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# STABILIZATION OF POWER SYSTEM INCLUDING WIND FARM BY PWM VOLTAGE SOURCE CONVERTER AND CHOPPER CONTROLLED SMES

MD. SHAMIM ANOWER[1] & MD. RAFIQUL ISLAM SHEIKH[2]

**Abstract.** This paper presents a dynamic model of Superconducting Magnetic Energy Storage (SMES) device developed, which can significantly decrease the voltage and power fluctuations of grid connected fixed speed wind generators. The SMES system with a voltage-source IGBT converter and two-quadrant DC-DC chopper is analyzed as a controllable energy source. The objective of the proposed SMES control strategy is to smooth the wind farm output by absorbing or providing real power. Moreover, its reactive power output can also be controlled to keep the wind farm terminal voltage constant. The control methodology of SMES system is suitable for the two objectives stated above. The performance of the proposed system is evaluated by dynamic simulations using a test power system. Real wind speed data is used in the simulation analyses, which validates the effectiveness of the proposed control strategy. Simulation results clearly show that the proposed control strategy can smooth well the wind generator output power and also maintain the terminal voltage at rated level.

*Keywords*: Minimization of fluctuations; superconducting magnetic energy storage (SMES); wind generator stabilization; voltage source converter (VSC); DC-DC chopper

## 1.0 INTRODUCTION

Recently exhaustion of the fossil fuel and environmental problem such as global warming have become serious problems. Therefore it is necessary to introduce clean energy more in place of the fossil fuel. Because of the reason of almost no carbon dioxide ($CO_2$) emission, wind energy, solar energy, biomass, etc are considered as the clean energy sources. These energy sources are renewable, and the exhaustion problem of fossil fuel makes those prospective and alternate energy sources very attractive as the future energy sources. Although wind power is considered as a very prospective energy source, wind power fluctuation caused by randomly varying wind speed is still a serious problem for power grid companies or transmission system owners (TSOs), especially in the case of fixed-speed wind generators. Induction generators (IGs) are

[1] School of ITEE, UNSW@ADFA, Canberra, ACT 2600, Australia
[2] Kitami Institute of Technology, Hokkaido, Kitami, Japan
Email: [1]engr_js@yahoo.com , [2]ris_ruet@yahoo.com

used, in general, as fixed-speed wind generator because of their superior characteristics such as brushless and rugged construction, low cost, maintenance and operational simplicity. In 2004, the worldwide market share of fixed-speed wind generator was around 40%[1]. In some countries such as Japan, still the share of fixed-speed wind generators is more than around 70%.

Therefore, many researches have been performed for smoothing output power generated from fixed speed wind generators. Usually, stabilization of wind generator can be done by SVC (Static VAR Compensator) [2] or STATCOM (Static Compensator) [3]. However, SVC or STATCOM can control only reactive power. In [4], a flywheel energy storage system is proposed to smooth the wind power fluctuations. In [5], an energy capacitor system (ECS), which consists of power electronic devices and electric double layer capacitor (EDLC), is proposed to smooth wind farm output. But a flywheel system has, in general, high standby loss within the range of 5% of its power rating. Moreover, the control scheme of flywheel system is comparatively complex. Though battery energy storage system (BES) and ECS are good systems for the power smoothing considering their response speed and efficiency, their practical installation in large MW range applications is doubtful due to their high maintenance cost. In addition, BES has some drawbacks such as shorter life cycle and low discharge rate due to chemical reaction rates.

On the other hand, though SMES has high initial installation cost, intensive progress in power electronics and superconductivity has made it attractive to use SMES in power transmission and distribution systems. Since the successful commissioning test of the Bonneville Power Administration (BPA) 30 MJ unit [6], SMES systems have received much attention in power system applications, such as, diurnal load demand leveling, frequency control, automatic generation control, uninterruptible power supplies, etc. SMES is a large superconducting coil capable of storing electric energy in the magnetic field generated by DC current flowing through it. It has some merits superior to other types of storage systems, i.e., long service life due to having no mechanical part, high response speed in input/output of large power, and high storage efficiency, etc. The real power as well as the reactive power can be absorbed (charging) by or released (discharging) from the SMES coil according to the system power requirements. Depending on the control loop of its power conversion unit and switching characteristics, the SMES system can respond very rapidly. The SMES system is combined with the voltage source IGBT converter can effectively control and almost instantaneously supply both active and reactive powers into the power system. Therefore, SMES can be much suitable for wind generator stabilization.

To evaluate the effectiveness of SMES systems with respect to power system applications, different techniques have been used and many variations of mathematical description have been developed. In practical applications it is necessary to evaluate the impact of SMES on electromechanical processes of large power system and to analyze the effectiveness of complex control schemes with their nonlinear elements and delays adequately considered. Up to now, although various strategies for SMES control [7-11] have been proposed in the literature for the stabilization of synchronous generators, the real problem has been and still is the determination of the best or optimal control strategies. So, continuous attempts to explore new and effective control options are ongoing.

In this work a PWM voltage source converter and a two-quadrant DC-DC chopper using insulated-gate-bipolar-transistor (IGBT) are used for controlling SMES unit. Therefore, the SMES can be operated to supply real and reactive powers independently. Charge and discharge rates of SMES unit are determined by the chopper duty cycle. Another important thing to be noted here is that the wind speed variations result in variations of induction generator's real and reactive powers, which interact with the network and provoke voltage and power fluctuations. A SMES unit based on a PWM voltage source converter using IGBT is capable of controlling both active and reactive powers simultaneously and quickly. Therefore, it can be a good tool to decrease voltage and power fluctuations of the power systems. Considering these viewpoints, this paper proposes a control strategy of the SMES unit installed at a wind farm for decreasing fluctuations of output power and terminal voltage of the wind farm, which will be a good tool for entire power system.

## 2.0 MODEL SYSTEM FOR SIMULATION ANALYSES

The model system shown in Figure 1 has been used for the simulation analyses of wind generator stabilization in this work. The model system consists of one synchronous generator (100 MVA), SG, and five wind turbine generators (10 MVA induction generator, IG each), which are delivering power to an infinite bus through a transmission line with two circuits. Though a wind power station is composed of many generators practically, it is considered to be composed of five generators with the total power capacity of 50 MVA in this paper. There is a local transmission line with one circuit between the main transmission line and a transformer at the wind power station. A single squirrel-cage induction machine model, which is represented by a steady state equivalent circuit shown in Figure 2 where s denotes a rotational slip, is used for the wind generator. To establish the rotating magnetic field of the stator, reactive power is needed to be supplied from the network to the stator winding of the induction generator. So to compensate the reactive power demand at steady state, a capacitor bank is inserted at the terminal of IG [12-14]. The value of the capacitor C is so chosen that the power factor of the wind power station becomes unity when it is operating in the rated condition (V=1.0, P=0.5). The SMES unit is located at the induction generator terminal bus. The AVR (Automatic Voltage Regulator) and GOV (Governor) control system models shown in Figure 3 and Figure 4 respectively are used in the synchronous generator model. Generator parameters are shown in Table 1. The system base power is 100 MVA.

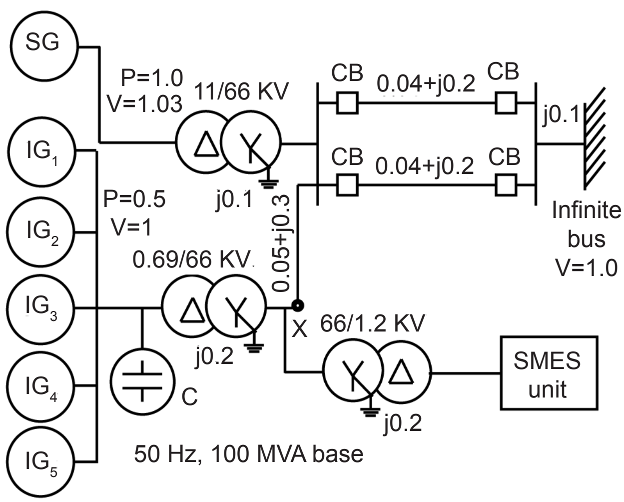



**Figure 1** Power system model

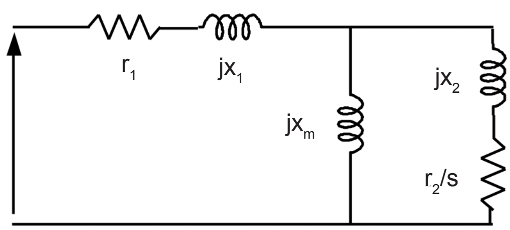



**Figure 2** Steady state equivalent circuit of single squirrel-case induction generator

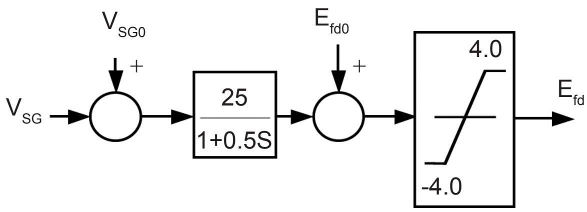



**Figure 3** AVR Model

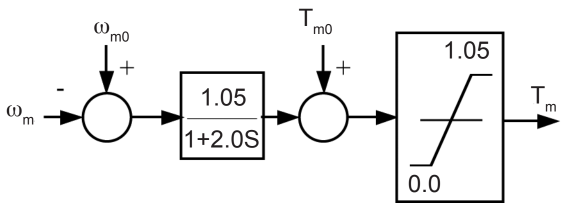



**Figure 4** GOV Model

**Table 1** Generator parameters

| SG | | IG | |
|---|---|---|---|
| MVA | 100 | MVA | 50 |
| Ra(pu) | 0.003 | $r_1$(pu) | 0.01' |
| Xa(pu) | 0.13 | $x_1$(pu) | 0.18 |
| Xd(pu) | 1.2 | Xmu(pu) | 10 |
| Xq(pu) | 0.7 | $r_2$ (pu) | 0.015 |
| Xd'(pu) | 0.3 | $x_2$(pu) | 0.12 |
| Xq'(pu) | 0.22 | H(sec) | 1.5 |
| Xd"(pu) | 0.22 | | |
| Xq"( pu) | 0.25 | | |
| Td0'(sec) | 5.0 | | |
| Td0"(sec) | 0.04 | | |
| Tq0"(sec) | 0.05 | | |
| H(sec) | 2.5 | | |

## 3.0 MODELING OF WIND TURBINE

The model of wind turbine rotor is complicated. According to the blade element theory [15], modeling of blade and shaft needs complicated and lengthy computations. Moreover, it also needs detailed and accurate information about rotor geometry. For that reason, considering only the electrical behavior of the system, a simplified method for modeling the wind turbine blade and shaft is normally used. The mathematical relation for the mechanical power extraction from the wind can be expressed as follows:

$$P_w = 0.5\rho\pi R^2 v_w^3 Cp(\beta,\lambda) \tag{1}$$

Where, $P_w$ is the extracted power from the wind, ρ is the air density [kg/m³], R is the blade radius [m], and $C_p$ is the power coefficient which is a function of both tip speed ratio, λ, and blade pitch angle, β[deg]. The $C_p$ equation has been taken from [16].

$$\lambda = \frac{V_w}{\omega B} \tag{2}$$

$$C_p = \frac{1}{2}\left(\lambda - 0.022\beta^2 - 5.6\right)e^{-0.17\lambda} \tag{3}$$

Where, $\omega_B$ is the rotational speed of turbine hub [rad/s]. Here wind speed, $V_w$, is in mile/hr. The $C_p$-λ curves are shown in Figure 5 for different values of β.

Power versus wind speed characteristic is also shown in Figure 6. When the wind velocity exceeds the rated speed, the pitch angle of the blade needs to be controlled to maintain the output at the rated level. Figure 6 is showing this pitch angle control with respect to the wind velocity. The turbine torque, $T_w$, can be calculated from Equation (4).

$$T_w = 0.5\rho\pi R^2 v_w^2 C_p\left(\beta,\lambda\right)/\lambda \tag{4}$$

The pitch angle controller shown in Figure 7 is modeled with a first order delay system with a time constant $T_d$=5 sec. Because the pitch actuation system cannot, in general, respond instantly, a rate limiter with a value of $10^0$/sec is added. For the step response, when the IG real power is sensed as the controller input, a low pass filter (LPF) is necessary to reduce the harmonices of the real power for the short duration. For this, a LPF is added with the pitch control system. The transfer function of the low pass filter, $F_{LP}(s)$, is shown in Equation (5).

$$F_{LP}(s) = \frac{1}{1 + 2\zeta\left(\frac{s}{\omega c}\right) + \left(\frac{s}{\omega c}\right)^2} \tag{5}$$

where, $\omega_c$=0.005 Hz, $T_c$=200 s, damping ratio, $\zeta$=1 and the characteristic frequency = 50 Hz.

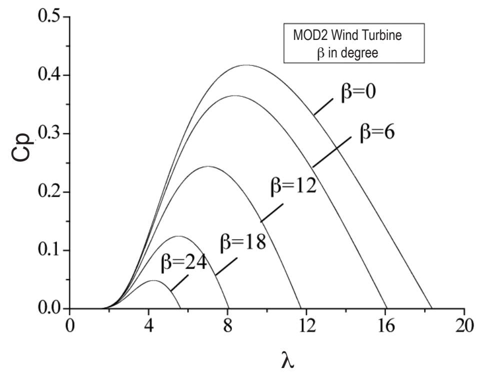



**Figure 5** $C_p$- λ curves for different pitch angles

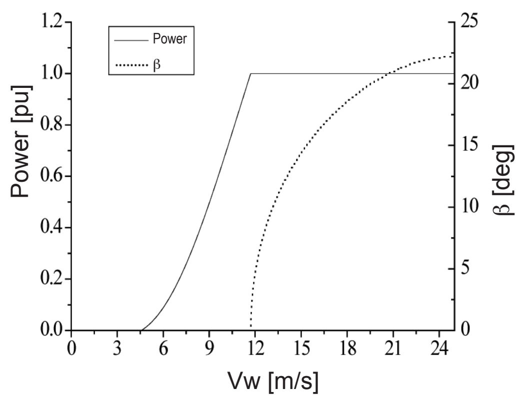



**Figure 6** Output power versus wind speed and pitch angle versus wind speed characteristics

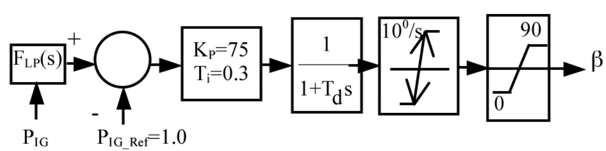



**Figure 7** Pitch angle controller

## 4.0 CONTROL SYSTEM OF SMES

### 4.1 Brief Overview of SMES System

The SMES system used in this paper is shown in Figure 8. It consists of a Wye-Delta transformer, a 6-pulse PWM voltage source converter (VSC) using IGBT, a DC link capacitor, a two-quadrant DC-DC chopper using IGBT, and a superconducting coil or inductor of 0.5 H. The VSC and the DC-DC chopper are linked by a DC link capacitor of 50 mF.

For an SMES system, the inductively stored energy (E in Joule) and the rated power (P in Watt) are commonly the given specifications for SMES devices, and can be expressed as follows:

$$E = \frac{1}{2} I_{sm}^2 L_{sm} \tag{6}$$

$$P = \frac{dE}{dt} = L_{sm} I_{sm} \frac{dI_{sm}}{dt} = V_{sm} I_{sm} \tag{7}$$

where $L_{sm}$ is the inductance of the coil, $I_{sm}$ is the DC current flowing through the coil, and $V_{sm}$ is the voltage across the coil. The proposed SMES has the rating of 30 MW, 0.5 MWH.

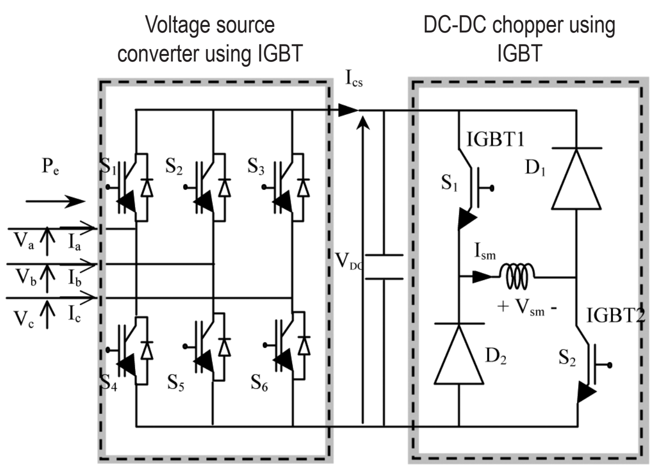



**Figure 8** The configuration of SMES unit

## 4.2 PWM Voltage Source Converter

The PWM voltage source converter provides a power electronic interface between AC power system and superconducting coil. DC link voltage $V_{dc}$ and grid point voltage $V_G$ are maintained as constant by the VSC. From the simplified VSC single-phase equivalent circuit, it is seen that active and reactive power of SMES are proportional to the d- and q-axis currents and thus also to the q- and d-axis voltages.

Based on this concept, the control system of the VSC is constructed. The control system of the VSC is shown in Figure 9. The PI controllers determine reference d- and q-axis currents by using difference between DC link voltage $V_{dc}$ and reference value $V_{dc\text{-}ref}$, and difference between terminal voltage $V_G$ and reference value $V_{G\text{-}ref}$ respectively. The reference signal for VSC is determined by converting d- and q-axis voltages, which are determined by difference between reference d-q axes currents and their detected values. Parameters of the PI controllers are determined by trial and error method for the better performance. The PWM signals are generated for IGBT switching by comparing the reference signals, which is converted to 3-phase sinusoidal wave with the triangular carrier signal. The frequency of the triangular carrier signal is chosen 450 Hz. The DC voltage across the capacitor is 2000 V, which is kept constant throughout by the 6-pulse PWM converter.

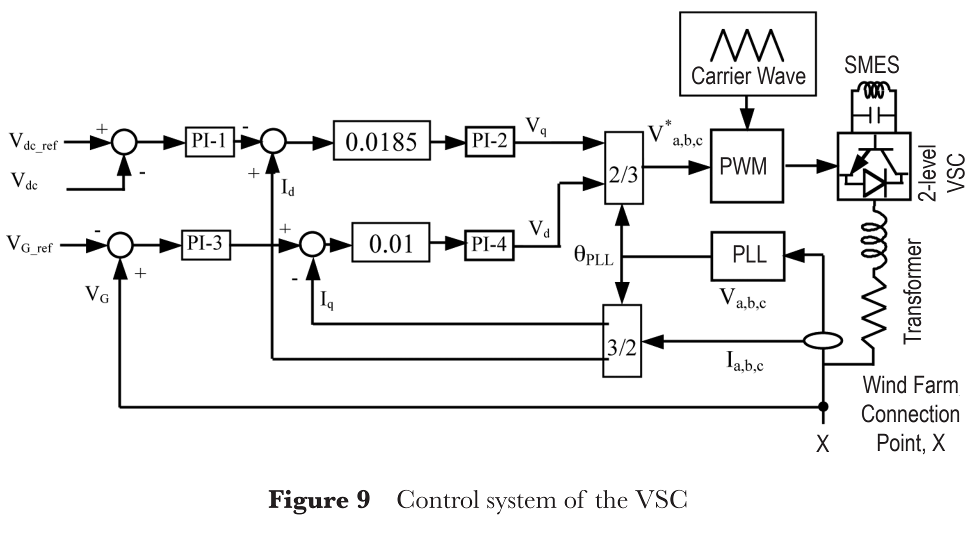
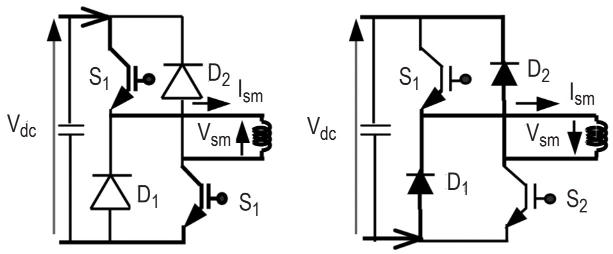



**Figure 9** Control system of the VSC

### 4.3 Two-Quadrant DC-DC Chopper

The superconducting coil is charged or discharged by adjusting the average (i.e., DC) voltage across the coil to be positive or negative values by means of the DC-DC chopper duty cycle, D. When the duty cycle is larger than 0.5 or less than 0.5, the coil is either charging or discharging respectively. The control concept of coil energy charging and discharging is shown in Figure 10. The DC-DC chopper is controlled to supply positive (IGBT is turned on) or negative (IGBT is turned off) voltage $V_{sm}$ to SMES coil and then the stored energy can be charged or discharged. When the unit is on standby, the coil current is kept constant, independent of the storage level, by adjusting the chopper duty cycle to 50%, resulting in the net voltage across the superconducting coil to be zero. In order to generate the gate signals for the IGBT's of the chopper, the PWM reference signal is compared with the saw tooth carrier signal as shown in Figure 11. The frequency of the saw tooth carrier signal for the chopper is chosen 100 Hz. The parameters of the PI controllers used in Figure 9 and Figure 11 are shown in Table 2.



(a) Charging mode (b) Discharging mode

**Figure 10** The control concept of SMES charging and discharging

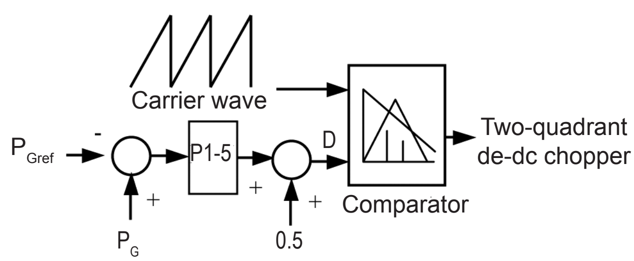



**Figure 11** Control system of two-quadrant dc-dc chopper

**Table 2** Parameters of PI controllers

| | PI-1 | PI-2 | PI-3 | PI-4 | PI-5 |
|---|---|---|---|---|---|
| $K_p$ | 1.0 | 0.1 | 1.0 | 0.1 | 1.0 |
| $T_i$ | 0.018 | 0.002 | 0.018 | 0.002 | 0.012 |

## 4.0 SIMULATION RESULTS

The simulation is performed using PSCAD/EMTDC [17]. To verify the effectiveness of the proposed system, simulation are carried out considering two cases:

*Case-I: A Unit Step Function is Used as Wind Data*

In this case, it is considered that initially the wind speed (for all the wind generators) is at rated speed, and then it experiences a step change as shown in Figure 12. The time step and simulation time have been chosen as 0.00005 sec and 20.0 sec respectively. Figure 13 to Figure 20 show the simulation results for this case. Figure 13 and Figure14 show the responses of wind farm grid volage and wind farm real power against line power respectively. It is seen that because of the use of the proposed controlled SMES wind farm can maintain line power and grid voltage at rated level. Figure 15 shows the line reactive power against wind farm reactive power. Figure 16 shows the turbine blade pitch angle(IG1). The pich controller works when the wind speed exceeds the rated speed to maintain output power constant. Figure 17 and Figure 18 show the SMES real and reactive power compensation from SMES to maintaion wind farm line real power and grid voltage constant respectively. Figure 19 and Figure 20 show the responses of SMES voltage and DC link voltage. The dc link voltage is maintain constant throughout.

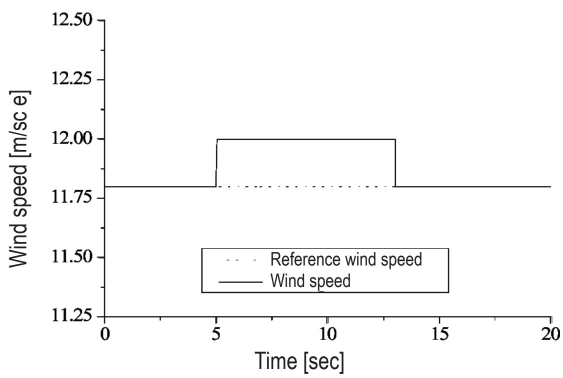



**Figure 12** Response of wind data

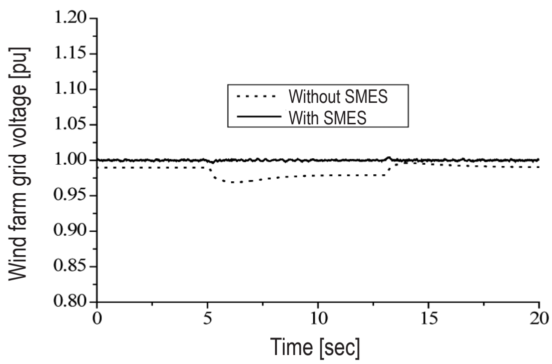



**Figure 13** Responses of wind farm grid voltages

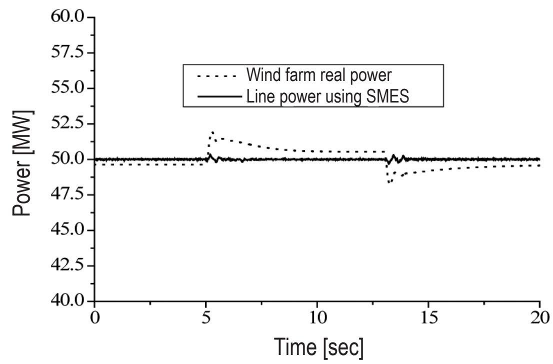



**Figure 14** Responses of line power against wind farm real power

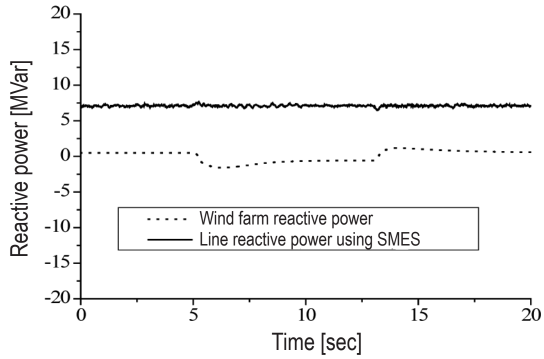



**Figure 15** Responses of line reactive power wind farm real power against wind farm reactive power

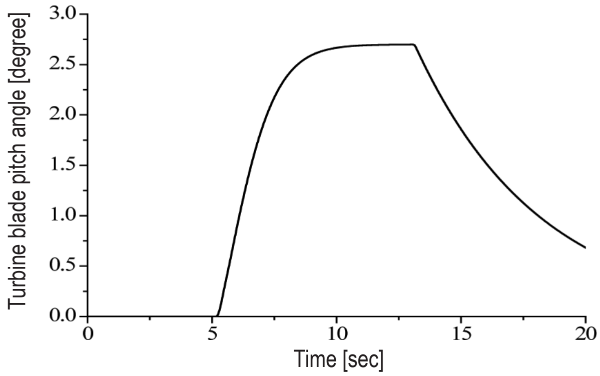



**Figure 16** Response of turbine blade pitch angle [IG1]

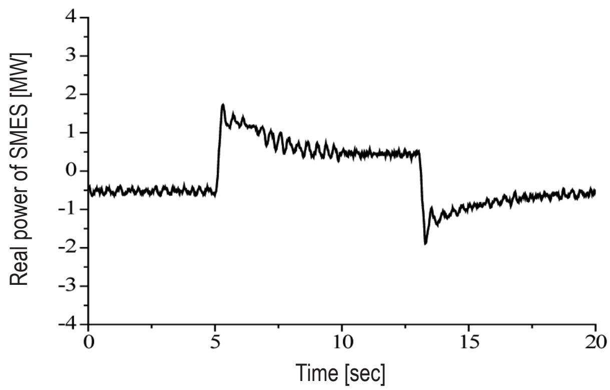



**Figure 17** Response of SMES real power

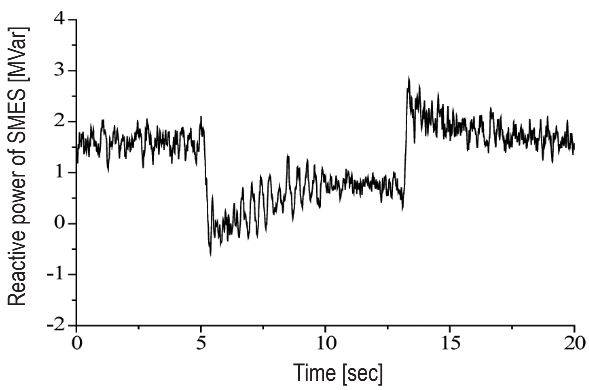



**Figure 18** Response of SMES reactive power

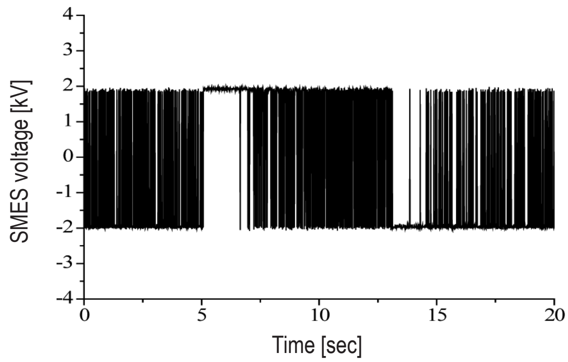



**Figure 19** Response of SMES voltage

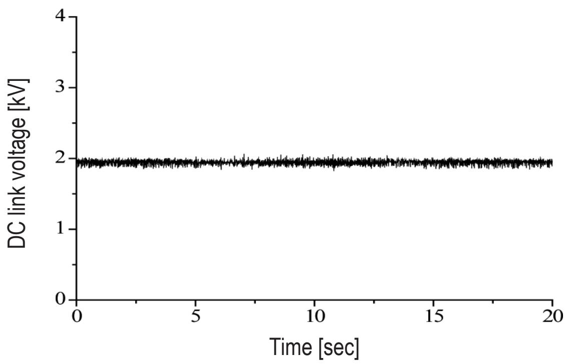



**Figure 20** Response of DC link voltage

*Case II: A Real Wind Data is Used as Wind Speed*

In this case, simulation analyses were performed using a real randomly varying wind speed data shown in Figure 21, which was obtained in Hokkaido Island, Japan. In this study, time step and simulation time have been chosen as 0.00001 sec and 100.0 sec respectively. Figures 22-28 show the simulation results for this case. Figure 22 shows the response of wind farm grid voltage. It is seen that wind farm grid voltage can be maintained constant by using the SMES. This fact indicates that the proposed controlled SMES can decrease the voltage fluctuations. Figure 23 shows the responses of line power and IG real power. It is seen that by using the proposed controlled SMES the line power can be smoothed well. In other words, the proposed SMES can decrease the fluctuations of line power of the system. Figure 24 shows the line reactive power against IG reactive power. Figure 25 shows the response of the SMES real power. It is seen that with the variation of wind speed the SMES provide proper compensation of real power to maintain IG grid line output constant. Figure 26 shows the response of reactive power of SMES. Which also provide reactive power compensation to maintain IG grid voltage to the rated value. Figures 27-28 show the responses of SMES voltage and DC link voltage respectively.

From the simulation result it can be concluded that the proposed controlled SMES can be considered as very effective means for minimizing voltage and frequency fluctuations of wind generator.

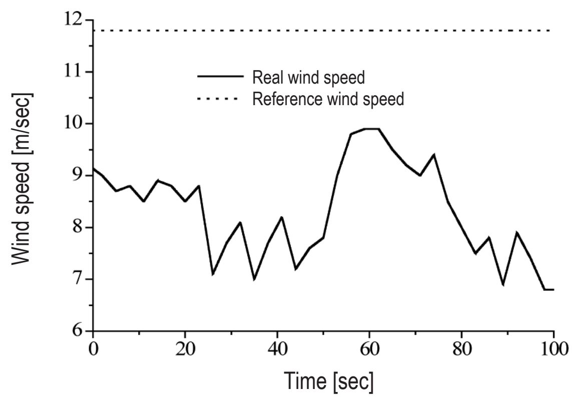



**Figure 21** Response of real wind data

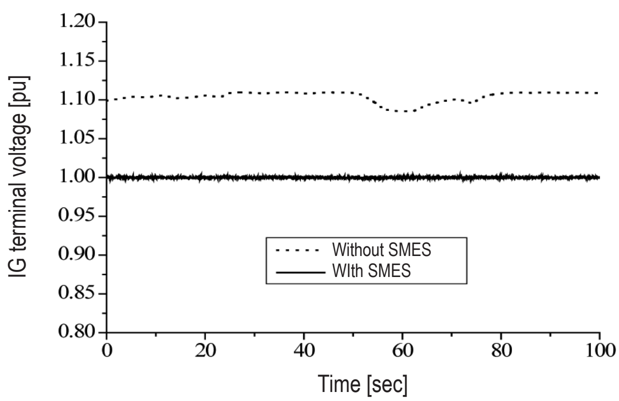



**Figure 22** Responses of wind farm grid voltage

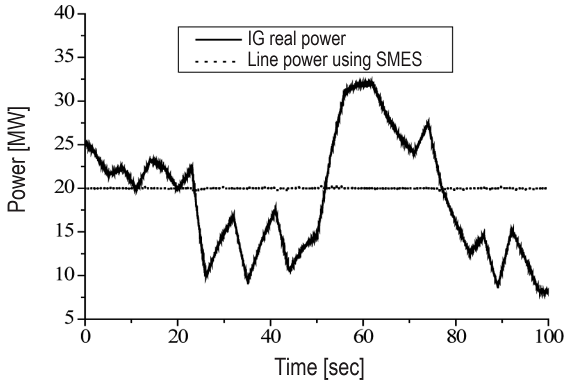



**Figure 23** Responses of line power against IG real power

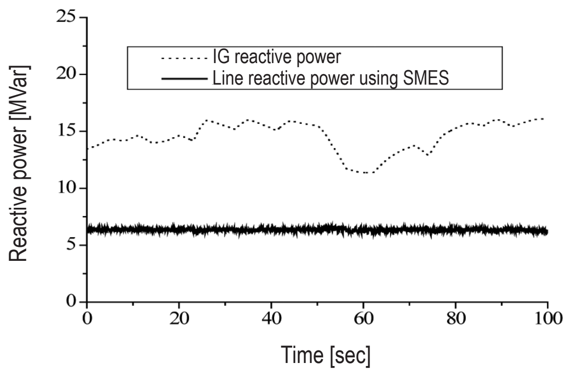



**Figure 24** Responses of line reactive power IG real power against IG reactive power

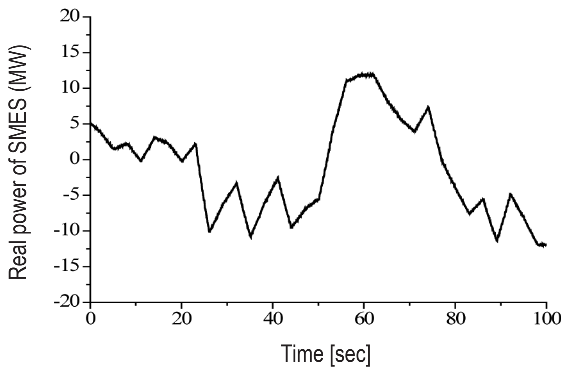



**Figure 25** Responses of SMES real power

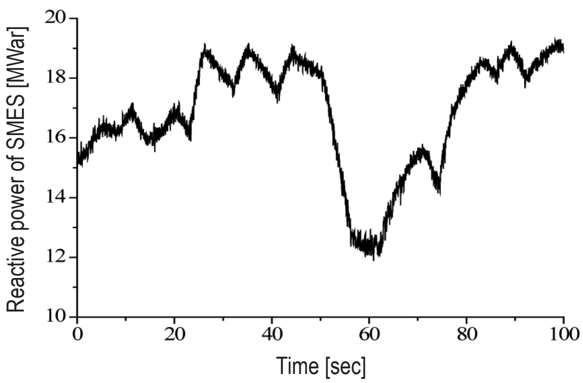



**Figure 26** Responses of SMES reactive power

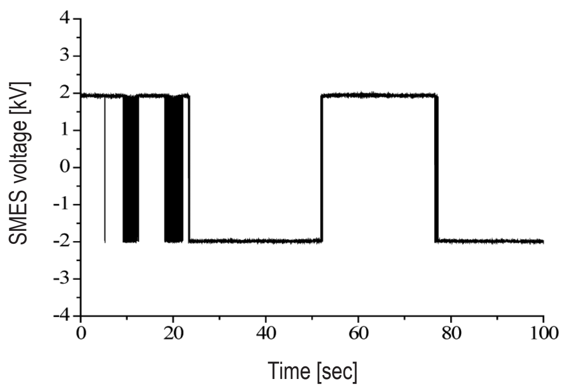



**Figure 27** Responses of SMES voltage

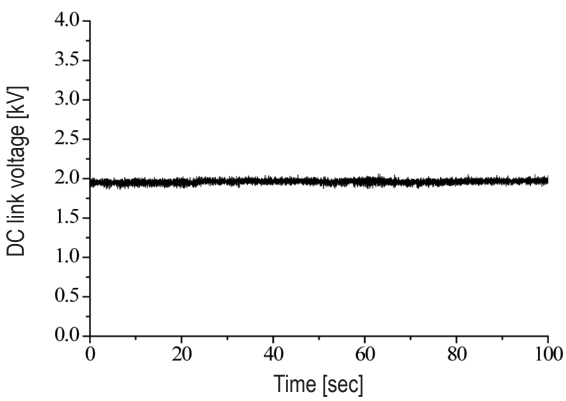



**Figure 28** Responses of DC link voltage

## 5.0 CONCLUSIONS

In this study, the control scheme of SMES for wind power application is presented. As wind is fluctuating in nature, the output power and terminal voltage of wind generator also fluctuate randomly. The proposed control system can smooth the wind generator output power. Moreover, it can also maintain constant voltage magnitude at wind farm terminal.

Although the cost of SMES system may be high, the salient properties such as real power absorption from and injection into the power system, and faster operation etc., prove the superiority as well as excellence of the SMES system. Finally, the simulation results clearly show the suitability of the proposed control system of SMES for wind power application. As a whole, it can be concluded that the proposed controlled SMES strategy provides a very simple and effective means of stability enhancement of electric power system including wind generators.

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