Gang SHI, Xu CAI[1], Zhe CHEN[2]

Shanghai Jiao Tong University (1), Aalborg University (2)

Design and Control of Multi-terminal VSC-HVDC for Large Offshore Wind Farms

***Abstract**. In this paper, the parameters design of VSC-HVDC terminal is proposed. A four-terminal VSC-HVDC system is configured as the simplified study system. The control schemes of coordinated control and master-slave control for MTDC system power delivery are investigated and their shortages are introduced. The control effect and power system stability is evaluated by three dynamic simulation cases based on PSCAD/EMTDC, which correspond to wind power fluctuation.*

***Streszczenie.** W artykule przedstawiono dobór parametrów układu VSC-HVDC. Badania oparto na układzie cztero-stronnym, z wykorzystaniem algorytmu sterowania mocą wyjściową systemu wielostronnego. Wykonano symulacje w PSCAD/EMTDC stanów dynamicznych, odzwierciedlające zmienność wiatru. (**Projekt i sterowanie dla wielostronnego systemu VSC-HVDC na potrzeby dużych poza lądowych farm wiatrowych**).*

Keywords: multi-terminal VSC-HVDC, offshore wind farm, parameter design, control scheme, BESS.
Słowa kluczowe: wielostronny system VSC-HVDC, poza lądowe farmy wiatrowe, dobór parametrów, schemat sterowania, BESS.

Introduction

Offshore environment is the first driver to utilize high voltage direct current (HVDC) technology to connect wind farms with longer distance to shore [1]. Voltage source converter (VSC) based HVDC provide more possibilities for the operation of offshore wind farms, including independent active and reactive power control, black start, and contribution to grid stabilization and ancillary services at point of common coupling. The Nord E. ON 1 project in Germany is the first application of VSC-HVDC for offshore wind power integration in the world [2]. However, currently commissioned point-to-point VSC-HVDC connection cannot be extended to large offshore wind farms, like 20 GW Dogger Bank. The multi-terminal HVDC (MTDC) network that interconnects several offshore wind farms widely dispersed may be a solution to this problem [3]. VSC-HVDC is the most feasible way to build a multi-terminal transmission network as it uses a common DC voltage at each converter station, making parallel connections easy to realize and control [4]. Line commutated converter (LCC) based HVDC is much more difficult to implement in a parallel multi-terminal configuration, because it needs to change the DC voltage polarity for power flow reversal with interruption of the MTDC system. As a result, for large-scale offshore transmission grids such as the European Super Grid [4] and North Sea wind farms [3, 5], multi-terminal VSC-HVDC should be a recommended technology.

The remainder of this paper mainly focuses on VSC-HVDC for MTDC system and its parameter design and control scheme. The detailed design work is implemented in Section II based on one VSC-HVDC terminal. A simplified study system of four-terminal MTDC network is configured in Section III. Section IV details two control schemes for power delivery of MTDC system, including coordinated DC voltage droop control and master-slave control. For master-slave control, battery energy storage system (BESS) integration is suggested to improve control flexibility. Section V carries out three dynamic simulation cases to evaluate the effect of designed control schemes based on PSCAD/EMTDC and conclusions are given in Section VI.

Design of VSC-HVDC Terminal

The design work is based on one HVDC converter station. However, this method can be applied to all VSC-HVDC terminals in the MTDC system. The configuration of VSC-HVDC is shown in Fig. 1, which consists of transformer, AC filter, phase reactor, converter, DC capacitor and DC cable.

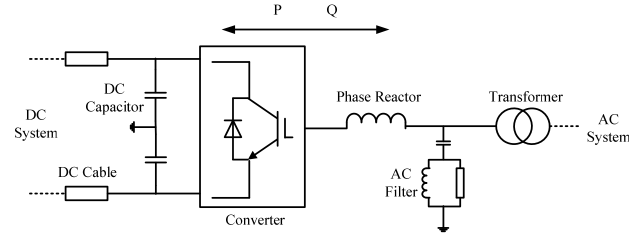

Fig.1. Configuration of VSC-HVDC

A. Converter

There are mainly three kinds of converter topologies applied in VSC-HVDC, which are two level, three level and multi-level configuration [6]. These topologies have been commissioned in engineering projects by HVDC Light® of ABB, HVDC Plus® of Siemens, and HVDC MaxSine® of AREVA. The modulation method is the key technology of VSC control. The converter is typically controlled through sinusoidal PWM (SPWM), and the harmonics are directly associated with the switching frequency. The other modulation methods include the Space Vector PWM (SVPWM), Optimum PWM (OPWM), and so on [7]. Because the converter is not mainly discussed in this paper, simple two-level VSC is used at the MTDC terminal, modulated by SPWM.

B. Transformer

Normally, the VSC-HVDC is connected to the AC system via transformer. The main function of the transformer is to transform the AC voltage of upper power system to a level suitable for AC side of the converter. Transformers usually have a leakage inductance between 0.1-0.2 p.u. [8]. Because AC filter is normally located between converter and transformer, standard transform can be used in VSC-HVDC system. In the future, if the DC bus voltage is high enough, the connected transformer in VSC-HVDC system may be eliminated by setting appropriate DC bus voltage.

C. Phase reactor

One of the responsibilities of the phase reactor is to control the active and reactive power flow of VSC by regulating the current through it. The phase reactor can also act as a current filter to reduce high frequency harmonic contents in AC current caused by the switching operation of the VSC. The design criteria for the phase reactor are according to these two aspects, as follows:

- Active and reactive power [9]

(1) $$L \le \frac{E_m{}^2 \sin\varphi\cos\varphi + E_m \cos\varphi\sqrt{E_m{}^2 \sin^2\varphi + 0.25V_{dc}{}^2 - E_m{}^2}}{2Pw_1}$$

or

(2) $$L \le \frac{E_m{}^2 \sin\varphi + E_m \sin\varphi\sqrt{E_m{}^2 \sin^2\varphi + 0.25V_{dc}{}^2 - E_m{}^2}}{2Qw_1}$$

where: E_m -peak phase voltage of AC side, φ - power factor angle.

- *Current harmonics* [10]

(3) $$L = Max(\frac{V_h}{h\omega_0 I_h})$$

where: h - harmonic number, V_h – the harmonic voltage determined from voltage harmonic table for sinusoidal PWM, I_h - the amount of acceptable harmonic current, which can refer to the harmonic standard, such as IEEE-519 [11].

According to [8], the reactors are usually about 0.15 p.u. impedance. Part of the series phase inductance required can be obtained from the leakage inductance of the connected transformer, if transformer is used.

D. AC filter

Normally, passive high-pass damped filters are selected to filter the high order harmonics. In that the second-order high pass filter obtains relatively wide pass band, good filter characteristics, resonant and mistune issues are avoided. Therefore, this paper selects second-order high-pass filter as AC filter for VSC-HVDC system.

The component parameters of the second-order high pass filter are calculated as [7]:

(4) $$C = \frac{Q_s}{2\pi f_1 U_s^2}$$

(5) $$R = \frac{1}{2\pi f_0 C}$$

(6) $$L = mR^2C$$

where: Q_s - reactive power of the high pass filter, U_s – AC side line-to-line voltage, f_1 - fundamental frequency, f_0 - cut-off frequency of the second-order filter, m - a parameter directly related to the shape of filter impedance-frequency curve. The appropriate value of m is selected from 0.5~2 according the engineering practice [7].

E. DC capacitor

There are normally two DC capacitors with identical capacity parallel connected at DC side of VSC-HVDC system, which are in charge of providing an energy buffer to keep the power balance during transients and reducing the voltage ripple on the DC side. The capacity of DC capacitor depends on the DC voltage. For SPWM technology, the DC voltage should meet the requirement as follows [9]:

(7) $$V_{dc} \ge 2E_m$$

where: E_m - peak phase voltage of AC side.

The DC capacitor size is attributed to a time constant τ, defined as the ratio between the stored energy at the rated DC voltage and the nominal apparent power of the converter S_N:

(8) $$\tau = \frac{C_{dc}V_{dc}^2}{2S_N}$$

Taking the speed of current controllers (which are fastest of all controllers in the VSC-HVDC) into consideration, a time constant of not less than 5 ms was suggested in literature [8].

Configuration of MTDC System

In this paper, a four-terminal VSC-HVDC transmission topology is taken into account as a simplified study system for the control scheme investigation and simulation to demonstrate the control design, as shown in Fig. 2, which consists of two wind farm VSC stations (WFVSC) and two grid side VSC stations (GSVSC). It is assumed that offshore wind farm is composed of fix speed squirrel cage induction generators (SCIG). DC cables are used to connect WFVSC and GSVSC. Further a tie-cable is used to interconnect two WFVSCs. Fast DC circuit breakers are installed at each end of every cable for protection of multi-terminal VSC-HVDC transmission system against DC faults. The arrows represent the positive of the power flow. The main parameters of this system are designed according to the given parameters and the theory introduced before, as shown in Table 1.

Table 1. The parameters of the test system

Devices	Specifications	Value
VSC-HVDC	Rated Power	200 MVA
	AC Voltage	150 kV
	DC Voltage	±150 kV
	Switching Frequency	1950 HZ
Phase Reactor	Inductance	54 mH
First Order AC Filter	Resistance	38.462 Ω
	Inductance	1.57 mH
	Capacitance	2.122 µF
Second Order AC Filter	Resistance	57.692 Ω
	Inductance	1.177 mH
	Capacitance	0.7 µF
DC Capacitor	Capacitance	44 µF
DC Cable	Resistance	28.2 mH/km

.

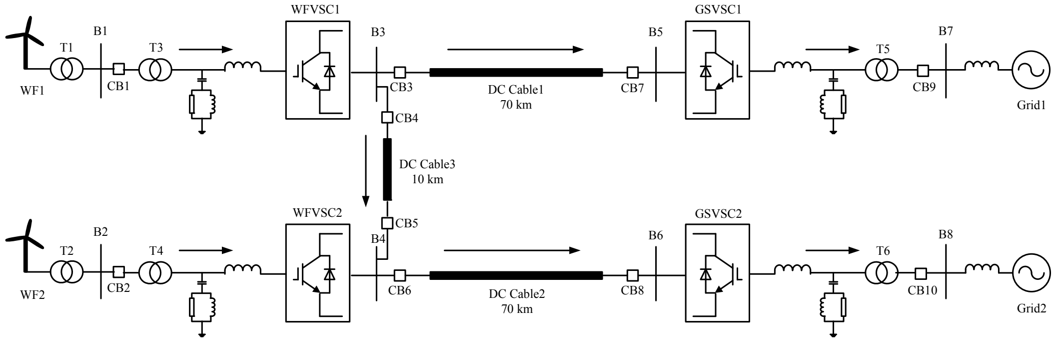

Fig.2. Four-terminal VSC-HVDC transmission system connecting two offshore wind farms to the grid

Coordinated control between GSVSCs and BESS

For coordinated control scheme of GSVSC, as shown in Fig. 3, power transmitted to onshore can also be regulated instantaneously by the use of DC voltage droop control [12]**Błąd! Nie można odnaleźć źródła odwołania.**. This control strategy for coordinated control mode is analogous to the frequency droop control in AC grids, except that the controlled object is HVDC voltage. Each converter has a defined linear relationship between HVDC voltage and current as

$$E_{gs}^{*} = E_{gs}^{\min} + I_{gs} / k_{gs} \tag{9}$$

From Fig. 2, assuming that DC voltage control is effective, DC voltage of two GSVSCs respectively is

$$\begin{cases} E_{B5} = E_{gs}^{\min} + I_{cable1} / k_{gs1} \\ E_{B6} = E_{gs}^{\min} + I_{cable2} / k_{gs2} \end{cases} \tag{10}$$

According to Fig. 2, E_{B3} and E_{B4}can be expressed as

$$\begin{cases} E_{B3} = E_{B5} + I_{cable1} R_{cable1} \\ E_{B4} = E_{B6} + I_{cable2} R_{cable2} \\ E_{B3} - E_{B4} = I_{cable3} R_{cable3} \approx 0 \end{cases} \tag{11}$$

E_{B3} and E_{B4} can be roughly regarded as equal due to relatively smaller value of I_{cable3} and R_{cable3}.

Then substituting (10) into (11) yields

$$\frac{I_{cable1}}{I_{cable2}} = \frac{R_{cable2} + 1 / k_{gs2}}{R_{cable1} + 1 / k_{gs1}} \tag{12}$$

If all cable resistances are ignored, the power delivery ratio between Grid1 and Grid2 can be represented as

$$\frac{P_{grid1}}{P_{grid2}} = \frac{I_{cable1}}{I_{cable2}} = \frac{k_{gs1}}{k_{gs2}} \tag{13}$$

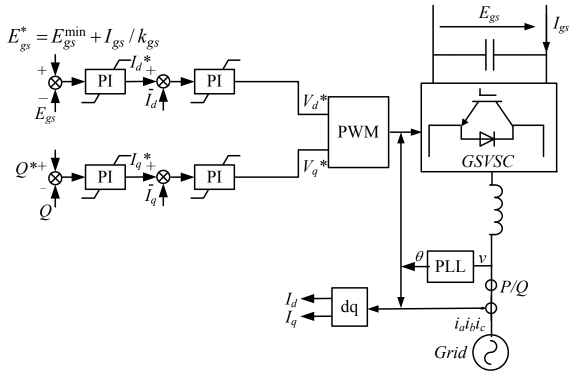

Fig. 3. DC voltage droop control of GSVSC

However, if the DC grid layout is complex with a large number of GSVSCs, it is difficult to derive a simple relationship between the droops and power transmission ratios of different GSVSCs [12]. In reality, if large number of GSVSCs are connected to the MTDC system, master-slave control with communication can be adopted instead of coordinated droop control [13]. One GSVSC is used to regulate the DC bus voltage, whilst the other GSVSCs follow a given power reference which can be constant or assigned by a master converter. The converter controlling the DC voltage will act as a slack node without power control ability, which needs to provide or absorb sufficient active power to achieve a power balance in the MTDC system. Therefore, this converter will suffer large power fluctuation according to wind variation when the other converters set a constant power order.

This kind of control strategy may not be practical if GSVSCs connect to different countries or if none of the converter terminal can be guaranteed to be linked to a strong grid, because the fluctuant power transferred may not meet the grid code of local TSO. This paper proposes the use of battery energy storage system (BESS) to compensate fluctuant power transmission at the slack node, as illustrated in Fig. 4.

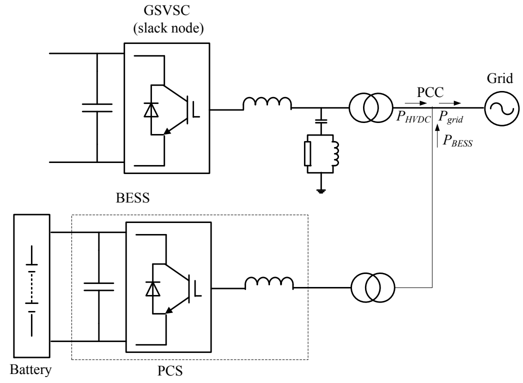

Fig. 4. BESS integration at the slack node GSVSC

BESS is shunt connected with GSVSC to the AC grid at point of common coupling (PCC). BESS consists of the battery and power condition system (PCS), whose topology adopted in this report is also a three phase VSC. The BESS can charge and discharge through PCS to smooth the power injected to the onshore grid served as a slack node within its designed capacity. The desired set point P_{grid} is then subtracted from the actual GSVSC power output P_{HVDC} to get P_{BESS}, which indicates the amount of power the BESS should compensate. If $P_{HVDC} < P_{grid}$, BESS starts to discharge to fill the power gap, and if $P_{HVDC} > P_{grid}$, BESS starts to charge itself to absorb the excess power. Therefore, BESS integration can keep PCC voltage and frequency fluctuation of the slack node within an accepted level, even for large wind variation and weak grid connected. The detailed control scheme of BESS is presented in Fig. 5.

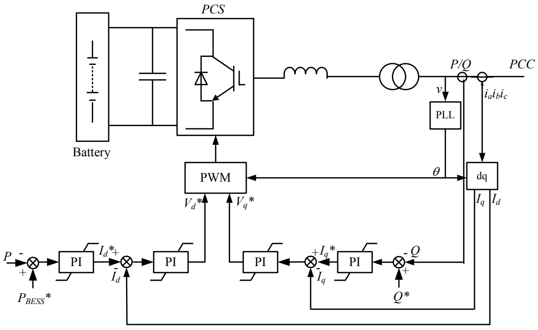

Fig. 5. BESS control scheme

Simulation Results and Discussion

To evaluate the parameters design and control effect of the proposed MTDC system, three dynamic simulation cases under wind power fluctuation are implemented as characterized in Table 2. Two control schemes for GSVSCs' power delivery, such as coordinated control and master-slave control, are compared. Then for GSVSC master-slave control, BESS is integrated to smooth the power output at the slack node.

Fig. 6 illustrates the wind source with mean wind speed at hub height and a random noise generation. The mean wind speed is 9 m/s of wind farm 1 and 8 m/s of wind farm 2.

Table 2. Simulation cases setup

Case Description	Main operation modes
Wind power fluctuation	GSVSC coordinated control by DC voltage droop
	GSVSC master slave control
	GSVSC master slave control with BESS at slack node

Fig. 6. Wind speed

A. GSVSC coordinated control by DC voltage droop

The active power of the wind farm varies correspondingly with fluctuant wind speed. Because the wind farm is equivalent to an induction generator in the simulation, the inertia element of induction generator brings the wind power certain delay and smoothing effect. It is practical in the real wind farm. Because two GSVSCs adopt the same DC voltage-current droop control, they share the wind power generation and smooth the power fluctuation exported to the grid, as shown in Fig. 7. The power transferred through the tie-cable also varies simultaneously to balance the power transmitting to each GSVSC. That means the power flow of tie-cable is positive when power generation of wind farm 1 is more than wind farm 2, and the power flow of tie-cable is negative when power generation of wind farm 1 is less than wind farm 2.

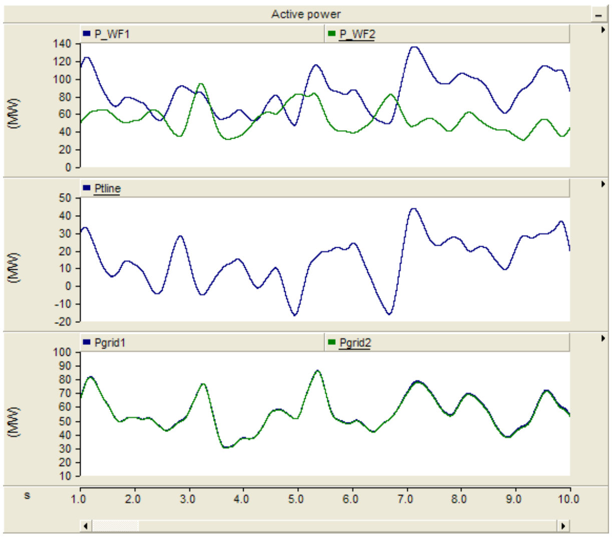

Fig. 7. Active power of offshore wind farms, tie-cable, and onshore grids

B. GSVSC master-slave control

The power generation from two wind farm is still variable due to wind fluctuation. It can be learned from Fig. 8 that GSVSC1 controlling the DC voltage will act as a slack node, which means it will provide or absorb sufficient active power to achieve a power balance of the DC system. Therefore, this converter will suffer large power fluctuation according to wind variation when GSVSC2 sets a constant power order of 70 MW.

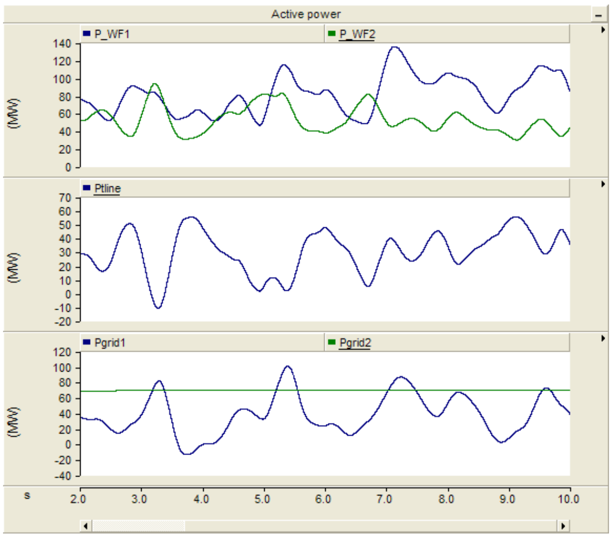

Fig. 8. Active power of offshore wind farms, tie-cable, and onshore grids

C. GSVSC master-slave control with BESS at slack node

As shown in Fig. 9, if $P_{GSVSC1}<P_{grid1}$, BESS starts to discharge to fill the power gap, and if $P_{GSVSC1}>P_{grid1}$, BESS starts to charge itself to absorb the excess power. Therefore, the active power transferred to onshore grid 1 can also be regulated nearly to the set value, 50 MW.

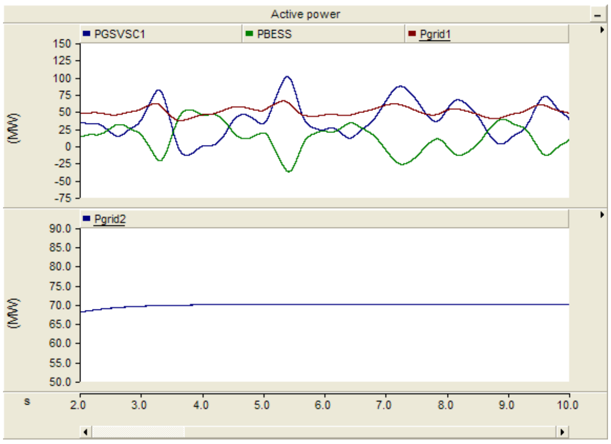

Fig. 9. Active power of GSVSC1, BESS and onshore grids

Some discussions of the simulation results are summarized as follows:

- With identical DC voltage droop control, GSVSC can share the active power exported to the grid equally with the variation of wind power generation. When wind power generation is different at two wind farms, excessive power will transmit through the tie-cable between the wind farms to balance the GSVSC power output. Because of power sharing, the fluctuation extent of power transferred is less than master-slave control.
- Integration of BESS can smooth the fluctuant power output from GSVSC within BESS capacity. This method can improve the power quality to meet the grid code especially for weak grid.

Conclusion

Voltage source converter based multi-terminal HVDC transmission system technology is proposed for network interconnection and integrating large offshore wind farms over long distance. One of potential application would be for a North Sea Super Grid, a network of DC transmission across North Sea.

Parameters of VSC-HVDC main components are designed according to HVDC operation principle and their values from engineering experience are also introduced. Taking a four-terminal MTDC network as the simplified study system, main components are configured according to the design theory and experienced value. Two kinds of power delivery control, coordinated DC voltage droop control and master slave control are investigated and their advantages and disadvantages are presented. Especially, BESS is suggested to integrate at the slack node for master-slave control, in order to smooth the fluctuant power transferred to the onshore AC grid. Three dynamic simulation cases related to wind power fluctuation are implemented based on PSCAD/EMTDC and the results show the control effect is satisfactory under transient conditions.

The research work is sponsored by China Doctoral Program Fund 20100073110019 and State Key Laboratory of Ocean Engineering Program Fund GKZD010053-20.

REFERENCES

[1] Xu L., Andersen B. R., A. Grid connection of large offshore wind farms using HVDC, Wind Energy, 9 (2006), 371-382

[2] ABB, Grid connection of offshore wind farms-BorWin1, 2009, On Line Available: www.abb.com/hvdc

[3] Rudion K., Orths A., Eriksen P. B., et al, Toward a Benchmark test system for the offshore grid in the North Sea, Power and Energy Society General Meeting, Minneapolis, USA, 2010

[4] Hertem D. V., Ghandhari M., Multi-terminal VSC HVDC for the European supergrid obstacles, Renewable and Sustainable Energy Reviews, 14 (2010), No. 9, 3156-3163

[5] Vrana T. K., Torres-Olguin R. E., Liu B., et al, The North Sea Super Grid - A technical perspective, International Conference on AC and DC Power Transmission, London, UK, 2010

[6] Flourentzou N., Agelidis V. G., Demetriades G. D., VSC-Based HVDC power transmission systems: an overview, IEEE Transactions on Power Electrionics, 24 (2009), No. 3, 592-602

[7] Tang G., Voltage Source Converter Based High Voltage Direct Current Transmission Technology, Book, Beijing, 2010

[8] Du C., The control of VSC-HVDC and its use for large industrial power systems, Literature Thesis, Chalmers University, 2003

[9] Zhang C., Zhang X., PWM Rectifier and Its Control, Book, Beijing, 2002

[10] Haileselassie T. M., Control of multi-terminal VSC-HVDC systems, Master Thesis, Norwegian University of Science and Technology, 2008

[11] IEEE recommended practices and requirements for harmonic control and electrical power systems, Standard, IEEE 519, New York, 1993

[12] Yao L., Xu L., Bazargan M., Critchley R., Multi-terminal HVDC grid for network interconnection and renewable energy integration, CIGRE 2010, Paris, French, 2010

[13] Gomis-Bellmunt O., Liang J., Ekanayake J., et al, Topologies of multiterminal HVDC-VSC transmission for large offshore wind farms, Electric Power Systems Research, 81 (2011), No. 2, 271-281

***Authors**: Dr. Gang Shi, Wind Power Research Center & State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Shanghai, China, E-mail: renzhegang@gmail.com*