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Analysis of Superconducting Magnetic Energy Storage Used in A Submarine HVAC Cable Based Offshore Wind System

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Abstract

Because of the booming development of offshore wind power around the world, a stable transmission system which is used for the connection between the offshore wind farms and the onshore grid is required. For the offshore wind farms not far from the coast, high voltage alternating current (HVAC) transmission system is the best choice. Aiming to study the transient problems caused by cable operation, a 60km submarine cable is modeled in this paper using ATP-EMTP. The larger capacitance effect of HVAC submarine cables will cause more severe transient problems. Also, the variable wind power generated by offshore wind farm will bring undesired impact on the onshore power grid. This paper proposes a superconducting magnetic energy storage (SMES) system which can mitigate both the high frequency fluctuation of wind power and the transient over voltage of the HVAC cable system. In addition, SMES sizing study has been done to achieve the proposed functions.

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Keywords: HVAC submarine cable; transient problems; superconducting magnetic energy storage system (SMES); offshore wimd farm; ATP-EMTP.

1. Introduction

Significant changes of the structure of the world energy market could be noticed in recent years. Although the fossil fuel is still the main recourse to generate electricity on a world scale, the past few decades witnessed a remarkable development of the renewable energy. Considering about the environment, location, sustainability and economical and technical attractiveness, wind power is the one that worthy of promotion in the UK [1]. Delay and Jennings in [2] predicted that total wind power capacity in 2020 will be 40GW, equivalent to 31% of total UK electricity supply, of which 25% (29GW) derives from offshore wind and 6% (11GW) from onshore wind [2].

Therefore, a stable transmission system which is used for the connection between the offshore wind farms and the grid is required. High voltage dc systems have been studied using in offshore wind farm [3, 4]. However, the high cost of converter stations makes this technology suit for large wind farm with a

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long distance transmission line. For the offshore wind farms not far from the coast (normally less than 60 km), HVAC transmission system is the best choice for its economical and technical attraction [4]. However, because of the low resistivity of sea water and the larger capacitance of HVAC cables, the electromagnetic transients of HVAC cable transmission system are different from that of the traditional overhead lines and such as high voltage and current transients. In addition, the instability and the intermittence limited the applicability of the offshore wind power as electric power generated by wind turbines is highly erratic and may have undesired impact on power system. Hence, this paper proposed SMES that is capable of mitigating transient overvoltage and smoothing short-term fluctuation of wind power.

The principle advantages of SMES have been shown [5] to include: high power density, high discharging efficiency and long service life. Because of the ability of offering a huge of power in short time, SMES have already been used in many applications, such as fluctuation suppression [6], voltage stability maintenance [7] and improving wind generator stability [8], etc. However, when SMES is used for an offshore wind farm using a HVAC transmission system, the characteristics of the HVAC submarine cables should be taken into account. This paper has built an offshore wind power system with submarine HVAC cables in ATP-EMTP and designed a SMES used in the wind farm and cable connection point to mitigate the overvoltage transient cased by operation of the HVAC cables. In addition, the proposed superconducting magnetic energy storage system can be used for the wind power fluctuation compensation.

2. System description

A representative offshore wind power system including a 50MW wind farm, a 60km submarine cable transmission system and a SMES unit has been developed in ATP-EMTP and used to demonstrate the operation of the offshore system (Fig. 1). As it can be seen from Fig. 1, the SMES is installed in the connection point of the offshore wind farm and the cable system via an AC/DC convertor and a DC/DC chopper. An aggregate model offshore wind farm is built based on previous work described in [9].

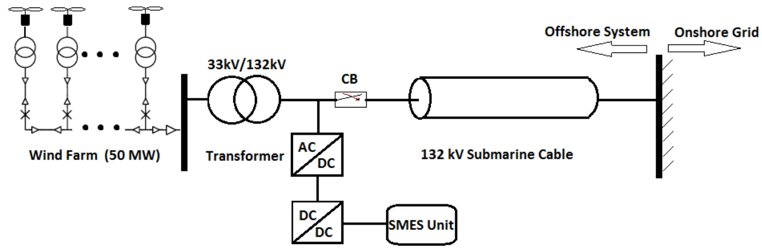

Fig. 1. Offshore wind farm with HVAC submarine cable transmission system and SMES

3. SMES unit modeling and control method

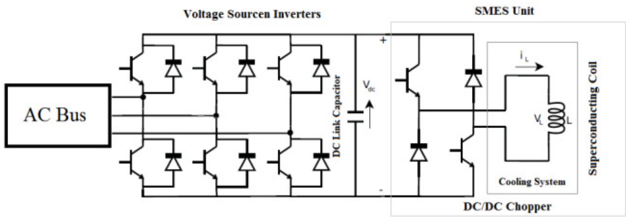

Fig. 2. Modeling of voltage source converter (VSC) based SMES unit

SMES is a device that stores energy in the magnetic field which is created by a DC current flowing through a superconducting coil. Fig. 2 shows a voltage source converter (VSC) based SMES system including an AC/DC VSC system with a DC/DC chopper interface, a superconductor coil and a refrigerating system.

Superconducting coil is connected to a DC link and is charged or discharged by adjusting the voltage V_{DC} by a DC/DC chopper as shown in Fig. 3. V_{DC} is taken as the feedback signal and adjusted by a reference value V_{Ref}. A proportional and integral controller (PI) is used to refine the differential value. The output of the first PI adjusted by the current of the superconducting coils to generator PWM signals controlling the DC chopper. As a result, the capable of controlling the stored energy or more exactly the charging/discharging current is achieved by adjust DC voltage of the DC chopper.

- If $V_{DC} > V_{Ref}$, SMES will be charged by the surplus power.
- If $V_{DC} < V_{Ref}$, SMES will be discharged supplying power.

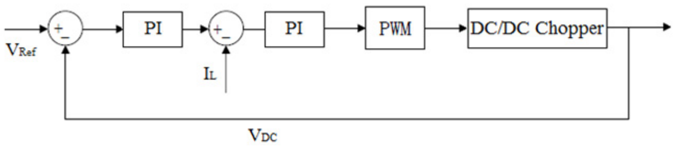

Fig. 3. Control strategy of the SMES unit

Therefore, the SMES will charge and discharge according to the voltage signal and used to maintain this voltage in a reference value hence maintaining the stability of the system.

4. SMES sizing study

Sizing study is necessary when design an energy storage system. In this paper, SMES is sized by two constrains.

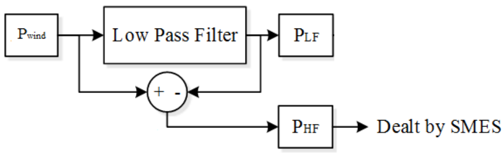

Fig. 4. Obtain high frequency components of output wind power.

Firstly, as shown in Fig. 4, wind power output comes through a low-pass filter in order to obtain the high frequency power fluctuation (P_{HF}) which could be used to determine the size of SMES. Hence, the energy stored/released by SMES E_{SMES} should be able to deal with the P_{HF} all the time (simulation time Ts, in this paper) as shown in Eq. (1)

$$E_{SMES} \geq \int_0^{T_s} P_{HF} dt \qquad (1)$$

Secondly, SMES should be big enough to compensate the overvoltage caused by the energisation of the submarine cable. Normally, in the worst case, the over voltage can reach as high as 3.0 p.u. and as long as 20ms. Hence, the second constraint is shown in Eq. (2), where U_{over}, and I are the voltage and current of circuit breaker (CB), t is the over voltage duration.

$$E_{SMES} \geq \sqrt{3} U_{over} I t \qquad (2)$$

Due to the better performance [10], the second-generation high-temperature superconductor is selected to design the SMES. Optimal configuration algorithm is done according to [11]. Based on the proposed system, the superconducting magnetic energy storage system is sized as 9MJ.

5. Submarine cable modeling

The purpose of electrical cables is to transport the electricity from the power source to different substations or loads. Although there are various kinds of power cables aiming accomplish this goal, the cable is mainly consisted of some key components: conductors, insulation and the sheath. These three parts were considered and modeled in ATPDraw.

The parameters of the power cable will change because of the skin effect. Frequency dependent model is required. Previous work had been done to study the modeling of a submarine cable connected to an offshore wind farm and compared the characteristics of both onshore cable and offshore cable [12]. The results in [12] illustrates that "when using the J. Marti model, the submarine cable can be modeled as the one in the ground and has equivalent resistivity". Hence, based on the characteristics of a commercially available 132 kV 3-core cables (selected conductor cross-section 630 x 3), the parameters can be obtained. In addition, parameters modifications have been done using the method described in [12, 13] in order to describe an accurate model in ATP-EMTP. A 60 km, 132 kV 3-core HVAC cable system have been built in ATP-EMTP and the Table 1 gives the cable size and Table 2 gives the Equivalent parameters

Table 1. Cable size

Cross-section area (630 x 3 mm^2)	Core	Sheath	Armor
Inner Diameter	0	30.0 mm	67.0mm
Outer Diameter	29.8 mm	66.6 mm	204.0 mm

Table 2. Equivalent parameters for the selected cable

Parameters	Equivalent values
Capacitance	0.19 μF/km
Inductance	0.38 mH/km
Buried depth	3.4m
Conductor relative permeability	1
Sheath relative permeability	1
Conductor resistivity	1.7E-8 Ωm
Insulation relative permittivity	3.1
Outer insulation relative permittivity	2.3

6. Simulation Results and Discussion

Fig. 5 gives the simulation results of wind power output with and without superconducting SMES. It is obvious that the power generated from the wind turbine contains a large amount of high frequency component see the red curve in Fig. 5. (a). However, when applied the proposed SMES into the offshore wind power system, the high frequency fluctuation is compensated and the wind farm gives a more smoothing output, see the green curve in Fig. 5.(a). Also, as can be seen from the charging/discharging power of SMES, the SMES have successfully absorbed the fluctuation of wind power.

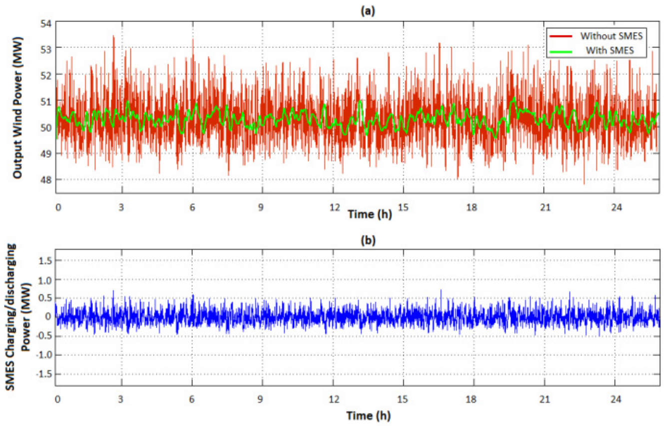

Fig. 5. (a) Comparison of power outputs from offshore wind farm with SMES system (green one) and without SMES system (red one); (b) Charging/discharging power of SMES

It should be noted that superconducting magnetic energy storage system has high power density but low energy density. As a result, it cannot deal with the low frequency fluctuation (still exist in the green curve in Fig. 5. (a)) which need large energy to compensate. Therefore a SMES-battery hybrid energy storage system needs to be designed in the future.

This paper mainly studies the system transient overvoltage caused by cable energisation. Fig. 6 gives the simulation results that describe the transient overvoltage with and without SMES. Obviously, the SMES can mitigate the transient overvoltage from 2.7 p.u. to less than 1.3 p.u.

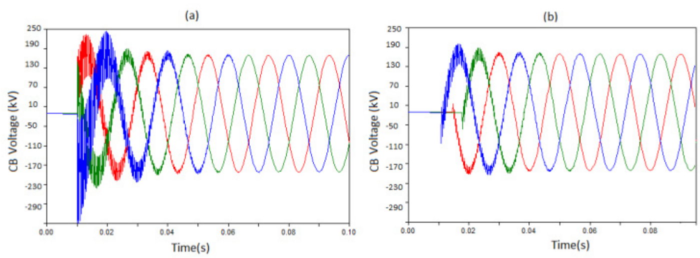

Fig. 6. (a). Three phase overvoltages caused by cable energisation without SMES; (b). three phase overvoltages are mitigated by SMES.

The submarine cable system may cause other transient problems such as Zero-missing Phenomenon, transformer Inrush current and resonance problems. The proposed SMES system and SMES sizing method can be used to the other applications to solve different transient problems.

7. Conclusion

This paper proposes a superconducting magnetic energy storage system which can be used for both functions of smoothing power fluctuation and transient overvoltage mitigation. A representative offshore wind power system including a 50MW wind farm a 60km submarine cable and a SMES unit has been developed in ATP-EMTP. Simulation results shows that: a). SMES can charge/discharge with the high frequency component of the wind power hence able to compensate the high frequency fluctuation; b).

SMES can mitigate transient over voltages caused by cable energisation. A SMES hybrid energy storage system may have a better performance which needs to be studied in the further.

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