Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Fault Ride Through of Large Offshore Wind Farms Using HVDC Transmission

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***Abstract*-- This paper investigates system fault ride through when voltage source converter (VSC) based HVDC system is used to connect large offshore wind farms. Due to the reduction of transmitted power during onshore grid AC fault, either the generated power by the wind farm is reduced or generated power is damped if fault ride through is to be achieved. Three different strategies, i.e., telecommunication based, offshore frequency modulation, and DC damping resistor have been investigated. Simulation results corresponding to three-phase grid AC faults have been studied and the results showed that fault ride through can be achieved by all the three strategies. The DC damping resistor option is the simplest, requiring no coordination between the VSC converters and the wind turbines, and results in least disturbance to the offshore network.**

***Index Terms*-- Converter, fault ride through, frequency modulation, HVDC, VSC, wind farm.**

I. INTRODUCTION

Offshore wind farms have been identified as one of the key solutions for combating global warming and meeting government renewable energy targets. Large offshore wind farms have been planed in Europe and around the world. The integration of such offshore wind farms to the grid over distances of tens, and sometimes hundreds, of kilometers is one of the main challenges facing developers and system operators [1, 2]. It has been identified in a number of previous studies that high voltage DC (HVDC) transmission system has a number of advantages for integrating large offshore wind farms over AC connections, including fully controlled power flow, transmission distance using DC not affected by cable charging currents, and fewer cables required [3, 4]. This can result in significant economic and environmental benefit.

Various studies using HVDC technologies based on both the line commutated converter (LCC) [3-7] and the voltage source converter (VSC) [3, 8-11] have been carried out for wind farm integration. It has been identified that VSC scheme is superior to LCC systems in terms of independent reactive power control, no need for external voltage source, and fast system control. On the other hand, LCC system has the advantages of being more reliable, lower power loss, and low cost for large installation [3, 4]. Apart from the point-to-point system, multi-terminal VSC-HVDC system which contains an offshore DC grid has also been proposed for connecting large wind farms [13-15].

Fault ride through (FRT) is one of the main requirements for connecting wind farms in both the existing and the emerging offshore grid codes. When DC connection is used, the key challenge is how to balance the generated and transmitted power immediately after grid fault while maintaining the offshore AC network. The objectives of this paper are to develop strategies to control and coordinate the VSC-HVDC system and the wind farms, in order to provide smooth operation and to achieve satisfactory FRT during onshore grid fault conditions. Various control options including offshore AC frequency modulation, fast telecommunication, and DC damping resistor are examined. Simulation results using PSCAD/EMTDC will be presented to validate the FRT capability of the VSC-HVDC connection system.

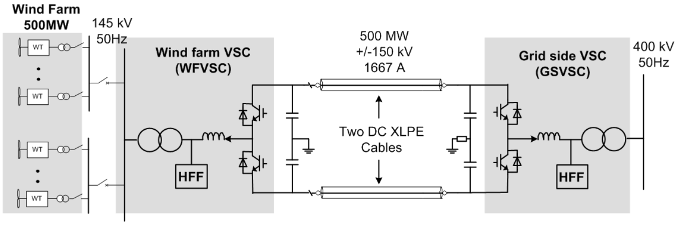

Fig. 1 Single-line diagram of wind farm integration using VSC-HVDC transmission.

II. SYSTEM OUTLINE AND OPERATION PRINCIPLE

Fig. 1 shows the single-line diagram of a typical VSC-HVDC system for integrating offshore wind farms. The wind farm considered is based on wind turbines using full-sized converter and rated at 500 MW. Other wind turbines such as those based on doubly-fed induction generator (DFIG) can also be used. The VSC-HVDC system contains a wind farm VSC station (WFVSC), a grid side VSC station (GSVSC), and a pair of DC XLPE cables.

The WFVSC collects energy from the offshore wind farm and then transmits it to the grid via the GSVSC. The WFVSC also controls the AC voltage and frequency of the wind farm network. Apart from transmitting active power, the GSVSC can also provide reactive power/AC voltage control to the grid. This can be very useful as the grid network at the point of connection is sometimes weak with a low short circuit ratio.

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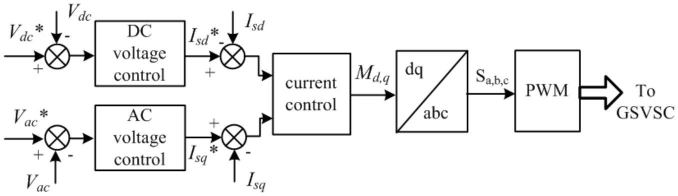
978-1-4244-2235-7/09/$25.00 ©2009 IEEE

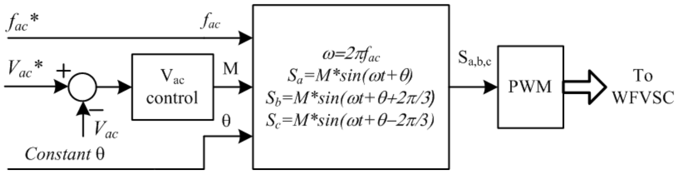
A high pass filter (HFF) is connected at each side to absorb the high frequency harmonics generated by the converters during operation.

Under normal operation, the DC voltage of the VSC-HVDC system must be maintained at a constant value. Abnormal DC link voltage can cause the system to trip and disrupt its operation. Furthermore, a constant DC voltage indicates balanced active power flow between the two sides. To achieve this balance, the GSVSC is controlled as the DC voltage regulator ensuring the generated wind energy is transmitted to the grid network through the WFVSC, the DC link, and the GSVSC. The main tasks for the WFVSC are then to collect energy from the wind farm and to control the local AC voltage and frequency of the offshore wind farm power network.

The same control strategy used for controlling the DC voltage regulator in a VSC-HVDC system for connecting two conventional AC systems can be used for the GSVSC [16]. An outer DC / AC voltage loop and an inner current loop which is defined in the synchronous reference frame fixed to the external network voltage are usually designed as shown in Fig. 2 (a). [16]



(a) GSVSC



(b) WFVSC

Fig. 2 Simplified control blocks for the GSVSC and WFVSC

Unlike synchronous or induction generators, for wind turbines using full-sized converters or DFIGs, network frequency variations have no direct influence on the power generation. Therefore, to simplify the control system design, the control strategy adopted for the WFVSC is to resemble an infinite voltage source with constant frequency, voltage amplitude and phase angle. Thus, as in the case when a wind farm is connected to an infinite AC system, the power generated by the wind farm is automatically absorbed by the source resembled by the WFVSC and then transmitted to the DC side. The control system for the WFVSC does not need to identify whether the power is active or reactive and no extra frequency or active power control loops are required.

The schematic diagram of the control strategy for the WFVSC is shown in Fig. 2 (b) [3]. The WFVSC is controlled and operated as a voltage source with constant AC frequency (f) and phase angle (θ). The only feedback control loop used is the AC voltage control via the modulation index M of the converter. This is similar to a synchronous generator but with improved frequency control capability as the output AC frequency is set directly by the output of the WFVSC.

III. SYSTEM CONTROL DURING GRID FAULT

To ensure fault ride through (FRT) of the VSC-HVDC system during close fault on the onshore AC network, the following two requirements must be satisfied:

1. Generated and transmitted / consumed active power must be balanced during fault. During an AC fault on the onshore grid network, the active power exchange between the GSVSC and the grid may be significantly reduced due to the reduced AC voltage. It is thus important that either the active power generated by the offshore wind farm is reduced or the wind farm generated power is damped (consumed) in a separate device such that the DC voltage of the VSC-HVDC system can be maintained and system tripping can be avoided.
2. Offshore AC system needs to be maintained with limited frequency and voltage variations such that when onshore fault is cleared, the system can go back to normal operation quickly.

A. GSVSC

Under normal operation, the mean value of the DC voltage is well controlled by the GSVSC and the variation range is limited. During grid fault, due to the reduction of the power transmitted by the GSVSC, the DC voltage could exceed its normal variation range. Therefore, abnormal DC voltage can be used as an indication of fault condition on the grid side. As the GSVSC is no longer able to control the DC voltage under such fault conditions, the GSVSC is switched to current limit operation upon the detection of abnormal DC voltage. The schematic diagram shown in Fig. 3 illustrates this approach.

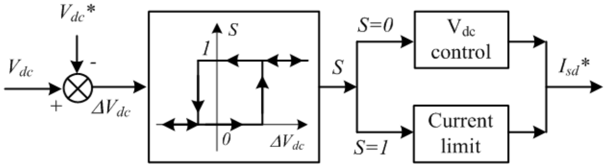


Fig. 3 GSVSC control switch during grid fault

B. WFVSC

Since the GSVSC is now operated at current limit mode, the WFVSC must regulate the DC voltage. In order to maintain the DC voltage, the active power generated by the wind farm must match the total transmitted / consumed power by the system. A number of options exist:

- *Option 1*: Fast telecommunication between the WFVSC and individual wind turbine. Once DC over-voltage is detected, signals are sent to each wind turbines using telecommunications such that the active power output from the wind turbines are reduced immediately. However, this approach might be difficult to achieve in practical systems and small signal delay could cause unacceptable DC over voltage.
- *Option 2:* Offshore wind farm network frequency modulation. In this approach, the offshore AC system

frequency is increased using the WFVSC during fault, and the active power from the wind turbines is automatically reduced upon the detection of abnormal AC frequency.

- *Option 3*: DC damping resistor on the GSVSC station. A DC damping resistor is place on the DC side of the GSVSC and it is switched in upon the detection of DC over-voltage. Thus the wind farm and WFVSC can operate as normal with no disruption. However, the DC resistor must be rated properly.

1) *Option 1 - communication based*

During a close AC fault, the power capability of the GSVSC is likely to be significantly reduced. Consequently, the DC voltage will increase, as the WFVSC continues to feed energy into the DC system. When the DC over voltage reaches a certain threshold, the WFVSC will switch to DC voltage control by regulating its phase angle output. At the same time a power order signal is sent to the wind farm using fast telecommunication, to temporarily over-ride the system operator's power order. This process is schematically shown in Fig. 4. The wind farm power output is reduced in accordance with the new power order and consequently the DC voltage of the VSC-HVDC system is regulated. The AC frequency / voltage of the wind farm network stays at its nominal value. When the fault is cleared the onshore AC voltage recovers rapidly. The power output from the GSVSC to the grid is also significantly increased and this causes the DC voltage to drop. The voltage drop is detected by both converters and the GSVSC and WFVSC return to DC voltage control and infinite voltage source modes, respectively. The wind farm power over-ride signal is removed when the control has changed back. The wind generator will speed up during the fault due to the reduced electric power output. However, this is unlikely to be a major concern due to the variable speed wind turbine operation.

2) *Option2 - offshore frequency modulation*

Unlike Option 1, this method uses the common offshore AC network for transmitting the requirement for power reduction to individual wind turbine. AC frequency, rate of AC frequency change, rate of AC voltage change, etc, can all be used as the indication of fault. In this paper, only the AC frequency is used.

Fig. 5 shows the schematic diagram of the control method for the WFVSC during grid fault. As can be seen, once abnormal DC voltage is detected, the controller is switched from infinite voltage source mode to frequency modulation. Thus the frequency reference for the WFVSC output is increased. In the meantime, an extra DC voltage control loop regulating the phase angle of the WFVSC output is also employed to reduce the DC over voltage. The DC voltage reference during fault V_{dcf}* is set slightly above nominal value (say +3%). As usual, AC voltage control is carried out through controlling the modulation index. Once the fault is cleared and the DC voltage back to its nominal value, the WFVSC is switched back to infinite voltage source mode with constant frequency and phase angle.

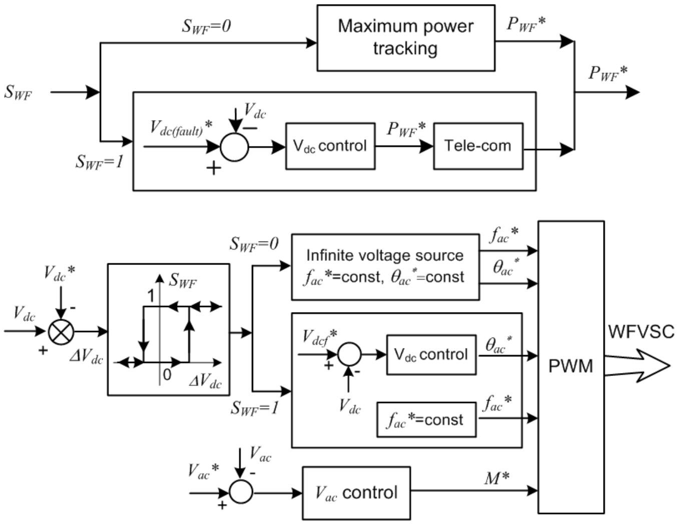


Fig. 4 Automatic power balancing during grid side fault (Option1)

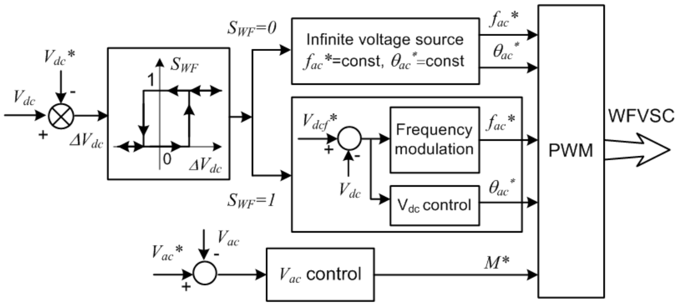


Fig. 5 WFVSC control switch during grid fault (Option 2)

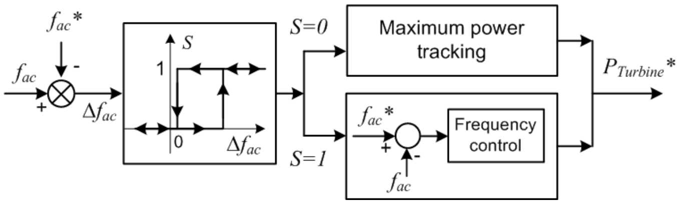


Fig. 6 Wind turbine frequency control during fault

As AC frequency plays no direct part in active and reactive power in wind turbines with full-sized converter, it is essential to add an extra outer frequency loop to the nominal power controller at each turbine in order to provide a satisfactory response during fault conditions. Upon detecting abnormal frequency at each turbine, the normal wind turbine active power order is replaced immediately by the output from the frequency controller as schematically shown in Fig. 6. Thus the wind farm output active power is reduced immediately.

3) *DC damping resistor*

The principle of this method is to damp excessive energy in the system into DC resistors during onshore AC fault. The DC resistor can be connected to the DC terminals of the GSVSC via a controllable power device such as an IGBT valve. If the DC damping resistor is rated at the full system rating, the power output from the wind farm through WFVSC will not be affected and their normal operates undisrupted even during a close AC fault to the GSVSC terminal. A simple hysteresis control can be used to control the power switch as schematically shown in Fig. 7. As seen, during AC fault, the DC damping resistor is switched in and out as so to maintain the GSVSC's DC voltage within the control band. Once the AC fault is cleared and the AC voltage recovers, the power output from the GSVSC will increase rapidly. This causes the DC voltage to drop immediately and results in the switching of the GSVSC's control from current limit to DC voltage control. The DC voltage is then regulated and the wind farm and the WFVSC continue to operate normally.

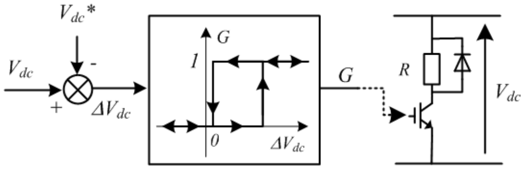


Fig. 7 Control of DC damping resistor

The method requires no coordination between the WFVSC and individual wind turbines and provides a reliable and secure way of operation. The drawback for this method is the extra cost of the DC damping resistor and switching devices which all have to be rated at the full system rating.

IV. SIMULATION RESULTS

Simulation studies of the proposed VSC-HVDC system for integrating a 500 MW wind farm based on full-sized converter using permanent magnet generator have been performed using EMTDC/PSCAD. The system comprises a 500 MW wind farm and a 500 MW/300 kV VSC-HVDC system based on conventional 2-level Converter. The main DC capacitor on each side is 100 µF and the length of the DC cables is 100km. As previously described, the power output from wind turbines using full-sized converter is controlled by their power electronics converters and their operating speeds do not directly affect the dynamic response of the system. The most critical condition for system control and operation refers to the wind farm operating at close to full power. Therefore, the wind farm is simulated as one lumped 500 MW wind generator model for simplicity. The GSVSC is connected to an AC source with a SCR of 5. The switching frequency for both VSC stations is 1.5 kHz. One HFF rated at 80 MVar is used at each end and is connected permanently to the respective networks as shown in Fig. 1.

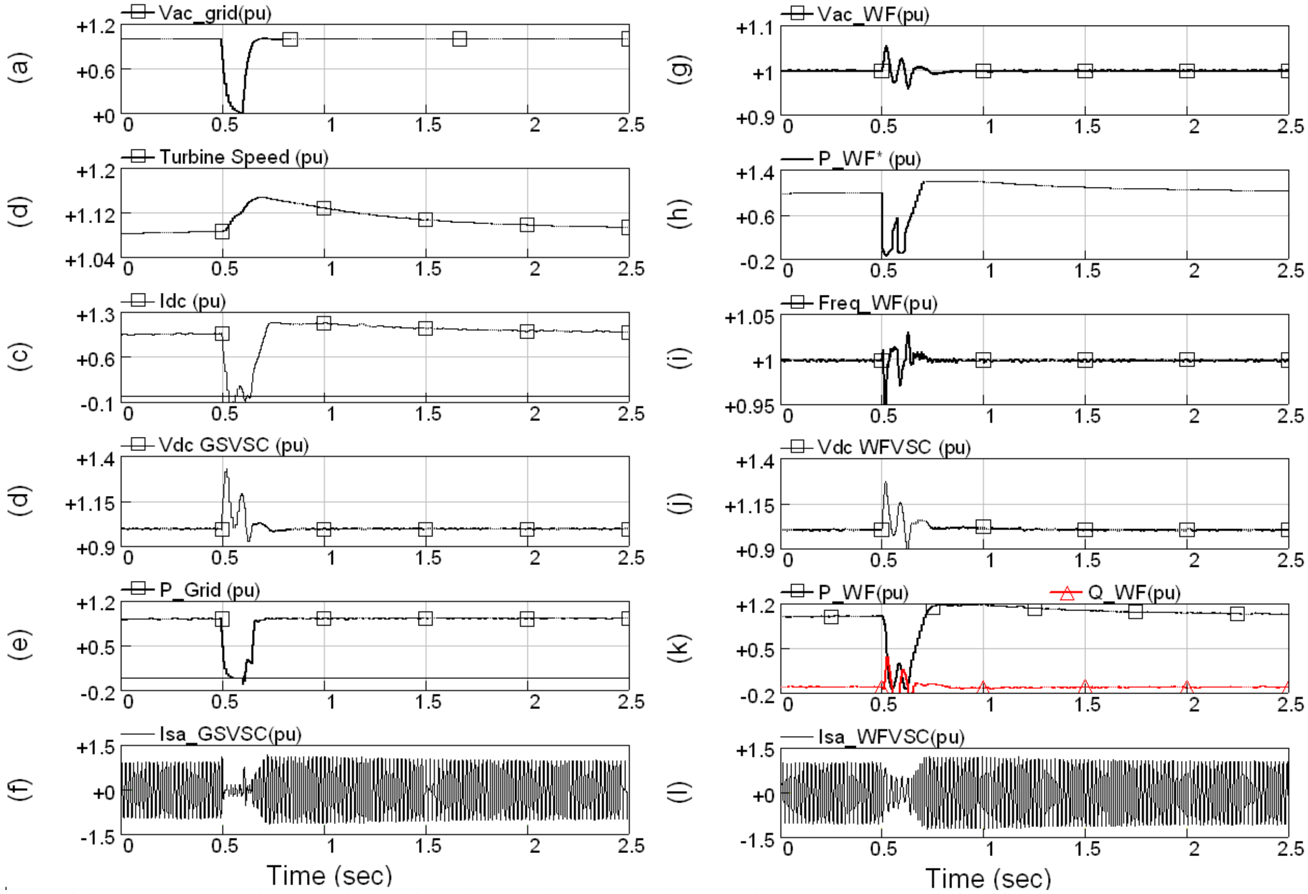


Fig. 8 Simulation results with grid side AC fault with Option 1 – telecommunication: (a) Grid AC voltage; (b) Wind turbine speed; (c) Converter DC current; (d) GSVSC DC voltage; (e) Active power output to the grid by the GSVSC (f) GSVSC phase current; (g) Wind farm AC voltage; (h) Wind farm power reference; (i) Wind farm AC frequency; (j) WFVSC DC voltage; (k) Active and reactive power from the wind farm; (l) WFVSC phase current.

A. Option 1

Fig. 8 shows the simulated results with Option 1 when a solid 3-phase to ground fault is applied to the primary side of the GSVSC coupling transformer at 0.5 s. Prior to the fault, the system is operating around its full power of 500 MW. Upon the AC fault, the rapid reduction of the power export by the GSVSC causes the DC voltage to rise quickly, as can be seen from Fig. 8 (d), (e) & (j). When the DC over-voltage reaches 8%, the WFVSC switches to DC voltage control and generates the active power order for the wand farm which is transmitted to the turbines using telecommunication. Only a very small telecom delay of 1 ms is used in the simulation. As can be seen in Fig. 8 (h) & (k), the wind farm output active power is reduced and so as the DC voltage. During the fault, the GSVSC operates in current limit mode. The maximum DC over voltages for this study are around 34% and 27% for the GSVSC and WFVSC respectively. Due to the reduced electric power output during the fault the wind turbine speeds up as shown in Fig. 8 (d). The wind turbine inertia constant used in the simulation was 2 s which is substantially less than that in a real system. Thus the speed increase in practice would be much less than those shown in Fig. 8 (d).

When the fault is cleared at 0.6 s, the DC voltage drops and the WFVSC and the GSVSC switch back to infinite AC voltage source mode and DC voltage control mode respectively. A 20% over-load capability is assumed for the whole system. As can be seen, the accumulated energy in the turbine during the fault period is transferred back to the grid and the system eventually back to normal operation.

As can be seen, FRT can be achieved although considerable DC over voltage is observed. System operation with larger communication delay was found to be more problematic.

B. Option 2

With the same operating condition, Fig. 9 shows the system response with Option 2. Again, the AC fault causes a rapid reduction of the exported active power by the GSVSC. Consequently, the DC voltages on both converters increased quickly and exceeded the upper threshold of 1.08pu. The control mode for the GSVSC was then switched to current limit. Meanwhile, the WFVSC was switched to frequency modulation and DC voltage control mode. The wind farm AC frequency started to rise due to the control action by the WFVSC as can be seen in Fig. 9 (h) & (i). The abnormal AC frequency was detected by the wind turbines and once the threshold of 1.03 pu is exceed, their output active power is reduced. Consequently, the DC over-voltage is reduced. The maximum DC over voltages for this study are about 32% and 25% for the GSVSC and WFVSC respectively. The maximum AC frequency increase on the wind farm is about 15%.

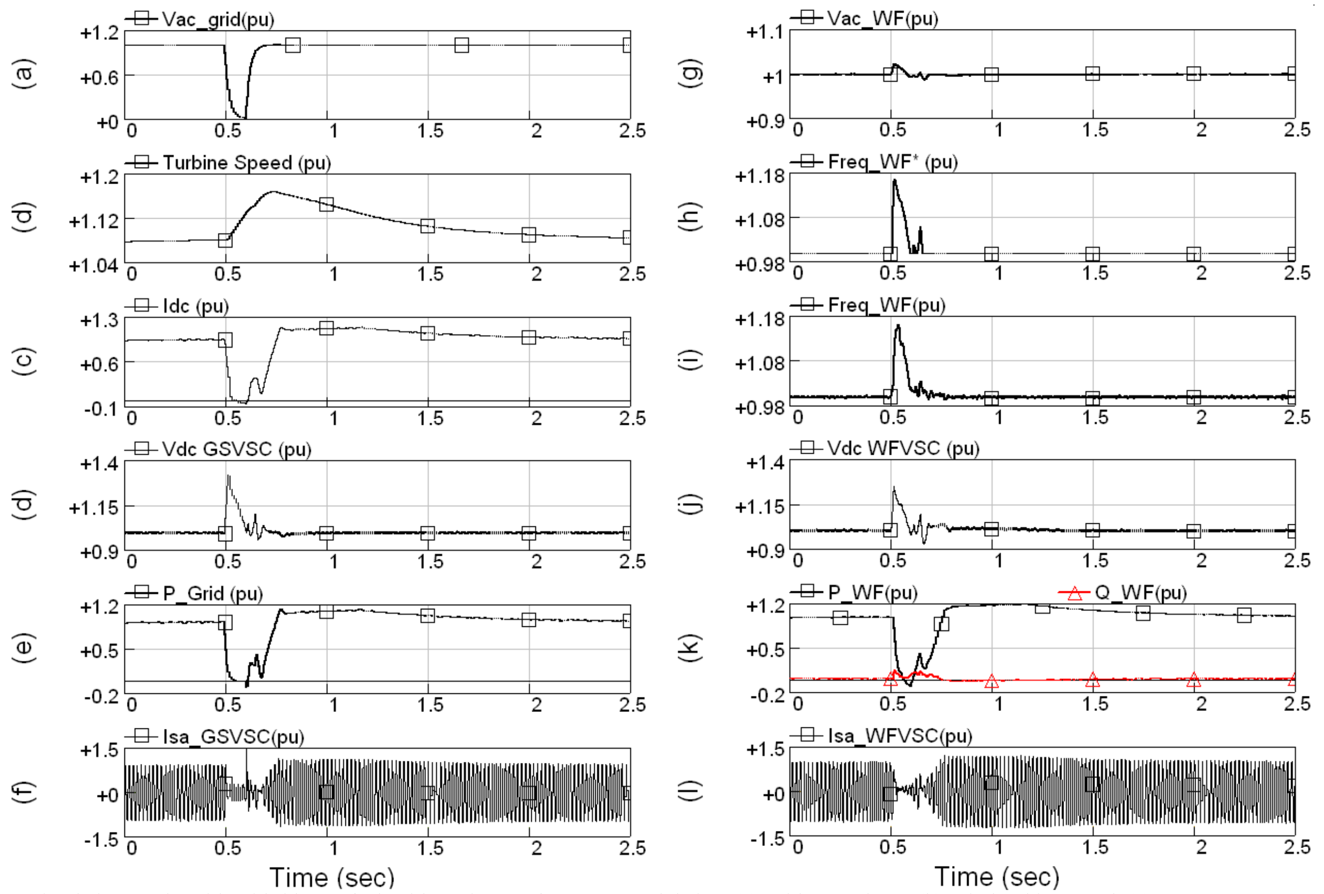


Fig. 9 Simulation results with grid side AC fault with Option 2 – frequency modulation: (a) Grid AC voltage; (b) Wind turbine speed; (c) Converter DC current; (d) GSVSC DC voltage; (e) Active power output to the grid by the GSVSC (f) GSVSC phase current; (g) Wind farm AC voltage; (h) Wind farm AC frequency reference; (i) Wind farm AC frequency; (j) WFVSC DC voltage; (k) Active and reactive power from the wind farm; (l) WFVSC phase current.

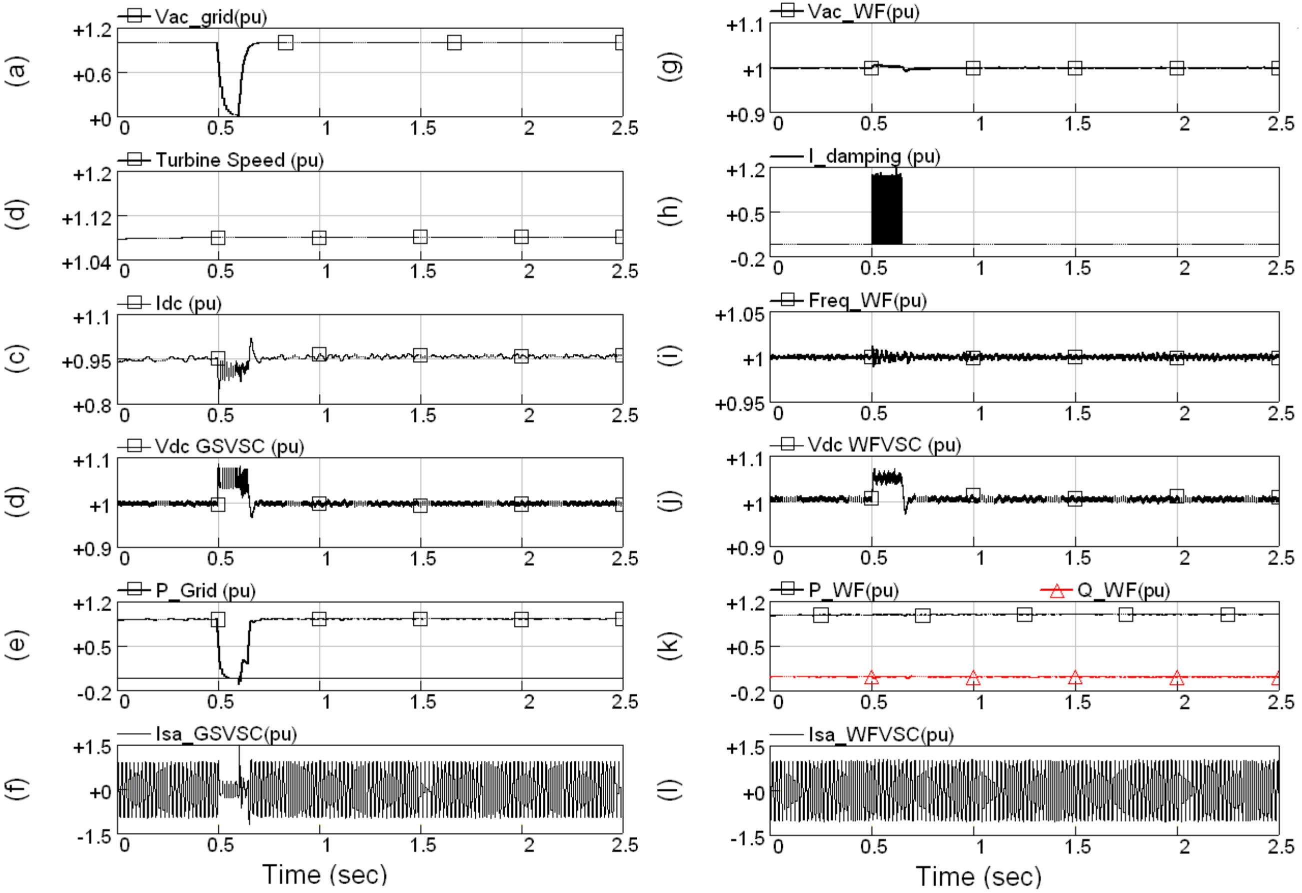


Fig. 10 Simulation results with grid side AC fault with Option 3 – DC damping resistor: (a) Grid AC voltage; (b) Wind turbine speed; (c) Converter DC current; (d) GSVSC DC voltage; (e) Active power output to the grid by the GSVSC (f) GSVSC phase current; (g) Wind farm AC voltage; (h) DC damping resistor current; (i) Wind farm AC frequency; (j) WFVSC DC voltage; (k) Active and reactive power from the wind farm; (l) WFVSC phase current.

When the fault is cleared at 0.6s, the exported active power by the GSVSC increases rapidly as shown in Fig. 9(e). Consequently the DC voltage on both converters drops and causes the GSVSC and the WFVSC to switch back to DC voltage control and infinite voltage source mode respectively. The wind farm AC frequency also returned to its nominal value. Again, FRT is achieved with this method although high DC over voltage is noticed.

C. Option 3

In this study, a DC damping resistor of 180 Ω was connected to the GSVSC's DC terminal via a controllable switch. This ensures the consumption of 500 MW by the DC resistor under most critical condition. The DC voltage band was set at 1.05 pu and 1.04 pu respectively. As can be seen in Fig. 10 (d), (h) & (j), when AC fault occurs, the energy generated by the wind farm is consumed by the DC damping resistor and the DC over voltage is limited. The WFVSC and the turbines operate unaffected with little voltage and frequency variation for the offshore AC network. As the turbines continue to generate power, their speeds do not increase as previous seen with Options 1, and 2.

Once the fault is cleared, the DC voltage drops and the DC damping resistor automatically comes out of operation. The system can back to normal operation very quickly and the transition is very smooth and satisfactory.

V. CONCLUSIONS

Integration of large offshore wind farms into transmission networks using VSC-HVDC system has been studied in this paper with specific considerations on fault ride through capability. To ensure safe operation of the VSC-HVDC system, the total generated and transmitted / consumed power must be balanced under any conditions. Three different strategies, i.e., telecommunication based, offshore frequency modulation, and DC damping resistor, for ensuring satisfactory fault ride through have been investigated. Simulation results corresponding to three-phase grid AC faults have been studied and the results showed that fault ride through can be achieved by all the three strategies providing adequate DC/AC over voltage and AC frequency variation being taking into account in the design stage. The DC damping resistor option is the simplest and most reliable among the three methods. It requires no coordination between the VSC converters and the wind turbines, and also results in least disturbance to the offshore network.

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VII. BIOGRAPHIES

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