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CONTROL OF A SUPER CONDUCTING GENERATOR OPERATING IN A MULTI MACHINE ENVIRONMENT

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ABSTRACT

The paper describes a technique for the controller design and performance analysis of a super conducting generator, operating in a multi machine environment. The air-cored nature of the new machine and the very long time constant of the exciter renders that the governor control to be considered only.Initially, the a multi-stage phase advance controller is designed with the object of increasing phase margin while ensuring a satisfactory transient performance. A full nonlinear simulation of a multi machine system, including a super conducting generator has been built and is used to test the developed multi-stage phase advance controller. A complete set of simulation results has been presented illustrating that the dangerous oscillatory modes associated with the introduction of this new machine can be adequately dumped using the control design technique that presented in this paper. Moreover, the results illustrate clearly that the controller on the super conducting unit improve both the performance of that unit as well as that of the other conventional units even those which located at remote ends.The results indicate clearly that a well designed controller for the super conducting generator becomes necessary before synchronizing this new machine into the power networks.

1. INTRODUCTION

The continuous increase in demand for electrical power and the continuous up-rating of generator output renders installation of large and large generating units over the years [1]. . Generating units of ratings greater than 1000 MW are now in service, and sizes of 2000 MVA output have been considered as an economical size by the end of 1980s [1]. There are some difficulties in increasing the size of conventional generators beyond the present sizes and it has been revealed that the design parameters of such large conventional machines reduces the stability margin and adversely affect the system performance [1]. A possible way of overcoming these problems would be by developing super conducting machines. Super conducting generator (SCG) is a new machine which is expected to commission into large scale systems before the end of this century.Most of the literature at present are related to the design and field analysis of the new machine [2-9]. However, research work in the area of synchronization of this new machine seems to be very little.

Control of super conducting conducting generators when synchronized into power networks represents an interesting area. This due to that the air cored nature and different construction criterion of the new machine make the control requirements and dynamic oscillatory modes different from those of conventional generators. The new machine has higher efficiency, smaller size and weight, and lower per-unit reactances compared with the conventional generator.This improves system stability but at the expense of the inherent low damping characteristics of this machine. Control of conventional generators has been of a subject of growing interest since the late 60's. It has been revealed that most of the external damping could be easily added via the excitation loops rather than the governor one. Unfortunately, this is not the case in super conducting generators since the excitation loop is ineffective due to the long time constant of this loop(about 750 s). Therefore the only available loop is the governor loop. Publications regarding the control of a single machine connected to an infinite bus bar considers only this loop [10-12]. Moreover, examination of the influence of the introduction of a super conducting machine into a system with conventional generators has already been documented [13,14].

The object of this paper is to design and implement by computer simulation a wide range controller for a super conducting generator operating in multi machine environment. A multistage phase advance network is designed for the governor control loop using the frequency domain technique. The controller is applied using a detailed nonlinear simulation and the results are presented.

2. MULTI MACHINE SYSTEM

The multi machine system considered in this investigation is shown in Fig.1. It consists of four generating units with the generator sizes and load areas distributed as shown in the figure.. All generators are represented in detail with their additional control loops. The parameters of generators 1,2 and 4 were taken from reference [15] with their conventional control circuit shown in Fig.2 .Also, A high gain of the Automatic Voltage Regulator (AVR) of each generator was considered while the Power System Stabilizer (PSS) parameters for each conventional generator was also given in [15]. The network parameters are given on Fig.1 and each transmission line is represented by the π-method.

3. MODELING

Modeling of the conventional synchronous machines ,in this paper, followed the traditional d-q Parks representation, including their excitation and additional control loops. Detailed representation of multi-machine systems for control studies are now well documented [16]. Therefore, modeling of onventional generators and the theory of multi-machine representation will not included. However, details of super conducting generator modeling is reported subsequently while the construction and theory of operation of this unit are well documented in [2-9].

3.1 REPRESENTATION OF A SUPER CONDUCTING GENERATOR

For seeking accurate results relating to the control of this new machine, the generator should be represented in detail. This ,however, will be at the expense of the computation time. Therefore it has been decided that detailed representation of the generator be considered and only a few number of machines be represented. Due to the air cored nature of the super- conducting generator and the pronounced effect of the end windings, parameters which were obtained based upon a three-dimensional field analysis [9] have been used in this thesis. The most critical part in the modeling of the super conducting machines is that which is concerned with the rotor screens (shield and damper). The shielding and damping functions of the two rotor screens require conflicting screen properties. The shielding increases with increased time constant of the screen, while optimum damping for the rotor oscillations requires a time constant of value corresponding to the condition at which the damper screen current changes from resistance to inductance limited . However, it may be deduced from the short-circuit nature of the screens that it is not the absolute parameters of the screens that matter but their time constants [5]. The accuracy of representing the rotor screens by lumped parameters depends upon the relative value of the skin depth of the screen in comparison with its thickness [4]. However, more accurate modeling for the screens may be achieved by representing each one by more than one coil, but that would be at the expense of computation. Moreover, it has been found that each screen may be represented by one coil of fixed parameters on each axis without loss of accuracy in control studies [12]. The parameters of this model were computed with the aid of the numerical-analytical technique [9] and employed in this study.

The following non-linear equations are based on Park's model, are used to represent the super conducting generator [4].

(i) *Stator representation :*

$$p\,\psi_d = \omega_o\,(\,V_d + i_d\,R_a + \psi_q\,) + \omega\,\psi_q \tag{1}$$

$$p\,\psi_q = \omega_o\,(\,V_q + i_q\,R_a - \psi_d\,) - \omega\,\psi_d \tag{2}$$

(ii) *Outer screen representation :*

$$p\,\psi_{D1} = -\,\omega_o\,i_{D1}\,R_{D1} \tag{3}$$

$$p\,\psi_{Q1} = -\,\omega_o\,i_{Q1}\,R_{Q1} \tag{4}$$

(iii) *Inner screen representation :*

$$p\,\psi_{D2} = -\,\omega_o\,i_{D2}\,R_{D2} \tag{5}$$

$$p\,\psi_{Q2} = -\omega_o\,i_{Q2}R_{Q2} \tag{6}$$

(iv) *Field circuit representation :*

$$p\,\psi_f = \omega_o\,(\,V_f - i_f\,R_f\,) \tag{7}$$

The currents in equations 1-7, may be calculated as follows:

$$\begin{bmatrix} i_f \\ i_d \\ i_{D1} \\ i_{D2} \end{bmatrix} = \begin{bmatrix} X_f & -X_{fd} & X_{fD1} & X_{fD2} \\ X_{fd} & -(X_d + X_e) & X_{dD1} & X_{dD2} \\ X_{fD1} & -X_{dD1} & X_{D1} & X_{D1D2} \\ X_{fD2} & -X_{dD2} & X_{D1D2} & X_{D2} \end{bmatrix}^{-1} \begin{bmatrix} \psi_f \\ \psi_d \\ \psi_{D1} \\ \psi_{D2} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} i_q \\ i_{Q1} \\ i_{Q2} \end{bmatrix} = \begin{bmatrix} -(X_q + X_e) & X_{qQ1} & X_{qQ2} \\ -X_{qQ1} & X_{Q1} & X_{Q1Q2} \\ -X_{qQ2} & X_{Q1Q2} & X_{Q2} \end{bmatrix}^{-1} \begin{bmatrix} \psi_q \\ \psi_{Q1} \\ \psi_{Q2} \end{bmatrix} \quad (9)$$

(v) *Mechanical equations :*

$$p\,\delta = \omega \quad (10)$$

$$p\,\omega = \frac{\omega_o}{2\,H}\,(T_m - T_e) \quad (11)$$

Where :

$$T_e = \psi_d\, i_q - \psi_q\, i_d \quad (12)$$

(vi) *Terminal power :*

$$P_t = V_d\, I_d + V_q\, I_q \quad (13)$$

(vii) *Terminal voltage :*

$$V_t^2 = V_d^2 + V_q^2 \quad (14)$$

(viii) *Transformer and transmission line :*

$$V_d = V_b \sin\delta + R_e\, I_d - X_e\, I_q \quad (15)$$

$$V_q = V_b \cos\delta + R_e\, I_q + X_e\, I_d \quad (16)$$

Where X_e represents the external reactance that connects the generator to the large power system.

i.e: $X_e = X_T + X_L$ & $R_e = R_T + R_L$

3.2 EXCITATION SYSTEM OF SUPER CONDUCTING GENERATORS

The normal load excitation requirements of the super conducting generator are very small, i.e., 1000 amperes at about 5 volts for 1200-MVA super conducting generator . However, effective forcing requires several hundred volts to reach the permissible maximum ceiling limits. The super conducting field winding has a larger inductance, so that higher voltage is necessary to raise the field winding flux immediately. In a conceptual design of a 1000-MW super conducting generator, the field winding excitation voltage is set to be 5 volts at steady state and 5000 volts at transient state [8]. A thyristor controlled static excitation system for the use with large super conducting generators has been designed, whose harmonic content is low so as to avoid appreciable heating in the superconductors .

3.3 PRIME-MOVER REQUIREMENTS

Various models that represent the turbine dynamics are given in the IEEE technical committee report [17].However,the turbine system that derives super conducting alternators should be fast response with fast valving routine [18]. The turbine and governor system employed with the parameters are shown elsewhere [18]The parameters and time constants are within the limits recommended by the IEEE and have already been used in previous studies [10,12] concerning this new machines. . The turbine/governor model represents a three stage steam turbine with reheat. Fast acting electrohydraulic governors fitted to the inlet and interceptor valves and parallel governing system are assumed . The turbine and governor are represented by a sixth-order model with appropriate limits on valve position and velocity. Detailed of the system are shown elsewhere [18].

4. DIGITAL SIMULATION

A detailed computer program has been built to solve the interconnected multi machine system shown in Fig.1. The simulation takes accounts of all nonlinearities and constraints imposed on the control signals, valves movements and excitation voltages ceiling values for each generator. The ceiling values of excitation voltage is taken + 5.5 p.u for the steam and nuclear units while that for the hydro-electric varies from 0 to 7.3 p.u [15]. Since excitation control is ineffective for the superconductor generator, this loop has not been considered. The droop characteristics has been taken ,4% [18]. A fast valving is considered for the steam and nuclear units (rate of valve movements = +6.7 pu/sec) with maximum number of 3 successive valve movements . This accords with recent turbine manufacture recommendations. The IEEE Type - 1 representation of excitation systems [15] has been

considered for the conventional generators.
The simulation involves simultaneous solution of the nonlinear equation along with the linear network equtions The loads are represented by lumped impedances while the transmission lines are represented using π- method. The simulation program reads the initial loading conditions and generates the steady state solution. during disturbances the speeds of the machines change which makes their individual references oscillate with respect to the common reference frame. The nonlinear equations have been solved numerically using the Runge-Kutta integration method. Further details about digital simulation of multi machine systems for control applications may be found elsewhere [16].

5.MULTISTAGE CONTROLLER FOR SUPER CONDUCTING GENERATOR

It has been revealed that the long time constant of the excitation system of super conducting generators renders the ineffectiveness to add positive damping for the hunting oscillations [10,11]. Moreover,any additional damping may only consider the governor loop . Previous trials considered the design of either a phase advance network or an optimal stabilization scheme to substitute for the low inherent damping of a single machine connected to an infinite bus [10]. Also, an adaptive stabilizer have been designed and tested by computer simulation for a single machine system [11]. More recently, a multi-stage phase advance network has been designed for a single machine using the frequency domain technique [12] . All these controllers have been designed for a single machine, connected to an infinite bus considering the governor loop.

5.1 DESIGN PHILOSOPHY

Problems in designing a suitable controller for a super conducting generator operating in multi-machine systems may be summarized in the following broad lines :

(i) The suitable control strategy that is cabals of adding positive damping over a wide range of operating conditions and could be implemented via the governor loop.
(ii)The model on which the controller should be based.

With regarding to point (i), a multi-stage control design process [19] will be considered. This approach proved satisfactory when applied to multi-machine systems with only conventional generators [19] and when used with governor loop of a single super conducting generator[12]. With regard to point (ii) the model obtained is based on the assumption that any small disturbance may not affect generators at remote ends . This allow an equivalent modeling technique [16] to be used for obtaining the model on which the controller will be based. This is similar to that described in [16] with the transmission network replaced by an equivalent impedance obtained as described in this Reference. Fig.3 illustrate how to obtain the equivalent impedance.

5.2 DESIGN PROCEDURES

The phase advance network is a lead/lag compensator, whose transfer function F(s) is given by [19]:

$$F(s) = G\left|\frac{1 + T_1 s}{1 + T_2 s}\right|^{n} \tag{17}$$

The possibility of improving the performance of the super conducting generator by incorporating a phase advance network in the governor control loop depends on the choice of the gain and time constants The recommended time constant ratio for super conducting generator is 50 i.eT_1 and T_2 equal 0.5 and 0.01 sec. respectively. The design details of the gain G in a way to achieve maximum damping over a wide range of operating points is described elsewhere [19].

5.3 IMPLEMENTATION

The conventional controllers with their power system stabilizer has been used with generator 1,2 and 4 . The multi-stage phase advance network is designed for the super conducting generator as described in [16] and replacing the transmission line impedance by its equivalent substitute as follows :

$$\frac{1}{Z_e} = \sum_{\substack{j=1 \\ j=3}}^{j=n} \frac{1}{Z_{3j}} \tag{18}$$

Where Z_{3j} is the impedance connected generator 3 with the jth node as the super conducting generator connected to node 3. The equivalent model for the present system may be obtained easily with the aid of Fig. 3. It is important to point out that this approximation has only been made in the controller design stage . However, testing the controller and all simulation results are obtained using the full nonlinear simulation .

6.RESULTS AND DISCUSSIONS

Before the full test of the designed controller using the multi machine model, the controller has been examined using an equivalent power system model comprises the super conducting generator connected to a large power system via the equivalent transmission impedance obtained. This result is shown in Fig. 4. which illustrate that the controller introduce a positive damping to the system and reduces the rotor first swing which indicates an increase in system stability. The terminal voltage instability has been eliminated and there is no rxcessive valve movements. The controller is then tested using the full nonlinear multi machine simulation and the results are shown in Figs. 5-7. It may be stated that the machine-1 has been taken as a reference and therefore the oscillations of the other machines shown in Figs. 5-7 are obtained with respect to that unit. For purpose of comparison, the results are obtained under the following conditions :

(i) There is no controllers in the system
(ii) PSS on all units
(iii) As (ii) plus the improved controller on the super conducting unit

It may be emphasis that the controllers used in (ii) represent conventional Automatic Voltage Regulator and power system stabilizers on all conventional units plus speed governing system on the super conducting unit .The results illustrate system instability without controllers(condition i). The system performance is improved when the conventional generators equipped with their controllers . However, the most important feature may be observed when the new controller is introduced on the super conducting unit. The controller further improve damping, reduces rotor first swing of the superconductor generator as well as all other conventional units. This is due to the fact that the new controller on the SCG decouples and damped the undesirable modes of that unit.

7.CONCLUSIONS

The paper presented a technique for the design of controller for a super conducting generator operating in a multi machine environment. This is a multistage phase advance which improve phase margin and ensures satisfactory transient performance. The controller has been tested using a detailed nonlinear simulation and the results illustrate well damping of system oscillations and reduction of rotor first swing which indicates an increase in overall stability. The controller has the effects of improving the performance of both the super conducting and all other units in the system.

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L_1 = -0.8-J0.155
L_2 = -0.25-J0.155
L_3 = -0.5-J0.309
L_4 = -0.25-J0.155

Z = J0.12

Y = 0.0
Z_1= 0.09+J0.15
Y_1= -J0.07
Z_2= 0.2+J0.3
Y_2= -J0.098

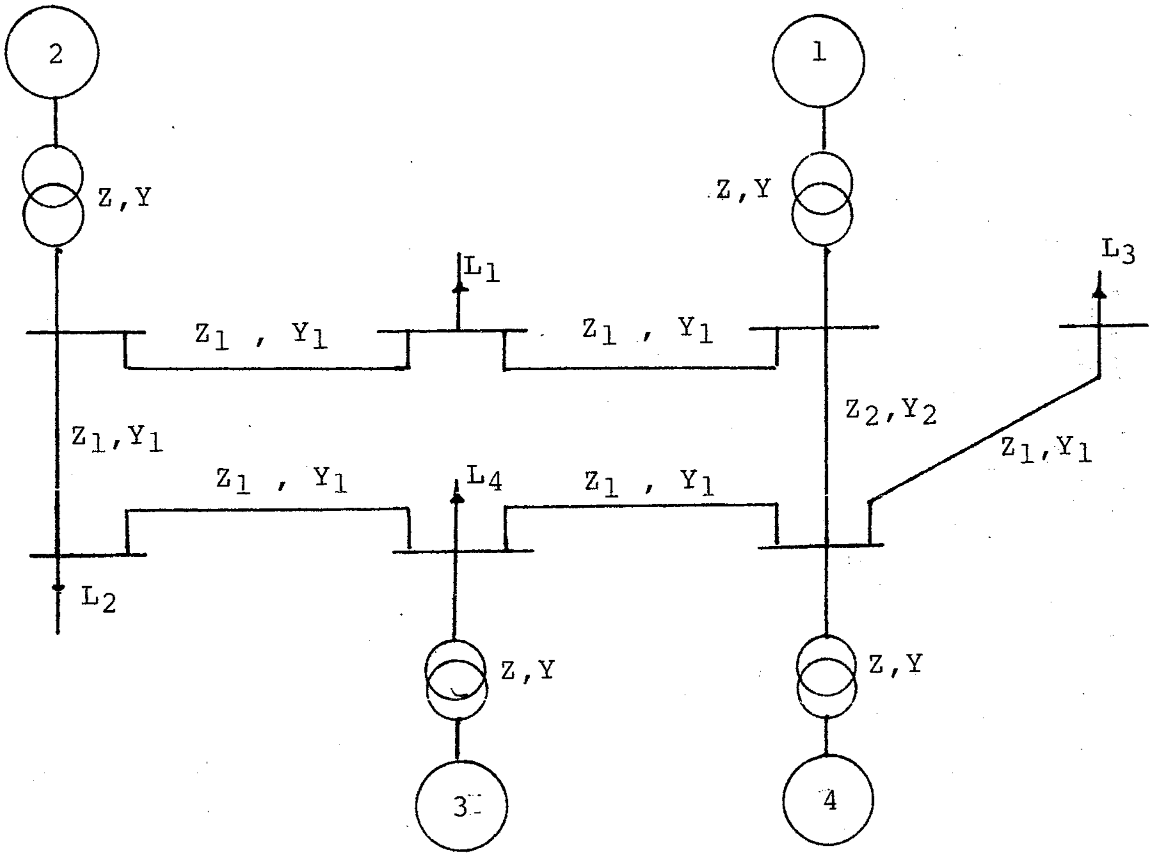

Fig. 1: System studied.

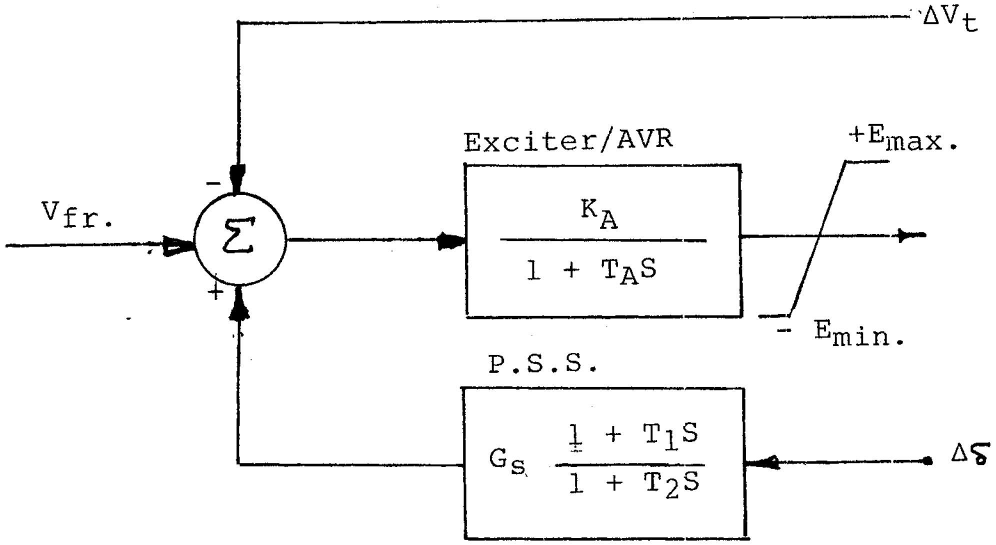

Fig. 2: Controllers of conventional generators.

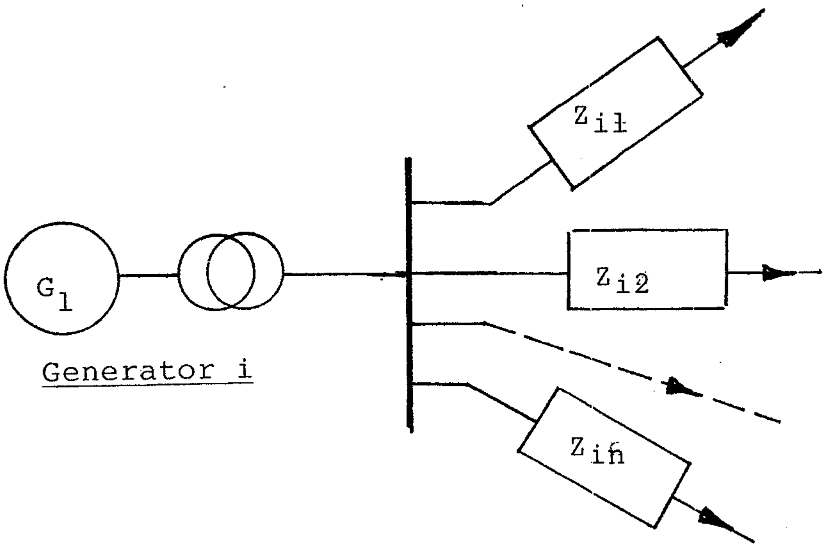

Fig. 3: Equivalent model for the ith generator.

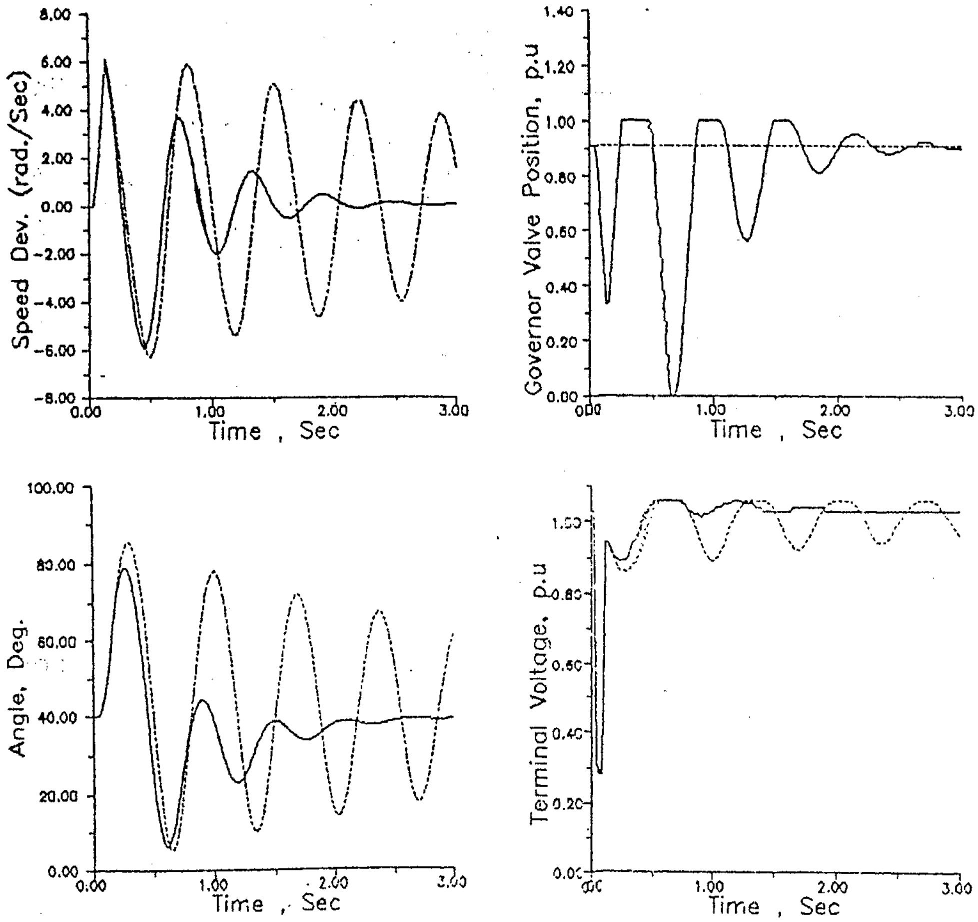

Fig.4 :Transient response of a superconducting unit connected to the large power system via the equivalent impedance, Eqn. 20.

-------- without controller.

———— with controller.

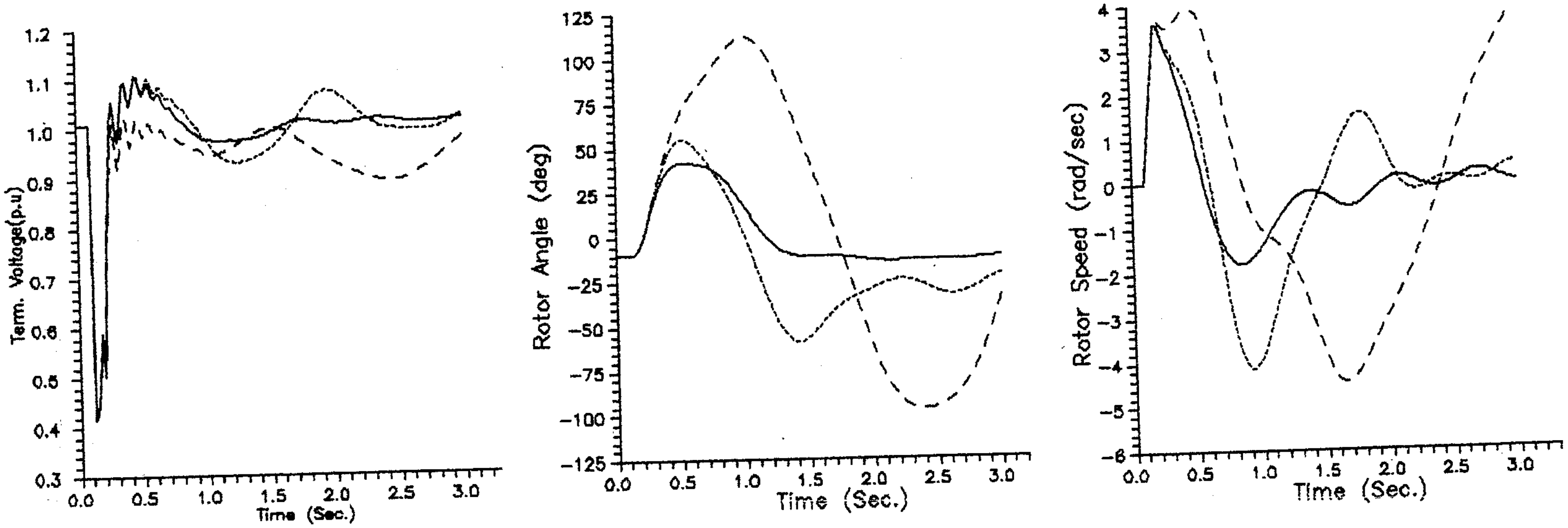

Fig. 5 Effects Of The Superconducting Units On Controller On The Time Response Of Machine 2.

------ Without Controllers.

...... With PSS On All Conventional Units.

——— With Controller On The Super conducting Unit.

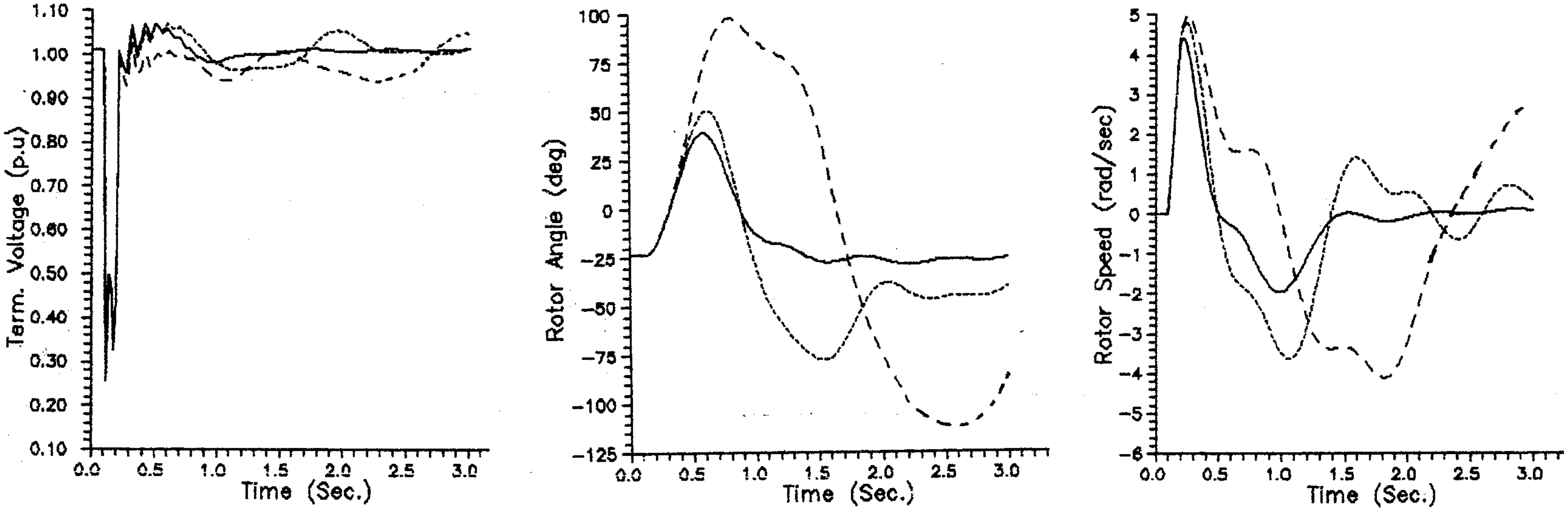

Fig. 6 Effects Of The Improved Controller On The Time Response Of The Superconducting Unit.

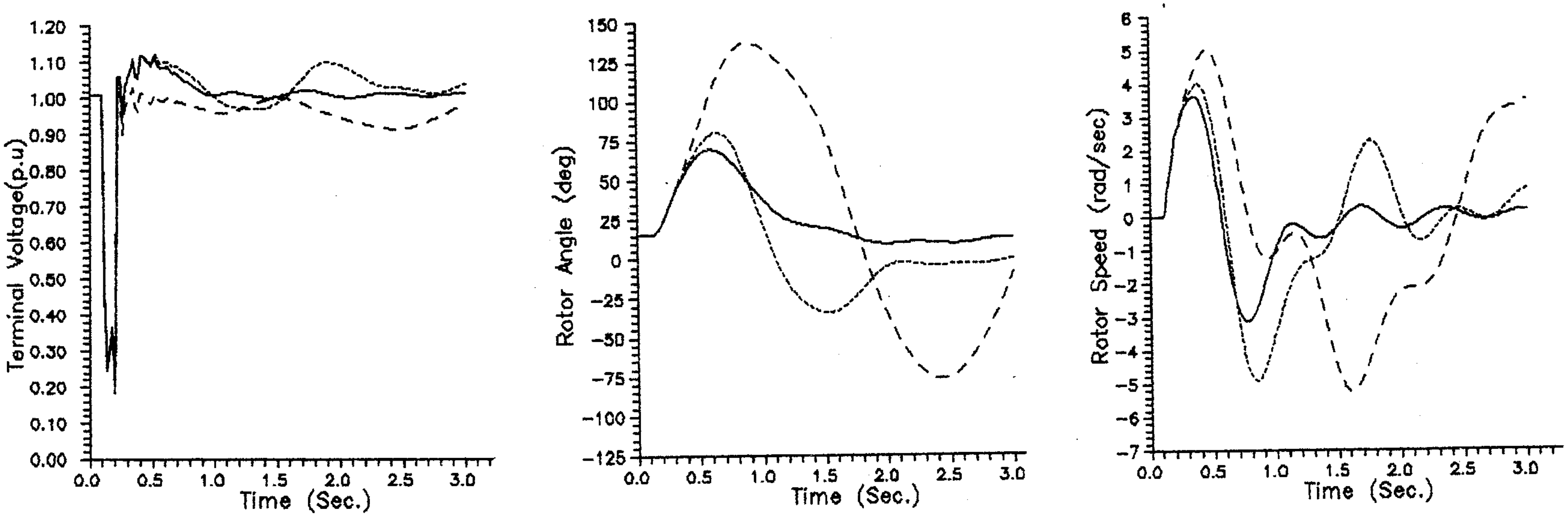

Fig. 7 Effects Of The Superconducting Unit Controller Of The Time Response Of The Hydroelectric Unit.

" التحكم فى ألة ذات توصيل فائق تعمل فى نظام متعدد الآلات "

نظرا للمتطلبات المستقبلية الكبيرة فى الطاقة الكهربية ونظرا لان الالات التقليدية لن تفى بالمطلوب فظهرت أهمية الآلات الكهربية ذات التوصيل الفائق لما لها من مميزات عديدة ليس فقط بالنسبة للحجم ولكن لأمكانية التوليد بجهد الشبكة مباشرة وتحسين الاتزان • ولكن من عيوب هذة الآله صعوبة التحكم فيها لان الثابت الزمنى لدائرة المجال كبير (حوالى ١٥ دقيقة) وبالتالى فأى أشارة تدخل فى هذا الاتجاة (دائرة المجال) لا يمكنها تحسين الأداء ولا توفر عزم الأخماد المطلوب ولذلك يصبح أتجاة التحكم فى هذة الآله وتحسين آدائها عن طريق التحكم فى منظم بخار التوربين •

يقدم هذا البحث كيفية التحكم فى آله ذات توصيل فائق عندما تدخل فى نظام متعدد الماكينات التقليدية حيث تم الحصول على نموذج مكافئ للآله عندما تعمل فى النظام المتعدد • وتم تصميم حاكم يعمل فى مدى كبير من القدرات وتم أختبار هذا الحاكم على الآله باستخدام تمثيل دقيق للمعادلات الغير خطية للنظام وعمل مقارنة شملت استخدام أنواع متعددة من الحاكمات وتم دراسة تأثير دخول الحاكم على الآله ذات التوصيل الفائق وكذلك تأثير نفس هذا الحاكم على الآلات التقليدية المجاورة •

وأكدت نتائج البحث الى ان الحاكم بالطريقة المقترحة يحسن من آداء الآله ذات التوصيل الفائق بالاضافة الى ان هذا الحاكم له تأثير فعال على تحسين آداء الآلات التقليدية المجاورة بالرغم من عدم تغيير الحاكمات عليها •