International Journal of Smart Grid and Clean Energy

Control system for offshore wind power generation system with DFIG and VSC-based HVDC transmission

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Abstract

This paper proposes a fundamental and efficient control technique for introducing VSC (voltage source converter)-based HVDC (high voltage direct current) transmission into a large-scale offshore wind power generation system with DFIGs (doubly-fed induction generators). The electric power from the offshore wind turbine DFIG is considerably fluctuating and unstable, and needs to be transmitted from offshore to the on-land major AC system generally accompanied with long distance cable transmission. From these points of view, VSC-based HVDC transmission is considered to be an efficient choice. In this paper, control systems for the AC/DC converter at the offshore side and the DC/AC inverter at the land side are proposed and presented in details. These controls aim at mitigating the impact of wind power fluctuation on the on-land AC system, while securing the stable operation of the HVDC circuit. Furthermore, by proper control applied to the converter, voltage and frequency of the offshore AC system at the wind power plant side is stabilized so as to facilitate the stable operation of DFIGs, which is modeled by a self-excitation type with HVDC link circuit in this study. Digital simulation studies were conducted and the results have verified the effectiveness of the proposed systems.

Keywords: Offshore wind power, DFIG, VSC HVDC, self-commutated converter, voltage control, reactive power control, frequency control

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1. Introduction

In the last decades, driven by the increasing concern of the issue s of global environment and limited fossil resources supply, introduction of renewable energies including wind power is extended and attracts great attentions. Among these renewable power generations, wind power has the advantage of large unit-capacity and easy to develop large-scale generating stations that may lead to a relatively lower generation cost over the other ones, and is therefore thought as the most promising alternative renewable energy in the future [1]. However, on-land wind power has some problems including low energy density, low rate of operation and with limitation of natural environments such as the topography of land. In some areas, like Japan, few suitable sites are still available for building large wind farms, and the introduction of offshore wind power is especially expected for the purpose of renewable power expansion [2].

Compared with the land wind, offshore wind power generation has advantages in wind condition, unit capacity, scale of installation, rate of operation and environmental impacts, etc. Offshore wind power generating stations can be constructed to an extremely large scale with hundreds of wind generators of 5 MW classes that are distributed over a wide remote offshore area. And it has been confirmed that the offshore wind is more stable and strong than land wind, because there are few natural obstacles such as mountains and few restriction/impact of land conditions. This also results in a better rate of generator operation (ability for long time and continuous operation due to less time of weak wind) [3]-[5]. For these reasons, it can be expected that the introduction of large-scale offshore wind power generation will increase and be effectively used as an important energy source in the future. And of cause, the technical problems related to the utilization of offshore wind power need to be well established.

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* Manuscript received June 8, 2013; revised July 29, 2013.

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As the technical problems of wind power utilization, the main challenge is associated with the unpredictability and fluctuation of wind power output, which fluctuates considerably in proportional to the cube of the wind velocity. In addition, if the wind power penetrates into a relatively weak power grid directly, it may cause serious stability problems with the frequency and voltage in the main power system. Therefore, the wind farms are usually required by the main power system side to strictly stratify the Technical Guideline of Grid Interconnection, and the voltage fluctuation at the point where the wind farm interconnects into the power grid needs to be properly suppressed by measures taken in the wind farm side. In addition, development of the power electronic technology has advanced remarkably in the last decades. And as a result, these above mentioned technical needs have facilitated the application of HVDC (high voltage direct current) transmission on offshore wind power generation systems, which provide a good solution for transferring offshore wind power to the on-land power grid, and many projects have been planned or under construction [3], [4], [6]. In the application of HVDC technology to the wind power, HVDC system using self-commuted type converter is considered suitable for offshore wind power transmission, because self-commuted HVDC has been demonstrated to be slightly affected by the capacitive current from the submarine cable and with small transmission losses, and it is easy to apply the independent control of active power and reactive power simultaneously so as to enhance the stabilities for both the offshore wind system and the on-land power grid side, and furthermore, offshore wind generators can be isolated and protected from the faults occurred in the power grid side. For these reasons, VSC (voltage source converter) based self-commuted HVDC systems are thought as a suitable way for the offshore wind power transmission [7]-[10].

In addition, most of the present wind turbine generators are induction ones, because this type of generator is simple and low cost. However, it has also obvious shortages such as lack of operation stability, e.g. FRT (fault ride-through) problem as well as violent fluctuation of power output [9]. For this reason, DFIG (doubly-fed induction generator) is increasingly adopted in the recent wind farms [10].

In this paper, we have studied the control problem for a self-commutated HVDC connected to a large-scale wind farm with DFIGs. The main contribution of this work is that the proposed control system has taking into consideration of the voltage and frequency stability at the offshore wind farm side, while maintaining the voltage stability of both the HVDC system and the on-land AC terminal bus. Digital simulation studies have been conducted by use of Matlab/Simulink and the simulation results have illustrated the validity of the proposed system.

This paper is constituted as follows. In Section 2, an outline of the system configuration of an offshore wind farm constructed in this work is presented. In Section 3, the details of the VSC-based HVDC system and DFIG generation system are addressed. The proposed control system for HVDC transmission is described in Section 4 and flowed by the simulation results for verifying the basic operation of the whole system and the effectiveness of the designed control system in the next section. The conclusions are summarized in the last.

2. Overview of Offshore Wind Power Generation System

The structure of the offshore wind farm system model designed in this study is shown in Fig. 1. It has a typical structure with dozens of wind turbine generators divided into different groups connecting to a voltage source based HVDC transmission system. These generators may be the types of IG (induction generator), DFIG (double-feed induction generator) or SG (synchronous generator), and the DFIG type one is preferred for offshore wind power generation use in terms of stable operation.

In this configuration, DC transmission system consists of converter stations and AC filters at both offshore and on-land sides interconnected by a DC transmission circuit. The converter station at the offshore side includes a conversion transformer and an AC/DC converter, and the inverter station at the on-land side includes a conversion transformer and DC/AC inverter. The DC transmission circuit consists of DC filters at both sides and submarine DC cable for transferring wind power from the converter side to the inverter side. Both of the switching devices for the converter and inverter are using IGBTs modulated by PWM control. Since extremely high switching frequency can be adopted for IGBT to implement PWM control, harmonics problem can be therefore effectively mitigated.

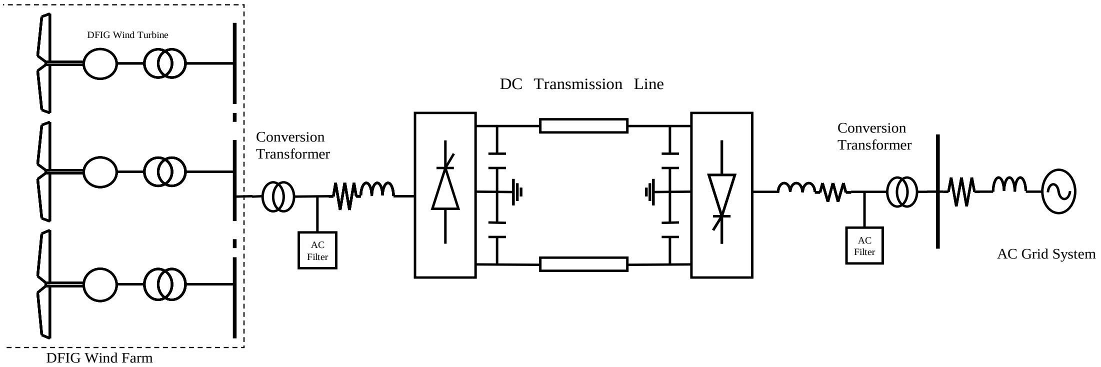

Fig. 1. Offshore wind farm and HVDC transmission system.

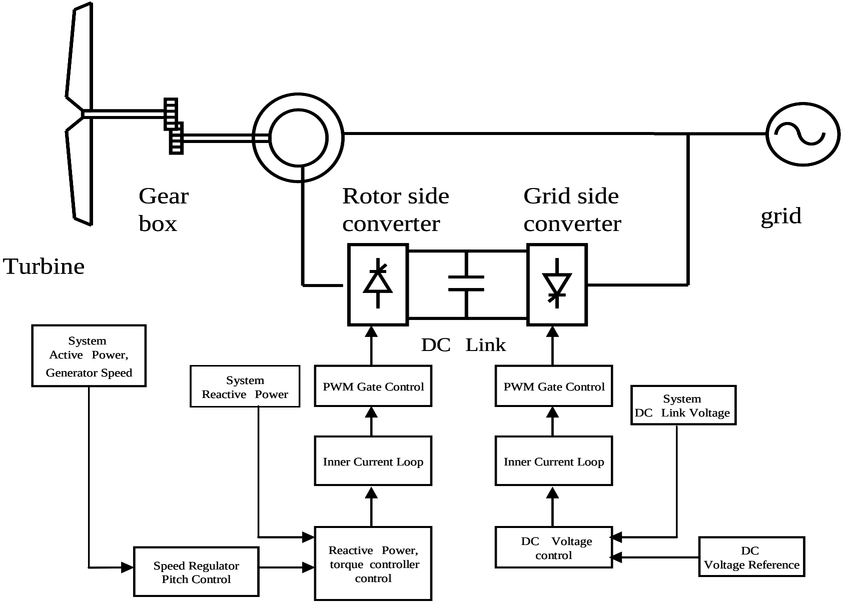

Fig. 2. DFIG model.

3. VSC-Based HVDC System and DFIG Model

In Fig. 1, the VSC-based converter and inverter are using the same structure with typical neutral-point clamp type 3-level bridge, which can be found in many books on Power Electronic Engineering. The 3-level bridge circuit in this model consists of three arms with 4 power switching devices in series added by neutral clamp diodes. In order to obtain 3-level phase voltage, these four switching devices are further divided into 2 switching element groups and are triggered in a proper timing for each phase. And the neutral point voltages at the middle point of three arms form the three-phase AC voltages.

In order to obtain the necessary DC voltage for connecting to AC systems, transformers are introduced at both sides with appropriately selected capacity and transformation ratio. DC transmission line is simulated by use of a π type equivalent circuit. Parameters and models of the VSC-based converter, transformers and DC line are using the standard ones prepared by the simulation tool of Matlab/Simulink.

The DFIG model used in this study is shown in Fig. 2. Turbine and drive train parameters are using that given in [11]. From Fig. 2, it is known that the grid side converter is performed by DC voltage control so as to keep constant DC link voltage. In this work, the converter is assumed to operate with constant power-factor and the current in q axis is set to zero. Then the generally so-called "decoupling control" is applied to the d and q axis inner current loop to obtain the reference voltage value for PWM control of this converter. On the other hand, the rotor side converter is used to control the rotor speed and the reactive power. In this study, the rotor speed is controlled to trace a beforehand defined velocity characteristic for obtaining maximum power output. Similarly, the decoupling current control is applied to this converter as well for PWM voltage control.

4. Control System for HVDC Transmission

Herein, control systems that apply to the self-commutated HVDC system are described. The purposes of these controls aim at transferring power from offshore to on-land side stably and with less impact of wind power fluctuation on the on-land AC system, as well as securing the continuous operation even in case with system contingencies. And in the meantime, HVDC transmission circuit can work as a stable source of voltage and frequency in the AC system at the offshore side.

4.1. Control system for DC/AC inverter

Wind power that is transmitted by HVDC line penetrates into the on-land AC power grid through a DC/AC inverter. Control system designed in this work for this inverter is shown in Fig. 3, which consists of the following two basic blocks:

- DC voltage control

DC voltage of HVDC transmission system is changing at all time due to the wind power fluctuations that is flowing into the DC circuit through the converter at the offshore side. This control keeps and stabilizes the DC voltage for the exact operation of those VSC-based equipments, and the wind power is reasonably transmitted to the on-land AC system under this control.

- Reactive power control

This control system is used for supporting the voltage stability in the on-land AC system. The reactive power reference can be calculated based on an AC voltage stabilization control or a constant power factor control. In this simulation study, the reactive power reference is assumed as constant in spite of the variation in active power.

In Fig. 3, after the current references of d and q axis are obtained by these basic control blocks, the conventional decoupling current control in d and q axis is applied to calculate the voltage references of d and q axis, and then three-phase voltage reference values is obtained for VSC-based PWM control.

In these control systems, a transformation between three-phase and dq axis is required. For doing this, the phase angle of AC voltage is necessary. In this study, the phase angle of AC voltage at the bus after the conversion transformer in Fig. 1 is measured by use of a PLL phase detector.

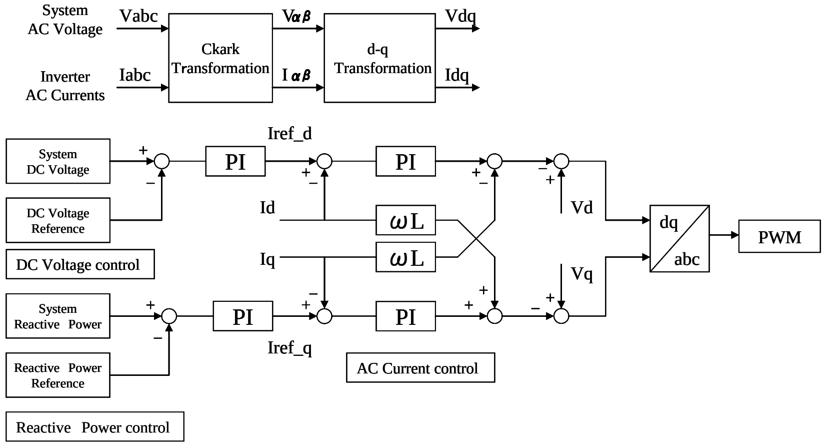

Fig. 3. Control blocks for sending side inverter.

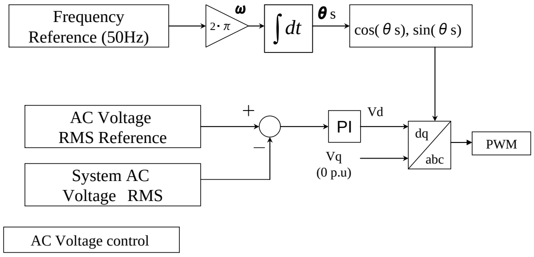

Fig. 4. Control blocks for AC/DC converter.

4.2. Control system for AC/DC converter

The AC power generated by offshore wind turbine generators should be properly converted into DC power through the converter at the offshore side. In this study, the control of converter is designed to actuate as a stable frequency and voltage source for the offshore AC system that includes many wind generators. This is desirable because both the frequency and voltage of DFIG wind turbine generators are considerably fluctuating and none of them can be used as the stable source in this AC system. Control block for the converter is composed of an AC voltage control with constant frequency as shown in Fig. 4.

In this system, the error between the measured AC voltage and its reference at the converter side is calculated, and then through a PI control, the d axis voltage reference is obtained. The q axis voltage reference is set to zero. In order to compute the three-phase voltage reference for PWM control, an inverse dq transformation (dq to three-phase) has to be performed and the phase angle for AC voltage is necessary for this transformation. Herein, this phase angle is calculated based on a nominal frequency that is determined for the offshore AC system, and in this study, it is assumed to be 50 Hz. According to this control strategy, the converter is operating with constant voltage and frequency in the offshore AC system, and can be treated as a slack-bus of this AC system. Therefore, it is known that although there is no power control applied to the converter, the power generated by wind turbine generators can be adequately sent to the DC side.

5. Simulation Studies

In this study, the simulation is conducted by use of Matlab/Simulink. Offshore wind power system model is created based on that in Fig. 1 and is shown in Fig. 5. For simplification, 20units of 10 MW class offshore wind turbine generator are equivalently simulated by a single DFIG generator with a capacity of 200 MW. Basic specifications of the VSC-based HVDC system is tabulated in Table 1.

The purpose of this simulation study is to verify the following matters:

A) Whether the voltage and frequency of AC system at the offshore side can be effectively controlled by the converter while DFIG is driven by significantly fluctuating offshore wind.

B) Whether the DC voltage of HVDC transmission system can be effectively stabilized by the control of the inverter in case of both normal operation and contingency.

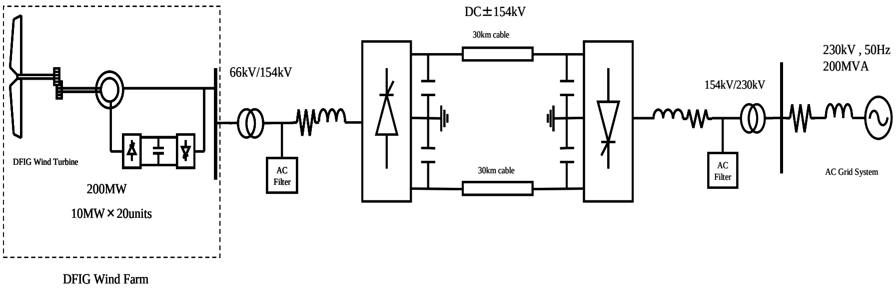

Fig. 5. Wind power system model.

Table 1. Specifications and parameters of VSC-based HVDC system

Transformer Capacity	200 MVA	Rated DC Voltage	±154 kV
AC Frequency	50 Hz	Transmission line	30 km
Transformation Ratio of Converter Transformer	66/154 kV	PWM Pulse	2 kHz
Transformation Ratio of Inverter Transformer	154/230 kV	Switching Device	IGBT

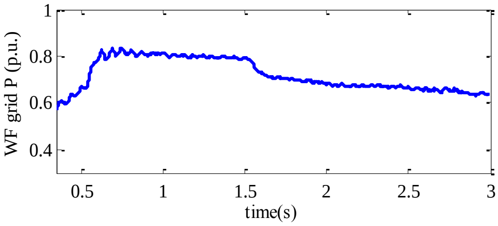

Fig. 6. Active power of DFIG generator.

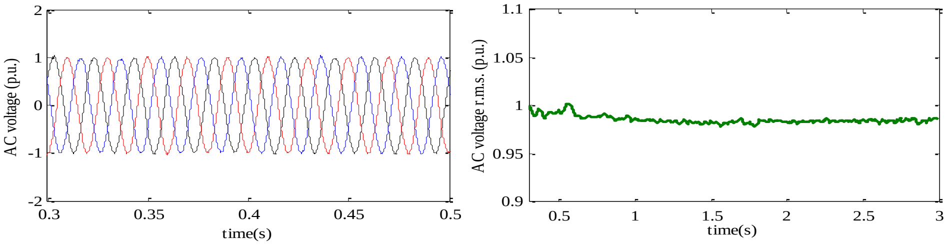

Fig. 7. AC Voltage of offshore wind farm side.

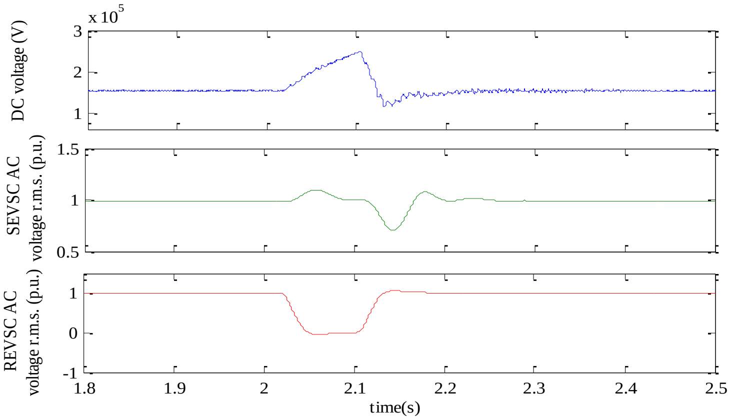

Fig. 8. Waveforms of DC voltage, AC voltages (r.m.s) at offshore farm and on-land AC grid sides.

For this purpose, offshore wind velocity is set to 11 m/s during the time of 0-0.5 sec., 15 m/s during the time of 0.5-1.5 sec. and 12 m/s during the time of 1.5-3.0 sec. As the simulation results, the active power generated by the DFIG is given in Fig. 6, and the three-phase voltage waveform and its r.m.s value are shown in Fig. 7, respectively. From Fig. 6, it is known that the DFIG is stably operating excited by its HVDC link feed circuit and control systems, and its power output is changed responding to the offshore wind velocity. And Fig. 7 indicates that stable AC voltage (r.m.s) can be obtained as the result of the AC voltage control with the DC/AC converter even if the wind power is significantly fluctuating. In addition, it turns out that the AC system at the offshore side is keeping continuous operation with the designed frequency of 50 Hz.

Furthermore, a three-phase ground fault lasting 80 ms is supposed to occur in the on-land AC system side. In this case, the waveforms of DC voltage, r.m.s of both the AC voltage at the offshore farm side and the on-land AC grid side are shown in Fig 8. From Fig. 8, it is seen that in the time without disturbance, both the DC voltage and the AC voltage are effectively kept to be stable and constant tracing their reference values, even though the offshore wind is considerably fluctuating. On the other hand, during the time of fault, the voltage of on-land AC grid decreases temporarily due to the accident, and hence the power that can be transmitted from HVDC system to the on-land AC grid reduces simultaneously, therefore, the DC voltage and the AC voltage at offshore side are observed to increase during this time. However, after the contingency, this transient process is confirmed to be promptly stabilized by the DC voltage control of inverter and the AC voltage control of converter.

6. Conclusions

This paper has presented the control systems for a VSC–based HVDC transmission for large-scale offshore wind power generation system with DFIGs. Under these coordinate controls applied to both the converter at the offshore side and the inverter at the on-land side, wind power can be stably transmitted to the on-land AC power grid with less negative impacts, while stable and continuous operation of HVDC system can be secured as well. Meanwhile, the HVDC transmission circuit can stabilize the voltage and frequency in the AC system at the offshore side as well, which is deteriorated by the fluctuation of wind power.

In addition, detailed models of VSC-based HVDC transmission circuit and DFIG are completed based on power electronic technologies and introduced into a typical offshore wind power system. Digital simulations in case with fluctuating offshore wind and on-land AC system contingency are conducted in this study. The simulation results have illustrated the validity of this proposed system.

As the future works, the control systems will be further improved and the case with multi DFIG wind turbine generators will be investigated.

Acknowledgments

We would like to thank IEEJ (Institute of Electrical Engineers of Japan) for providing the IEEJ International Conference Travel Grant that made it possible to attend this conference.

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