Excitation Control System Design of Superconducting Generator with High Response Excitation in Consideration of SMES Effect for Improving Stability in Multi-Machine Power System

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Abstract – Superconducting generator (SCG) with superconducting field winding has many advantages such as small size, light weight, high generation efficiency. In particular, the property of low synchronous reactances, which is not realized in conventional generators, is able to improve power system stability. In addition, transient stability can be improved by effect of high response excitation of self-excited SCG which enables the rapid change of field current and in turn of excitation power. The field winding connected to the power system through converter is considered as a superconducting magnetic energy storage (SMES); hence, the effect is called "SMES effect". In this paper, excitation control system for SCG with high response excitation considering SMES effect is proposed for stability improvement by employing eigenvalue sensitivity. The control performance of the proposed exictation control system is examined in IEEJ East 10-machine and West 10-machine systems. It is made clear that the SMES effect of SCG is utilized effectively and results in both transient and dynamic stabiilty improvement. However, the performance depends on the locations of SCGs and fault contingencies.

Keywords: Superconducting generator, High response excitation, Excitation power, SMES Effect, Power system stabilizer, Excitation system, Stability

1 INTRODUCTION

Superconducting generator (SCG) with superconducting field winding offers various advantages, such as high efficiency, small-size light weight, and so forth. A prominent advantage is to improve stability of power system owing to low synchronous reactance compared with the conventional generators [1]. SCG can be divided roughly into two types: SCG with low response excitation and high response excitation. The former has a rotor with thermal radiation shield having damping effect that can screen time-varying magnetic flux not to enter field winding part, but the latter has one without damping effect. With such structure, the SCG with high response excitation can enables very rapid change in field current. The excitation power by the quick change of field current is large and has a rapid change enough to affect the conditions of power system in self-excited operation of the generator [2]. This is an additional characteristic of this type of SCG, which is expected to contribute to transient stability improvement. Since the field winding is made of superconducting wire and is connected to the generator terminal through AC-DC converter, the field winding coupling with the converter can be considered as a superconducting magnetic energy storage (SMES) that has been known as not only a load-leveling device but also a flexible AC transmission system (FACTS) device; it is used to store or release energy from/to the power system through the converter in order to improve system stability. Hence, the effect of the exciter coupling with the AC-DC converter is called "SMES effect". It is expected that SCG with high response excitation using appropriate excitation control system can improve system stability by effectively utilizing the SMES effect.

Several works have been done for examining SMES effect and proposing appropriate excitation control systems for SCG with high response excitation. In single machine to infinite bus system, influence of SCG with high response excitation on power system stability and its control system have been experimentally studied [2]; high response excitation control of SCG with high response excitation for stability of superconducting field winding has been conducted [3]. In multi-machine power system, calculation methods of the equilibrium state considering SMES effect of the power flow and dynamic simulation of multi-machine power system including SCG with high response excitation and control system design based on energy function for SCG have been proposed [4]. It has been reported that the SMES effect contributes to the improvement of system stability; however, the control system is complicated and requires information from all generators in the system.

In this paper, excitation control system for SCG with high response excitation considering SMES effect is designed for stability improvement in multi-machine power system by employing eigenvalue sensitivity based eigenvalue control technique. The SMES effect is considered to be coupled with power system as a nonlinear load and is taken into account in control system design through eigenvalue consideration. The control performance of the proposed excitation control system is examined by digital dynamic simulations in two power systems, IEEJ East 10-machine system and IEEJ West 10-machine system. It is made clear that the SMES effect of SCG is utilized effectively and results in improvement of both transient stability and dynamic stability. However, the performance depends on the locations of SCGs and fault contingencies.

2 SCG WITH HIGH RESPONSE EXCITATION

A typical structure of SCG is shown in Fig. 1. SCG can produce very high magnetic field by its superconducting field winding cooled in the cryogen such as liquid helium, which can not be realized by the conventional generator. Multi-cylindrical structure which consists of field winding, thermal radiation shield and room temperature damper is adopted in the extreme cold region. Since generated magnetic field is large enough that it is not necessary to use magnetic iron to enhance magnetic flux; instead, air-core geometry can be used; SCG can have stator windings with the "air-gap" type, which leads to the advantage of avoiding flux saturation and low synchronous reactance. Magnetic shield is installed outside for confining flux in the machine.

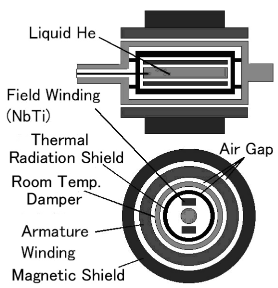

Figure 1: Structure of SCG

The equivalent circuit of SCG with high response excitation can be considered as that of the conventional generator. Contrary to SCG with low response excitation, a thermal radiation shield of SCG with high response excitation has no damping effect; it can be considered that SCG with high response excitation seems to have only one damping winding in each axis equivalent circuit, equivalent to amortisseur winding in the conventional generator.

3 SMES EFFECT

3.1 Concept

SCG with high response excitation enables the rapid change of field current; the excitation power becomes large and changes rapidly enough to affect the conditions of power system in self-excited operation of the generator. The simplified model of SCG with high response self-excitation is depicted in Fig. 2. The field winding is connected to SCG bus through the AC-DC converter. Since the field winding is made of superconductors, the field winding coupling with the converter can be considered as SMES and its effect is thus called "SMES effect".

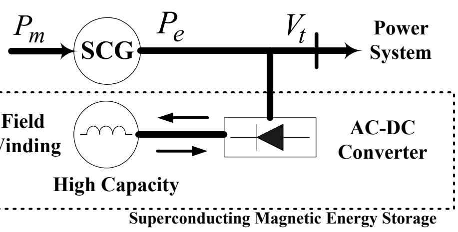

Figure 2: SCG with high response excitation in self-excitation mode

The excitation power in SMES effect can be evaluated by (1), which depends on some machine parameters. It should be noted that the excitation power of the SCG is smaller than that of the conventional generator due to the very small resistance of superconducting field winding.

$$P_f = v_f i_f = \frac{e_f e_{q1}}{T'_{do}\omega_0\left(X_d - X'_d\right)} \tag{1}$$

where v_f, i_f, and e_f are the applied voltage at rotor circuit, excitation current and excitation voltage, respectively. e_{q1} is the generator internal voltage.

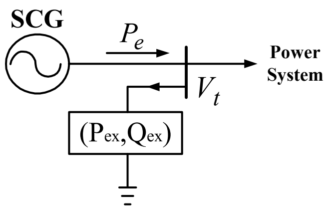

Figure 3: Equivalent model for SCG with high response excitation considering SMES effect

From the simplified model of SCG in self-excitation mode in Fig. 2, the excitation system including the AC-DC converter can be considered as a nonlinear load. Active and reactive powers flowing into excitation system are assumed as P_{ex} and Q_{ex}, respectively; hence, the equivalent model for SCG with high response excitation can be obtained as shown in Fig. 3. Without any loss in transfer power, active power P_{ex} is the same as the excitation power of SCG; reactive power Q_{ex} can be adjusted by self-commutated type converter for supporting the generator terminal voltage.

3.2 Consideration of SMES Effect in Power System

According to the assumption of SMES effect as a nonlinear load in the power system, the relationship between current flowing into excitation system and bus voltage at the SCG with high response excitation in self-excitation mode can be obtained by (2) in *d* and *q* axes with consideration of P_{ex} and Q_{ex}.

$$\begin{bmatrix} I_{exD} \\ I_{exQ} \end{bmatrix} = \frac{1}{V_t^2} \cdot \begin{bmatrix} P_{ex} & Q_{ex} \\ -Q_{ex} & P_{ex} \end{bmatrix} \begin{bmatrix} V_D \\ V_Q \end{bmatrix} \tag{2}$$

where V_D *a*nd V_Q are *d* and *q*-axes terminal voltage components of SCG bus, respectively.

Assuming that I_G is the vector of currents through generators, I_{ex} is the vector of currents of all nonlinear loads connecting to generator buses, which includes the SMES effect, V_G is the vector of generator bus voltages, V_L is the vector of load bus voltages, Y is the admittance bus matrix which consists of four sub-matrices Y_{GG}, Y_{GL}, Y_{LG}, and Y_{LL}, the relationship of currents and bus voltages of power system in a matrix-form is given in (3).

$$\begin{bmatrix} I_G - I_{ex} \\ 0 \end{bmatrix} = Y \begin{bmatrix} V_G \\ V_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{3}$$

Rearranging (3);

$$I_G = \left(Y_{GG} - Y_{GL} Y_{LL}^{-1} Y_{LG}\right) V_G + I_{ex} \quad (4)$$

Considering impedances and internal induced voltages of all generators, generator current can be rearranged as shown in (5).

$$I_G = Y_G E_G + K_L I_{ex} \quad (5)$$

$$Y_G = \left(I + Y'Z'\right)^{-1} Y' \quad (6)$$

$$K_L = \left(I + Y'Z'\right)^{-1} \quad (7)$$

$$Y' = Y_{GG} - Y_{GL} Y_{LL}^{-1} Y_{LG} \quad (8)$$

where E_G is the vector of internal induced voltages of generators and Z' is the matrix of internal impedances of generators.

By the above equations, SMES effect can be taken into account in multi-machine power system.

4 EXCITATION CONTROL SYSTEM

4.1 Design Concept

In this section, the excitation control system for SCG with high response excitation is proposed. The excitation control system design of SCG with high response excitation is constrained by two issues: (1) the transient open-circuit time constant T'_{do} being relatively large, (2) SMES effect.

Initially, AVR and speed governor are assumed to be used in SCG as the 1st order time-lag transfer function controller blocks. The first constraint leading to the slow response and longer storing of energy in the field winding, requires the larger AVR gain in SCG to step up the excitation voltage to ceiling voltage level so fast that the voltage regulation can be achieved; however, large AVR gain results in degradation of power system stability. Power system stabilizer (PSS) is a general solution for this problem. The main function of PSS is to add damping to the generator rotor oscillation by controlling the excitation using auxiliary stabilizing signal(s). It is expected to improve both transient and dynamic stability. By this reason, AVR and PSS will be used as excitation control system for SCG with high response excitation. The control scheme and design is described below.

4.2 Power System Stabilizer

Output power is used as an input of PSS which consists of stabilizer gain, signal washout and phase compensation block as shown in Fig. 4. The PSS output is added to the AVR as a supplementary control signal. Excitation limiter is required for the AVR output to restrict the level of excitation voltage. Parameters of PSS are determined by eigenvalue sensitivity based parameter optimization method described in the next section.

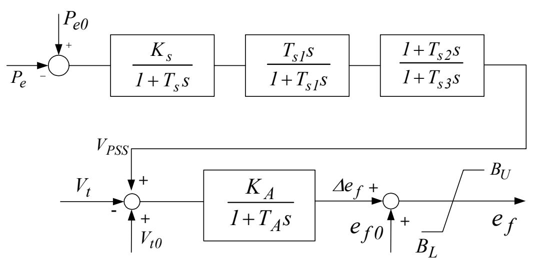

Figure 4: Power input type power system stabilizer (P-PSS)

4.3Eigenvalue Sensitivity based Parameter Optimization [5]

The state equations shown in (9) and (10) are obtained by linearizing nonlinear differential equations of power system around an operating point.

$$A_G \dot{x}_g + B_G \Delta V = C_G x_g \quad (9)$$

$$Y \Delta V = D_G x_g \quad (10)$$

where x_g is the vector of state variables of generators, ΔV is the vector of deviations of generator terminal voltages.

By eliminating ΔV from equations (9) and (10),

$$x_g = A x_g \quad (11)$$

$$A = A_G^{-1}\left(C_G - B_G Y^{-1} D_G\right) \quad (12)$$

Eigenvalue sensitivity can be evaluated by (13).

$$S_{ij} = \frac{\partial \lambda_i}{\partial \alpha_j} = v_i^T \frac{\partial A}{\partial \alpha_j} u_i \quad (13)$$

where S_{ij} is the sensitivity of i^{th} eigenvalue (λ_i) with respect to parameter α_j, A is the state matrix, v_i^T and u_i are the left and right eigenvectors associated to λ_i, respectively.

This parameter optimization method employs eigenvalue sensitivity to form an objective function expressed in (14) and parameters can be evaluated under the conditions that all eigenvalues have their own real parts less than the threshold value σ_D (<=0). It is constrained by limits of parameter changes and parameters as shown in (15) and (16) and all observed eigenvalues are guaranteed to be in LHP by (17). This optimization problem is solved by the simplex method.

$$\min \quad f = \sum_{j=1}^{p}\left[\sum_{i \in U_C} Re\left(\frac{d\lambda_i}{d\alpha_j}\right)\right]\Delta\alpha_j \quad (14)$$

$$\left|\Delta\alpha_j\right| \le d_j \quad (15)$$

$$\alpha_{j,min} \le \alpha_j + \Delta\alpha_j \le \alpha_{j,max} \quad (16)$$

$$\sum_{j=1}^{p}\left[\sum_{i \in U_M} Re\left(\frac{d\lambda_i}{d\alpha_j}\right)\right]\Delta\alpha_j \le 0 \quad (17)$$

where p is the number of control parameters, d_j (>0) is the bound value of step change of α_j, $\alpha_{j,min}$, $\alpha_{j,max}$ are the minimum and maximum values of α_j, U_C is the set of controlled eigenvalues, U_M is the set of observed eigenvalues.

4.4 SMES effect as Load Model

The second constraint to be considered in excitation control system design is SMES effect. As shown in section (3.2) that SMES effect is considered as a nonlinear load with current flowing out of the generator terminal as given in (2), the variation of those currents can be obtained as shown in (18).

$$\begin{bmatrix}\Delta I_{exD}\\ \Delta I_{exQ}\end{bmatrix}=\left\{\frac{-2}{V_{t0}^4}\cdot\begin{bmatrix}P_{ex0} & Q_{ex0}\\ -Q_{ex0} & P_{ex0}\end{bmatrix}\begin{bmatrix}V_{D0}^2 & V_{D0}V_{Q0}\\ V_{D0}V_{Q0} & V_{Q0}^2\end{bmatrix}\right.$$
$$\left.+\frac{1}{V_{t0}^2}\begin{bmatrix}P_{ex0} & Q_{ex0}\\ -Q_{ex0} & P_{ex0}\end{bmatrix}\right\}\begin{bmatrix}\Delta V_D\\ \Delta V_Q\end{bmatrix}$$
$$+\frac{1}{V_{t0}^2}\begin{bmatrix}V_{D0}\\ V_{Q0}\end{bmatrix}\Delta P_{ex}+\frac{1}{V_{t0}^2}\begin{bmatrix}V_{Q0}\\ -V_{D0}\end{bmatrix}\Delta Q_{ex} \qquad (18)$$

Since P_{ex} can be evaluated in terms of generator variables as shown in (1), the variation of excitation power can be determined by (19).

$$\Delta P_{ex}=v_{f0}\Delta i_f+i_{f0}\Delta v_f \qquad (19)$$

Δi_f and Δv_f are considered as state variables of generators (SCG). SMES effect in the form of current can be considered by combining (19) into (18), the state-matrix of power system in (9) and (10) are evaluated to determine the eigenvalues and eigenvalue sensitivity based parameter optimization method is employed to determine optimal control parameters.

As for Q_{ex}, it can be adjusted by AC-DC converter according to the external control signal value (such as what is shown in the next section). It can be set to be zero when no control is applied for this value.

4.5 Reactive Power Control (Q_{ex} -Control)

As described in (4.4) that Q_{ex} can be adjusted by AC-DC converter according to external control signal. In order to support and improve voltage stability, here, the simple control system in the form of the 1st order time-lag transfer function control block with bus voltage input as shown in Fig. 5 is applied to control reactive power of SMES effect. Mathematical expression of the controller is shown in (20).

$$\Delta\dot{Q}_{ex}=\frac{1}{T_q}\left(-\Delta Q_{ex}+K_q\left(V_{t0}-V_t\right)\right) \qquad (20)$$

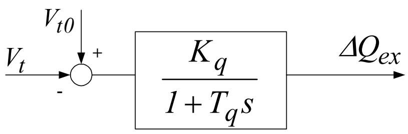

Figure 5: Reactive power controller

5 NUMERICAL EXAMPLES

The digital simulations are conducted in two model power systems, which are IEEJ East 10-machine and West 10-machine systems, to examine the performance of the proposed excitation control systems of SCG with high response excitation. In each model system, for one pattern of replacing one conventional generator (CG) by one SCG whose parameters shown in Table 1, five cases of different generator types, excitation modes (operation), and excitation control schemes as shown in Table 2 are considered. In cases 2~5, excitation control systems are PSS-AVR (Q_{ex}-Control is added only in case 5) whose parameters determined by the eigenvalue sensitivity based parameter optimization method.

Table 1: Parameters of SCG with high response excitation

d-axis synchronous reactance	X_d	0.40 [p.u.]
d-axis transient reactance	X'_d	0.30 [p.u.]
d-axis subtransient reactance	X''_d	0.20 [p.u.]
q-axis synchronous reactance	X_q	0.40 [p.u.]
q-axis subtransient reactance	X''_q	0.20 [p.u.]
Leakage reactance	X_l	0.15 [p.u.]
d-axis transient open circuit time constant	T'_{do}	100 [sec]
d-axis subtransient open circuit time constant	T''_{do}	0.03 [sec]
q-axis subtransient open circuit time constant	T''_{qo}	0.03[sec]
Inertia constant	H	5 [sec]
Damping coefficient	D	0 [p.u.]

Table 2: Generator types and control schemes

Case	Machine	Operation	Excitation Control System
1	CG	Separately	AVR
2	CG	Self	PSS-AVR
3	SCG	Separately	PSS-AVR
4	SCG	Self	PSS-AVR
5	SCG	Self	PSS-AVR + Q_{ex}-Control

5.1 IEEJ East 10-machine System

The model system consisting of 10 generators and 47 buses is shown in Fig. 6. The structure of the system is a loop network with radial line connected at node 17. Three patterns of replacement of conventional generator by SCG with high response excitation at nodes 2, 5, and 10 are taken into account. Excitation control systems for each pattern are designed and eigenvalues of power system are evaluated; only dominant eigenvalues are considered and shown in Table 3.

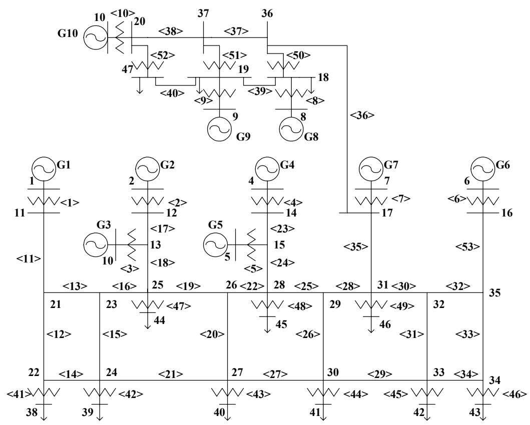

Figure 6: IEEJ East 10-machine system

As shown in Table 3, comparing with case 1, when PSS-AVRs are designed by employing eigenvalue sensitivity based parameter optimization method for generators, it can be seen that damping of system is improved well in all patterns and all cases. When CG is replaced by SCG in cases 3~5, there are some cases that damping of one mode is improved but the other is not and there are also some cases that both cases are improved and both are not. The reason is that when SCG is introduced to the system at some locations, it may itself degrade the dynamic stability of the system and coupling SMES effect by considering the exciter as a nonlinear load to the system may affect dynamic stability. In patterns 1 and 3, the proposed excitation control systems (cases 4 and 5) can improve dynamic stability well.

Table 3: Dominant modes of IEEJ East 10-machine system

Control	Pattern 1 (Node 2)	Pattern 2 (Node 5)	Pattern 3 (Node 10)
Case 1	-0.1403+j2.1138	-0.1403+j2.1138	-0.1403+j2.1138
	-0.1828+j3.3703	-0.1828+j3.3703	-0.1828+j3.3703
Case 2	-0.4490+j1.4408	-0.3759+j1.8700	-0.2157+j1.4967
	-0.3018+j2.4699	-0.5662+j2.4225	-0.3210+j2.9447
Case 3	-0.5630+j1.6721	-0.3185+j1.9154	-0.4147+j1.5182
	-0.3853+j2.4046	-0.6316+j2.5020	-0.3851+j3.2901
Case 4	-0.5531+j1.6837	-0.2972+j1.7976	-0.4578+j1.3914
	-0.4052+j2.4020	-0.4496+j2.5992	-0.3498+j3.2262
Case 5	-0.4856+j1.6662	-0.2314+j1.8253	-0.7701+j1.3846
	-0.4108+j2.4820	-0.4744+j2.7150	-0.4950+j2.6182

As for transient simulation, in pattern 3, 3LG fault with 70ms duration is considered to occur at node 40. Generator 3 is considered as a reference generator of the system. Figures 7 and 8 show the rotor angle differences of generators 6 and 10, which are respectively in loop part and radial line. Figures 9, 10 and 11 show the output power, excitation power and terminal voltage of node 10 where CG is replaced by SCG (node 10).

As shown in Figs. 7 and 8, when applying proposed excitation control system (PSS-AVR) considering SMES effect to SCG with high response excitation (case 4), amplitude of oscillation in rotor angles of generators is greatly reduced comparing with cases 1 to 3, and in case 5, where reactive power control is applied, the amplitude of oscillation is more reduced than in case 4. From Fig. 9, after the fault is cleared, output powers and their slopes in cases 3 and 4 are very high and they get back to the steady state more quickly compared with cases 1 and 2; however, case 4 is better. This is the reason why the amplitudes of generator oscillation are lessened. Although output power in case 5 does not change and get back to steady-state so rapidly as in

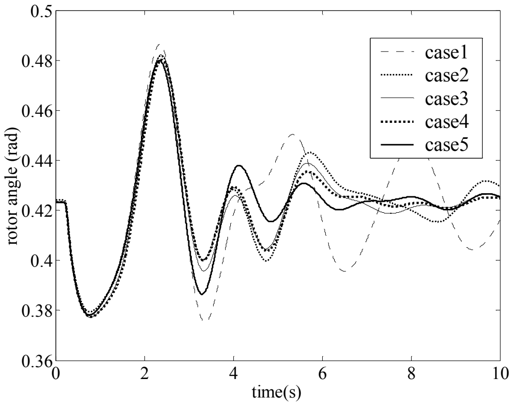

Figure 7: Rotor angle of generator 6

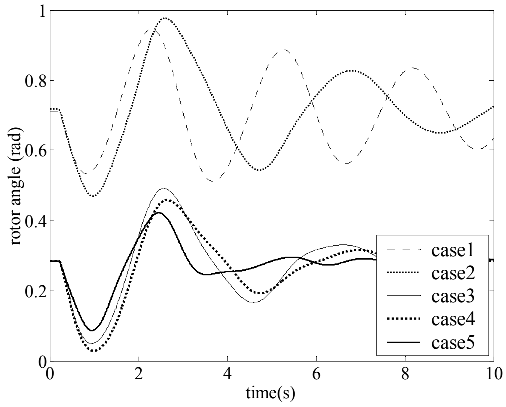

Figure 8: Rotor angle of generator 10

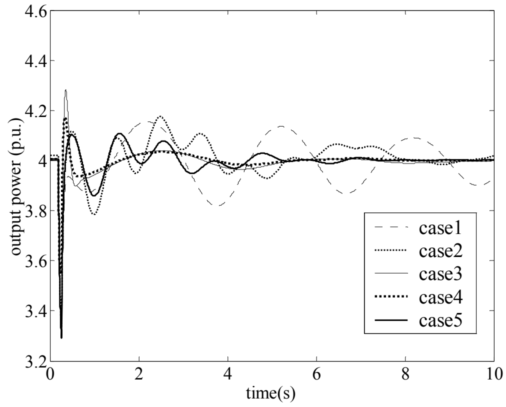

Figure 9: Output power of generator 10

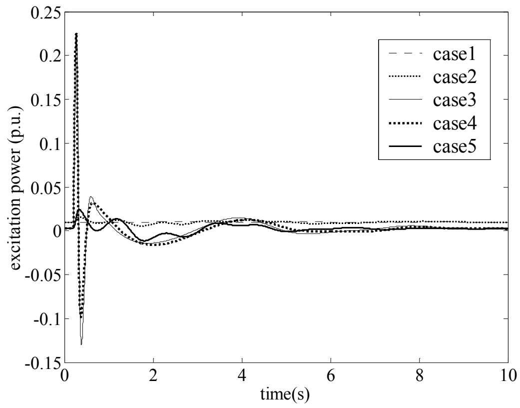

Figure 10: Excitation power of generator 10

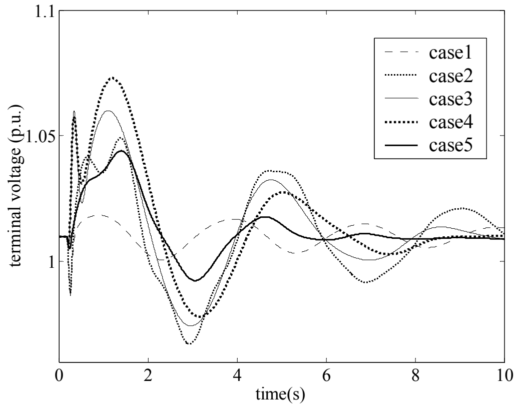

Figure 11: Terminal voltage of generator 10

cases 3 and 4, reactive power control is involved in improving system stability. It is clearly seen from Fig 10, that the excitation power rises up to around 0.2 [p.u.] and then back to around -0.1 [p.u.] in case 4, which reflects much power to absorb (inject) from (to) the system at SCG node, mostly from (to) SCG; it results in increase (decrease) of output power. Excitation power in case 3 goes up to the same level as case 4, but less stability improvement is obtained. This shows that SMES effect contribute to transient stability improvement. From Fig.11, the first swing of terminal voltage in case 4 is higher than other cases due to the PSS output signal; however, it is reduced and the oscillation of terminal voltage is improved well in case 5 from the effect of reactive power control.

In order to assess the performance of the excitation control system, an index as shown in (21) is introduced; it is the total curve area of variables with respect to the reference values in all generators in a system.

$$AREA = \sum_{g \in G} \int_{T} \left| X_g - X_{g0} \right| \, dt \qquad (21)$$

where X_g is the considered variable, X_{g0} is the steady state value of considered variable, G is the set of generators, and T is the period of time.

Here, the rotor angle difference of each generator is considered as the variables for assessment and T is set to be 10 sec. In addition to the previous simulation, other fault contingencies are also considered for each pattern of SCG installation, which are 3LG faults at nodes 43, 45 and 36. Assessment values are determined by (21) for all cases, and the results are shown in Table 4. It can be said that system stability can be improved well by the proposed excitation control system (cases 4 and 5) of SCG with high response excitation; even if there are some contingencies that the control systems may not be effective.

Table 4: Total curve areas in IEEJ East 10-machine system

Pattern	3LG node	Case 1	Case 2	Case 3	Case 4	Case 5
1	40	3.8102	3.1752	2.7183	2.4923	2.4639
	43	2.0661	1.8013	1.5332	1.4513	1.4280
	45	2.9074	2.2857	1.8821	1.7362	1.6988
	36	4.2508	2.3900	2.1015	2.1218	2.0670
2	40	3.8102	2.8731	2.9119	2.7849	2.6471
	43	2.0661	1.7032	1.6824	1.6760	1.5755
	45	2.9074	2.0213	2.0850	1.9282	1.8269
	36	4.2508	2.8400	3.0294	2.9056	3.3776
3	40	3.8102	2.9484	2.4355	2.2213	1.6851
	43	2.0661	1.8720	1.6260	1.5744	1.2247
	45	2.9047	2.3535	1.9741	1.8205	1.4145
	36	4.2508	2.4754	1.5609	1.6883	2.1563

5.2 IEEJ West 10-Machine System

The model system consisting of 10 generators and 27 buses is shown in Fig. 12. Three patterns of replacement of one conventional generator by SCG with high response excitation at nodes 1, 4, and 7 are considered and excitation control systems are designed as in the previous section. Dominant eigenvalues are shown in Table 5. They can be considered in the same way as in the previous IEEJ East system.

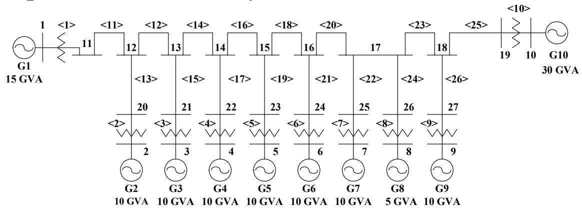

Figure 12: IEEJ West 10-machine system

Table 5: Dominant modes of IEEJ West 10-machine system

Control	Pattern 1 (node 1)	Pattern 2 (node 4)	Pattern 3 (node 7)
Case 1	-0.3030+j1.2062	-0.3030+j1.2062	-0.3030+j1.2062
	-0.3893+j2.7765	-0.3893+j2.7765	-0.3893+j2.7765
Case 2	-0.3994+j1.0643	-0.3223+j1.2381	-0.3415+j1.0763
	-0.4915+j2.6936	-0.4118+j2.8522	-0.4022+j2.8200
Case 3	-0.4715+j1.0251	-0.3083+j1.2899	-0.3141+j1.1933
	-0.5788+j2.6588	-0.4132+j2.9019	-0.3794+j2.8263
Case 4	-0.4759+j1.1014	-0.3210+j1.3672	-0.3249+j 1.0063
	-0.5078+j2.7976	-0.4355+j2.9851	-0.3894+j 2.8512
Case 5	-0.4964+j0.9790	-0.4051+j1.2359	-0.2822+j 0.9883
	-0.5278+j3.0365	-0.6418+j2.6019	-0.3999+j 2.8651

As for transient simulation, in pattern 2, 3LG fault with 70ms duration is considered to occur at node 24. Generator 10 is considered as a reference generator of the system. Figures 13 and 14 show the rotor angle difference of generators 4 and 8 and Figs. 15, 16 and 17 respectively show the output power, excitation power and terminal voltage at the SCG node (node 4).

It can be seen from the results that system stability is improved well by the proposed excitation control

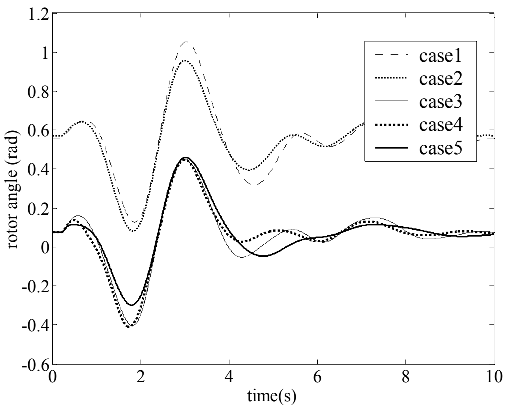

Figure 13: Rotor angle of generator 4

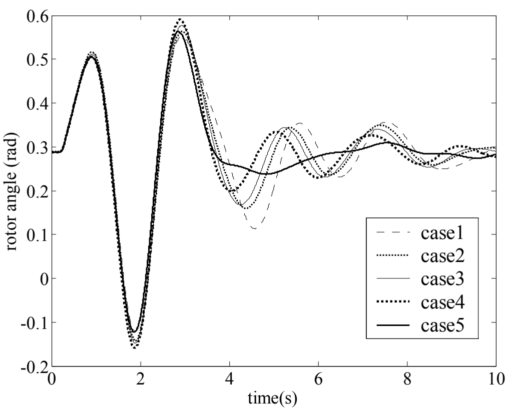

Figure 14: Rotor angle of generator 8

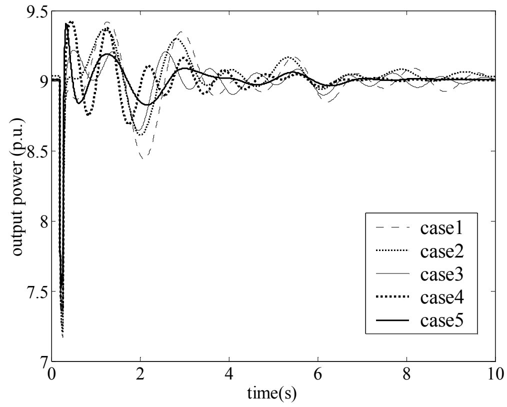

Figure 15: Output power of generator 4

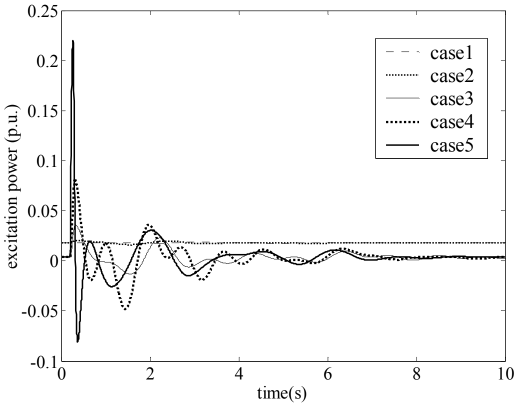

Figure 16: Excitation power of generator 4

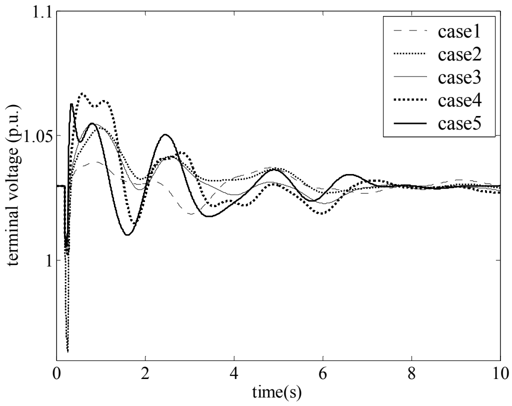

Figure 17: Terminal voltage of generator 4

systems (cases 4 and 5). The mechanism of how the excitation control system gets involved in system stabilization can be described by the same way as the previous system. This shows that SMES effect influences the improvement of system stability.

Other fault contingencies, which are 3LG faults at nodes 21, 15 and 18, are also considered and assessment values are shown in Table 6. It is made clear that system stability can be improved well by the proposed excitation control systems.

5.3 Discussion

From the simulations in both test systems, it can be seen that the proposed excitation control system (cases 4 and 5) with consideration of SMES effect that are designed by employing eigenvalue sensitivity based parameter optimization method can improve both transient stability and dynamic stability of the power system. Although there are some cases that dynamic stability (by eigenvalue consideration) seems not to be improved, but with transient stabilization by SMES effect, the overall system stability is ultimately improved. It is also clearly seen that the control performance of the excitation control systems depends on the locations of SCGs and fault contingencies. The research on SCG locations is still under investigation and development [6].

Table 6: Total curve areas in IEEJ West 10-machine system

Pattern	3LG Node	Case 1	Case 2	Case 3	Case 4	Case 5
1	24	9.8936	8.4337	8.1085	7.5809	7.3806
	21	13.094	7.7233	7.5177	8.6231	9.2547
	15	8.2223	7.4420	7.2801	6.6485	6.9940
	18	12.2120	9.0039	8.2573	8.8941	8.0202
2	24	9.8936	9.0450	8.7814	8.2136	8.0522
	21	13.094	12.371	11.331	9.3627	9.4277
	15	8.2223	7.4198	6.9209	6.1613	5.6269
	18	12.2120	11.609	11.432	10.993	10.892
3	24	9.8936	8.5386	9.1280	8.3048	7.9144
	21	13.0940	9.4779	12.620	8.4961	8.8224
	15	8.2223	7.8262	7.7477	7.9916	7.8501
	18	12.2120	9.3330	12.108	9.1907	8.7984

6 CONCLUSIONS

Excitation control system for SCG with high response excitation is proposed by applying AVR and PSS which is designed by employing eigenvalue sensitivity. Reactive power control at SCG node is also added into excitation control system. The SMES effect is modeled and put into consideration when designing control system. The control performance is examined in IEEJ East 10-machine and West 10-machine power systems and the results show that, coupling with SMES effect, the proposed excitation control system is effective to improve both transient stability and dynamic stability.

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