

STABILITY IMPROVEMENT OF SUPERCONDUCTING GENERATORS USING ARTIFICIAL INTELLIGENCE-BASED STATIC VAR COMPENSATOR

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ABSTRACT

In this paper, superconducting generator (SCG) stability enhancement via coordinated design of a governor controller (GC) and a static VAR compensator (SVC)-based fuzzy logic stabilizer is investigated. The GC is a conventional lead stabilizer activated by the speed error signal, while the signal produced by the SVC-based stabilizer is based on the SCG speed deviation and acceleration, and on two fuzzy membership functions reflecting few simple control rules. An objective function is defined and the design problem of efficient GC and SVC-based fuzzy stabilizer is formulated as an optimization problem. Particle swarm optimization (PSO) technique is employed to search for optimal parameters of GC and SVC-based stabilizer. Simulation results show that the proposed PSO-tuned control scheme provides good damping to the SCG, and enhances its stability over a range of operating conditions.

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Keywords: Superconducting generator, Transient stability, FACTS, Fuzzy logic control, 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]. Despite these advantages, SCG field winding has an extremely large time constant. The excitation system is therefore not able to change quickly the field current to meet the grid requirements under transient

conditions. SCG is also characterized by low inertia and low inherent damping, each of which adversely affects the machine stability when connected to a power system. Inevitably, governor control becomes the feasible technique to enhance stability of superconducting generators. 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 in the governor feedback loop, activated by the speed error signal.

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 [10-11]. In addition, FACTS devices regulate power flow and, through rapid control actions, can mitigate low frequency oscillations and enhance power system stability [12-13].

On the other hand, fuzzy logic stabilizers have appeared as a viable alternative to the conventional stabilizers for enhancing power system stability [14-15]. Control scheme based on fuzzy logic is important to consider in view of its potentially lower computational burden and flexible reconstruction. The application of fuzzy control techniques appears to be particularly useful whenever the system to be controlled is complex and has uncertainty and imprecision. These properties certainly apply to power systems incorporating superconducting generators.

Early investigation on the dynamic performance of a SCG when equipped with a static VAR compensator at its terminal was reported in Ref. [16]. In that study, the stabilizing signal was not optimized. Moreover, the governor role in damping the machine oscillation was not considered. However, some efforts have been made towards stability enhancement of SCG using coordinated governor controller and FACTS device-based conventional stabilizer [17]. 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, there should be a degree of robustness in the conventional stabilizer to be able to stabilize the system over a wide range of operating conditions.

In this paper, enhancement of SCG stability using coordinated design of a static VAR compensator (SVC)-based fuzzy stabilizer and a governor controller (GC) is studied. The coordinated optimal parameters of SVC-based fuzzy stabilizer and GC are sought by utilizing the PSO technique [18]. Incorporation of PSO into stabilizer design adds an intelligent dimension to the stabilizer, and reduces the time consumed in the design process. Various non-linear simulation studies 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 [19]. 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 the Appendix.

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

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

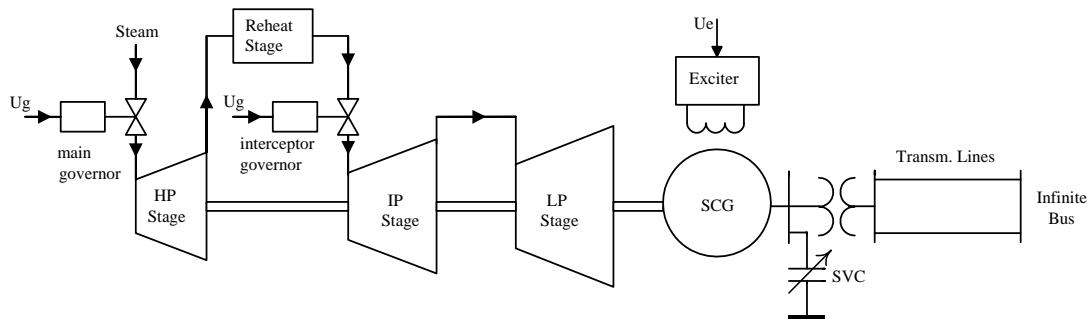


Fig. 1 SCG interconnected to an infinite bus

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 [20].

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:

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

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.

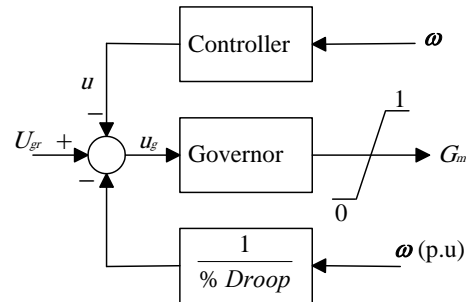


Fig.2 The governor control system

The second signal is produced via a SVC-based fuzzy 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 fuzzy stabilizer

The block diagram of an SVC with a fuzzy stabilizer is shown in Fig. 3. Functionally, 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. [21]. 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 fuzzy stabilizer installed in the feedback loop of the SVC shown in Fig. 3.

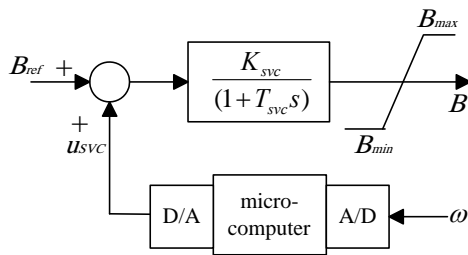


Fig.3 SVC with digital (fuzzy) stabilizer

The signal u_{SVC} is synthesized using fuzzy logic as follows. Fuzzy logic is the logic underlying modes of reasoning which are approximate rather than exact. Thus it is closer to human reasoning and real world than formal logic.

The SCG condition is defined at every sampling time, kT_s , in terms of its speed deviation and scaled acceleration, $[\omega(k), F * d\omega(k)/dt]$, where $d\omega(k)/dt = [\omega(k) - \omega(k-1)]/T_s$, T_s is the sampling interval and F is a predefined scaling factor. This condition represents a certain point, Z , in the $[\omega(k), F * d\omega(k)/dt]$ phase plane as shown in Fig. 4. The polar displacement $D(k)$ of this point from the origin, and the corresponding angle $\theta(k)$ are computed as:

$$D(k) = [(\omega(k))^2 + (F * \dot{\omega}(k))^2]^{0.5} \quad (20)$$

$$\theta(k) = \tan^{-1}(F * \dot{\omega}(k) / \omega(k)) \quad (21)$$

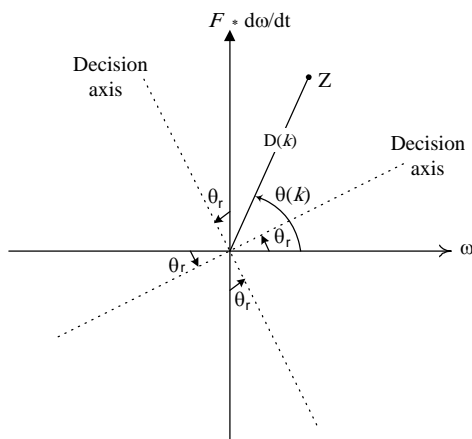


Fig.4 Definition of SCG condition in the phase plane

The phase plane is divided into four quadrants. Each quadrant has simple control rules according to the degree of deceleration and/or acceleration control required to restore the machine condition, after the disturbance, to the origin of the phase plane as soon as possible with an acceptable performance.

Generally, deceleration control and hence a positive control signal, is only required when the SCG status locates in a certain quadrant (say the first quadrant). Acceleration control and hence a negative control signal is required only when the SCG status lies in the opposite quadrant (i.e. the third quadrant). Decreasing (or increasing) deceleration and increasing (or decreasing) acceleration as well are required when the SCG status lies in the other two (i.e. the second and the fourth) quadrants. Two fuzzy membership functions, $N(\theta)$, shown in Fig. 5, associated with the desired deceleration, and $P(\theta)$ associated with the desired acceleration, are defined in terms of the polar angle, θ , defined by equation (21) to reflect the actions of the control rules. The defining relations for $N(\theta)$ and $P(\theta)$ are:

$$N(\theta) = \begin{cases} 1 & \text{for } \theta \leq \theta_1 \\ (\theta_1 - \theta) / (\theta_1 - \theta_i) & \text{for } \theta_i < \theta \leq \theta_1 \\ 0 & \text{for } \theta_1 < \theta \leq \theta_2 \\ (\theta - \theta_2) / (\theta_f - \theta_2) & \text{for } \theta_2 < \theta \leq \theta_f \end{cases} \quad (22)$$

$$P(\theta) = 1 - N(\theta) \quad \text{for all } \theta \quad (23)$$

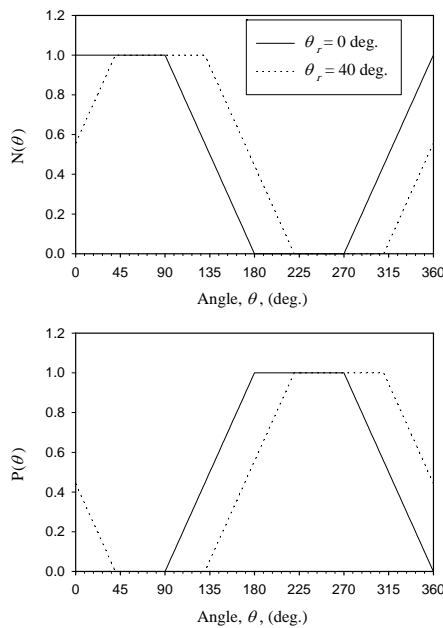


Fig.5 Proposed fuzzy membership functions

The angles θ_i , θ_1 , θ_2 , and θ_f are normally fixed at 90, 180, 270 and 360 degrees respectively with excitation control of conventional generators [22]. The fuzzy membership functions described by equations (22) and (23) can be portrayed in terms of a pair of what can be termed "decision axes", shown in Fig. 4, on the phase plane. It was found by the present investigator that, for best results, the angles θ_i , θ_1 , θ_2 , and θ_f should again progress in 90 degree

steps, but that an offset angle θ_r between the phase plane axis set (i.e. the $\omega(k)$ and $F^*d\omega(k)/dt$ axes) and the decision axis set (i.e. quadrant boundaries) should be introduced as shown in Fig. 4. This offset angle θ_r , which can be regarded as a new tuning parameter, is hence introduced when designing the fuzzy logic-based stabilizer. It specifies the best location for each quadrant with its particular control rules on the phase plane. In effect, the offset angle θ_r rotates the decision axis set anti-clockwise until the minimum of a predefined performance index is obtained.

This has the effect in turn of changing the final shapes of fuzzy membership functions over the whole universe of discourse, i.e. another set of control rules is generated according to the degree of rotation θ_r . The resulting two membership functions then lead to a governor control signal, $u_{SVC}(k)$, given by:

$$u_{SVC}(k) = G(k) [N(\theta(k)) - P(\theta(k))]u_{max} \quad (24)$$

where $G(k)$ is the gain whose value is defined as:

$$G(k) = D(k)/D_r \quad \text{for } D(k) < D_r \quad (25)$$

$$G(k) = 1 \quad \text{for } D(k) \geq D_r \quad (26)$$

The parameter D_r is a set value of polar displacement at which the gain is required to saturate at unity. However, the implementation of the above SVC-based fuzzy stabilizer requires the following steps in each sampling time:

Step1: SCG speed deviation, $\omega(k)$, is sampled and the scaled acceleration, $F^*d\omega(k)/dt$, is computed.

Step2: $D(k)$ and $\theta(k)$ are determined using equations (20, 21).

Step3: Values of both fuzzy membership functions, $N(\theta)$ and $P(\theta)$, are calculated.

Step4: The control signal $u_{SVC}(k)$ is determined using equation (24).

Both of u and u_{SVC} has upper and lower limits, i.e.

$$u_{min} \leq (u, u_{SVC}) \leq u_{max} \quad (27)$$

5. Stabilizer Parameters Selection Using PSO

Recently, a heuristic search method called *particle swarm optimization* (PSO) has been introduced [23]. PSO is characterized as a simple concept, easy to implement, and computationally efficient. These 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 [18].

The tuning parameters of the proposed coordinated control scheme are F , D_r and θ_r for the SVC-based fuzzy stabilizer and G_s , T_1 and T_2 for the governor controller (GC). u_{max} (the maximum size of the

control signal) is a pre-specified, constant parameter. For optimal settings of the tuning parameters, the quadratic performance index, J , defined by equation (28) is also used. For convenience, it is recalled here:

$$J = \sum_{k=1}^N \{ [kT \cdot \omega(k)]^2 + [\Delta\delta(k)]^2 + [\Delta G_M]^2 \} \quad (28)$$

Where $\Delta\delta(k)$ and $\Delta G_M(k)$ are the deviations of the rotor angle and the governor valve position respectively from their steady state values. In addition, N denotes the total number of time steps. This index is chosen because a low value of it reflects small settling time, small steady state error, and small overshoots in each of rotor speed, rotor angle, and valve position. The tuning parameters are selected to minimize this performance index subject to the following constraints:

$$F_{min} \leq F \leq F_{max} \quad (29)$$

$$D_{r,min} \leq D_r \leq D_{r,max} \quad (30)$$

$$\theta_{r,min} \leq \theta_r \leq \theta_{r,max} \quad (31)$$

$$G_{s,min} \leq G_s \leq G_{s,max} \quad (32)$$

$$T_{1,min} \leq T_1 \leq T_{1,max} \quad (33)$$

$$T_{2,min} \leq T_2 \leq T_{2,max} \quad (34)$$

The digital simulation for the SCG system is used in conjunction with the PSO process, which is then used to search for the optimal set of the tuning parameters, which minimizes the performance index chosen. 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} . These parameters and other PSO parameters are set as in [17].

6. Simulation Results

A number of simulation studies has been performed to investigate the effectiveness of the proposed SVC-based fuzzy stabilizer in improving stability of the SCG under study. 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 ($P_r=0.8$ p.u., $Q_r=0.6$ p.u). Variation of the performance index J with the number of iterations is shown in Fig. 6 in two cases. In the first case, the optimal set of (F, D_r, θ_r) for the SVC-based fuzzy stabilizer was searched for; considering governor controller (GC) with $G_s=0.1$, $T_1=0.5$ s and $T_2=0.01$ s [24]. In the second case, coordinated design for best combination of (F, D_r, θ_r) for the SVC-based fuzzy stabilizer and (G_s, T_1, T_2) for the GC was sought. From this figure, it is concluded that the coordinated design (using PSO) for the SVC-based fuzzy

stabilizer and the GC results in more improvement in the SCG performance.

The optimal coordinated values selected by PSO for (F, D_r, θ_r) and (G_s, T_1, T_2) are $(0.028, 0.923, 3.84^\circ)$ and $(0.061, 1, 0.01)$ respectively. Performance of the SCG system with the optimally designed control scheme following a 3-phase short circuit fault, at $[(P_t, Q_t) = (0.8, 0.6), (0.7, -0.2) \text{ p.u}]$ is shown in Fig. 7 and Fig. 8. Figures 9 and 10 show the system response to a temporary (100-ms long) 10% step increase in the governor set point (U_{gr}) at the considered loading conditions.

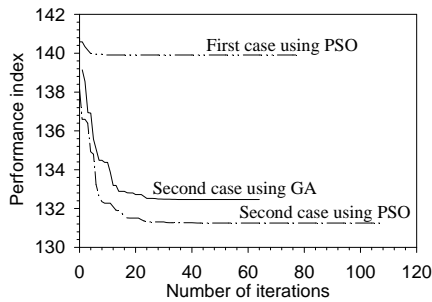


Fig. 6 Convergence of performance index with iterations using PSO & GA

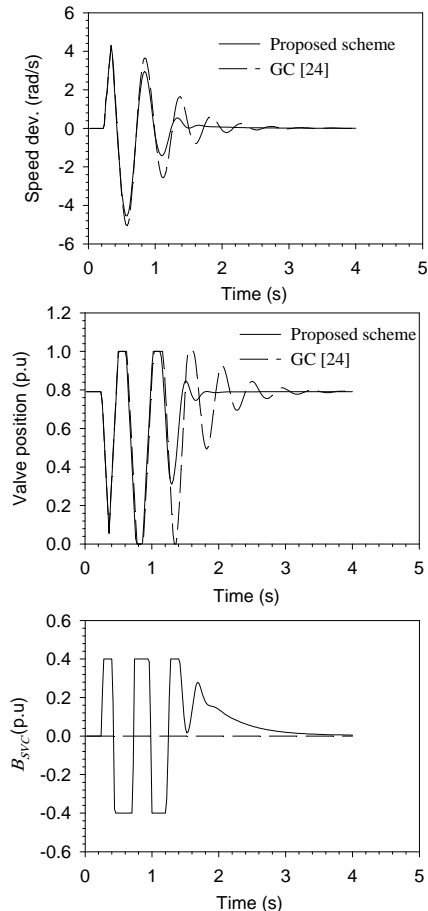


Fig. 7 Response to a 3-phase SC at $P_t=0.8 \text{ pu}$, $Q_t=0.6 \text{ pu}$

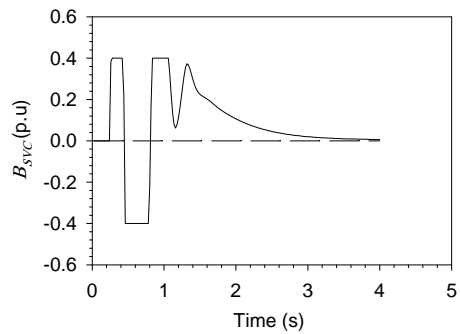
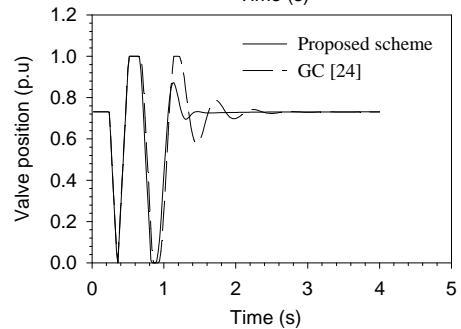
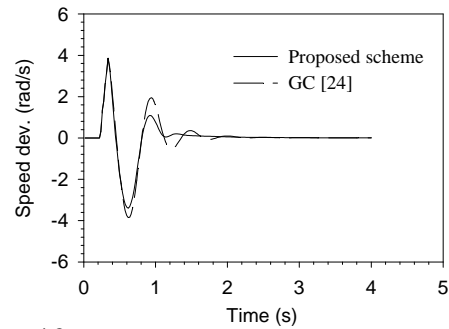


Fig. 8 Response to a 3-phase SC at $P_t=0.7 \text{ pu}$, $Q_t=-0.2 \text{ pu}$

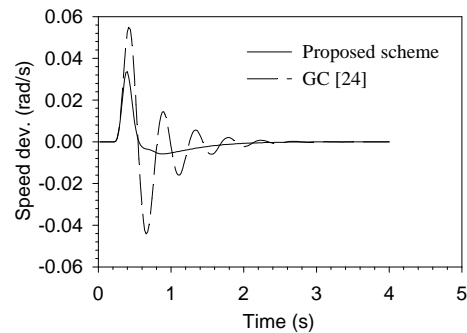


Fig. 9 Response to a 10% pulse in U_{gr} at $P_t=0.8 \text{ pu}$, $Q_t=0.6 \text{ pu}$

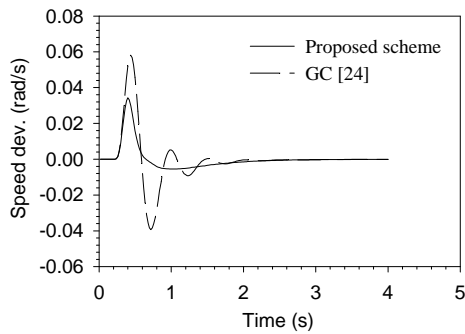


Fig. 10 Response to a 10% pulse in U_{gr} at $P_t=0.7$ pu, $Q_t=-0.2$ pu

The results show that the proposed control scheme results in a significant improvement in the SCG transient performance (after major and minor disturbances) and a considerable reduction in the rotor oscillations with acceptable valve movements at various loading conditions. The corresponding results of damping and synchronizing torques analysis, using the technique described in [17], are shown in Table 1, in comparison with other schemes (viz. SVC with GC [17], and GC [24] only).

Table 1: 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
Proposed scheme	131.25	0.25	1.996	0.242	1.223
SVC with GC [17]	130.2	0.231	1.941	0.212	1.184
GC [24]	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 the operating points studied. It provides the SCG system with the highest possible degree of damping while keeping the synchronizing torque at a high level.

7. Conclusion

This paper investigated the application of one of FACTS devices for stability enhancement of superconducting generators. An approach was proposed for the design of a static VAR compensator-based fuzzy 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 fuzzy 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 was used to provide another quantitative assessment of the SCG performance with the designed SVC-based fuzzy stabilizer and GC. Results of non-linear simulation studies show the effectiveness of the proposed approach in enhancing SCG stability.

8. References

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9. Appendix

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:

$$L_f=0.541, L_d=L_q=0.5435, L_{D1}=L_{Q1}=0.2567,$$

$$L_{D2}=L_{Q2}=0.4225$$

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

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

$$\tau_f=750, R_d=R_q=0.003$$

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

$$H=3 \text{ kW.s/kVA}$$

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:

$$\tau_{GM}=\tau_{GI}=0.1, \tau_{HP}=0.1, \tau_{RH}=10,$$

$$\tau_{IP}=\tau_{LP}=0.3, P_o = 1.2 \text{ p.u.}$$

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

Valve position and movement constraints are defined by:

$$0 \leq (G_M, G_I) \leq 1 \text{ and } -6.7 \leq (pG_M, pG_I) \leq 6.7$$

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