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Islanded Operation and Control of Offshore Wind Farms Connected through a VSC-HVDC Link

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Abstract. A new control scheme for the operation of offshore wind farms connected through a VSC-HVDC link to the main onshore grid is presented in the paper. The control strategy has been developed to allow the islanded operation and black-start of the wind farm as these requirements will probably be of great interest in the future due to the progressive increase of distributed generation. A complete model of the offshore wind farm with a VSC-HVDC link and its control scheme has been developed and analyzed through PSCAD simulations. Results show that the proposed control scheme is able to operate the plant under different steady-state and transient conditions.

Key words

Offshore wind power, VSC-HVDC transmission systems, islanded operation of wind farms, VSC control.

1. Introduction

The use of high voltage direct current (HVDC) transmission lines with voltage source converters (VSC) at both ends of the link is gaining great attention for applications where long distance (l > 50 km) underground or submarine cables are installed. The application of VSC instead of line-commutated converters (LCC) for HVDC has some important advantages related mainly to higher control capabilities. Since 1999, when the first VSC-HVDC link for an offshore wind farm was built, this technology has continuously been developed growing in power and voltage levels. Nowadays, several wind farm projects are under development, mainly in the North of Europe, reaching voltage levels up to 300 kV for the HVDC link and power levels up to 800 MW [1].

In this kind of system, the existence of voltage source converters at both sides of the DC line together with the Front-End Inverters of the wind turbines allow the implementation of different control strategies [2]. For example, the VSC Rectifier of the DC link could be used to form the AC offshore grid providing voltage and frequency control although this task could also be provided by the Front-End Inverters. At the other side of the DC line, the VSC Inverter can contribute to stabilize the AC network, supporting frequency control through active power flow control and voltage regulation through reactive control. Finally, both the rectifier and the inverter could be used to control the DC link voltage level.

In order to develop the best control strategy for the wind farm it is paramount to consider the new requirements that could be imposed in the future to this kind of generation systems. In this sense, the "Network Code for Requirements for Grid Connection Applicable to all Generators" published by ENTSO-E in June 2012 [3] establishes different requirements for the performance of electric generators. Although not mandatory for all the generators in a specific area, one of the most severe requirements in the case of offshore wind farms could be the "Black-start capability" which requires the ability to start from shut down within a timeframe without any external supply. In the case of offshore wind farms connected through LCC-HVDC links to the main grid this requirement could be very difficult to fulfill as these systems can only connect two active networks.

The use of a VSC-HVDC link can facilitate the black-start capability of the wind farm as the VSC Rectifier can be used together with the Front-End Inverters of the turbines to form the offshore grid, controlling voltage and frequency. This islanded mode of operation could also be used to keep energized the HVDC line facilitating, in this way, the start-up procedure of the whole electrical power system in the case of a black-out or brown-out in the main grid.

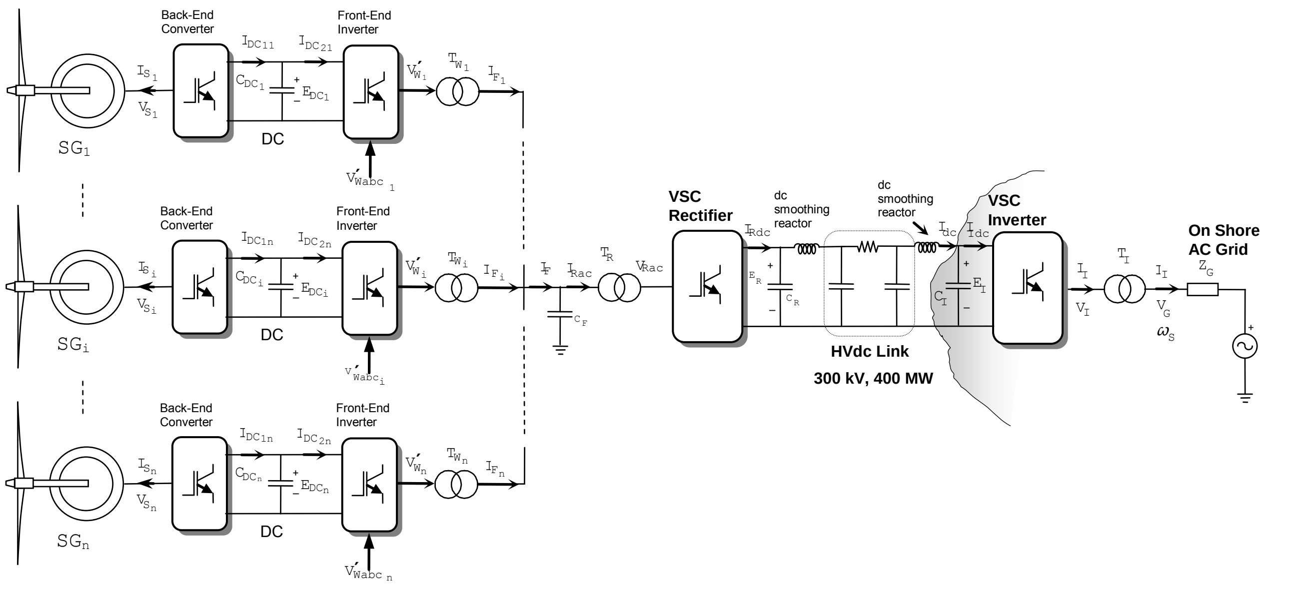

Fig. 1. Model of the wind farm with the HVDC link

The main objective of the paper is the presentation of a new control scheme for an offshore wind farm with a HVDC link allowing the control of the whole system under normal operating conditions (wind farm connected to the main grid) and under abnormal operating conditions such as islanded operation, black-start and sudden disconnection. The paper is organized as follows. Section 2 presents the model of all the components of the wind farm including the HVDC line. The control strategy is explained in Section 3 for different operation modes and simulation results are presented in Section 4.

2. System Model

A complete model of the system is shown in Fig. 1 which includes the wind turbines, the Back-End and Front-End converters for each turbine, the offshore grid with the corresponding transformers, the HVDC link with the VSC-Rectifier and the VSC-Inverter and the onshore AC grid.

The offshore wind farm is composed of a number of 5 MW permanent-magnet synchronous generators (SG) with fully rated converters. The wind turbines have been aggregated, for the sake of simplicity, into five turbines with different nominal powers (S_1 = 5 MW, S_2 = 40 MW, S_3 = 80 MW, S_4 = 120 MW, S_5 = 155 MW).

Wind turbines have been mechanically modeled using a standard equivalent of two elastically connected masses. Mechanical parameters of the set turbine-generator are extracted from [4] and shown in Table I.

Each aggregation is connected to the offshore AC grid through a transformer Tw_i. The transformer shunt branch is neglected as its magnetizing inductance is too large to be considered except for very low loads. The offshore AC-line impedances are also neglected because of their small value compared to the transformers impedances.

Table I. – Mechanical parameters

Parameter	Value
Wind turbine inertia (kg m^2)	10 x 10^6
Generator rotor inertia (kg m^2)	100 x 10^3
Shaft stiffness (Nm/rad)	1.6 10^9
Wind turbine damping (Nm/rad/s)	20
Generator rotor damping (Nm/rad/s)	100

Table II. – Electrical parameters

Front-End Transformers		
Tw_1: 5 MVA	Rw_1 = 1089.00 mΩ	Lw_1 = 41.60 mH
Tw_2: 40 MVA	Rw_2 = 136.13 mΩ	Lw_2 =5.20 mH
Tw_3: 80 MVA	Rw_3 = 68.06 mΩ	Lw_3 = 2.60 mH
Tw_4: 120 MVA	Rw_4 = 45.38 mΩ	Lw_4 = 1.73 mH
Tw_5: 155 MVA	Rw_5 = 35.13 mΩ	Lw_5 = 1.34 mH
Offshore AC grid		
V_F = 33 kV C_F = 67.5 µF		
T_R = 33/150 kV 500 MVA		
R_R = 21.78 mΩ L_R = 0.485 mH		
HVDC line		
300 kV 400 MW C_I = C_R = 35.5 µF		
Smoothing reactor = 0.1 H		
Cable: C_H = 14.08 µF L_H = 11.16 mH R_H = 1.399 Ω		
Onshore AC grid		
400 kV , L_{SG} = 0.102 H		
T_I: 150/400 kV 500 MVA R_I = 3.2 mΩ L_I =0.0713 mH		

Table III. – Generator electrical parameters

Parameter	Value
Rated voltage (kV)	2
Rated frequency (Hz)	20
R_S (mΩ)	13.6
L_{sd} (mH)	5.09
L_{sq} (mH)	6.37
λ_m (Wb)	9.31
Pole pairs p	80

The capacitor C_F represents the parallel equivalent of the capacitors used to compensate the reactive power of each offshore transformer.

The HVDC link is modeled using a T-equivalent. Characteristics of the different elements are shown in Table II according to [5] and [6]. Specific electrical parameters for the generators are shown in Table III.

3. Control scheme

The control strategy for the whole system shown in Fig. 1 has been developed in order to allow both a grid-connected mode of operation and an islanded operation. This last mode of operation will also be used for the black-start of the wind farm. For grid-connected operation the following requirements are defined:

- Maximize the active power supplied to the grid. This means that wind turbines must work at optimal rotating speed for each value of the wind speed.
- Keep offshore grid voltage and frequency and HVDC line voltage in rated values.
- Support voltage regulation for the onshore grid.

For the islanded mode of operation the following requirement are considered:

- Wind turbines must supply the active power corresponding to power losses in the whole system.
- The HVDC line must be energized keeping the voltage rated value.
- Keep offshore grid voltage and frequency values.
- Limit mechanical stresses to the wind turbines during connection and disconnection transients.
- Black-start capability.
- Limit currents during the energization of the HVDC line.

As stated before five main electrical variables are to be controlled, i.e. offshore grid voltage and frequency, P and Q flows and HVDC link voltage. Simultaneously, the wind turbines will be controlled through pitch control and electromagnetic torque control. Taking into account the stated requirements the following control functions distribution have been defined. The VSC Rectifier is responsible for the control of the HVDC link voltage level. The VSC Inverter regulates the flows of P and Q supplied to the onshore grid. Finally, the Front-End Inverters form the AC offshore grid controlling its voltage and frequency through a standard droop control.

The implementation of each of the proposed controls is described as follows.

A. Wind turbine control

The turbine rotor aerodynamics are modelled using the aerodynamic power coefficient $C_p(\lambda, \beta)$ defined in [7] where λ is the tip speed ratio and β is the pitch angle. The optimal rotating speed is achieved through electromagnetic torque control. Fig. 2 shows the wind turbine rotating speed control loop. Pitch angle control is used when the rotating speed is close to its maximum value.

The wind turbine dc-link voltage (E_{DC}) is controlled using the Back-End Converter current i_{sq} as developed in [4]. For the synchronous generator the following equations can be written adopting a synchronous reference frame rotating at w_r.

$$V_{sd} = R_s I_{sd} + L_{sd} \frac{dI_{sd}}{dt} - w_r L_{sq} I_{sq} + u_d \qquad (1)$$

$$V_{sq} = R_s I_{sq} + L_{sd} \frac{dI_{sq}}{dt} + w_r L_{sd} I_{sd} + w_r \lambda_m + u_q \qquad (2)$$

The current component I_{sd} is controlled to be null so the electromagnetic torque just depends on I_{sq} as follows:

$$T_G = 3 p \lambda_m I_{sq} \qquad (3)$$

The dc-link voltage control loop is shown in Fig. 3.

B. Offshore grid voltage and frequency control

The offshore grid can be considered as a microgrid fed by the Front-End Inverters. Its predominant inductive impedance allows the implementation of a standard f/P – V/Q droop control to properly share active and reactive powers between the inverters [9-10]. To assign the same load level for each generator the droop characteristics shown in Fig. 4 have been implemented. Electrical variables are expressed in pu, consequently, if the base power for each generator (P_{base-i}) is taken as its nominal power, all the generators will work with the same load level with respect to the nominal powers. However, wind conditions can be different for each generator so, a different distribution of powers would be of interest. In that case, P_{base-i} can be defined as the maximum available power for the i generator depending on wind speed. This maximum available power can be estimated, for example, as shown in [8]. With this strategy, all the generators have the same load level with respect to their maximum value. Thus all generators reach the maximum available power in the wind at the same time. Therefore this control strategy allows to maximize the generated power in all generators.

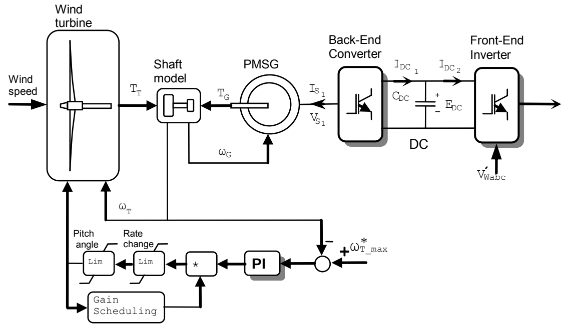

Fig. 2. Wind turbine rotating speed control loop

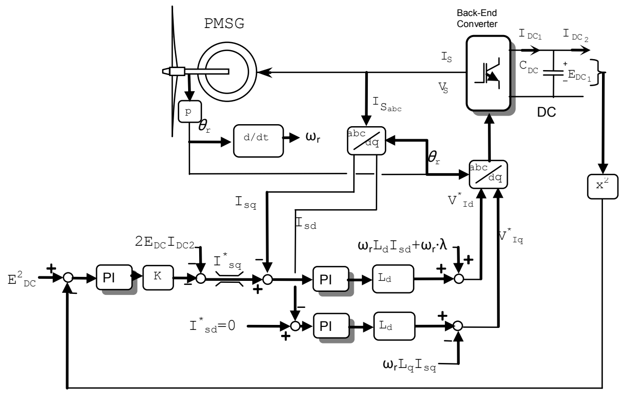

Fig. 3. Wind turbine dc-link voltage control

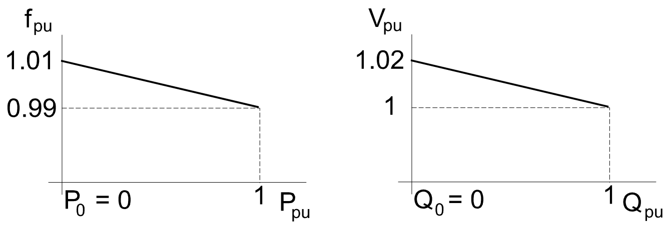

Fig. 4. Droop characteristics

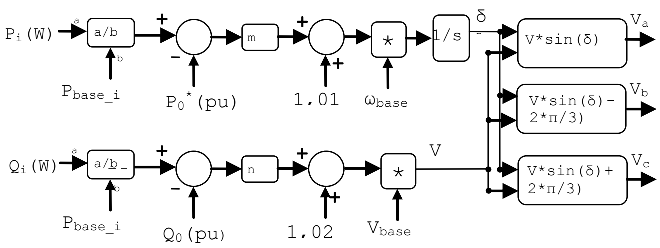

Fig. 5. Frequency and voltage control for each generator

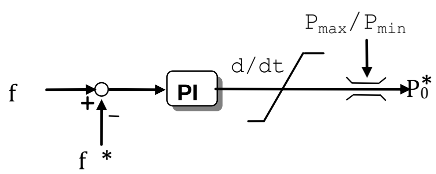

Fig. 6. Offshore grid frequency secondary control

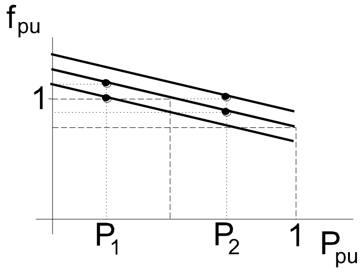

Fig. 7. Modification of the droop characteristic to avoid a permanent frequency deviation

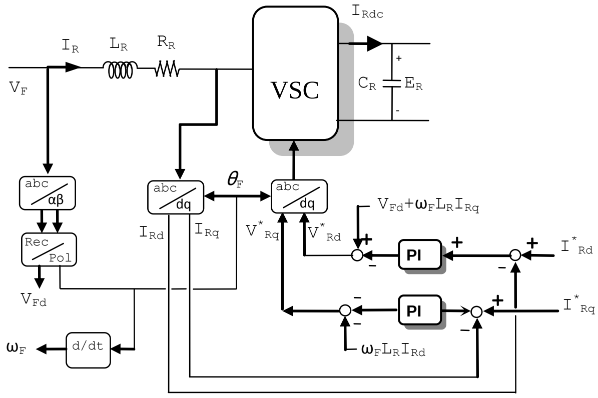

Fig. 8. Currents control loop for the VSC Rectifier

The equations corresponding to Fig. 4 are written as (4) and (5). As shown, a 2 % variation for the frequency and the voltage are allowed although broader variations could be accepted. Droop control is implemented for each generator as a local control as shown in Fig. 5. The obtained voltage signals are directly used as reference values to control the corresponding Front-End Inverter.

$$f = f_0 + m(P - P_0) = 1.01 - 0.02(P - 0) \tag{4}$$

$$V = V_0 + n(Q - Q_0) = 1.01 - 0.02(Q - 0) \tag{5}$$

To avoid a permanent deviation in the frequency of the offshore grid, the previous control is complemented with a secondary centralized control which modifies the value of P_0 for all the generators simultaneously. The control loop is shown in Fig. 6 and the effect on the droop characteristics is represented in Fig. 7 for two different operating points.

C. E_I control

The control of the HVDC link voltage is carried out by the VSC Rectifier through the control of the active current I_{Rd} in the offshore grid as explained in [2]. For the transformer T_R the following equations, equivalent to (1) and (2), can be written adopting a synchronous reference frame rotating at w_F and oriented on V_F ($V_{Fq} = 0$):

$$V_{Fd} - V_{Rd} = L_R \frac{dI_{Rd}}{dt} - w_F L_R I_{Rq} + R_R I_{Rd} \qquad (6)$$

$$0 - V_{Rq} = L_R \frac{dI_{Rq}}{dt} + w_F L_R I_{Rd} + R_R I_{Rq} \qquad (7)$$

The active current I_{Rd} can be related to the voltage E_I considering a power balance between the AC side and the DC side of the VSC Rectifier [2]. The control diagram shown in Fig. 8 and based on equations (6) and (7) is employed to regulate the active current and, consequently, the HVDC link voltage.

D. P and Q control

In the connected mode of operation, the flow of active power to the onshore grid (and consequently the power flow in the HVDC link) is controlled by the VSC Inverter using control loops equivalent to those shown in Fig. 8. In order to continuously supply the power produced by the wind plant the VSC Inverter must have information about the power generated by each generator and the maximum power available for each one according to wind speed. A communication system between the onshore VSC Inverter control system and the wind generators is necessary to maximize the active power supplied by the wind plant.

Onshore grid voltage control support can also be offered by this converter through reactive power regulation.

In the islanded mode of operation, the Front-End Converters of the wind turbines supply the active power corresponding to the power losses of the whole system. The VSC Rectifier can also be used to supply reactive power to the offshore grid.

4. Results

The described control scheme has been applied to different situations to validate its performance in steady-state and transient conditions. A special interest has been dedicated to analyse the mechanical dynamics of the wind turbines during transients. The results are explained in the following items.

A. Grid-Connected mode of operation

The results for this mode operation have been widely explained in a previous work shown in [2]. The system presents a good dynamic response for variations in the voltage, frequency and power references and has also a good ride-through capability for faults in the onshore grid.

B. Black-start and islanded operation

The black-start process is explained through Fig. 9 and Fig. 10. It is considered that an auxiliary generation system provides power to the control and operating systems of the wind plant during the start-up in islanded mode.

Initially, the HVDC link is not connected to the offshore grid. The frequency reference for the offshore grid is kept constant at 50 Hz (1 pu) and a ramp signal for the voltage reference is applied from t = 0.7 s to t = 1.5 s (Fig. 9). Once the offshore grid is formed, the HVDC line is connected to the offshore grid at t = 3 s through a current limiting resistor. At the beginning, the VSC Rectifier behaves like an uncontrolled full-bridge rectifier due to the presence of the anti-parallel diodes so, the HVDC line is energised with a voltage level of 0.707 pu ($\sqrt{2} \times 150 / 300$). Once the connection transient current is reduced, the limiting resistor is bypassed and a voltage reference ramp is set to the VSC Rectifier from t = 6 s to t = 6.5 s. The HVDC link voltage increases to 1 pu. The current peak during the process has a value of 0.2 pu.

During the islanded mode of operation, the wind turbines provide the power losses of the whole system. Fig. 10 shows the behaviour of a turbine during the start-up process considering a wind speed of 8 m/s. As the active power supplied by the wind generators is much less that the available mechanical power, the turbine tends to speed up so the pitch control takes the turbine to its maximum allowable rotating speed value (14.9 rpm). In this way, the turbines store a great amount of kinetic energy that could be useful for onshore grid restoration. It can also be seen in Fig. 10 that the mechanical power supplied by the turbines is very small, close to zero, and equivalent to the active power losses in the system. During the energization of the offshore grid first and the HVDC line later, a small increase in the mechanical and electrical powers is produced causing small variations in the turbine rotating speed. The pitch control restores the rotating speed to its reference value as shown.

C. Onshore grid connection and disconnection transients

The onshore grid connection transient process has also been simulated and the results show a good behaviour of the whole system. The wind plant is first energyzed and once the HVDC link reaches its rated voltage value, it is connected to the onshore grid. Then the active power supplied to the grid is increased up to a 1 pu value following a ramp signal. During the process, both the offshore grid and the HVDC line are able to keep the voltage and frequency rated values. The turbine mechanical variables have also been analysed and the results show that mechanical transients are not relevant. Both pitch control and electromagnetic torque control keep the turbines rotating speed and the mechanical power under specified values.

Similarly, a programmed disconnection process has been simulated when the wind plant is supplying the rated active power. First the power delivered by the VSC-Inverter to the onshore grid is reduced progressively. At the same time the pitch control of each turbine reduces the mechanical power to avoid overspeeding. When the active power supplied to the onshore grid is null, the wind farm is disconnected and starts working in the islanded mode. Both electrical and mechanical variables are satisfactorily kept under control during the process.

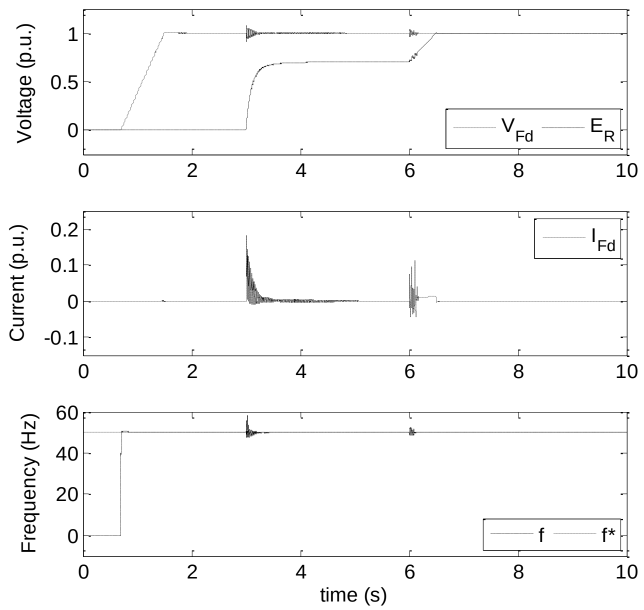

Fig. 9. Electrical variables during the start-up

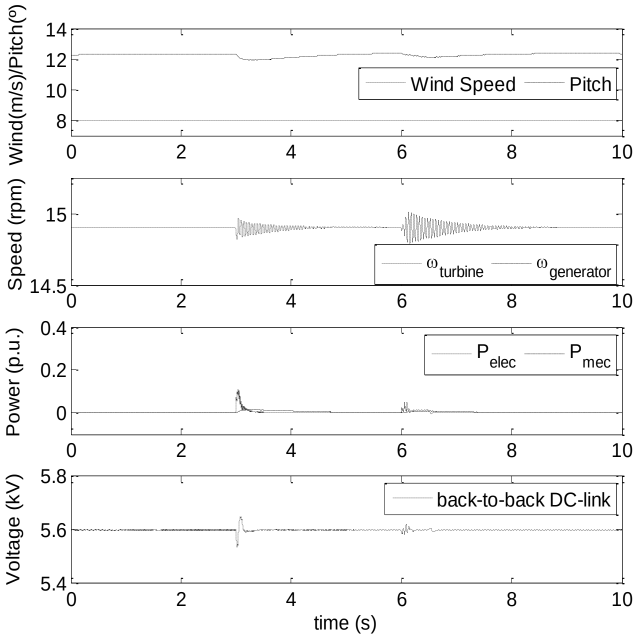

Fig. 10. Wind turbine mechanical behaviour and back-to-back DC link voltage

4. Conclusion

A new control scheme for the operation of wind farms with a HVDC link has been presented in the paper. The control system allows the operation in islanded mode and the black-start of the wind farm. A complete model of the wind plant has been derived taking into account the mechanical behaviour of the wind turbines. Simulation results show a general good behaviour of the system for different scenarios. In particular the proposed control scheme offers the following main advantages.

- In the grid-connected mode, the power supplied to the onshore grid is maximized and the VSC Inverter offers voltage regulation support to the main grid.
- The wind farm can be started up in an islanded mode of operation keeping energyzed the HVDC line for fast power system restoration if necessary. The offshore grid maintains its voltage and frequency rated values using a droop control strategy.
- The mechanical stresses to the wind turbines during all the connection and disconnection transients are limited to acceptable values.

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