Implementing Fault Ride-through Support for an Offshore Wind Farm Fed VSC-HVDC System

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Abstract— Developing large Offshore Wind Farms (OWFs) represent an efficient and reliable power generation. To improve the efficiency of such OWFs, Voltage Source Converter based High Voltage DC transmission (VSC based HVDC) system is used. However, the VSC-based HVDC transmission systems are subjected to DC faults frequently, and dc circuit breakers of higher rating are required to provide protection against such faults. Hence the Offshore Wind farms integrated by VSC-HVDC are expected to have fault ride-through (FRT) capability during such DC fault conditions. This research work proposes a VSC based HVDC system provided with a Fault Tolerant Breaker (FTB), in between the DC line in order to limit the DC fault current. This provides an efficient and reliable power transfer in the system without disturbing the power supply during any such DC fault conditions. The simulations are performed through MATLAB/Simulink software and results were obtained.

Key words: Offshore Wind Farm, Voltage Source Converter based High Voltage DC Transmission, Fault Ride-through, DC fault

I. INTRODUCTION

The installation of large offshore wind farms is picking up attraction in many parts of the world recently. The generation capacities of a large offshore wind farms will be in range of dozens of megawatts to even hundreds of megawatts, as like the generation of conventional power plants. With the expanding coordination of huge offshore wind farms with AC power grids, it definitely prompts the retirement of conventional power plants. In this manner, to keep up the stability of power systems with high wind penetration, these wind farms are required to work like conventional power plants [1]¹¹. When an OWF is connected to main grid through VSC-based HVDC, the HVDC voltage is controlled by the onshore HVDC converter which transfers the power to the onshore ac network. When a fault occurs at the ac grid, the onshore converter is unable to transmit all the active power to the ac grid, but OWF still inject active power to offshore converter, which will result in power imbalance between onshore converter and offshore converter. The resulting power imbalance will charge the capacitance in the dc-link. Therefore some strategies should be taken to regulate the power imbalance.

As the capacity of modern OWFs is approaching that of the conventional generation and the number of OWFs integrated to the grid is growing, the influence of the OWFs power on the grid operation has become significant. An abrupt disconnection of a OWF delivering a large amount of power may significantly disturb the power balance in the grid. To minimize the occurrence of such an event, most grid codes impose Fault Ride through (FRT) requirements in which the OWFs have to remain connected during a temporary voltage dip caused by a fault in the grid.

VSC based HVDC transmission moreover has different other advantages, such as, completely controlled power flow, independent controlling of active and reactive power, and independent control of reactive power at each AC end. On one hand, WFs would not be directly influenced by onshore grid system disturbances because of the decoupling of VSC-HVDC. On one hand, this decoupling would keep OWFs from immediate reacting to system disturbances of the onshore AC power grid system. For a disturbance in system frequency, it is apparent that WFs cannot give immediate response following the frequency transient because of communication delay [2]. VSC-HVDC, which performs good on support of voltage. The interaction of VSC-HVDC-connected WFs in the system frequency regulation is examined. Be that as it may, every one of these studies focused just on creating artificial coupling strategies between offshore and onshore systems utilizing the VSC-HVDC join, yet did not test into the voltage frequency deviation response of VSC-HVDC itself [11].

II. FAULT RIDE THROUGH

When an OWF is connected to main grid through VSC-based HVDC, the HVDC voltage is controlled by the onshore HVDC converter which transfers the power to the onshore ac network. When a fault occurs at the ac grid, the onshore converter is unable to transmit all the active power to the ac grid, but OWF still inject active power to offshore converter, which will result in power imbalance between onshore converter and offshore converter. The resulting power imbalance will charge the capacitance in the dc-link.

This chapter mainly refers to different fault ride through (FRT) strategies as shown in following [4]:
- Chopper resistor for FRT.
- Wind turbine power set point adjustment for FRT.
- Wind turbine active current control for FRT.
- Offshore voltage reduction for FRT.
- Enhanced FRT method.

A. General Methodology for Fault Ride Through:

In general, direct control and vector control are the most widely used methods for VSC-HVDC. In direct control, the instantaneous active power and reactive power is controlled directly by controlling the phase angle and amplitude of the converter output voltage. On the other hand, vector control utilizes the converter as a controllable current source, where the injected current vector follows a reference current vector. Vector control has many advantages over direct control, e.g. decoupled control of active power and reactive power, better power quality. The basic types of control techniques for a VSC are [5]:
– Direct Control.
– Vector Control.

The VSC-HVDC system consists of a rectifier station and an inverter station. The general control techniques used for these converter stations are as follows:

The rectifier station is controlled using Constant Current (CC) technique and the inverter station is controlled using Constant Extinction Angle (CEA) control technique.

B. Constant Current Technique:

The CC technique constantly monitors the current stress level of the power electronic switches present in the rectifier station. As in case of any DC side faults, the current stress in the switches of rectifier station tends to increase, depending on the intensity of fault occurred. As the current through the switches increase beyond a threshold value, the CC control unit issues a signal. This in turn initiates a trip off signal to the PWM controller firing the power electronic switches.

The PWM controller in turn stops the firing pulses for the converter unit. Thus the rectifier unit is turned off and the power transfer to the remaining part of the VSC-HVDC system is disturbed. Thus the reliability of the system is lost.

In order to maintain a continuous power supply even in the presence of a fault in the system, the control technique must be modified such that, the rectifier station is not turned off even in the presence of a fault. Which in turn increases the cost of designing a sophisticated control technique. Hence a cost effective control technique is proposed as discussed as follows.

III. FAULT RIDE THROUGH USING FAULT TOLERANT BREAKER

A. Fault Tolerant Breaker:

Many components of a modern micro grid operate using a dc interface including solar panels, fuel cells, and battery energy storage. For this reason, a dc micro grid has been suggested and utilized in some power systems. This paper starts with consideration of the dc micro grid with protection placed on each component. With the absence of a zero-crossing in the current waveform, the dc breaker faces a unique challenge in that there is no natural method of extinguishing an arc that occurs during breaker operation. This is handled in practice by using over-sized ac breakers or using a solid-state breaker. A recently introduced z-source breaker is a unique form of the solid-state breaker that automatically responds to system faults. It has the ability to clear the fault within microseconds. Furthermore, the source will not experience the fault current.

B. Operation of Fault Tolerant Breaker:

This work begins with the introduction of a novel dc circuit breaker which is shown in Fig 1. Therein, the fault tolerant breaker consists of an SCR, a crossed L-C connection, diodes, and resistors. The system load is represented by the RC circuit consisting of R and C. A fault is depicted by the conductance G. The z-source L-C connection was initially suggested as a novel type of inverter input circuit that could operate in boost, as well as the standard buck, mode. The reason for this is that the z-source allows another state wherein the inverter can short-circuit its dc bus. Herein, this feature is adopted for fault handling in dc power systems.

When the fault occurs in this system, there is no direct short of the z-source capacitor voltages, because of the inductors in the z-source circuit. The breaker components act together to quickly mitigate faults in a dc system. When a fault occurs at the output of a z-source breaker, current sources into the fault from the downstream system capacitance C, as well as from the z-source capacitances as shown by the fault conduction path in Fig 1.

Neglecting the SCR and inductor resistance voltage drops, the steady-state SCR current is [3]

$$i_{SCR} = \frac{V_s}{R_1}$$  \hspace{1cm} (1)

The initial transient is based on the fault conductance. For the purpose of this analysis, the conductance is assumed to ramp from zero to a final value with a ramp rate of [6]

$$K = \frac{1}{dt \cdot R_k}$$  \hspace{1cm} (2)

![Fig. 1: Fault Tolerant Breaker Operation](Image)

Where $dt$ is the time for the conductance to ramp to its final value which is the reciprocal of $s/R$. For the first part of the analysis, it is assumed that the inductor current remains constant. Then, the transient fault current takes a path supplied by the capacitances. Since the fault current is related to the output voltage by [3]

$$i_f = G_i \cdot V_o = KV_g \cdot I$$  \hspace{1cm} (3)

The fault current is being supplied from two capacitances; one being the load and one being the series combination of the z-source capacitors. Considering these impedances and the current division rule, the capacitor currents due to the fault are [3]

$$i_c = \left( \frac{C}{C + 2C} \right) i_f = \frac{C}{C} i_f$$  \hspace{1cm} (4)

$$i_l = \left( \frac{2C}{C + 2C} \right) i_f = \frac{2C}{C} i_f$$  \hspace{1cm} (5)

After the z-source breaker interrupts a fault, the SCR must go through its reverse recovery process. The resonance of the L-C circuit allows a time for this to occur. Sufficient sizing of the inductor and capacitor components must be carried out to ensure that the SCR has time to completely switch off before the resonance results in a forward bias of the SCR. After the SCR current goes to zero, the output voltage collapses in a matter of microseconds; the exact time depending on the amount of source inductance. With the output voltage at zero, the inductor voltage equals the capacitor voltage $V_i = V_C$, with $V_o = 0$, the SCR voltage is

$$V_{SCR} = V_C - 2V_C$$  \hspace{1cm} (6)

IV. TEST SYSTEM AND ITS DISCUSSION

A. Layout of the Test System:

The VSC-HVDC system used for the analysis is shown in Figure.1. The PMSG output is fed to rectifier station from
where the AC power from PMSG is converted to DC and fed to the inverter station through the HVDC link in between. The FTB is connected in between the HVDC link. The DC fault occurs in between the HVDC line. The mathematical description and modeling of the system in MATLAB/Simulink software is explained as follows.

The control methodology for the system is shown in Fig.3

B. Simulation and Control:
The MATLAB simulation model is shown in Fig.4. The PMSG with Wind farm side converter (WF-VSC) is created as a subsystem. The output DC power from this block is fed to the Grid side VSC. In between which, a DC fault is simulated using a static switch. The static switch is controlled by means of a signal generator. The fault current is measured using a multimeter block and plotted. Following the fault, the proposed Fault Tolerant Breaker is connected across the line. The breaker consists of an SCR, a crossed L-C connection, diodes, and resistors. The system load is represented by the RC circuit consisting of R and C. A fault is depicted by the conductance G. The z-source L-C connection was initially suggested as a novel type of inverter input circuit that could operate in boost, as well as the standard buck, mode.

The simulation model of the Fault Tolerant Breaker is as shown in Fig.4. The breaker limits the fault current by varying the impedance of the line. The line impedance is varied by adding or removing certain pair of inductance and capacitance.

The DC line parameters are tabulated in Table.2 as follows.

C. Fault Tolerant Breaker:
This work begins with the introduction of a novel dc circuit breaker which is shown in Fig 1. Therein, the fault tolerant breaker consists of an SCR, a crossed L-C connection, diodes, and resistors. The system load is represented by the RC circuit consisting of R, and C. A fault is depicted by the conductance G. The z-source L-C connection was initially suggested as a novel type of inverter input circuit that could operate in boost, as well as the standard buck, mode.

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The DC line parameters are tabulated in Table.2 as follows.
V. RESULTS AND DISCUSSION

A. Current Stress in Rectifier Unit during Normal Operating Condition:

The current stress in rectifier unit during normal operating condition is shown in Fig.5.

Under normal operating condition, the output current of the rectifier is observed to be in the range of 1.3 to 1.4 A.

Fig. 5: Rectifier output during normal operating condition

B. Fault Condition without Breaker:

During a DC fault condition, the fault current level is at a higher range of up to 60A. Thus such a high fault current feeds a higher range of current stress into the rectifier unit (i.e) the source to the DC line. The fault current without breaker is shown in Fig.7

The rectifier experiences a higher current stress due to this high fault current. The rectifier current stress is shown in Fig.8

It is observed that the current stress level reaches up to a range of 3.7 to 5.5A in the rectifier.

Fig. 6: MATLAB Simulation model of the complete system

Fig. 7: Fault Current without Breaker

Fig. 8: Rectifier current stress without breaker
C. Fault condition with Breaker:
During a DC fault condition, using the Fault Tolerant Breaker, the fault current level is reduced to half the value of that of the previous condition (i.e) 30A. Thus it does not feed a higher range of current stress into the rectifier unit (i.e) the source to the DC line. The fault current without breaker is shown in Fig.9.

The rectifier experiences a reduced current stress due to this fault current. The rectifier current stress is shown in Fig.10.

VI. CONCLUSION
The FRT support for the VSC-HVDC system is provided with a cost effective technique. On utilizing the Fault Tolerant Breaker, reliability of the system is improved. The rectifier current during normal operating conditions is observed in the range of 1.3 to 1.4A. Whereas the current stress during fault condition increases up to 3.7 to 5.5A, due to the high fault current of 60A. This high current stress triggers the CC control to initiate a trip off signal to the rectifier station, and the power transfer to the remaining system is disturbed.

Using the proposed Fault Tolerant Breaker (FTB) in the DC line, the fault current is reduced to 30A and which in turn reduces the fault current. The current stress of the rectifier station is reduced to a range of 1.9 to 3.2A (similar to normal operating condition). Thus the CC control does not initiate a trip signal to the rectifier station. Thereby power transfer to the remaining system is maintained constant, which in turn improves the reliability of the system.

REFERENCES