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Performance analysis of SMES integrated with offshore wind farms to power systems through MT-HVDC

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ABSTRACT

With the increase in the development of offshore wind farm (OWF) around the world, this paper describes OWF consisting of permanent magnet synchronous generator (PMSG) wind turbines connected to active network (AC grid) and passive network (loads) through multi-terminal high voltage direct current (MT-HVDC) transmission system. This paper discusses the effect of using a Superconducting Magnetic Energy Storage (SMES) unit in a hybrid power system that contains OWF. In this paper, we have aggregated 300 wind turbines of 1.5 MW PMSG using an aggregation technique [multi full aggregated model using equivalent wind speed (MFAM_EWS)]. The active network in this paper should have a minimum of 150 MW power to be supplied by controlling the SMES unit (absorbing or providing power according to the system requirement). Simulation has been carried out by MATLAB/Simulink program to test the effectiveness of the SMES unit during tripping some of the wind turbines, fluctuation in wind speeds, load change and voltage dips.

INTRODUCTION

There are many benefits of offshore wind farms (OWFs) compared to conventional onshore wind farms. Higher wind speeds, allowing for larger size of wind turbines and the unlimited available locations in the sea to install new wind farms are some of the advantages of OWFs. So, in the recent years, the number of OWFs has increased. The output power from OWFs is connected to the main AC network using transmission systems based on both AC and DC technology. The selection of one of these technologies depends on the cost of the installation, the transmission distance and power output (Guo et al., 2012).

Long distance cable connections of HVDC technology is the best solution for OWFs. Regarding DC transmission systems, there are two possible technologies: voltage source converter high voltage direct current (VSC-HVDC) or Line commutated converter high voltage direct current (LCC-HVDC) (HVDC classical) technology (Guo et al., 2012). This paper operates with VSC-Based HVDC power transmission systems to transmit the generated output power to the networks. VSC HVDC is capable of supplying both active and passive systems.

For large scale offshore wind generation, multi-terminal HVDC (MT-HVDC) based voltage source converter becomes an attractive solution. It consists of more than one converter connected through DC cables. It can reduce the number of converters and improve the flexibility and reliability, when compared to numerous point to point HVDC systems. By MT-HVDC, the wind farm (WF) can be connected to more than one onshore grid that may or may not be synchronized to each other (Raza et al., 2016; Beerten et al., 2014; Gengyin et al., 2006).

In recent years, energy storage systems are becoming popular for transmission and grid applications. There is offered a variety of storage technologies in the market; one of the recent technologies is superconducting

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magnetic energy storage (SMES) devices. They have faster response in time than any other storage systems. The important section of a SMES system is the superconducting coil. It is placed in a cryostat or dewar consisting of a vacuum vessel and a liquid vessel. Liquid vessel protects the system temperature by saving proper cooling setup cryogenic system, it also keeps the temperature below the critical temperature (Ali et al., 2010; Nomura et al., 2005).

SMES device is stores energy or discharges large quantities of power almost instantaneously. The system is capable of compensating high levels of power during sudden loss or dip in line power. The capacity of the SMES unit is based on the application and charging/ discharging duration (Nomura et al., 2005).

Various applications of the SMES are power quality improvement, custom power, stabilization, voltage/VAR control, load leveling, dynamic response, minimization of power and voltage fluctuations, and frequency control application. It has also the ability to retain the grid active power stable in the face of any kind of disturbance that may occur in the power system, since this might extend to the grid and affect or even damage other power devices (Ali et al., 2010).

Popescu and Mastorakis (2010) and A Wind Farm Balancing Analysis (2010) presents a computer modeling of a wind farm in Romania and Greece, continuing with a study of balance of a turbine by using MATLAB simulation program. It studies also the stability of a wind power. Popescu and Mastorakis (2010) present the system based on Energomanager application installed on large energy consumers. It used data acquisition system used to monitor power and energy is composed of counters equipped with pulse outputs of several types. Beerten et al. (2014) introduces the OWFs connected to the grid through multi-terminal HVDC (MT-HVDC) transmission system. Three MT-HVDC configurations, each with different control strategies are discussed. The results of simulation study showed the performance of control during a change in power demand from the grid side converter and disconnection of VSC. Reference (Hasanien, 2014) presents the adaptive artificial neural network (ANN) to control SMES for enhancing the wind generator dynamic stability coupled to the main AC grid. It compares the proposed system and a conventional PI controlled superconducting magnetic energy storage using the standard PSCAD/EMTDC environment. It deduces that the system using adaptive ANN controlled SMES is found better damped than using PI controlled SMES and it improves wind turbine generators transient stability.

OWFs consisting of PMSG connected to active and passive networks through MT-HVDC transmission system are widely used in present time in many countries. Normally, the passive network will have first priority over the other terminal (active network) for the power generated by the OWF. If the power generated of OWF is not enough for the load demand (passive network), the grid power will supply the rest power to the load demand. This paper aims to make the main AC grid (active system) stable without providing any power to the passive network (load) during any disturbances like tripping some of the wind turbines or increasing on demand load. This is done by putting SMES unit in the DC link in the MT-HVDC transmission system. It also shows the importance of SMES unit in compensating the fluctuation of output power which produced from fluctuations in wind speeds. These fluctuations in wind speeds may cause some various problems such as frequency and voltage oscillations when a major number of wind power generators are connected to the grid system.

SYSTEM DESCRIPTION

As shown in Figure 1, the system consists of 450 MW OWF merging 300* 1.5MW PMSG wind turbines. They are all connected at the common bus of 145 kV through 30 km offshore cable and 690V/145 kV step up transformer. They are aggregated by using multi full aggregated model using equivalent wind speed (MFAM_EWS) technique (García et al., 2015; Ali et al., 2013). This is due to it achieves a better approximation of voltage, active and reactive power at the point of common coupling to the complete WF model. The output generation power is transferred through MT-HVDC transmission system to the 380 kV AC grid (active system) with 50 Hz frequency and three phase pure resistive load (passive system) by using submarine DC cables. The parameters of the transmission line for both AC and DC cables are given in Appendix A. The rating of the VSC-Based HVDC Transmission Link is 500 MVA (450 MW/0.9), +/- 200 kV. The SMES unit is coupled to the DC side of the WF via a DC-DC chopper. It is located between the OWF and the AC grid as an interface device.

As shown in Figure 1, the PMSG wind farm connected to two systems (active and passive system) through MT-HVDC while the SMES is connected at DC link. The control of the converter station (inverter) that directly connects the active system (AC grid) usually works in constant DC voltage control mode. The control of the converter that directly connects the passive system (load) works in constant AC voltage control mode (Gengyin et al., 2006). The components of VCS-HVDC and SMES unit with their controller will be study next.

VOLTAGE SOURCE CONVERTER MODEL

Figure 1 shows the power transmitted from a WF to the

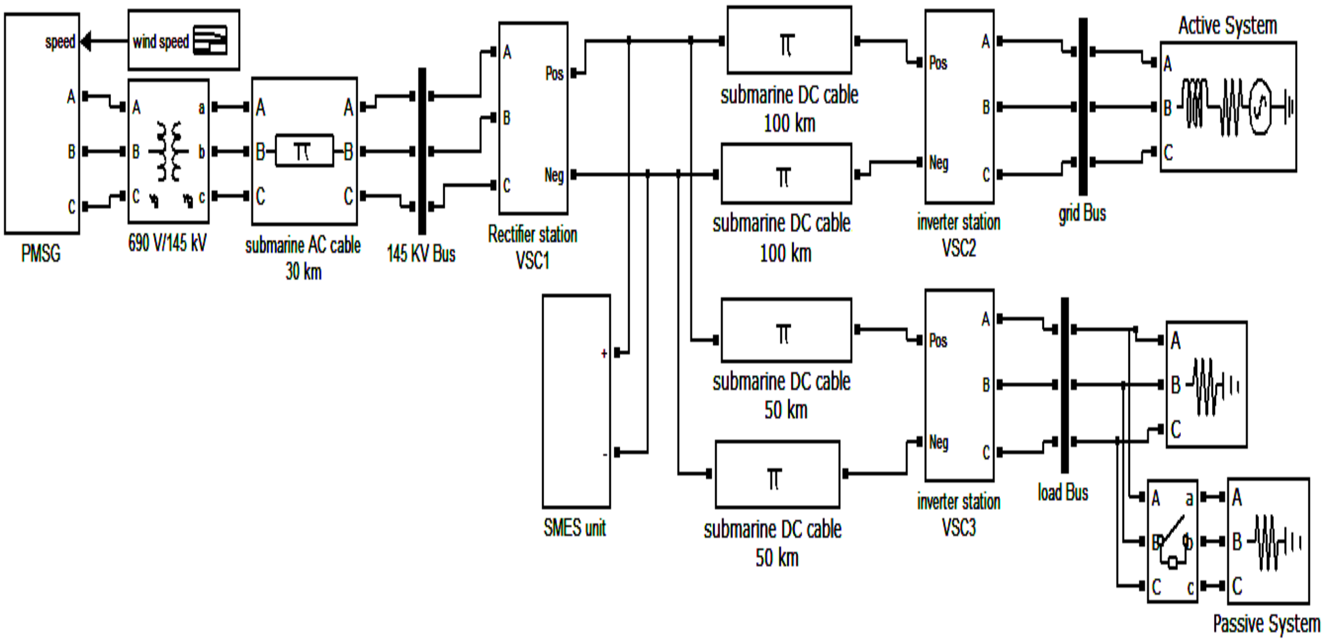

Figure 1. Offshore wind farm with MT-HVDC system and SMES.

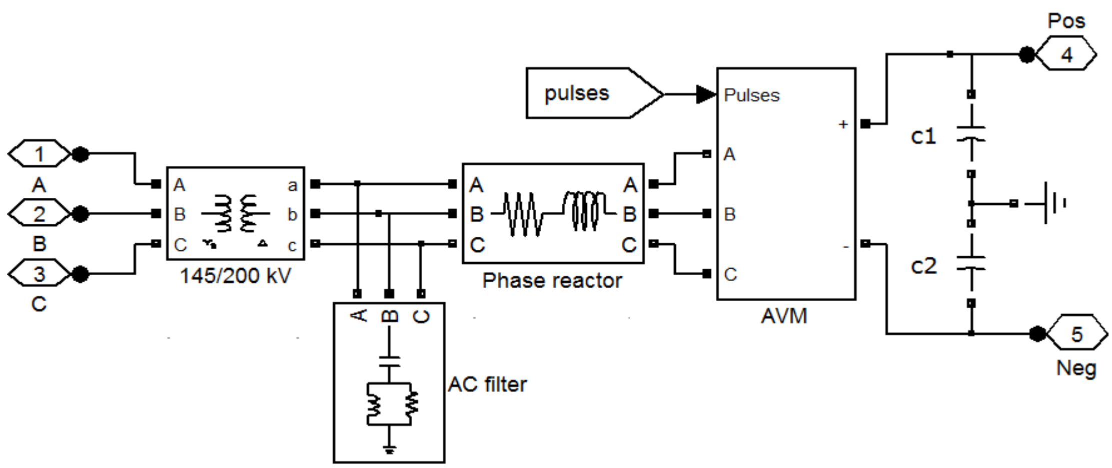

Figure 2. Components of converter station.

AC grid through three-level VSC based HVDC system. VSC-HVDC transmission system essentially consists of a converter transformer, 3 level VSC, a shunt AC filters on the AC side, DC line capacitor and phase reactor as shown in Figure 2. The high-frequency filter is used for blocking higher frequency harmonics. The converter reactor and transformer leakage reactance can control the converter's output terminal voltage and output power. On the DC side, the DC capacitor acts as a DC voltage source to maintain the power balance between the AC and DC power. The VSC is modeled as an average value model (Ouquelle et al., 2009).

In HVDC transmission system, there are two voltage source converters one acts as a rectifier connected to the OWF and the other acts as an inverter connected to the AC grid. The control strategies of both converters are given below.

Mathematical model

Conversion of *abc* to rotating *dq* reference frame can be

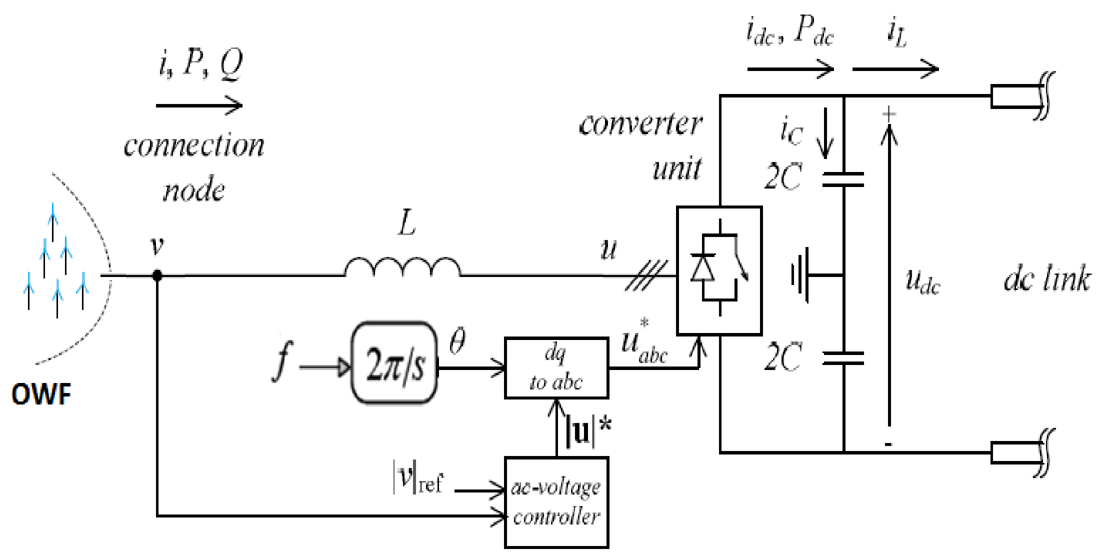

Figure 3. Control scheme of Offshore VSC.

mathematically modeled in terms of decoupled direct and quadrature converter current components i_d and i_q, respectively (Wang et al., 2014):

$$L\frac{di_d}{dt} = -Ri_d + \omega L i_q - u_{dconv} + u_d \quad (1)$$

$$L\frac{di_q}{dt} = -Ri_q + \omega L i_d - u_{qconv} + u_q \quad (2)$$

where L is the converter inductance, R is the converter resistance, ω is the grid pulsation, (u_d, u_q) is the voltage at the PCC, u_{conv} is the converter voltage and (u_{dconv}, u_{qconv}) are used in order to control the converter currents i_d and i_q.

The relationship of the power balance between the AC input and DC output is given as (Yazdani and Iravani, 2010):

$$p = \frac{3}{2}\left(u_d i_d + u_q i_q\right) = u_{dc} i_{dc} \quad (3)$$

Where u_{dc} is the DC link capacitor voltage and i_{dc} is the DC link capacitor current.

The vector of the grid voltage is known (Yazdani and Iravani, 2010) to be along with the direction d-axis, so a virtual grid flux vector can be supposed to be acting along with the direction q-axis. With this alignment, u_q = 0 and the active and reactive power absorbed from or injected into the AC system are given by (Yazdani and Iravani, 2010):

$$p = \frac{3}{2} u_d i_d \quad (4)$$

$$q = -\frac{3}{2} u_d i_q \quad (5)$$

Hence, the current is split into two portions according to the rotating d-q coordinate system oriented with respect to the vector of the grid voltage. The first portion determines the desired power flow into the DC side and the second portion defines the condition of reactive power. Equations 4 and 5 show the possibility to control the components of the two currents independently.

VSC connected to offshore wind farm and its controller

The aim of the offshore VSC is to convert the active power generated by the OWF and to set a voltage reference for WFs. This is carried out by using an AC voltage controller consisting of a PI controller as shown in Figure 3 (Xu and Andersen, 2006).

VSC connected to grid and its controller

The controller of onshore VSC has the objectives to regulate the DC voltage and reactive power exchanged with the AC grid. In order to obtain a decoupled control of active and reactive power, the vector control method is applied (Li et al., 2014). As described in Figure 4, the control scheme of the Onshore VSC consists of a phase-

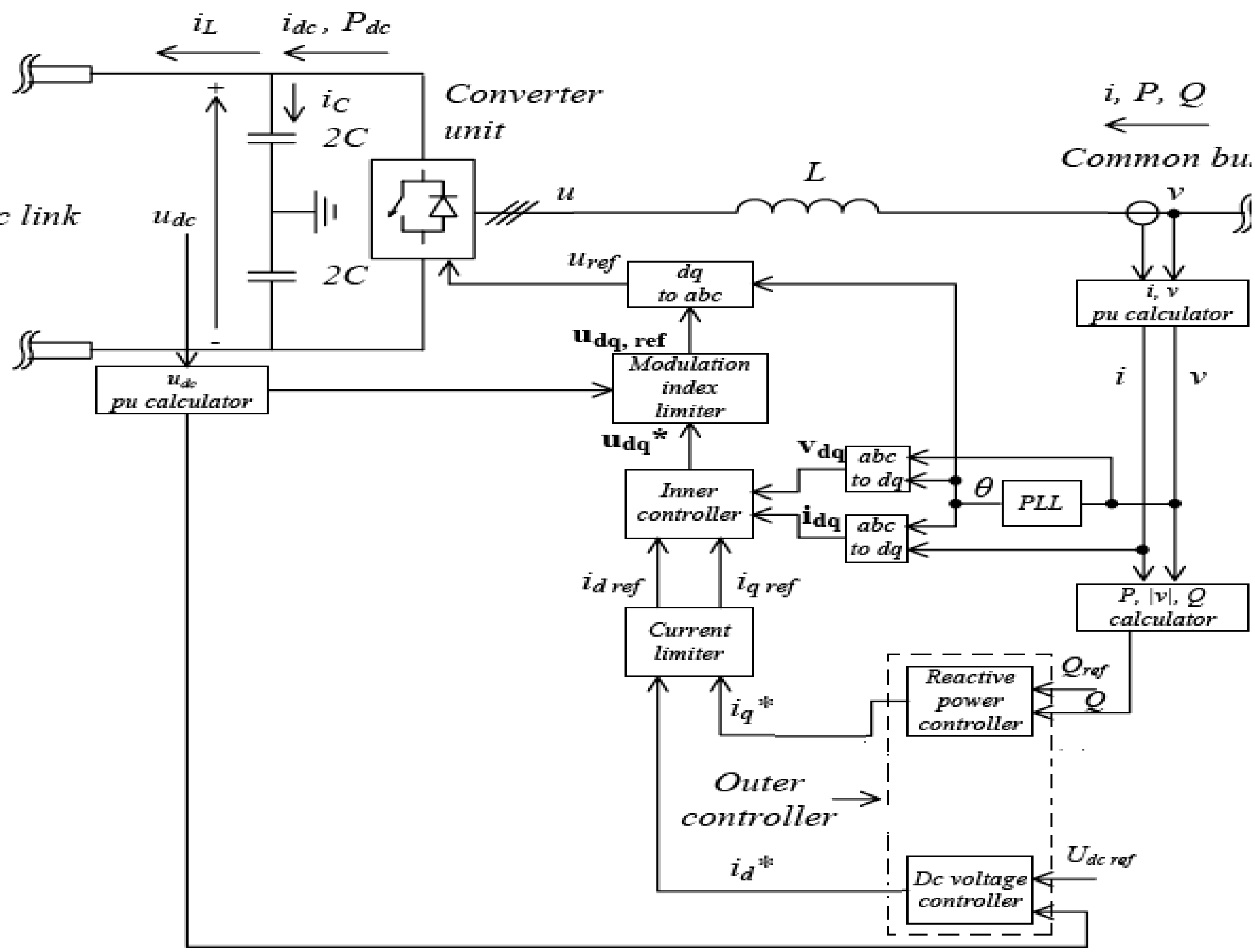

Figure 4. Control scheme of Onshore VSC.

locked loop (PLL), an inner controller for the current, a limiter of this current, and two outer controllers. The controller of inner current has the objective to follow the values of the reference current produced by the outer controllers, to obtain the reference of converter voltage values (u_d* and u_q*) (Li et al., 2014).

SMES SYSTEM AND ITS CONTROL SYSTEM

The SMES unit is one of the significant storage system solutions. SMES is a device that stores energy in the magnetic field formed by a DC current flowing through a large superconducting coil. The ability of this coil is to retain the magnetic energy for a long time with almost no losses this is due to that the coiling has cryogenically cool to its superconducting critical temperature. This means that during operation the ohmic losses will be very low, almost close to zero (Hasanien and Abdelaziz, 2015). The stored energy (E_{SMES}) and rated power (P_{SMES}) in the coil are:

$$E_{SMES} = \frac{1}{2} L_{SMES} I_{SMES}^2 \quad (6)$$

$$P_{SMES} = \frac{dE_{SMES}}{dt} = V_{SMES} I_{SMES} \quad (7)$$

where L_{SMES} is the inductance of the coil, I_{SMES} is the DC current flowing through the coil, V_{SMES} is voltage across the SMES coil.

As shown in Figure 5 the SMES unit consists of two main parts, DC-DC chopper (Type - D chopper) (Hasanien, 2014) and the superconductor coil, which has an extremely low resistance.

The configuration of the type D chopper with SMES coil is shown in Fig. 5. When the two choppers (IGBT 1, IGBT 2) are ON the SMES is in the charging mode and the relation between the voltage of SMES coil and DC link

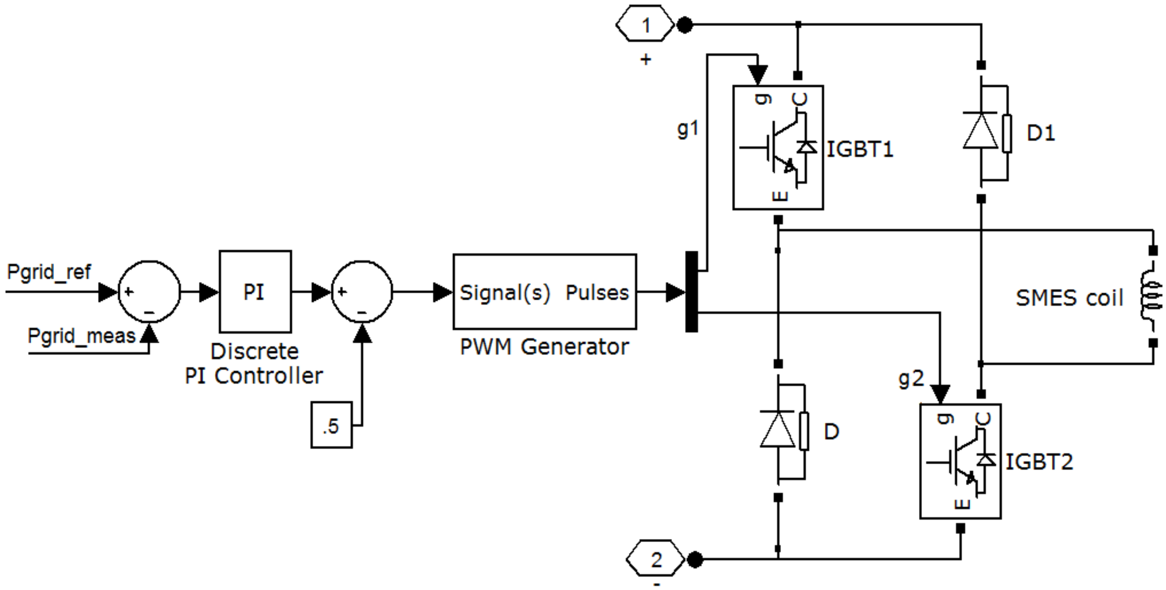

Figure 5. SMES unit components and control of the chopper.

capacitor is expressed by (Hasanien, 2014):

$$V_{SMES} = D * u_{dc} \tag{8}$$

where D is the chopper duty cycle.

When the two choppers are OFF and diodes D_1 and D_2 start conducting, the SMES is in discharging mode and the relationship between the voltages are:

$$-V_{SMES} = (1 - D)u_{dc} \tag{9}$$

The SMES coil is in standby mode (freewheeling mode) when one of the two choppers is ON and the other is OFF. During this operation mode, the DC current is continuously circulating in a closed loop through the SMES coil with no significant loss due to low resistance.

The DC-DC chopper control scheme is shown in Figure 5. It is designed to make the grid stable without providing any power to the load during any disturbances. The coil of SMES is discharged or charged by adjusting the average (that is, DC) voltage across the coil to be negative or positive values by means of the duty cycle of DC-DC chopper. It compares the required reference power of AC grid and the measuring power on the grid bus to PI controller. According to parameters of PI controller, it reduces the wind generator output power fluctuations due to wind speed variations. The power magnitude and direction exchanged between the AC grid and the coil of SMES are determined by the duty cycle (D) (Liu et al., 2015).

SIMULATION RESULTS

To evaluate the performance of SMES in the power system, the system in Figure 1 was simulated by MATLAB /Simulink for four different cases of instability: wind speed fluctuation, tripping out of some of the wind turbines, changing of the load demand and voltage drop. The specification of the SMES unit and the power system in the design system are given in Appendix C. The VSC controller (VSC1) connected to OWF controls the offshore grid voltage with constant frequency 50Hz. The VSC controller (VSC2) connected to active system regulates the DC voltage and the reactive power (Q=0). The control of the VSC3 that directly connects the passive system is in constant AC voltage control mode. In this paper, the system is designed to be able to supply the required power to the grid during normal or abnormal conditions. This means that the grid is not providing any power during any kind of disturbance that may occur in power system. This is done by controlling the duty cycle DC-DC chopper connected to the SMES coil as depicted in Figure 6. In this article, the system is designed to supply 150 MW to the grid. The simulation results show the performance of the SMES coil integrated with the HVDC system into the grid during steady state and transient operating conditions.

Case 1: Wind speed fluctuations

The first case is the fluctuations in wind speed. These fluctuations cause fluctuation in the output power of the

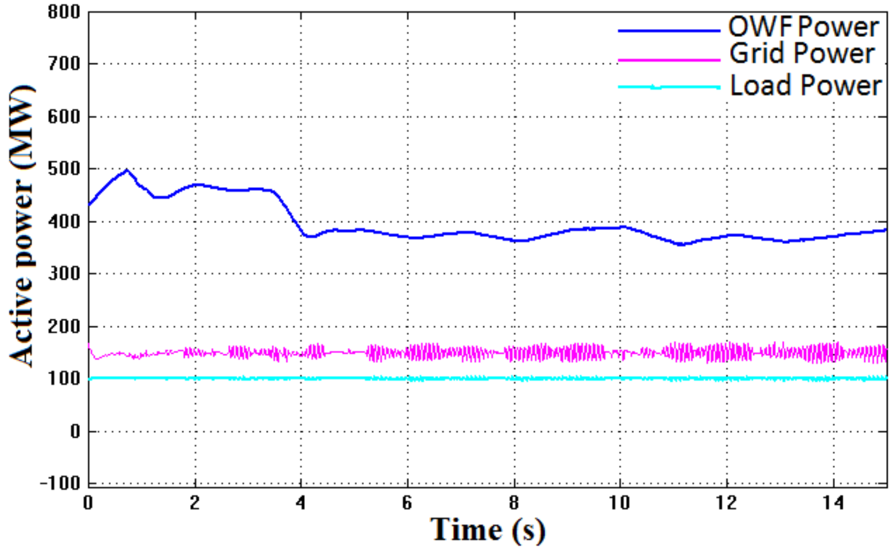

Figure 6. Active power in case 1.

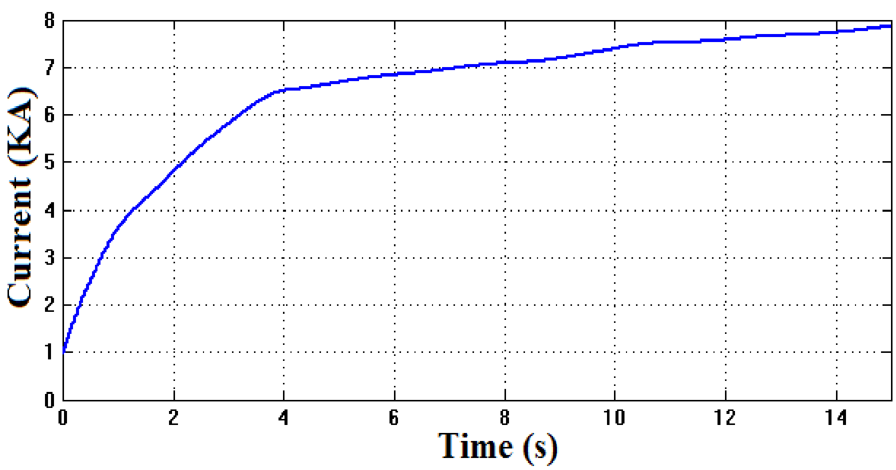

Figure 7. SMES current during case 1.

OWF as shown in the blue line in Figure 6. These fluctuations are transferred to the AC grid and may cause interruption to the power system. The effect of a SMES in smoothing the fluctuation in output power is shown in Figures 6 and 7.

Using SMES coil connected between OWF and the AC grid, it can absorb these fluctuation and supply power to AC grid without any fluctuation in power as shown in the magenta line in Figure 6. In this study, the DC-DC chopper is controlled to provide 150 MW to the active system. The cyan line in Figure 6 is the power delivered to load demand (passive network). Figure 7 shows the current in the SMES coil. It is obvious from this figure that SMES coil can absorb fluctuations. So the SMES in the DC link can stabilize the power system such that the large variations may reach the grid. In such a way the smoothed power reaches the customers.

Case 2: Load change

The system in this case is tested while increasing the load power considering constant wind speed. Firstly, the load demand is 100 MW then it is increased to 300 MW during 3 s at time t= 8 s, and for 1 s at time t= 14 s as shown in Figure 8. The results and the performance of SMES coil are shown in Figures 8 and 9.

According to the designed system the grid power does

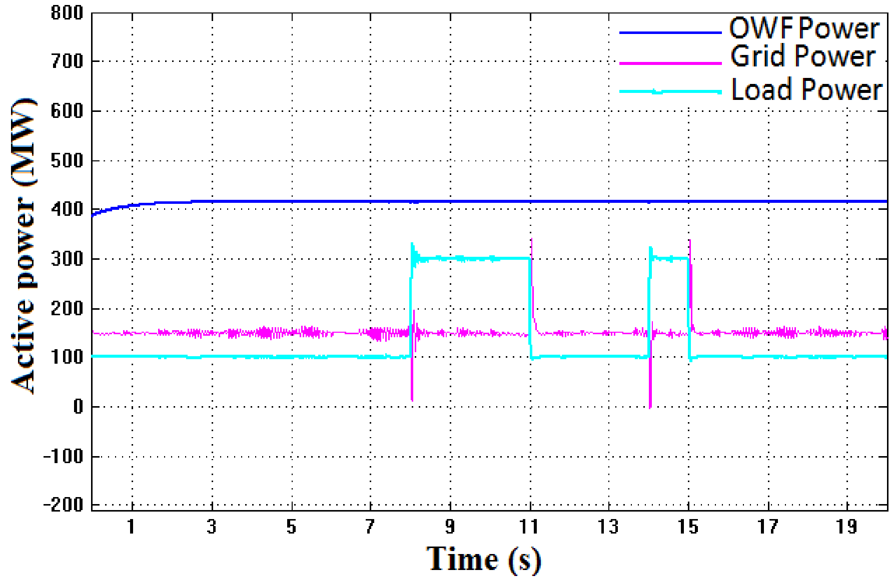

Figure 8. Active power in case 2.

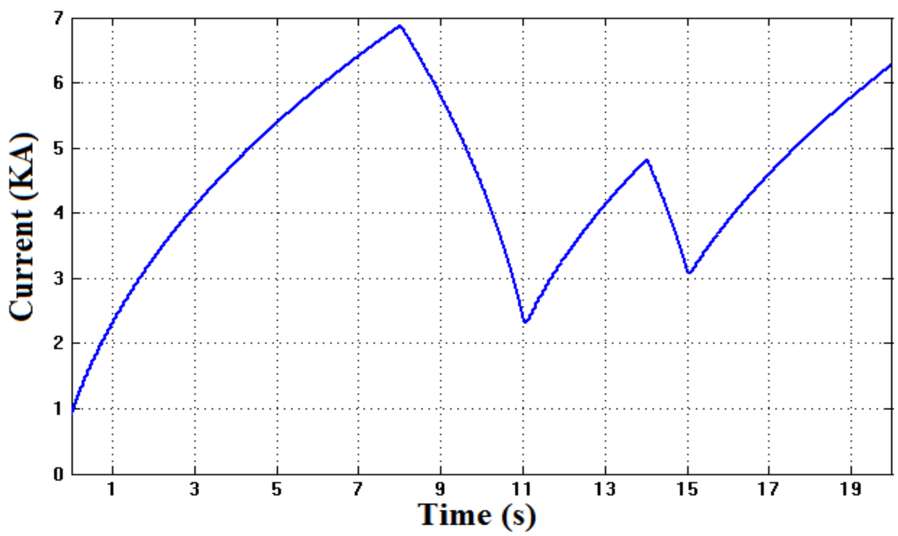

Figure 9. SMES current during case 2.

not provide any power. This occurs in Figure 8 the grid power is still in 150 MW. The SMES coil can supply the load demand during the disturbance period as shown in Figure 9. It absorbs surplus energy and during increasing in load it releases the required power to the load.

Case 3: Tripping out of some turbines

In the case of tripping out some of the wind turbines, it is assumed that 150 PMSG wind turbines are tripping out from OWF for 3 s starting at time t= 12 s as shown in Figure 10.

As shown in Figure 10, the SMES begin to export power to compensate energy shortages during tripping out some of the wind turbines and when the wind turbines return back into service the SMES charges. The SMES coil can supply power to demand load during these three seconds, and is trying to make the grid power stable as shown in Figure 11. It shows that SMES is discharged for

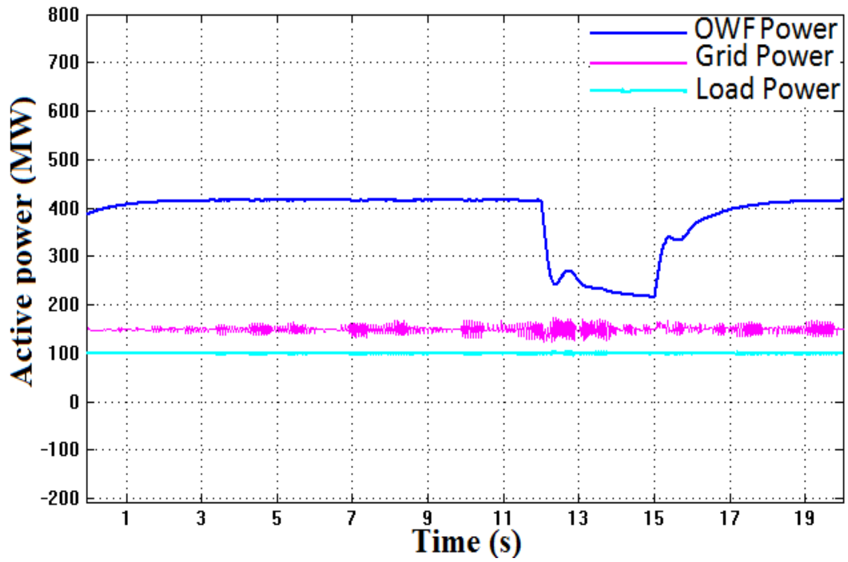

Figure 10. Active power in case 3.

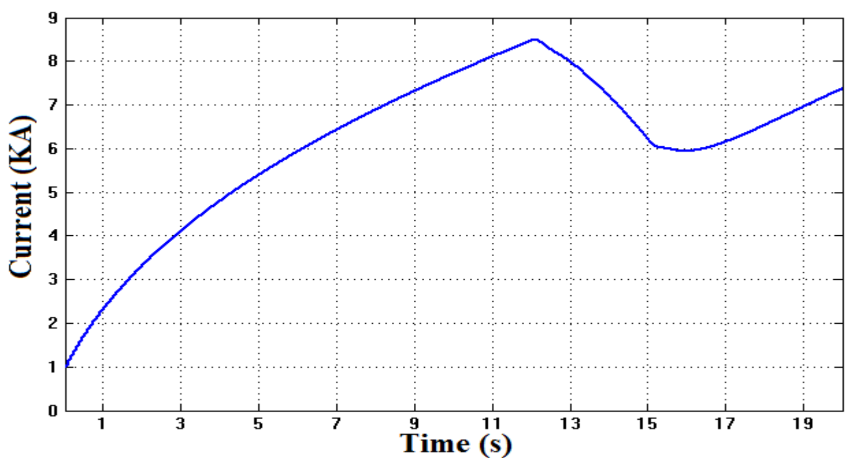

Figure 11. SMES current during case 3.

four second, this is due to the time is taken to reach the previous value of wind power and charge again.

Case 4: Voltage dip

In this case, the system is tested when the voltage of the AC grid (active network) suffers from a dip. It is supposed that the AC voltage is dropped to 0.5 p.u for 500 ms between 10-10.5 s. The performance of the SMES coil is shown in Figures 12, 13 and 14.

When the voltage dips on the grid side converter terminal bus, the power transfer capability of the grid is reduced. In such a case the WF may be commanded to reduce the power generation. This is causes unbalance in DC transmission system. Any excess power fed into the DC link would result in DC overvoltage as shown in Figure 12 where it shows the system behavior without the SMES. When a SMES coil put in the DC system, it removes this overvoltage in the DC link. The system behavior with SMES is shown in Figures 13 and 14. Figure 13 shows the stability of DC voltage at 1 p.u and the effectiveness of SMES coil in stabilizing the system.

Conclusion

This paper presented OWF containing PMSG wind

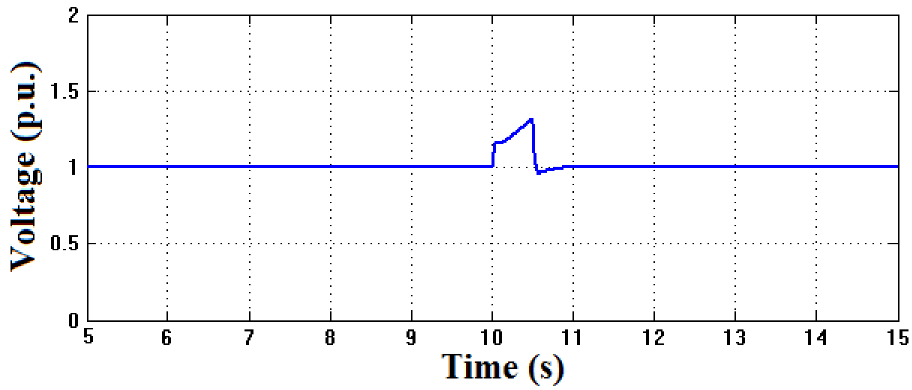

Figure 12. DC voltage without SMES.

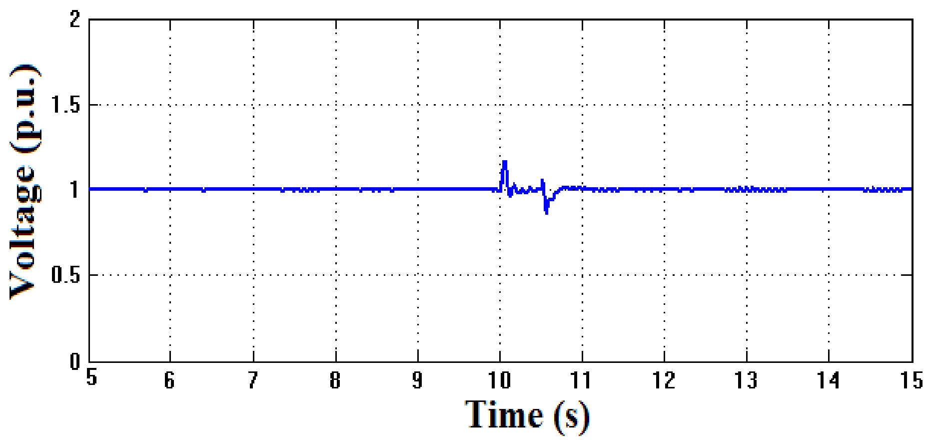

Figure 13. DC voltage with SMES.

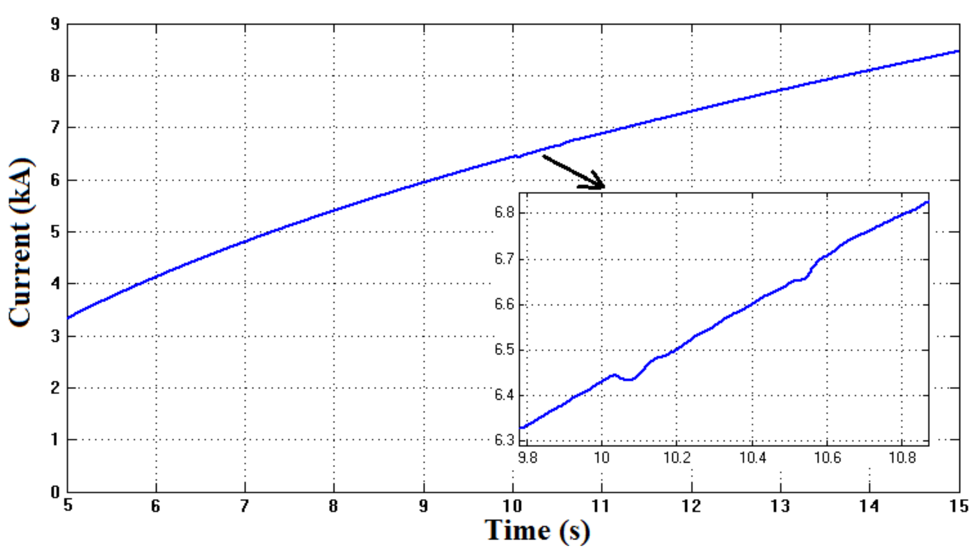

Figure 14. SMES current during case 4.

turbines connected to the active network and passive system through MT-HVDC. It also studies the performance of the SMES unit integrated with the system. It has analyzed the performance of this unit by presenting transient responses of a WF such as tripping some of the wind turbines, increasing of load and voltage drop. The active power grid without SMES unit is affected to a greater or lesser extent according to error range. This paper worked on to make the active power grid stable without providing any power to the passive network (load) during any disturbances. The transient simulation results of this work show that SMES system can be a good stabilizer for power system oscillations. It can also maintain the DC link voltage stable at nominal voltage during voltage drop. Moreover, the results show that SMES was capable of smoothing out power fluctuation caused by fluctuation in wind speed which causing power system instability. The limitation of SMES unit is in its capacity, especially when using a large wind farm. Furthermore, increasing in SMES unit capacity means increasing in the cost.

Future work

Comparison between SMES unit and different types of energy storage devices with a large offshore wind farm.

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Appendix

Appendix A. Parameters of transmission line.

Line data	R [Ω/km]	L [mH/km]	C [μF/km]
AC cable 145 kV	0.0843	0.2526	0.1837
DC cable +/-200 kV	0.0095	2.1110	0.2104

Appendix B. Wind turbines parameters.

Parameter	Symbol	PMSG	Unit
Nominal mechanical output power	P_{mec}	1.5	MW
Nominal electrical power	P_e	1.5/.9	MVA
Nominal voltage (L-L)	V_{nom}	690	V
Base frequency	f	50	Hz
Stator resistance	R_s	0.027	p.u.
Number of pole pairs	N_p	48	-
Wind speeds incident on the wind turbines	u	11	m/s

Appendix C. Specification of the SMES.

SMES energy capacity [GJ]	1
Rated current [kA]	10
Superconducting coil inductance [H]	20
DC-DC chopper carrier frequency [Hz]	27*50
Proportional gain of the DC-DC chopper [p.u.]	0.1
Integrating gain the DC-DC chopper [p.u.]	10