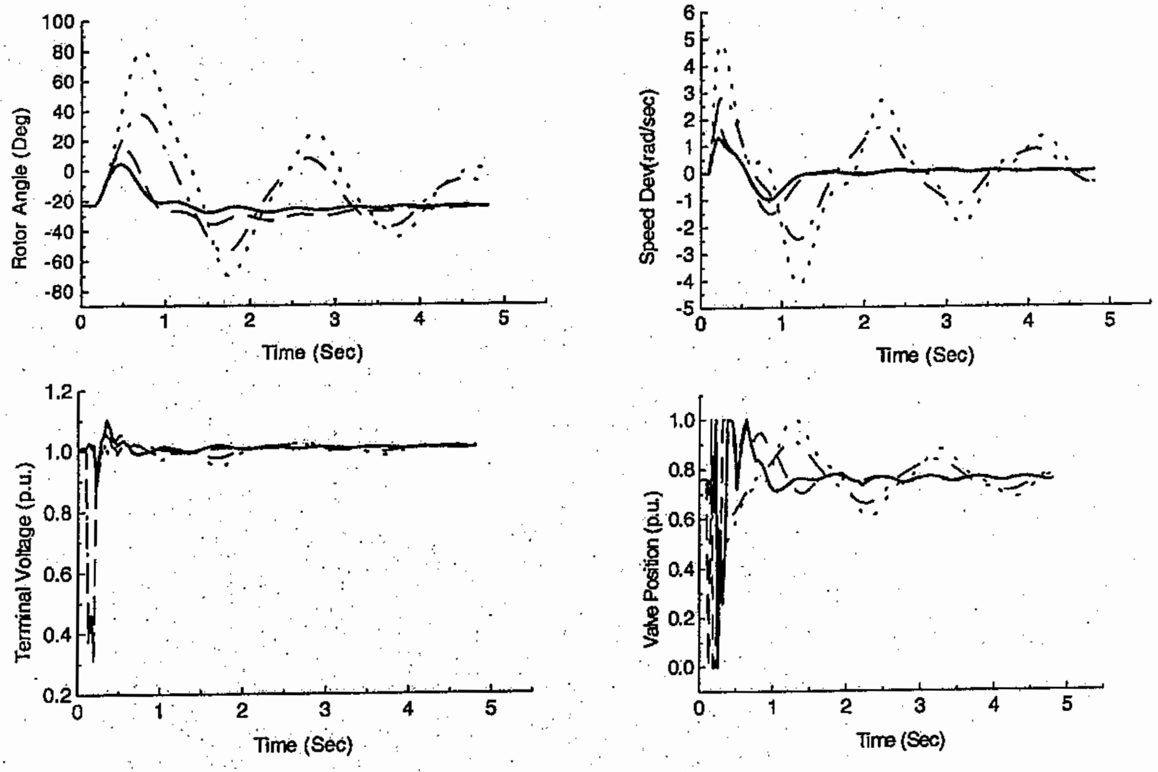
Conventional machines parameters (p.u.)

	Steam unit (G_1)	Nuclear unit (G_2)	Hydro- unit (G_4)
MVA	590	1300	615
X_d	2.11	2.13	0.898
X_q	2.02	2.07	0.646
X_{ad}	1.955	1.88	0.658
X_F	2.089	2.12	0.724
X_D	2.07	1.97	0.668
X_Q	1.93	1.88	0.457
R_a	0.0046	0.0029	0.0014
R_F	0.00013	0.00092	0.00026
R_D	0.02	0.018	0.012
R_Q	0.024	0.0212	0.02
H	2.32	2.52	5.15



For G2

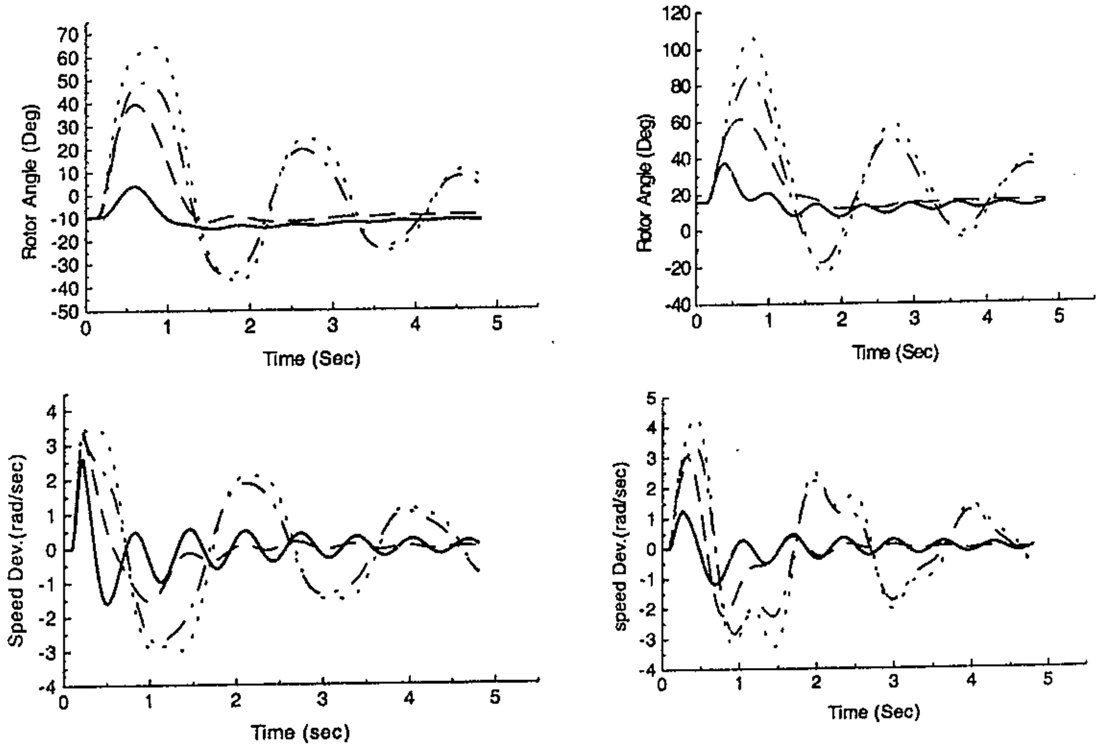
For G4



For G3

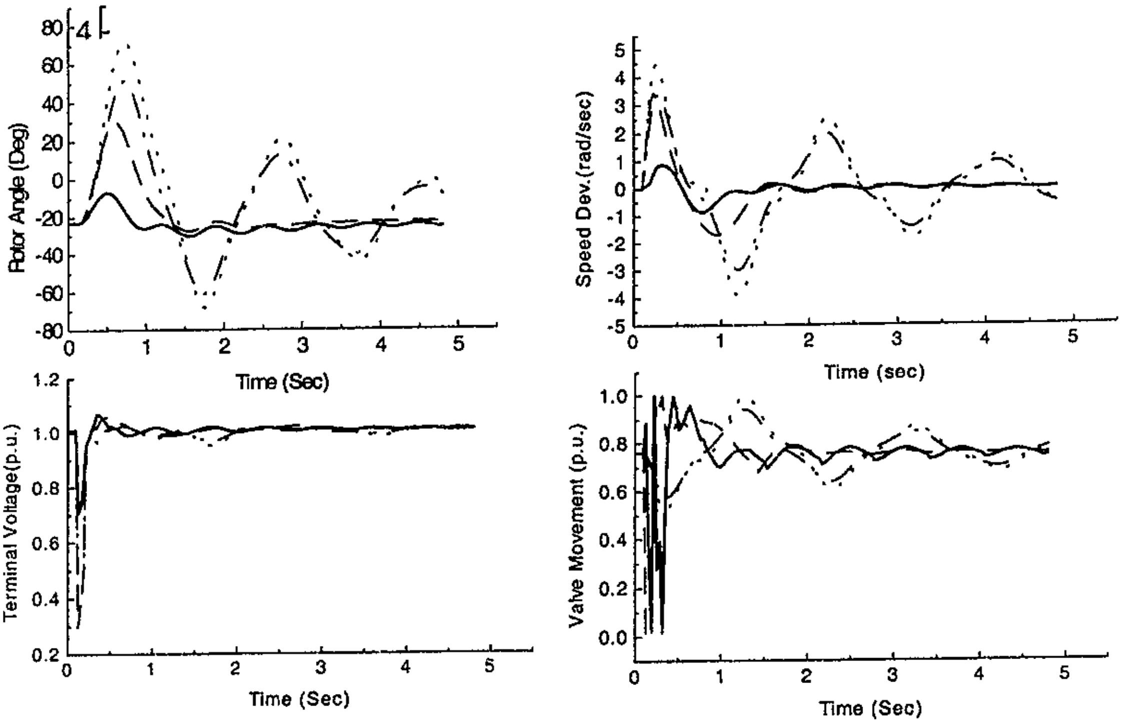
Fig. 4 Transient response to a 3-phase short circuit with 200 ms duration at F1

——— TCSR at G3 + FLC on SCG + PSS on conventional units
- - - - - - FLC on SCG + PSS on conventional units
.... With SG on SCG + AVR on conventional un
- . - . - . - TCSR at G3 + SG on SCG + AVR on conventional units



For G2

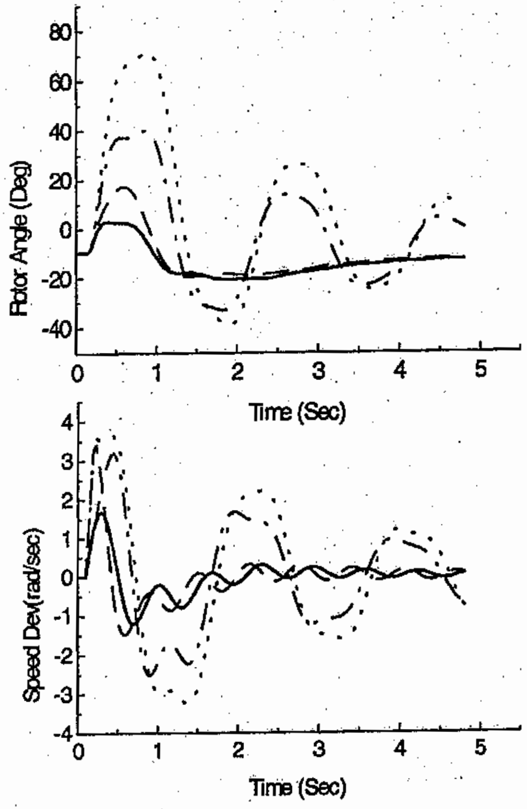
For G4



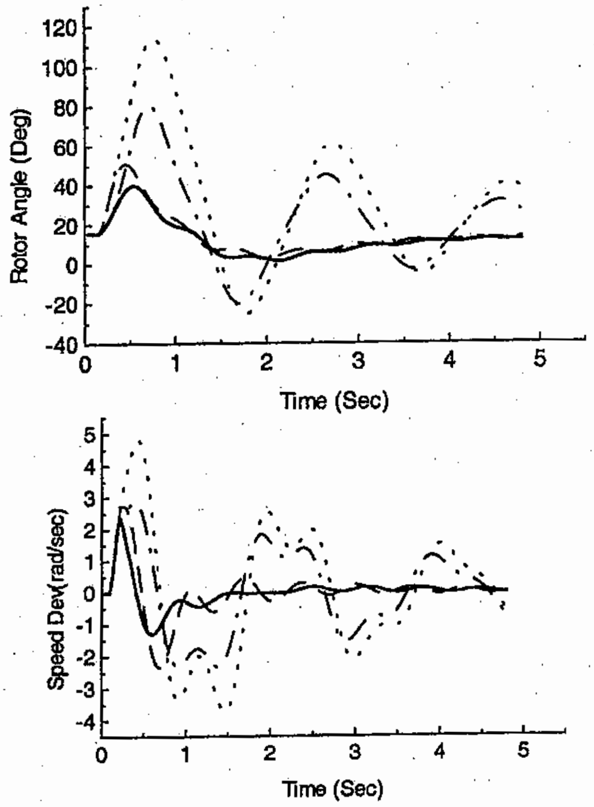
For G3

Fig.5 Transient response to a 3-phase short circuit with 200 ms at F2

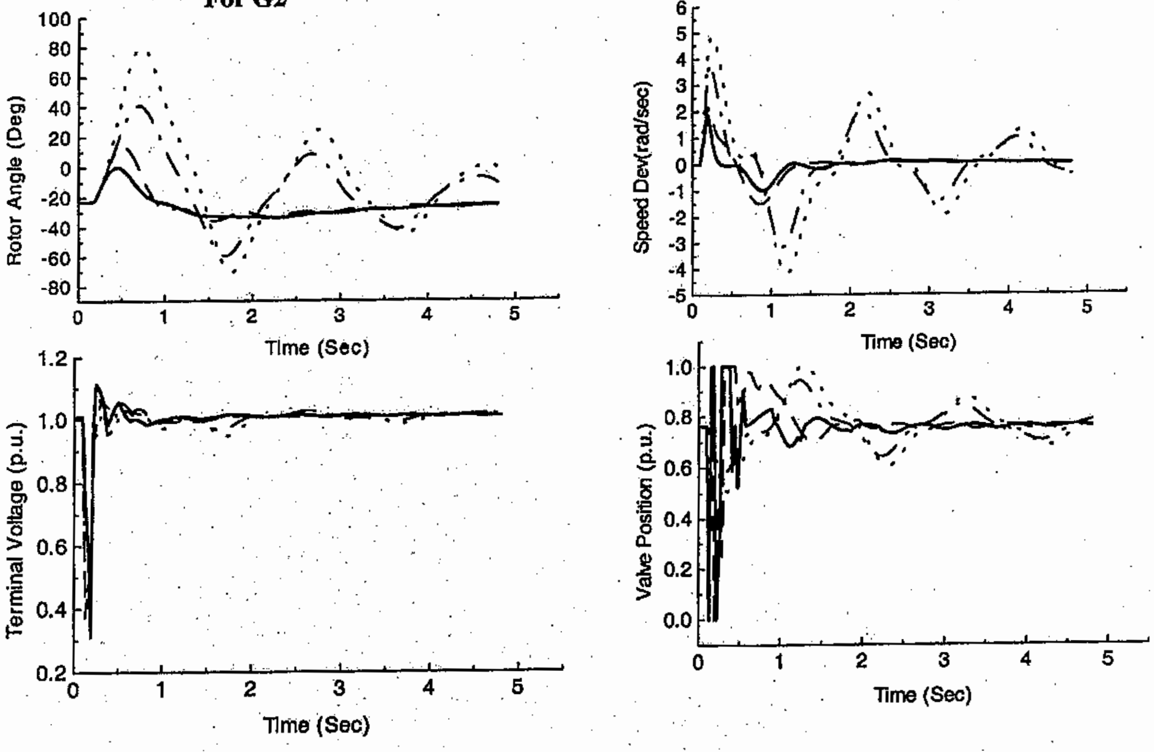
——— TCSR at G3 + FLC on SCG + PSS on conventional units
------- FLC on SCG + PSS on conventional units
.... With SG on SCG + AVR on conventional units
-·-·-·-·- TCSR at G3 + SG on SCG + AVR on conventional units



For G2



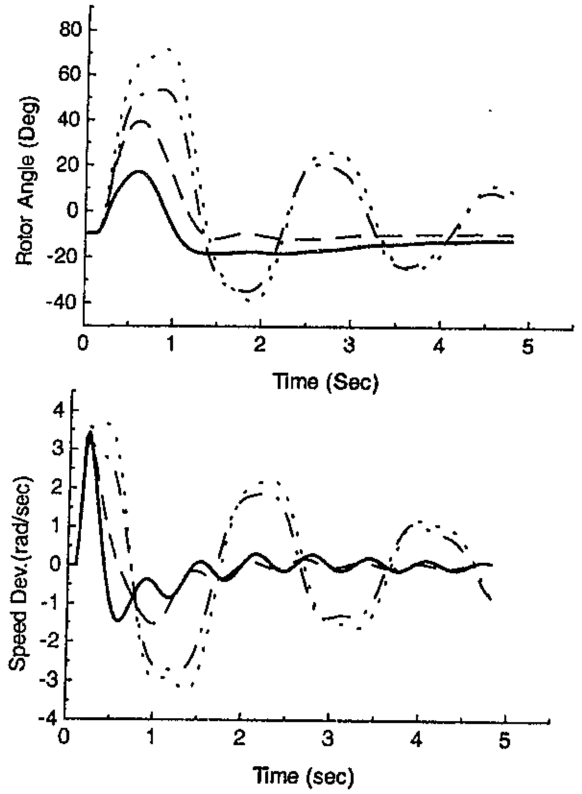
For G4



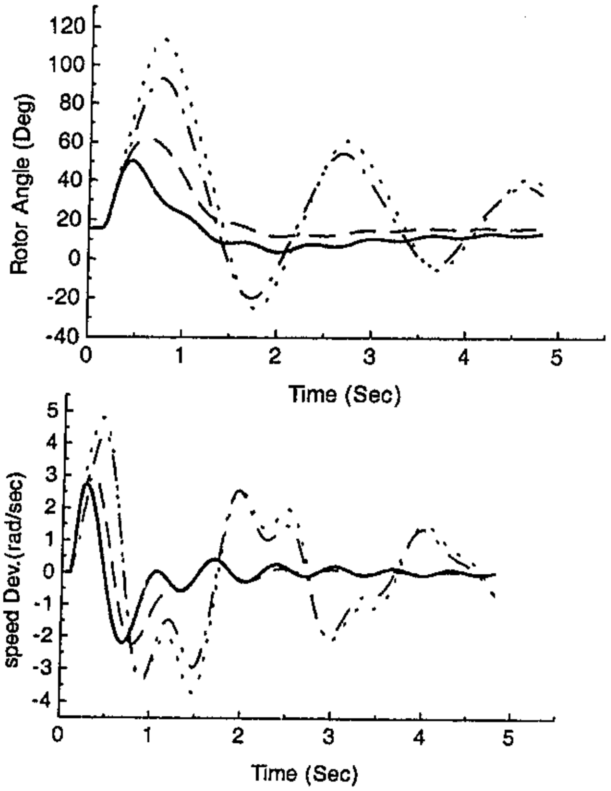
For G3

Fig. 6 Transient response to a 3-phase short circuit with 200 ms duration at F1

——— TCSR at G2 + FLC on SCG + PSS on conventional units
- - - - - - FLC on SCG + PSS on conventional units
·········· With SG on SCG + AVR on conventional units
-·-·-·-·- TCSR at G2 + SG on SCG + AVR on conventional units



For G2



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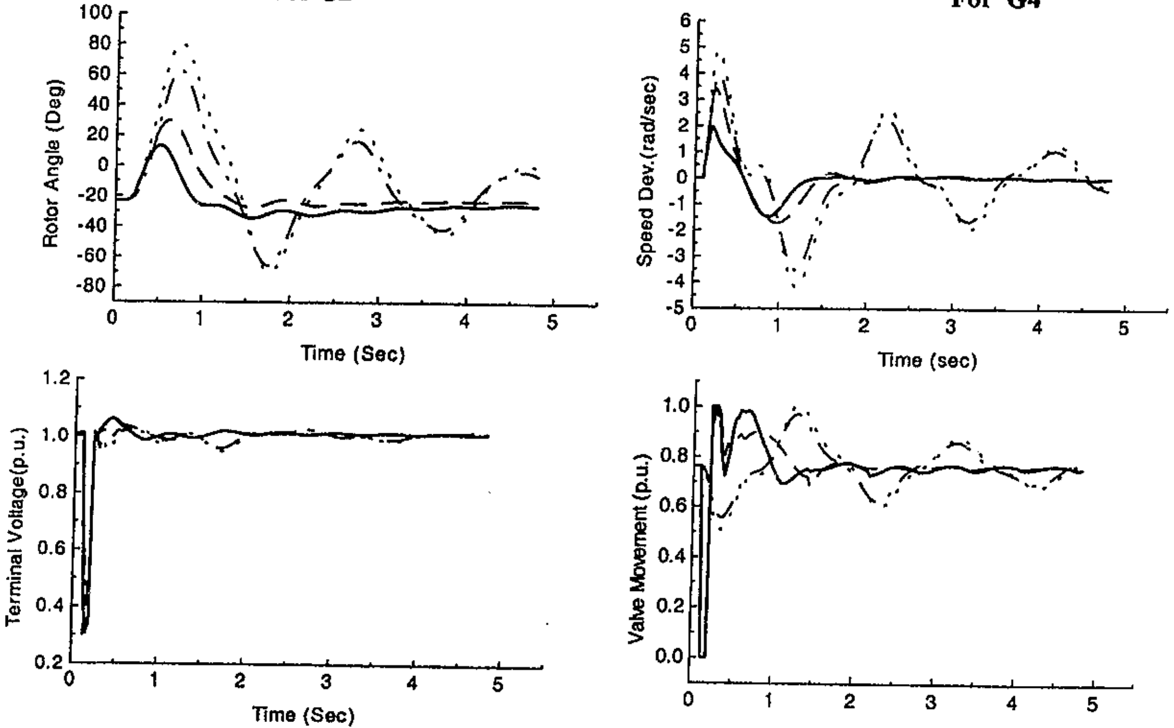
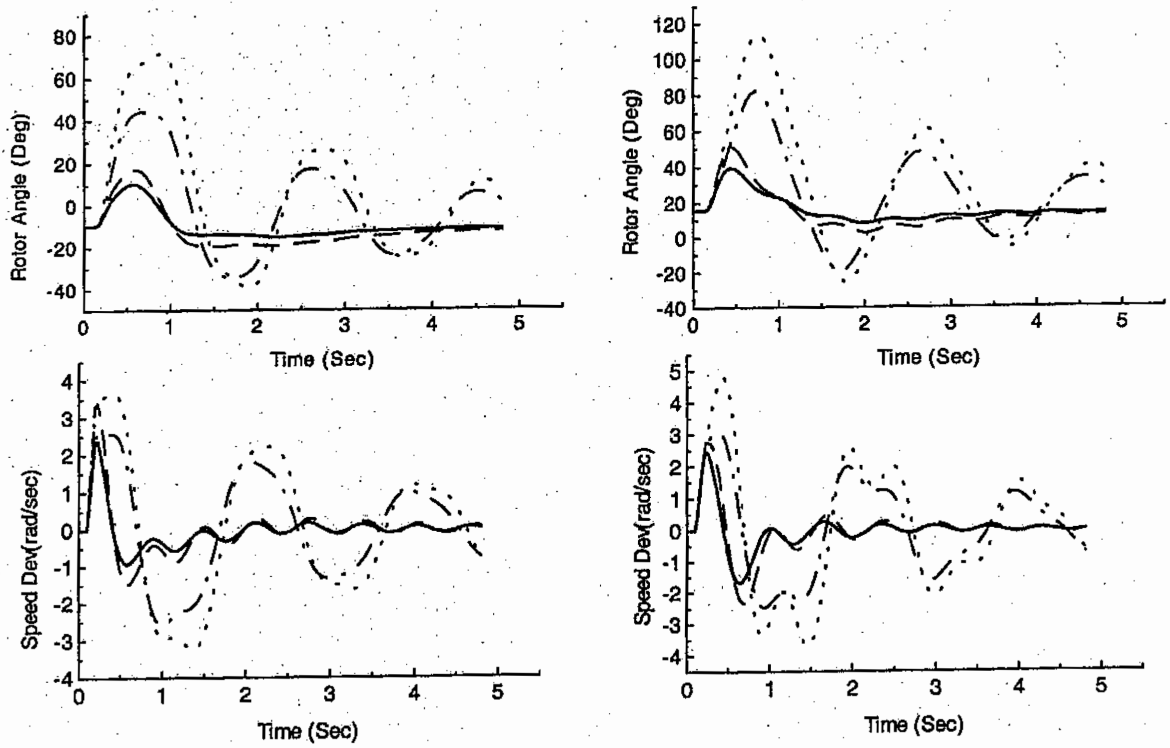


For G3

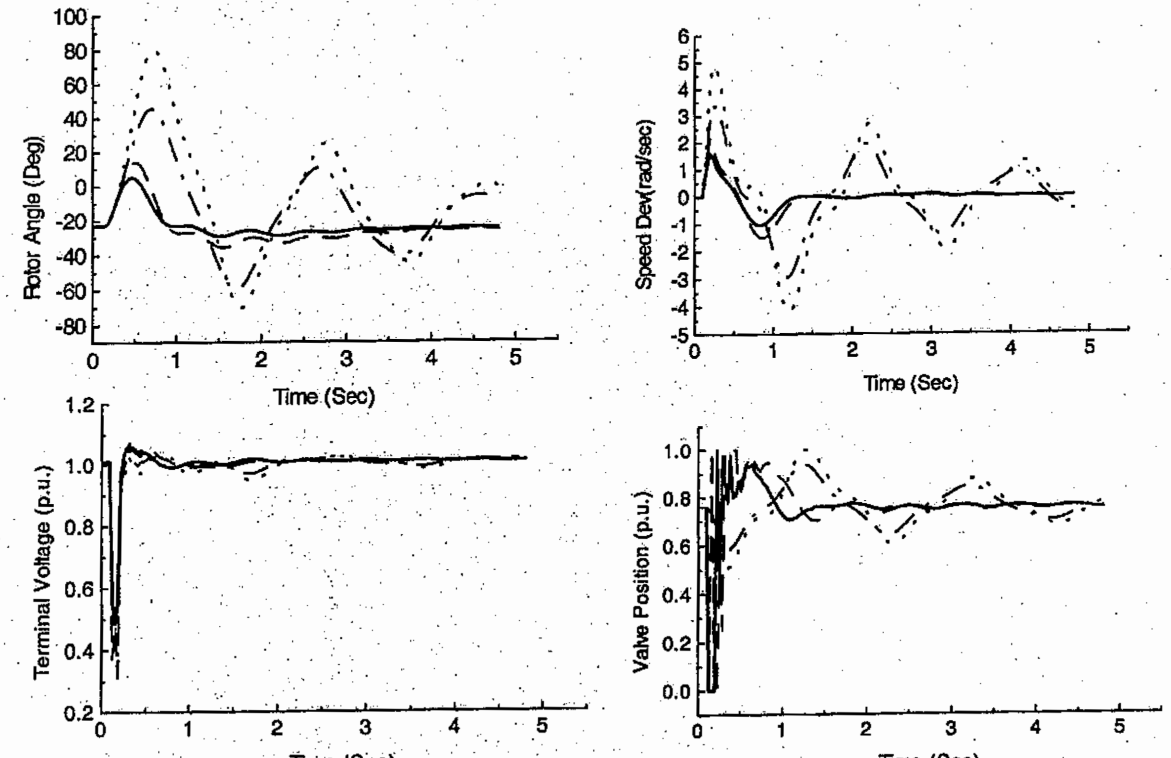
Fig.7 Transient response to a 3-phase short circuit with 200 ms duration at F2

—— TCSR at G4 + FLC on SCG + PSS on conventional units
- - - - - - FLC on SCG + PSS on conventional units
.... With SG on SCG + AVR on conventional units
-·-·-·- TCSR at G4 + SG on SCG + AVR on conventional units



For G2

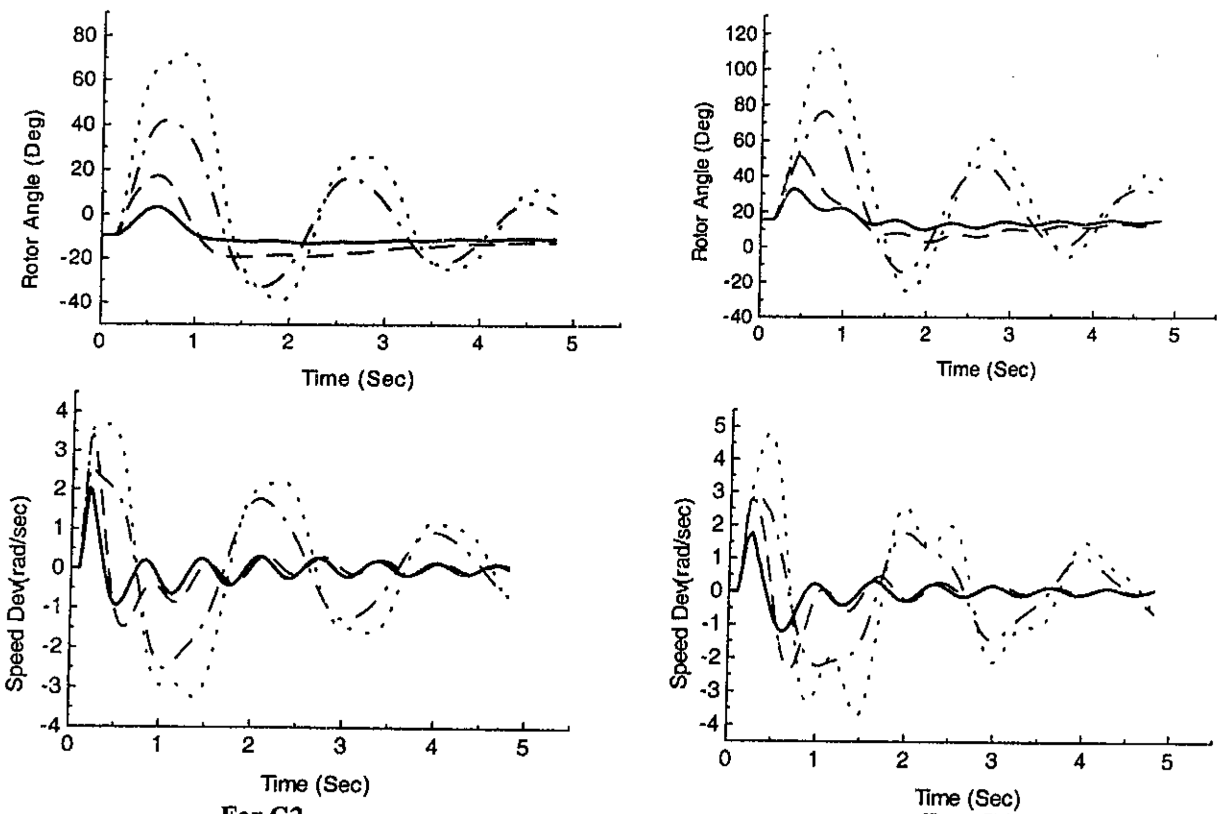
For G4



For G3

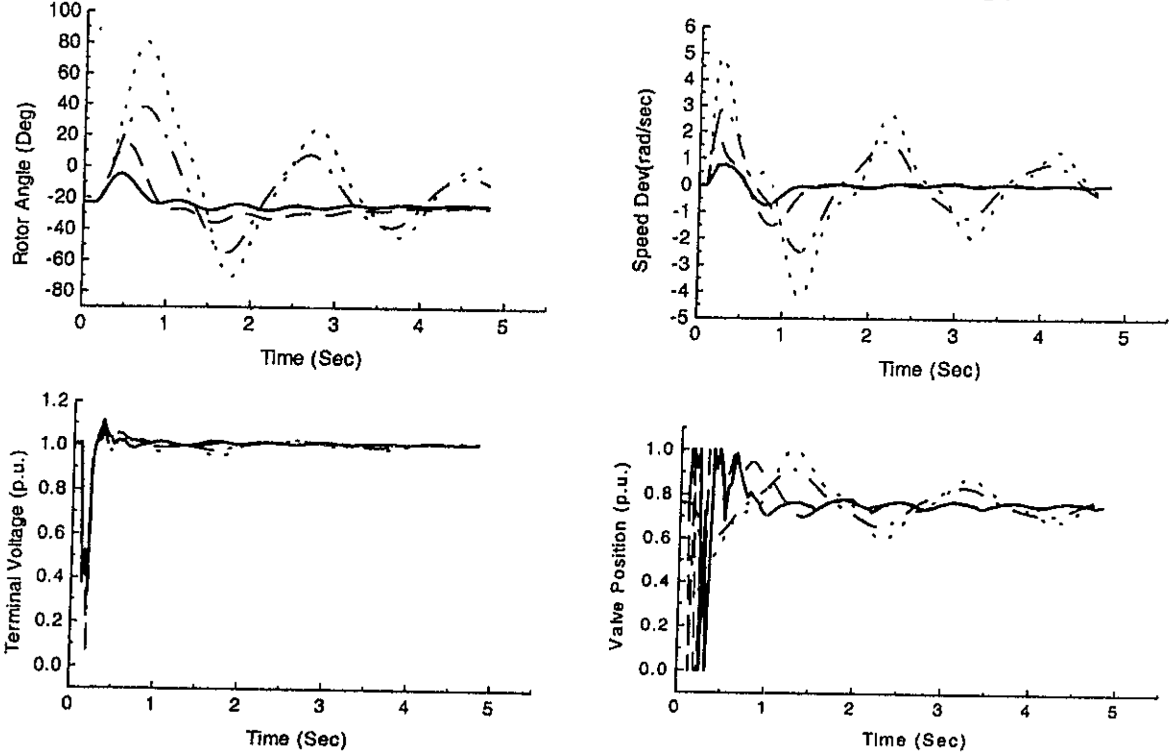
Fig.8 Transient response to a 3-phase short circuit with 200 ms duration at F1

━━━━ TCSR at G2 and G3 + FLC on SCG + PSS on conventional units
- - - - - - - FLC on SCG + PSS on conventional units
·············· With SG on SCG + AVR on conventional units
-·-·-·- TCSR at G2 and G3+ SG on SCG + AVR on conventional units



For G2

For G4



For G3

Fig. 9 Transient response to a 3-phase short circuit with 200 ms duration at F1

—— TCSR at G3 and G4 + FLC on SCG + PSS on conventional units
- - - - - FLC on SCG + PSS on conventional units
·········· With SG on SCG + AVR on conventional units
-·-·-·- TCSR at G3 and G4+ SG on SCG + AVR on conventional units