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IMPROVEMENT OF DYNAMIC CHARACTERISTICS FOR POWER SYSTEM WITH WIND FARM USING COMPENSATION DEVICES

Chia-Yu Jihyeong Hsu
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C

Tzu-Yang Tien
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C

Pei-Hwa Huang
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C, b0104@mail.ntou.edu.tw

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IMPROVEMENT OF DYNAMIC CHARACTERISTICS FOR POWER SYSTEM WITH WIND FARM USING COMPENSATION DEVICES

Chia-Yu Hsu, Tzu-Yang Tien, and Pei-Hwa Huang

Key words: wind farm, battery energy storage system, static var compensator, static synchronous compensator, dynamic characteristic.

ABSTRACT

The main purpose of this paper is to study the applications of energy storage devices based on Flexible AC Transmission System (FACTS) techniques, namely the Static Var Compensator (SVC), the Static Synchronous Compensator (STATCOM) and the Battery Energy Storage System (BESS), for the improvement of dynamic characteristics of the power systems with wind generation. The system dynamic characteristics are investigated under occurrence of a three-phase short circuit fault at the point of interconnection of the system and the wind farm, without and with the installation of SVC, STATCOM and BESS. The system dynamic behaviors are also examined when the wind power output is decreased due to the wind speed variation. The results show that with a three-phase short circuit fault occurring at the point of interconnection of the system and the wind farm, the compensation equipment will provide reactive power in order to improve the voltage profile, and when the wind power output is decreased, the BESS improves the frequency transient because it can provide real power during system transient.

I. INTRODUCTION

Due to the increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources. One of the ways of generating electricity from renewable sources is to use wind generation that converts the energy contained in flowing air into electricity (Heier, 2006; Manwell et al., 2009). Wind-based generation is now present at all scales, ranging from multi-megawatt units installed in large numbers in wind farms. With more generation from the onshore and offshore wind farms and thus increase in proportion from wind farms in the total system generation, the wind generation exerts more influence on the system and the regulation of parallel operation because the wind generation has been becoming more and more stringent (Lubosny, 2003). The fast increase in wind power penetration level during the last decade has caused reasonable concern about possible stability threats on the power system (Bianchi et al., 2006). The dynamic behavior of the overall power system is determined by the interactions of the system synchronous generators when the wind power penetration is low. The increasing penetration of wind generation in the conventional power system has presented a tremendous challenge to the power system operators and planners, who have to ensure reliable and secure grid operations (Ackermann, 2005).

As wind power generation is significantly increasing, it is of paramount importance to study the effect of wind generation on the overall system dynamic characteristics. Flexible AC Transmission Systems (FACTS) based power electronic converters like the Static Var Compensator (SVC), the Static Synchronous Compensator (STATCOM) and the Battery Energy Storage System (BESS), are being used extensively in the power systems because of their ability to enhance system dynamics (Ackermann, 2005; Pereira et al., 2014; Chen et al., 2016 ; Liu et al., 2017; Wang et al., 2017; Xie et al., 2017). The main purpose of this paper is to investigate the improvement of dynamic characteristics of the wind farm system using SVC, STATCOM and BESS (Swierczynski et al., 2010; Bhart et al., 2016; Demirovic, 2016). The system dynamic features are investigated under occurrence of a three-phase fault at the point of interconnection of the system, without and with the installation of SVC, STATCOM and BESS.

The remainder of this paper is organized as follows. Section 2 presents the general structure of the proposed wind generation model. Section 3 presents the compensation device model. Section 4 reports the results of case studies. Section 5 is conclusions of the paper.

II. WIND GENERATION

The Western Electricity Coordinating Council (WECC) Mo-

Paper submitted 10/24/17; accepted 04/30/18. Author for correspondence: Pei-Hwa Huang (e-mail: b0104@mail.ntou.edu.tw).
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.

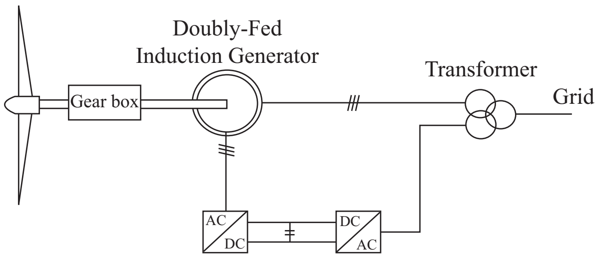

Fig. 1. The structure of Doubly-fed induction generator (DFIG) (Anaya-Lara et al., 2009; Wu et al., 2011; Electric Power Research Institute, 2013).

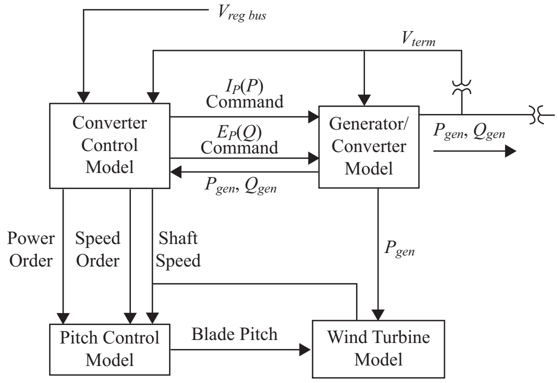

Fig. 2. DFIG generic model WT3 (General Electric International, 2010; Asmine et al., 2011).

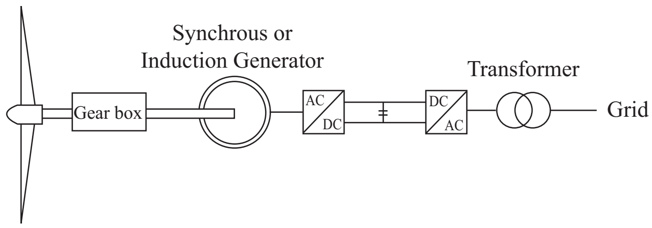

Fig. 3. The structure of full-converter generator (Anaya-Lara et al., 2009; Wu et al., 2011; Electric Power Research Institute, 2013).

deling & Validation Working Group recently initiated an effort to develop and validate a series of generic dynamic models for wind turbine generators (WTG) (Wu et al., 2011; Electric Power Research Institute, 2013). Wind turbine generators have been classified into four basic types:

(1) Type 1: Squirrel Cage Induction Generator
(2) Type 2: Wound Rotor Induction Generator
(3) Type 3: Doubly-Fed Induction Generator (DFIG)
(4) Type 4: Full-Converter Generator

In this paper, the wind generators to be installed include two types: Doubly-Fed Induction Generator (DFIG) and Full-Converter Generator.

1. Doubly-Fed Induction Generator (DFIG)

The DFIG is a common variable speed topology which utilizes wound-rotor induction machines with an AC/DC/AC converter between the stator and rotor terminals. The AC/DC/AC converter is divided into two parts, that is, rotor side and grid side. The rotor is fed by the rotor side power converter and the grid side power converter is used to generate or absorb power in order to keep the DC link voltage constant. The generator stator winding is directly coupled to the grid. Generation of power at variable speeds ranging from below synchronous speed to above synchronous speed can be achieved using DFIG. Fig. 1 shows the structure of DFIG (Anaya-Lara et al., 2009; Wu et al., 2011; Electric Power Research Institute, 2013).

The wind turbine model is used for the dynamic simulation study with the objective of simulating the dynamic performance of a wind turbine employing DFIG technology. The generic model is included as a standard model in the dynamic model library. The generic wind turbine model consists of the following main models: Generator/converter model, converter control model, wind turbine model and pitch control model. Fig. 2 shows the interaction between these modules (General Electric International, 2010; Asmine et al., 2011).

2. Full-Converter Generator

The configuration of the full converter generator is illustrated in Fig. 3. The full converter generator consists of a generator which is interfaced directly to the grid via an AC/DC/AC converter. The induction machines, wound-rotor synchronous machines, and permanent magnet synchronous machines have been all used in practice for these turbines, with both geared and gearless options. The back-to-back converter has the same rating as the generator. The rotor side converter ensures the rotational speed being adjusted within a large range, whereas its grid side converter provides reactive power support to the grid (Anaya-Lara et al., 2009; Wu et al., 2011; Electric Power Research Institute, 2013).

The wind turbine model is used for the dynamic simulation study with the objective of simulating the dynamic performance of a wind turbine employing full-converter generator technology. The WT4 model comprises modules as follows: Generator/converter model and electrical control model (Asmine et al., 2011). Fig. 4 shows the interaction between these models. This model features an AC/DC/AC power converter through which the entire power of the generator is processed. The power converter module calculates the current injection to the grid based on filtered active and reactive power commands from the electrical control model (General Electric International, 2010; Asmine et al., 2011).

III. COMPENSATION DEVICES

1. Static Var Compensator (SVC)

SVC is basically a shunt connected static var generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control the specific power system vari-

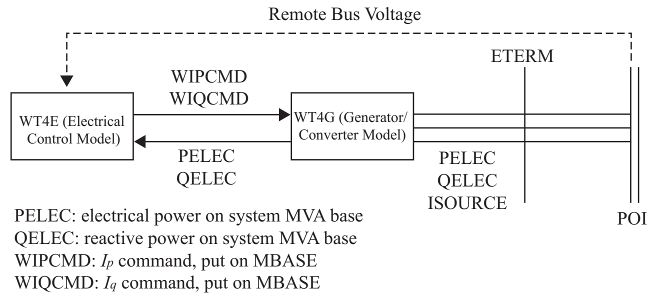

Fig. 4. Full-converter generator generic model WT4 (General Electric International, 2010; Asmine et al., 2011).

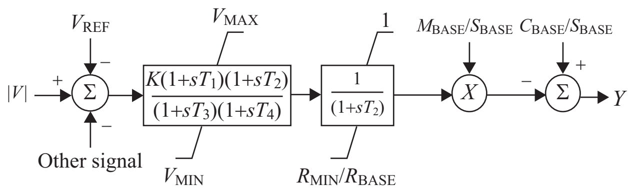

Fig. 5. Block diagram of SVC (Johansson et al., 2009).

ables. The main construction of SVC is of a thyristor-switched capacitor (TSC), a thyristor-controlled reactor (TCR), together with filters. With proper coordination of the capacitor switching and reactor control, the reactive power output can be varied continuously between the capacitive and inductive ratings of the equipment to regulate the ac voltage (Kundur, 1994; Pereira et al., 2014). The block diagram is shown as Fig. 5 (Johansson et al., 2009), in which V_{REF} is the voltage regulator reference; $|V|$ is the voltage magnitude on the high side of generator step-up transformer, if present; $M_{\rm BASE}$ is capacity of SVC; $C_{\rm BASE}$ is capacity of capacitance; Y is output admittance of SVC; K and T are the transfer function gain and time constant, respectively.

2. Static Synchronous Compensator (STATCOM)

STATCOM is a voltage-source converter based device, which converts a DC input voltage into an AC output voltage in order to compensate the active and reactive needs of the system. It is generally a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals (Ghorbanian et al., 2014). A STATCOM is a controlled reactive power source. The block diagram is shown as Fig. 6 (Ghorbanian et al., 2014; Sedaghati et al., 2014), in which the output is STATCOM current; V_{REF} is the voltage regulator reference; $|V|$ is the voltage magnitude on the high side of generator step-up transformer, if present; V_T is the bus voltage of STATCOM; $M_{\rm BASE}$ is capacity of STATCOM; X_t is the transformer reactance; and K and T are the transfer function gain and time constant, respectively.

Fig. 7 illustrate the V-I characteristics of STATCOM versus SVC (Kundur, 1994). It is clear that STATCOM and SVC can supply both the capacitive and the inductive compensation. The

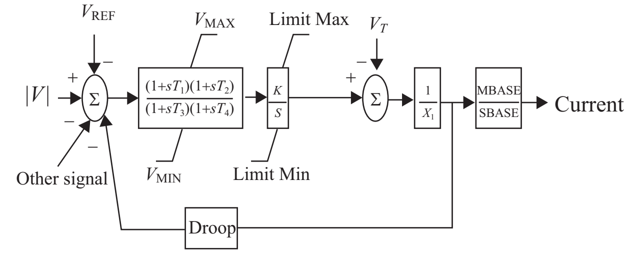

Fig. 6. Block diagram of STATCOM (Ghorbanian et al., 2014; Sedaghati et al., 2014).

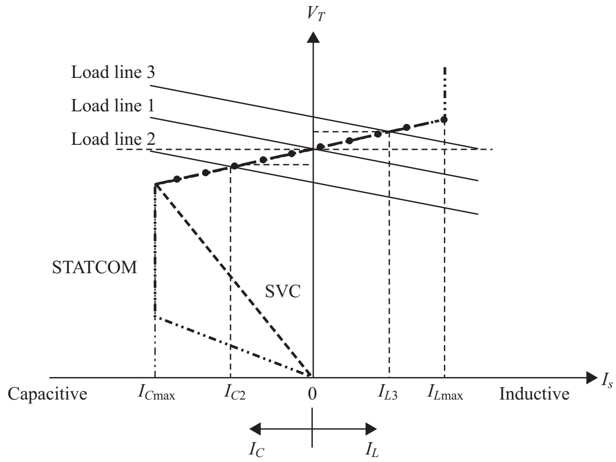

Fig. 7. V-I characteristics of STATCOM versus SVC (Pereira et al., 2014).

STATCOM is operated as a functional equivalent of SVC, and it provides faster control and improves control range. Thus, the STATCOM has better reactive power control than an SVC device (Pereira et al., 2014).

3. Battery Energy Storage Systems (BESS)

The Battery is likely the most widely known type of energy storage. A battery is an electrochemical power source which liberates energy in a chemical reaction to be converted directly into electricity (Srivastava et al., 2011; Shahooei et al., 2015). The battery can be charged during low-peak load periods and discharged during peak loads. Battery energy storage systems (BESS) can provide regulating reserves, a type of ancillary service, by modulating active power for frequency control, referred to as load frequency control, to reduce frequency deviations caused by sudden changes in renewable generation (Such, 2013; Shahooei et al., 2015).

The BESS model is based on the Electric Power Research Institute (EPRI) battery model CBEST. The CBEST model is used as part of the user defined model for simulations in this paper. The CBEST model includes both the real power and the reactive power sections (Such, 2013).

The real power section of the CBEST model is shown as Fig. 8 (Such, 2013). Its inputs are P_{AUX} and P_{INIT}, where P_{AUX} is the real power command which has been compensated by the

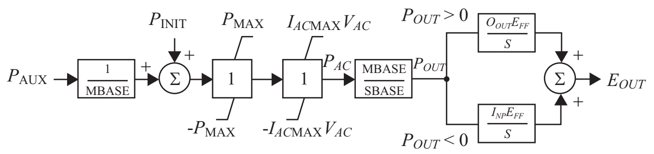

Fig. 8. Real power section of CBEST model (Such, 2013).

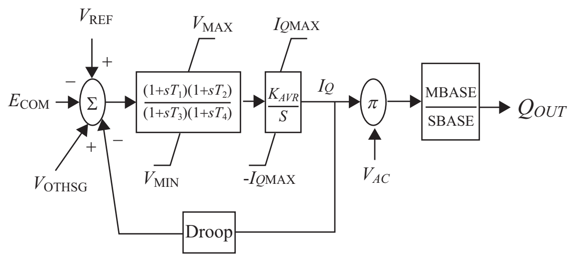

Fig. 9. Reactive power section of the CBEST model (Such, 2013).

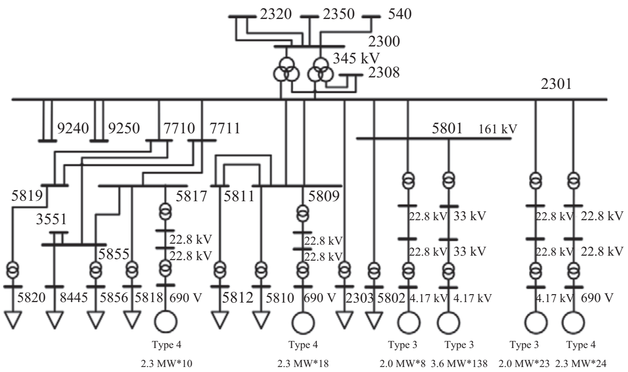

Fig. 10. Single-line diagram of sample power system.

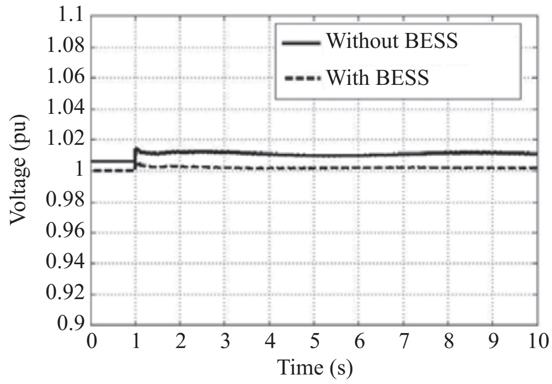

Fig. 11. Voltage response with and without compensation.

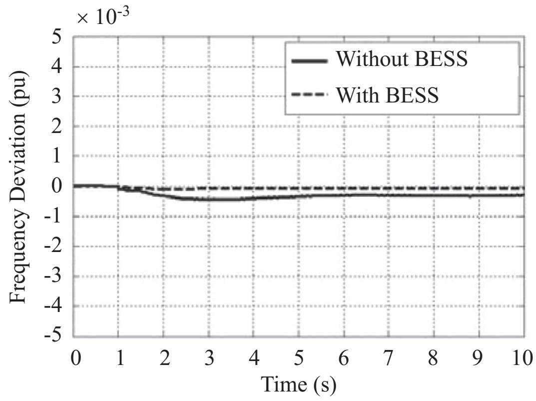

Fig. 12. Frequency response with and without compensation.

response time of the P_{INIT} is the initial power at the start of the simulation.

The reactive power section of the CBEST model is shown in Fig. 9 (Such, 2013), where V_{REF} is the voltage regulator reference; E_{COMP} is the voltage regulator, E_{OUT} is output voltage of BESS, respectively.

SYSTEM DYNAMICS

1. Study System

In this paper, a sample power system is considered to be the study system. Both the incorporating wind farms on system voltage and the advantages of reactive power compensation for improving system dynamic characteristics are investigated. The single-line diagrams are shown in Fig. 10. The wind generators to be installed include two types: 169 units with type of Doubly-Fed Induction Generator (DFIG) and 52 units with type of Full-Converter Generator. The wind farm comprises 221 wind generators, and the total capacity of the wind farm is 678.4 MW. The wind farms in the study system are divided into six groups, and use step-up transformers 22.8/161 kV for connected to the 161 kV system.

The main purpose of this paper is to study the applications of energy storage devices from Flexible AC Transmission System (FACTS) techniques, namely the Static Var Compensator (SVC), the Static Synchronous Compensator (STATCOM) and the Battery Energy Storage System (BESS), for the improvement of dynamic characteristics of power systems with wind generation. According to reference (U.S. Department of Energy, 2013) reserves are at least as large as the single largest resource (e.g., the single largest generation unit) serving the system and reserve capacity is equivalent to 15% to 20% of the normal electric supply capacity. Therefore, for the purpose of comparison, capacity of 100 MVA (about 15% of the wind farm capacity) is to be installed at the bus 5801 for the analysis of system dynamics.

2. System Dynamic on Wind Power Output Reduction from 678.4WM (100%) to 610.56 MW (90%)

The use of BESS to improve system dynamics are discussed in this section through several case studies. In this case, the system dynamic features are investigated when the wind farms output are decreased from 678.4 WM (100%) to 610.56 MW (90%), with and without the installation of BESS and then the system dynamic responses are recorded.

Fig. 11 shows the voltage response of Bus 5801 under the con-

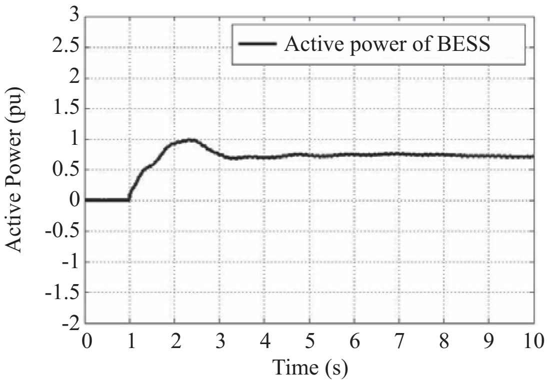

Fig. 13. Active power output of BESS.

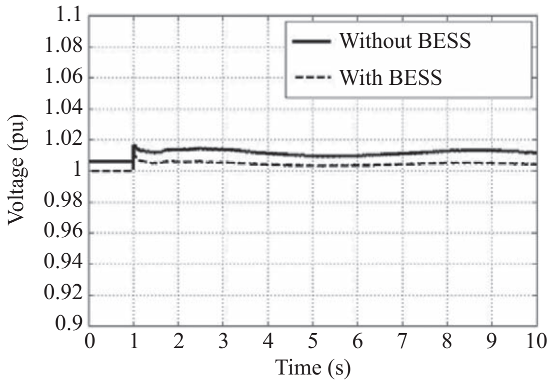

Fig. 15. Voltage response with and without compensation.

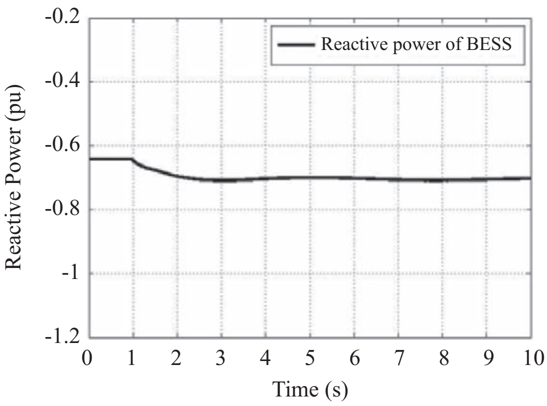

Fig. 14. Reactive power output of BESS.

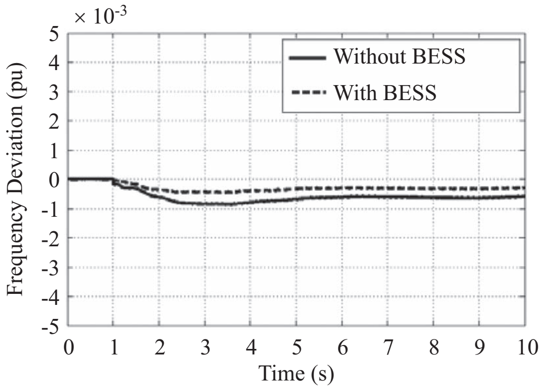

Fig. 16. Frequency response with and without compensation.

ditions that the wind farms output is decreased with and without BESS device. The wind farms output without BESS fall to 90% after 1 s, which causes the voltage at Bus 5801 to rise to 1.0019 pu. It can be seen from Fig. 11 that the use of BESS is effective in enhancement of dynamic voltage of the system, in which bus voltage is maintained about 1 pu.

Fig. 12 shows the simulation results for the frequency responses of the wind farms. It can be observed from Fig. 12 that the wind farms with BESS improve the frequency transient because it can provide real power during system transient.

Fig. 13 and Fig. 14 show the simulation results of the wind farms operating with wind output reduction after the BESS is connected. Fig. 13 and Fig. 14 reveal that the BESS can inject/absorb active as well as reactive power into the grid.

3. System Dynamic on Wind Power Output Reduction from 678.4 WM (100%) to 542.72 MW (80%)

The use of BESS to improve system dynamics is discussed in this section through several case studies. In this case, the system dynamic features are investigated when the wind farms output is decreased from 678.4 WM (100%) to 542.72 MW (80%), with and without the installation of BESS and then the system dynamic responses are recorded.

Fig. 15 shows the voltage response of Bus 5801 under the condition that wind farms output is decreased with and without BESS device. The wind farms output without BESS falls to 80% after 1s, which causes the voltage at Bus 5801 to rise to 1.0121 pu. It can be seen from Fig. 15 that the use of BESS is effective in enhancement of dynamic voltage of the system, in which bus voltage is maintained about 1 pu.

Fig. 16 shows the simulation results for the frequency responses of the wind farms. It can be observed from Fig. 16 that the wind farms with BESS improve the frequency transient because it can provide real power during system transient.

Fig. 17 and Fig. 18 show the simulation results of the wind farms operating with wind output reduction after the BESS is connected. Fig. 17 and Fig. 18 reveal that the BESS can inject/absorb active as well as reactive power into the grid.

4. Comparison of Compensation Devices

The simulation work to be conducted starts with a three-phase short circuit fault set to occur at bus 5801. The fault is cleared after four cycles and then the dynamic responses of the wind farm are recorded under four conditions: system without any compensation device, system with a BESS, system with a SVC, and system with a STATCOM. The comparison is made between the performances of the wind farm equipped with and without compensation device to improve the wind farm voltage

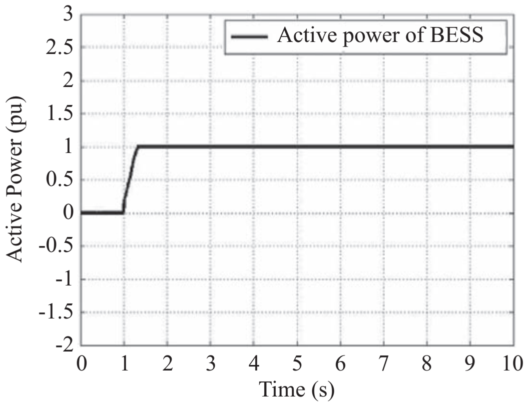

Fig. 17. Active power output of BESS.

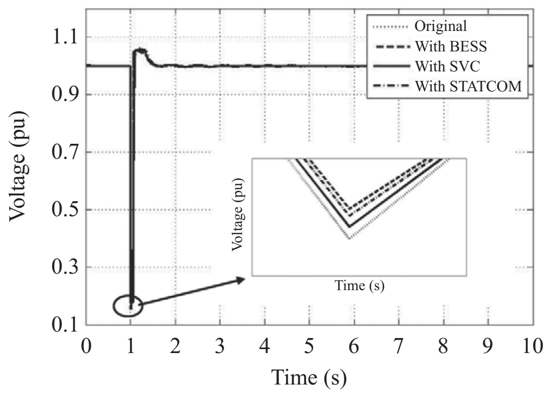

Fig. 19. Voltage responses of wind generation.

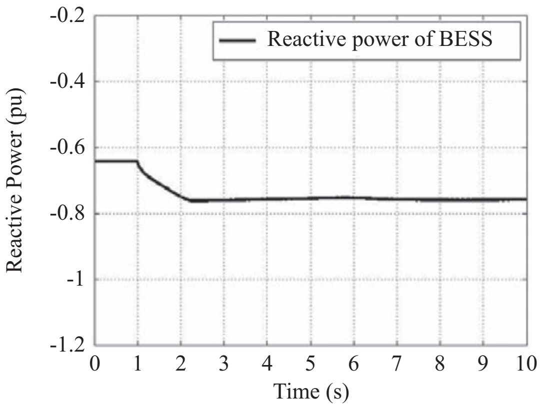

Fig. 18. Reactive power output of BESS.

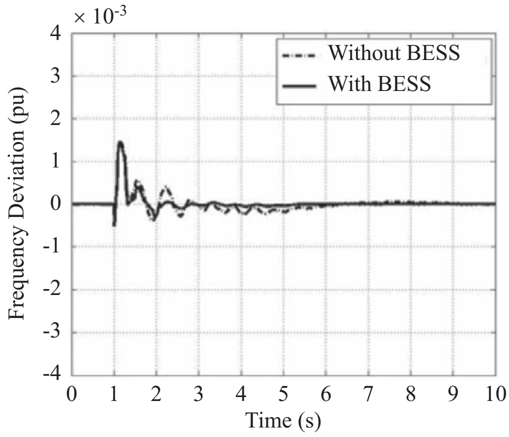

Fig. 20. Frequency deviation responses of bus 2301.

during and after fault.

The simulation results are compared with and without compensation, which is shown as Fig. 19. According to the simulation, BESS performs much better than other compensation devices based on the use of SVC and STATCOM in terms of voltage support.

Fig. 20 shows the frequency deviation responses of bus 2301 during system fault conditions. It can be observed that during and after fault, the system with BESS is able to supply active power, thus allowing a faster frequency recovery.

V. CONCLUSIONS

The main objective of this paper is to investigate the performance of compensation devices in the improvement of dynamic characteristics of power systems with the wind farms. The wind farms with BESS dynamic behaviors are investigated when wind farms output is decreased. The system voltage dynamic features are also examined under occurrence of a three-phase fault at the point of interconnection of the study system, without and with the installation of SVC, STATCOM and BESS. The results demonstrate that the BESS improves the operation of voltage and frequency because it can send out or take in active/reactive power. When the study system is subject to a three-phase short circuit fault, the compensation performance of the BESS is better than those of the SVC and the STATCOM. Therefore, the BESS is a feasible option to improve the system dynamic characteristics. The utilization of BESS presents advantages over compensation equipments based on SVC or STATCOM, because an injection of active power along with reactive power is needed to return to a stable operating state under wind power reduction and a grid fault condition.

ACKNOWLEDGEMENTS

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