Indonesian Journal of Electrical Engineering and Computer Science
Vol. 4, No. 1, October 2016, pp. 1 ~ 9
DOI: 10.11591/ijeecs.v4.i1.pp1-9

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)). Furthermore, we have used a detector to detect any tripping of any wind turbine and substitute the shortage of power due to this loss of wind turbines immediately through SMES. 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.

Keywords: *offshore wind farm, superconducting magnetic energy storage and PMSG.*

1. Introduction

There are many benefits of OWFs compared to conventional onshore wind farms. Such as, higher wind speeds, allowing the larger size of wind turbines and the unlimited available locations in the sea to install new wind farms. So, in the recent years, the number of OWFs has increased. The output power from OWFs connected to the main AC network using transmission systems based on AC or DC technology. The selection of these technologies depends on the cost of the installation, the transmission distance and power output.

Long distance cable connections HVDC technology is the best solution for OWFs. Regarding DC transmission systems, There are two possible technologies: LCC-HVDC (HVDC classical) or VSC-HVDC technology [1]. 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. The control of the converter station that directly connects the active system usually is in constant DC voltage control mode. The control of the converter that directly connects the passive system is in constant AC voltage control mode [2]. For large scale offshore wind generation, multi-terminal DC based on voltage source converter (VSC-MTDC) becomes an attractive solution. By VSC-MTDC, the wind farm (WF) can be connected to more than one onshore grid that may or may not be synchronized to each other [3, 4].

Recent years energy storage systems are becoming popular for transmission and grid applications. There is a variety of storage technologies in the market; one of them is superconducting magnetic energy storage (SMES). It has faster response time than any other storage systems. The important section of 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, also keeps the temperature below the critical temperature [5, 6].

Received May 3, 2016; Revised August 26, 2016; Accepted September 11, 2016

SMES stores 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.

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 [5]. 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.

This paper works in connecting PMSG OWF to active and passive networks through MTDC systems based on VSC. 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 which are verified in [7] or increasing on demand load. This is done by putting SMES unit in the DC link in the MTDC 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.

2. System Description

As shown in Figure 1, the system consists of 450 MW OWF merging 300 * 1.5MW PMSG wind turbines. They are aggregated at the common bus of 145KV 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) [8, 9]. 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 MTDC transmission system to the 380KV 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), +/- 200kV.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.

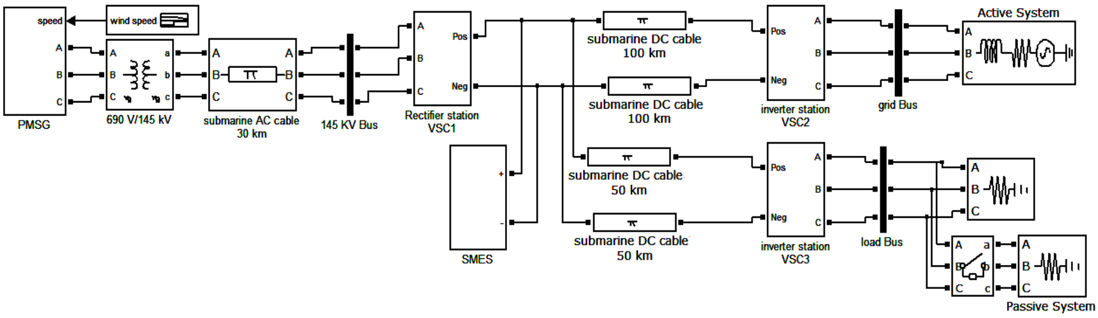

Figure 1. Offshore wind farm with HVDC system and SMES

3. Voltage Source Converter Model

Figure 1 shows the power transmitted from a WF to the AC grid through three-level VSC based HVDC system. VSC-HVDC transmission system essentially contains of converter transformer, 3 level VSC, shunt AC filters on the AC side, DC line capacitor and phase reactor as shown in Figure 2. The high-frequency filters are 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 [10].

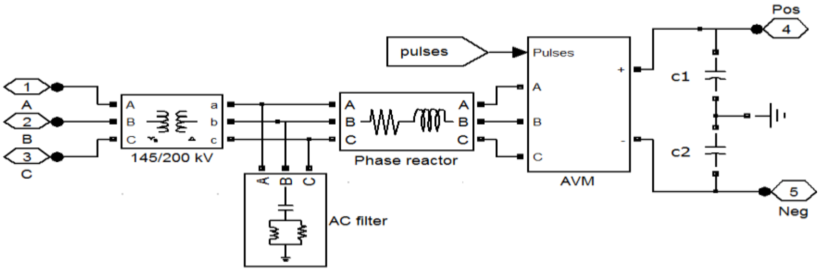

Figure 2. Components of converter station

In HVDC transmission system, there are two voltage source converters one acts as a rectifier connecting to OWF and the other acts as an inverter connecting the AC grid. The control strategies of each one are given in section 3.2 and 3.3.

3.1. Mathematical Model

Conversion of abc to rotating dq reference frame can be mathematically modeled in terms of decoupled direct and quadrature converter current components id and iq respectively [11]:

$$L\frac{di_d}{dt} = -Ri_d + \omega Li_\mathrm{q} - u_{dconv} + u_d \qquad (1)$$

$$L\frac{di_q}{dt} = -Ri_q + \omega Li_\mathrm{d} - u_{qconv} + u_q \qquad (2)$$

Where udconv and uqconv are used in order to control the converter currents id and iq.

The relationship of the power balance between the AC input and DC output is given as:

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

The vector of the grid voltage is known 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, uq = 0 and the active and reactive power absorbed from or injected into the AC system are given by [12]:

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

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

Hence, the current is split into two portions according to 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, 5) show the possibility to control the components of two current independently.

3.2. VSC Connected to OWF and its Controller

The aim of the offshore VSC is to transmit 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 [13].

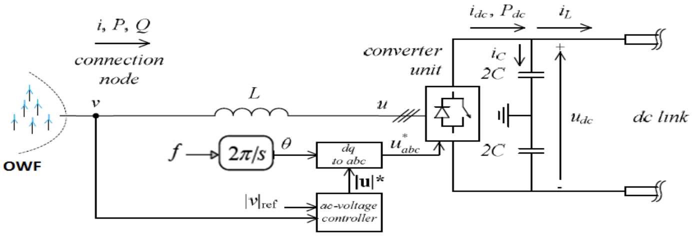

Figure 3. Control scheme of Offshore VSC

3.3. 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 is applied, [14]. As described in Figure 4, the control scheme of the Onshore VSC consists of a phase-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 (ud* and uq*).

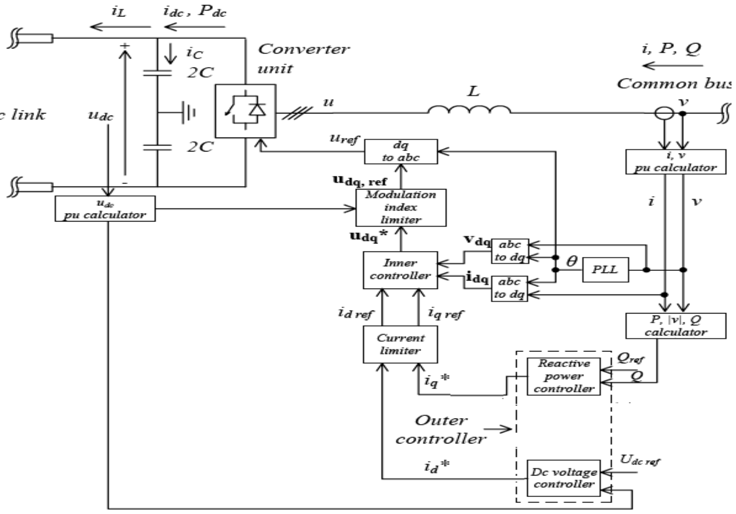

Figure 4. Control scheme of Onshore VSC

4. SMES System and Controlling

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 the coil has cryogenically cool to its superconducting critical temperature. This means that during operation ohmic losses will be very low, close to zero [15].

The stored energy (ESMES) and rated power (PSMES) in the coil are:

$$E_{SMES} = \frac{1}{2} L_{SMES} I_{SMES}^2 \tag{6}$$

$$P_{SMES} = \frac{dE_{SMES}}{dt} = V_{SMES} I_{SMES} \tag{7}$$

As shown in Figure 5 the SMES unit consists of two main parts, DC-DC chopper (Type - D chopper) [16] and the superconductor coil, which has an extremely low resistance.

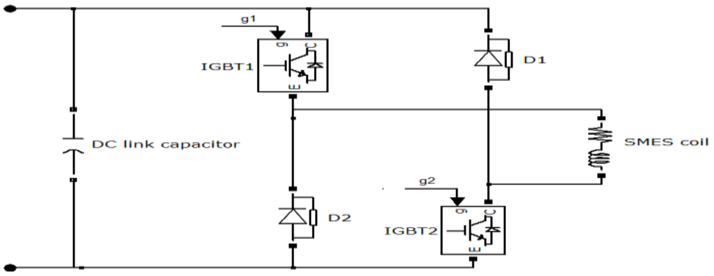

Figure 5. SMES unit components

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

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

When the two choppers are OFF and diodes D1 and D2 start conducting, the SMES is in discharging mode and the relationship between the voltages are:

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

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.

As shown in Figure 6, the DC-DC chopper control scheme. 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 (i.e., 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). When D is larger than 0.5 the coil is charging and when the duty cycle is less than 0.5 the coil is discharging [17].

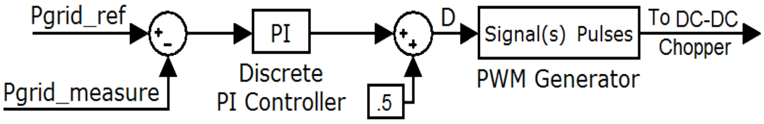

Figure 6. Control of the chopper

5. Simulation Results

To evaluate the performance of SMES in the power system, the system in Figure 1 was performed by MATLAB /Simulink with four different instability cases: wind speed fluctuation, tripping 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 150MW 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 transients.

5.1. Case 1: Wind Speed Fluctuations

The fluctuations of the wind speeds cause fluctuation in the output power of the OWF as shown in Figure 7 (blue line). These fluctuations are transferred to the AC grid and may cause interruption to the power system. But, using SMES coil it can absorb these fluctuation and supply power to AC grid without any fluctuation as shown in Figure 7 (magenta line) where the DC -DC chopper is controlled to provide 150 MW to the active system. The cyan line in Figure 7 is the power to load demand (passive network). Figure 8 shows the current in the SMES coil. It is obvious from this figure that SMES coil can absorb fluctuations. So the SMES in DC link can stabilize the power system where the large variations do not reach the grid. In such a way the smoothed power reach the customers.

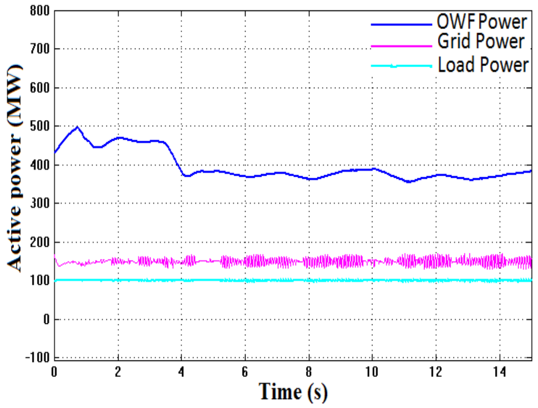

Figure 7. Active power in case 1

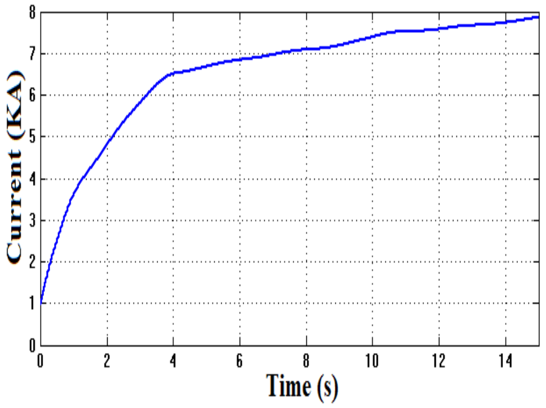

Figure 8. SMES current during case 1

5.2. 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 increased to 300MW during 3 Sec at time t= 8 Sec and for 1 sec at time t= 14 Sec. According to the designed system the grid power does not provide any power. This occurs in Fig. 9 the grid power is still in 150MW. The SMES coil can supply the load demand during the disturbance period as shown in Fig. 10. It absorbs surplus energy and during increasing in load it releases the required power to the load.

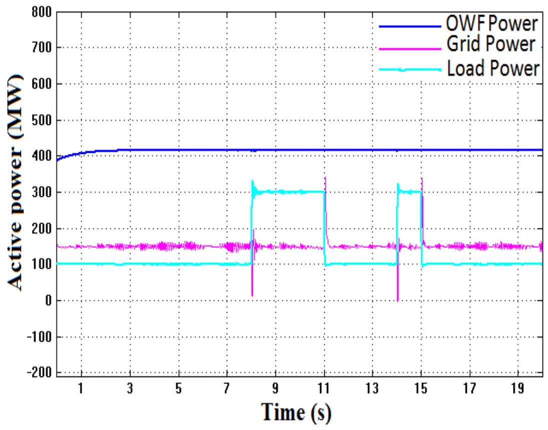

Figure 9. Active power in case 2

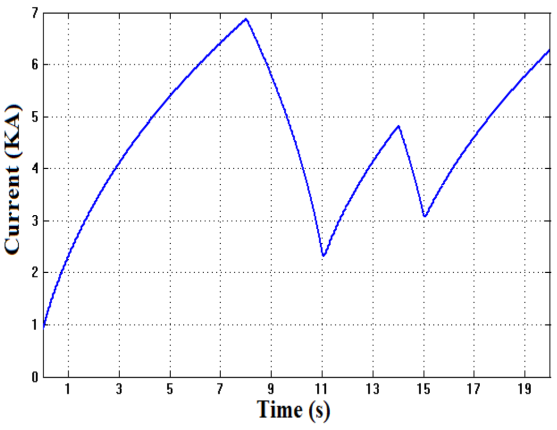

Figure 10. SMES current during case 2

5.3. Case 3: Tripping out some Turbines

By using a detector in the system to detect any of wind turbines is tripping out or return back to service during simulation. In the case of tripping out some of the wind turbines, the SMES begin to export power to compensate energy shortages and when the wind turbines become in service the SMES charges. It is assumed that 150 PMSG wind turbines are tripping out from OWF for 3 Sec starting at time t=12 Sec as shown in Figure 11. The SMES coil can supply power to demand load and trying to make the grid power stable as shown in Figure 12. It shows that SMES is discharged for 4 second this is due to the time is taken to reach the previous value of wind power and charge again.

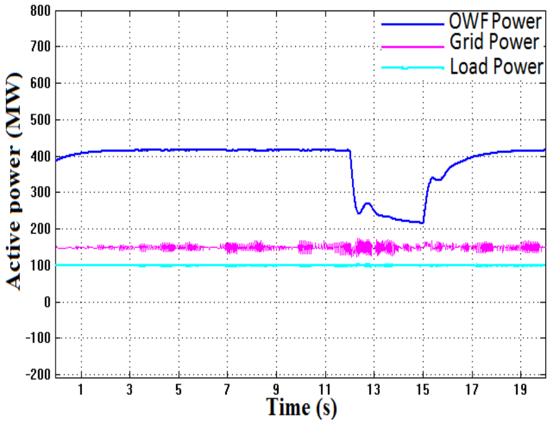

Figure 11. Active power in case 3

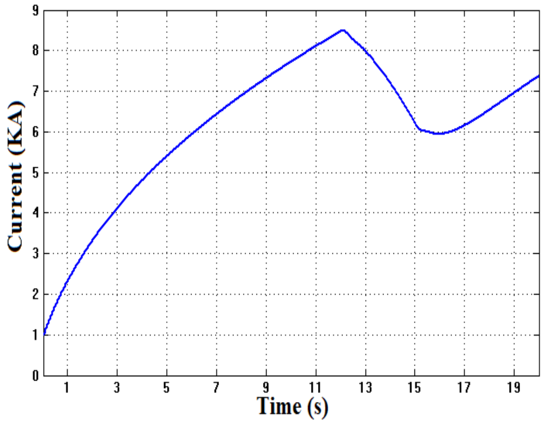

Figure 12. SMES current during case 3

5.4. Case 4: Voltage dip

In this case, the system is tested when the voltage of the AC grid (active network) is a dip. It is supposed that the AC voltage is dropped to 0.5 p.u. for 500 ms at period 10-10.5 Sec. 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. Any excess power fed into the dc link would result in DC over voltage as shown in Figure 13 where it shows the system behavior without the SMES. The system behavior with SMES is shown in Figure 14 shows the stability of DC voltage at 1 p.u. It shows the effectiveness of SMES coil in stabilizing the system.

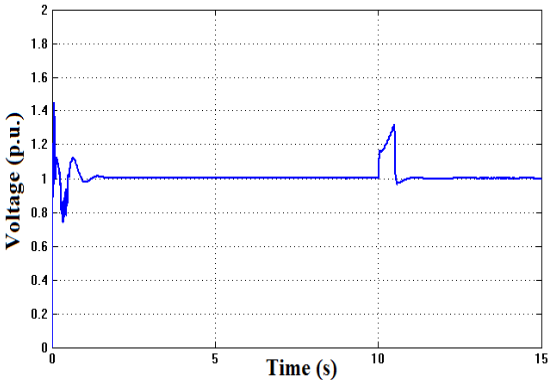

Figure 13. DC voltage without SMES

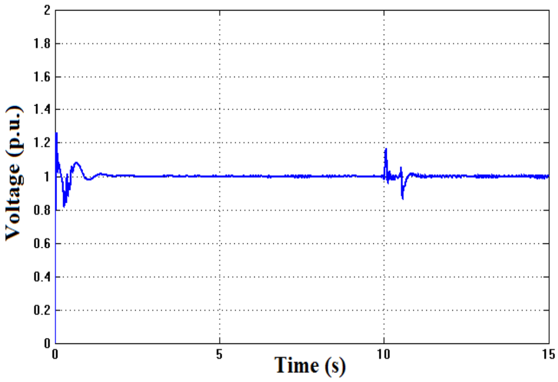

Figure 14. DC voltage with SMES

6. Conclusion

This paper presented OWF containing PMSG wind turbines connected to the active network and passive system through MTDC. 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.

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Appendix A. Parameters of transmission line

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

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

Symbols and Abbreviations

OWF	offshore wind farm
PMSG	permanent magnet synchronous generator
VSC	voltage source converter
LCC	line commuted converter
HVDC	high voltage direct current
MT-HVDC	multi-terminal high voltage direct current
WF	wind farm
R	the converter resistance
L	the converter inductance
uconv	the converter voltage
ud, uq	the voltage at the PCC
ω	the grid pulsation
udc	the DC link capacitor voltage
idc	the DC link capacitor t current
LSMES	the inductance of the coil
ISMES	the DC current flowing through the coil
VSMES	voltage across the SMES coil.
D	the chopper duty cycle.