Paper

Real-time Simulation Study on Stability-improving Effects of Superconducting Generator in Power Systems by use of Digital Type Generator Model and Analog Type Power System Simulator

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Superconducting Generator (SCG) has many advantages such as small size, high generation efficiency, low impedance, and so on. An improved power system with many potential good properties may be obtained by introduction of SCG. In order to study the behaviors of SCG in power systems, a digital type SCG model for an existing analog type real-time power system simulator is developed in this work, which is suitable for real-time simulations when the generator constants and control systems are changed frequently. By use of the above-mentioned equipments, real-time simulation in cases of SCG with different generator constants and in case of SCG in multi-machine power system has been conducted. The real-time simulation results verify the effects of SCG on power system stability enhancement and show the influence of generator constants on its stability-improving effects.

Keywords: superconducting generator, SCG, digital type SCG model, analog type real-time power system simulator, real-time simulation, power system stability

1. Introduction

Superconducting Generator (SCG) has a superconducting field winding, which leads to many advantages such as small size, high generation efficiency, low impedance, and so on. Many researches have shown the feasibilities of design, manufacture (1) and control of SCGs (2). In Japan, a national project (Super-GM) to develop a SCG model machine begun in 1988, as a result, a 70 MW class SCG was manufactured and many experiments have been done for the purpose of development of large capacity SCGs (3). From a design point of view, generator constants of SCG are more flexible. The fact that SCG can bring stability-improving effects in power systems was also confirmed by digital simulation (4).

A digital type SCG model is developed for an existing analog type real-time power system simulator in this work. It is suitable for accomplishing a lot of real-time simulations when the generator constants and control systems are changed frequently. The construct and some experimental results on the characteristics of the developed SCG model were introduced in the former paper by the authors (5), but few experimental results were given about the behaviors of SCG in power system networks. In this paper, besides a brief explanation of the developed digital type SCG models, real-time simulation results obtained by use of the above-mentioned equipments are given to show the improving-effects of SCG on power system stability. The real-time simulations of SCG in power systems are the first time carried out in this work. And, as the first step of a series of study on the behaviors of SCG in power system networks, this paper presents some basic real-time simulation results about this point, further studies utilizing these equipments will be done and introduced in the future works. Some of the conclusions from this work are the same as those by method of digital simulations, and this demonstrates the validity and reliability of the developed SCG model and real-time power system simulator. Some other conclusions that have never been studied by digital simulations are obtained and introduced as well.

The article is organized in six sections. The structure of a SCG model machine, which is studied in this work, is simply introduced in the second section. Experimental setup including SCG and conventional generator (CG) model, transmission line and load model is explained in

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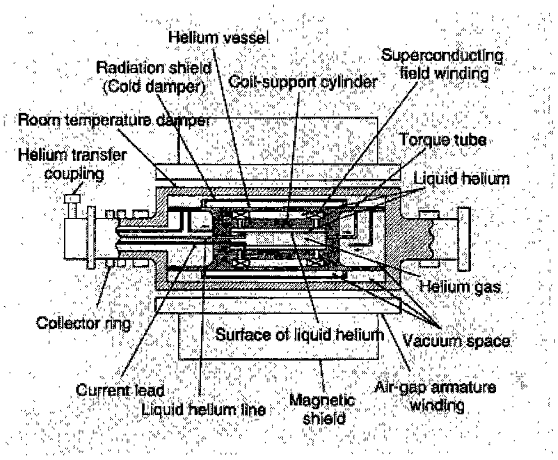

Fig. 1. Structure of SCG with low response excitation

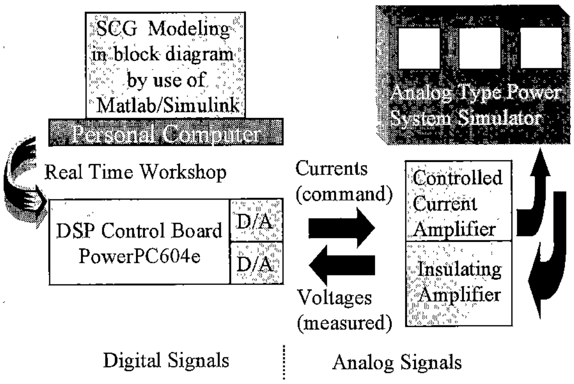

Fig. 2. Outline of digital type SCG model

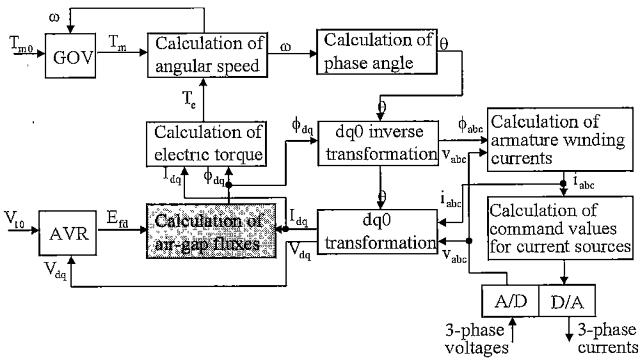

Fig. 3. Mathematical Model for SCG

the third section. In this section, the structure of the developed digital type SCG model is briefly explained as well. In the fourth section, experimental results from one-machine infinite bus power system model in cases of different SCG generator constants are given to show the effects of these constants on SCG's stability-improving effects, followed by those results from three-machine infinite bus power system model for the comparison of the ability of SCG and CG in multi-machine power systems. In the fifth section, conclusion and future works are presented. At the last, acknowledgement to the supporter of this work is addressed.

2. Structure of SCG

By now, two types of SCG were manufactured and thoroughly investigated. In this work, SCG with low response excitation is studied.

The front view of SCG with low response excitation in section is shown in Fig. 1. Because SCG has a superconducting field winding cooled by liquid helium, multi-cylindrical structure is adopted. Besides the room temperature damper, a radiation shield is added in the cold region and works as a cold damper. As the superconducting field winding can generate very high magnetic field, SCG does not need iron core around the armature winding, this leads to the advantages of avoiding flux saturation and of low synchronous reactance.

Because SCG has different structure from the conventional generator, the mathematical model for conventional generator cannot be used for the simulation of SCG, therefore, a new mathematical model for SCG is necessary.

3. Experimental Setup

The real-time simulation experiment is carried out by use of a digital type generator model and a set of analog type real-time power system simulator. The power system grid is assembled on the transmission line panel of this simulator, and the digital type generator model and analog generator models are connected to the power system grid through a simple synchronism indicator & switches unite. The generator outputs are recorded or measured by oscilloscopes or by measuring instruments.

3.1 SCG Model In this experiment, a digital type generator model developed by the authors is used for the simulation of SCG. This model is suitable for simulations when the generator constants and control systems are changed frequently. The construct and some experimental results on the characteristics of this model were introduced in the paper by the authors (5). In this paper, we briefly give some explanations of this model.

3.1.1 Structure of digital SCG model An outline of the digital type SCG model is shown in Fig. 2. SCG model is constructed by use of DSP (Digital Signal Processor) board for generator modeling and controlled current source for connecting to the existing analog type real-time power system simulator.

In Fig. 2, the mathematical model of SCG can be made in block diagram by use of Matlab/Simulink, which is a widely used CAD tool, and then downloaded via a toolbox called Real Time Workshop into DSP for the real-time simulation. Therefore, it is easy to change the generator constants or construct new control systems in this model. Time interval for real-time simulation is set to 50 μs.

The mathematical model for SCG modeling in Fig. 2 can be obtained by both of method based on equivalent circuit of synchronous machine and of method based on operational impedances from electromagnetic analysis. In this paper, the operational impedance based method is adopted. Flow chart for SCG modeling is shown in Fig. 3.

In Fig. 3, the air-gap fluxes ϕ_{ad} and ϕ_{aq} are calculated from the exciting voltage E_{fd} of AVR and the armature currents I_d and I_q; angular frequency ω and generator phase angle θ are computed from the instantaneous applied torque T_m of GOV and the electric torque T_e; the armature winding currents are obtained by use of the measured generator terminal voltages and the internal induced voltages. Then, the calculated digital signals of three-phase armature-winding currents are conversed into analog signals through A/D and D/A converters, and these analog signals are used to control the current sources for connecting to the analog type real-time power system simulator.

Because some of these mathematical formulas in Fig. 3 are the same as those for the conventional generator that can be found in many articles, and some of them have already been introduced in Ref. (5), only equations for computation of air-gap fluxes (shadowed block in Fig. 3) that are different from the conventional generator and specially related to the SCG's structure are presented here.

Equation for calculation of air-gap fluxes is given by

$$\left.\begin{aligned} \varphi_{ad}(s) &= -\frac{X_{ad}(s)}{\omega_0} I_d(s) + \frac{G(s)}{\omega_0} E_{fd}(s) \\ \varphi_{aq}(s) &= -\frac{X_{aq}(s)}{\omega_0} I_q(s) \end{aligned}\right\} \cdots\cdots (1)$$

Where,

$\varphi_{ad}(s), \varphi_{aq}(s)$: dq axis air-gap fluxes

$X_{ad}(s), X_{aq}(s)$: dq axis operational impedance

$I_d(s), I_q(s)$: dq axis armature winding currents

$E_{fd}(s)$: Exciting voltage applied on field winding

$G(s)/\omega_0$: Transfer function from $E_{fd}(s)$ to $\varphi_{ad}(s)$

For dynamic analysis of SCG, the exact relationship between generator constants and SCG's structural design was studied [6]. Referred to the results, the operational impedances for SCG with low response excitation can be expressed as

$$\left.\begin{aligned} X_{ad}(s) &= X_{ad}\frac{(1+sT'_d)(1+sT''_d)(1+sT'''_d)}{(1+sT'_{d0})(1+sT''_{d0})(1+sT'''_{d0})} \\ X_{aq}(s) &= X_{aq}\frac{(1+sT''_q)(1+sT'''_q)}{(1+sT''_{q0})(1+sT'''_{q0})} \\ G(s) &= \frac{M_{af0}}{r_f}\cdot\frac{1}{1+s(T'_{d0}+T''_{q0})+s^2T'_{d0}T''_f} \end{aligned}\right\} \cdots (2)$$

Where,

T'_d, T''_d, T'''_d: d-axis short-circuit transient time constant, d-axis short-circuit sub transient time constant and d-axis short-circuit sub-sub transient time constant, respectively

$T'_{d0}, T''_{d0}, T'''_{d0}$: d-axis open-circuit time constant, d-axis open-circuit sub transient time constant, d-axis open-circuit sub-sub transient time constant, respectively

M_{af0}: Mutual impedance between armature winding and field winding

r_f: Field circuit resistance

T''_f: Time constant computed from T''_{q0}

Time constants for q-axis are defined as same as those for d-axis.

From equation (2), we know that SCG has one more time constant (sub-sub transient time constant) than that of the conventional generator. This is because SCG has one more damper - cold damper besides the room temperature damper (see Fig. 1).

3.1.2 Characteristics of digital type SCG model In order to verify the validity of the developed SCG model, several experiments with single-machine model were carried out [5]. The Direct-axis impedances $X_d(X_{ad}+X_l)$ are measured in steady-state condition by method of short-circuit experiment for different X_d values set in the generator model, and the experimental results showed that the errors between the set and measured values in X_d are very little; For transient condition, we know from equation (2) that, beside X_{ad}, time constants such as $T'_{d0}, T''_{d0}, T'''_{d0}$, T'_d, T''_d, T'''_d, etc. are also critical parameters for the transient dynamic characteristics of SCG, therefore, the values of T'_{d0} and T''_d, T'''_d are tested for transient-state condition by method of open-circuit and sudden short-circuit experiments, and the experimental results showed that there are less than 5% relative errors occurred in the measured value of T'_{d0} and T''_d from the set values. Because T'_d is much longer than T''_d, the relative error in T'_d should be less than that in T''_d. However, the relative error in T'''_d is relatively larger, this is because of the loss of accuracy when they are obtained from the transient waves, since T'''_d is too short to be measured with good precision.

From the experimental results on electrical characteristics with single-machine model, it was verified that the developed model could simulate the behavior of SCG with satisfied accuracy. By the way, if current resources with better accuracy are utilized, better accuracy in these generator constants could be obtained.

3.2 Conventional Generator (CG) Model

Conventional generator models of analog type real-time power system simulator are used. Generator is modeled base on Park equations and computations are done in real-time by use of analog amplifier. These generator models give three-phase instantaneous values of power output. The generator parameters such as operational impedances and time constants are fixed. Three types of AVR and GOV models can be chosen for generator controls.

3.3 Transmission Line and Load Models

Transmission line models of analog type real-time power system simulator are used. Transmission line is simulated by use of coils and capacitors. Typical impedance of 500 kv transmission line is adopted for these models. Several types of transmission line length (8 km, 12 km, 16 km, 20 km, 30 km, 40 km, 50 km or double of them) can be selected. Circuit breakers (CB) are simulated by use of thyristor switches.

RLC load (constant-impedance static load) model of analog type real-time power system simulator are used in this experiment. Resistance, reactance and capacitance can be set respectively, and several values of R,

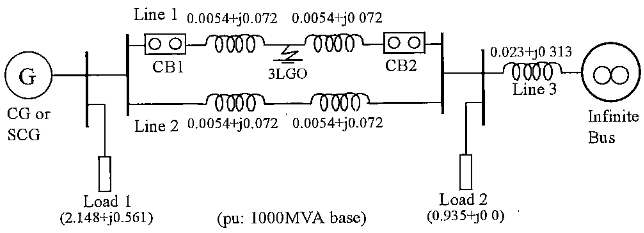

Fig. 4. One-machine infinite bus (1G-IB) model

Table 1. Experimental cases and generator constants (5000 MVA based values) for 1G-IB system

CASES	1	2	3	4	5	6	7	8
Type	CG	SCG						
Xd(pu)	1.7	0.42	0.6	0.6	0.6	0.6	0.6	0.6
X'd(pu)	0.35	0.328	0.328	0.42	0.42	0.42	0.42	0.42
X"d(pu)	0.25	0.23	0.23	0.23	0.35	0.35	0.35	0.35
X'"d(pu)	--	0.177	0.177	0.177	0.177	0.177	0.177	0.177
Xq(pu)	1.7	0.42	0.6	0.6	0.6	0.6	0.6	0.6
X'q(pu)	0.35	--	--	--	--	--	--	--
X"q(pu)	0.25	0.23	0.23	0.23	0.35	0.35	0.35	0.35
X'"q(pu)	--	0.178	0.178	0.178	0.178	0.178	0.178	0.178
T'd0(sec)	4.857	15.88	15.88	15.88	15.88	15.88	80.0	15.88
T"d0(sec)	0.042	0.107	0.107	0.107	0.107	0.107	0.107	0.107
T'"d0(sec)	--	0.013	0.013	0.013	0.013	0.013	0.013	0.013
T'q0(sec)	1.001	--	--	--	--	--	--	--
T"q0(sec)	0.042	0.33	0.33	0.33	0.33	0.33	0.33	0.33
T'"q0(sec)	--	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Xl(pu)	0.225	0.2	0.2	0.2	0.2	0.32	0.32	0.32
Ta(sec)	0.4	0.12	0.12	0.12	0.12	0.12	0.12	0.24
M(sec)	8.0	7.4	7.4	7.4	7.4	7.4	7.4	7.4

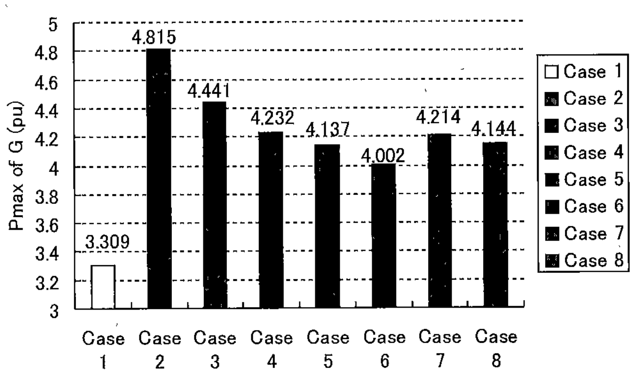

Fig. 5. Maximum values of generator power outputs in cases of different generator constants

L and C can be used for construction of different load values.

4. Experimental Results

4.1 Experimental Results in cases of Different Generator Constants One-machine infinite bus (1G-IB) model shown in Fig. 4 is used. The fault is assumed to be a 70 msec 3 LG on transmission line 1 which is cleared by opening the circuit breakers of both ends. Generator terminal voltage is 1.05 pu; In order to study the ability of the main bodies of SCG and CG, no AVR and GOV control are considered for both CG and SCG in these experiments.

Generator constants for CG and SCG are listed in Table 1. IEEJ (The Institute of Electrical Engineers of Japan) standard generator constants are adopted for CG (case1) [7]. Generator constants of the 70 MW class SCG model machine are used for SCG (case2). Generator constants in cases 3~8 are based on those in case2.

Maximum generator power outputs (P_{max}, 1000 MVA based pu values) in these cases are measured by real-time simulation and illustrated in Fig. 5.

By comparing P_{max} in case 2~8 (SCG) with that in case1 (CG), it is known that generator power output increase of 20~40% by use of SCGs.

The change in P_{max} following the change in generator constants can be studied based on the results in Fig. reff5. From these results, when AVR control is not considered, the following conclusion in Table 2 can be summarized.

Table 2. Dependence of P_{max} upon SCG constants

(1) Among SCG generator constants, the value of Xd and T'_{d0} affects Pmax most strongly
(2) Smaller values in Xd, X'd, X"d, Ta and Xl result in a larger Pmax; the changes (to be smaller) in Xd, X'd and Xl bring about better effects than the change in X"d and Ta
(3) More Pmax is obtained with longer time constants T'_{d0}

From the results in this experiment, it have been clarified that, when no control systems are considered, SCG can give much more stable power output than CG. In other wards, even without any complex control, SCG can keep enough power output on account of its own good stability that CG does not have, this is because SCG have the features of lower impedances, shorter Ta and much longer T'_{d0} than that of CG. The property is very attractive especially for the power system including remote site fluctuating power plants while the maximum generator power output is limited by power system stability.

It is also cleared that different generator constant for SCG may bring about different effect on system stability, especially the conclusion (3). Usually, we think that the long time constant of T'_{d0} may not be a good property for SCG, however, it is known from this experiment that, longer time constant is absolutely a good property for SCG when AVR control is not adopted.

In conclusion, because there is more flexibility in design of generator constants for SCG, these generator constants should be selected formerly in order to obtain the most adequate P_{max} for a power system.

4.2 Experimental Results in Multi-machine Power System Model 3-machine infinite bus (3G-IB) power system model shown in Fig. 6 is used to study the characteristic of SCG in a multi-machine power system. In this model, G1 is a group of generators with enough power resource for the future increase in Load 2, Load 3 and loads included in the infinite bus; the infinite bus is actually a large group of generators and loads; G2 and G3 are supplying the power for the local loads.

IEEJ standard generator constants (case1 in Table 1) are used for all CG; generator constants of 70 MW class SCG model machine (case2 in Table 1) are used for

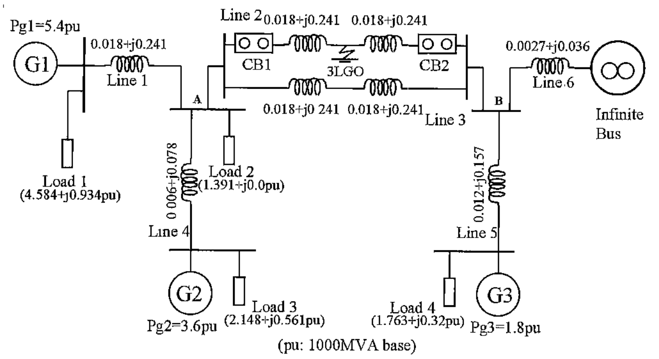

Fig. 6. 3-machine infinite bus system model

Table 3. Experimental cases for 3-machine infinite bus system

	G1	G2	G3	Measured parameter
Case 1	SCG	CG	CG	P_{G1}
Case 2	CG	CG	CG	P_{G1}
Case 3	CG	SCG	CG	P_{G2}
Case 4	CG	CG	CG	P_{G2}

1. Generator that is not shadowed keeps constant output as that in the initial condition
2. All loads are kept constant as that in the initial condition

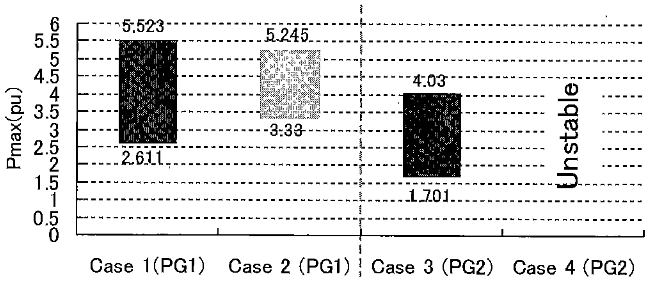

Fig. 7. Available generator power outputs in 3G-IB power system mode

SCG. The fault on transmission line 2 is assumed to be a 70 msec 3 LG and cleared by opening the circuit breakers of both ends. Generator terminal voltage for all generators is 1.05 pu. For the same reason mentioned in section 4.1, no AVR and GOV control are considered for both SCG and CG.

Experimental cases shown in Table 3 are done for the power system in Fig. 6.

The maximum values of generator power output P_{max} (1000 MVA based pu values) are measured and given in Fig. 7. Please note that, we are using pu values for SCG/CG modeling, although the generator constants in 5000 MVA based pu values are adopted for generator modeling, generator capacity can be more than 5000 MVA.

From Fig. 7, when no AVR control is considered for both SCG and CG, the following conclusions can be obtained:

(1) By replacing G1 from CG to SCG, the available power output range of G1 is extended from 1.915 pu to 2.912 pu with an increase of 52.06%. A larger P_{max} for G1 means more power can be transmitted from G1 to the loads included in infinite buses through the long tie transmission lines. On the other hand, a lower P_{min} for G1 means G1 can reduce more power so as to have more of the remainder power in infinite bus be transmitted to the loads in the left side of this system, e.g., in the case when those loads included in infinite buses become lighter during the nighttime.

(2) Because the tie transmission line 2 & 3 are very long, after the fault, the voltage of bus A is mainly kept by G1 and G2. Since transmission line for G1 is longer and power output and local load for G1 is heavier than that for G2, G2 is playing a great role in keeping the voltage of bus A during the fault. When G2 is CG (without AVR control), during the fault, the voltage of bus A becomes very low, and the very slow oscillation between the left side (G1 & G2 group) and right side (G3 & IB group) cannot be suppressed, the whole system tends to be unstable. However, if G2 is SCG, because SCG owns high stability itself even without AVR control, the system can operate with a large available power output range from 1.701 pu to 4.03 pu without causing any stability problems.

(3) There exists not only a maximum value, but also a minimum value in the generator power output for this power system. This result reminds us that, in power system operation, not only the available maximum generator power output should be paid great attentions, but also the available minimum generator power output should be considered as well.

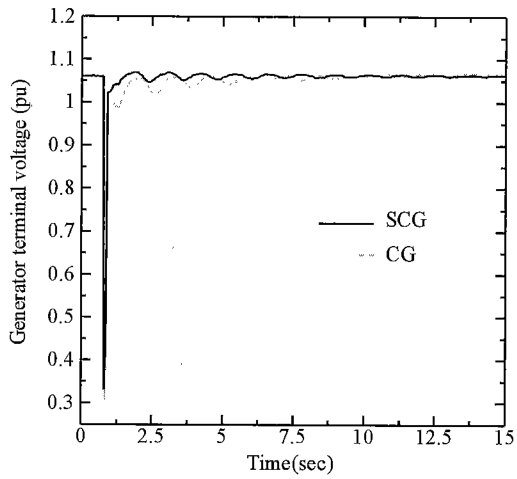

Fig. 8. Generator terminal voltage of G1 during the fault

In order to know the reason why SCG has better stability effects than that of CG, the swing curves of generator terminal voltage of G1, when G1 is SCG or CG under the same operating condition, are shown in Fig. 8. It can be seen that, the generator terminal voltage drop at fault is smaller and the terminal voltage recovers much quickly in the case of SCG than that of CG. This is because of that, SCG have the ability in keeping higher internal fluxes during the fault and therefore can withstand a contingency under heavier operating condition than CG.

5. Conclusions

With many advantages that may lead to some good properties in an improved power system, superconducting generator (SCG) is one of candidates to meet the needs of higher stability and higher efficiency in the future power system networks.

In this work, a digital type SCG model for an existing analog type real-time power system simulator is developed and introduced. By use of the above-mentioned equipments, real-time simulations in one-machine infinite bus power system model in cases of SCG with different generator constants and real-time simulations in case of SCG in multi-machine power system are carried out. By this simulation study, the influence of different generator constants on stability-improving effects of SCG has been clarified, and the advantages of the main body (without control systems) of SCG over CG for power system stability enhancement has been verified—the available generator power output range of SCG is wider and terminal voltage drop at fault of SCG is smaller than that of CG.

Further studies utilizing these equipments will be done and introduced in the future works, which will show the effects of SCG on power system abilities under the power system network open-access environment.

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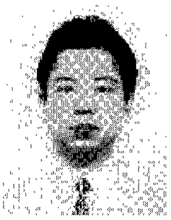

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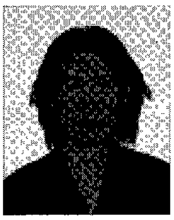

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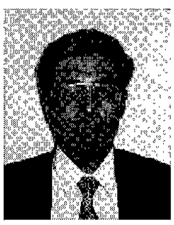

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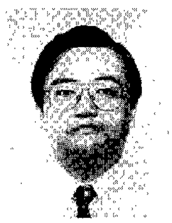

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