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STABILITY ENHANCEMENT OF A SUPERCONDUCTING GENERATOR USING AN OPTIMIZED SVC-BASED STABILIZER

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ABSTRACT

An important aspect in developing superconducting generator (SCG) concerns stability following a major system disturbance. This paper presents a method for enhancing stability of a SCG connected to an infinite-bus system using one of FACTS devices. In this method, a static VAR compensator (SVC)-based stabilizer is designed in coordination with a governor controller (GC) to effectively damp the mechanical oscillations which arise in the system when subjected to a disturbance. A time response-based objective function is defined and the design problem of SVC-based stabilizer and GC is formulated into an optimization problem. Particle swarm optimization (PSO) technique is employed to find out an optimal set of parameters for SVC-based stabilizer and GC. Simulation results, damping torque analysis, and small signal analysis show that the proposed PSO-based control scheme provides more damping to the SCG, and enhances its stability over a range of operating conditions.

يعتبر استقرار المولد فائق التوصيل أمرا ضروريا في تطوير هذه الآلة. يقدم هذا البحث طريقة لتحسين استقرار مولد فائق التوصيل متصل بنظام قوى لانهائي باستخدام أحد نظم نقل التيار المتردد المرنة. في هذه الدراسة يتم تصميم موازن مؤسس على معوض ساكن للقدرة غير الفعالة بالتنسيق مع ضابط الحاكم, وذلك لإخماد الذبذبات الميكانيكية التي تنشأ في النظام عندما يتعرض لظرف عارض بفعالية. تم تعريف دالة هدف مبنية على الأداء الزمني, ومن ثم تم صياغة مشكلة تصميم الموازن المقترح مع ضابط الحاكم في صورة مشكلة أمثلة. ولقد تم استخدام طريقة أمثلة حديثة (تحاكى أسلوب أسراب الطيور في الوصول إلى أهدافها) لتحديد أفضل مجموعة لقيم ثوابت الموازن والضابط . توضح نتائج المحاكاة وتحليل عزم التخميد والقيم المميزة أن الموازن المقترح و المصمم بالتنسيق مع ضابط الحاكم يؤدى إلى تحسن ملحوظ في أداء واستقرار النظام المدروس على مدى واسع من أحوال التشغيل.

Keywords: Superconducting generator, Transient stability, FACTS, Particle swarm optimization

1. Introduction

Superconducting generators have several potential advantages such as small size, light weight, high efficiency and increased steady state stability limit [1-2]. The advantages of SCG have drawn more interest in industrial countries since 1970's, such as in USA, UK and Japan where many R&D projects on SCGs have been conducted at utility companies, power plant manufacturers and other organization toward a 200 MW class pilot-machine [3-7]. However, superconducting generators also have characteristics that degrade their stability when connected to the power system. Moreover, the very long field winding time constant and the shielding effect of the two rotor screens make the achievement of acceptable dynamic performance very difficult using excitation control. Governor control hence becomes the only technique feasible for stability enhancement of the SCG. The availability of electro-hydraulic governors and fast operation of steam valves has now made it possible to obtain very fast turbine response. Research works reported in Ref. [8-9] have shown that SCG stability can be improved by introducing a phase advance network (conventional stabilizer) in the governor feedback loop, activated by the speed error signal. The conventional stabilizer parameters are fixed to ensure optimum performance at a specific operating point. However, because of the high nonlinearity of the machine/power system combination, the stabilizer's performance becomes lower when the system operating condition moves significantly away from the specific point. Therefore, the conventional stabilizer should have some degree of robustness to be able to stabilize the system over a wide range of operating conditions. Many attempts along with comprehensive analysis have been made to improve matters a) by retuning the conventional stabilizer, b) by utilizing adaptive control technique and c) by adopting a fuzzy logic stabilizer [10]. In all these attempts, stabilizers' parameters were selected using genetic algorithm (GA) technique.

Recently, the flexible AC transmission systems (FACTS) have been introduced, in which various power electronics-based controllers are used to maximize the utilization of transmission assets efficiently and reliably [11-12]. In addition, FACTS devices regulate power flow and, through rapid control actions, can mitigate low frequency oscillations and enhance power system stability [13-14]. A literature survey on the work done on the application of FACTS devices along with the excitation control to enhance damping of conventional generator oscillations is given in the introduction of Ref. [14].

Early investigation on the dynamic performance of a SCG when equipped with a static VAR compensator at its terminal was reported in Ref. [15]. In that study, the stabilizing signal was not optimized. Moreover, the governor role in damping the machine oscillation was not considered. However, no or little efforts have been made towards stability enhancement of SCG using coordinated governor controller and FACTS device-based stabilizer. In this paper, enhancement of SCG stability using coordinated design of a static VAR compensator (SVC)-based stabilizer and a governor controller (GC) is studied. The optimal parameters of SVC-based stabilizer and GC are sought by utilizing the PSO technique [16]. Non-linear simulation and small signal analysis are carried out to investigate the effectiveness of the proposed scheme.

2. System Description

The system considered in this study is a SCG connected to an infinite bus power system as shown in Fig. 1. The SCG has superconducting field windings in the rotor, surrounded by two separate screens. The inner screen, which has a relatively long time constant, shields the superconducting field windings from external, time varying magnetic fields. The outer screen serves as a damper and has a substantially shorter time constant than that of the inner screen [17]. The SCG is driven by a three-stage steam turbine with reheat between the high pressure and intermediate pressure stages. The turbine is controlled by fast acting electro-hydraulic governors fitted to the main and interceptor valves, which are working in unison. The system is equipped with a governor controller and a SVC at the terminal of the SCG. The exciter voltage, U_e , of the SCG is kept constant during transients.

3. Mathematical Model

The mathematical models for SCG, turbine and governor are shown below, while the parameter values and physical constraints are given in Appendix A.

3.1. Superconducting generator model

Based on Park's *d*-*q* axis representation, seven non-linear differential equations are used to represent the mathematical model of the SCG's electric circuits. These equations along with the mechanical equations of motion give the flux linkage model of the SCG [9] as follows:

$$p\psi_d = \omega_o[V_d + i_d R_a + \psi_q] + \psi_q \omega \quad (1)$$

$$p\psi_q = \omega_o[V_q + i_q R_a - \psi_d] - \psi_d \omega \quad (2)$$

$$p\psi_{D1} = -\omega_o i_{D1} R_{D1} \quad (3)$$

$$p\psi_{Q1} = -\omega_o i_{Q1} R_{Q1} \quad (4)$$

$$p\psi_{D2} = -\omega_o i_{D2} R_{D2} \quad (5)$$

$$p\psi_{Q2} = -\omega_o i_{Q2} R_{Q2} \quad (6)$$

$$p\psi_f = \omega_o[V_f - i_f R_f] \quad (7)$$

$$p\delta = \omega \quad (8)$$

$$p\omega = \frac{\omega_o}{2H}[T_m - T_e] \quad (9)$$

$$T_e = \psi_d i_q - \psi_q i_d \quad (10)$$

where:

P : derivative operator

ψ : flux linkage

ω_o : synchronous speed (rad/s)

ω : rotor speed deviation from ω_o

δ : rotor angle with respect to infinite bus

H : inertia constant

T_m : mechanical torque

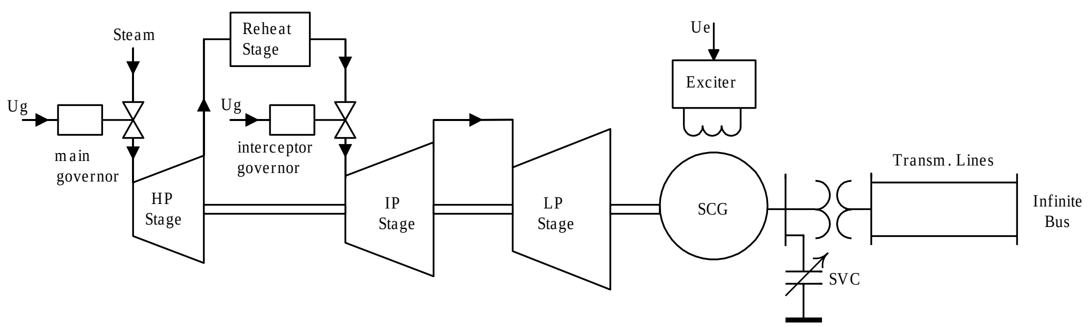

Fig.1 SCG system under study with SVC

3.2. Turbine and governor model

The mathematical model of the turbine and governor system is represented by six non-linear differential equations [18] as follows:

$$pY_{HP} = (G_M P_o - Y_{HP})/\tau_{HP} \quad (11)$$

$$pY_{RH} = (Y_{HP} - Y_{RH})/\tau_{RH} \quad (12)$$

$$pY_{IP} = (G_I Y_{RH} - Y_{IP})/\tau_{IP} \quad (13)$$

$$pY_{LP} = (Y_{IP} - Y_{LP})/\tau_{LP} \quad (14)$$

$$pG_M = (U_g - G_M)/\tau_{GM} \quad (15)$$

$$pG_I = (U_g - G_I)/\tau_{GI} \quad (16)$$

The output mechanical torque is given as:

$$T_m = F_{HP}Y_{HP} + F_{IP}Y_{IP} + F_{LP}Y_{LP} \quad (17)$$

where:

P_o : boiler steam pressure

Y : output of a turbine or reheat stage

τ : time constant of stage

G_M, G_I : main and interceptor valve positions

F_{HP}, F_{IP}, F_{LP}: fractional contributions of turbine stages into T_m

U_g : governor actuating signal

The main and interceptor valves are conventionally actuated by a normalized speed error signal incorporating a droop, typically 4%. Constraints are imposed on valve positions and rates of movement. The rate constraint is based on complete opening or closing time for the valves of 150 ms. The rate limits correspond to the fastest valve operation reportedly available in literature [18].

4. The Proposed Approach

4.1. Control objective

The control objective is to generate two stabilizing signals using the speed error signal. The first control signal is produced via a conventional controller and then introduced into the governor loop of the SCG system as shown in Fig. 2. The control signal, u, generated by the conventional controller is given as:

$$u = G_s \cdot \frac{(1+T_1 s)}{(1+T_2 s)} . \omega \quad (18)$$

where ω is the speed error signal, G_s , T_1 and T_2 are the controller parameters, which have to be designed properly to achieve a satisfactory performance.

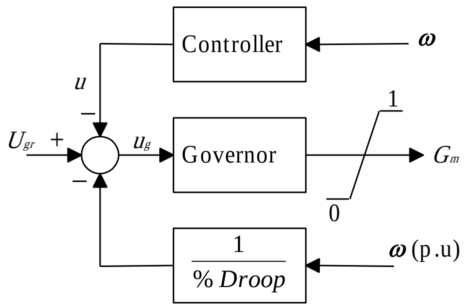

Fig.2 The governor control system

The second signal is produced via a SVC-based conventional lead stabilizer. The two stabilizing signals are coordinated to enhance the damping of the rotor oscillations after disturbances, and hence to improve the transient and dynamic performance of the system.

4.2. SVC-based stabilizer

The block diagram of an SVC with a conventional lead stabilizer is shown in Fig. 3. Functionality, the SVC is thought of as an adjustable shunt susceptance that can be varied with sufficient rapidity. Elaborated model for SVC can be seen in Ref. [19]. However, the susceptance, B, of the SVC can simply be expressed as:

$$pB = (K_{svc}(B_{ref} + u_{SVC}) - B)/T_{svc} \quad (19)$$

where K_{svc} and T_{svc} are the gain and time constant of the SVC. B_{ref} is the reference susceptance of the SVC and u_{SVC} is the stabilizing signal generated by the conventional stabilizer installed in the feedback loop of the SVC as shown in Fig. 3.

$$u_{SVC} = K_v \cdot \frac{(1+T_3 s)}{(1+T_4 s)} . \omega \quad (20)$$

where K_v , T_3 and T_4 are the SVC-based stabilizer parameters, which need a careful selection to enhance the system stability. Both of u and u_{SVC} has upper and lower limits, i.e.

$$u_{min} \le (u, u_{SVC}) \le u_{max} \quad (21)$$

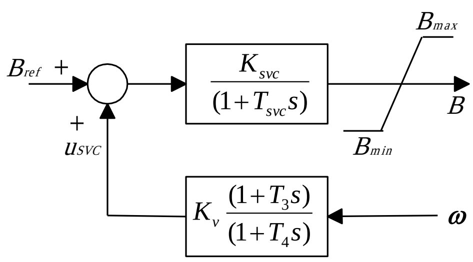

Fig.3 SVC with lead stabilizer

5. Stabilizer Parameters Selection Using PSO

Recently, a heuristic search method called *particle swarm optimization* (PSO) has been introduced [20]. PSO is characterized as a simple concept, easy to implement, and computationally efficient. Theses features make PSO technique able to accomplish the same goal as GA optimization in a new and faster way. A number of very recent successful applications of PSO on various power system problems have been reported in literature [16].

The tuning parameters in the proposed approach are G_s , T_1 and T_2 for GC, and K_v , T_3 and T_4 for SVC-based stabilizer. Usually, T_2 and T_4 are prespecified leaving the other four parameters, G_s , T_1 , K_v and T_3 to be tuned [14, 21]. Here, the degree of freedom in the design problem is increased by letting T_2 and T_4 be freely selected as well as the other four tuning parameters. This addition is intended to enhance the effectiveness of the proposed stabilizer. Therefore, we have now six parameters to be optimally chosen. This task is achieved using the PSO technique. To do so, the following quadratic performance index, J, is first defined.

$$J = \sum_{k=1}^{N} \{[kT_s.\omega(k)]^2 + [\Delta\delta(k)]^2 + [\Delta G_M]^2\} \quad (22)$$

where $\Delta\delta(k)=(\delta(k)-\delta_o)$ denotes the deviations (in radians) of the instantaneous rotor angle from its steady state value, δ_o, and $\Delta G_M(k)=(G_M(k)-G_{Mo})$ is the deviation of the instantaneous governor valve position $G_M(k)$ from its value in the steady state, G_{Mo}. This choice of performance index seeks to minimize the mechanical-mode oscillations of the SCG system with minimum governor valve movements. As is seen, the speed deviation, $\omega(k)$, is weighted by the elapsed time kT. Thus, a low value of J corresponds to a small settling time, a small steady state error, and small overshoots in rotor speed, rotor angle and valve position. The performance index is minimized subject to the following constraints:

$$G_{S,\min} \le G_S \le G_{S,\max} \quad (23)$$

$$T_{1,\min} \le T_1 \le T_{1,\max} \quad (24)$$

$$T_{2,\min} \le T_2 \le T_{2,\max} \quad (25)$$

$$K_{v,\min} \le K_v \le K_{v,\max} \quad (26)$$

$$T_{3,\min} \le T_3 \le T_{3,\max} \quad (27)$$

$$T_{4,\min} \le T_4 \le T_{4,\max} \quad (28)$$

The PSO algorithm iteratively updates the velocity of each particle using its current velocity and its distance from "global best position" (g_{best}) and "personal best position" (p_{best}) according to the following equation:

$$v_i^k = w^k v_i^{k-1} + c_1 r_1 (p_{best,i} - x_i^{k-1}) + c_2 r_2 (g_{best,i} - x_i^{k-1}) \quad (29)$$

where:

$i = 1, 2, 3, \dots, m$

v_i^k is the velocity of particle i at iteration k

x_i^k is the position of particle i at iteration k

r_1, r_2 are uniformly distributed random numbers in the range [0-1]

c_1, c_2 are positive constants

w^k is the inertia weight at iteration k, decreasing as $w^k = \alpha\, w^k$.

m is the number of particles in a swarm, and α is a decrement constant.

PSO itself has a number of parameters to be properly specified. The main PSO parameters are the initial inertia weight, w^0, and the maximum allowable velocity, V_{max}. w^0 is set at 1, and V_{max} at 12.5% of the search space for each tuning parameters. The swarm size is chosen to be 60 particles. Other parameters are set as decrement constant α=0.98, and $c_1 = c_2$ =2.

6. Simulation Results

The author examined a number of alternatives in developing the proposed scheme. The performance index was evaluated, in all cases, in response to a three-phase to ground fault of 120-ms duration with the operating point (P_t=0.8 p.u, Q_t=0.6 p.u). The first attempt was the individual design for the SVC-based stabilizer; considering no governor controller, i.e. u=0. Then, the optimal set of (K_v , T_3, T_4) for SVC-based stabilizer was searched for; considering governor controller with G_s=0.1 T_1,=0.5s and T_2=0.01s [8, 22]. Finally, coordinated design for best combination of (G_s , T_1, T_2) for GC, and (K_v , T_3, T_4) for SVC-based stabilizer was sought.

Variation of the performance index J with the number of iterations at different seed values is shown in Fig. 4. The optimal coordinated values selected by PSO for (G_s , T_1, T_2) and (K_v , T_3, T_4) are (0.065, 1, 0.01) and (1.142, 0.183, 0.063) respectively.

Performance of the SCG system with the proposed control scheme following a 3-phase short circuit fault, at [(P_t, Q_t) = (0.8, 0.6), (0.9, 0), (0.7, -0.2) p.u] is shown in Figs. 5 to 7. Figures 8, 9 and 10 show the system response to a temporary (100-ms long) 10% step increase in the governor set point at the previous loading conditions.

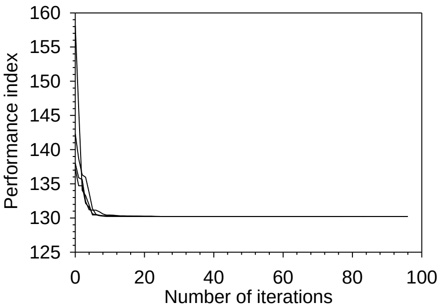

Fig. 4 Convergence of performance index with iterations at different seed values

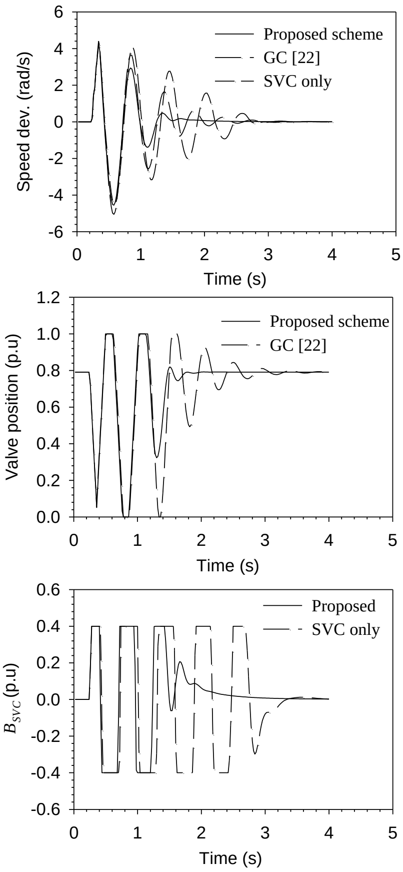

Fig. 5 Response to a 3-phase SC at P_t=0.8 pu , Q_t=0.6 pu

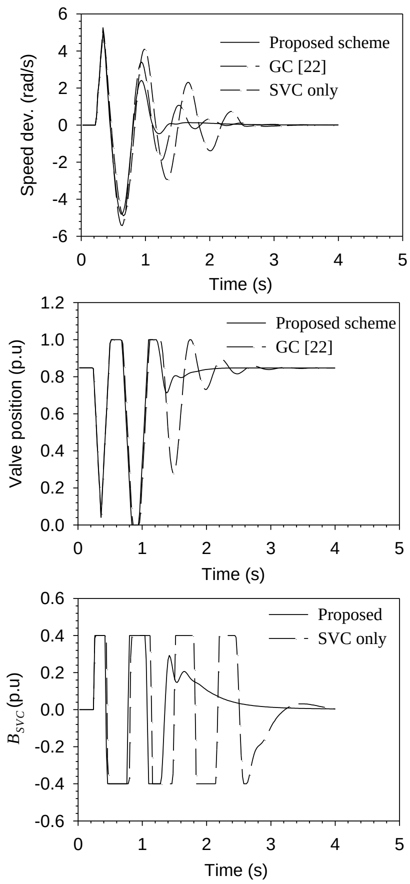

Fig. 6 Response to a 3-phase SC at P_t=0.9 pu , Q_t=0 pu

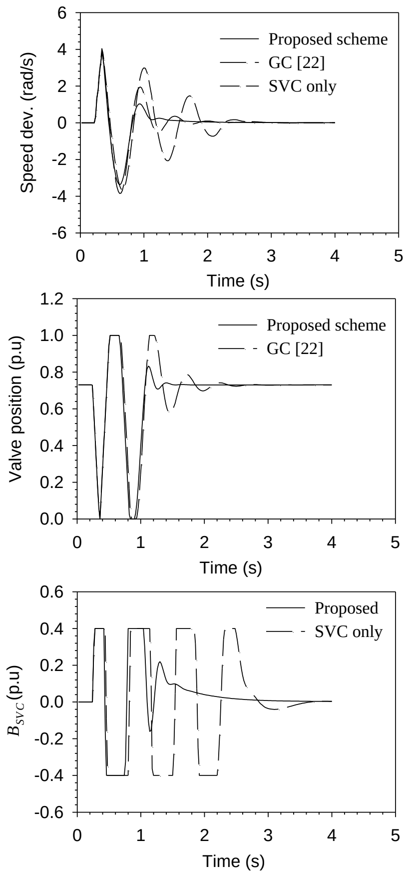

Fig. 7 Response to a 3-phase SC at P_t=0.7 pu , Q_t=-0.2 pu

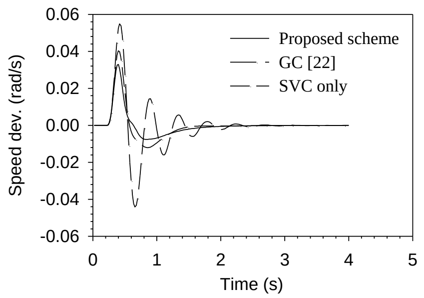

Fig.8 Response to a 10% pulse in U_{gr} at P_t=0.8 pu , Q_t=0.6 pu

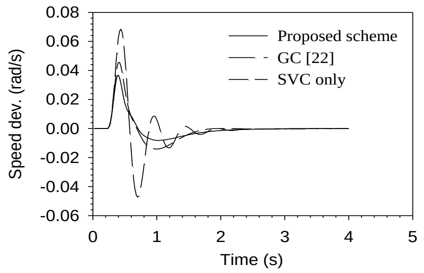

Fig.9 Response to a 10% pulse in U_{gr} at P_t=0.9 pu , Q_t=0 pu

The results show that the proposed control scheme results in a significant improvement in the SCG transient performance and a considerable reduction in the rotor oscillations with acceptable valve movements.

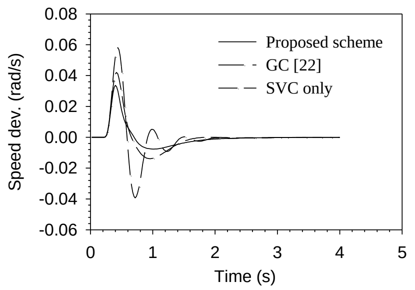

Fig.10 Response to a 10% pulse in U_{gr} at P_t=0.7 pu , Q_t=-0.2 pu

7. Damping and Synchronizing Torques Analysis

The object of this section is to investigate the effects of the proposed control scheme and other schemes on the SCG dynamic performance using the concept of damping and synchronizing torques, which was initially introduced by Demello and Concordia [23]. This concept indicates that, at any given frequency of rotor oscillations, there exists oscillatory electrical torque acting on the rotor which has the same frequency and whose amplitude is proportional to the amplitude of the oscillations. The change in this torque ΔT_e can be divided into two components: one is in time phase with, and proportional to the rotor angle deviation $\Delta\delta$. This is called the "synchronizing torque". The other, which is in time phase with and proportional to the rotor speed deviation ω is called the "damping torque". Therefore, the change in electrical torque can be written as follows:

$$\Delta T_e = K_s \Delta\delta + K_d \omega \quad (30)$$

where K_s and K_d are the synchronizing and damping coefficients respectively. It is now well recognized that machine stability is highly degraded if there is lack of either or both of synchronizing and damping torques. The values of K_s and K_d are determined from the time responses of electrical torque, rotor angle and rotor speed, using the technique explained in Ref. [24-25]. In that technique, the error between the actual torque deviation and that obtained by summing the damping and synchronizing torque components is defined as:

$$E(t) = \Delta T_e(t) - [K_s \Delta\delta(t) + K_d \omega(t)] \quad (31)$$

The error squares can be summed over the simulation time period. Minimizing this summation with respect to K_s and K_d yields the following dependent algebraic equations:

$$\sum_n \Delta T_e \Delta\delta = K_s \sum_n (\Delta\delta)^2 + K_d \sum_n \omega\Delta\delta \quad (32)$$

$$\sum_n \Delta T_e \omega = K_d \sum_n \omega^2 + K_s \sum_n \omega\Delta\delta \quad (33)$$

Solving the equations (32) and (33) gives the values of K_s and K_d, where n is the discrete-simulation time.

A summarized comparison of the proposed scheme and other schemes (viz. SVC with GC [22], and GC [22] only) is shown in Table 1.

<u>Table 1:</u> Comparison of the proposed scheme and other schemes

(P_t, Q_t) p.u	**(0.8, 0.6)**			**(0.7, -0.2)**	
	J	***K_d***	***k_s***	***K_d***	***k_s***
Coordinated SVC with GC	**130.2**	**0.231**	**1.941**	**0.212**	**1.184**
SVC with GC [22]	**138.4**	**0.166**	**1.836**	**0.142**	**1.11**
GC [22] only	**261.7**	**0.014**	**2.011**	**0.016**	**1.251**

From this table, it can be concluded that the proposed scheme outperforms the other considered schemes at all operating points studied. It provides the SCG system with the highest possible degree of damping while keeping the synchronizing torque at a high level.

8. Small Signal Analysis

In this section, the dynamic behaviour of the SCG system with the proposed control scheme is investigated using the eigenvalues technique to get another quantitative assessment of the damping provided by the SVC-based stabilizer with the GC. The non-linear system equations are linearized about a quiescent operating point. The linearized model's equations can be expressed in the state-space form as follows:

$$[dx/dt] = [A][x] + [B][u] \qquad (34)$$

where [x] is the state vector defined as:

$$[x] = [\Delta\delta, \Delta\omega, \Delta\psi_f, \Delta\psi_d, \Delta\psi_{D1}, \Delta\psi_{D2}, \Delta\psi_q, \Delta\psi_{Q1}, \Delta\psi_{Q2}, \Delta Y_{HP}, \Delta Y_{RH}, \Delta Y_{IP}, \Delta Y_{LP}, \Delta G_M, \Delta B]^T$$

The dynamic response of the SCG system can be determined from the eigenvalues of the matrix [A]. The eigenvalues related to the rotor mode of oscillation at two operating points are given in Table 2. The results show clearly that the rotor oscillation without any stabilizer is slightly damped, its damping ratio, ξ , being only 0.011 at the first operating point. It is also shown that this mechanical oscillation becomes well damped when the GC is included. The damping ratio in case of the proposed scheme is about 2.3 times that with the GC alone. This confirms that the coordinated SVC-based stabilizer and GC provide more damping to the SCG rotor oscillations.

Table 2: Eigenvalues related to rotor mode of oscillation

(P_t, Q_t)	**(0.8, 0.6) p.u**		**(0.7, -0.2) p.u**
	Eigenvalues	ξ	Eigenvalues
Proposed SVC with GC	-11.88±j24.3	0.439	-12.8±j23.16
SVC with GC [22]	-10.97±j21.46	0.455	-11.94±j20.35
GC [22] only	-2.676±j13.74	0.191	-3.526± j11.81
Without stabilizers	-0.118±j11.02	0.011	-0.216± j9.045

9. Conclusion

This study described the utilization of one of FACTS devices for stability enhancement of superconducting generators. An approach was proposed for the design of a static VAR compensator-based stabilizer in coordination with a governor controller to provide more damping to mechanical oscillations of the SCG studied. A performance index was defined and the PSO technique was used to select the optimal parameters of both SVC-based stabilizer and GC. Simulation results show the effectiveness of the proposed control scheme in damping the rotor oscillations, and enhancing the SCG stability over a range of operating conditions and various disturbances. Analysis of damping and synchronizing torques, and small signal analysis were used to provide other quantitative assessments of the SCG performance with the designed SVC-based stabilizer and GC. Results of these analyses verify the effectiveness of the proposed approach with the SCG system studied.

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11. Appendix A

The parameters of the SCG system used in this study (inductance and resistance values in p.u; time constants in seconds) are [8, 9]:

Superconducting generator parameters:

L_f=0.541, L_d=L_q=0.5435, L_{D1}=L_{Q1}=0.2567, L_{D2}=L_{Q2}=0.4225

L_{fd}=L_{fD1}=L_{dD1}=L_{dD2}=L_{D1D2}=0.237

L_{fD2}=0.3898, L_{qQ1}=L_{qQ2}=L_{Q1Q2}=0.237

τ_f=750, R_d=R_q=0.003

R_{D1}=R_{Q1}=0.01008, R_{D2}=R_{Q2}=0.00134

H=3 kW.s/kVA

Transformer and transmission line parameters:

X_T=0.15, R_T=0.003, X_L=0.05, R_L=0.005

Turbine and governor parameters:

τ_{GM}=τ_{GI}=0.1, τ_{HP}=0.1, τ_{RH}=10,

τ_{IP}=τ_{LP}=0.3, P_o = 1.2 p.u.

F_{HP} = 0.26, F_{IP} = 0.42, F_{LP} = 0.32

Valve position and movement constraints are defined by:

$0 \le (G_M, G_I) \le 1$ and $-6.7 \le (pG_M, pG_I) \le 6.7$