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Coordinated control for wind turbine and VSC-HVDC transmission to enhance FRT capability

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Abstract

The integration of large-scale offshore wind farms into electricity networks without causing stability hazards is one of the future challenges for interconnecting large offshore wind farms into national grids. This paper presents enhanced control strategies for offshore wind farm arrays interconnected via an HVDC link. To improve fault ride-through capabilities of the HVDC link and wind farms, a frequency controller is proposed and the third harmonic injection technique is applied as a means to improve the reliability of the offshore arrays. This new controller can easily coordinate the power flow from different sources (i.e. large-scale wind farms and conventional power stations). The power production from the offshore wind farms will depend upon the type of wind turbines installed. Thus, the performance of wind farms based on DFIG and FRC wint turbines is compared aiming to give a better understanding and to identify areas where control improvements can be introduced to optimise offshore wind power transmission.

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Keywords: Offshore wind farms, cluster collection platforms, offshore network connection, HVDC single point connection.

1. Introduction-----

Due mainly to European CO_2 targets for 2020 and 2030 offshore wind energy has become a key area in future energy production. Increasing energy production from individual turbines and the installation of large scale offshore wind farms should bring onshore a high amount of energy which should help to meet these targets [1].

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Thereby, in recent years installation of variable-speed wind turbines in deep waters has become a primary concern, as wind speed is steadier and there is less turbulence. However, the controllability and reliability of large offshore wind farms and their cluster platforms are challenging. To increase their reliability and achieve power transfer HVDC transmission is seen as a key element. There are two HVDC transmission configurations: the classical Line-Commutated Converter-HVDC (LCC-HVDC), which can transmit high amounts of power and the second option, the Voltage Source Converter (VSC-HVDC) technology [2-5], which has higher flexibility [6, 7], and allows faster control during normal operation or large transients [8, 9].

The aim of this research is to evaluate and to compare performances of VSC-HVDC for Doubly Fed Induction Generator (DFIG) and Fully Rated Converter (FRC) wind farms (WFs) during large transients. Control strategies that balance the active and reactive power transferred and the dc power during large transients are proposed and explored. Finally, this paper also evaluates the VSC control performance (flexibility and reliability) and fault ride-through capability of a proposed ac star wind farm layout during large transients, shown in Fig. 1.

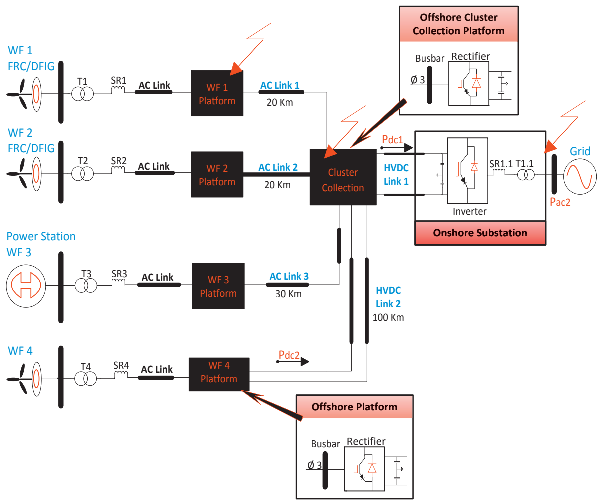


Fig. 1. Test system.

In the test system shown in Fig. 1 the DFIG/FRC wind farms are connected to the cluster collection platform through ac cables. To maintain the offshore system reference ac voltage and frequency, a synchronous generator has been added to the offshore scheme. Then this generator has been linked to the cluster by ac cables. Finally, an extra wind farm is connected to the cluster by dc cables and the HVDC system is connected onshore through a point-to-point connection.

2. VSC Control Strategy

The introduction of self-commutating IGBT in VSC converters has radically boosted their installation in industrial operation. The IGBT has improved performance of the controlled system during normal and/or abnormal operation improving power transmission through HVDC connection [10-12].

For offshore layouts VSC-HVDC offers advantages as they can recover and stabilize rated ac voltage and frequency without introducing expensive electronic equipment (STATCOM or SVC) [13]. During initialization of offshore schemes, wind farms perform as loads (active and reactive power is consumed). Hence, active and reactive power must be transferred from onshore through the HVDC link. Rated ac voltage and frequency can be achieved because the VSC control system hold the V_{dc} at rated operation mode until these parameters are stabilised to their normal values. The VSC-HVDC can also exchange power with passive or weak grids [7, 8, 14, 15]. Fig. 2 shows a basic VSC configuration.

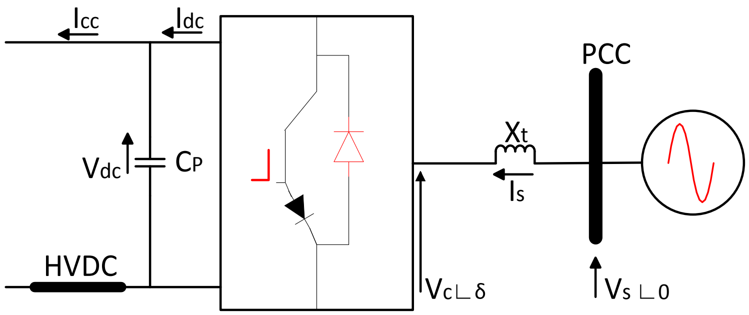


Fig. 2. Basic VSC Scheme

2.1 Basic VSC Control "Load or Phase Angle Technique"

The load or phase angle control is a basic control technique. This control technique can be explained by the idea of controlling the active and the reactive power transferred between two systems which are connected by an inductance, Fig. 3 [16]. The VSC system controls the power exchange by controlling the angle between the sending and the receiving voltages (δ). The difference between the angle in the PCC (Eg) and the angle in the converter side (V_t) determines the power transfer and the direction of this power [16-18]. This is possible because of the VSC flexibility, which allows this converter to work in the four-quadrants; thus, active and reactive power can be re-directed under abnormal circumstances or after a transient.

Fig. 3 shows a the principle of the load angle control [12].

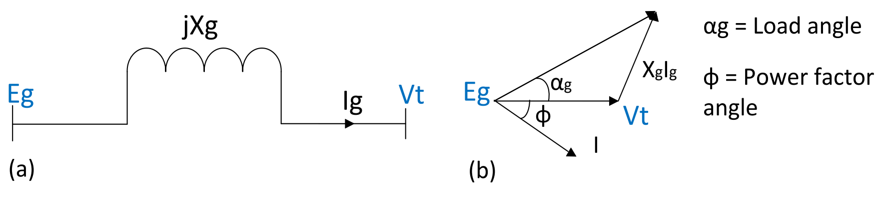


Fig. 3. Power transfer between two sources (Kundur 1944), (a) equivalent circuit diagram and (b) phasor diagram

$$P = \frac{E_g V_t}{X_g} \sin X_g \quad (1)$$

$$Q = \frac{E_g^2}{X_g} - \frac{E_g V_t}{X_g} \cos X_g \quad (2)$$

2.2 Vector control or Direct control

This technique is considered to have higher control capability than the previous technique. Thus, it allows controlling a layout with higher accuracy (data acquisition, controllability) than the load angle technique and has the same flexibility. This is because the active and reactive power (i_d^* and I_q^*) are transformed into numerical values (which are faster and more precise to control) and are used as reference signals for the inner and outer current controllers [12, 19].

To return the dq components (numerical values) into sinusoidal values, a PLL calculates and synchronize the phase angle, which then is mixed with the new inputs of the modulation signal (u_{dq}). These inputs are then introduced into the PWM system. The mathematical model based on the dq frame decoupled for instantaneous active and reactive power at the PCC can be given by [11, 12, 20]:

$$P_{dq}\,(t) = \frac{3}{2}\left[V_d(t)i_d(t) + V_q(t)i_q(t)\right] \quad (3)$$

$$Q_{dq}\,(t) = \frac{3}{2}\left[-V_d(t)i_q(t) + V_q(t)i_d(t)\right] \quad (4)$$

The reactive power should be equal to zero, $V_q \approx 0$. Thus, the instantaneous active and reactive can be re-written as:

$$P_{dq}\,(t) = \frac{3}{2}[V_d(t)i_d(t)] \quad (5)$$

$$Q_{dq}\,(t) = \frac{3}{2}[-V_d(t)i_q(t)] \quad (6)$$

2.2.1 Inner and Outer Current Controller

The inner and outer current controller is a fast reference tracking method which controls the active and reactive power separately. In addition, this control system is hierarchical and prioritizes the acquisition of the I_q^* referential signal over the i_d^* referential signal. This occurs because the I_q^* controller loop is faster than the i_d^* controller loop.

Fig. 4 shows the basic structure of an inner and outer current controller. In order to design control loops for the current controller, the active and reactive power, the voltage and current of the investigated scheme are been decoupled in the *dq* frame [21-23]:

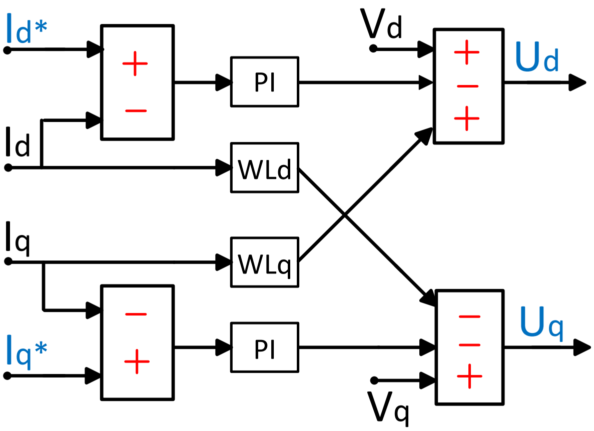


Fig. 4. Inner and Outer Current Controller.

$$U_d = \frac{di_d}{dt} = k_{p1}(i_d^* - i_d) + k_{i1} \int (i_d^* - i_d)dt \qquad (7)$$

$$U_q = \frac{di_q}{dt} = k_{p1}(i_q^* - i_q) + k_{i1} \int (i_q^* - i_q)dt \qquad (8)$$

K_{p1} and K_{i1} are the proportional and integral gain of the ac voltage regulator and * is used to identify the reference signals.

The u_{dq} is the new control inputs of the modulation signal which is fitted into the PWM system. These new dc control signals (U_{dq}) are mixed with the phase angle and the modulation signal, which is going to be compared with the triangular signal in the PWM system, is obtained [19, 24, 25]. The modulation index (m) is the square ratio of the new control inputs of the dc voltage (U_{dq}); thus the modulation index controls the amplitude of the modulation voltage (fundamental voltage introduced in the PWM system). Moreover, the modulation index should be equal to or smaller than 1 ($|m| \leq 1$). Otherwise, if the modulation index is greater than 1, the system will reach over-modulation and become unstable [11, 20]. The control of the active and reactive power in the *dq*-frame in steady state could be given by [19, 24]:

$$m(t) = \frac{U_{dq}(t)*2}{V_{dc}(t)} \qquad (9)$$

2.3 Cluster Platform Control Strategy

The total power transferred from offshore to onshore is 500 MVA. This power transferred is divided in two parts, the ac star layout (WF1, WF2 and WF3) produces 300 MW and the second part is the WF4 (HVDC Link 2), which produces 200 MVA. As was mentioned before, WF3 maintains the ac reference voltage and frequency.

2.3.1 Voltage Control Strategy

As the power control of the offshore VSC converter has already been explained in the inner and outer current controller section of this paper, a short explanation of a voltage control method is introduced here. Because the power produced by the wind turbines is controlled in the wind farms platforms the cluster collection platform must control and maintain the ac line voltage of the entire ac layout. Furthermore, the voltage of the three ac lines is collected in the cluster platform "busbar"; these ac voltages are used to obtain I_d* for the inner and outer current controller which is used in the inner and outer current controller for VSC control. Equations used to calculate i_d* can be seen from (3-9), especially equation (7). Fig. 5. shows the ac voltage controller.

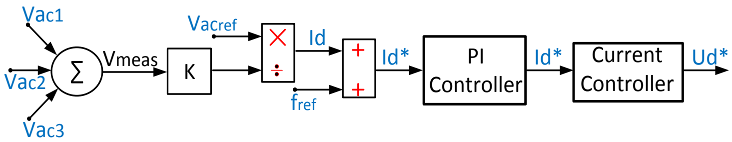


Fig. 5. Voltage controller.

The v_{meas} (in the above diagram) is used to obtain the referential signal for the inner and outer current controller, so the I_{d*} reference signal. The P_{ac1} and the Q_{ac1} are the total power obtained from WF1, WF2 and WF3, which is collected in the cluster platform busbar (PCC). A simple equation of the voltage control can be described as:

$$V_{meas} = \sum(V_{ac1} + V_{ac2} + V_{ac3})\,;\ P_{ac1} = \sum(P_{wf1} + P_{wf2} + P_{wf3}) \qquad (10)$$

Fig. 6 shows a VSC system with implementation of the ac voltage and frequency controllers.

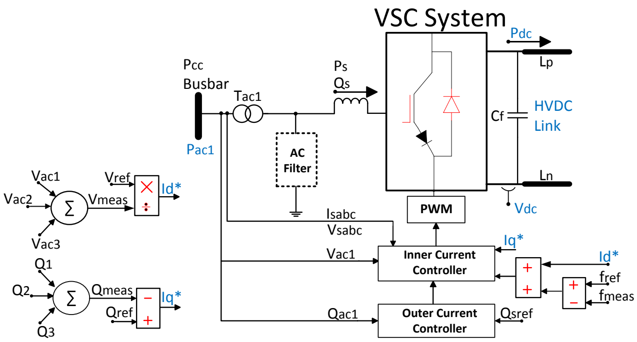


Fig. 6. Control strategy for the scheme under research.

P_{ca1} is the power collected in the cluster platform. Therefore, the V_{ac1} and I_{ca1} are voltage and current of the cluster platform respectively and consequently P_{ac1} should be equal to the P_{dc1} (no losses are considered)

$$P_{ac1} = P_{dc1} \quad (11)$$

$$P_{ac1}\,"(V_{ac1} * I_{ac1})" = P_{dc1}\,"(V_{dc1} * I_{dc1})" \quad (12)$$

The total power transferred from offshore to onshore should be equal to the total power in the onshore platform (P_{ac2}) and equal to the total offshore power, the sum of the P_{dc1} and P_{dc2}.

$$P_{ac2} = P_{dc1} + P_{dc2}$$

$$V_{ac2} * I_{ac2} = (V_{dc1} * I_{dc1}) * +(V_{dc2} * I_{dc2}) \quad (13)$$

Therefore, from the total power transferred from offshore to onshore, it is possible to obtain the I_{d*} in the inverter substation (Fig. 7).

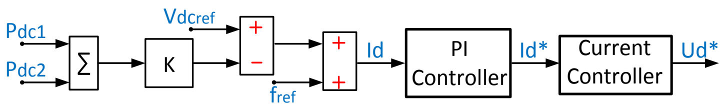


Fig. 7. DC current controller.

The dc current controller (i_d*) has similar equations to the inner and outer current controller for control of the offshore cluster platform (7-13).

$$i_d^* = \frac{dV_{dc}}{dt} = k_{p2}(V_{dc}^* - V_{dc}) + k_{i2}\int (V_{dc}^* - V_{dc})dt \quad (14)$$

K_{p2} and K_{i2} are the proportional and integral gain of the dc voltage regulator [26].

Moreover, both controllers are used to improve and to balance the active, reactive power and the dc power [27, 28]. Equation of the frequency controller can be given by:

$$e_f = k_{pi}\int (f - f_o)\, dt \quad (15)$$

The frequency reference signal is introduced along with the reference power signal into the inner and outer current controller and is given by (i_d*):

$$i_d^* = \int e_f + i_d\, dt \quad (16)$$

3 System outline

Fig. 1 presents the ac star layout where three wind farms platforms are connected to one cluster collection platform and then through HVDC link 1. The active and reactive powers are subsequently transferred to an onshore platform; a second HVC Link 2 transfers 200 MW to the HVDC Link 1. To analyse the dynamic performance and fault ride-through capability of this ac star layout, three faults have been applied. They are located in WF1, the cluster collection platform and in the onshore substation. The focus of the study is on the control system of the HVDC and WTs, the active and reactive power performances and the fault ride-through capability of the ac star layout. The investigation was conducted in Matlab/Simulink.

4 Simulation Results

In this section, a model of both ac star layouts and their capability to recover from large transients are investigated. These layouts are used to compare different VSC control techniques and their fault ride-through capability.

4.2 Wind Farms Collection Platforms

Fig. 8(a) and (b) show respectively performances of the ac voltage and current in the DFIG and FRC wind farms during the first transient 6.5s. These two figures are divided into 4 plots; first two plots are DFIG or FRC wind farms, third plot is the synchronous generator and fourth plot is the wind farms which are connected to the cluster collection platform by HVDC link.

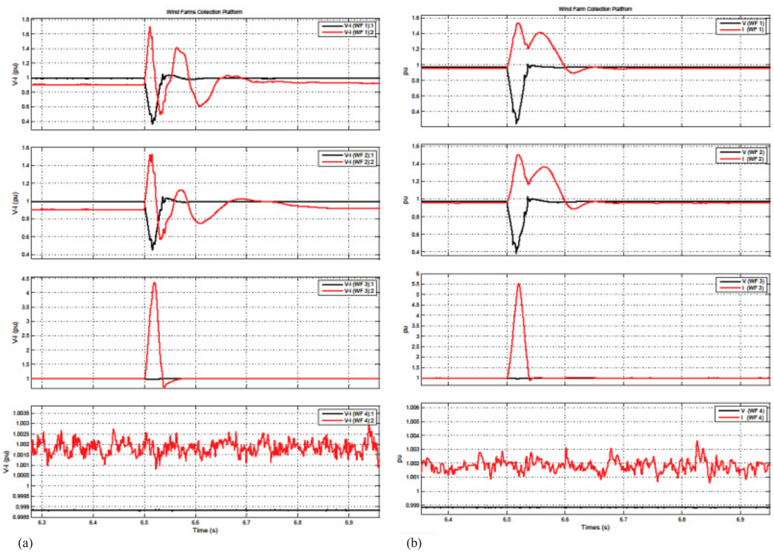


Fig. 8(a) DFIG Scheme (b) FRC Scheme.

As can be seen in Fig. 8(a) and Fig. 8(b) peaks current are higher in the DFIG wind farms than in the FRC wind farms. In both simulations fault ride-through of both layouts have been achieved.

Fig. 9(a) and Fig. 9(b) show performances of DFIG and FRC wind farms when a fault is triggered in the cluster collection platform. It is clear to see that performances of wind farms platform are different in each case (DFIG/FRC wind farms, the synchronous generator and the HVDC Link 2).

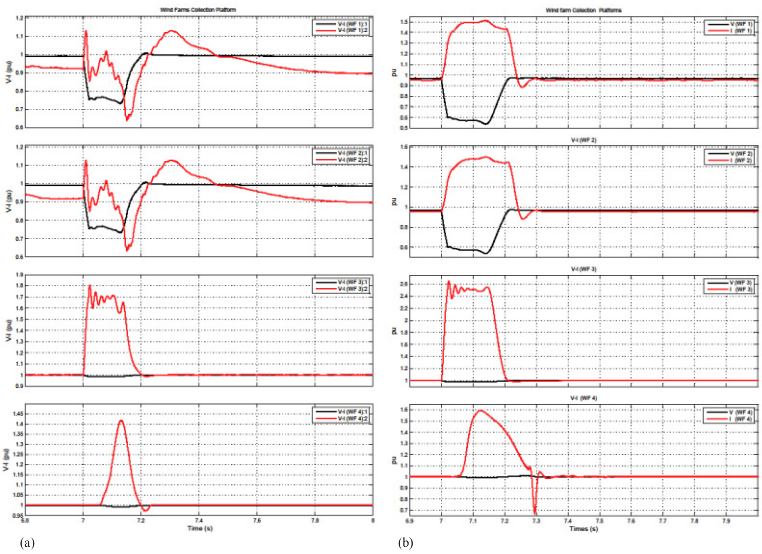


Fig. 9(a) DFIG Scheme, (b) FRC Scheme.

4.3 Cluster Collection Platform and Grid

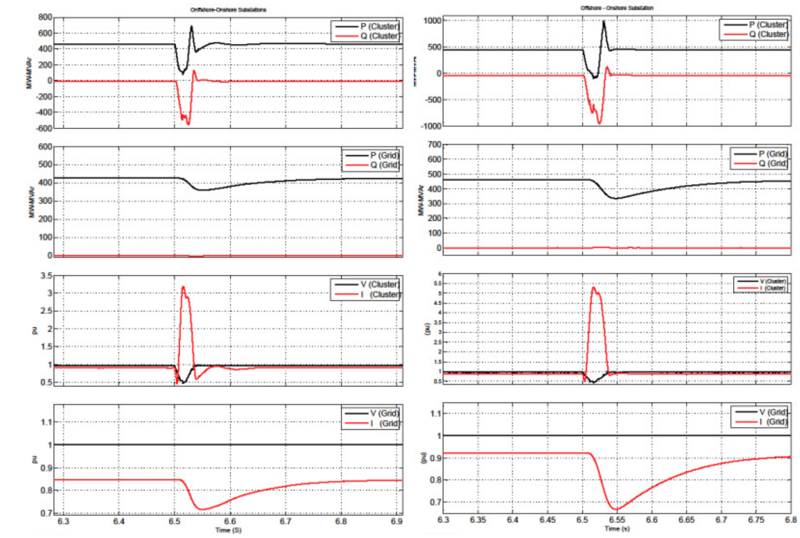
Fig. 10(a) and Fig. 10(b) show performances of the active and reactive power, ac voltage and current in the cluster platform and the onshore platform during a fault in the cluster collection platform (6.5-6.51s). Both figures show a slight difference in the ac voltage but an important difference is observed in the current performance, which reaches over 5 p.u. in the FRC scheme.

5 Conclusions

Comparison between DFIG and FRC offshore wind farms in an ac star layout has been presented. The proposed scheme has been validated with dynamic simulations, applying large transients in the offshore and in the onshore area.

The results further demonstrate flexibility of the proposed control system to integrate different offshore wind farms during these transients. In addition, it has been shown also high improvements in the fault ride-through capability of both systems. Thus, mentioned controllers have improved the recovery time from large transients in the ac and dc scheme. By using a voltage and the frequency controller, accurate control of the dc voltage and the third harmonic injection technique, the results has shown great controllability of the power transferred from both schemes.

Thus, it is possible to conclude that incorporation of DGIG/FRC wind farms in the same scheme will not alter significantly the operational mode of the offshore and the onshore platforms during large transients.



(a) (b)

Fig. 10. (a) DFIG Cluster-Grid, (b) FRC Cluster-Grid.

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