Development of a Quick-Response Superconducting Generator Model for Electromagnetic Transient Analysis of Power Systems

Reiko Kato and Orie Sakamoto
Dept. of Engineering and Applied Sciences
Sophia University
Tokyo, Japan
kato_r13@eagle.sophia.ac.jp

Abstract— **In Japan, to realize low-carbon society, Advanced Low Carbon Technology Research and Development (ALCA) Project has been promoted to develop low-carbon technologies. The hydrogen cooled super-conducting generator (SCG) is one of them. SCGs have advantages such as low synchronous reactance and expansion of leading power factor operation, which expands the stability limit of power grid. Therefore, hydrogen cooled SCGs can be effective not only to low carbonization but also to stabilize high renewable energy (RE) penetration power grid. This study intend to model SCG with quick response excitation on electromagnetic transient (EMT) analysis software named eXpandable Transient Analysis Program (XTAP) and analyze grid stability, behavior of machines at power system fault situation, etc. accurately in order to reveal advantages of installing SCGs with quick response excitation.**

Index Terms—**Electromagnetic transient analysis, power system, superconducting generator, synchronous machine, XTAP.**

I. Introduction

CO_2 accounts for the largest percentage of greenhouse gases, and it is hoped that its production will be suppressed by creating a low-carbon society. The Advanced Low Carbon Technology Research and Development Program (ALCA) was started in 2010 to develop low-carbon technologies in Japan. One of target practical application programs of ALCA is to develop superconducting generators (SCGs) cooled by hydrogen. SCGs use hydrogen as an energy carrier, and the use of this fuel can greatly reduce CO_2 emissions from their present levels. It is hoped that the creation of a hydrogen infrastructure will lead to the introduction of hydrogen-cooled SCGs into power grids. Hydrogen-cooled SCGs, which are suitable for generation systems using hydrogen turbines, are expected to result in a high system efficiency and low CO_2 emissions. SCGs are also considered to enhance the stability of power systems highly penetrated by renewable energy (RE) systems.

This work was supported by the Advanced Low Carbon Technology Research and Development (ALCA), Japan Science and Technology Agency.

SCGs have a quarter of the synchronization reactance of conventional synchronous generators. Therefore, when SCGs are introduced into power grids, they enable high effective power outputs at small internal phase angles, which improves the synchronous stability. SCGs do not require iron cores, which cause magnetic saturation. Therefore, the operating range can be expanded and this also can support power grid voltage stability.

SCGs have been developed in different countries since the 1970s with the development of superconductor technologies. In Japan, a 70 MW class SCG was developed as part of the Super-GM project, and an operating test was successfully conducted in an actual power grid [1]. Thus, a low-temperature SCG is now already at the stage of practical use. Furthermore, a superconductor synchronous condenser has been developed in the United States [2]. This machine is based on a high-temperature superconductor and is already operating on the grid.

In this study, a new quick-response excitation SCG model was developed using electromagnetic transient (EMT) software called eXpandable Transient Analysis Program (XTAP). Generally, EMT software such as Electromagnetic Transients Program (EMTP) uses the trapezoidal rule. However, since the trapezoidal rule is a single-step method, fluctuations in the numerical results tend to arise when the inductor current and capacitor voltage change suddenly. This problem is exacerbated when large numbers of power electronic devices are connected and switching operations are executed. In contrast, the rotating machine model developed by the present authors in XTAP uses an approach combining a two-stage diagonally implicit Runge-Kutta method (2S-DIRK) and a second-order Runge-Kutta method (RK2) [3]. This approach overcomes the problem of fluctuations in the numerical results. XTAP also has the advantage of ease of model expansion in its graphical user interface and modularized components. Therefore, XTAP is very useful in the analysis of power systems containing rotating machines and power electronic devices, such as inverter connected photovoltaic generators.

The aim of this study is to model an SCG with quick-response excitation using XTAP and accurately analyze the power grid stability and behavior of machines at power system fault situation with the ultimate goal of achieving the practical implementation of quick-response excitation SCGs with hydrogen cooling.

II. NEWLY DEVELOPED SCG MODEL

A. *Target of Modeling*

There are two types of low-temperature SCGs: slow- and quick-response excitation SCGs. The slow-response excitation SCG has two damper cylinders in the rotor, a low-temperature damper and a room-temperature damper, as shown in Fig. 2 in [4]. These damper cylinders isolate field windings from the outer magnetic variation. The characteristics of the magnetic flux that originate in these damper cylinders must be considered when modeling the slow-excitation SCG. The numerical equations of this type of SCG are shown in [5].

In the developed model, the characteristics of a low-temperature SCG with a quick-response excitation were considered. The quick-response excitation SCG model is operated by the quick excitation of the field current and has one low-temperature damper cylinder with no magnetic shielding to transmit the effect of the excitation control to the armature of the rotor. This dynamic excitation and low synchronous reactance of the SCG enables the improvement of the power grid.

MgB_2 is considered as a candidate material for the field winding of this SCG. It can achieve a strong magnetic field at high temperatures around 20 K, which reduces the cooling cost. Therefore, the hydrogen-cooled SCG studied by ALCA is expected to be more economical than existing SCGs. This hydrogen cooled SCG is intended to be introduced not only as large capacity generator in distant areas but also as small and medium capacity generator near load center.

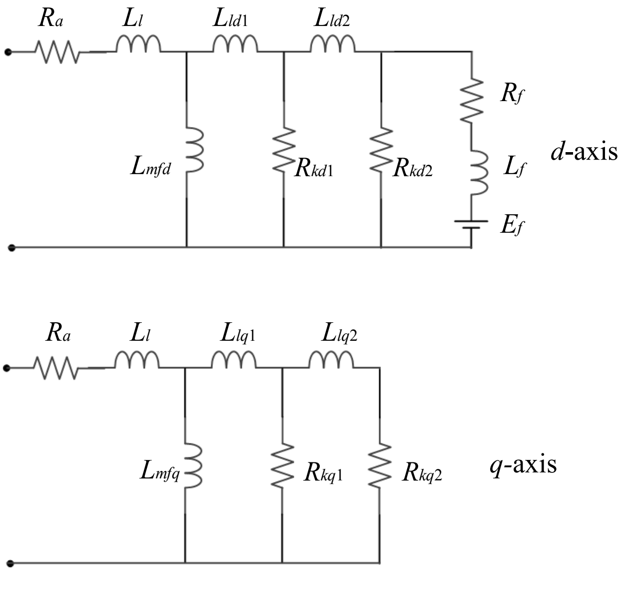


Figure. 1. Equivalent circuit used for developed SCG model based on [6].

B. *Equivalent Circuit used in the Developed SCG Model*

A study was previously conducted on the equivalent circuit modeling of the 70 MW class quick-response SCG [6]. It has been confirmed that the equivalent circuit has high accuracy including variations in the field current in comparison with the test results of the SCG. Therefore, this equivalent circuit was adopted for the SCG model developed in this study.

Fig. 1 shows the configuration of the *d*- and *q*-axis equivalent circuits used in the developed SCG model. The *d*- and *q*-axis equivalent circuits each have two damper windings, and the *d*-axis circuit has one more branch than the *q*-axis circuit, which represents the field winding.

C. *Numerical Equations*

The numerical equations of the developed SCG model are given in this section.

Synchronous reactance X_d in the steady state and the reactances and time constants in the transient time domain, in which the rotor current flows through the field circuit, numerical equations are given as

$$X_d = X_l + X_{mfd}, \tag{1}$$

$$X'_d = X_l + X_{mfd}//(X_{ld1} + X_{ld2} + X_f), \tag{2}$$

$$T'_{do} = (X_{mfd} + X_{ld1} + X_{ld2} + X_f)/(2\pi f_0 R_f), \tag{3}$$

$$T'_d = T''_d X'_d / X''_d, \tag{4}$$

$$X''_d = X_l + X_{mfd}//X_{ld1}, \tag{5}$$

$$T''_{do} = (X_{mfd} + X_{ld1})//(X_{ld2} + X_f)/(2\pi f_0 R_f)\ , \tag{6}$$

where X_d is the *d*-axis synchronous reactance, X'_d is the *d*-axis transient reactance, X''_d is the *d*-axis sub-transient reactance, X_l is the armature leakage reactance, X_{ld1} is the *d*-axis room-temperature leakage reactance, X_{ld2} is the *d*-axis low-temperature leakage reactance, X_{ld3} is the *d*-axis vessel and winding shaft leakage reactance, T'_d is the *d*-axis transient short circuit (S/C) time constant, T'_{do} is the *d*-axis transient open circuit (O/C) time constant, T''_{do} is the *d*-axis sub-transient O/C time constant, and R_f is the field resistance.

In the sub-transient time domain, in which the damper current flows through the room-temperature damper branch in the rotor side circuit, the numerical equations are given as

$$T''_d = T''_{do} X''_d / X'_d, \tag{7}$$

where the T''_d is the *d*-axis sub-transient S/C time constant.

In the *q*-axis, the same equations hold except without a field circuit branch. The numerical equations are given as

$$X_q = X_l + X_{mfq}, \tag{8}$$

$$X''_q = X_l + X_{mfq}//X_{lq1}, \tag{9}$$

$$T''_{qo} = (X_{mfq} + X_{ld1})/(2\pi f_0 R_{kq1}), \tag{10}$$

$$T_q'' = T_{qo}'' X_q'' / X_q, \qquad (11)$$

where X_q is the q-axis synchronous reactance, X''_q is the q-axis sub-transient axis, X_{ld1} is the q-axis room-temperature leakage reactance, T''_q is the d-axis sub-transient S/C time constant, T''_{qo} is the q-axis sub-transient O/C time constant, and R_{kq1} is the q-axis room-temperature equivalent resistance.

The armature time constant T_a is given as

$$T_a = (X_d'' + X_q'')/2/(2\pi f_0 R_f). \qquad (13)$$

The values of the inductances and resistances were automatically calculated and set in the model based on the given machine constants. Steady-state initialization is available for the developed model. The initial values for the currents in the inductances in the model were set based on the initial values obtained through the initial load flow calculation supported by XTAP. These features contribute to the reduction of time and labor costs for power system simulations. The basic constitution of the model such as connection to external system is same as previous developed slow response type SCG model [5].

III. Simulation on Single-Machine Infinite Bus System

A. Conditions of Simulation

As an example, the 10 kV power system depicted in Fig. 2 was simulated using the developed SCG model. This system simulates large capacity SCG introduced in distant area.

TABLE I. Generator Machine Constants

Symbol	Quantity	Unit	Value	
			SCG	***CG***
X_d	d-axis synchronous reactance	p.u.	0.35	1.7
X'_d	d-axis transient reactance	p.u.	0.31	0.35
X''_d	d-axis sub-transient reactance	p.u.	0.16	0.25
X_q	q-axis transient reactance	p.u.	0.35	1.7
X''_q	q-axis sub-transient reactance	p.u.	0.16	0.25
X_l	armature winding leakage reactance	p.u.	0.12	0.225
T'_d	d-axis transient S/C time constant	s	7.6	0.1
T''_d	d-axis sub-transient S/C time constant	s	0.06	0.03
T''_q	q-axis sub-transient S/C time constant	s	0.06	0.03
T_a	Armature time constant	s	0.12	0.4
M	Unit inertia constant	s	7.4	8
D	Damping coefficient	p.u.	0.0	0.0

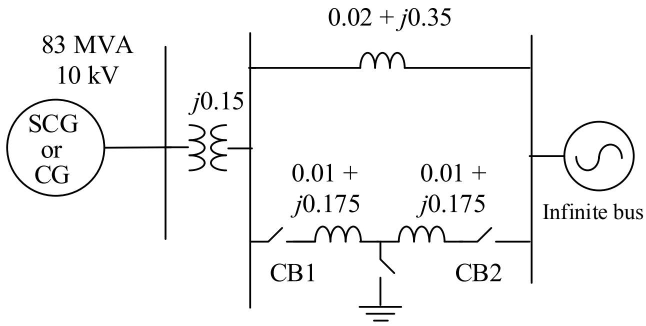


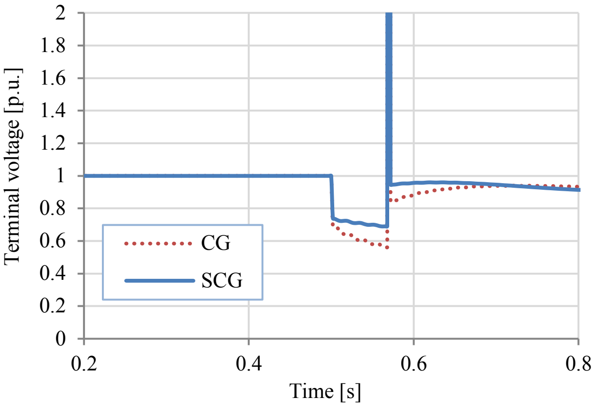
Figure. 1. Configuration of the simulated single-machine infinite bus system.

The system consists of a generator G1, a step-up transformer simulated by a reactance of $j0.15$, and a set of parallel transmission lines to an infinite bus. An SCG or a conventional (i.e., normal-conducting) generator (CG) was used for G1. For the sake of simplicity, the SCG was operated at the fixed field current, and the CG was operated at the fixed field voltage. A three-lines-to-ground (3LG) fault occurred at 0.5 s, and circuit breakers at both sides of the transmission line were opened at 0.57 s and reclosed at 1.25 s.

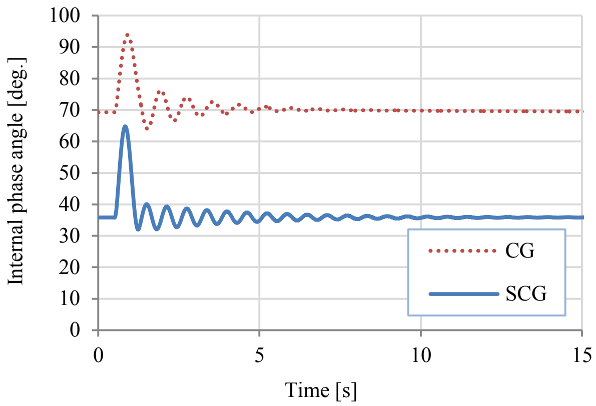
The generator constants are listed in Table I. Because MgB_2 wire for the target machine is under development, the machine constants of an existing quick-response SCG of 83 MVA were used in the simulations [4]. A parameter study to design the machine constants of the target SCG will be conducted in a future work. The reference values of the line voltage, capacity, and frequency for the per-unit system are 10 kV, 83 MVA, and 60 Hz, respectively; these are also the rated values of the CG. The corresponding rated values of the SCG are 10 kV, 83 MVA, and 60 Hz.

B. Result of the Simulation

Fig. 3(a) shows the terminal voltage of the SCG and CG at 0.5 s when the 3LG fault was applied to the system. The voltage depression of the SCG was smaller than that of the CG. Since SCGs can keep their internal magnetic flux and thus their terminal voltage higher than CGs in this type of fault situation, they are advantageous in terms of voltage stability. In present-day power systems, voltage stability problems have been drawing attention again due to the large integration of RE systems and the resulting disconnections of local thermal units. Since SCGs can manage their terminal voltage stable, they will contribute to maintaining the system voltage of power grids under the high penetration of RE sources.



(a) Terminal voltage.



(b) Internal phase angle.

Figure. 2. Simulation results of the single-machine infinite bus system.

The internal phase angle results in Fig. 3(b) show that SCGs take a longer time than CGs to return to the initial condition after the fault. Since quick-response excitation SCGs have no magnetic shields in their low-temperature dampers, they are susceptible to system faults. Another reason for this is their small unit inertia constant. However, this problem can be solved by designing a proper control system. In this simulation, the characteristics of the machine itself were examined.

Furthermore, the internal phase angle of SCG remained lower than that of the CG both before and after the fault. Because SCGs have a small synchronous reactance, as described in the previous sections, the internal phase angles of the SCG were sufficiently small at the fault. If the SCG is equipped with a proper control system, its capability to support the synchronous stability of the system with these characteristics is expected to be enhanced.

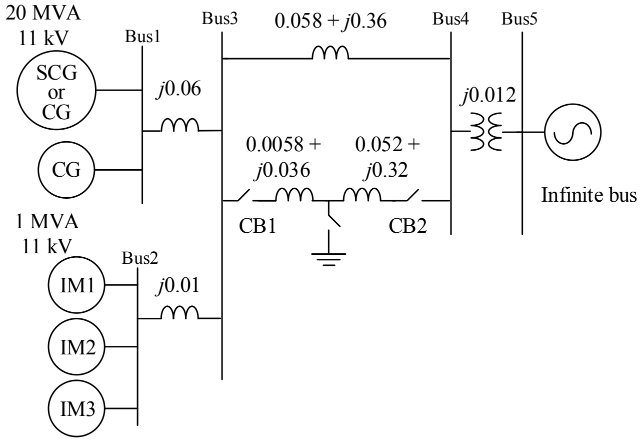


Figure. 3. Configuration of the simulated double-machine infinite bus system

TABLE II. GENERATOR MACHINE CONSTANTS

Symbol	Quantity	Unit	Value	
			SCG	***CG***
X_d	d-axis synchronous reactance	p.u.	0.35	1.41
X'_d	d-axis transient reactance	p.u.	0.31	0.206
X''_d	d-axis sub-transient reactance	p.u.	0.16	0.111
X_q	q-axis transient reactance	p.u.	0.35	1.17
X''_q	q-axis sub-transient reactance	p.u.	0.16	0.111
X_l	armature winding leakage reactance	p.u.	0.12	0.0888
T'_d	d-axis transient S/C time constant	s	7.6	0.0292
T''_d	d-axis sub-transient S/C time constant	s	0.06	0.00843
T''_q	q-axis sub-transient S/C time constant	s	0.06	0.00843
T_a	Armature time constant	s	0.12	0.0882
M	Unit inertia constant	s	3.3	4
D	Damping coefficient	p.u.	0.0	0.0

IV. SIMULATION ON DOUBLE-MACHINE INFINITE BUS SYSTEM

A. Conditions of Simulation

Fig. 4 shows the double-machine infinite bus system. This system was developed assuming a local power system in which local generators and induction motor loads are connected to a substation through a step-up transformer and a set of parallel transmission line. The rated voltages of Buses 1 to 5 were assumed to be 11, 11, 66, 66, and 275 kV, respectively. For simplicity, the step-up transformer and the substation were simulated as impedances.

The system contains two generators: G1 and G2. A CG or SCG was used for G1, and G2 was a CG. Three induction motors (IMs) were connected as loads. By analyzing this system, the stability of the grid when some of CGs are replaced by SCGs in actual local power systems can be estimated.

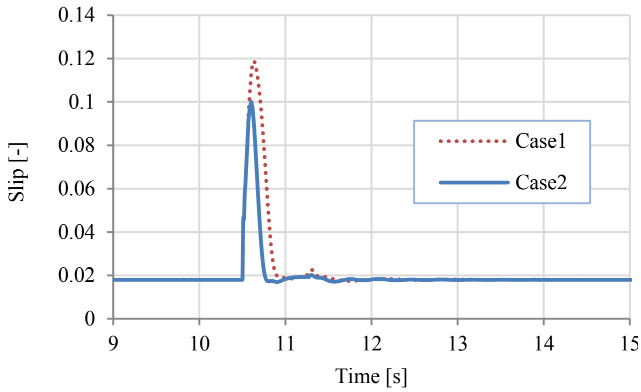
The three lines to ground fault occurred at 10.5 s, CBs at the both sides of the transmission line were opened at 10.57 s, and closed again at 11.25 s. 10 seconds before the fault was taken to start and bring the IMs into steady state operation.

The generator constants are listed in Table II. The reference value of the line voltage, capacity, and frequency for per-unit system are 11 kV, 20 MVA, and 60 Hz, respectively. The rated values of the machines are also the same as these values.

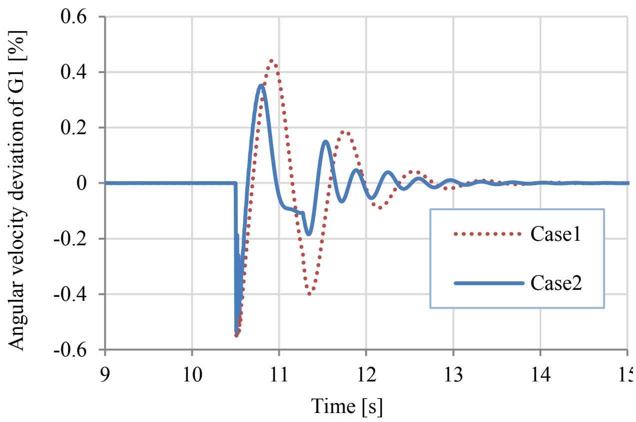
B. Result of the Simulation

Fig. 5 shows the simulation results. G1 was a CG in Case 1 and an SCG in Case 2. The CG connected as G1 in Case 1 has the same characteristics and machine constants and is operated by same the AVR as G2.

The angular velocity deviation of one of the IMs is shown in Fig. 5(a). The depression of the angular velocity deviation at the fault was smaller in Case 2 than in Case 1. Therefore, at the fault situation, the SCG connected to the grid is more stable under loading conditions. Furthermore, the fluctuation in the angular velocity deviation after the depression settled earlier in Case 2 than in Case 1.



(a) Slip of IM1 connected to the grid.



(b) Angular velocity deviation of G1.

Figure. 4. Simulation results of the double-machine infinite bus system.

In Fig. 5(b), the angular velocity deviations in G1 in both cases are shown. In Case 2, the fluctuations remained smaller and returned to stable conditions earlier than in Case 1. This shows that the SCG can be stable even when introduced into a system with a CG. The introduction of hydrogen-cooled SCGs into local grids is expected to improve power qualities during system faults and lead to the stable operation of IM loads in local power grids.

V. Conclusion

The quick-response excitation SCG model for the power system analysis with EMT software XTAP has been developed in this study. The utility of SCGs were shown in simulations: single-machine infinite bus system simulation and double-machine infinite bus system simulation. In the former simulation, the voltage stability and synchronous stability of SCG were shown. The advantage of SCGs to the CG- introduced system was shown in latter simulation. In the future work, parameter study to design machine constants according to expected role in the grids and investigating of control system of quick-response excitation SCGs considering characteristics of MgB_2 wire will be needed in order to operate SCGs properly in RE generation penetrated system.

References

[1] H. Kaminosono, Superconducting generators, 2004. (in Japanese)

[2] Swarn S. Kalsi, David Madura, and Mike Ingram, "Superconductor synchronous condenser for reactive power support in an electric grid," IEEE Trans. Appl. Supercond., vol. 15, no. 2, pp. 2146-2149, June, 2005.

[3] T. Noda, T. Takenaka, and T. Inoue, "Numerical integration by the 2-stage diagonally implicit Runge-Kutta method for electromagnetic transient simulations," IEEE Trans. Power Del., vol. 24, no. 1, pp. 390–399, Jan. 2009.

[4] O. Sakamoto, T. Nitta, "Consideration on damper cylinder design for effectiveness of superconducting generator," IEEE Trans. Appl. Supercond., vol. 16, no. 2, pp.1493-1496, June, 2006.

[5] O. Sakamoto, Y. Hitotsubashi, T. Nitta "Development of a new superconducting generator model for power system transient analysis with XTAP," IEEE Trans. Appl. Supercond., vol. 25, no. 3, #5203304, June, 2015.

[6] H. Amano, H. Kameda, T. Kumano, H. Taniguchi, H. Nakamura and Y. Imai "Equivalent circuit modeling of a quick-response type superconducting generator," Trans. IEE Jpn., vol. 121-B, no. 11, pp. 1250–1256, Nov. 2001. (in Japanese).