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Minimization of Fluctuations of Output Power and Terminal Voltage of Wind Generator by Using STATCOM/SMES

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Abstract-- **Due to random variations of wind speed, the output power and terminal voltage of a fixed speed wind generator fluctuate continuously. These irregularities in power output are characteristic of intermittent energy sources such as wind energy, affecting both the power quality and planning of the energy storage system. It is reported that STATCOM/SMES (superconducting magnetic energy storage) topology can significantly decrease voltage and power fluctuations of grid connected fixed speed wind generator. But the main problem in wind generator output power smoothing is setting of the reference output power. Constant output power reference can cause large energy storage capacity in the cases when wind speed is very low. In this paper, the STATCOM/SMES topology is proposed, in which both SMA (simple moving average) and EMA (exponential moving average) are used to generate output power reference. 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 STATCOM/ SMES topology can smooth well the wind generator output power and also maintain the terminal voltage at rated level in both cases when SMA or EMA is used to generate output reference power. Finally, it is shown that reference output power generated by EMA provides better performance with reduced SMES storage capacity than that generated by SMA.**

Index Terms—**Minimization of fluctuations, fixed speed wind generator, STATCOM/SMES, simple moving average (SMA) and exponential moving average (EMA).**

I. Introduction

Due to the degradation and cost increase of conventional fuel and also the environmental problem such as global warming, it is necessary to introduce clean energy more in place of the fossil fuel. Because of the reason of almost no carbon dioxide (CO2) emission, wind energy, solar energy, biomass, etc. have attracted the attention remarkably in the world due to their clean energy characteristics. These energy sources are renewable, and the exhaustion problem of fossil fuel makes those prospective and alternate energy sources of the future world. Although wind power is considered as a very prospective clean energy source, wind power fluctuation caused by randomly varying wind speed is still a serious problem for power grid companies and transmission system owners (TSOs), especially in the case of fixed-speed wind generators. Induction generators (IGs) are used, in general, as fixed-speed wind generator because of their superior characteristics such as brushless and rugged construction, low cost, maintenance and operational simplicities. However, the induction generators need reactive power for their operations. As the reactive power drained by the induction generators is coupled to the active power generated by them, the variation of wind speed causes the variations of IGs real and reactive powers. These active and reactive power variations interact with the network and thus initiate voltage and frequency fluctuations. The fast acting energy storage devices can improve the performance under these conditions.

Recently, FACTS with energy storage system (ESS) have emerged as promising devices for power system applications [1-2]. Since the successful commissioning test of the Bonneville Power Administration (BPA) 30 MJ unit, SMES systems have received much attention in power system applications [3]. The SMES is a system where energy is stored within a magnet that is capable of quickly releasing megawatt amounts of power. The real power as well as the reactive power can be absorbed by or released from the SMES unit according to the system power requirements. The ability of injecting/absorbing real or reactive power can increase the effectiveness of the control, provide operation flexibility and enhance system reliability, and thus the SMES can be a prospective option in building a FACTS.

The current article proposes a model of a STATCOM/ SMES unit and its control algorithm to decrease voltage and power fluctuations of wind generator during random wind speed variations. A comparison is also made between two cases in which SMA and EMA are used to generate the output reference power. A PWM (pulse width modulation) voltage source converter and a two-quadrant DC-DC chopper using IGBT are used for controlling SMES unit. Charge and discharge of SMES are determined by the chopper duty cycle. Therefore, the SMES is capable of controlling both active and reactive powers simultaneously, independently, and quickly [4-5]. Considering these viewpoints, this paper proposes a novel control strategy of the STATCOM/SMES installed at a wind farm for decreasing fluctuations of output power and terminal voltage of the wind farm.

II. Model System

The model system shown in Fig. 1 is used in the simulation analyses of wind generator stabilization in this work. The model system consists of one synchronous generator (100MVA), SG, and one wind turbine generator (50MVA

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induction generator, IG), 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 a single generator with the total power capacity 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 squirrel-cage induction machine model 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 [5-8]. 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 are same as that used in [5]. Generator parameters are shown in Table I. The system base power is 100 MVA.

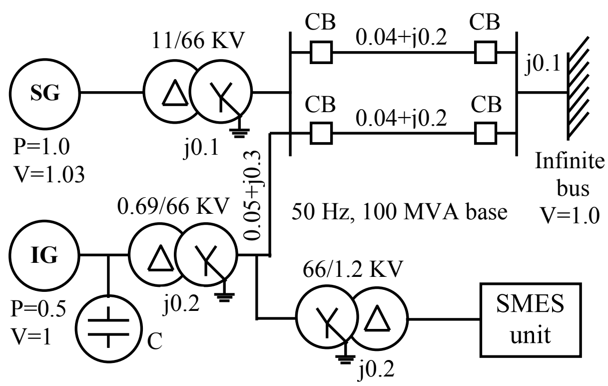

Fig. 1. Power system model

TABLE I
GENERATOR PARAMETERS

SG		IG	
MVA	100	MVA	50
Ra(pu)	0.003	r1(pu)	0.01
Xa(pu)	0.13	x1(pu)	0.18
Xd(pu)	1.20	Xmu(pu)	10
Xq(pu)	0.70	r2 (pu)	0.015
Xd′(pu)	0.30	x2(pu)	0.12
Xd″(pu)	0.22	H(sec)	1.5
Xq″(pu)	0.25		
Td0′(sec)	5.00		
Td0″(sec)	0.04		
Tq0″(sec)	0.05		
H(sec)	2.50		

III. Modeling of Wind Turbine

The model of wind turbine rotor is complicated. According to the blade element theory [9], 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 of modeling of 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/m^3], 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 [10].

$$\lambda = \frac{V_w}{\omega_B} \tag{2}$$

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

Where, ω_B is the rotational speed of turbine hub [rad/s]. Here wind speed, V_w, is in mile/hr. The C_p-λ curves for different values of β are shown in [5]. Power versus wind speed characteristic is shown in Fig. 2, in which the characteristic of pitch angle control is also shown with respect to the variation of wind velocity. 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.

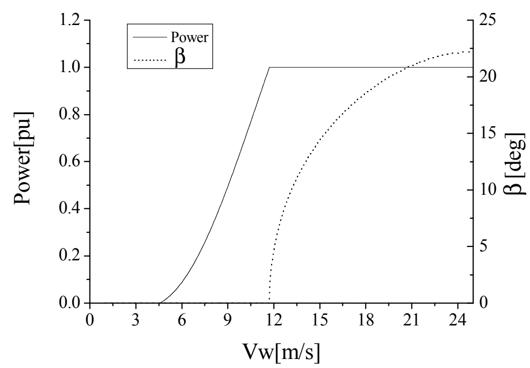

Fig. 2. Output power versus wind speed and pitch angle versus wind speed characteristics

The pitch angle controller shown in Fig. 3 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.

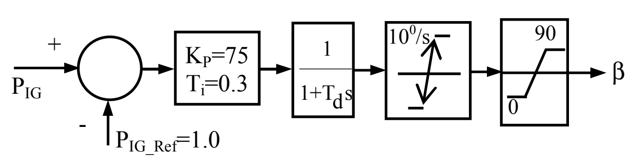

Fig. 3. Pitch angle controller

IV. STATCOM/SMES TOPOLOGY

A. Brief Overview of SMES System

The SMES system used in this study 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. 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 0.2 pu leakage reactance (100MVA Base).

For a 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:

$$E = \frac{1}{2} I_{sm}^{2} L_{sm} \tag{4}$$

$$P = \frac{dE}{dt} = L_{sm} I_{sm} \frac{dI_{sm}}{dt} = V_{sm} I_{sm} \tag{5}$$

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 power rating and energy capacity of 30 MW and 0.5 MWh respectively.

B. PWM Voltage Source Converter(VSC)

In this study, the well-known cascade control scheme with independent control of the active and reactive currents was developed as shown in Fig. 4. The aim of the control is to maintain the magnitude of voltage at the wind farm terminal to be at the desired level. The DC link voltage (V_{dc}) is also kept 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. 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 1000 Hz. The rated DC link voltage is 2 kV.

C. 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. These regions of operation are known as charge/discharge/standby operation. The average voltage appearing across the SMES coil and chopper current at any instant of time can be represented by (6),

$$V_{SM\_av}=[1-2D]\,V_{dc\_av}$$
$$I_{dc\_av}=[1-2D]\,I_{SM\_av} \tag{6}$$

where V_{SM_av} is the average voltage across the SMES coil, I_{SM_av} is the average current through the SMES coil, V_{dc_av} is the average dc source voltage, I_{dc_av} is the average dc source current, and D is the duty cycle of the chopper (D=IGBT conduction time/period of one switching cycle).

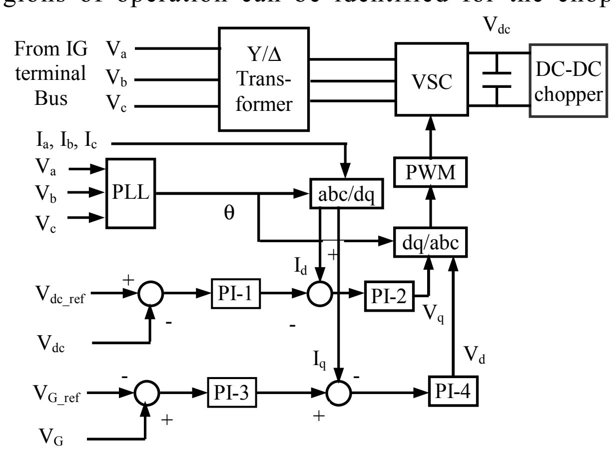

Fig. 4. The control system of the VSC

Adjusting the duty cycle of the IGBT firing signals controls the rate of charging /discharging. Thus when the duty cycle is larger than 0.5 or less than 0.5, the coil is either charging or discharging respectively. 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 winding 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 Fig. 5. The frequency of the saw tooth carrier signal for the chopper is chosen 100 Hz. The parameters of the PI controllers used in Fig. 4 and Fig. 5 are shown in Table II.

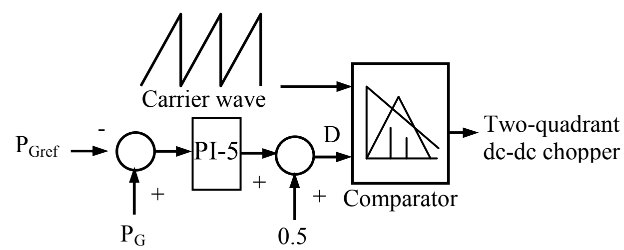

Fig. 5. Control system of two-quadrant dc-dc chopper

TABLE II
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	0.02	0.002	0.02	0.002	0.02

D. Generation of Line Power Reference, P_{ref}

IG line output power reference signal, P_{ref}, is generated by the following ways:

(i) SMA: The n period SMA [11] for period d is computed by:

$$SMA_d = \frac{\sum_{i=1}^{n} M_{(d-i)+1}}{n}\,;\ (n \le d) \tag{7}$$

If ten measurements, M_1 through M_{10}, are available, the successive 4 period simple moving average, for example, are as follows:

$$SMA_4=(M_4+M_3+M_2+M_1)/4$$
$$SMA_5=(M_5+M_4+M_3+M_2)/4 \tag{8}$$
$$\vdots$$
$$SMA_{10}=(M_{10}+M_9+M_8+M_7)/4$$

It is not possible to compute a 4 period moving average until 4 periods data are available. That's why the first moving average in the above example is SMA_4.

(ii) EMA: N periods EMA [11] is calculated using the formula shown below.

$$EMA(C)=[(C-P)\times K]+P \quad (9)$$

where C= current value, P= previous period's EMA and K= weighting factor. For a period-based EMA, "K" is equal to 2 /(1 + N), where N is the specified number of periods. For example, a 10-period EMA's "weighting factor" is calculated like this: 2/(1+10)=0.1818.

V. SIMULATION RESULTS

To verify the effectiveness of the proposed control system, two different patterns of real wind speed data, which were obtained in Hokkaido Island, Japan, are used in the simulation analyses. The time step and simulation time have been chosen 0.00001sec and 600sec respectively. The simulations have been done by using PSCAD/EMTDC [12]. Two cases are considered to show the effectiveness of STATCOM/SMES topology for output power and terminal voltage smoothing.

Case I: SMA is used to generate IG output power reference.

Case II: EMA is used to generate IG output power reference.

A. Simulation using widely varying wind speed data

In this case, wind pattern with wide variations shown in Fig. 6 was used. Fig. 7 and Fig. 8 show the IG terminal voltage and IG real power responses without STATCOM/SMES considered respectively. It is seen that when there is no STATCOM/SMES the terminal voltage of IG cannot be maintained constant and also the wind generator line power output cannot be smoothed. Fig. 8 shows the IG line power responses also in the two cases when STATCOM/SMES is connected to IG terminal. It is clear from Fig. 8 that the STATCOM/SMES can smooth the IG line power well in both cases. Fig. 9 shows the real power compensation from the STATCOM/SMES for both cases. But comparatively more compensation is required in case I. In Fig. 10 IG terminal voltage responses are presented for both cases when STATCOM/SMES is used. It is seen that STATCOM/SMES can maintain the terminal voltage constant in both cases. Fig. 11 and Fig. 12 show the responses of SMES reactive power and SMES stored energy respectively.

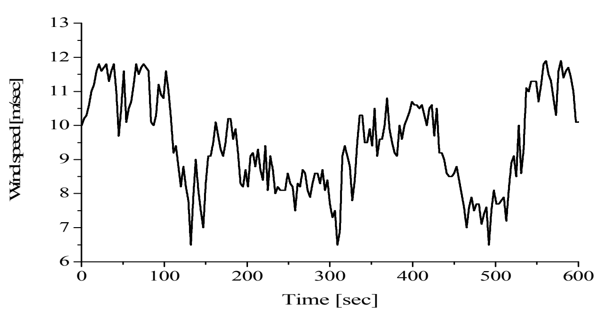

FIG. 6. Response of real wind data (A)

It is also clear from Fig. 11 and Fig. 12 that more reactive power compensation and larger SMES energy storage capacity are needed in case I than Case II.

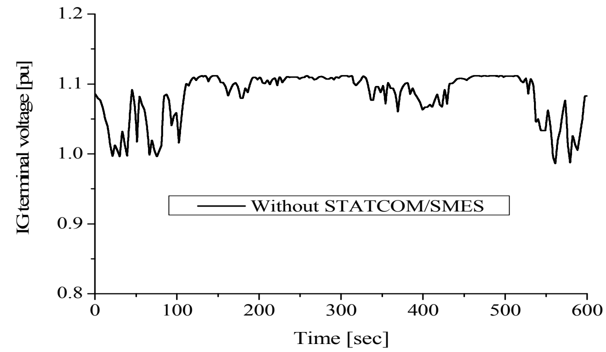

Fig. 7. Terminal voltage response of IG without STATCOM/SMES

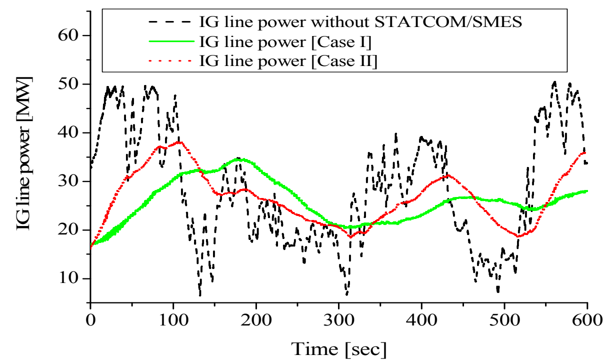

Fig. 8. Responses of IG line power with and without STATCOM/SMES

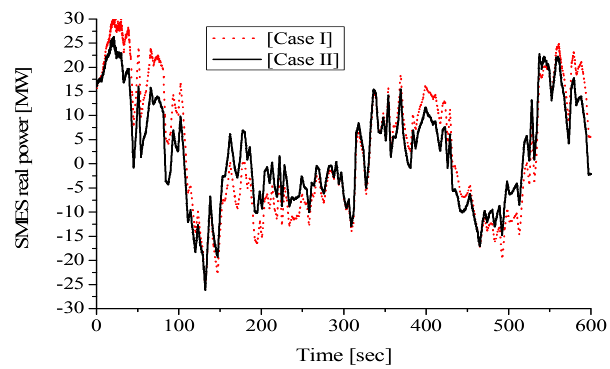

Fig. 9. Responses of SMES real power

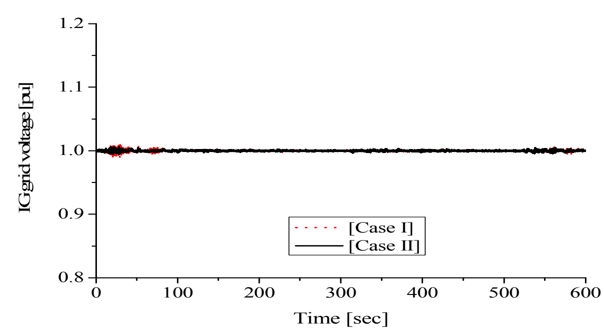

Fig. 10. Responses of IG terminal voltage with STATCOM/SMES

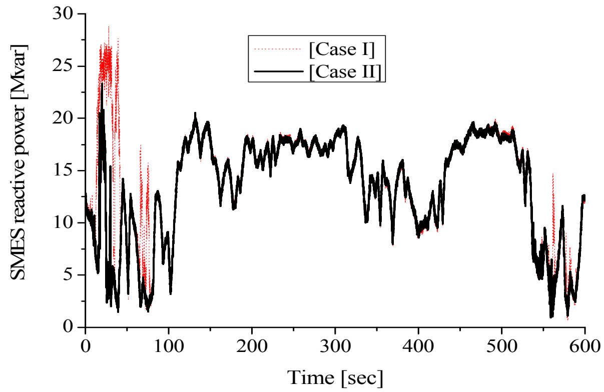

Fig. 11. Responses of SMES reactive power

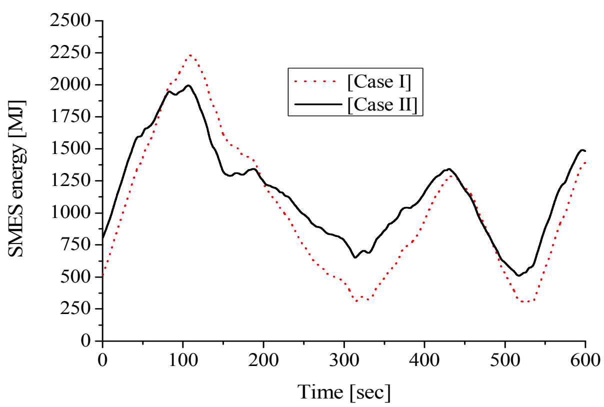

Fig. 12. Responses of SMES energy

B. *Simulation using moderate wind speed data*

In this case, moderate wind speed pattern shown in Fig. 13 is used. Fig. 14 and Fig. 15 show the IG terminal voltage and IG real power responses without STATCOM/SMES considered respectively. These figures show that the terminal voltage cannot be regulated constant and also the wind generator line power output cannot be smoothed well only by the conventional pitch controller. Fig. 15 also shows the IG line power responses for both cases when the STATCOM/SMES is connected to IG terminal. For this wind data, it is clear from Fig. 15 that the STATCOM/SMES can smooth the IG line power well in both cases.

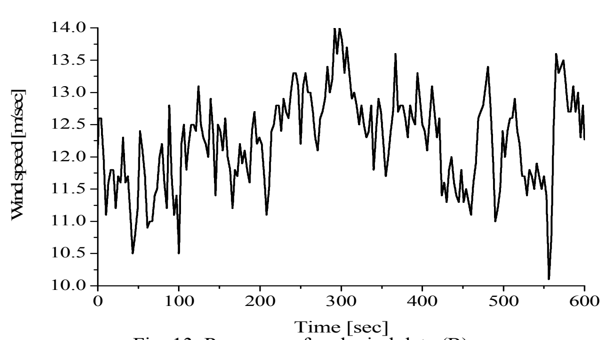

Fig. 13. Response of real wind data (B)

Fig. 16 shows the real power compensation from the STATCOM/SMES for both cases. In Fig. 17 IG terminal voltage responses are presented for both cases when the STATCOM/SMES is used. It is also seen that STATCOM/SMES can maintain the terminal voltage constant in both cases. Fig. 18 and Fig. 19 show the responses of SMES reactive power and SMES stored energy respectively. It is also clear from Fig. 19 that larger SMES energy storage capacity is needed in case I than Case II.

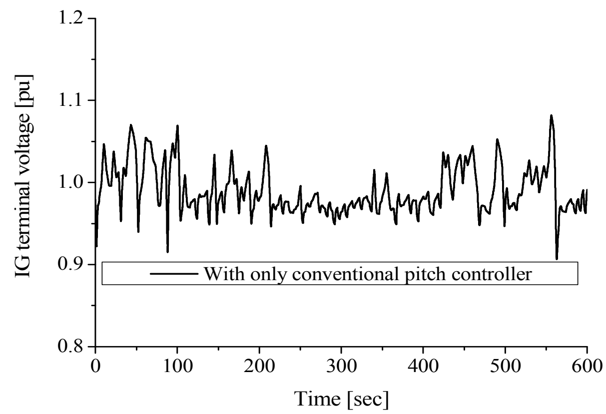

Fig. 14. Terminal voltage response of IG without STATCOM/SMES

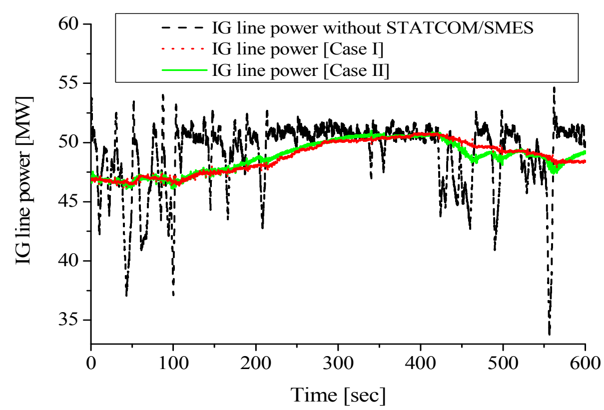

Fig. 15. Responses of IG line power with and without STATCOM/SMES

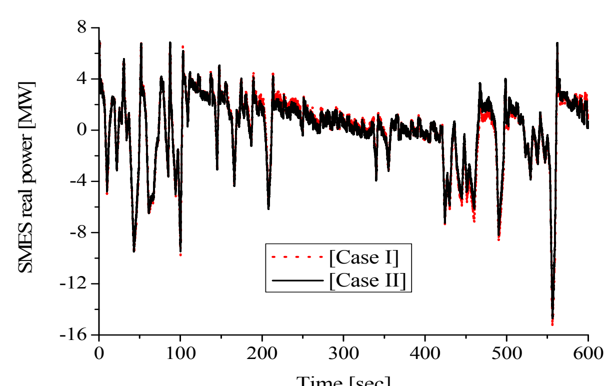

Fig. 16. Responses of SMES real power

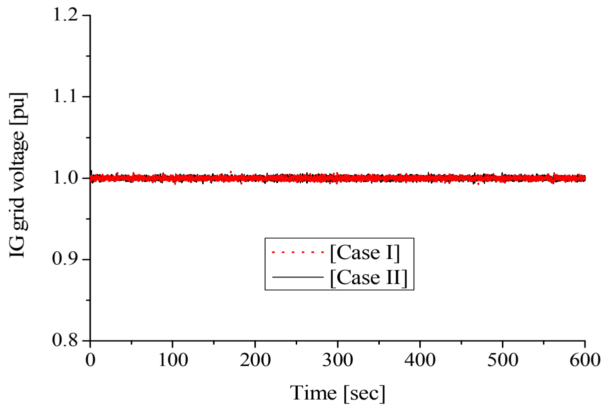

Fig. 17. Responses of IG terminal voltage with STATCOM/SMES

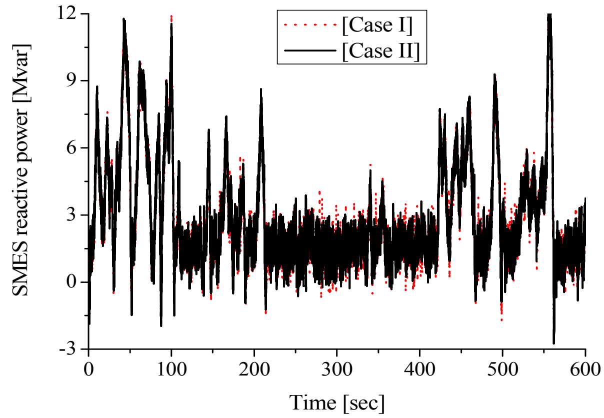

Fig. 18. Responses of SMES reactive power

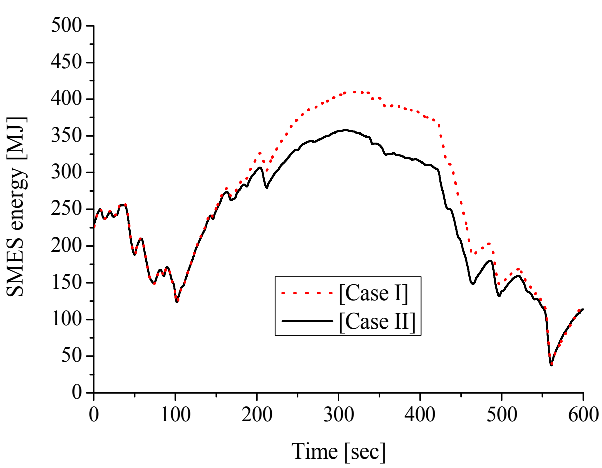

Fig. 19. Responses of SMES energy

VI. CONCLUSIONS

In this study, the control scheme of STATCOM/SMES topology for wind power application is presented. Two wind speed patterns are used to perform simulation analyses. As wind is fluctuating in nature, the output power and terminal voltage of wind generator also fluctuate randomly. The effectiveness of the proposed STATCOM/SMES topology on smoothing the wind generator line power output and terminal voltage is investigated, in which both SMA and EMA are used to generate output power reference. It is seen that the proposed control system can smooth the wind generator output power as well as maintain constant voltage magnitude at wind farm terminal in both cases with the two power references used. But comparatively larger SMES real power and reactive power compensation and also more energy storage capacity are needed in the case with SMA used. These requirements are more significant when wind speed varies widely. Finally, it can be concluded that the proposed STATCOM/SMES topology is effective to minimize the output power fluctuations of wind generator and decrease the terminal voltage deviations.

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