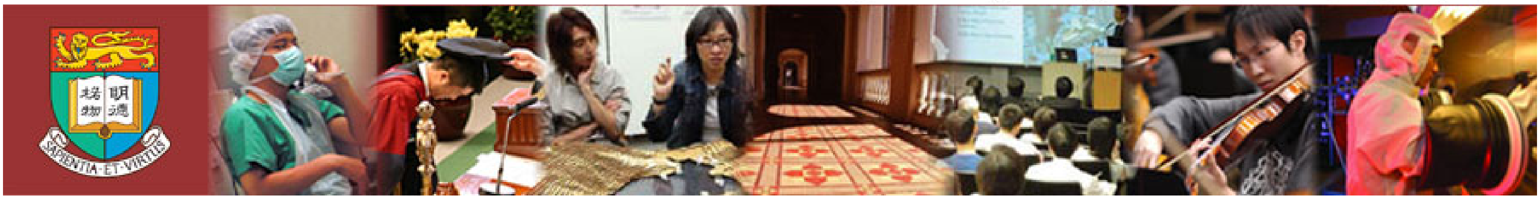

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Fault Characteristics Analysis of Two HVDC Technologies for Wind Power Integration

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***Abstract*—This paper analyzes the operation and control principle of the two transmission technologies, i.e. Line-Commutated Converter-HVDC (LCC-HVDC) and Voltage Source Converter-HVDC (VSC-HVDC) for wind farm integration. It explores the fault ride-through (FRT) capability of the two HVDC under fault conditions according to the characteristics of the two kinds of converters. To ensure satisfactory ride through grid faults, the current limit controller is initiated to reduce the active power injected into the HVDC during the fault. The approach adopted may avoid the overcurrent or overvoltage in the converter and the tripping of the wind turbines, as well as facilitate the fast recovery. Comparative simulation results verified that LCC-HVDC and VSC-HVDC could prevent the fault propagation and ensure the wind farm operation continuously in the event of severe grid fault.**

***Index Terms*-- Wind power integration; Voltage Source Converter; Line-Commutated Converter; grid fault.**

I. INTRODUCTION

In recent years, the wind power development is accelerating significantly all over the world. The wind power transmission is a tough problem for the sake of both technical and regulatory reasons [1]. If the wind power transmission capability can't catch up with the construction of the wind farms, it will be bound to jeopardize the achievement of wind power development goal and increase the cost of the renewable resource integration [2].

Meanwhile, the expanded scale of the wind farms, will cause a serious impact on the stability and reliability of the power system. For example, in 2011, owing to the lack of fault ride-through capability of the wind turbine, several serious incidents concerned with the wind turbine disconnection occurred in China [3]. New technologies need to be developed and continuously improved toward the wind turbine and wind power transmission, to accommodate large-capacity wind power increase.

AC transmission of small-scale wind farm is economical for short distances and small scale wind farms integration [4][5]. However, ac transmission becomes less feasible over about 200 MW and 50-100 km for the sake of larger charging current and losses related to the longer distance. From the present operational experience, ac voltage fluctuation is the main reason for the wind turbine tripping.

HVDC offers a number of advantages for large-scale and long-distance wind power transmission. The present HVDC technologies, the thyristor based line-commutated current-source converters (LCC) and the gate turn-off bipolar transistors (IGBTs) based voltage source converter VSC, have been considered for wind farm integration.

LCC-HVDC transmission technology has been operating with high reliability and little maintenance for nearly 40 year. LCC has the natural ability to withstand short circuits due to the dc inductor can limit the current under the fault condition [6]. It's suitable for bulk power and high voltage transmission in spite of the reactive power compensation and control problem. This technology is highly susceptible to ac grid disturbances and tends to result in converter commutation failures, which can temporarily shut down the complete HVDC system [7].

VSC-HVDC possesses lots of advantages and is desirable for wind farm integration with the scale below 500MW due to the capacity limit of VSC [8]. The power electronic converters have no over-loading capabilities during faults and the dc voltage tends to be out of control which might lead to the HVDC tripping [9].

Most grid codes impose fault ride-through (FRT) requirements on wind farms [10]. It specifies that wind farm should be able to remain connected to the grid during a temporary voltage dip caused by a fault in the grid [11]. By utilizing HVDC as a firewall against faults, HVDC interconnection could prevent the fault propagation and thus stop cascade through the grid.

The paper is organized as follows. Section II and section

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III present the operation and control of LCC-HVDC and VSC-HVDC for wind farm integration, respectively, and the modified controllers are implemented. Section IV validates and evaluates the FRT capability of two technologies through simulation in PSCAD/EMTDC.

II. LCC-HVDC TECHNOLOGY

LCC-HVDC is considered as a suitable solution for grid-integration of the large-capacity (above 500MW) and long-distance (more than 100km) wind farm. However, to ensure the successful commutation of the thyristor based converter, the grid connected to the converter is required to be strong. In the case of weak grid or no synchronous generator existing, the integration configuration of LCC-HVDC with STATCOM is proposed [12]. STATCOM is responsible for controlling the ac-grid voltage and frequency to guarantee the proper operation of the converter.

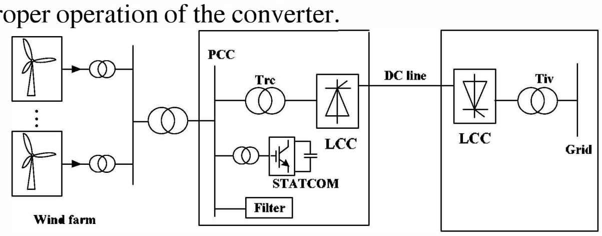

Fig.1 Configuration of wind farm integration using LCC-HVD with STATCOM

A thyristor based LCC-HVDC transmission system is shown in Fig.1. It consists of the wind farm, converter transformers, filters, DC line and the rectifier/inverter converters. The auxiliary device STATCOM is required to provide the necessary commutation voltage to the converter as well as the reactive power compensation during the transient conditions.

The LCC-HVDC control is eventually achieved by regulating the firing angle on both rectifier and inverter sides. With different control strategies, the operating performance of dc system and ac system can be improved significantly. For a most popular used monopole HVDC system, it consists of two six-pulse converters, which could be equivalent as a dc voltage source during analysis. The dc voltage on the rectifier side could be expressed as:

$$U_{dZ} = (6\sqrt{2}/\pi)E_Z\cos\alpha - (6/\pi)X_{\gamma Z}I_d \qquad (1)$$

where α denotes the firing delay angle; E_Z is the ac line voltage RMS of the converter with no-load; $X_{\gamma Z}$ is the equivalent commutation reactor of the rectifier. The reactor value is multiplied by 6/π, deemed as the internal impedance of the voltage source.

Equation (1) indicates that the dc voltage could be adjusted by altering the firing angle and the ac voltage.

STATCOM provides the commutation voltage and the reactive power compensation to the converter. It's aiming to keep the bus voltage and frequency constant. Hence, the control objective for the STATCOM is to obtain the desired ac bus voltage U_G by means of controlling the STATCOM ac voltage U_s. The double closed-loop control is adopted and is shown in Fig.2.

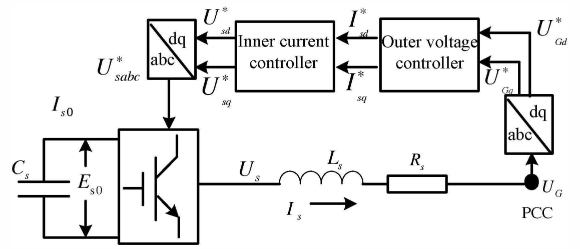

Fig.2 Configuration for STATCOM controller

The rectifier is responsible for transmitting all the active power produced by the wind farm and maintaining the power balance on the rectifier side. Since the power unbalance is closely related with the dc-link voltage of STATCOM, the active power flowing into the STATCOM will result in the dc-link voltage rise and the STATCOM outputting the active power causes the dc-link voltage decrease. Therefore, the active power balance could be realized by controlling the dc-link voltage of STATCOM. The linear relationship between HVDC link current I_{dc} and the square of STATCOM dc-link voltage E_{s0}^2 could be achieved as shown below [13].

$$C_s\frac{dE_{s0}^2}{dt} = 3U_{Gd}\left[\frac{2}{3}\left(\frac{6\sqrt{2}}{\pi}\cos\alpha\right)I_{dc} - I_{Gd}\right] \qquad (2)$$

where E_{s0} is the dc-link voltage; I_{dc} is the dc current of HVDC; U_{Gd} and I_{Gd} denote the d-axis component of ac voltage and current at PCC.

Under the assumption that the ac bus voltage U_{Gd} is totally controlled at the given value $U_{Gd} = U_{Gd}^*$, the dc current I_{dc} and E_{s0}^2 present the linear relationship in (2). As a result, the linear controller could be adopted for the voltage outer loop design so as to realize the power balance on the ac side of the rectifier. The inner current controller is designed to control the delay firing angle α of HVDC.

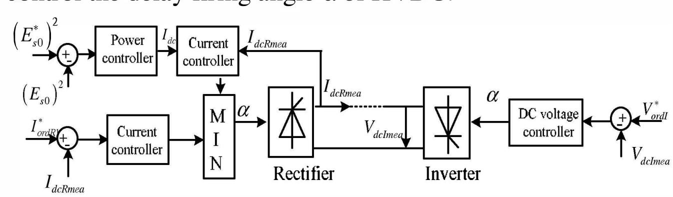

Fig.3 Control diagram for LCC-HVDC

The inverter is assigned to maintain a constant dc link voltage. The firing angle for the inverter is generated by comparing the measured value of the dc voltage with the reference value. The error goes through a proportional integral (PI) controller to produce the desirable firing angle. The control structure for the HVDC is shown in Fig.3.

During a fault on the grid, the inverter ac voltage falls sharply and the commutation failure is incurred. The dc voltage collapses and the dc power transmission is interrupted. However, the wind farm continues to produce the power. The excess power will be absorbed by the STATCOM and its dc-link voltage will rise. The dc current climbs up sharply and the firing angle α increases and tries to suppress the over current.

The increasing α results in large amount of reactive power demand, which could be reduced by decreasing the active dc current. The voltage-dependent current limitation (VDCL) is usually implemented at the controller of the rectifier to decay or raise the dc current order at a rate according to the dc voltage variation in a range during the fault. However, the extreme case, that is, the dc voltage falling to zero is not considered in VDCL [14]. The effect of VDCL is not so desirable in decreasing the reactive power demand on the wind farm side.

In Fig.3, during the fault, the rectifier controller switches to the limit current control. When the dc voltage falls below a defined limit, the current controller is activated. The setting current order is compared with the measured one to produce the firing angle to rectifier. It could realize the fast reduction of the power injected into the dc system. Therefore, the surplus of reactive power from the filters could be partly absorbed by the STATCOM and also partly compensated by the rectifier by setting the current order at a proper value.

III. VSC-HVDC TECHNOLOGY

Since VSC uses self-commutating semiconductors devices and no external voltage source is required, it significantly avoids the risk of commutation failures. VSC can control both active and reactive power independently without extra compensating equipment. When the receiving end fault occurs, VSC may provide the dynamic reactive power compensation to support the voltage sage. These features enable it well-suited for the wind farm integration [15].

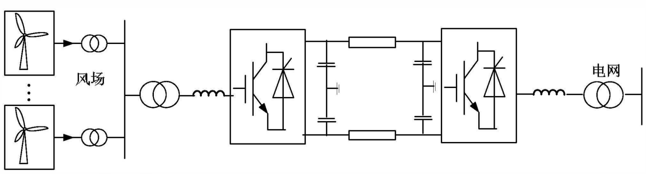

Fig.4 VSC configuration for wind farm integration

The main task for the wind farm VSC (WVSC) is to absorb all wind power that is generated by the wind farm and control the voltage and frequency of the ac grid on the wind farm side. This can be achieved by operating the converter as a voltage source with a defined amplitude and frequency. The WVSC thus serves as the voltage reference for the grid on wind farm side. Therefore, only a simple ac voltage magnitude controller is utilized.

The grid side VSC (GVSC) is assigned to maintain the dc system voltage and ensure all the dc power transmitted to the grid. When the VSC-HVDC is in the normal operation for wind power transmission, the dc voltage should be held up to a constant value. The constant dc voltage indicates the balance of active power exchange between the two converters. So the dc voltage and the constant ac voltage control are employed by GVSC.

During a fault on the grid, the power delivered by the inverter is decreased significantly. While the wind farm is continuously injecting the active power into the HVDC, this power imbalance yields to an acceleration of the wind turbine rotor and increases the damaging risk of the converter and the dc-link capacitor itself, if no caution measures are taken into account in the design of the control.

The fault ride-through (FRT) methods for wind farm integration using VSC-HVDC include the energy dissipation and the fast power reduction of the wind farm [16][17]. In the first method, a dc chopper could be employed to dissipate the excess power in a resistor during the ac voltage dip. The main advantage of this method lies in the wind farm output power will not be affected completely. However, the cost of the additional dc chopper with the large capacity is high.

The second method, reducing the wind power actively to maintain the power balance in a lower level, may be accomplished by the fast communication, the voltage reduction and the frequency modulation. The application of the frequency modulation method or the voltage reduction method requires additional control loop.

In this scheme shown in Fig.5, the dc voltage is detected constantly and is taken as the control switch indicator for a fault in the ac grid. If the dc voltage exceeds the threshold as a result of the ac system fault, the converter equipped with the constant dc voltage control will switch to the current control mode, so as to constrain the dc current. The HVDC can keep operation and transmit a lower level dc power. When the fault is cleared, the control mode will be switched back. The ac system voltage rises up and the dc power increases. The system is brought back to the normal operation. This control strategy can not only avoid the overcurrent, but also allow the dc voltage controllable. Typically, ± 50% dc voltage deviation is chosen as the threshold.

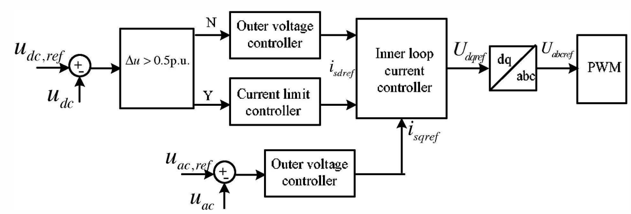

Fig.5 Voltage controller for GVSC

IV. FAULT CASE VERIFICATION

To validate the contribution of LCC-HVDC and VSC-HVDC for wind power integration in improving the dynamic behavior and low voltage ride-through capability, two HVDC systems models are developed in PSCAD/EMTDC. The wind farm is represented by DFIG-based aggregate model.

Case1—fault on the ac side of LCC inverter

The LCC-HVDC is composed of two 12-pluse converters in monopole configuration with the rated 500kV voltage and 1000MW power. The detailed parameters of the system are referred to the Benchmark model of HVDC [18]. The three-phase short-circuit fault was applied on the grid ac side at 1s and was cleared after 100ms. Fig.6 shows the dc system performance during the fault conditions. The ac voltage of the inverter drops to zero during the fault in Fig.6(a). The extinction angle γ decreases rapidly and thus the commutation failure occurs in Fig.6(b). The failure causes an abrupt reduction of the dc voltage in Fig.6(c). Fig.6(d) shows that the power transferred reduces sharply in the dc system.

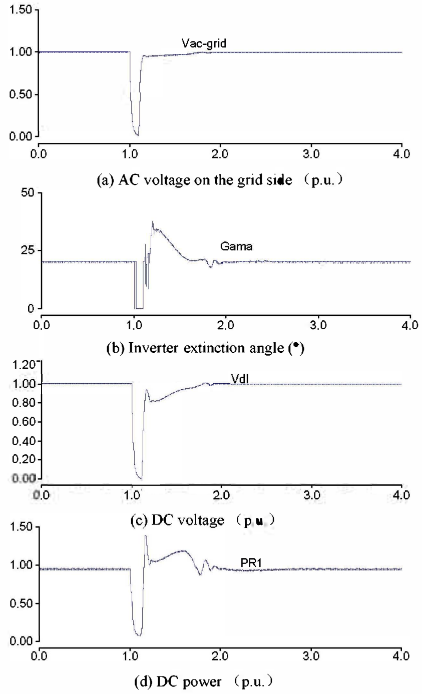

Fig. 6 Simulation results for ac grid fault in LCC-HVDC

In Fig.6(e)-(h), during the steady state, the real power is well balanced with almost all the wind power being injected into the ac gird. The STATCOM real power is kept at zero without considering the power losses. As the fault occurs, as a result of the ac voltage dip on the wind farm side, the wind farm output power goes down at the initial fault stage. STATCOM provides the dynamic reactive power support during the fault and the ac voltage of the rectifier rises gradually. The active power output of the wind farm increases tremendously. Since the wind farm output power can't be delivered by the rectifier, STATCOM absorbs the excess active power on the ac side of the rectifier and tries to balance the active power. As a consequence, the dc-link voltage of the STATCOM climbs up quickly as shown in Fig.6(g) and reaches a maximum voltage 2.8 p.u.. The dc current order reduces as expected and the wind farm power is falling. The dc-link voltage of STATCOM stops rising. The voltage on the ac side of the wind farm is controlled around ±0.1p.u. deviation as shown in Fig.6(g). For a sufficiently high current limit, the controller could be able to maintain the ac voltage at the PCC.

After the fault is cleared, the power coming from wind farm is transferred to the HVDC again and the dc voltage returns to the normal level. The inverter is recovering from the commutation failure. The dc system voltage is established again and the dc power transfer resumes. Meanwhile, the STATCOM dc-link voltage returns to the rated value.

From the simulation result, it is derived that the current limit will significantly influence the dynamics of the system during and after a fault at the grid side. The proposed control system is crucial to avoid the tripping of the wind farm.

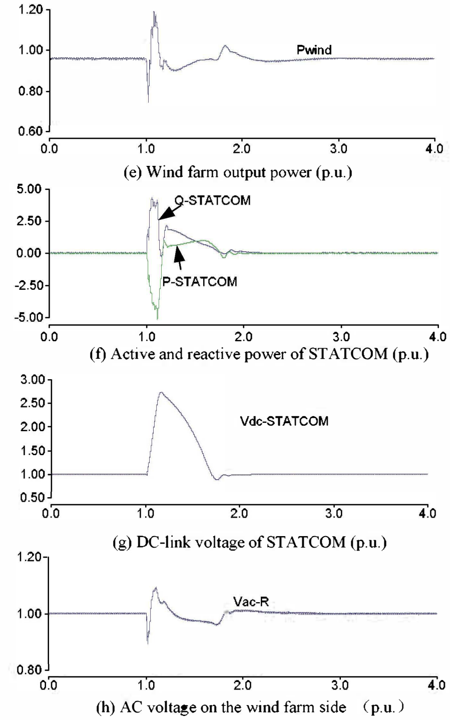

Fig. 6 Simulation results for ac grid fault in LCC-HVDC

Case2—fault on the ac side of VSC inverter

The wind farm is connected to the VSC through a step-up transformer. The wind farm capacity is 500MW and is connected to the converter through the step-up transformer. The rated dc voltage is ±150kV and the rated power 500MW for VSC-HVDC. Detailed parameters are referred to [19].

The same fault as that of LCC-HVDC was applied on the grid ac side at 1s. When the fault occurs, the active power from the wind farm remains to inject into the HVDC by WVSC. If the GVSC can't feed all the power into the grid during the grid fault, the power unbalance will charge the capacitance and the dc over voltage will occur to destroy the converter.

In Fig.7(a), the ac voltage on the grid side declines to 0. The active power can't be fed into the grid, resulting in the voltage across the parallel capacitor of VSC rising as Fig.7(b) depicted. The dc voltage exceeds the setting threshold 0.5p.u. and reaches 1.6p.u. due to the delay. The current limit controller is activated and the voltage will be reduced sharply so as to ensure a sufficient power decrease. In Fig.7 (c) and (d), the wind farm output power decreases and the dc power transfer drops. The reducing output power of the wind farm is the most effective method to alleviate the fault influence.

The active power injected by the rectifier is reduced and a lower dc power transmission could be maintained. However, the rectifier employs the constant ac voltage control, which is sensitive to the voltage fluctuation. Without the current limiting measure, the reactive power will vary significantly, resulting in very high over-voltage. This method can successfully maintain the dc voltage below 1.6p.u..

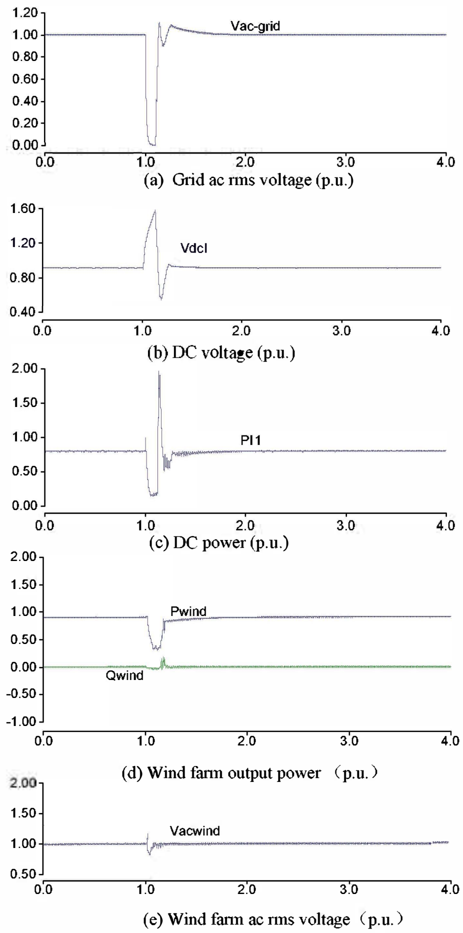

Fig. 7 Simulation results for ac grid fault in VSC-HVDC

After the fault clearance, the ac voltage returns to the original value and the dc power transmission is restored quickly. The wind power delivered by VSC-HVDC could be restored quickly.

For large-scale wind farm with capacity above 1000MW, the LCC-HVDC technology is preferred. However, the large size as well as the requirement on the ac system connected restricts its application for offshore wind farm integration. Besides, to ensure the normal operation of the converter, large amount of reactive power compensation devices are installed. Despite the LCC-HVDC may isolate the wind farm from the grid disturbance, the ac voltage dip on the grid side tends to cause the commutation failure and the dc power transmission temporarily interrupts.

Since VSC-HVDC decouples the wind farm and the grid, the disturbance on the wind farm imposed by the grid side fault could be mitigated. The independent active power and reactive power control of VSC-HVDC plays an important role in the wind farm recovery. The reactive power needed by the wind turbine during recovery could be provided by VSC and thus the bus voltage at PCC returns to normal in a short time. As a result, the active power from the wind farm could be outputted successfully. The rotor speed increase of the wind turbine could be constrained.

CONCLUSION

The fault analysis on the two HVDC technologies is performed in this paper. Comparative simulation results show that when implementing the proposed current limit control, satisfactory ride through grid faults are achieved, avoiding the overcurrent and the tripping of the wind farm and attributing to the recovery of the power system.

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