Research on STATCOM/BESS Control Strategy for Wind Turbine with Squirrel-cage Induction Generator

Wenping Wang
College of Energy and Power Engineering
Inner Mongolia University of Technology
Hohhot, China
nmgwwp@163.com

Shengtie Wang
College of Electric Power
Inner Mongolia University of Technology
Hohhot, China
wang_shengtie@imut.edu.cn

Guizhen Tian
College of Electric Power
Inner Mongolia University of Technology
Hohhot, China
tianguizhen@imut.edu.cn

***Abstract*—STATCOM/BESS decoupling control strategies of active and reactive power is proposed for a single wind turbine with squirrel-cage induction generator (WSG). This control strategy can not only effectively suppress power fluctuations of WSG output, achieve unity power factor and grid connected control so as to significantly improve the power quality of WSG, but also real-timely adjust extra power into the grid according to the state of BESS, make BESS always work in a reasonable state so as to avoid overcharging, increase its service life time and reliability. The overall simulation model of the system is established, including wind turbines, BESS, STATCOM/BESS control strategy. And under both the constant disturbance wind speed and the step disturbance wind speed, a simulation study is conducted to verify that the STATCOM/BESS decoupling control strategy is reasonable and feasible.**

Keywords*—*wind turbine with squirrel-cage induction generator (WSG); power quality; STATCOM; battery energy storage system (BESS); decoupling control strategy

I. INTRODUCTION

WSG has a mature technology and cost advantages, and occupies a higher market share in the practical application. WSG connected to the grid directly produces changeable active power and absorb or emit reactive power because of random wind speed so that grid power quality is affected. According to China's newly released wind turbines grid connection regulations, WSG grid connected operation will face a severe test. The whole STATCOM/BESS was studied, and STATCOM/BESS is ideal one of the electric power compensation device in large-scale grid connected wind farms. In the literature [1] and [2], the STATCOM/BESS integration as a whole, can not only improve the performance of existing STATCOM devices, and it's operating range is also run by the internal regulator reactive two quadrants expand into four quadrants. In the literature [3], the studied STATCOM/BESS system can provide both reactive power and active power, which makes the transient stability of the system improved. In the literature [4], STATCOM/BESS inverter topology and its control strategy are introduced, and simulation of STATCOM/BESS system is implemented. In the literature [5], STATCOM/BESS system mathematical model is established, its control strategies are designed, and simulation of STATCOM/BESS was more effective than using separate STATCOM.In the literature [6-7], low-pass filter is used to calculate output average active power of the WSG, the output active power of WSG can be smooth, but it does not consider BESS's SOC, and BESS is also not protected. In the literature [8-9], proposed using a variable time constant instead of the scheduled time constant low-pass filter control SOC of energy storage device, but when the variable time constant is not appropriate to make the output active power fluctuations of wind farms, not at the same time balancing the protection of energy storage system and smooth active power output of wind farms.

This paper deeply analyzes the control strategy of WSG with STATCOM/BESS, and the control strategies of STATCOM/BESS working in guarantee reliable energy storage system is given on the basis of STATCOM/BESS given calculation methods of the control strategy of active power, WSG by using low-pass filter computing the average of the active power output, and increase the calculating module, considering the regulation of battery state guarantee power quality of wind turbine grid, and ensure the battery work in a safe area for a long time. In the MATLAB simulation environment, simulation model of the whole system is established, including wind turbine simulation model, battery simulation model, simulation model of STATCOM/BESS control strategy, to study STATCOM/ BESS control strategy of WSG output power quality improvement under the constant distance speed and step distance wind speed so as to verify the rationality and feasibility of the proposed control strategy.

II. SYSTEM STRUCTURE AND WORKING PRINCIPLE

A. Overall System Topology

Overall system topology is shown in Fig.1, which includes WSG, transformer and STATCOM/BESS systems. The basic principle of STATCOM/BESS system to improve wind turbine output of active power and reactive power is as follows.

B. Regulation of Active Power

When WSG parallel operates, the output of the active power of WSG is remembered to P_1. The active power of

978-1-4673-8644-9/16/$31.00

WSG output is obtained by filter after the average to remember to $\bar{P}$, to absorb the STATCOM/BESS or issued for active power to remember to P_2, active power to the grid to remember to P_3. It is seen from the energy conservation law, when, the battery will output the active power which is $P_2 = P_3 - \bar{P}$ to meet the power requirements. When $\bar{P} > P_3$, the battery will absorb the active power which is $P_2 = \bar{P} - P_3$ to meet the power requirements and store energy for later use when power shortage, in order to maintain the active basically stable output.

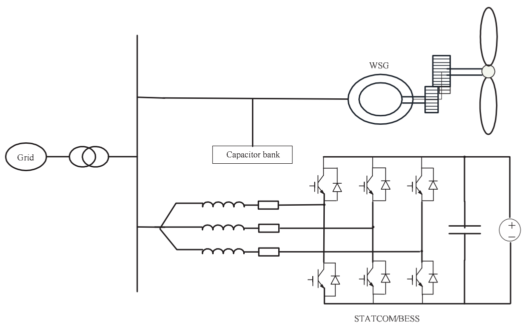


Fig.1 Overall system topology

But when the battery terminal voltage is greater than the upper limit voltage also need to continue to absorb active power, it needs to protect the battery charge current is reduced to prevent them from over-charging; when the battery terminal voltage is less than the output voltage limit will also be required to continue active when the battery needs to be protected but also reduce its discharge current to prevent its excessive discharge; so that not only meets the smooth active power fluctuations, and the battery has been effectively protected.

C. Simultanuous Regulation of Active Power and Reactive Power

WSG in normal operating, needs to absorb reactive power from the grid, and the absorption of reactive power with the change of active power output of the WSG varies. By the STATCOM/BESS known works, as long as the adjustment STATCOM/BESS device output voltage magnitude, you can control the rapid succession STATCOM / BESS or absorb reactive power output size.

In most of the actual situation is the reactive power and active power always need to be done the output or input at the same time, thus, STATCOM/BESS system real-time running in four quadrants, need to be implemented accurately and rapidly the wind turbines and the power system of the flexible link, complete the two-way flow of e

III. Mathematical model of STATCOM/BESS

STATCOM/BESS through the filter circuit are connected via a voltage rating of 0.69/0.69kV isolation transformer and 0.69/35kV step-up transformer and the power grid. Because there are some nonlinear components in the circuit, it increases the difficulty of mathematical modeling. Therefore, does not affect the system, on the basis of accurate modeling, derivation set several ideal situations:

(1)The system side is symmetrical three-phase sinusoidal voltage;

(2)Ignore the influence of voltage and current harmonics;

(3) Does not consider the energy consumption of the device itself;

(4)STATCOM converter switching system is ideal switch.

STATCOM/BESS system topology shown in simplified Fig. 2.

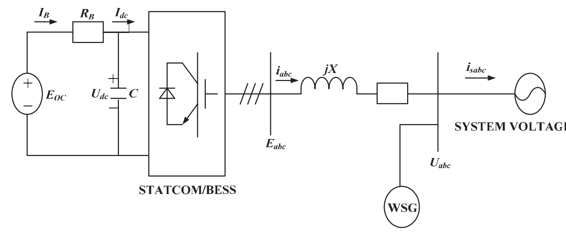


Fig.2. Simplified topology of STATCOM/BESS

Where the battery is equivalent to an ideal voltage source in series small resistor, U_{abc} is three-phase power grid phase voltage, E_{abc} is the output voltage STATCOM / BESS system, E is the maximum of E_{abc}; E_{OC} is the open-circuit voltage of the energy storage system,R_B is the internal resistance of the energy storage system,I_B is the output current of the energy storage system; I_B is the output current of the energy storage system; U_{dc} is the terminal voltage of DC capacitor, R is the equivalent resistance of the STATCOM, X is the equivalent reactance of the circuit and isolation transformer; make $m = E/U_{dc}$ for STATCOM/BESS modulation ratio; U_{abc} is the reference voltage, make an initial phase angle for θ , take its initial phase of 0, the phase difference of U_{abc} and E_{abc} is σ.

Let AC side of the STATCOM/BESS is symmetrical three-phase circuit according to Fig.2 shows.

$$\begin{pmatrix} E_a \\ E_b \\ E_c \end{pmatrix} - \begin{pmatrix} U_a \\ U_b \\ U_c \end{pmatrix} = R \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + L \frac{d}{d_t} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{1}$$

The three-phase voltage of AC side and system side respectively is:

$$\begin{pmatrix} E_a \\ E_b \\ E_c \end{pmatrix} = E\begin{pmatrix} \cos(\omega t+\sigma) \\ \cos(\omega t+\sigma-2\pi/3) \\ \cos(\omega t+\sigma+2\pi/3) \end{pmatrix} = mU_{dc}\begin{pmatrix} \cos(\omega t+\sigma) \\ \cos(\omega t+\sigma-2\pi/3) \\ \cos(\omega t+\sigma+2\pi/3) \end{pmatrix} \tag{2}$$

It is concluded that STATCOM/BESS mathematical model for state equation：

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ u_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{\sqrt{3}m}{\sqrt{2}C}\sin\sigma \\ -\omega & -\frac{R}{L} & -\frac{\sqrt{3}m}{\sqrt{2}C}\cos\sigma \\ \frac{\sqrt{3}m}{\sqrt{2}C}\sin\sigma & \frac{\sqrt{3}m}{\sqrt{2}C}\cos\sigma & 0 \end{bmatrix}\begin{bmatrix} i_d \\ iq \\ u_{uc} \end{bmatrix} + \begin{bmatrix} \frac{\sqrt{3}}{L} \\ 0 \\ 0 \end{bmatrix} U_S \tag{3}$$

IV. DECOUPLING CONTROL STRATEGIES OF STATCOM/BESS ACTIVE AND REACTIVE POWER

A. Decoupling Control Strategies of Active and Reative Power

STATCOM/BESS decoupling control of active and reactive strategy block diagram is shown in Fig. 3.

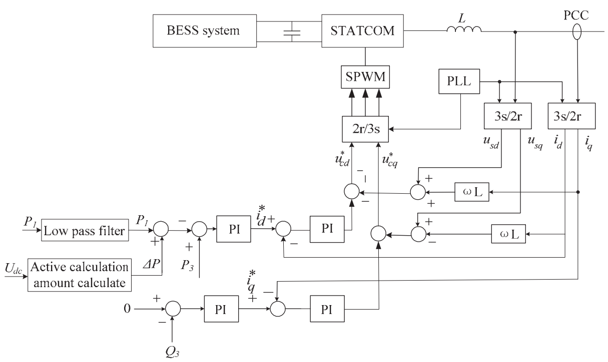


Fig.3 Control block diagram of STATCOM/BESS

For active power control, the acquisition of active WSG outlet *P1*, through a first-order filter calculates its straight flow $\overline{P_1}$, let the grid power *P3* compared to the resulting difference is the battery pack should be absorbed or released from active value. But the control values for the battery pack to ensure work in a safe area, module in the charge-discharge power adjustment amount determined in accordance with this added computing battery status output ΔP , error after comparing its generated by the outer loop PI regulator calculated active current reference signal i_d^* , and compared with the measured line current i_d , through inner PI regulator decoupling calculated intermediate variable used by the *X*, by the calculation of intermediate variables, obtained need STATCOM/BESS output voltage reference signal U_{cd}^* , followed by inverse transform, from *dq0* two-phase rotating coordinate system transformed into *abc* three-phase static coordinate system， and with the phase-locked loop circuit of power grid voltage phase angle θ through the calculation of SPWM module， get three-phase SPWM modulation signal， control IGBT conduction, to control the active power of the STATCOM/BESS output.

Reactive power control is concerned to take unity power factor control mode. Reactive power of wind turbine output target value is 0, comparing with the detected power grid reactive power Q_3 , the error calculated by the outer loop PI regulator reactive current reference signal i_q^* , and compared with the measured reactive current i_q .After the inner PI regulator decoupling calculated intermediate variable used by the X, by the calculation of intermediate variables, Obtain required STATCOM/BESS output voltage reference signal U_{cq}^* . After the transformation, from dq0 two-phase rotating coordinate system transformed to *abc* three-phase static coordinate system, and with the phase-locked loop circuit of power grid voltage phase angle θ, through the calculation of SPWM module, get three-phase SPWM modulation signal, control IGBT conduction, to control the reactive power of the STATCOM/BESS output.

B. Active Power Adjustment amount Considering Battery Status

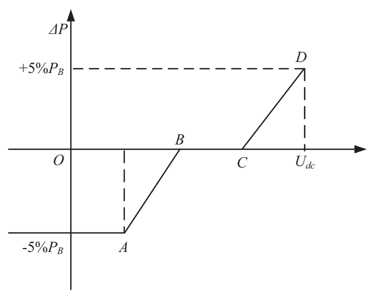


Fig. 4 Relationship curve between ΔP and U_{dc}

$$\Delta P = \begin{cases} 5\%P_B & U_D \le U_{dc} \\ \frac{5\%P_B}{U_D-U_C}\times U_{dc} + \frac{5\%P_B}{U_C-U_D}\times U_C & U_C \le U_{dc} < U_D \\ 0 & U_B \le U_{dc} < U_C \\ \frac{5\%P_B}{U_B-U_A}\times U_{dc} + \frac{5\%P_B}{U_A-U_B}\times U_B & U_A \le U_{dc} < U_B \\ -5\%P_B & U_{dc} < U_A \end{cases} \tag{4}$$

The size of the active power to adjust quantity decides the response speed of the battery charge and discharge protection, also indirectly reflects the performance control strategy whether good or bad. So make sure the range value of the amount of the power regulation $\Delta P = \pm 5\%$, which P_B is the capacity of the battery. Relationship power regulation ΔP and the real time voltage of the battery U_{dc} is shown in Fig.4.

Set A, B, C, D points of the voltage respectively is U_A, U_B, U_C and U_D .

In this paper, set $U_A = 2030V, U_B = 2080V, U_C = 2200V$ and $U_D = 2250V$.

C. Active Power Low-pass Filter Design

Using first-order low-pass filter filters the high frequency components of wind turbine output active power, it's value is as the output average power, reduce the battery charge and discharge times, increase the service life of the battery.

First order filter transfer function is:

$$G(s) = \frac{1}{Ts+1} \tag{5}$$

In this paper set $T = 0.33s$.

V. SIMULATION MODEL AND PARAMETERS

A. Simulation Model

In the MATLAB/SIMULINK software environment, based on the system overall structure system simulation model is set up. Wind power generator output voltage is 0.69kV, through 0.69/35 kV transformer and 35/110 kV transformer into 110kV power grid. At the outlet of the WSG parallel access STATCOM/BESS device.

B. Simulation Parameter

Power grid transmission line uses π equivalent circuit representation, length is 2 km. Parameters of power grid transmission line, WSG and STATCOM are shown respectively in Tab.1-3.

Tab.1 Parameters of power grid transmission line

Resistance(Ω)	Inductor(H)	Capacitance(μF)
0.54	0.0026	0.0088

Tab.2 Parameters of Siemens SWT-2.3-93 wind turbine

Rated output power (MW)	Rated wind speed (m/s)	Rated line voltage (V)
2.30	15	690

Tab.3 Parameters of STATCOM

Rated capacity(MVar)	AC voltage (V)	DC voltage (V)
2.0	690	2000

Single battery terminal voltage of BESS system is 12V, system is consists of 167 batteries in series, total terminal voltage is 2004, it meet the requirements of DC voltage. Output current of single battery is about 100A, BESS system is consists of five groups consisting of parallel branches, shared the 835 pieces of monomer battery. Parameters of STATCOM/BESS system main circuit are shown in Tab.4.

Tab.4 Parameters of STATCOM/BESS system main circuit

Filter inductor(H)	Filter capacitor(μF)	DC capacitor(μF)
1.175	30	50000

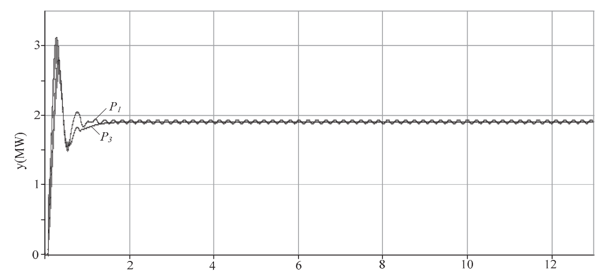
Set the disturbance wind speed according to the form of sine wave is:

$$V_0(t) = 0.2 \times \sin 30t \tag{6}$$

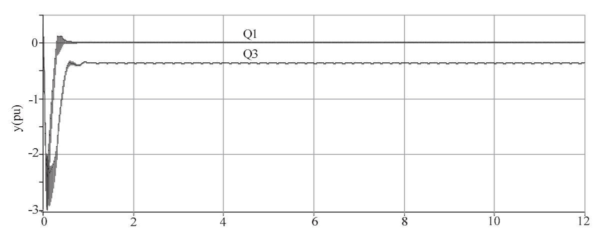
VI. SIMULATION RESULT AND ANALYSIS

A. Simulation Results of Constant Disturbance Wind Speed

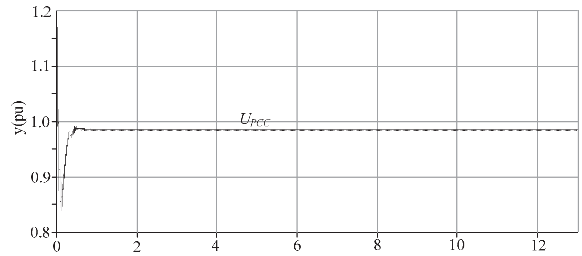
At a constant wind speed of $12\,m/s$, interference range for $\pm 0.2\,m/s$ wind, change the angular frequency of $30\,rad/s$, join STATCOM/BESS system interconnection before and after the active and reactive power, and node voltage, battery parameters as shown in Fig.5.



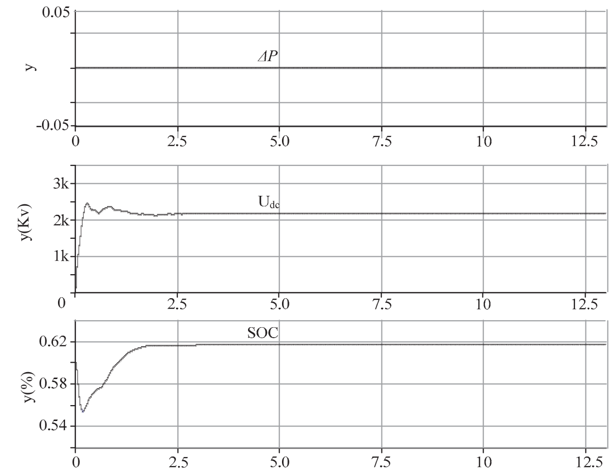
(a) Active power fluctuation curve before and after comparison STATCOM/BESS access



(b) Reactive power contrast curve before and after comparison STATCOM / BESS access



(c) PCC voltage simulation curve



(d) BESS system parameter simulation curve

Fig.5 Simulation results of constant and disturbance wind

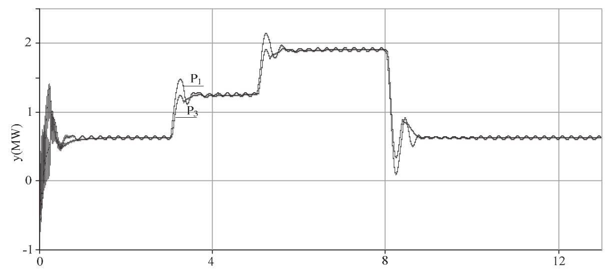
It can be seen from Fig.5 (a) and (b), after joining the STATCOM/BESS system, the active power fluctuation range of fan output decreased greatly, have played an important role in smoothing the active power output. When wind turbine do not take reactive power compensation device, it is necessary to absorb from the grid, about 1Mvar reactive power, shunt capacitor compensation 0.6Mvar, STATCOM/BESS compensation 0.4Mvar, so the wind turbine hardly absorb reactive power from the grid.

Because DC voltage of STATCOM is basically stable. So the voltage across battery is basically stable, as shown in Fig.5 (d). U_{dc} fluctuates between *2.14 kV* to *2.16 kV*, the magnitude of the active power regulation signal has remained to 0, battery discharge when fan start, then SOC gradually smooth remain at around 0.6, work in a safe area.

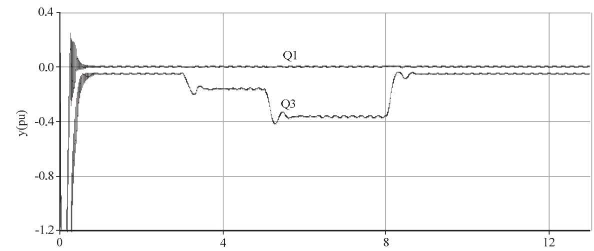
B. Simulation Results of Step Disturbance Wind Speed

In this paper, the design step disturbance wind speed is：

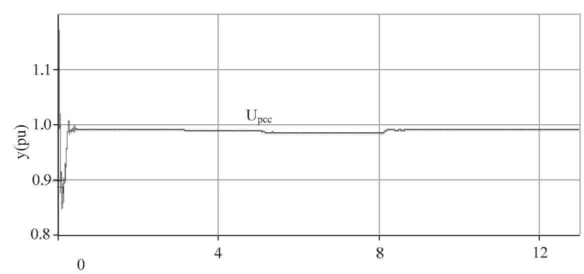
$$V_2(t)=\begin{cases}10 & 3\le t\le 5\\ 12 & 5<t\le 8\\ 8 & t>8\ or\ t<3\end{cases}+V_0(t) \tag{7}$$



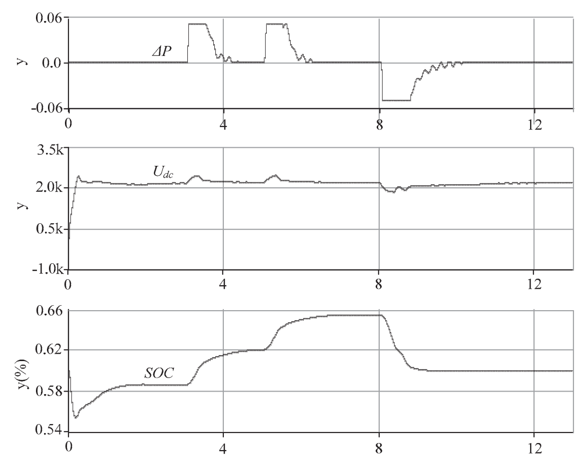
(a) Active power fluctuation curve before and after comparison STATCOM/BESS access



(b) Reactive power contrast curve before and after comparison STATCOM / BESS access



(c) PCC voltage simulation curve



(d) BESS system parameter simulation curve

Fig. 6 Simulation results of step and disturbance wind

Disturbance wind speed range are $\pm 0.2m/s$, the angular frequency is $30rad/s$ .Join STATCOM/BESS system before and after the interconnection of active and reactive power, and node voltage, battery parameters is shown in Fig. 6.

It can be seen From Fig.6 (a), (b), after adding STATCOM/BESS systems, active output fluctuation range is significantly reduced, in the case of wind speed mutated, can quickly track and reduce volatility, so active the average power output of the smoothing. The wind turbine from the grid to absorb reactive power, when the wind speed is around 8 m/s, need to absorb reactive power is about 0.7Mvar, the parallel capacitor group compensates 0.65Mvar, STATCOM/BESS compensates 0.05Mvar. When the wind speed is about 10m/s, the wind turbine need to absorb reactive power is about 0.8Mvar, the parallel capacitor group compensates 0.65Mvar, STATCOM/BESS compensates 0.15 Mvar. When the wind speed is about 12m/s, the wind turbine need to absorb reactive power is about 1Mvar, the parallel capacitor group compensates 0.65Mvar, STATCOM/BESS compensates 0.35Mvar. Mutation caused due to wind speed wind turbines need to absorb reactive power change, STATCOM/BESS system can quickly and accurately to reactive power compensation is zero, do it when the power grid is hardly absorb reactive power from the grid.

It can be seen from the Fig.6 (d), at 3s, because the wind speed increased suddenly from 8m/s to 10m/s, active power of the wind turbine increases, the battery needs to absorb more active power, so the battery SOC and its terminal voltage rise more than the set value, the regulation of active power calculation module began to play a role increase output, reduce the absorption of active power.SOC increases will slow. The battery terminal voltage gradually decreased until it is restored to the rated value. Adjusting the amount of active power calculation module output value decreased gradually as the terminal voltage is reduced to zero. So according to the battery working condition to determine the amount of charge and discharge power regulation calculation module to prevent the battery from charging full stop working quickly, also have played an important role in smoothing the STATCOM dc voltage. In the 5s, because the wind speed suddenly increased from 10 m/s to 12 m/s, its working principle is the same as the 3s. In the 8s, because the wind speed suddenly dropped from 12 m/s to 8 m/s, active power from the wind turbine suddenly decreases, and battery need to release the active power, so the battery SOC decreases, and its terminal voltage drop more than the set value, active power in a given calculation module starts to work to increase the output (negative), reduce the speed of the battery pack release active so that SOC becomes slow decrease, battery terminal voltage gradually increased until it is restored to its nominal value, active power adjusting the output value calculation module with terminal voltage rises gradually reduced to zero, to prevent the battery pack caused due to excessive discharge terminal voltage drops too quickly leading to STATCOM DC side of the inverter voltage drop influence working conditions occur.

VII. Conclusion

The wind turbine based on the study of STATCOM/BESS to improve output power quality control strategy on the basis of the proposed protection of energy storage device of optimizing control strategy of active power given. This control strategy can not only smooth wind turbine active power output and achieve unity power factor, but also real-timely adjust to the grid power according to the state of the battery, ensure the BESS always work in a reasonable scope, prolonging the life of the energy storage system. The simulation results show that at a constant wind speed and the step disturbance wind speed, the control strategy of STATCOM/BESS can significantly improve output power quality of the cage wind turbine, and make BESS work in the reasonable state so as to verify the rationality and feasibility of the control strategy proposed in this paper.

Acknowledgment

This project was supported by National Natural Science Foundation of China (51267015), Specialized Research Fund for the Doctoral Program of Higher Education of China (2012 1514110005)

References

[1] Yang Z, Crow M L, Shen C, et al. The steady state characteristics of a STATCOM with energy storage[C]. Power Engineering Society Summer Meeting 2000 IEEE. IEEE, 2000, 2: 669-674.

[2] Shen C, Yang Z, Atcitty S, et al. Control of STATCOM with energy storage device[C]. Power Engineering Society Winter Meeting 2000 IEEE. IEEE, 2000, 4: 2722-2728.

[3] Arsoy A, Liu Y, Chen S, et al. Dynamic performance of a static synchronous compensator with energy storage[C]. Power Engineering Society Winter Meeting 2001 IEEE. IEEE, 2001, 2: 605-610.

[4] Fei wan min, Zhang yan li, Lü zheng yu. Investigation on the Integration of BESS with STATCOM[J]. Automation of Electric Power Systems ,2005, 29(10): 41-44.

[5] Baran M E, Teleke S, Anderson L, STATCOM with energy storage for smoothing intermittent wind farm power[C]. Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE. IEEE, 2008: 1-6.

[6] Paatero J V, Lund P D. Effect of energy storage on variations in wind power[J]. Wind Energy, 2005, 8(4): 421-441

[7] Abbey C, Joos G. Supercapacitor energy storage for wind energy applications[J]. Industry Applications, IEEE Transactions on, 2007, 43(3): 769-776.

[8] Kim Y H, Kim S H, Lim C J, et al. Control strategy of energy storage system for power stability in a wind farm[C]. Power Electronics and ECCE Asia, 2011 IEEE 8th International Conference on. IEEE, 2011: 2970-2973.

[9] Zhang Ye, Guo Li, Jia Hong Jie, et al. An Energy Storage Control Method Based on State of Charge and Variable Filter Time Constant[J] .Automation of Electric Power Systems, 2012, 36(6): 34-38.