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STABILIZATION OF WIND FARM INTERCONNECTED LARGE POWER SYSTEM BY USING SMES

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Abstract- In this paper, the influence of a Superconducting Magnetic Energy Storage (SMES) unit on the performance of the wind farm interconnected power system is investigated. SMES system can improve the performance of wind generators for smoothing voltage and output power fluctuations of a large-scale wind power generation system. A control system model for the SMES unit based on a PWM voltage source converter and two-quadrant dc-dc chopper using IGBT is considered. When the wind speed of each wind generator varies randomly, the power system frequency and voltage of the grid system also vary. These fluctuations caused by the wind farm can be decreased significantly by using the proposed SMES. It is also seen that, using the proposed SMES the Low Voltage Ride Through (LVRT) capability of the wind farm can be enhanced significantly during the fault in the power system. Thus SMES system enhances the system reliability effectively. Detail procedure with simulation results i.e., block diagram, description of the system simulation wave shapes and performance analysis are presented in this paper in such a sequential manner that would be advantageous for the beginners as well as for the advanced readers who are interested to research with such systems.

Keywords: Output fluctuations, power system frequency, wind farm stabilization, superconducting magnetic energy storage (SMES) and low voltage ride through (LVRT) capability.

1. INTRODUCTION

In the conventional operation of wind power generators, when the wind speed is between the rated speed and the cut out speed, the wind power generator output is controlled at the rated value by a pitch control system. On the other hand, when the wind speed is between the cut in speed and the rated speed, the blade pitch angle is maintained constant (= 0 deg), in general, for the wind turbine to capture the maximum power from the wind turbine. Therefore, the wind power generator output fluctuates due to wind speed variations in the latter condition, because wind turbine output is proportional to the cubic of wind speed, the wind turbine generator output fluctuations due to wind speed variations. Hence, if the power capacity of wind power generators becomes large, wind power generator output can have a serious influence on the power system frequency due to large incorporation of wind farm to the grid has some adverse effect on power system operation.

On the other hand, the fixed speed wind generator that uses the squirrel cage induction generator needs additional tool to enhance the low voltage ride through (LVRT) capability. This is because it requires large reactive power to recover the air gap flux when a short circuit fault occurs in the power system. If sufficient reactive power cannot be supplied, the balance between mechanical and electromagnetic torques cannot be maintained and induction generator becomes unstable, resulting in a disconnection from the power system. However, the recent trend is to decrease the shut down operation, because a shut down of large winds farm can have a serious effect on the power system operatio. The shut down phenomenon has been reduced by adopting the LVRT requirement set by grid operator. The wind farm compatible grid code is more or less similar to each other. In this paper, the simulation analysis is performed in light of the US grid code, set by Federal Energy Regulatory Commission (FERC), which states that if the terminal voltages of wind farm satisfy some conditions, the plant must stay online. Therefore, it is important to investigate a suitable method to enhance the LVRT capability of fixed speed wind generators.

Since Superconducting Magnetic Energy Storage (SMES) system has the ability to provide both active and reactive power simultaneously and quickly, it can improve the performance of wind generators. Therefore, this paper proposes a SMES system for smoothing voltage and output power fluctuations of a large-scale wind power generation system.

The organization of this paper is as follows, section 2 presents the model system, which will be analyzed here, section 3 contains the synchronous generator model. Description of SMES unit is given in section 4.

Simulation results, discussion and conclusion are presented in section 5, 6, and 7 respectively.

2. THE MODEL SYSTEM ANALYSIS

The model system used in the simulation analyses is shown in Figure 1. The model system consists of a wind farm (WF), a hydropower generator SG1, two thermal power generators SG2 and SG3, a nuclear power generator SG4, and a load. The wind farm consists of five wind power generators (squirrel cage induction machines, IGn, n=1, 2,… 5). SG1 and SG3 are operated under load frequency control (LFC). SG2 is operated under governor-free (GF) control, and SG4 is operated under load limiting (LL) control. LFC is used to control frequency .fluctuations with a long period of more than a few minutes, and GF is used to control .fluctuations with a short period of less than 1 minute. LL is used to output constant power. The SMES system is connected to the wind farm terminal bus.

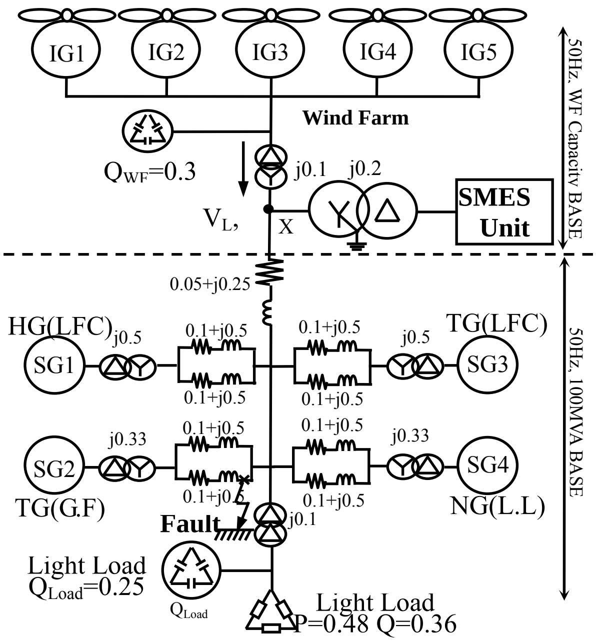

Fig.1: Model System

Here, Q_{WF} and Q_{Load} are capacitor banks, where Q_{WF} is used at the terminal of the wind farm to compensate the reactive power demand in the steady state. The value of the capacitor is chosen so that power factor of the wind power station during the rated operation becomes unity [4]. In addition, QLoad is used at the terminal of the load to compensate for the voltage drop by the impedance of the transmission lines. The initial conditions and parameters of the IGs and SGs are shown in Tables 1 and 2, respectively [1].

Table 1: Parameters of Generator

Induction Generator			
	SQUIRREL CAGE TYPE (IGN,N=1,2,3)		
MVA	3	5	10
R_1 [pu]	0.01		
X_1 [pu]	0.18		
X_m [pu]	10		
R_2 [pu]	0.015		
X_2 [pu]	0.12		
2H [sec]	1.5		
Synchronous Generator			
	Salient pole type (HG)	Cylindrical type (TG)	
MVA	100	100	
Xd[pu]	1.2	2.11	
Xq[pu]	0.7	2.02	
Xd'(pu)	0.3	0.28	
Xd"(pu)	0.22	0.215	
Xq"(pu)	0.25	0.25	
Tdo'(s)	5.0	4.2	
Tdo"(s)	0.05	0.032	
Tqo"(s)	0.14	0.062	
H(s)	2.5	2.32	

Table 2: Initial Conditions

	IG	SG1	SG2
P	0.03/0.05/0.1	1.00	1.00
V	1.00	1.05	1.05
Q	0.00		
s(Slip)	-1.733%		

3. SYNCHRONOUS GENERATOR MODEL

Here governor model for synchronous generators [8] (hydro, thermal and nuclear) are discussed. Also the automatic voltage regulator (AVR) model and load frequency control (LFC) model are discussed.

3.1 Governor for Hydro, Thermal, and Nuclear Generators

The IEEE non-elastic water column without surge tank turbine model and PID control including pilot and servo dynamics speed-governing system [5], shown in Figure 2, is used for the synchronous generator, SG1. The IEEE generic turbine model and approximate mechanical-hydraulic speed governing system [6], shown in Figure 3, is used for the synchronous generators, SG2, SG3, and SG4.

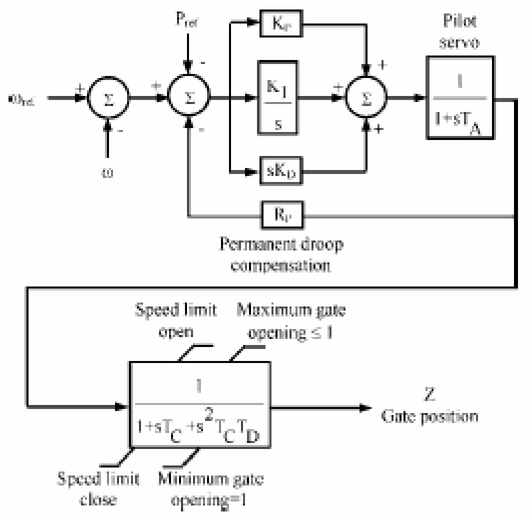

Fig.2: Hydro governor

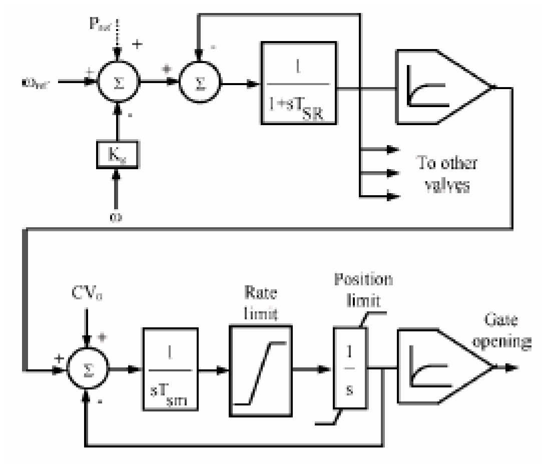

Fig.3: Thermal and Nuclear governor

In the governor models shown in Figures 2 and 3, the values of P_{ref}, initial output P_0, and turbine maximum output torque $T_{m,\,max}$, are shown in Table 3, where $\Delta\omega = \omega ref - \omega$, and the revolution speed deviation (in pu) is set to zero for SG1 and SG3 because these generators are operated under LFC in order to control frequency fluctuations having a relatively long period.

Table 3: Values of P_{ref}, P_o and $T_{m.max}$

Load 100 MVA				
SG No.	Frequency Control	P_{ref}	P_0	$T_{m.max}$
SG1	LFC	LFC signal		No limit
SG2	GF		0.80	No limit
SG3	LFC	LFC signal	0.70	
SG4	LL		0.90	0.80
Load 60 MVA				
SG No.	Frequency Control	P_{ref}	P_0	$T_{m.max}$
SG1	LFC	LFC signal	0.75	
SG2	GF		0.40	
SG3				
SG4	LL		0.90	0.80

3.2 Automatic Voltage Regulator (AVR)

An automatic voltage regulator (AVR) is needed in order to maintain the voltage of the synchronous generators constant. In the simulation analyses, the IEEE alternator supplied rectifier excitation system (AC1A) [7], is used in the exciter model of all synchronous generators.

3.3 Load Frequency Control (LFC) Model

For application of LFC, the output power signal is sent to each power plant when frequency deviation is detected in the power system. Then, the governor output of each power plant is changed according to the LFC signals, and the power plant output is changed. The LFC model used here is shown in Figure 4, where Tc2 (the LFC period) =200 seconds, ωc (LFC frequency) =1/Tc2=0.005 Hz, ζ (damping ratio) =1. The frequency deviation is input into a low pass filter (LPF) to remove fluctuations having a short period, because the LFC is used to control frequency fluctuations having a long period. The parameters in Figure 4 are chosen by a trial and error method to obtain better performance from the system.

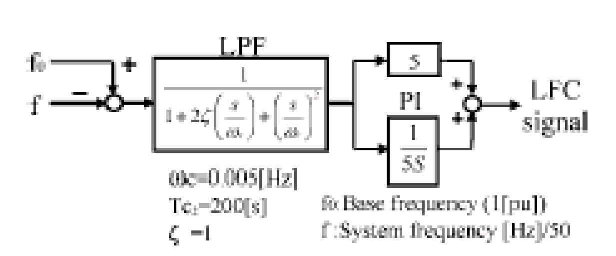

Fig.4: LFC model

4. SMES CONTROL SYSTEM

The SMES system shown in Figure 6 consists of a wye-delta transformer, a six-pulse PWM VSC using IGBT, a DC link capacitor, a two-quadrant DC–DC chopper using IGBT, and a superconducting coil. The detailed switching model is considered in the SMES modeling instead of the time-averaged model, and hence losses in the power converters are taken into consideration in the present study. The VSC and the DC–DC chopper are linked by a DC link capacitor of 50 mF. The SMES is coupled to the 66 kV line through a single step-down transformer (66/1.2 kV) with a 0.384615 pu leakage reactance on the base value of 10MVA.

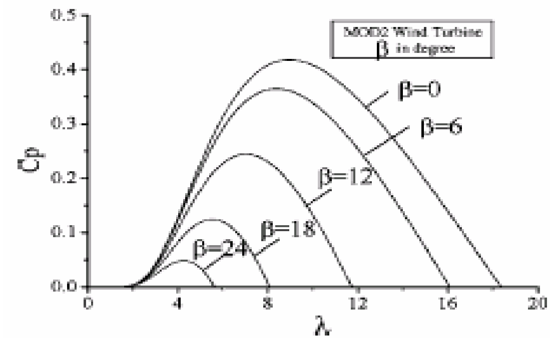

Fig.5: C_p-λ curves for different values of pitch angle

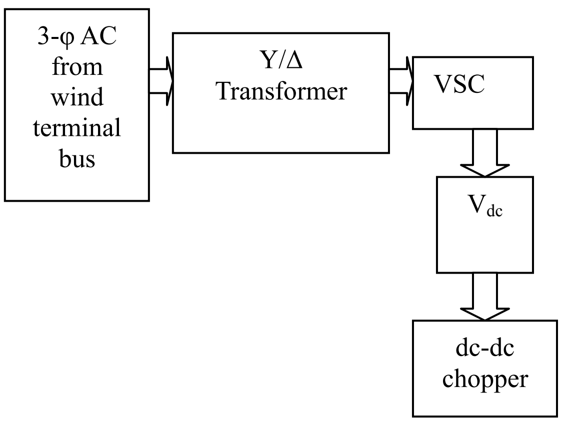

Fig.6: Block diagram of SMES unit

$$E = \frac{1}{2} I_{sm}^2 L_{sm} \qquad (1)$$

$$P = \frac{dE}{dt} = L_{sm} I_{sm} \frac{dI_{sm}}{dt} = V_{sm} I_{sm} \qquad (2)$$

For an SMES system, the inductively stored energy (E in Joule) and the rated power (P in Watt) are commonly given as specifications for SMES devices and can be expressed as above. Where Lsm is the inductance of the coil, Ism is the DC current flowing through the coil and Vsm is the voltage across the coil. The proposed SMES system has a power rating of 2.6 MW and an energy capacity of 312 MJ.

4.1 PWM Voltage Source Converter (VSC)

In the present study, a cascade control scheme with independent control of the active and reactive currents was developed. The goal of this control is to maintain the magnitude of the voltage at the wind farm terminal at the desired level. The DC link voltage (VDC) is also maintained constant at the rated value. Finally, the three-phase reference signals are compared with the triangular carrier wave signal in order to generate the switching signals for the IGBT-switched VSC. In the present study, the interpolated .ring pulses are used in the sinusoidal PWM controller. The interpolated firing pulse circuit is a simulation technique for generating .ring pulses through an interpolation procedure. This allows for exact switching between time steps based on the comparison of the sinusoidal reference and the high-frequency carrier signal. High switching frequencies can be used to improve the efficiency of the converter, without incurring significant switching losses. In the simulation, the switching frequency is chosen to be 1000 Hz. The rated DC link voltage is 2 kV.

4.2 Two-Quadrant DC–DC Chopper

Depending upon the values of chopper duty cycle D, three regions of operation can be identified for the chopper arrangement, as shown in Figure 7. These regions of operation are charge/discharge/standby operation.

The average voltage appearing across the SMES coil and chopper current at any instant of time can be represented by the following equations:

$$\mathrm{VSM\_av} = [1 - 2D]\mathrm{Vdc\_av} \qquad (3)$$
$$\mathrm{Idc\_av} = [1 - 2D]\mathrm{ISM\_av} \qquad (4)$$

Where VSM_av is the average voltage across the SMES coil, ISM_av is the average current through the SMES coil, Vdc_av is the average DC source voltage, Idc_av is the average dc source current, and D is the duty cycle of the chopper, which is equal to the IGBT conduction time/period of one switching cycle.

Adjusting the duty cycle of the GTO firing signals controls the rate of charging/discharging. Thus, when the duty cycle is greater than 0.5, the coil is charging, and when the duty cycle is less than 0.5, the coil is discharging. When the unit is in standby mode, the coil current is maintained constant, independent of the storage level, by adjusting the chopper duty cycle to 50%, resulting in the net voltage across the superconducting

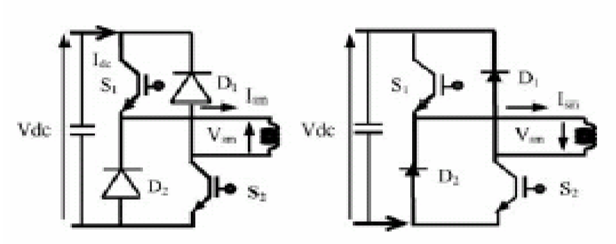

Fig.7: Control concept of SMES charging and discharging

winding being zero. In order to generate the gate signals for the IGBTs of the chopper, the PWM reference signal is compared with the saw tooth carrier signal. The frequency of the saw tooth carrier signal for the chopper is chosen to be 100 Hz. The parameters of the PI controllers are determined by a trial and error method.

5. SIMULATION RESULTS

Simulations have been carried out to investigate the performance of the power system frequency with the increased wind power penetration using real wind speed data. The wind speed data is the real data, which was obtained in Hokkaido Island, Japan. The wind speed data applied to the wind generators. Simulation analyses have been carried out for, frequency response and terminal

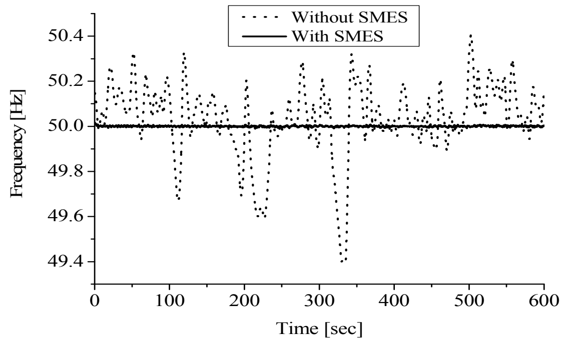

Fig.8: Response of power system frequency

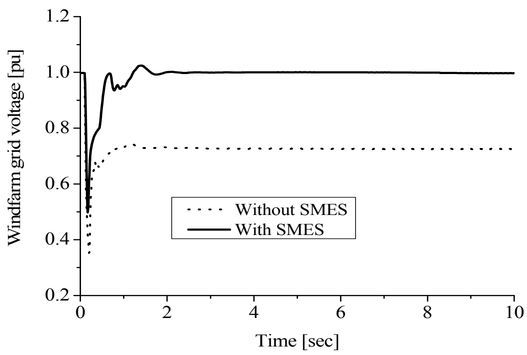

Fig.9: Response of wind farm terminal voltage

voltage. The simulation analyses have been performed using PSCAD/EMTDC [3]. When the wind speed of each wind generator varies randomly, the power system frequency and voltage of the grid system also vary. These fluctuations caused by the wind farm can be decreased significantly by using the proposed SMES. Thus SMES system enhances the system reliability effectively.

Figure 8 shows that when the winds speed of each wind generator varies randomly, the power system frequency of the grid system also vary. These fluctuations caused by the wind farm can be decreased significantly by using the proposed SMES. The straight line shows the frequency response performance with SMES and the dotted line also shows the frequency response performance without SMES.

Figure 9 also shows that when the wind speed of each wind generator varies randomly, the power system terminal voltage of the grid system also varies. These fluctuations also can be decreased significantly by using the proposed SMES. The straight line shows the terminal voltage response with SMES and the dotted line also shows the terminal voltage response without SMES.

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6. DISCUSSION

The simulation analyses using PSCAD/EMTDC shows that, when the wind speed of each wind generator varies randomly, the power system frequency and voltage of the grid system also varies. These fluctuations caused by the wind farm can be decreased significantly by using the proposed SMES. Thus SMES system enhances the system reliability effectively.

7. CONCLUSIONS

This paper proposes SMES for smoothing output power fluctuations of wind farms in order to maintain the grid frequency deviation to within an acceptable range. The effect of the smoothing control is evaluated using a power system model installed with the SMES unit. These values of the SMES power rating and energy capacity are found to be optimum for the wind speed pattern obtained in Hokkaido, Japan, in which the speed fluctuation is very large compared with that in Europe. The simulation analyses show that, using the proposed SMES system, the wind farm output fluctuations can be decreased, and hence the frequency of the grid system, can be maintained to within an acceptable range. Therefore, the integration of the proposed SMES system into a wind farm can be an effective means of mitigating the frequency fluctuations of the grid system.

8. REFERENCES

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9. NOMENCLATURE

Symbol	Meaning	Unit
R1	Stator resistance	Ω
X1	Stator reactance	Ω
Xmu	Magnetizing reactance	Ω
R21	Rotor 1st cage resistance	Ω
X21	Rotor 1st cage reactance	Ω
R22	Rotor 2nd cage resistance	Ω
X22	Rotor 2nd cage reactance	Ω
Xd	Direct-axis synchronous reactance	Ω
Xq	Quadrature-axis synchronous reactance	Ω
H	Inertia constant	Second
QWF	Wind farm terminal capacitor bank	Var
Q_{LOAD}	Load capacitor bank	Var

Pref	Reference value of transmission line power	Watt
$T_{m.max}$	Turbine maximum output torque	N-m
Lsm	Inductance of the coil	Henry
Ism	DC current flowing through the coil	Ampere
Vsm	voltage across the coil	Volt
V	Wind velocity	m/sec
D	Duty cycle of chopper	
C_p	Power coefficient	
λ	Tip speed ratio	