INTEGRATION OF LARGE OFFSHORE WIND FARM - DOUBLY FED INDUCTION GENERATORS WITH CLASSICAL HVDC

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ABSTRACT

Due to the fast increase in wind power production there is a need for detailed studies of integration problems. Integration problems arise from the characteristics of wind power and various technologies used in wind energy industry. In this paper, a case study of doubly fed induction generators connected with classical HVDC line commutated converter - thyristor bridge is investigated. Operation strategies and corresponding controllers with and without STATCOM are proposed, dynamic models in Matlab/Simulink are developed, and simulation results are presented.

Keywords: *Classical HVDC Link, Control Method, DFIG, Thyristor Bridge*

1. INTRODUCTION

Wind power installation increases very fast through out the world in recent years. The offshore wind power draws special attention. The average wind speed offshore is higher than onshore which means larger energy production, the turbulence and wind shear effect is lower offshore than onshore which implies higher power quality. These benefits initialize the plans of developing large offshore wind farms in many countries. Unlike the onshore wind turbines which are often dispersed in the distribution grid, the offshore wind turbines will be connected to the transmission grid as large wind farms. The connections between offshore wind farm and power grid can be high voltage ac (HVAC) or high voltage dc (HVDC) with classical HVDC LCC (line commutated converter) using thyristor bridge, or HVDC VSC (voltage source converter) using IGBTs. HVDC VSC has better dynamic behaviors than HVDC CSC, but they are expensive and have larger power loss. The three integration methods are compared in [5], [11], [12], and [14]. It is concluded that HVAC can be used for medium wind farm, 200MW for example, and short transmission distance, 50km for example. For large power capacities and long transmission distances, HVDC transmissions are more favorable. Considering the cost and efficiency, HVDC using thyristor bridges can be used for extremely large wind farm, 600 MW for example, which is connected with strong ac grid. HVDC using IGBTs can be integrated with relatively weak grid for its capability to provide dynamic reactive power.

Doubly fed induction generator (DFIG) dominates today's wind energy market because it is excited from the rotor VSC, and doesn't need to absorb reactive power from the grid. It will not have transient voltage stability problem during grid fault and thus has better low voltage ride through (LVRT) capability than full size induction generator (FSIG). Compared with permanent magnet generator (PMG) with full scale VSC on the stator, the DFIG is more economical as the scale of VSC on the rotor is only about 30% of the full power, depends on the allowable variable speed range.

Based on the above discussions, the configuration of DFIG with HVDC LCC is studied because it may have the best compromise between dynamical and economical performances. In this paper, two operation strategies with or without central static compensator (STATCOM) unit are discussed. New controller of DFIG is designed when no STATCOM is installed in the wind farm. The reason is that the traditional grid voltage oriented controller can't work when the DFIG is not connected to strong power grid. Dynamic models are built and controllers are developed in Matlab/Simulink [15]. Simulation results show that both strategies seem to work well, though further investigations under grid faults are required.

2. SYSTEM OF DFIGS WITH CLASSICAL HVDC CONNECTION

The studied wind park is composed of two DFIG, which is necessary to study the possible interaction between wind turbines inside the wind park. Reactive power compensation is installed with HVDC LCC, in order to minimize reactive power absorbed from the grid and keep the ac voltage constant. One choice of reactive power compensation is to use STATCOM, which can provide dynamic reactive power compensation and also works as an energy buffer. Another choice is to use shunt capacitor to balance the steady state reactive power consumed by HVDC thyristor bridge rectifier. The DFIG is controlled to provide dynamic reactive power compensation. Unlike the normal power grid, it is not necessary to keep the voltage level inside wind farm constant. The voltage of wind farm can be varied to change the power transferred through the HVDC LCC. The topology is shown in the Fig. 1 and the operation strategies of both cases are discussed in the following sections.

2.1. Operation strategy when STATCOM installed

At the wind farm side, STATCOM is installed to provide dynamic reactive power compensation for the HVDC thyristor rectifier. More importantly its dc

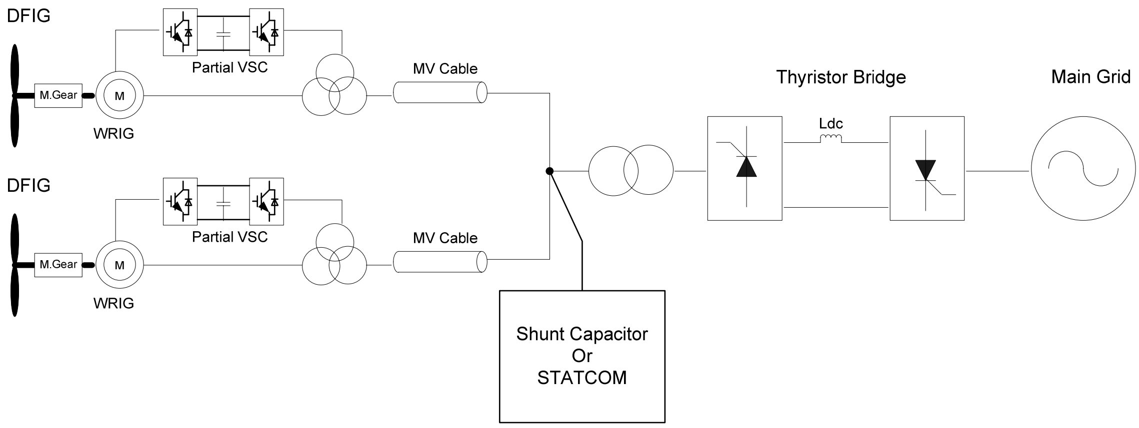

Fig. 1 Topology of DFIG with classical HVDC LCC integration

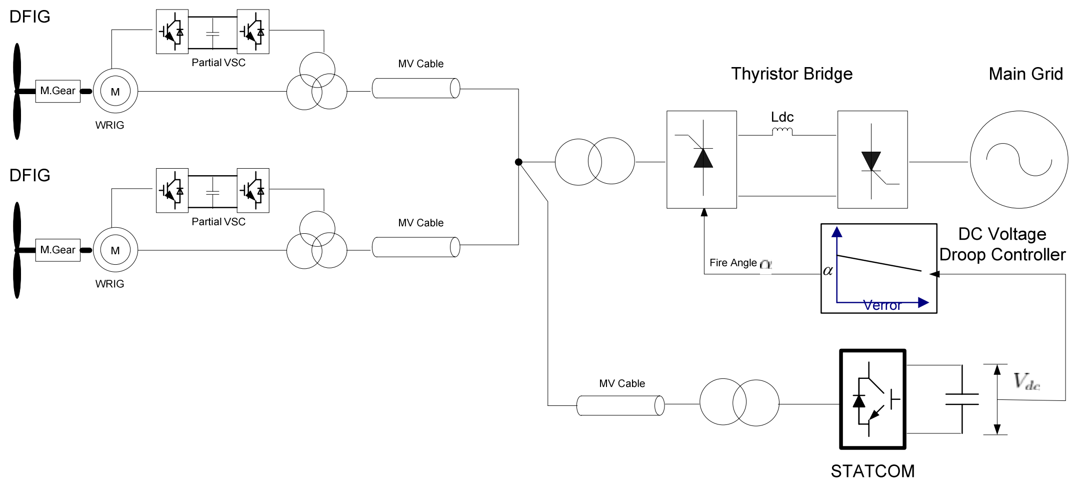

Fig. 2 Operation of DFIG with classical HVDC LCC integration and STATCOM

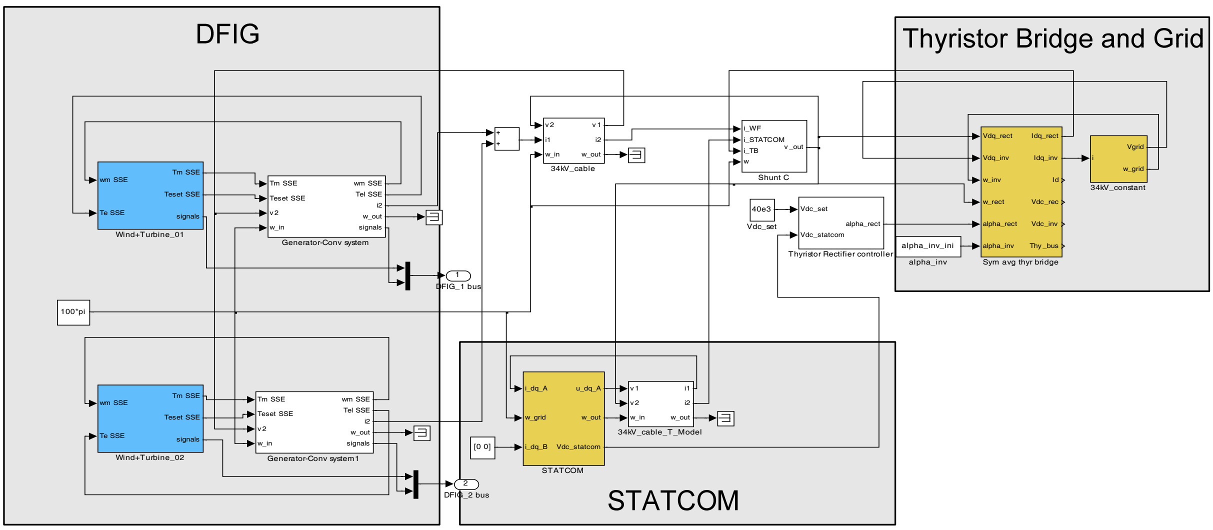

Fig. 3 Simulink Model of DFIG with classical HVDC LCC integration and STATCOM

capacitance is used as transient energy storage buffer. It is used to balance the power produced by wind turbine and transmitted through HVDC LCC. The wind speed is not constant, so the power produced by DFIG is also varying. It is difficult to predict the total power produced by the whole wind farm very accurately. The imbalance between total power produced by DFIGs and power transferred through HVDC CSC is temporaly accumulated on the dc capacitance, and cause dc voltage variations. Thus the dc voltage of STATCOM can be used to control the fire angle of thyristor rectifier, which controls the active power transmitted through HVDC LCC.

2.2. Operation strategy without STATCOM

Unlike the normal power grid, the ac voltage at wind farm side is not necessarily to be constant as long as it is not too high to damage the insulation. The thyristor bridge can be looked as a constant impedance load when its fire angle is constant. Thus by changing the ac voltage magnitude, the active power transferred by the HVDC is changed. Based on the above reason, it is possible to design operation strategy when DFIGs are directly connected with HVDC LCC.

In this configuration, the fire angles of both rectifier and inverter are kept as constant. The active power transferred through HVDC LCC is changed by varying the ac voltage magnitude at wind farm side. Shunt capacitor bank is used to provide steady state reactive power compensation. The DFIGs provides dynamic reactive power compensation for the HVDC thyristor rectifier.

3. CONTROLLERS OF DFIGS WITH CLASSICAL HVDC CONNECTION

Based on the previously discussed operation strategies, controllers of DFIGs and HVDC CSC are designed and they are simulated in Matlab/Simulink.

3.1. Dynamic models

Dynamic models using Park's transformation are developed in Matlab/Simulink [15]. All the electric models are developed in dq synchronously rotating reference frame, including generator, transformer, transmission line and etc. For the generator model, the advantage of using the Park transformation is the elimination of changes of coupling inductors in three phase windings. For the grid components, such as transformer and transmission line, the advantage is that voltages and currents under steady state and balanced three phase system after Park transformation are dc values. Large simulation time steps can be used, and thus the simulation speed is greatly improved. The models include generator, transformer, transmission line and voltage source converter. Unlike the voltage source converters using IGBTs which can be modeled by switching functions, the thyristor bridge model is difficult to be modeled because of its uncontrollable switch-off characteristics. Five models are developed in Matlab/Simulink in this paper. They are compromises between simulation purposes and simulation speed. For electromechanical simulation purpose, the quasi-steady state model is accurate enough, while for electromagnetic simulations purpose, the instantaneous model is required.

Table 1 Models of thyristor bridge

Quasi-steady state models	Model 1	Symmetrical quasi-steady model
	Model 2	Unsymmetrical quasi-steady model using Fourier analysis
	Model 3	Unsymmetrical quasi-steady model using partial symmetric
Instantaneous models	Model 4	Instantaneous model without commutation effects
	Model 5	Instantaneous model with commutation effects

These thyristor bridge models are compared with power system blockset in Matlab/Simulink and the results prove that these models are fast and accurate [15].

In this paper, the symmetrical quasi-steady state model is used, as the simulation purpose is to investigate the electromechanical interactions between DFIGs and HVDC CSC.

3.2. Controllers When STATCOM installed

When a STATCOM is installed, the DFIGs and HVDC CSC can be assumed in connection with strong power grid. ac voltage at the point of common coupling between wind farm and HVDC link is constant. Thus, the traditional grid voltage oriented controller of DFIG can be used. The grid voltage oriented control is explained in many literatures [16], [17]. The generator's voltages and currents are transformed to the synchronous rotating reference frame, which is in the direction of the grid voltage vector. The generator's stator and rotor equations in this reference frame are:

$$v_{ds} = -R_S i_{ds} - \omega_S \psi_{qs} + \frac{d\psi_{ds}}{dt} \tag{1}$$

$$v_{qs} = -R_S i_{qs} + \omega_S \psi_{ds} + \frac{d\psi_{qs}}{dt} \tag{2}$$

$$v_{dr} = -R_r i_{dr} - s\omega_S \psi_{qr} + \frac{d\psi_{dr}}{dt} \tag{3}$$

$$v_{qr} = -R_r i_{qr} + s\omega_S \psi_{dr} + \frac{d\psi_{qr}}{dt} \tag{4}$$

By aligning the reference frame in the direction of grid voltage vector, omitting the stator resistance and assuming a steady state operation, those equations are simplified to:

$$v_{ds} = -\omega_S \psi_{qs} = 0 \tag{5}$$

$$v_{qs} = \omega_S \psi_{ds} = |v_s| \tag{6}$$

$$v_{dr} = -R_r i_{dr} - s\omega_S \psi_{qr} \tag{7}$$

$$v_{qr} = -R_r i_{qr} + s\omega_S \psi_{dr} \tag{8}$$

The rotor voltage can be used to control rotor currents, and the rotor currents control the stator currents. And the generator's active and reactive powers are thus controlled by the rotor voltages as equations (9) and (10).

$$\begin{aligned} P_s &= v_{ds} i_{ds} + v_{qs} i_{qs} \\ &= v_{qs} \frac{L_m}{L_s + L_m} i_{qr} \end{aligned} \tag{9}$$

$$\begin{aligned} Q_s &= v_{qs} i_{ds} - v_{ds} i_{qs} \\ &= \frac{v_{qs}}{L_s + L_m} \psi_{ds} - \frac{v_{qs} L_m}{L_s + L_m} i_{dr} \end{aligned} \tag{10}$$

Fig. 3 shows the Simulink model of DFIG with HVDC LCC and a STATCOM.

The controller of HVDC LCC is similar to the traditional controller. The inverter is in constant fire angle mode, and the rectifier is used to control the active power flow through the HVDC LCC. The power order or current order for the rectifier controller is determined by the dc voltage of the STATCOM. Here a simple droop controller is used shown as Fig. 4 and equation (11).

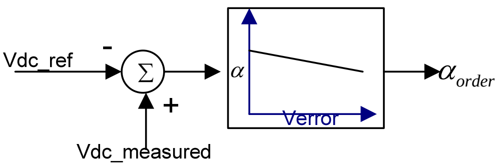

Fig. 4 Fire angle droop controller of HVDC's rectifier.

$$\alpha - \alpha_0 = D \cdot (V_{dc} - V_{dc\_ref}) \tag{11}$$

Where α, α_0 are the desired fire angle and nominal fire angle of the thyristor rectifier, respectively; V_{dc}, V_{dc_ref} are the actual and nominal dc voltage, respectively; D is the droop ratio which is a negative value.

It is used to control the dc voltage of STATCOM and thus minimize the imbalance between the power produced by wind farm and transferred through HVDC LCC. From (11), it is seen that the fire angle is reverse proportional to the dc voltage difference V_{error}. If the actual dc voltage is larger than the reference value, it implies that the active power produced by wind turbine is larger than the power transmitted through HVDC LCC. Then the fire angle α of HVDC thyristor rectifier is decreased. Consequently, the dc voltage at the rectifier side is increased, and the active power transmitted through HVDC LCC will be increased.

The simulation results of DFIG wind park with HVDC LCC connection and STATCOM are shown from Fig. 5 to Fig. 6. The STATCOM works as a transient energy buffer. It balances the active power produced by wind turbines and transmitted through HVDC LCC. Controlled by the droop controller of STATCOM's dc voltage, the fire angle of Thyristor rectifier follows the change of dc voltage and all the active power produced by wind farm are transmitted through the Thyristor Bridge. Besides, a simple feed-forward loop is added on DFIG's reactive power control loop to use DFIG to produce reactive power in proportion with its own active power. The reactive power reference depends on the power factor of Thyristor rectifier and equals to $P_{DFIG} \cdot \sin\alpha$, where α is the fire angle of the Thyristor rectifier. By this way, the reactive power consumed by Thyristor rectifier will not only be provided by STATCOM, but by all DFIGs instead. Additional function loops can be added to prevent commutation failure, dc over current and etc. However these additional function loops can be found in many literatures [8], and are not the study purpose of this paper.

In all, the STATCOM is only required to balance the active power transiently, and to provide part of the reactive power consumed by the Thyristor rectifier. Thus the required power rating of STATCOM is limited.

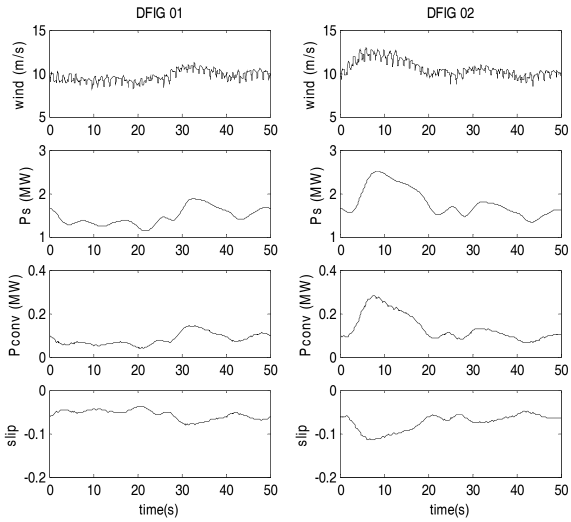

Fig. 5 DFIG - HVDC LCC with STATCOM, DFIGs' effective wind speed, stator active power, rotor active power, and generator's rotor slip

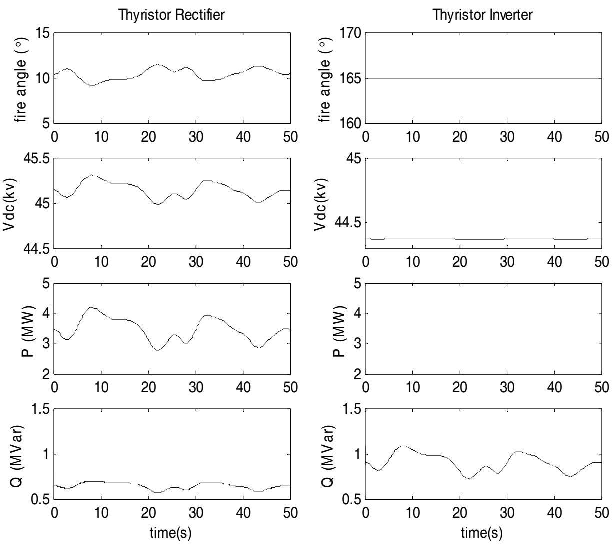

Fig. 6 DFIG - HVDC LCC with STATCOM, thyristor rectifier and inverter's fire angle, dc voltage, active and reactive power.

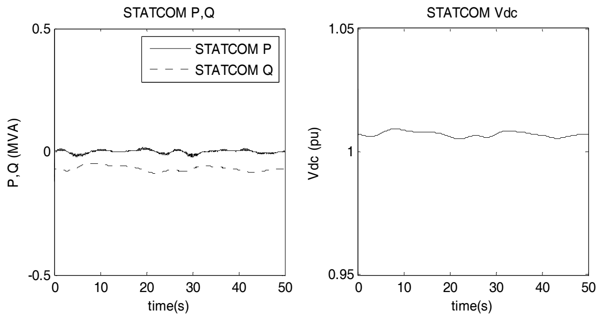

Fig. 7 DFIG - HVDC LCC with STATCOM, STATCOM's active, reactive power, and dc voltage

3.3. Controllers without STATCOM

Without STATCOM to control the ac voltage, the DFIGs and HVDC CSC cannot be assumed in connection with stiff power grid. The grid voltage oriented control of DFIG cannot be used. More important, it is difficult to determine the power that should be transferred through the HVDC link, because the varying wind speed makes the total power produced by the wind farm in uncertainty.

When the fire angle of thyristor bridge is kept constant, it is the same as a constant impedance load. Thus the DFIGs can be looked as in islanded operation with impedance load. The ac voltage magnitude can be controlled by the DFIGs' fluxes, and be used to change the power transferred by the HVDC link. In [17] the controller of a single DFIG with islanded operation is proposed. An energy storage device such as flywheel was used to balance the power produced by the DFIG and power consumed by load.

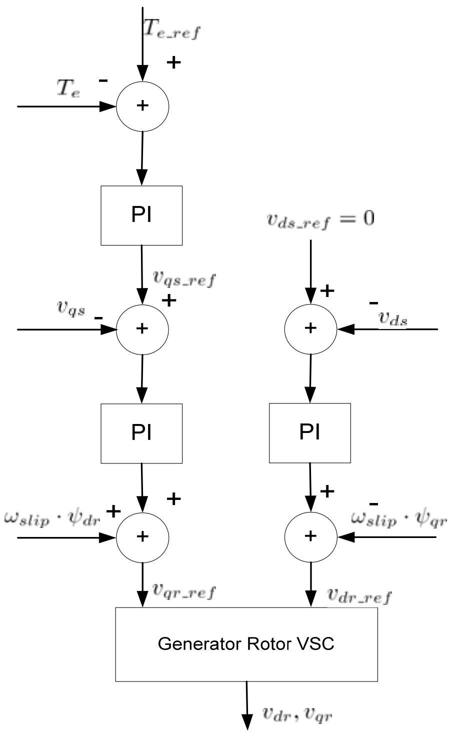

Fig. 8 Terminal voltage controller of DFIG for classical HVDC connection.

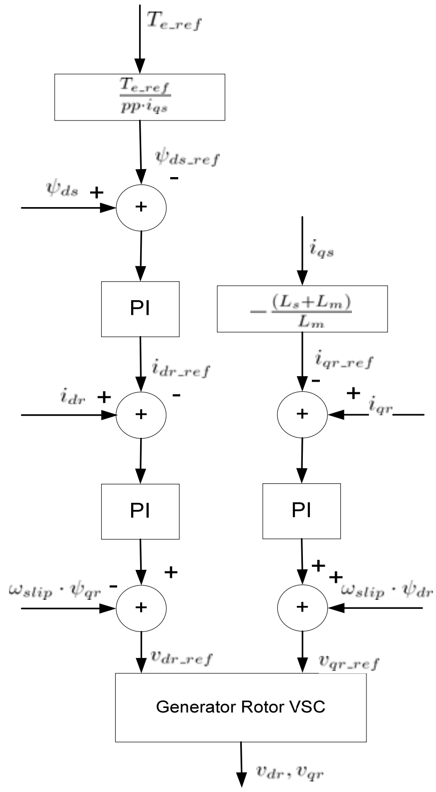

Fig. 9 Self stator flux controller of DFIG for classical HVDC connection.

In this paper, the flux level or the terminal voltage is varied in proportional with the active power, thus no energy device is required. Two controllers are designed, one is terminal voltage controller and the other is self stator flux controller. The topologies of the controllers are shown as Fig. 8 and Fig. 9.

The simulink model is similar as Fig. 3, only where the STATCOM is replaced by a shunt capacitor. Simulation results of DFIGs - classical HVDC without STATCOM are shown as Fig. 10.

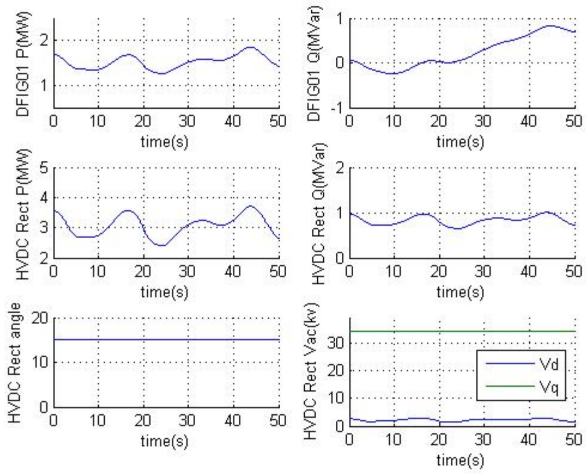

Fig. 10 DFIG - HVDC LCC without STATCOM, DFIG's active and reactive power, HVDC rectifier's active power, reactive power, fire angle, and ac voltage

Comparing with the situation with STATCOM installed in wind farm, in this configuration the reactive power has to be supported by the DFIGs. The fire angle of rectifier is kept constant, and the ac voltage is varied thus to change the total active power transferred by the HVDC link. However, because of the interactions between different DFIGs, the reactive power flow inside wind farm needs further investigation.

4. CONCLUSIONS AND RECOMMENDATIONS

In this paper, configuration of DFIGs in connection with classical HVDC link is studied. Operation strategies with and without STATCOM are proposed. Controllers of DFIGs and HVDC link are designed and simulated in Matlab/Simulink. Simulation results show that both concepts seem to work well under normal conditions. Further studies of these concepts under grid fault conditions are required.

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BIOGRAPHIES

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