Smooth Wind Power Fluctuation Based on Battery Energy Storage System for Wind Farm

Zhang Wei*, Byung Young Moon** and Young Hoon Joo[†]

Abstract – This paper addresses on a wind power system with BESS(Battery Energy Storage System). The concerned system consists of four parts: the wind speed production model, the wind turbine model, configure capacity of the battery energy storage, battery model and control of the BESS. First of all, we produce wind speed by 4-component composite wind speed model. Secondly, the maximum available wind power is determined by analyzing the produced wind speed and the characteristic curve of wind power. Thirdly, we configure capacity of the BESS according to wind speed and characteristic curve of wind speed-power. Then, we propose a control strategy to track the power reference. Finally, some simulations have been demonstrated to visualize the feasibility of the proposed methodology.

Keywords: Wind speed, Wind turbine, Wind farm, ESS(Energy Storage System), BESS(Battery energy storage system), Smooth wind power fluctuation

1. Introduction

The availability of fossil fuels has had a crucial role in the development of the modern civilization in the last two centuries. However, the raise of primary energy request caused by the demographic growth in developing countries and by an energy starving style of life in developed countries, will lead to an unsustainable situation in the near future, due to the limited fossil fuel reserves still available. Therefore, studies and researches oriented to a broader exploitation of renewable energy sources are powered, as a response to difficulties today experienced in industrialized countries in primary energy procurement[1-2].

Moreover, renewable energy sources represent a quite viable solution to the worrisome increase of air pollution, because of their zero or very low emissions. However, the intermittent nature of wind is the biggest problem associated with wind power. As the installed capacity of wind increases, the problems associated with wind power become magnified. So we need to ensure stability of the wind power system [3, 4].

Energy storage systems are regarded as possible solutions to these problems. Energy storage systems can be used to store electricity at times of high wind and can be discharged in low wind speed, so the electricity is provided when it is needed. Energy storage may also increase the penetration levels attainable by wind energy into generation systems and reduce the amount of alternative generation required as the stored electricity will be reliable and predictable. Many storage systems are suitable for this application.

There are many researchers researched how to stabilize output power for wind farm. Smoothing wind power fluctuations by controlling the pitch angle was proposed by [16] and [17]. Although this control strategy can smooth the output power of wind farm, the pitch angle cannot fast respond when output power of wind farm need to adjust quickly. Because the pitch angle can be adjusted 7 degrees per second. So the wind farm needs some transition time. Therefore, the output power of wind farm cannot track the power reference quickly. [20] proposed an output power smoothing method by a simple coordinated control of DC-link voltage and pitch angle of a wind energy conversion system. Although the output power fluctuations of the wind power in the low and high frequency domains are smoothed by the pitch angle control and the DC-link voltage control, the DC-link voltage will have a large fluctuation. The large fluctuation is not conductive to wind power system stabilization. [18] and [19] proposed the method for smoothing the output power of wind farm by using the energy storage system. Although the proposed ESS can smooth the output power of wind farm when the wind speed is variable, they do not consider tracking the power reference of grid.

This paper addresses the design and the implementation issues on a control strategy for a wind farm, which is made up exclusively of the DFIG(doubly fed induction generators). We mainly contribute to propose a control strategy to smooth output power. The proposed control strategy is as follows: Firstly, we produce the wind speed and obtain the maximum available wind power by analyzing the characteristic curve of the wind power. Next, we configure the capacity of storage system according to wind speed probability distribution and wind speed-power characteristic

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curve of wind turbine. Finally, some simulations have been demonstrated to visualize the feasibility of the proposed methodology.

2. Preliminary

2.1 Wind speed model

Currently, there are various models to produce the wind speed in the wind power system, such as the Weibull distribution model [5], 4-component composite wind speed model [6], equivalent wind speed model [7] and so on. In this paper, we use the 4-component composite wind speed model to produce the wind speed.

4-component composite wind speed V_{wt} is given by [6]

$$V_{wt} = V_{wb} + V_{wg} + V_{wc} + V_{wr}$$

where V_{wb} is the basic wind, V_{wg} is the gust, V_{wc} is the gradual change wind, and V_{wr} is the stochastic wind.

2.2 Wind turbine model

A wind turbine is a device that converts kinetic energy from the wind into mechanical one. It consists of four parts: the wind turbine blades, the gearbox, the DFIG, and the converter. Fig. 1 shows configuration of wind turbine.

The wind turbine power conversion P is given by [8]

$$P = \frac{1}{2} \rho \pi R^2 V_{wt} C_p(\lambda, \beta)$$

where ρ is the air density, R is the rotor radius, V_{wt} is the wind speed, C_p is the power efficiency coefficient, λ is the tip speed ratio, and β is the blade pitch angle.

2.3 Energy storage systems

With the rapid development of electronic technology, there are several types of energy storage system, for example BESS, PHS (pumped hydro-system), FESS (flywheel energy storage system), SMESS (superconducting magnetic energy storage system), CAES (compressed air energy storage) and so on [14].

PHS needs large scale installation with heavy environment impact. CAES and FESS have reduced size respect pumped hydro but not respect batteries. They need complex balance of plant. However, batteries show high efficiency and can be containerized and easy installed in distributed and centralized applications. Also, BESS technology has been very mature. So operating costs and life cycle have been greatly improved. Therefore, we choose BESS to smooth fluctuant wind energy for wind farm.

2.4 Battery model

Battery model can usually be divided into experimental model, electrochemical model and equivalent circuit model. Among them, the equivalent circuit model is most suitable for dynamic simulation [15].

The controlled voltage source E for dynamic simulation is given by [9]

$$E = E_0 - K \frac{Q}{Q - \int i_b dt} + A \exp(-B \cdot \int i_b dt)$$

where E is no-load voltage (V), E_0 is battery constant voltage (V), K is polarization voltage (V), Q is battery capacity (Ah), A is exponential zone amplitude (V) and B is exponential zone time constant inverse (Ah^{-1}).

3. Proposed Wind Power System and Control Strategy

3.1 Propose wind farm system

3.1.1 Wind turbine with BESS

The intermittent nature of wind is the biggest problem associated with wind power. Therefore, we use BESS to reduce the power fluctuations. Fig. 2 illustrates that the BESS is used to compensate for the intermittent output power of the wind turbine.

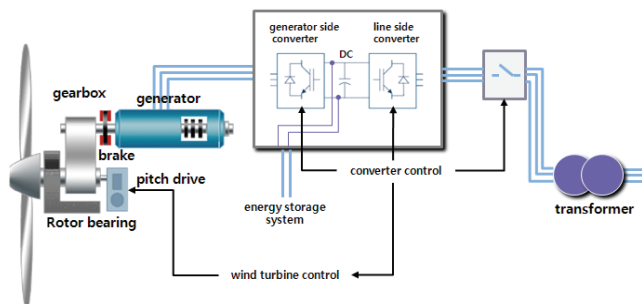As shown in Fig. 2, the DFIG is driven by a wind turbine and a gearbox. The mechanical power output of the

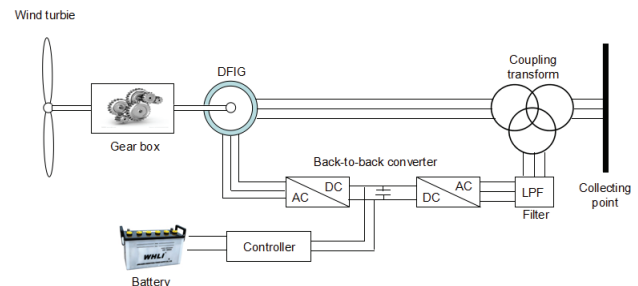**Fig. 1.** Configuration of wind turbine

Fig. 2. BESS integration with wind energy conversion system

wind turbine as a function of wind speed and blade pitch angle is described in the wind turbine model. The BESS is connected into the wind turbine between the DC/AC converter and AC/DC converter. Also, the BESS can be charged/discharged to smooth the output power.

3.1.2 Configure capacity of the BESS

The configuration of the BESS capacity is very important. If the configuration of the BESS capacity is not enough, the effect of stable output power is not obvious. Conversely, if the configuration of the BESS capacity is very large, the output power is relatively stable but economic costs will increase. So we need to reasonably configure capacity for BESS.

In the previous section, we obtain the wind speed and wind speed-power characteristics curve of wind turbine. Then BESS capacity can be calculated as follows:

We obtain the wind speed and wind speed-power characteristics curve by wind speed model and wind turbine model. Then the expected power of wind turbine of one hour E is calculated as follows:

$$E = \int_{v_{\text{cut-in}}}^{v_{\text{rated}}} P(v) \cdot q(v) dv + \int_{v_{\text{rated}}}^{v_{\text{cut-out}}} q(v) dv$$

where E is the expected power of wind turbine of one hour, $P(v)$ is the wind speed-power curve for wind turbine, $q(v)$ is the probability distribution of wind speed, v_{cut-in} is cut-in wind speed, v_{rated} is the rated wind speed and $v_{cut-out}$ is the cut-out wind speed.

The capacity of BESS S is calculated as follows:

$$S = E * H$$

Where H is the time of wind turbine keeping the stable output power.

3.1.3 Wind farm layout

The wind farm consists of several wind turbines. Its network layout is illustrated in Fig. 3. The wind farm control behaves as a single centralized unit [10, 11]. It receives input demand from the system operator and measures output from the PCC(point of common coupling). Depending on the actual network status, the system
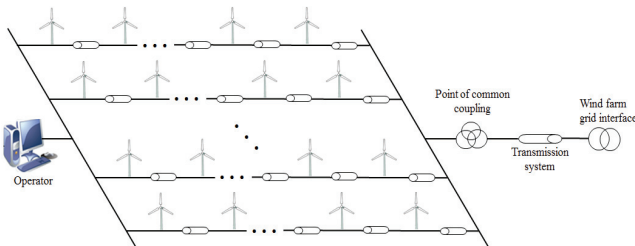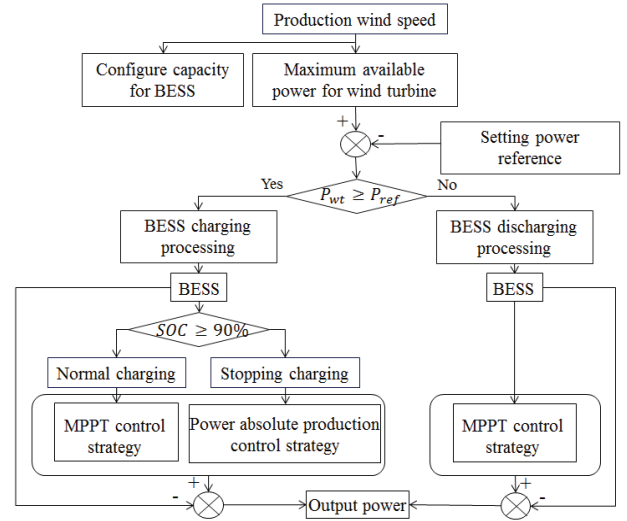

Fig. 3. The network layout of the wind farm

Fig. 4. Control block diagram of wind turbine with BESS

operator requires a certain operation to the wind farm, i.e. operates either with normal production or with absolute production.

3.2 Proposed control strategy

The control block diagram of wind turbine with BESS is shown in Fig. 4. As shown in the Fig. 4, the proposed control strategy is divided into two parts. 1) Control for charging/discharging of BESS. 2) Control the wind turbine.

3.2.1 Control for charging/discharging of BESS

As mentioned above, the main challenge for wind energy resources is to smooth their intermittent power output. Hence, our problem becomes to develop a method to charge or discharge the BESS in order to smooth their intermittent power output. Also, the state of charging limitations of the BESS should be considered. For this purpose, we use the power difference between the measured power of wind turbine and power reference in order to control charging or discharging of the BESS. The BESS may be divided into a charging phase and a discharging phase as follows:

1) Battery charging phase: This phase is called power peak. The battery stores extra energy when the power reference is smaller than the measured power of wind turbine.

$$P_{wt} - P_{ref} = P_{com} \geq 0$$

2) Battery discharging phase: This phase is called power valley. The battery releases energy when the power reference is larger than measured power of wind turbine.

$$P_{wt} - P_{ref} = P_{com} \leq 0$$

Where, P_{wt} is the measurement power of wind turbine, P_{ref} is the power reference of wind turbine and P_{com} is the power command of BESS.

3.2.2 Control of the wind turbine

For smoothing the output power fluctuation and protecting the BESS, we propose that the wind turbine control is divided into two parts: The first one is that wind turbine is controlled during the battery charging phase. The other one is that wind turbine is controlled during the battery discharging phase. Moreover, SOC (state of charge) of battery has an important impact on the smoothing control of wind power. SOC is defined as the percentage of the capacity Q. SOC is calculated as follows:

$$SOC = \frac{E_m - \int_0^t U_b * I_b}{E_b}$$

Where, E_m is the initial capacity of the battery, E_h is the rated capacity of the battery, U_h is the voltage of the battery and I_h is the current of the battery.

➤ **Battery charging phase**: The battery storage system stores extra energy. In this phase, we limit SOC to prevent the over-charging of BESS. Therefore, the battery charging phase for SOC is divided into two phase.
  1) $SOC \leq SOC_{max}$ phase: When SOC is smaller than upper limit percentage of the capacity SOC_{max}, we use MPPT control strategy for wind turbines.
  2) $SOC \geq SOC_{max}$ phase: For preventing the over-charging of battery, charging is stopped when the SOC is larger than SOC_{max}. Therefore, in this phase, we use the power absolute production control strategy to control the wind turbines.

➤ **Battery discharging phase**: In this phase, we use MPPT control strategy in order to maximize the utilization of wind energy,

MPPT(maximum power point track) and power absolute production control strategy are as follows:
- MPPT

  1) Power optimization strategy(below rated wind speed): where the energy capture is maximized by tracking the maximum power coefficient.
  2) Power limitation strategy to the rated power value(above rated wind speed): where the power is limited to the rated power of the turbine.

- Power absolute production control strategy
This control strategy will limit the power production to a set maximum power point. Then the measure output power will track the power reference. In here, we use

the wind turbine pitch angle to limit the output power. The mathematic model of pitch actuator can be simplified as first-order structure with time delay.

$$\beta(t) = \frac{e^{-T_{cd}s}}{\tau_\beta s + 1} \beta_{ref}(t)$$

Where, τ_β is the time constant of pitch actuator, T_{cd} is the total time delay, including the communication interval and control cycle and β_{ref} is the reference value of pitch angle.

3.2.3 Control of the wind farm

The wind farm consists of several wind turbines that BESS are integrated into wind turbines to smooth the output power of wind farm. The power reference of wind farm is distributed to each wind turbine by operator. Then each wind turbine tracks the power reference of each wind turbine by BESS.

4. Simulation Results

The effectiveness of BESS is demonstrated through computer simulation by using Matlab/Simulink. The wind farm is connected to the end of transmission line by collecting point. The network layout of the wind farm is illustrated in Fig. 5. Each of the three wind turbines WT1, WT2, WT3 is connected to its own terminal. Both the connection of the wind farm to the station and the station itself are modeled by the actual physical components (transformers, line, busbar). BESS is connected into the back-to-back converter of each wind turbine through the DC bus. Therefore BESS can compensate the output power fluctuation of each wind turbine.

The wind farm is connected to a 25kV distribution system exports power to a 120kV grid through a 30km 25kV feeder. Wind turbines use DFIG. The stator winding is connected directly to the PCC and the rotor is driven by a variable-pitch controled wind turbine. The wind farm simulation structure is shown in Fig. 6.
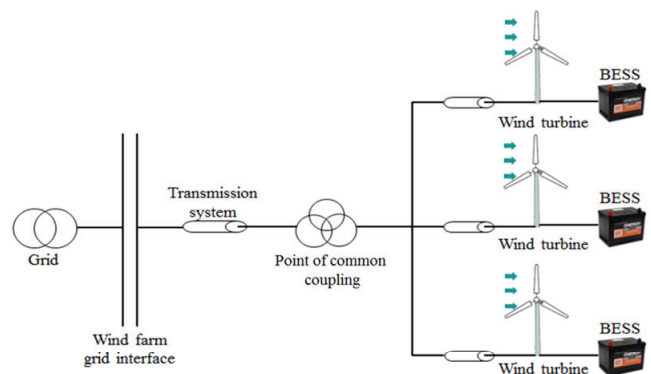

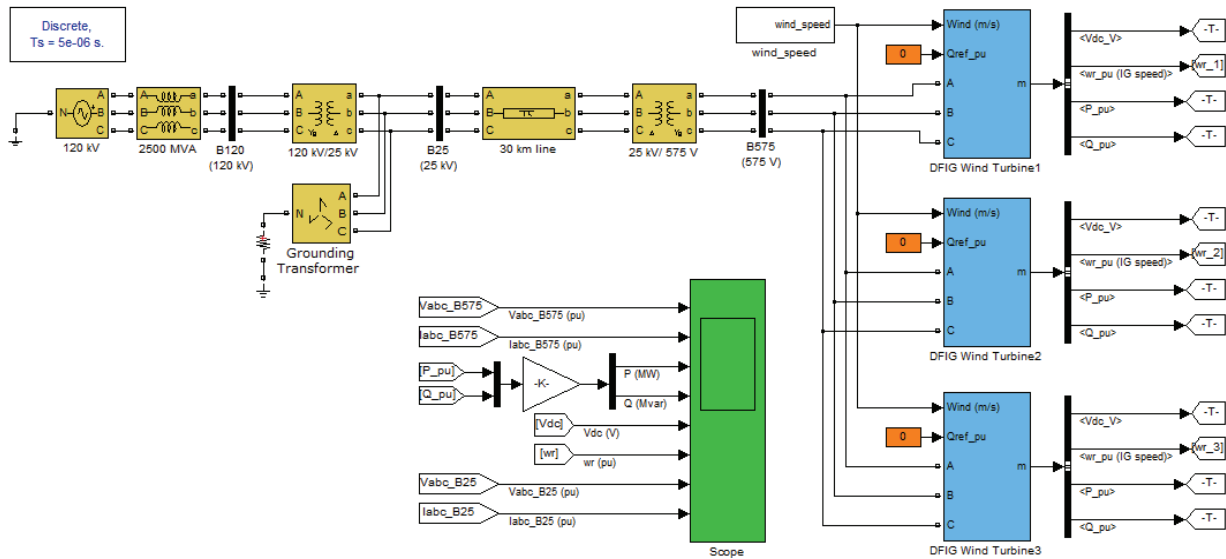
Fig. 5. Wind farm with three wind turbines
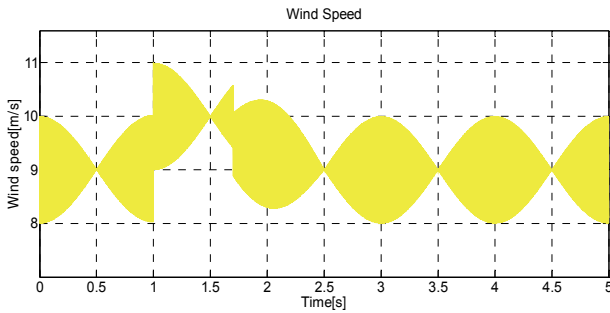
Fig. 6. Wind farm simulation structure

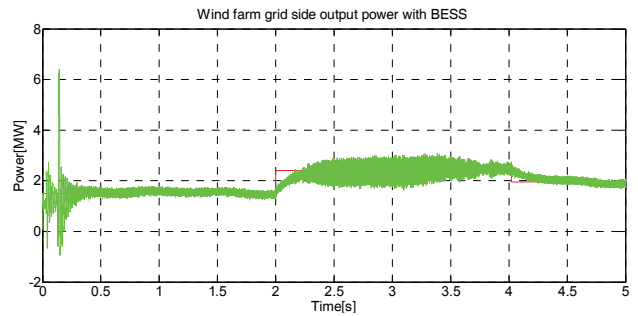**Fig. 7.** The 4-component composite wind speed model of the concerned wind farm
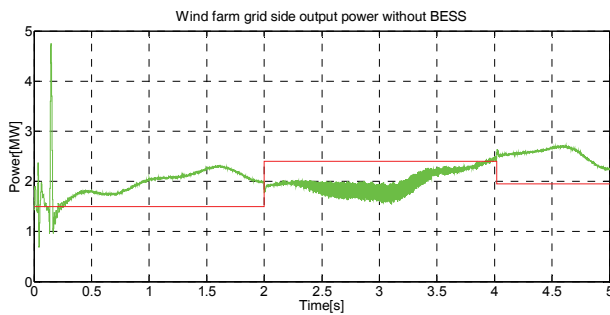

Fig. 8. Output power in wind farm grid side without BESS

The parameters of the performance coefficient of wind turbine are obtained from [12]. And the model of the wind turbine generators is obtained from [13]. The model of the equivalent circuit of BESS is obtained from [9].

The wind speed is produced by 4-component composite wind speed model. In the 4-component composite wind speed model, the basic wind is 9m/s, the gust and the gradual change wind are performed from 0s to 1s and from 1s to 2.5s, respectively, the maximum gradient wind is assumed from 1s to 1.7s and the variable gradient wind is assumed from 1.7s to 2.5s. The stochastic wind is

Fig. 9. output power in wind farm grid side with BESS

performed from 0s to 5s. Simulation result of the 4-component composite wind speed model of the wind farm is shown in Fig.7.

From Fig. 8, we can find that the output power fluctuation of the wind farm is caused by the variation of wind speed. With the wind farm without BESS, the output power of wind farm exists large fluctuations and the output power of wind farm cannot track the power reference of wind farm. So, the unstable power output will cause a great impact on the grid.

Fig. 9 shows output power of the wind farm with BESS. We can find that the power fluctuation of the wind farm can be rapidly smoothed and the extra power is absorbed or the absent power is compensated by the BESS. When $P_{com} \geq 0$, the BESS absorbs the extra power. When $P_{com} < 0$, the BESS provides the power to the grid to track the reference power.

Fig. 10 shows the power changing of BESS. Also, taking battery life into account in control, we set SOC_{max} =90% [21]. The BESS stores the extra power when the output power of wind farm is larger than the power reference of wind farm. Conversely, the BESS releases power when the output power of wind farm is smaller than the power reference of wind farm.
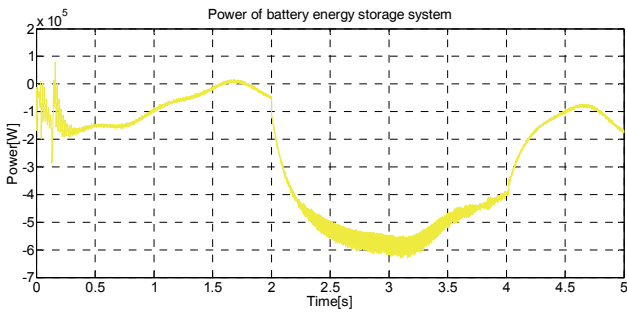
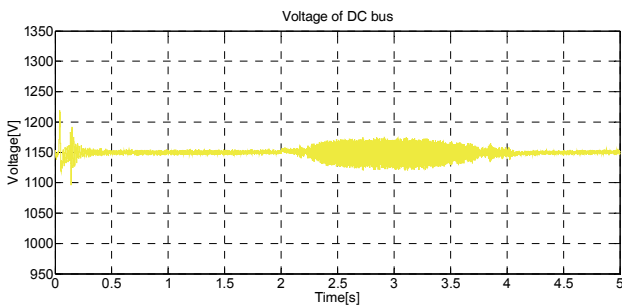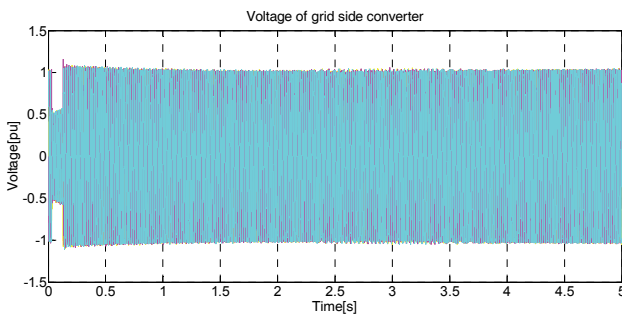**Fig. 10.** Power changing of the BESS
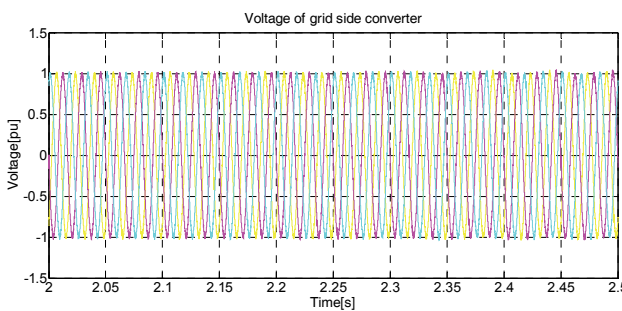

Fig. 11. Voltage of DC bus

(a) Voltage of grid side converter(0s-5s)

(b) Voltage of grid side converter(2s-2.5s)

Fig. 12. Three-phase voltage of grid side converter

Fig. 11 shows that the DC-link voltage of each wind turbine can be well maintained nearby 1150V through the voltage closed loop control of the generator side converter.

Fig. 12 shows the three-phase voltage of each wind turbine. The DC-link voltage is transformed by grid side converter.

5. Conclusion

In this paper, we proposed the control strategy for smoothing the wind power fluctuation based on BESS for wind farm. BESS in the DC link of each wind turbine has been investigated with the help of toolbox of MATLAB in order to smooth output power of the concerned wind farm. The proposed control strategy to smooth output power was follows: Firstly, we produced the wind speed and obtained the maximum available wind power by analyzing the characteristic curve of the wind power. Next, we configured the capacity of storage system according to wind speed probability distribution and wind speed-power characteristic curve of wind turbine. Then, we proposed a control strategy to track the power reference. Finally, some simulations have been demonstrated to visualize the feasibility of the proposed methodology. The simulation results show that the proposed control strategy has a strong theoretical forward-looking, it can better control wind power fluctuations and it can maintains the power balance between generation and grid requirement, contributes to the operational security of power system

Acknowledgement

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