Consideration of Effect of Excitation Power of Self-Excitation AVR on Synchronous Stability

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***Abstract*—Along with the increase of photovoltaics capacities in power systems, several thermal generation units must be stopped to maintain power supply-demand balance. As a result, the synchronous stability could be negatively affected by the lower system inertia. Hence, it is necessary to more accurately evaluate the stability of each generator. Therefore, phenomena which have been neglected due to the increase of calculation load in the past required to be considered in stability analysis. The focus of this study is the effect of the excitation power of self-excitation AVR on synchronous stability. The effect has been neglected in conventional stability analyses. However, in actual power systems, exciters of self-excitation AVRs are connected to generator terminals and exchange the excitation power with the power systems. In this study, the effect of the excitation power on the accuracy of stability analyses was evaluated using a linearized model and numerical simulations.**

***Index Terms*—Linearized model, numerical simulation, self-excitation AVR, synchronous generator, synchronous stability.**

I. Introduction

With the improvement of power electronics technology and increasing concerns about global warming, the installation of renewable energy system has been growing rapidly. However, the expanding installation of renewable energy systems, especially photovoltaic (PV) generation, can have a significant impact on power system behavior. Since PV systems are connected power grids through power conditioning systems (PCSs), PV systems do not have inertia. With the increasing capacity of PV generation in power systems, several thermal units must be stopped to maintain the power supply-demand balance. As a result, the synchronous stability could be negatively affected by the lower system inertia. This may make power system planning more difficult. Therefore, it is necessary to more accurately evaluate the stability of each generator.

Moreover, the performance of computers used for power system analysis has improved in recent years as a result of the improvement of semiconductor and calculation technology. The phenomena, which have been neglected due to the increase of calculation load in the past, can be included in stability analysis.

The focus of this study is the effect of excitation power of self-excitation AVR on synchronous stability. The effect has been neglected in conventional stability analyses and the design of excitation control systems. However, in actual power systems, the exciters of self-excitation AVRs are connected to generator terminals and exchange the excitation power with the power systems. In a previous study [1], equations considering the effect of the excitation power were derived for the design of an excitation control system in a superconducting generator (SCG) with high-response excitation and the effect of the excitation power on the synchronous stability was confirmed through numerical simulations. On the other hand, self-excitation AVRs are also used in conventional (i.e., normal-conducting) generators. Therefore, the accuracy in the design of excitation control systems and stability analyses can be improved in conventional generators by considering the effect of the excitation power of self-excitation AVRs. In this study, the effect of the excitation power used in conventional generators on the accuracy of stability analyses was evaluated using a linearized model and numerical simulations.

II. Linearized Model Considering the Excitation Power of Self-Excitation AVR

In this section, a previously proposed linearized model considering the excitation power of a self-excitation AVR [1] is briefly described.

A. *Effect of the Excitation Power of the Self-Excitation AVR of a Superconducting Generator with High-Response Excitation on Synchronous Stability*

SCGs with high-response excitation have self-excited thyristor systems. A simplified configuration of an SCG with a high-response self-excitation AVR is depicted in Fig. 1 [2].

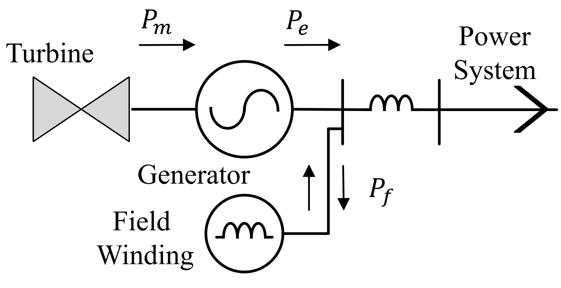

Figure 1. Simplified configuration of SCG with self-excitation AVR.

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Since SCGs have superconducting field windings, they have smaller field winding resistances and larger open-circuit time constants compared with conventional generators. Therefore, the ceiling voltage for high-response excitation SCG is designed very high and the capacity of the exciter becomes large. Thus, a large excitation power flows rapidly into the generator terminal by the rapid change of the field voltage after the fault occurred in the power system. The excitation power increases the electric load of the generator and suppresses acceleration of the generator after fault contingency.

B. Block Diagram for Small-Signal Stability Including the Effect of Excitation Power of the Self-Excitation AVR

A block diagram for small-signal stability including the effect of the excitation power of the self-excitation AVR was proposed in [1]. It was assumed that only the active power affects the condition of the power system. The equations describing the system are given by

$$\Delta P_g \cong X_e/(X_d{}' + X_e)\Delta P_f, \qquad (1)$$

$$\Delta P_f = V_{f0}/X_{afd}\left(\Delta E_{fd} + (\Delta E_q{}'/K_3) + K_4\Delta\delta\right), \qquad (2)$$

$$\Delta P_g \cong K_7\left(\Delta E_{fd} + (\Delta E_q{}'/K_3) + K_4\Delta\delta\right), \qquad (3)$$

$$K_7 = X_e/(X_d{}' + X_e) \cdot (V_{f0}/X_{afd}), \qquad (4)$$

where P_g is the generator active power, P_f, the excitation power, X_e, the line reactance, $X_d{}'$, the d-axis transient reactance, X_{afd}, the mutual reactance between the d-axis armature winding and the field winding, V_{f0}, the field voltage of operating point, E_{fd}, the field voltage, $E_q{}'$, the voltage behind the d-axis transient reactance, and δ, the internal phase angle. From equations (1) and (2), we got equations (3) and (4). The coefficient K_7 is newly defined in [1] and represents the effect of the excitation power on the synchronization torque. To consider the effect, the part drawn in the bold line in Fig. 2 was added based on equations (3). The block diagram for small-signal stability without considering the effect of the excitation power is the same as the diagram in Fig. 2 excluding the bold line.

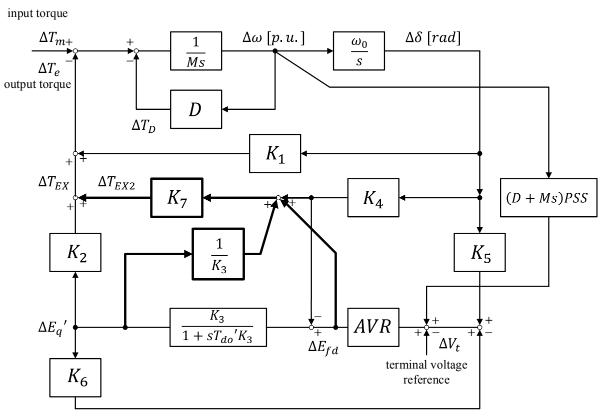


Figure 2. Block diagram for small-signal stability including effect of excitation power of self-excitation AVR.

Fig. 2 shows that the changes in the excitation voltage produce variation in the synchronization torque ΔT_{EX} without a time delay by the open circuit time constant $T_{do}{}'$. It shows the effect of the change of the excitation power to suppress acceleration of generator is faster than the stabilizing effect considered in conventional stability analysis.

III. Quantitative Evaluation of Effect of the Excitation Power

A. Magnitude of the Effect of Excitation Power on the Synchronization Torque

In this study, the effect of the excitation power on the synchronization torque was evaluated based on Fig. 2 using the machine constants of a thermal generation unit with a rated capacity of 555 MVA as an example [3]. In the case shown in Fig. 2, the effect of the field voltage on the synchronization torque is given as equation (5).

$$\Delta T_{EX2} = K_7\Delta E_{fd} + K_7\Delta E_{fd}/(1 + sT_{do}{}'K_3). \qquad (5)$$

A linearized model of single-machine infinite bus system with the same configuration as in [1] was considered in this study. The generator was connected to the infinite bus through a step-up transformer, the parallel transmission lines, and a connection transformer. The impedances of these parts are 0.1, 0.3, and 0.1 p.u., respectively, and yielding a total system reactance of 0.5 p.u. The rated values and machine constants of the generator, hereafter referred to as G1, are listed in Tables I and II. The operating point was at the rated load condition.

TABLE I. Rated Values of the Generators

Quantity	G1	G2	G3
Capacity	555 MVA	20 MVA	5 MVA
Voltage	24 kV	11 kV	11 kV
Frequency	60 Hz	60 Hz	60 Hz
Number of poles	2	4	4
Power Factor	0.9	0.9	0.9
Field voltage	241 V	45.8 V	22.9 V
Field current	3377 A	640.8 A	320.4 A

Note : The values of field voltage and current are on the rated load.

TABLE II. Machine Constants of the Generators

Quantity	G1	G2, 3	Quantity	G1	G2, 3
X_d (p.u.)	1.81	1.98	X_q (p.u.)	1.76	1.96
$X_d{}'$ (p.u.)	0.3	0.2	$X_q{}''$ (p.u.)	0.245	0.22
$X_d{}''$ (p.u.)	0.23	0.16	$T_d{}'$ (sec)	1.34	0.20
X_l (p.u.)	0.15	0.07	$T_d{}''$ (sec)	0.0755	0.0390
X_{afd} (p.u.)	1.66	1.91	$T_{do}{}'$ (sec)	8.07	1.98

TABLE III. COEFFICIENTS IN THE LINEARIZED MODEL

Coefficient	Value	Coefficient	Value
K_1	0.760	K_5	0.031
K_2	0.965	K_6	0.459
K_3	0.346	K_7	0.980
K_4	0.505		

The calculation results of the synchronizing power coefficients at the operating point are given in Table III. A coefficient value of $K_7 = 0.98$ was obtained from equation (4). As shown in Table III, the magnitude of K_7 is not smaller than those of the other coefficients. Therefore, the accuracy of excitation control system design and stability analyses in conventional generators can be improved by considering the effect of the excitation power.

B. Calculation of the Energy Stored in Field Winding

As an indication of the scale of the change in the excitation power of the self-excitation AVR, the magnetic energy stored in the field winding was estimated. The values for G1 listed in Table I were used for the calculation. The inductance of the field winding was 0.58 H. The energy stored in the field winding at the rated load is given by equation (6),

$$(1/2)L_{ffd}{I_f}^2 = (1/2)\cdot 0.58\cdot 3377^2 = 3.3\ [\text{MJ}], \qquad (6)$$

where I_f is the field current, and L_{ffd}, the inductance of the field winding. From equation (6), effect of the excitation power on the synchronous stability would be large enough to be considered in stability analysis and the design of excitation control systems, depending on the location of the fault and the magnitude of the change in the excitation power.

IV. NUMERICAL SIMULATION

The effect of the excitation power of self-excitation AVR on the synchronous stability indicated in the previous section was examined through numerical simulations by comparing the transient stability with the excitation power to that without. The excitation controllers used in this study are the conventional ones designed without considering the excitation power. The simulations were conducted using eXpandable Transient Analysis Program (XTAP) [4]. A program is widely used in Japan. The time step for the numerical integration was set to 100 µs.

A. Current Source Model

To confirm the effect of the excitation power on the synchronous stability through numerical simulation, the excitation power was simulated as a current source. The output of the model is given by

$$P_f = V_f \cdot I_f, \qquad (7)$$

$$I_{ref} = V_f \cdot I_f / V_t, \qquad (8)$$

where V_f is the field voltage, I_f, the field current, V_t, the terminal voltage, and I_{ref}, the output of current source. This model was connected to each phase of the generator terminal. It was assumed that one third of the excitation power P_f flowed equally to and from each phase.

B. Evaluation in Single-Machine Infinite Bus System

Fig. 3 shows the single-machine infinite bus system model used in the numerical simulations. The reference values of the line voltage, capacity, and frequency of the per-unit system are 24 kV, 555 MVA, and 60 Hz, respectively. The per-unit values of the line impedances are shown in Fig. 3. The rated values and machine constants of G1 are given in Tables I and II, respectively. As for the excitation controllers, G1 was equipped with the AVR and power system stabilizer (PSS) called LAT152 (Fig. 4), which is one of the standard models used in Japan [5]. The AVR in LAT152 is rapid type and used for large capacity generators. The characteristic of the speed governor (GOV) was given by

$$T_m = T_{m0}/\omega, \qquad (9)$$

where T_m is the mechanical torque, T_{m0}, the initial value of mechanical torque, and ω, the angular velocity. Magnetic saturation was not considered in this study.

To compare the transient stability with the excitation power to that without, the four different cases defined in Table IV were simulated. A symmetrical three-line-to-ground fault was assumed as a network disturbance to evaluate the transient stability. The fault occurred at the midpoint of Line 2 at 0.5 s. The circuit breakers CB1 and CB2 on both ends of the faulted line were opened at 0.57 s to clear the fault. The faulted line was reclosed at 1.57 s only in cases A and B. The transient stability limit powers were investigated in all four cases and the results are given in Table IV.

The simulation results of the internal phase angle and the output power in all four cases are shown in Fig. 5. The active powers of the generators were set to the transient stability limit power in case D (0.86 p.u.).

TABLE IV. SIMULATION CASE

	Reclosed : Pg	Not Reclosed : Pg
With excitation power	A : 0.865	C : 0.863
Without excitation power	B : 0.863	D : 0.860

Note : Pg is the transient stability limit power (p.u.).

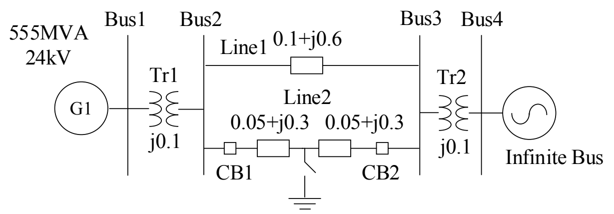


Figure 3. Single-machine infinite bus system model.

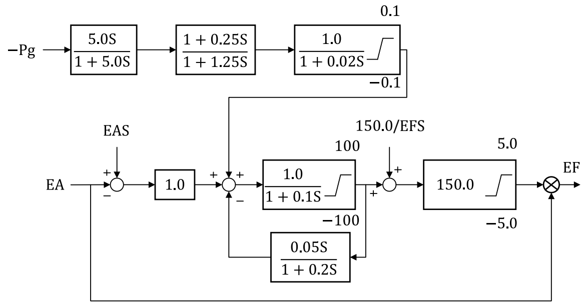
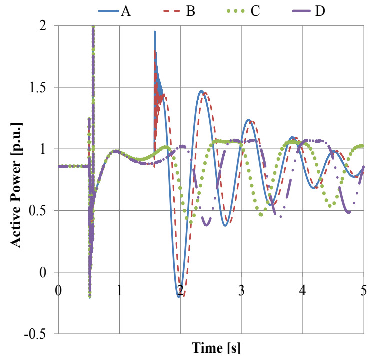
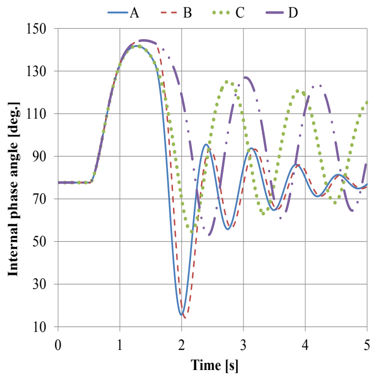


Figure 4. Block diagram of the AVR and PSS used for G1.



(a) Active power.



(b) Internal phase angle.

Figure 5. Results of the simulation of one machine infinite bus system.

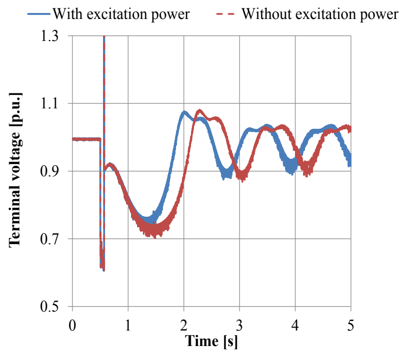
As shown in Fig. 5, when the excitation power was considered (A and C), the fluctuation of the active power and the internal phase angle decreased more rapidly than in the case without the excitation power (B and D).

In case C, since the line reactance remained large, the output power was not as large as in case A. Therefore, in case C, the ratio of the excitation power to the output power was larger, and the effect of the excitation power on the synchronous stability was more significant than in case A.

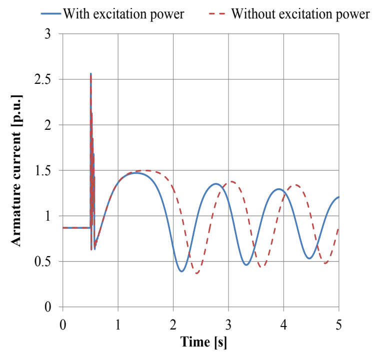
The simulation results of the terminal voltage, the armature current, field voltage, field current, and excitation power in cases C and D are shown in Fig. 6. The reference values of per unit system for the field voltage, the field current, and the excitation power of G1 are 92.7 V, 1300 A, 120.5 kW, respectively. In this study, the reference values for the quantities in the field circuit were defined as the values when the generators are operating at the rated rotating speed and the rated terminal voltage with no load.

As shown in Fig. 6 (a), in the case with the excitation power, the recovery of the terminal voltage was faster than in the case without the excitation power. This is because the armature current (Fig. 6 (b)) decreased faster in response to the decreases in the internal phase angle (Fig. 5 (b)) and the active power (Fig. 5 (a)) between 1.2 s and 2 s. During this period, the field voltage, the field current, and the resultant excitation power was large as seen in Fig. 5 (c) to (e). The excitation power increased the electric load of the generator, suppressed the acceleration of the generator and brought quick recoveries to the internal phase angle and the terminal voltage.

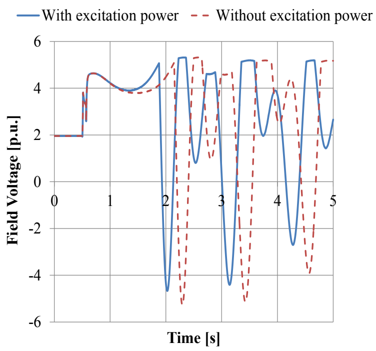
From these results, it is considered that the effect of the excitation power on the accuracy of stability analysis is larger when one line is stopped.



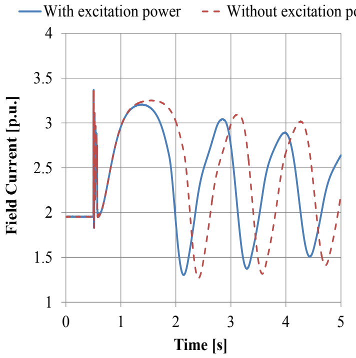
(a) Terminal voltage.



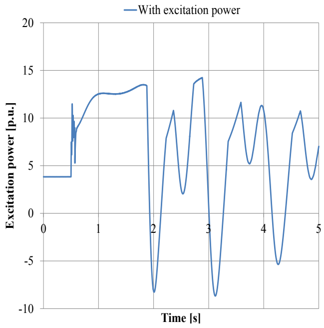
(b) Armature current.



(c) Field voltage.



(d) Field current.



(e) Excitation power.

Figure 6. Results of the simulation of single-machine infinite bus system (Case C and D).

C. Evaluation in Double-Machine Infinite Bus System

Fig. 7 shows the double-machines infinite bus system model used in the numerical simulation. This system was developed assuming an example of a local power system in which the double local generators with different capacities are connected to the higher voltage system through a step-up transformer, a set of parallel transmission lines, and a substation. The reference values of the line voltage, capacity, and frequency for the per-unit system are 11 kV, 20 MVA, and 60 Hz, respectively. The per-unit values of the line impedances are shown in Fig. 7. The rated voltages of Buses 1 to 4 were assumed to be 11, 66, 66, and 275 kV, respectively. For simplicity, the step-up transformer and the substation were simulated as impedances. The rated values and machine constants of the generators, hereafter referred to G2 and G3, are given in Tables I and II [6]. The rated values of field voltage and current were calculated from [3]. As for the excitation controllers, G2 was equipped with the AVR shown in Fig. 8 and G3 was equipped with an automatic reactive power regulator (AQR). The AVR shown in Fig. 8 is standard for middle capacity generators. A block diagram and parameters of the AQR and its parameters are given in [7]. The characteristic of the GOV is given by equation (9).

The fault sequence was the same as in case C. The fault occurred at the 10% point from Bus 2 of Line 2. The active powers of the generators were set to the transient stability power limit (0.685 p.u.).

The simulation results of the numerical simulations of the internal phase angle and the excitation power of G2 in cases with and without the excitation power are shown in Fig. 9. The reference values of per unit system for the field voltage, the field current, and the excitation power of G2 are 17.6 V, 246.5 A, 4.338 kW, respectively.

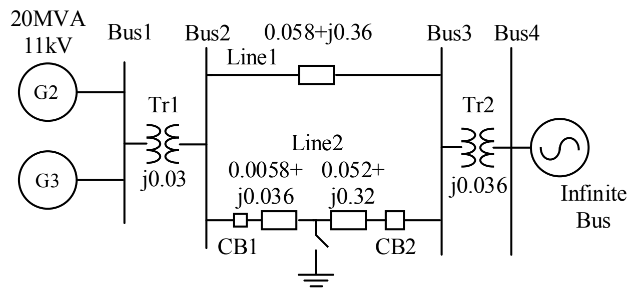


Figure 7. Double-machine infinite bus system model.

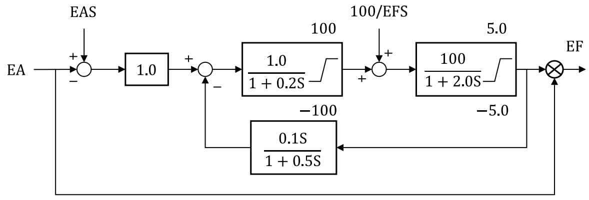
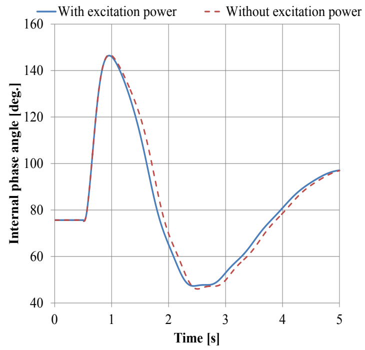
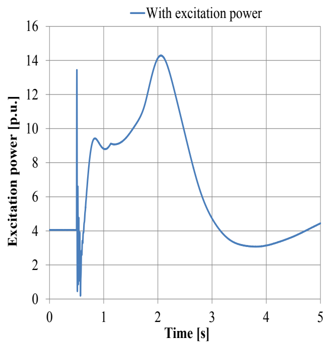


Figure 8. Block diagram of the AVR used for G2.



(a) Internal phase angle.

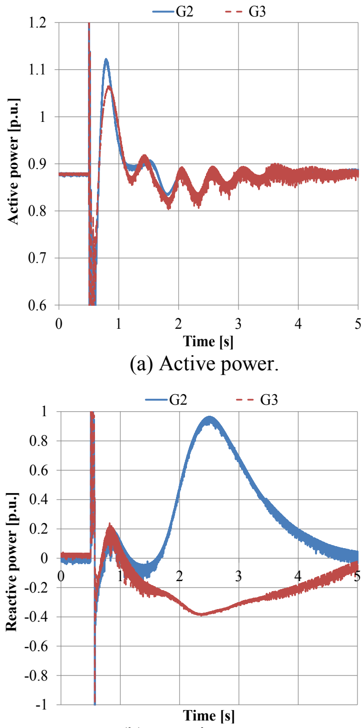


(b) Excitation power.

Figure 9. Results of G2 of the simulation of double-machine infinite bus system.

As shown in Fig. 9, in the case with the excitation power, the recovery of the internal phase angle was faster than in the case without the excitation power. However, in this situation, the difference between the cases with and without the excitation power was smaller than that in case C. Since the time constants of the AVR of G2 in this case were larger than G1 in case C, the excitation power in this case increased more slowly than in case C. Therefore, the effect in case with the excitation power was smaller.

The simulation results of the active and reactive power of G2 and G3 in case with considering the excitation power are shown in Fig. 10. The reference value of per unit system for the active and reactive power of G2 is 20 MVA and the value for those of G3 is 5 MVA; these are the rated capacity of each machine.



(a) Active power.

(b) Reactive power.

Figure 10. Results of G2 and G3 of the simulation of double-machine infinite bus system.

As seen in Fig. 10, the fluctuations in the active powers of G2 and G3 were in same phase. Therefore, it was confirmed that the effect of the excitation power on synchronous stability was examined without influence of exchange of active power between the two machines.

However, the variations in the reactive power of G2 and G3 were not in same phase. This is because cross-current compensation systems were not applied in this study and some inductive current flowed from G2 to G3. To verify the effect of the excitation power on the synchronous stability more precisely including voltage characteristics in multi-machine power systems, generators should be equipped with proper cross-current compensation systems.

V. Conclusion

In this study, the effect of the excitation power of self-excitation AVRs for conventional generators on the accuracy of stability analysis was evaluated using a linearized model and numerical simulations. It was confirmed that the accuracy of excitation control system design and the transient stability was improved when the effect of the excitation power was considered. This indicates that more accurate analysis may enable an increase in the amount of renewable energy generation in cases where the generation is restricted by constraints on the transient stability. The design of an excitation control system considering the effect of the excitation power and the evaluation of its effect on the power system stability remain as tasks for future studies.

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