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FUZZY LOGIC CONTROLLER FOR A SUPERCONDUCTING GENERATOR IN A MULTI-MACHINE POWER SYSTEM

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ABSTRACT

This paper presents the design and implementation of a fuzzy logic controller (FLC) for a superconducting generator (SCG) operating in a multi-machine power system. The controller is designed and tested in a multi-machine power system which includes conventional generators. The conventional generators are of different types and ratings. Conventional generators are equipped with their excitation and conventional control systems. To assess the new control strategy a fairly detailed nonlinear model is used. A comprehensive assessment of the proposed FLC is presented and the simulation results are obtained in comparison with others obtained with controllers designed based on conventional techniques. The results illustrate significant improvements in performance when FLC is used. This is obtained at different operating conditions and when the system is subjected to a variety of disturbances and changes in system configuration.

يقترح البحث حاكم غيمى لآلة فائقة التوصيل مربوطة ضمن نظام قوى كهربية متعدد الماكينات يتضمن وحدات توليد تقليدية من أنواع وأحجام مختلفة. والحاكم المقترح لة دخلين هما التغير فى السرعة عن السرعة المقننة ومعدل هذا التغير وهما دخلان يمكن قياسهما وبالتالى يسهل تطبيق الحاكم. وبعد تصميم الحاكم المقترح تم تطبيقه فى دائرة منظم السرعة للآلة فائقة التوصيل باستخدام نموذج غير خطى تفصيلى للنظام متعدد الماكينات وكانت الآلات الأخرى محكومة بالحاكمات التقليدية. وبدراسة أداء النظام عندما يتعرض لأنواع مختلفة من الأخطاء (مثل قصر ثلاثى الوجه عند مواضع مختلفة وكذلك حدوث زيادة مفاجئة في الدخل الميكانيكى للآلة فائقة التوصيل وأيضا تغير شكل النظام بخروج خطوط بعد القصر) ومقارنته بالأداء عندما يتم التحكم في الآلة فائقة التوصيل باستخدام حاكم تقليدى تبين مدى أفضلية الحاكم المقترح والتحسن في أداء وحدات التوليد المختلفة في النظام من حيث زيادة إخماد الإهتزازات وسرعة عودة المتغيرات إلي قيمها المبدئية.

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

1. INTRODUCTION

Today the need for increasing generation of electrical power is of major concern. This renders technological advances in generation and distribution and economical benefits of reducing unit cost of electricity and installation of large generating units [1]. The main design features of large generators are their high p.u. reactances and low inertia constants. However, the trend of these parameters tends to reduce stability limits and adversely affect the overall system performance. Also, increasing the number of generating units cause high dimensional system and practical constraints on transferring signals over long distances between power stations [2].

One area of considerable interest is the synchronization of superconducting generators in multi-machine environment. This is due to the several advantages of SCGs over conventional machines such as higher efficiency, annual savings, weight, volume and possibility of generation at transmission line voltages [3]. Moreover, SCGs are expected to break through the rating limits and hence replace conventional machines in supplying base loads in large power systems [4]. As the dynamics of large scale power systems are both nonlinear and interconnected [5]. A substantial effort has been prompted towards the development of improved methods of operation and control. Traditional fixed gain controllers were effectively used for damping out the low frequency oscillations. These controllers are designed based on linearized models of power systems for a particular operating system condition [6]. However, power systems are non-linear systems with a wide range of operating conditions and time varying configuration and parameters. Therefore, fixed parameter controllers which stabilize the system under specific operating conditions may no longer yield satisfactory results when there is a drastic change in the power system operating conditions and configurations. They are also not very effective in damping out the multi-mode oscillations of interconnected system. Considering the above facts, it is desirable to develop a controller which considers the non-linear time-varying nature of the system and has the ability to adjust its parameters according to its environment [7]. In recent years, intelligent control techniques such as fuzzy logic controllers (FLC) are good alternatives for such applications [8]. This is due to a variety of advantages such as : these controllers are model-free, i.e. the exact mathematical model of the controlled system is not required where it establishes directly from input and output data of the process, this is of particular important as the difficulty of accurately modeling the connected generators is expected to increase under power industry deregulation. Fuzzy controllers are customizable, since it is easier to understand and modify their rules, these decision rules are developed from the human expertise in natural linguistic terms.

Finally, fuzzy systems are soft computing approaches for modeling expert behavior [9]. Control algorithm based on fuzzy logic has successfully applied to many systems [10]. Reference [8] investigates the effectiveness of FLC in a single SCG againest infinite bus system. The object of this paper is to design a FLC in the governor control loop of a SCG operating in a multi-machine power system and to assess the performance of the whole system with the proposed controller via an extensive simulation study. The simulation results are obtained in a comparative form with others obtained when SCG equipped with phase advance network. The performance of the system are studied when subjected to a variety of disturbances such as three phase short circuit at different locations, step increase in the mechanical input of the SCG and changes in system configuration and operating conditions.

2. SYSTEM DESCRIPTION

The multi-machine power system under consideration consists of four generating units of different types and ratings. Fig.(1) shows the single line diagram of the tested multi-machine system. The arrangement of the units is taken as follows: a 590 MVA steam generator connected to bus 1; a 1300 MVA nuclear unit connected to bus 2 near loads; 2000 MVA superconducting generator at bus 3 and a 615 MVA hydro-electric generator to bus 4 at remote ends. These units are connected to four load areas through proper transmission network. Loads and network parameters are shown in the figure. For a high degree of accuracy in the obtained results, detailed representation were made for all system components including generators regardless of their location relative to disturbances. This is important especially for the superconducting generator which has a rather different construction criterion [1]. The system contains different types of exciters for conventional generators with different ceiling voltages. All non-linearities 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.

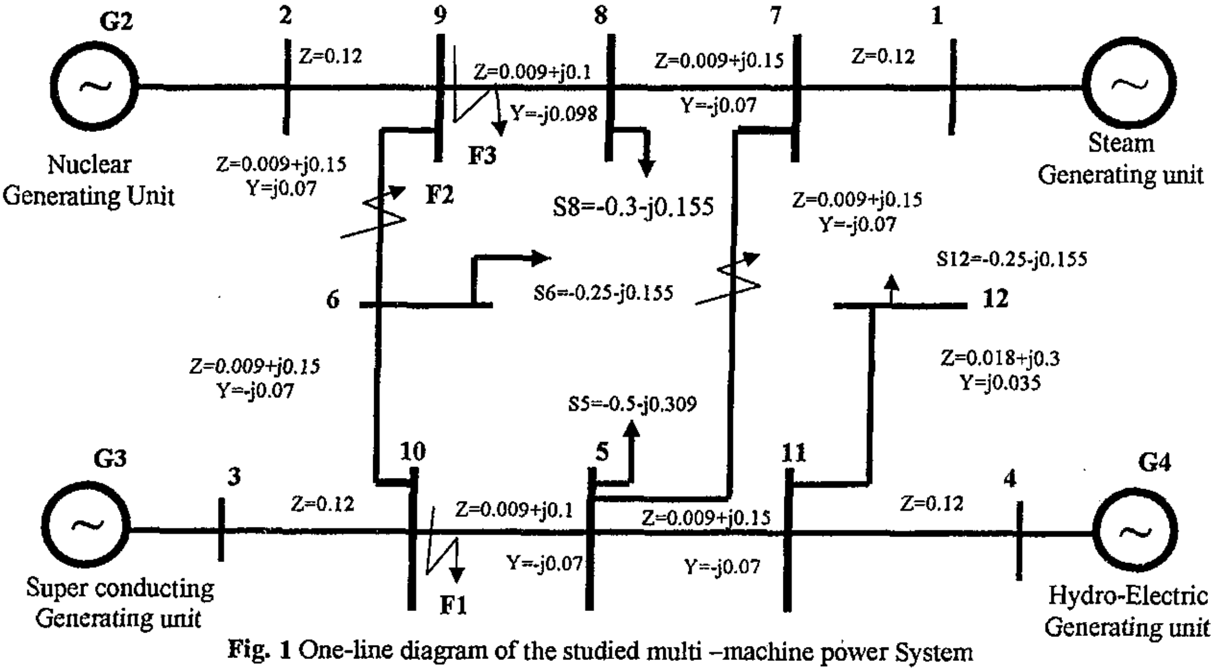

Fig. 1 One-line diagram of the studied multi –machine power System

3. MODELING OF GENERATORS AND EXCITATION SYSTEMS

In general, simple generator models are good for analysis purposes but not accurate enough for predicting its performance for control and on-line purposes. On the other hand, higher order models improve the validity of results [11]. So, for high level of accuracy in the obtained results detailed representation were made for all system components including generators regardless of their location relative to disturbances. A seventh order nonlinear mathematical model, based on Park's d-q axes representation is used to represent each conventional synchronous machine [1]. Also, the model used for the SCG which has a rather different construction criterion is a fairly detailed representation [12]. The most critical part in the modeling of SCG is that which is concerned with the rotor screens. In this study each screen is represented by one coil of fixed parameters on each axis[1]. Hence the order of the mathematical model increases to nine to cater for the doubly screened rotor. The parameters of the generators are listed in the Appendix. All network components are represented by lumped parameters, the transmission lines are represented using π method and the loads are represented by constant impedances [13]. The *mechanical* input to each conventional machine is considered fixed. This is due to that normal governor response has little effect on system damping in most situations [14]. So, excitation control is considered for these generators.

Various types of exciters have been used with different ceiling voltages. A high gain automatic voltage regulator (AVR) is used with each exciter to control generators terminal voltages. AVR parameters for each conventional machine are listed in Table (1), which are typical to the IEEE standardization. The block diagram of the excitation system for the conventional generators is shown in Fig. (2) [1]. 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, a power system stabilizer (PSS) is added with each excitation system to produce positive damping torques in phase with the speed [14, 15]. The transfer function of the pss is shown by broken line in Fig.(2). PSS is a lead-lag compensator with gain G_s and two time constants T_{s1} and T_{s2}.

For SCG and due to the different construction and the very long field winding time constant, it has been found that high ceiling voltage has very little effect in improving transient stability. This renders the necessity of considering only the governor control loop to enhance the system performance. However, adding positive damping via the governor loop is very difficult and requires a great deal of attention [8]. Therefore, the turbine-governor system that drives SCG is modeled in details and should be fast response with fast valving routine. This is to maintain and improve the stability of these low inertia units. Great improvements in the transient behavior can be achieved by the use of electro-hydraulic governor with fast valving turbine.

The interceptor and the main valves of the turbine are actuated by a speed error signal using a 4% droop. A full description of the turbine model is given in reference [16].

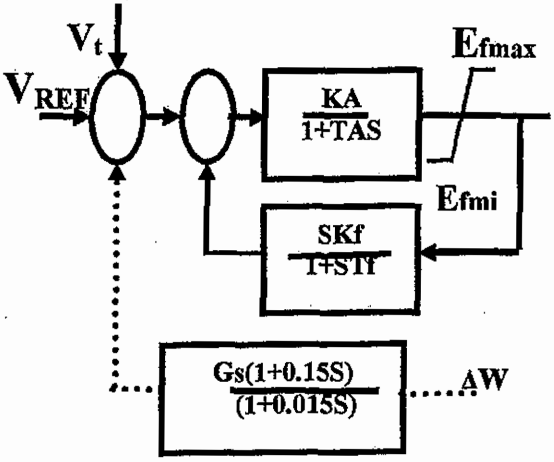

Fig. 2 Excitation system

4. DIGITAL SIMULATION

A detailed digital computer program has been built which solves the interconnected tested system including all non-linearities 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 [17]. Each generator is described by the non-linear equations expressed in park's reference frame, which is fixed to the machine rotor.

Table (1) Conventional generators excitation parameters

		KA	TA	TF	KF	Efmin p.u.	Efmax 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 network is described by lumped impedances and the solutions of currents and voltages at specified nodes are 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. 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.

5. FLC METHODOLOGY

Recently, fuzzy systems have been successfully applied to various control fields. The salient feature of these techniques that distinguish them from the traditional control approaches is that they provide a model free description of the control system. A fuzzy logic controller is a special type of knowledge based controller and it operates in a linguistic rule based manner [18]. The control strategy can be then expressed simply by a set of rules called fuzzy rules to adjust the effects of certain system stimulus. The fuzzy logic controller is introduced in the governor control loop of the SCG in replace of the phase advance network to enhance the performance of the multi-machine power system.

FLC consists of three main stages; the *fuzzification process, inference* (rule base) and defuzzification process [8]. Fuzzification process converts a crisp input, current value of the process state variable into a corresponding fuzzy set variable. In the proposed control scheme, the FLC input variables are the speed error e (k) and the error change, e (k), where

$$e(k) = Nd(k) - N(k)$$
$$e(k) = e(k) - e(k-1)$$

Nd(k) and N(k) are the desired and actual speed of the SCG at the Kth sampling interval respectively .The controller inputs e(k) and e(k) are normalized into the interval (-1,1) which is called the universe of discourse[19,20]. 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. In this paper , the fuzzy sets are chosen as Positive Big (PB) , Positive Medium (PM) , Positive Small (PS) , Zero (ZO) , Negative Small (NS) , Negative Medium (NM) and Negative Big (NB) . After specifying the fuzzy set, 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 49rules 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. These rules establish relations between conditions fuzzy sets and conclusion fuzzy sets [8].

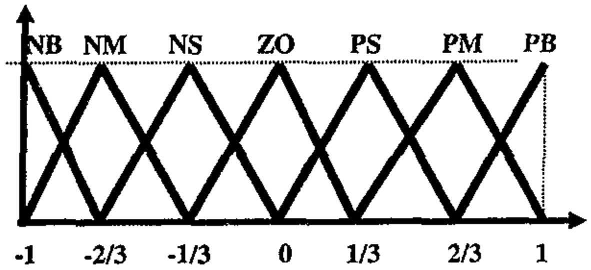

Fig. 3 Membership Function of the input and output

Table (2) Rule Base

e(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

Finally, the defuzzification process is the inverse of fuzzification process, it converts the fuzzy output of the fuzzy controller into a crisp value (numerical output) . Many strategies can be used for performing the defuzzification. The digital center of area method (COA) is used in this paper. The change of the controller output at the K^{th} sampling interval is defined by:

$$U(k) = \overset{n}{\underset{i=1}{}}\;{}_i(k)\,C_i(k)\,/\;\overset{n}{\underset{i=1}{}}\;{}_i(k)$$

Where, U denotes the center value of the output fuzzy set. The controller output U is mapped onto the respective actual output Us by the output scaling constant K_u.

6. RESULTS AND DISCUSSIONS

The introduction of SCGs increases the stability reserve of the multi-machine system, but with a slight reduction in the overall damping. Therefore, it is necessary to install controllers in order to have a good dynamic performance. The full order nonlinear model of the tested power system was simulated using a nonlinear transient digital computer simulation program. In order to validate the overall effectiveness of the proposed FLC on the post fault transient conditions for the multi-machine power system under different disturbances over a wide range of operating conditions. A number of simulation studies have been performed as follows:

Case no.1 (3-phase short circuit at different locations)

In this case, the performance of the considered multi-machine system with the designed fuzzy logic controller is examined when subjected to a three phase short circuit fault at different locations (F1, F2, F3 and F4 one at a time and others are not effective) as shown in Fig.(1). Fig.(4) show the time response for relative rotor angles and speed deviations for generators 2, 3 and 4 and in addition to the terminal voltage and the valve position for generator 3 (SCG) due to 3 phase-short circuit at F1 for 200ms duration. Each of the conventional machines has been equipped with power system stabilizer with predefined parameters. The SCG is equipped with either FLC or phase advance network in its governor control loop. The simulation results indicate a noticeable reduction in the first swing of all machines rotor angles and speed deviations especially for SCG which implies an increase in transient stability. This is basically due to the low synchronous reactance of SCG and the significant effect of the FLC. Smaller rotor angles increase synchronizing power flow between generating units, which is important for situations where generating units are to be located distant from load centers. Therefore, more power can then easily transmitted to the loads. Also, the system variables are quickly returns to their original values. Figs.(5) To.(7) shows the performance of generators for different locations of fault. The results show that the fault location does not significantly affect the damping performance of the proposed FLC. Therefore, substantial improvements can be achieved in both system damping and stability by incorporating FLC in the governor control loop of the SCG.

Case no.2 (Changing operating conditions)

This case presents the effect of changing the operating conditions on the performance of FLC. Results are shown in Fig.(8) for a 3-phase short circuit at location F1 and with different operating condition. Each conventional machine is equipped with pss however SCG operates with FLC or with phase advance network. The simulation results concluded that FLC is still very effective in improving transient stability limits

Case no.3 (10 % step increase in the mechanical input of the SCG)

Although three-phase short circuit faults are the most severe disturbances in the power system, the probabilities of their occurrence are relatively low. In this case, the system performance with FLC is examined when subjected to 10% step increase in the mechanical input of the superconducting alternator. Each of the conventional machines has been equipped with power system stabilizer and the superconducting unit is equipped with either FLC or phase advance network in its governor control loop.

From Fig. (9), it can be observed that FLC is achieving again the better response in comparison with phase advance network. This appeared from less overshoot and small settling time. Therefore, the proposed controller enhances the system response as oscillations are highly damped and the system variables are fast returned to their steady state values.

Case no. 4 (3-phase short circuit followed by line outage)

The disturbance in this case is large disturbance. The fault is a 3-phase short circuit at F1 followed by line (5-10) outage from both ends. Fig. (10) Shows the transient response of the multi-machine system generating units. These results shows that, using the FLC in the governor control loop of the SCG, all generators relative rotor angles are reaching steady state faster. The SCG rotor angle reaches its steady state close to the initial condition but rotor angles for conventional generators reaches steady state with rather difference in values. The relative speed deviations and terminal voltages are reached to their initial values but with some oscillations. However, these oscillations are fastly damped with the use of FLC.

7.CONCLUSIONS

The paper presents a FLC for a SCG in a multi-machine power system. This is to damp undesired electromechanical modes of oscillations after sever disturbances and to enhance the system transient stability. The effectiveness of the proposed controller were investigated through extensive studies when the system subjected to various disturbances as 3-phase short circuit at different locations, step increase in the mechanical input of the SCG and changes in system configuration and operating conditions. The study of different cases illustrates that the use of fuzzy logic controller on the governor control loop of the SCG increases overall damping and significantly improves the performance of all generators. This is clarified from variables fast return to their initial conditions and the increase in stability reserve indicated by the reduction in rotor angles first swing for all generators. In short, FLC provides a means for synthesizing, a more robust controller from engineering experiences that can enhance the system performance and which is insensitive to parameter variations.

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APPENDIX

SCG parameters :

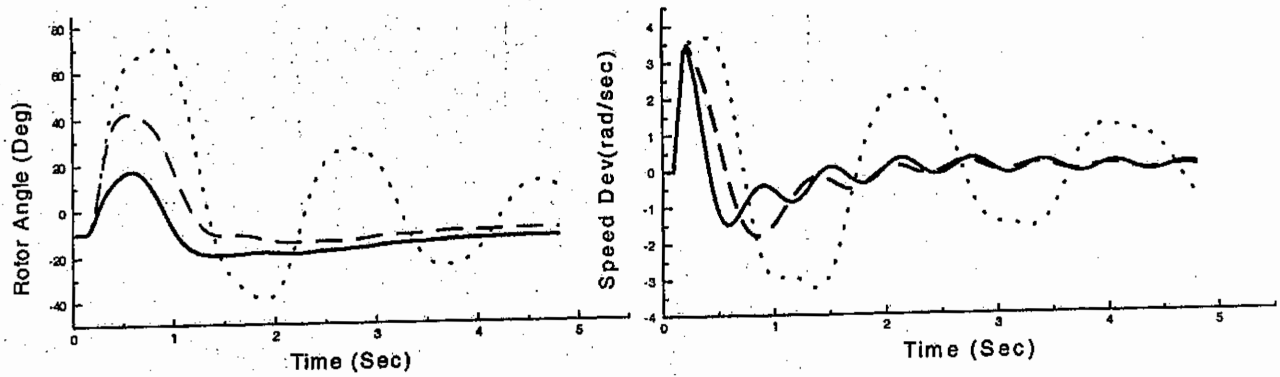
2000 MVA, 1700 MW, 3000 r.p.m
X_d= X_q=0.0453 p.u., X_f= 0.541 p.u. ,
X_{KD1}=X_{KQ1}=0.2567p.u., X_{fKD2}=0.3398p.u.
X_{af}=X_{fKD1}=X_{aD1}=X_{aD2}=X_{KD1KD2}=0.237p.u.,
X_{aQ1}=X_{aQ2}=X_{KQ1KQ2}=0.237p.u.
R_{KD1}=R_{KQ1}=0.01008p.u.,R_a=0.003 p.u.,
R_{KD2}=R_{KQ2}=0.00134p.u.
H=3.0 KWS/KVA.

Parameters for SCG Turbine and Governor :

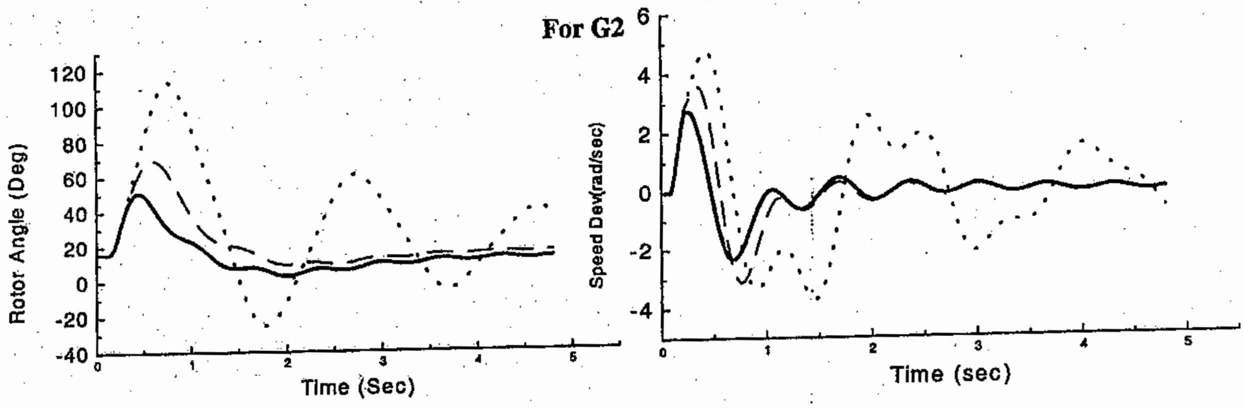
T_{HP}=0.1 sec , F_{HP}=0.26 , T_{IP}=0.3 sec , F_{IP}=0.42 ,
T_{LP}=0.3sec ,F_{LP}=0.32 , T_{RH}=10 sec ,
T_{GM}=T_{GI}=0.1 sec , P_o=1.2 P.U.

***Conventional machines parameters**

	Steam Unit (G1)	Nuclear Unit (G2)	Hydro-electric Unit (G4)
X_d	2.11	2.13	0.898p.u.
X_q	2.02	2.07	0,646p.u.
X_{ad}=X_{af}	1.955	1.88	0.658p.u.
X_{aq}	1.865	1.82	0.406p.u.
X_f	2.089	2.12	0.724p.u.
X_D	2.07	1.97	0.668p.u.
X_Q	1.93	1.88	0.457p.u
R_a	0.0046	0.0029	0.0014p.u.
R_f	0.00013	0.00092	0.00026p.u
R_D	0.02	0.018	0.012 p.u.
R_Q	0.024	0.0212	0.02 p.u.
H	2.32	2.52	5.15KW/KVA



For G2



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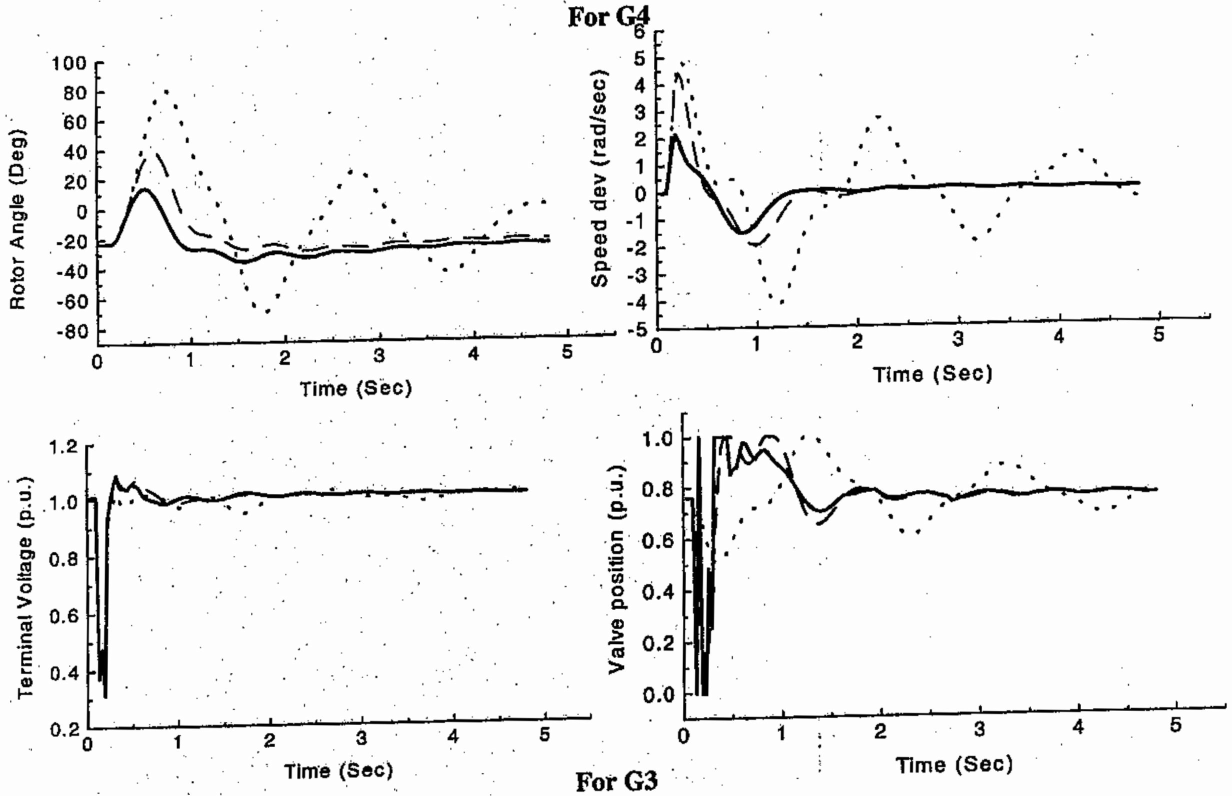


For G3

Fig. 4 Transient response to a 3-phase short circuit at F_1 with 200 ms

━━━━ With FLC on SCG + pss on conventional units
— — — — With phase advance on SCG + pss on conventional units
- - - - - - Speed governor on SCG + (AVR & Speed governor)on conventional units

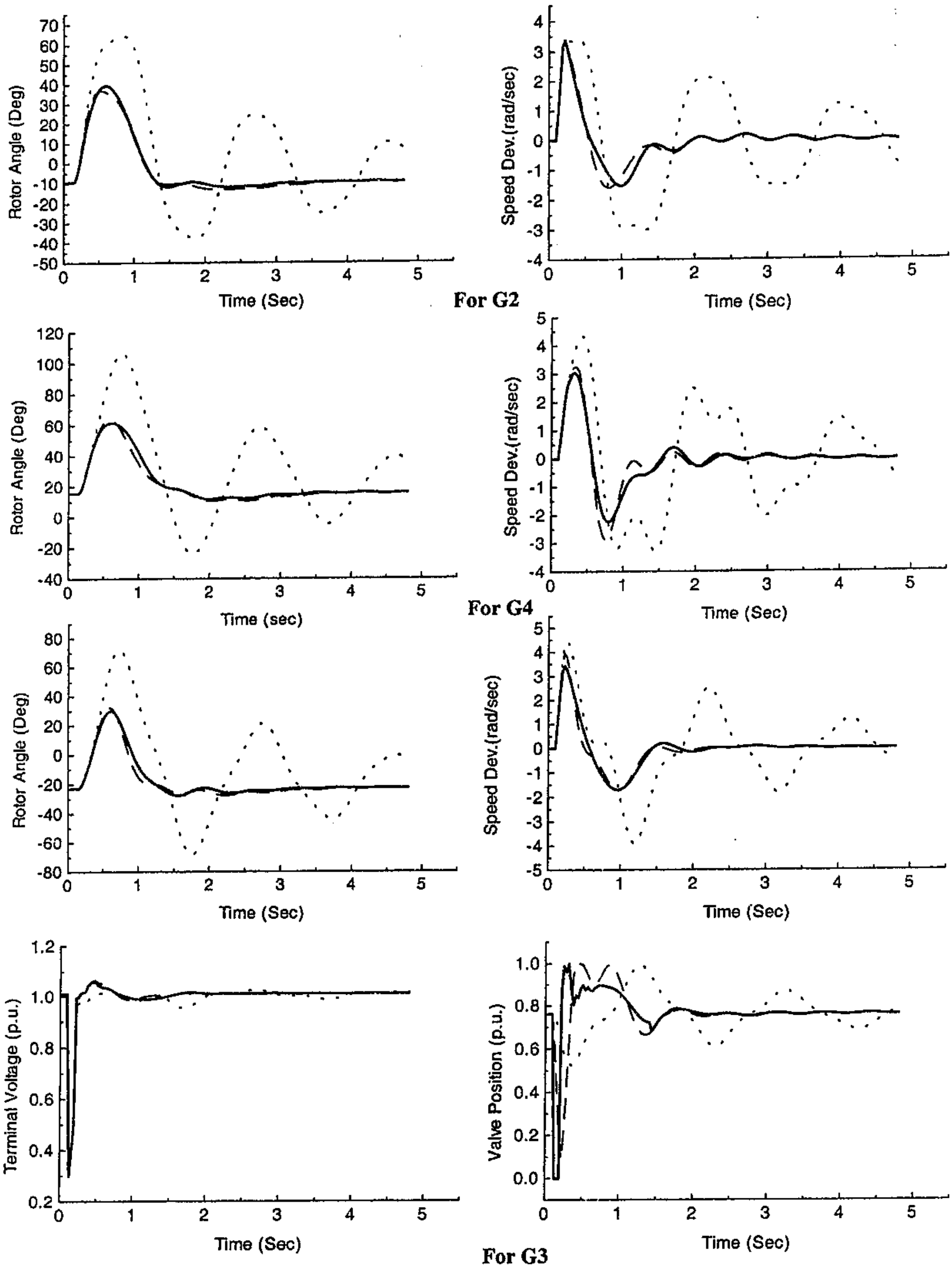
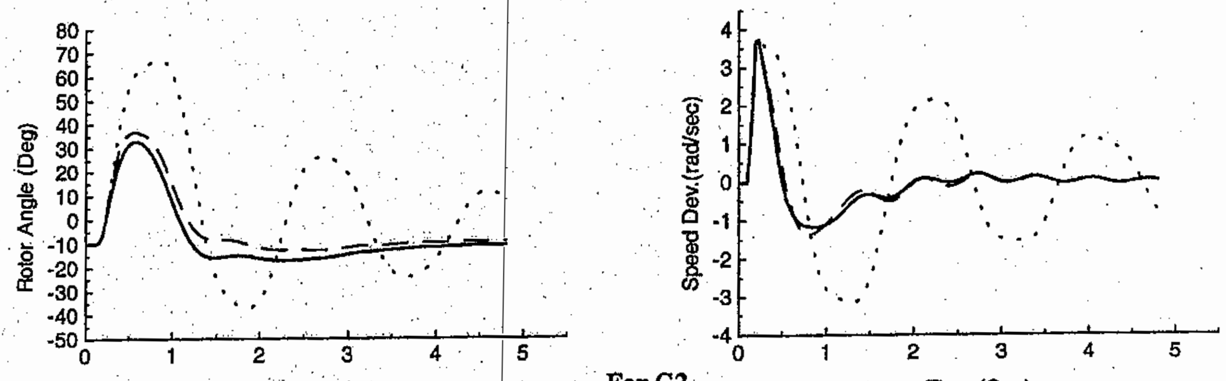


Fig. 5 Transient response to a 3-phase short circuit at F_2 with 200 ms

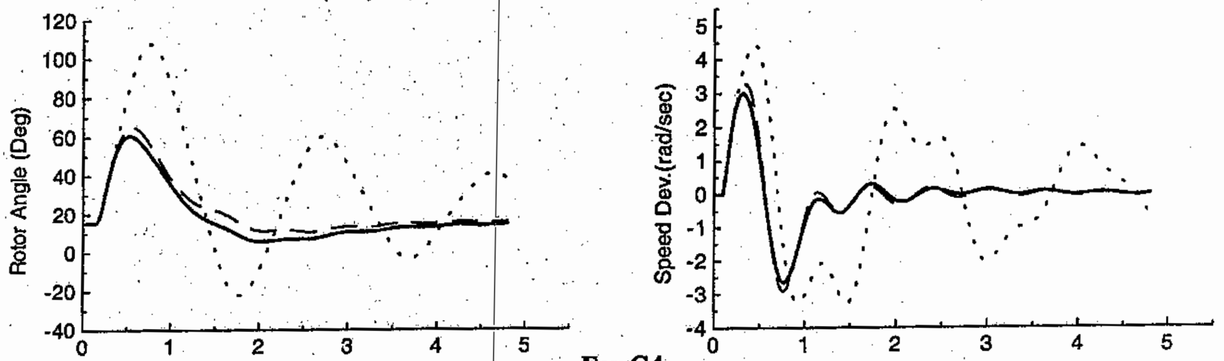
━━━━━ With FLC on SCG + pss on conventional units

— — — — — With phase advance on SCG + pss on conventional units

- - - - - - - - Speed governor on SCG + (AVR & Speed governor)on conventional units



For G2



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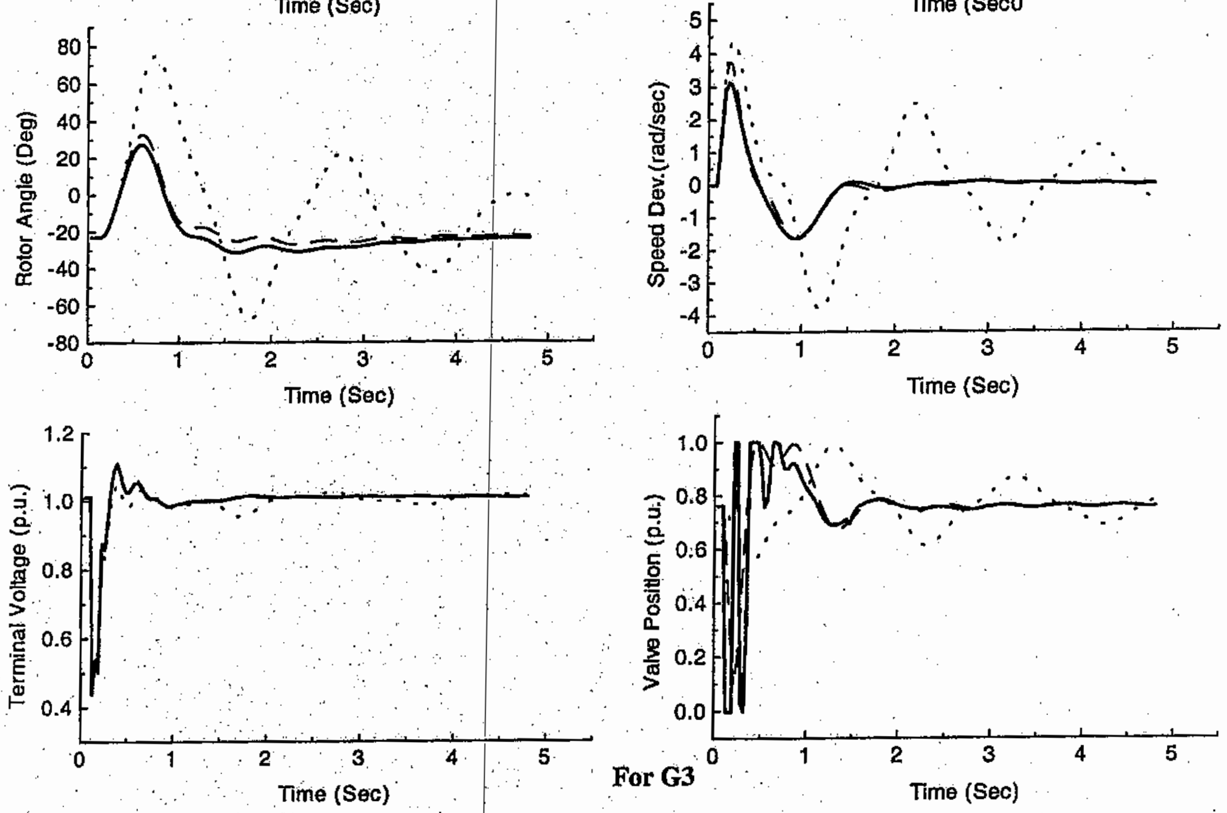


For G3

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

▬▬▬ With FLC on SCG + pss on conventional units
– – – – With phase advance on SCG + pss on conventional units
- - - - - - Speed governor on SCG + (AVR & Speed governor)on conventional units

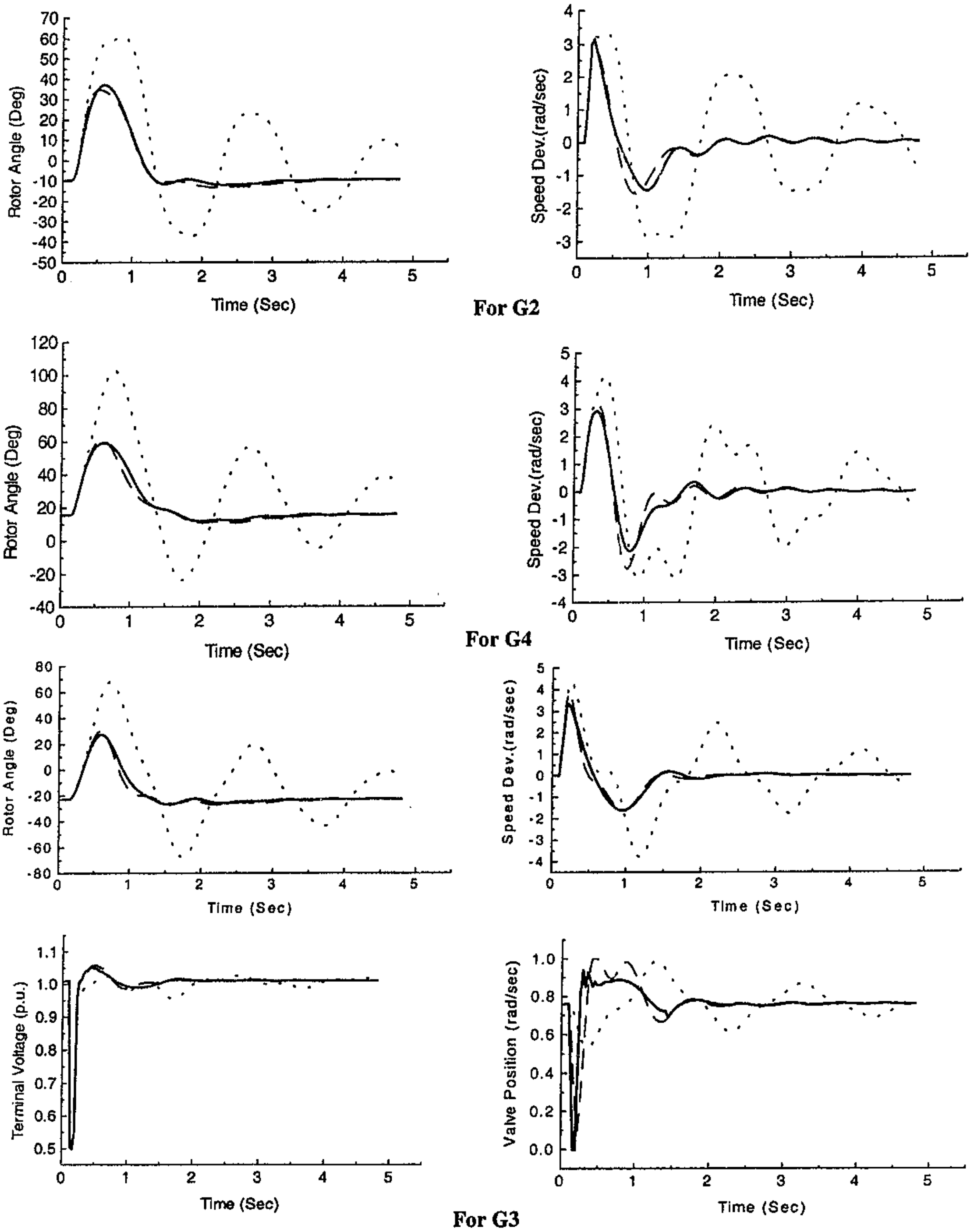
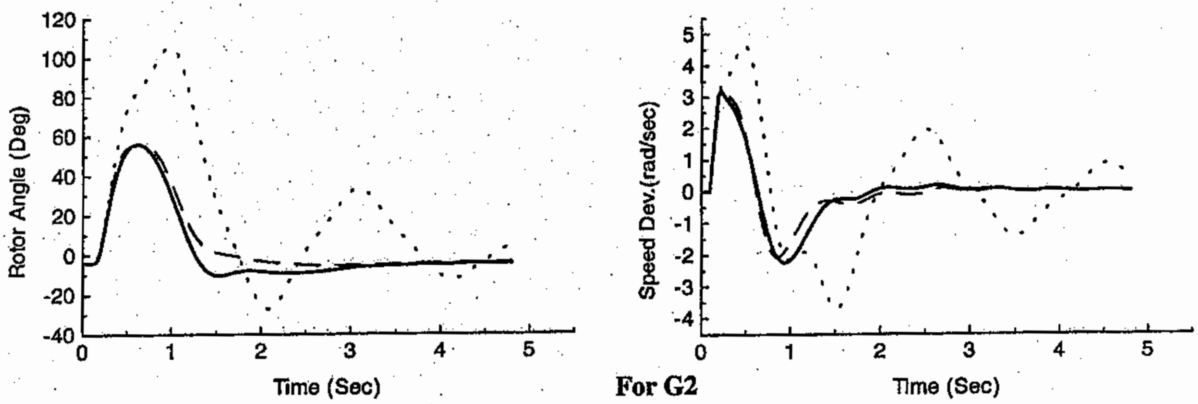
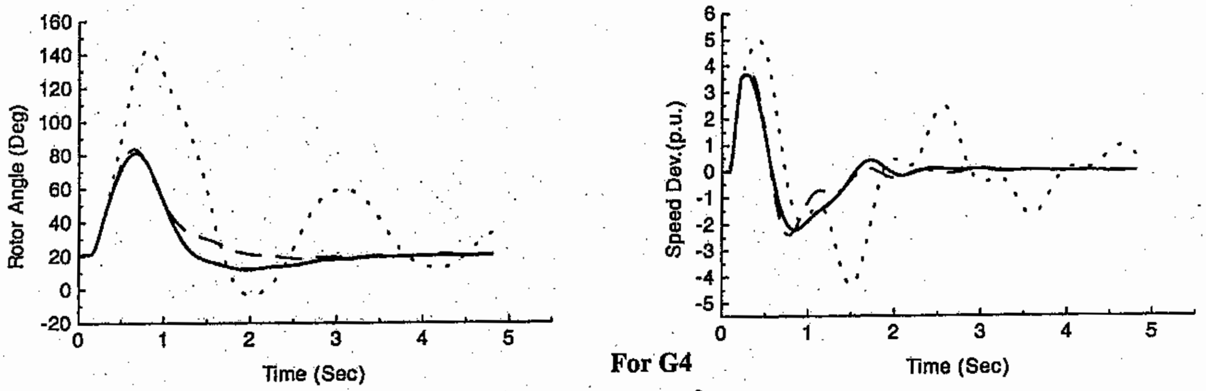


Fig. 7 Transient response to a 3-phase short circuit at F_4 with 200 ms

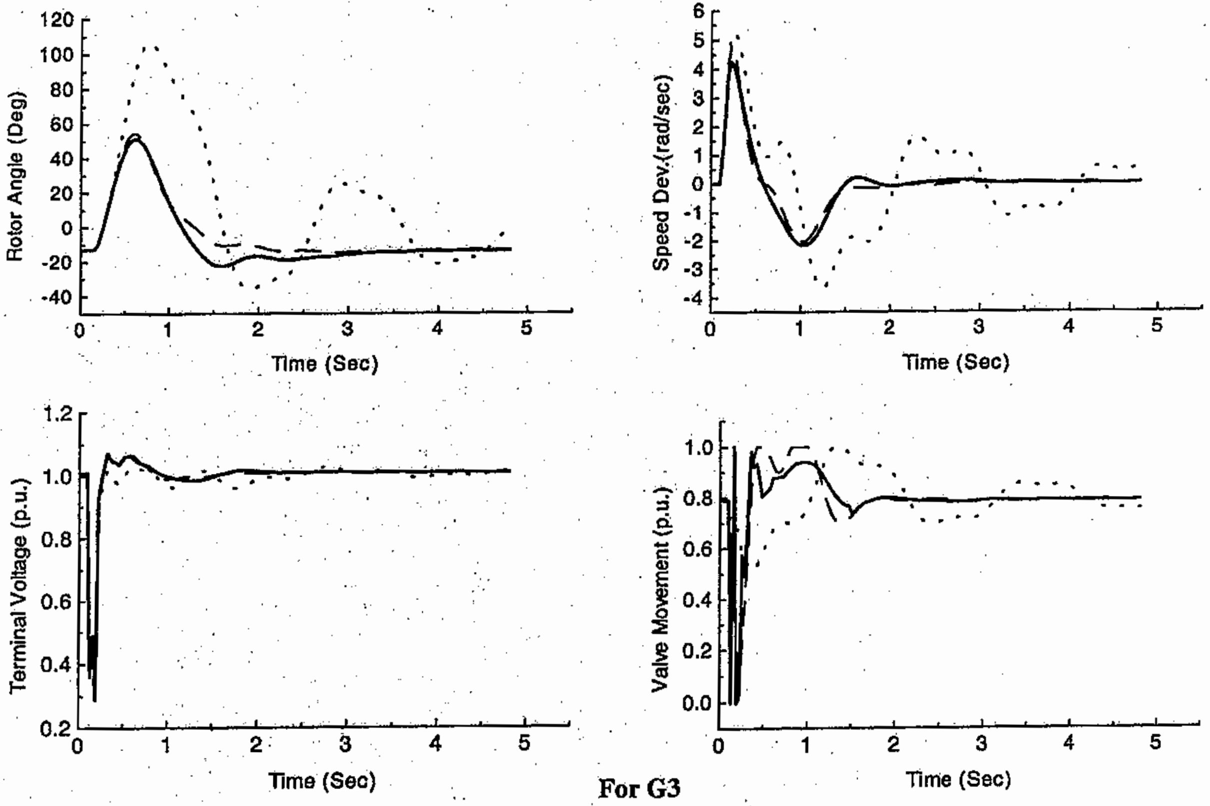
━━━━ With FLC on SCG + pss on conventional units
– – – – – With phase advance on SCG + pss on conventional units
- - - - - - - Speed governor on SCG + (AVR & Speed governor) on conventional units



For G2



For G4



For G3

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

▬▬▬	With FLC on SCG + pss on conventional units
— — — —	With phase advance on SCG + pss on conventional units
- - - - - - - -	Speed governor on SCG + (AVR & Speed governor) on conventional units

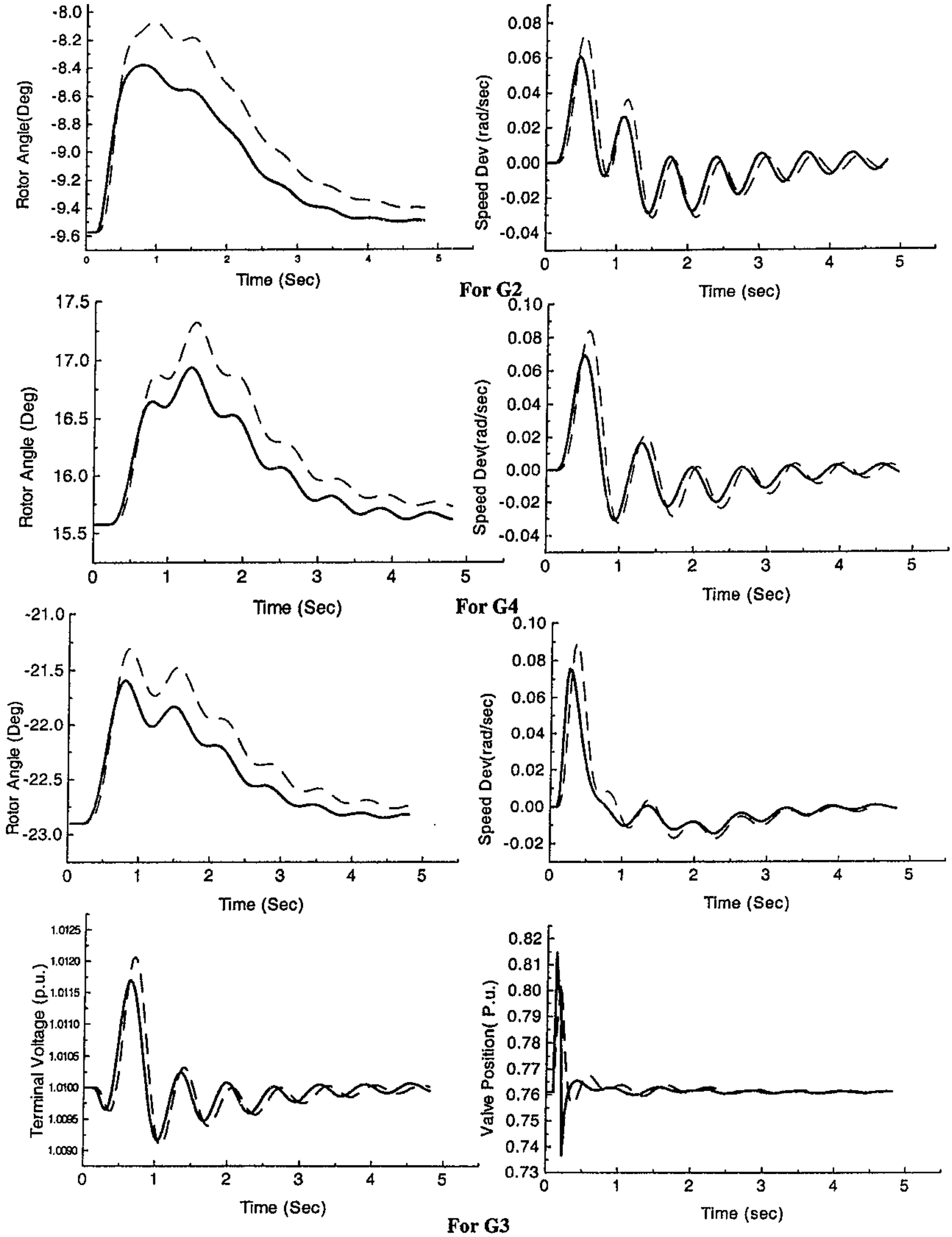


Fig. 9 Transient response for 10% step increase in mechanical input to G3

—— With FLC on SCG + pss on conventional units
- - - - - - - With phase advance on SCG + pss on conventional units