EFFECTS OF SUPERCONDUCTING GENERATOR ON MITIGATION OF VOLTAGE FLUCTUATION IN POWER SYSTEMS WITH WIND POWER GENERATION

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Abstract - In these days, installation of wind power generation is promoted as one of countermeasures against global warming. Power output of wind power generation is intermittent and fluctuates depending on wind condition. The fluctuation is thought to deteriorate electric power quality, particularly in terms of voltage and frequency.

Superconducting generators (SCGs) have many features such as capability to enhance power system stability, larger reactive power output capacity, and so on. Introduction of SCGs will offer great benefits to power systems with wind power generation of larger capacity in future, as well as current power systems.

In this work, a digital type real-time wind generator model for an existing analog type power system simulator was developed. Simulations by use of the equipment have been conducted to investigate effects of SCGs' introduction on mitigation of voltage fluctuation caused by wind power generation. SCG showed better effect than conventional generator. Details of the developed wind generator model, results of simulations and some considerations are presented in the paper.

Keywords - wind power, superconducting generator, voltage fluctuation, induction generator, analog type power system simulator

1 INTRODUCTION

DUE to rising demand for environmental-oriented policy, installation of wind power generation is promoted in these days. From a power system operation point of view, wind power generation has some problems. Its power output is intermittent and fluctuates depending on wind synopsis. Since some wind power generators are induction generators, there are matters of inrush current and voltage sag on their interconnection to power system. These power fluctuation, inrush current and voltage sag are thought to cause voltage fluctuation in power systems and deteriorate electric power quality.

Superconducting generators (SCGs) have many features such as high generation efficiency, small size, capability to enhance power system stability, and so on [1] – [3]. Introduction of SCGs will offer great benefits to power systems. In our laboratory, effects of introduction of SCGs with slow response excitation on power system stability have been investigated over recent years by use of the analog type power system simulator with the digital type real-time SCG model. Some results showed that SCGs can operate stable in wider range of power output than conventional generators. Installable amount of wind power generation is limited by marginal supply capability of each power system. These result will lead to the increase of the marginal supply capability.

In this study, electric power quality is considered mainly. It has been clarified through the former experiments that terminal voltage drop of an SCG at fault is smaller than that of a conventional generator[3]. The slow response excitation type SCG had lower synchronous reactance and longer transient time constants compared to the conventional generator, which was considered to be one reason for the mitigation of voltage fluctuation. The results offer good prospects of SCGs' ability to mitigate voltage fluctuation in power systems with wind power generation. It seems that no studies describe the effects in specific terms. Therefore it is thought to be very meaningful if a beneficial effect is demonstrated.

To verify the effect, the digital type real-time wind generator model for the existing analog type power system simulator was developed and some simulations were conducted by use of them. Characteristics of squirrel-cage induction generators were took into consideration. In this paper, details of the wind generator model and some considerations on effects of SCGs' introduction on mitigation of voltage fluctuation caused by wind power generation are presented.

2 DIGITAL TYPE REAL-TIME WIND GENERATOR MODEL FOR ANALOG TYPE POWER SYSTEM SIMULATOR

Most of the studies on characteristics of power systems including wind power generator are conducted by use of digital simulation so far. Fluctuation on wind power contains wide-ranging variable period. Therefor, simulations with analog type real-time power system simulator is also very useful. It offer us simulation with a time scale of seconds to day-long. In addition, if wind generator properties such as generator constants, control systems, characteristics of wind turbine are easy to change, it is useful to adopt appropriate property depending on purpose of simulation.

With these motives, a digital type real-time wind generator model for the existing analog type power system simulator was developed.

2.1 Analog type power system simulator

The developed wind generator model is used with the analog type power system simulator called TNS (Transient Network Simulator). Brief explanation about TNS is given here.

The simulator TNS[4] simulates power system characteristics in three phase instantaneous values in real time. It has generator models, transmission line models, load models, an infinite bus model and so on. The rated line voltage, current and frequency are 6.12 V, 10 – 100 mA and 50 Hz, respectively. A photo of TNS is shown in Figure 1.

Figure 1: Photo of the analog type power system simulator called TNS (Transient Network Simulator)

2.2 Structure of wind generator model

Basic concept of the digital type real-time wind generator model is illustrated in Figure 2. A computation segment for generator internal state is designed in shape of block diagram by use of MATLAB/Simulink. It is downloaded on a DSP, and generator internal state is computed on the board in real time.

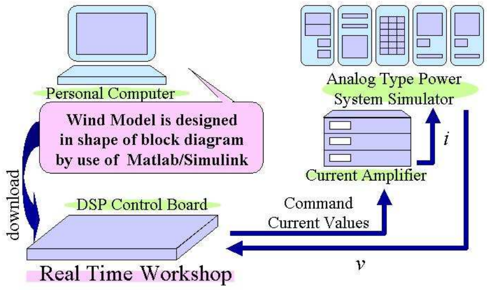


Figure 2: Basic concept of the digital type real-time wind generator model

Structure of the wind generator model is shown in Figure 3. The developed model consists of two components: the DSP component and analog circuit component. The DSP component is used to simulate wind generator's behavior and the analog circuit component is for connection to the analog type power system simulator.

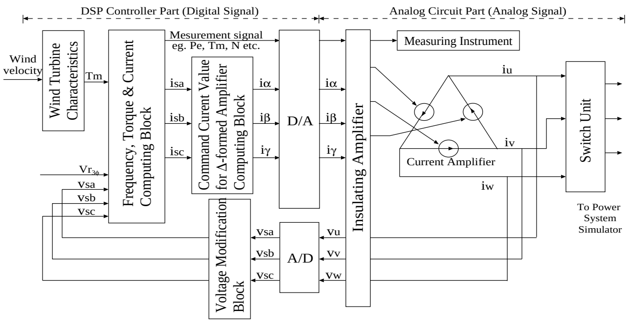


Figure 3: Structure of the digital type real-time wind generator model

In the wind generator model, characteristics of squirrel-cage induction generators were took into consideration. Digital values of induction generator state are computed in DSP component. These variables include the mechanical input torque T_m, the electrical output T_e, the stator currents i_{sm}(m=a,b,c), mechanical angular velocity ω_m, and so on. The computation is done in real time on DSP board. Digital signals of three-phase stator currents are conversed into analog signals through D/A converters. These analog signals are used to control Δ-formed three current amplifiers in the analog circuit component to generate three-phase currents flowing into TNS.

2.3 Rated values

Rated voltage of the wind generator model is the same as that of TNS. Rated current is variable. Main rated values are given below.

- Rated line voltage: 6.12 V
- Rated line current: 50 to 500 mA
- Electric frequency: 50 Hz

2.4 Mathematical model of induction generator model

As for mathematical model of the induction generator model, expressions shown below are adopted.

$$\frac{d}{dt}\boldsymbol{i} = \boldsymbol{A}\boldsymbol{i} + \dot{\theta}\boldsymbol{B}\boldsymbol{i} + \boldsymbol{D}\boldsymbol{v} \tag{1}$$

$$\boldsymbol{i} = \begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{rd} \\ i_{rq} \end{pmatrix}, \boldsymbol{v} = \begin{pmatrix} v_{s\alpha} \\ v_{s\beta} \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

$$\boldsymbol{A} = \frac{1}{b}\begin{pmatrix} R_sL_r & 0 & -R_rM & 0 \\ 0 & R_sL_r & 0 & -R_rM \\ -R_sM & 0 & R_rL_s & 0 \\ 0 & -R_sM & 0 & R_rL_s \end{pmatrix} \tag{3}$$

$$\boldsymbol{B} = \frac{1}{b}\begin{pmatrix} 0 & -M^2 & 0 & -L_rM \\ M^2 & 0 & L_sM & 0 \\ 0 & L_sM & 0 & L_sM \\ -L_sM & 0 & -L_sM & 0 \end{pmatrix} \tag{4}$$

$$\boldsymbol{D} = \frac{1}{b}\begin{pmatrix} -L_r & 0 & M & 0 \\ 0 & -L_r & 0 & M \\ M & 0 & -L_s & 0 \\ 0 & M & 0 & -L_s \end{pmatrix} \tag{5}$$

$$b = M^2 - L_sL_r \tag{6}$$

$$\theta = pG\theta_{mech} \tag{7}$$

Where R : resistance, L : inductance, $_s$: stator, $_r$: rotor, M : mutual inductance between stator inductance and rotor inductance, θ : electrical angle, θ_{mech} : mechanical angle, p : number of pole pairs , G : speed-increasing gear ratio.

Equation of motion and one of electrical output torque T_e are given by Equation (8) and (9), respectively.

$$J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = T_m - T_e \quad (8)$$

$$T_e = M(i_{s\beta} i_{rd} - i_{s\alpha} i_{rq}) \quad (9)$$

Where J : moment of inertia, B : coefficient of friction in rotating system, T_m : input mechanical torque from wind turbine.

Flow chart of computation procedure in the developed wind generator model is shown in Figure 4.

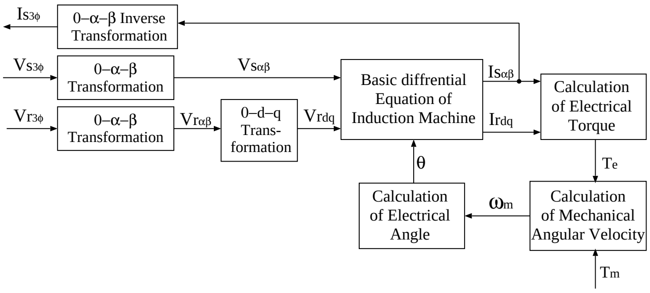


Figure 4: Flow chart of computation procedure in the wind generator model

2.5 *Characteristic test as induction machine model*

Validity of the induction generator part of the wind generator model was checked by adopting machine constants of a real induction machine.

Rating of the real three-phase induction motor are shown in Table 1.

capacity	3 H.P.
line voltage	200 V
line current	9.5 A
frequency	50 Hz
pole number	4
revolution speed	1400 rpm

Table 1: Rated values of induction machine

Machine constants used for the model are listed in Table 2.

R_s	resistance of rotor winding	0.0431 pu
R_r	resistance of stator winding	0.0378 pu
L_s	inductance of rotor winding	3.05 pu
L_r	inductance of stator winding	3.05 pu
M	mutual inductance	2.87 pu
p	number of pole pair	2
J	moment of inertia	20 Js^2

Table 2: Generator constants used in the model

These parameters were obtained from results of some tests on the real induction machine: measurement of resistance of stator winding, no load test, locked rotor test and load test. Since turn ratio was not clear, rotor winding resistance R_r was decided by characteristic test of the digital model so that the characteristics of the model corresponded to those of the real machine. Moment of inertia J was also decided based on the result of tests. As for inductance of stator L_s and that of rotor L_r, the values were decided by assuming that L_s is equals to L_r.

The results of the load test of real induction motor and the developed induction generator model is shown in Figure 5. The rated line voltage of TNS 6.12 V is converted into that of the real machine 200 V in the generator model when the load test was conducted. The characteristic of the model is well accorded with that of the real machine.

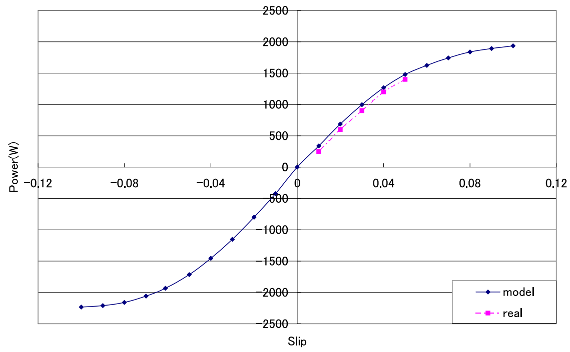


Figure 5: Result of load test of real induction motor and the developed real-time induction generator model

3 SIMULATIONS FOR EFFECTS OF SCG ON MITIGATION OF VOLTAGE FLUCTUATION CAUSED BY WIND POWER GENERATION

As concerns to wind power generation in power systems, there are some matters on electric power quality such as marginal supply capability, voltage fluctuation, frequency variation, and so on. In this work, voltage fluctuation is considered mainly.

By use of the developed wind generator model, TNS and SCG model, effects of SCG on mitigation of voltage fluctuation was studied. Conditions and results of simulations are shown in this section.

3.1 *Conditions*

3.1.1 *Power system model*

The configuration of power system model for the simulation is shown in Figure 6. Values given in the figure are power system capacity based value. Reference values for per unit system are shown in Figure 3.

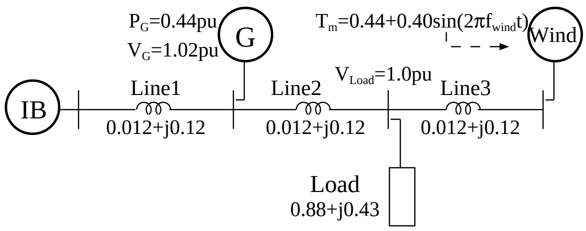


Figure 6: Power system configuration for the simulation. The values are power system based value.

Quantity	Reference value
system capacity	1.06 VA
frequency	50 Hz
line voltage	6.12 V
current	100 mA
impedance	35.33 Ω

Table 3: Reference values for per unit system

This power system simulates a kind of local site. It includes a wind generator $Wind$, a generator of another type G and a constant load $Load$. An SCG or conventional generator is installed as generator G. The local site connects to a power pool represented by an infinite bus model IB.

Available capacity of the $Wind$ is nearly equal to that of $Load$. Capacity of G is a half of $Wind$. In this simulation, generator G provided approximately half of the active power required by $Load$.

Fluctuating mechanical torque due to wind drove the wind generator $Wind$. Power fluctuation of $Wind$ caused voltage fluctuation at load voltage V_L. The purpose of the simulation is to compare effect of SCG or conventional generator on mitigation of voltage fluctuation of V_L.

3.1.2 *Superconducting generator model*

Besides the wind generator model mentioned in section 2, the simulator TNS and the digital type real-time SCG model were used for real-time simulations.

The digital type real-time SCG model is used with TNS. The exact relations between generator constants and SCG's structural design was studied [5]. Referred to the results, operational impedance-based method is adopted for obtaining the mathematical model of SCG. The detail of the model is introduced in Reference [6].

3.1.3 *Generator constants and controllers*

The digital type SCG model or conventional generator is used as Generator G in Figure 6.

Generator constants for SCG are listed in Table 4 and those for conventional generator, Table 5. The constants for SCG are made based on those of the Super-GM 70MW class model machine [7]. Sub-subtransient time constants T'''_{d0} and T'''_{q0} are time constants specific to SCGs. The constants for conventional generator are typical values of a large-capacity thermal power plant [8].

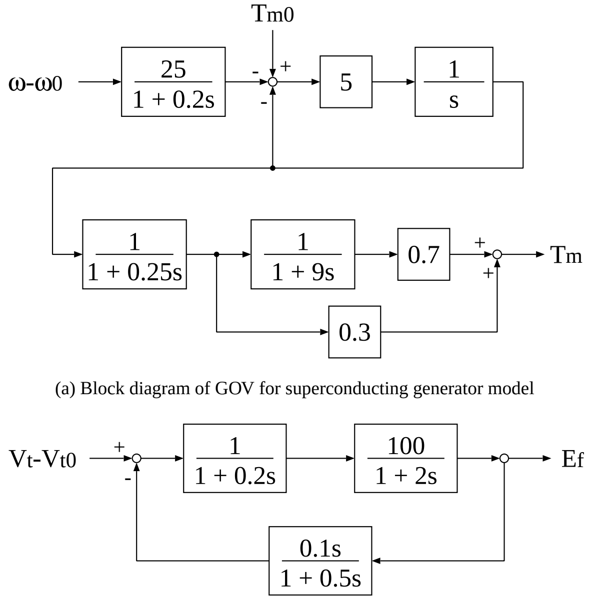
Symbol	Quantity	Value
X_d	d-axis synchronous reactance	0.42 p.u.
X'_d	d-axis transient reactance	0.328 p.u.
X''_d	d-axis subtransient reactance	0.23 p.u.
X'''_d	d-axis sub-subtransient reactance	0.177 p.u.
X_q	q-axis synchronous reactance	0.42 p.u.
X''_q	q-axis subtransient reactance	0.328 p.u.
X'''_q	q-axis sub-subtransient reactance	0.23 p.u.
X_l	leakage reactance	0.2 p.u.
T'_{d0}	d-axis transient open circuit time constant	15.88 s
T''_{d0}	d-axis subtransient open circuit time constant	0.107 s
T'''_{d0}	d-axis sub-subtransient open circuit time constant	0.013 s
T''_{q0}	q-axis subtransient open circuit time constant	0.33 s
T'''_{q0}	q-axis sub-subtransient open circuit time constant	0.029 s
T_a	armature time constant	0.12 s
M	generator inertial constant	6.0 p.u.

Table 4: Machine Constants for Superconducting Generator

Symbol	Quantity	Value
X_d	d-axis synchronous reactance	1.70 p.u.
X'_d	d-axis transient reactance	0.35 p.u.
X''_d	d-axis subtransient reactance	0.25 p.u.
X_q	q-axis synchronous reactance	1.70 p.u.
X'_q	q-axis transient reactance	0.35 p.u.
X''_q	q-axis subtransient reactance	0.25 p.u.
X_l	leakage reactance	0.225 p.u.
T'_d	d-axis transient short circuit time constant	1.0 s
T''_d	d-axis subtransient short circuit time constant	0.03 s
T'_q	q-axis transient short circuit time constant	0.206 s
T''_q	q-axis subtransient short circuit time constant	0.03 s
T_a	armature time constant	0.40 s
M	generator inertial constant	7.0 p.u.

Table 5: Machine Constants for Conventional Generator

Conventional generator was equipped with typical GOV and AVR. The IEEJ standard model for GOV and AVR control are used. Superconducting generator model has GOV. The block diagrams of them are shown in Fig. 7. No PSS was used in the simulations.



(a) Block diagram of GOV for superconducting generator model

(b) Block diagram of AVR for conventional generator model

Figure 7: Block diagram of generator control system

3.1.4 *Setup of power system model*

In this paper, continuous voltage fluctuation caused by wind power generator in normal operating condition is considered. Voltage sag in interconnection of wind generator to power system or fault was not took into consideration.

When initial condition of power system was established for the simulation, mechanical torque T_m inputted to the wind generator $Wind$ was kept to be 0.4 pu. Under that condition, generator G's active power P_G was set to 0.44 pu. Generator G's terminal voltage V_G was decided so that the value of V_L became 1.00 pu. The value of V_G was 1.02 pu. After the establishment of the system, mechanical torque T_m was inputted to the wind generator according to Equation (10). Active power output of $Wind$ varies almost full capacity of the induction generator. As for $Load$, constant impedance model of TNS was used. Capacity of $Load$ is 0.88 + j0.43 pu, power factor of $Load$ is 0.90.

$$T_m = 0.44 + 0.40 sin(2\pi f_{wind} t) \text{ [pu]} \qquad (10)$$

In Equation (10), f_{wind} is frequency of mechanical torque oscillation. The simulation was conducted for several values of f_{wind} from 0.025 Hz to 10 Hz.

After transient state was passed by, values such as V_L, P_G, V_G, generator G's reactive power Q_G were measured under continuous power oscillation.

3.2 *Results*

Figure 8 shows mechanical torque input to the wind generator T_m and its electrical output P_{wind} when f_{wind} is 1 Hz. Sinusoidal mechanical torque was certainly added to $Wind$ and sinusoidal power output was generated.

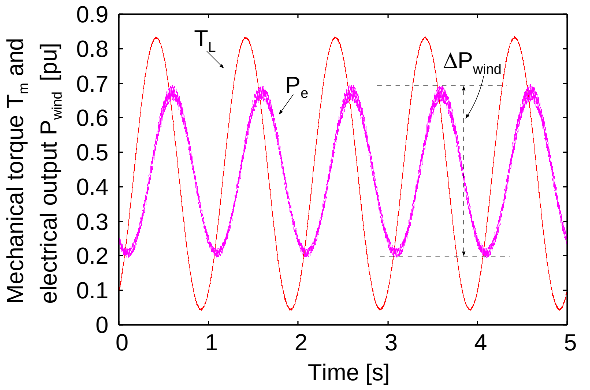


Figure 8: Mechanical torque input T_m and electrical output P_{wind} of wind generator $Wind$

Figure 9 shows measured voltage at load terminal V_L when f_{wind} is 1 Hz.

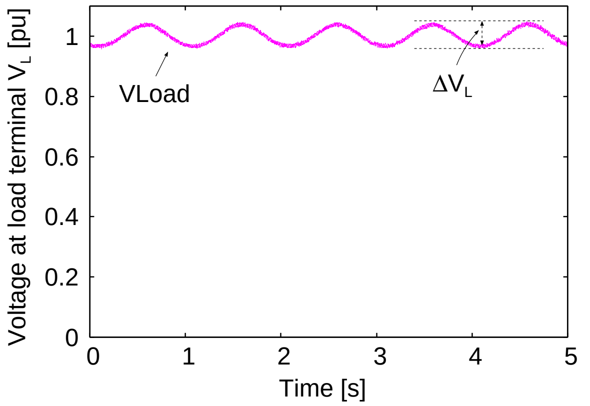


Figure 9: Measured voltage at load terminal V_L

Figure 10 shows amplitude of fluctuation of P_{wind} indicated by ΔP_{wind} in Figure 8 to frequency of mechanical torque oscillation f_{wind}. It is clear from Figure 10 that the lower frequency gave the bigger impact to the power system especially lower than 0.5 Hz.

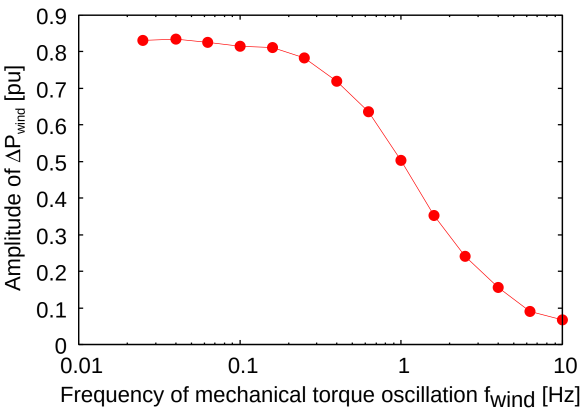


Figure 10: Amplitude of fluctuation of P_{wind} indicated by ΔP_{wind} in Figure 8 to frequency of mechanical torque oscillation f_{wind}

Figure 11 shows measured latitude of voltage fluctuation indicated by ΔV_L in Figure 9 to frequency of mechanical torque oscillation f_{wind}. The results shows that SCG has better effect on mitigation of voltage fluctuation than conventional generator against frequencies lower than 0.5 Hz in the power system model. This area of frequency T_m is important area shown in Figure 10. Besides, when f_{wind} is 0.04 and 0.063 Hz, conventional generator was tripped but SCG is still in stable operation.

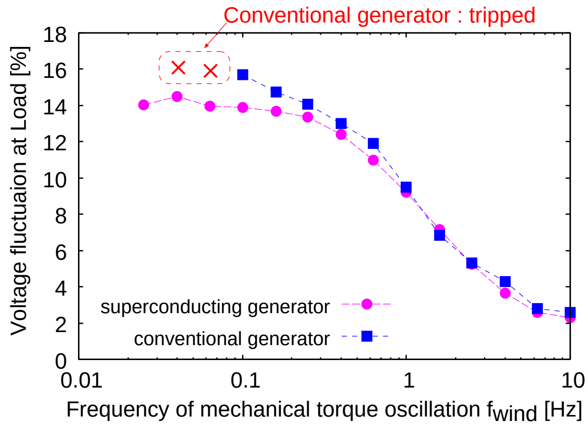


Figure 11: Measured latitude of voltage fluctuation indicated by ΔV_L in Figure 9

Figure 12 shows generator G's active power output to frequency of mechanical torque oscillation f_{wind}. It shows that eigen frequency of this power system is around 1 Hz. Therefore larger voltage fluctuation of V_L due to F_{wind} lower than 0.5 Hz shown in Figure 11 is not owe to resonance of the power system.

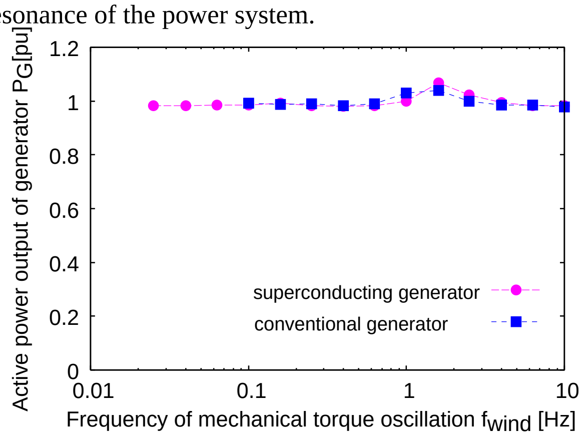


Figure 12: Generator G's active power output to frequency of mechanical torque oscillation f_{wind}

Figure 13 generator G's reactive power output Q_G to frequency of mechanical torque oscillation f_{wind}. The value of Q in the figure is the lower value of fluctuating reactive power. As seen in Figure 13, reactive power of conventional generator was very low when f_{wind} was lower than 0.5 Hz. Latitude of reactive power output of superconducting generator for these frequencies are smaller than those of conventional generator. Superconducting generator was in stable operation.

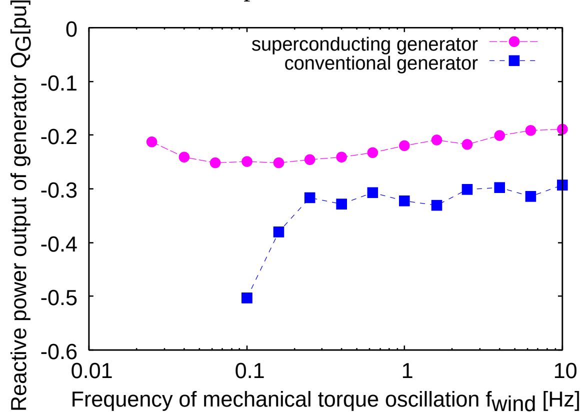


Figure 13: The lower value of fluctuation of generator reactive power

3.3 Considerations

One of large difference between SCG and conventional generator is the value of synchronous reactance X_d. In the simulation, the value of X_d for SCG was 0.42 pu and that for conventional generator was 1.7 pu, as listed in Table 4 and 5. The frequency of oscillation of T_m was corresponding to steady-state domain for both of SCG and conventional generator, as is clear from generator time constants given in Table 4 and 5. If a generator has larger X_d, it requires larger internal induced voltage to establish terminal voltage. Therefore the difference of values of X_d is thought to be one reason for SCG's better effect showed in Figure 11. In addition, the machine constants used for conventional generator model in the simulation were for high-class generators and the value of X_d for general-purpose generators are larger than 1.7 pu. Therefore, if effects of SCGs is compared to those generators, the difference of the effect will become larger. Verification of the effects of X_d on mitigation of voltage fluctuation is one of future works.

Simulations to compare SCG and conventional generator in various cases by changing power output of wind generator, frequency of wind power, ratio of length of transmission line should be also done. Not only AVR, other generator control systems should be checked in order to clarify SCG's benefits over conventional generators. From the result showed in Figure 13, it is obvious that SCG has capacity to provide much more reactive power and is operable much severer condition without AVR. As for conventional generator, if better generator control system is adapted according to condition of power flow, there is a possibility that capacity of marginal reactance power itself become insufficient with the increase of wind power generation. Besides, it is very difficult to design generator control system to ready for various power flow condition from wind power generation. Meanwhile, SCG has prospective for mitigation of voltage fluctuation taking advantage of sufficient provision of reactive power in wider range of power flow than conventional generators do.

4 CONCLUSIONS

The digital type real-time wind generator model for the existing analog type power system simulator was developed.

By use of the wind generator model, effects of SCG on mitigation of voltage fluctuation caused by wind power generation was investigated. The results showed that SCG without AVR has better effect than conventional generator wit AVR. As for reactive power, SCG kept stable value in contract that conventional generator become out of range in some severe case.

These result shows the possibility that introduction of SCGs restrain voltage fluctuation caused by wind power generation. It will lead to the increase of installable amount of wind power.

5 ACKNOWLEDGMENT

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