Fault Ride-Through of DFIG-based Wind Farms connected to the Grid through VSC-based HVDC Link

Christian Feltes
University of Duisburg-Essen
Duisburg, Germany
christian.feltes@uni-due.de

Holger Wrede
E.ON Engineering GmbH
Gelsenkirchen, Germany
holger.wrede@eon-engineering.com

Friedrich Koch
REpower Systems AG
Rendsburg, Germany
friedrich.koch@repower.de

István Erlich
University of Duisburg-Essen
Duisburg, Germany
istvan.erlich@uni-due.de

Abstract - This paper describes two new control approaches for DFIG-based offshore wind farms connected through voltage source converter (VSC) based HVDC link with extended fault ride-through (FRT) capability. These control strategies establish a coordination between the HVDC terminals and the wind turbines, allow safe operation of the wind farm during grid faults and also fulfill the actual grid code requirements. Both introduced FRT methods utilize different means for a fast and reliable power reduction in the wind farm to protect the HVDC transmission against overvoltages, which may occur as a result of a power imbalance between sending and receiving end during grid faults. This way the costs for a high rated DC chopper can be saved. For evaluation of these approaches detailed simulation models of the HVDC and the wind turbines are presented. The simulations are carried out in MATLAB/Simulink with SimPowerSystems Toolbox. The simulation results show an example of a severe three-phase grid fault, which proves the good performance of the proposed control strategies.

Keywords - Offshore Wind Energy, Doubly Fed Induction Generator, VSC-based HVDC, Fault Ride-Through, Coordinated control

1 Introduction

THE wind energy sector experiences a huge growth all over the world. While in the early 90's only single turbines with power ratings of less than a hundred kW were installed, today offshore wind farms (OWF) are planned with capacities of more than 1000 MW. These OWF may be located far away from shore and an HVDC link (Figure 1) should be considered for their grid connection, because AC transmission length and capacity is limited due to the large charging currents of the cables.

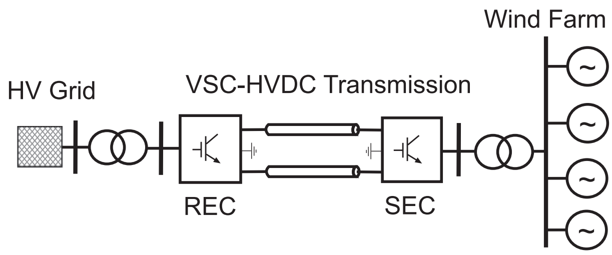

Figure 1: Wind Farm connected through VSC-based HVDC Transmission System

Since large OWF have capacities comparable to conventional power plants, grid operators require them to participate in grid voltage support in steady state and also during faults. The latter requirement means that OWF have to ride through grid faults and supply reactive currents to the grid as stated in the grid codes (e.g. the German E.ON grid code [1, 2]). This grid voltage support is the task of the grid side HVDC converter. Since the converters are using self-commutated IGBT valves, the decoupled control of active and reactive current is simple (section 3.1).
But if the wind farm is operating close to rated power when the fault occurs, the current limitation of the grid side HVDC converter with reactive current priority may lead to a reduction of its active current. Together with the reduced grid voltage, the resulting active power flow to the grid may become very small. Without a coordinated control of the HVDC link and the wind turbines this would lead to a significant unbalance between sending and receiving end power of the HVDC. As a result, the DC transmission voltage would increase rapidly, which is unacceptable. One way to limit the HVDC voltage is the use of a huge DC chopper to dissipate the excess power. But this solution requires a chopper rated for the full WF power, leading to higher investment costs. With the proposed control the active power output of the DFIG wind turbines can be reduced very fast and the DC transmission voltage can be maintained at an acceptable level without the need for a full-rated DC chopper.
Section 2 gives a short introduction to some requirements of the German E.ON grid code. Section 3 describes the HVDC system and its control. In section 4 the DFIG system is explained. In section 5 two methods for FRT of the system are introduced. Section 6 shows simulaton results and section 7 finally gives some conclusions.

2 Grid Code Requirements

In the past wind turbines were separated from the grid following grid faults. However, as of now, separation of wind turbines for voltage values below 80% of the nominal voltage would lead to loss of an undesirable portion of power generation. Therefore, utilities now require an FRT capability as specified in Fig. 2. Wind turbine must stay connected even when the voltage at the point of common coupling (PCC) with the grid drops to zero. The 150-ms

delay shown in the figure accounts for the normal operating time of protection relays. The red solid line in Fig. 2 marks the lower voltage boundary rather than any characteristic voltage behavior.
According to the new E.on (one of the major utilities in Germany) grid code of 2006 [3] short term interruption (STI) is allowed under specific circumstances. STI in area 3 requires resynchronization within 2 s and a power increase rate of at least 10% of the nominal power per second. In area 2 the interruption time allowed is much less, just a few hundred milliseconds. During fault-ride through, reactive power supply by wind turbines is a requirement. According to the German grid code wind turbines have to provide a mandatory voltage support during voltage dips. The corresponding voltage control characteristics are summarized in Fig.3. Accordingly wind turbines have to supply at least 1.0 p.u. reactive current already when the voltage falls below 50%. A dead band of 10% is introduced. Actually, for wind farms connected to the high voltage (HV) grid continuous voltage control without dead band is also under consideration.

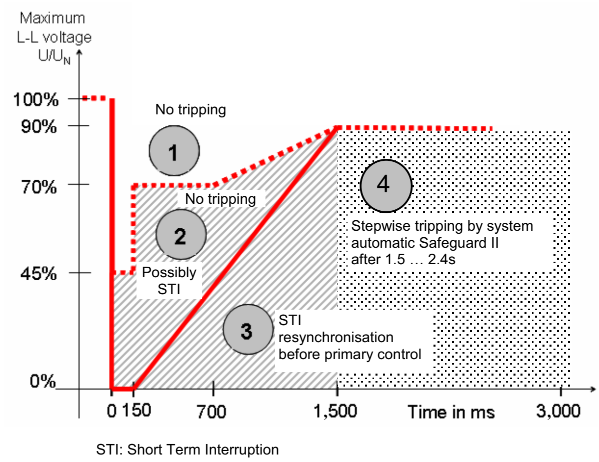

Figure 2: Fault-ride through requirements

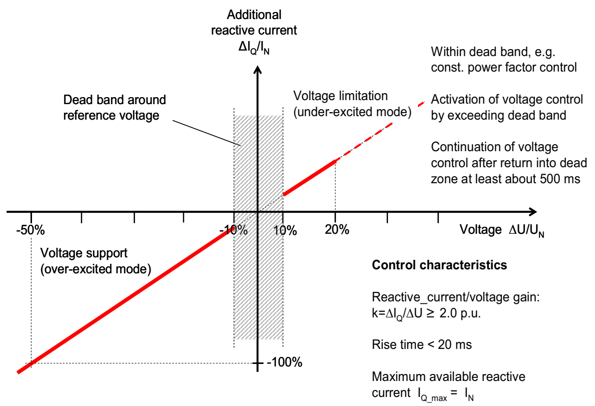

Figure 3: Characteristic of wind turbine voltage control

3 VSC-based HVDC

VSC-based HVDC transmission is applicable for connection of large offshore wind farms over long distances. The manufacturers offer systems with a transfer capability of 1100 MW at a DC transmission voltage of $\pm$300 kV [4]. The transmission lengths are only restricted through the losses in the cable resistances. The commonly used VSC system for HVDC is based on a two-level topology (Fig. 4). Each converter consists of 6 semiconductor switching devices, commutating inductors, harmonic filters and the DC-circuit capacitors.

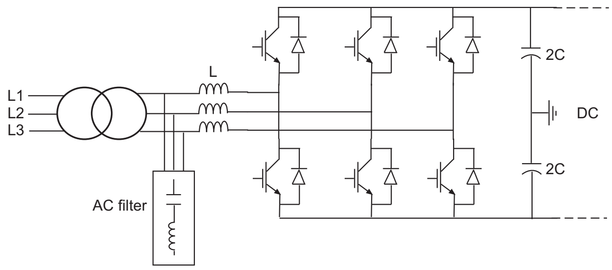

Figure 4: Two-level VSC

This topology is the simplest VSC-configuration as it requires a simple control, but it has high switching losses, especially at low power transfer. A lot of research has been done about alternative topologies, e.g. multi-level topologies and special soft-switching strategies. But the two-level topology is chosen because of its simplicity. The focus of this study is more on the FRT control methods used for coordination of the HVDC and the DFIG wind farm during grid faults. Those methods can be applied to different VSC topologies.

3.1 *Receiving End Converter*

The function of the receiving end converter (REC) is to feed in the active power transmitted by the sending end converter (SEC) while maintaining the DC voltage at the desired level. The reactive power channel is used to support the grid voltage during faults and also in steady-state [5, 6]. The control structure for the REC is shown in Fig. 5.

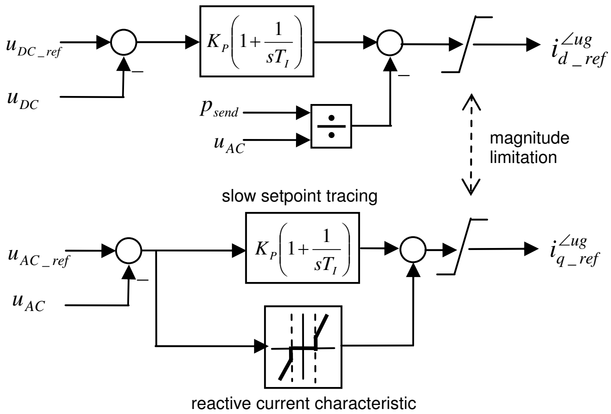

Figure 5: DC and AC voltage control of receiving end VSC

The PI-controller maintains DC voltage through active converter current under consideration of a feed-forward term representing the power transfer through the DC link. AC voltage control is performed by two controllers. The PI controller in the upper branch is slow and only responsible for set-point tracing in steady-state operation. The controller in the lower branch is a fast P controller with deadband. It is activated when the voltage error exceeds 0.1 p.u. and it is responsible for grid voltage support during faults. The magnitude of the current outputs is limited. In steady-state operation the DC voltage control and thus the d-component of the REC current has higher priority. In case of grid fault the priority is switched to reactive current to fulfill the grid code requirements concerning voltage support. The decoupled control of active and reactive current is achieved by a feed-forward current control with a very good dynamic response [7]. This control is based on a vector control approach with its rotating reference frame aligned to the grid voltage. Due to voltage orientation, active power can be controlled through d- and reactive power through q-component of the converter current. The utilized current control structure makes use of standard PI controllers (Fig. 6). The magnitude of the output voltages is limited by maximum modulation degree and DC voltage.

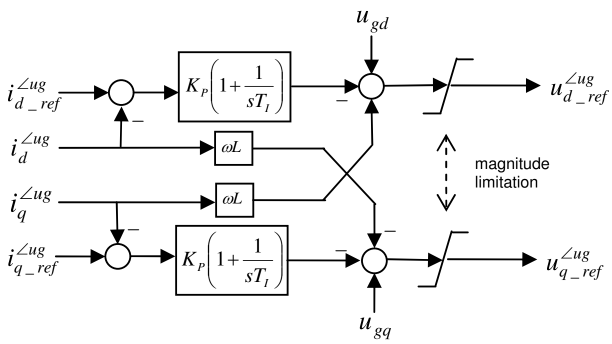

Figure 6: Feed-forward Decoupled Current Control

3.2 Sending End Converter

The SEC is responsible for transmitting the active power produced by the wind farm, while maintaining the AC voltage in the wind farm grid. Furthermore, it can be used for frequency control which in turn controls the slip of the DFIGs connected to the wind turbines. This may be used for reduction of active power transfer through the fractional rated converter in the DFIG rotor circuit [8]. As the power control is performed by the wind turbines, a simple voltage magnitude controller can be used for the SEC, thus fulfilling the aforementioned requirements. The frequency can be directly regulated without the need for a closed loop structure. Figure 7 shows the control structure of the SEC.

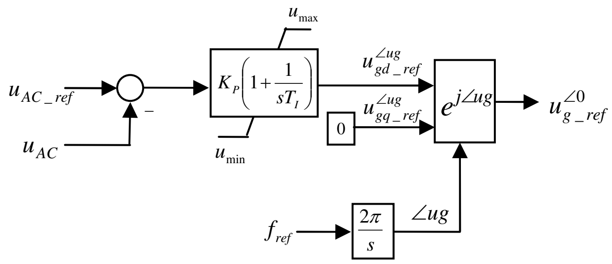

Figure 7: Sending end VSC control

Since no current control is used, a current limitation can only be achieved with an indirect method or by blocking the IGBTs during a severe fault in the wind farm grid. The voltage control capability of the SEC can be used to initiate a controlled voltage drop to reduce the WF power during FRT in HV grid.

4 DFIG-based wind turbines

The most commonly used generator type in modern wind turbines is the DFIG. A typical layout of a DFIG system is shown in Fig. 8. The back-to-back frequency converter in combination with pitch control of the rotor blades enable variable speed operation, leading to higher energy yields compared to fixed speed wind turbines. Since the IGBT-converter is located in the rotor circuit, it only has to be rated to a small portion of the total generator power (typically 20-30%, depending on the desired speed range). A rotor crowbar is used to protect the rotor side converter against over-currents and the DC capacitors against over-voltages [9]. A line inductor and an AC filter are used at the grid side converter to improve the power quality.

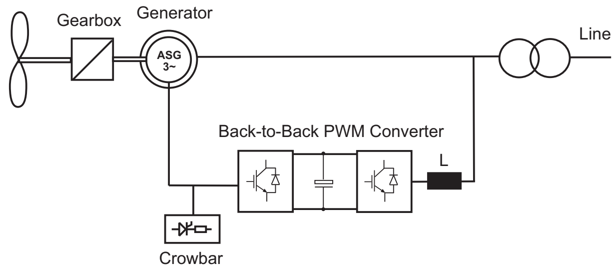

Figure 8: DFIG based wind turbine system

In a DFIG system the function of the grid side converter is to maintain the DC voltage and to support the grid with reactive power during a fault. Especially when the machine rotor is short circuited through the crowbar resistors, the generator consumes reactive power. This reactive power has to be compensated by the grid side converter. The rotor side converter controls active and reactive power of the DFIG and follows a tracking characteristic to adjust the generator speed for optimal power generation depending on wind speed. Both converter controls are using a feed-forward decoupled current control [10] similar to that used for the REC of the VSC-based HVDC. When the wind speed exceeds its nominal value, the pitch control reduces the mechanical torque by pitching the rotor blades to recover the generator rated speed. A detailed description of the complete DFIG control system can be found in [11].

5 FRT methods

To secure fault ride-through of the described system it has to be ensured that the generated wind power can be dissipated through the HVDC. Otherwise the HVDC voltage would increase above the acceptable limits. This can be avoided by use of a DC chopper rated for the full WF power, but this means higher investment costs. Another way, which is favoured here, is a coordinated control of REC, SEC and the DFIG WTs with a WF power reduction after fault detection.

When a fault occurs on the HV grid side, the receiving end HVDC converter can only deliver a small portion of the generated power to the grid, according to the following relationship:

$$p_{RC} = |\underline{u}_{RC}| i_{a,RC} \tag{1}$$

p_{RC}: Active power at REC in p.u.
u_{RC}: AC voltage at REC in p.u.
$i_{a,RC}$: Active current at REC in p.u.

During fault the current limitation of the REC switches to reactive current priority as a result of required voltage support, i.e., the active current is limited to:

$$i_{a,RC,lim} = \sqrt{i_{RC,lim}^2 - i_{r,RC}^2} \quad (2)$$

$i_{a,RC,lim}$: Active current limit at REC in p.u.
$i_{RC,lim}$: Current magnitude limit at REC in p.u.
$i_{r,RC}$: Reactive current at REC in p.u.

with reactive current according to the grid support characteristic:

$$i_{r,RC} = \begin{cases} 2(u_{RC} - u_{ref}), & \text{if } |u_{RC} - u_{ref}| \leqq 0.5p.u. \\ -1p.u., & \text{if } |u_{RC} - u_{ref}| > 0.5p.u. \end{cases} \quad (3)$$

u_{ref}: Pre-fault value of AC voltage at REC in p.u.

the maximum transferable power $p_{max,RC}$ (in p.u.) is:

$$p_{max,RC} = |u_{RC}|\sqrt{i_{RC,lim}^2 - i_{r,RC}^2} \quad (4)$$

To avoid a continous increase of the HVDC voltage, a power reduction in the WF has to be implemented. There are several ways for the realiziation, of which two will be discussed here:

- Reduction of WT output power by changing the active current setpoint in the machine side converter control.
- Controlled voltage drop in the wind farm grid with indirect power reduction.

5.1 *Active current reduction in the WT generator control*

This FRT approach requires full communication between the HVDC converters and the wind turbines. After fault detection at the REC, the active power of the WT generators can be reduced according to the following relationship:

$$p_{ref,WTi} = \begin{cases} p_{ref0,WTi}\frac{p_{max,RC}}{p_{0,WF}}, & \text{if } p_{max,RC} \leqq p_{0,WF} \\ p_{ref0,WTi}, & \text{if } p_{max,RC} > p_{0,WF} \end{cases} \quad (5)$$

$p_{ref,WTi}$: Active power setpoint of WT i in p.u.
$p_{ref0,WTi}$: Pre-fault active power setpoint of WT i in p.u.
$p_{0,WF}$: Pre-fault total active power of the WF in p.u.

In this setpoint calculation the transmission losses are neglected, bringing along a safety margin to avoid a power excess on the WF side HVDC converter. The resulting reference value is passed to the DFIG converter, which controls the rotor current of the generator to reach this value. Using this approach, the WF voltage is kept at a constant level. A communication delay between the two HVDC terminals and the WTs has to be considered.

5.2 *Controlled voltage drop in the WF grid*

This FRT method only requires communication between the two HVDC terminals. After fault detection the WF voltage is reduced to effect an indirect power lmitation of the WTs. The voltage support feature of the WTs should be disabled in this case. To enable a power balance between SEC and REC, the WF voltage has to be reduced to:

$$u_{ref,WF} = \begin{cases} \frac{p_{max,RC}}{i_{a,WF}}, & \text{if } p_{max,RC} \leqq p_{0,WF} \\ u_{ref0,WF}, & \text{if } p_{max,RC} > p_{0,WF} \end{cases} \quad (6)$$

Since no communication between HVDC and WTs and thus no direct power setpoint reduction is assumed here, the WTs will react to the voltage drop by increasing their active currents inside the limits. This has to be corrected by the HVDC voltage control through a further reduction of the WF voltage. The active current limits of the wind turbine should be set to a value close to rated current for this application anyway.
The controlled voltage drop in the WF grid should be done as fast as possible to maintain the HVDC voltage at an acceptable level. But if the voltage drop is too steep, it is like a short circuit for the generators, leading to DFIG short circuit currents [12] including high peaks and DC components. This also means mechanical stress for the generator and also for the DFIG converter. In worst case this may lead to a crowbar ignition at the DFIGs, which brings along a strongly restricted controlability and should be avoided urgently.
To get a fast voltage drop without the DC components in the generator currents a new method based on directed demagnetization of the machines is used here. For a simple explanation of this approach a virtual converter flux is introduced equivalent to the stator fluxes of the WT generators:

$$\underline{\psi}_{virt}(t) = \int \underline{u}_{conv}(t)dt + \underline{\psi}_{virt0} \quad (7)$$

$\underline{\psi}_{virt}$: Space vector of virtual flux in p.u.
$\underline{u}_{conv}$: Space vector of converter voltage in p.u.
$\underline{\psi}_{virt0}$: Space vector of initial virtual flux in p.u.

Figure 9 shows the effect of a steep voltage drop on this virtual flux without directed demagnetization.

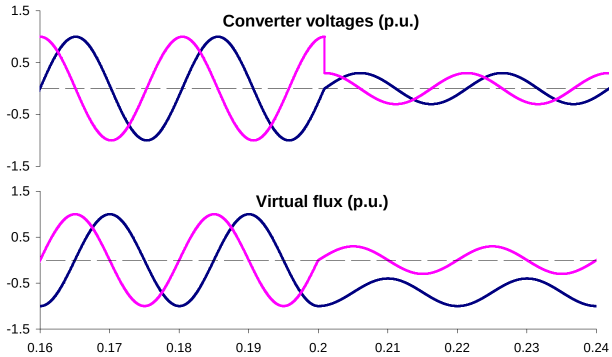

Figure 9: α,β-components of converter voltage and virtual flux during hard voltage drop

A DC offset in the flux also means DC components in the WF currents, which decay slowly with a time constant

depending on grid and generator parameters. Those DC components lead to high peak currents of the WT generators, which are fed to the offshore grid and have to be considered by additional reserve margins in the power electronics layout of the SEC. They also have an impact on the DFIG converter and may cause a fast increase of the DC link voltage, which triggers the protection circuits of the DFIG and may in worst case lead to a crowbar ignition. Additionally mechanical stress for the generators and the whole WT drive train is caused by this peak currents.
To suppress the DC offset in the virtual flux a time window is reserved for a smooth transition of the virtual flux magnitude from pre-fault value to the value during fault. The size of the time window depends on the maximum producible converter voltage. 5 ms are chosen here. The virtual fluxes at beginning and end of the time window can be calculated from converter voltage setpoints before and during fault (eq.6) by:

$$\underline{\psi}_{virt} = \frac{\underline{u}_{conv}}{\omega_0} e^{-j\frac{\pi}{2}} \tag{8}$$

ω_0: WF grid angular frequency in p.u.

When a linear flux transition is desired for demagnetization of the generators, the transition voltage can be calculated by:

$$\begin{aligned} \underline{u}_{tr} &= \frac{d\underline{\psi}_{virt}}{dt} = \frac{\Delta \underline{\psi}_{virt}}{\Delta t} \\ &= \frac{\underline{u}_{conv}(t_f + t_{tr}) - \underline{u}_{conv}(t_f)}{\omega_0 t_{tr}} e^{-j\frac{\pi}{2}} \end{aligned} \tag{9}$$

u_{tr}: Transition voltage at the HVDC converter in p.u.
t_f: Starting time of controlled voltage drop
t_{tr}: Transition time

Figure 10 shows the effect of a controlled voltage drop with directed demagnetization on the virtual flux. It contains no DC components.

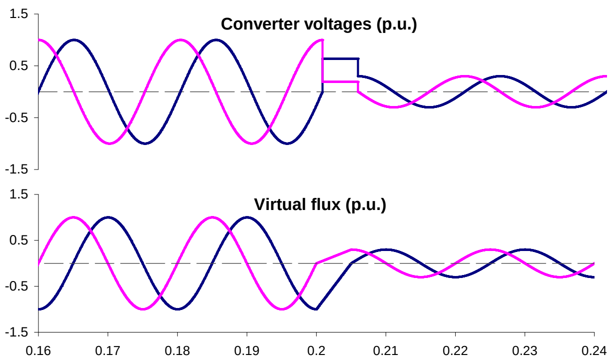

Figure 10: α,β-components of converter voltage and virtual flux during controlled voltage drop

Another way to prevent the DC offsets in the generator fluxes is an independent time-triggered voltage drop in all three phases. In this approach the voltage drop is triggered on the zero-crossings of the virtual flux. The results are similar to the previous method and not shown here.

6 Simulation results

Simulations have been carried out under MATLAB/Simulink with SimPowerSystems Toolbox using instantaneous value calculation. For the equivalent wind farm model a fifth-order induction generator model is used and the IGBT converters of the WT and HVDC are modeled as ideal switches with antiparallel diodes. The simulated test system consists of a 180 MW wind farm equivalent connected to the HV grid through a 200 MVA VSC-based HVDC system with a transmission voltage of $\pm$ 100 kV at a transmission length of 100 km.
The first simulation scenario (Fig.11) shows the behaviour of the system, when a three-phase grid fault occurs at a remote location in the HV grid leading to a voltage drop to approx. 20% of the rated voltage at the receiving end HVDC terminal. For this case the first FRT method (section 5.1) with full communication between the WF side HVDC terminal and the WTs is assumed. After fault detection the REC contributes in voltage support through reactive current. The setpoint of the WT active power controller is reduced after an estimated communication delay of 10 ms to avoid a steady imbalance between HVDC sending end and receiving end power. Due to the inertia of the WT power control there is a temporary power imbalance that leads to an overshoot of the HVDC voltage to approx. 135%. This is not critical for the cables, but it has to be considered in the converter design. The generator torque shows a very smooth behaviour and there is no mechanical stress for the wind turbines. After fault clearance the wind farm output power is increased with a ramp function to ensure a smooth power up of the system.
The second simulation scenario (Fig.12) shows the system response to the same fault in the HV grid, but with a different FRT strategy. In this case the controlled voltage drop (section 5.2) with directed demagnitization in the wind farm grid is started 10 ms after fault detection. The behaviour on the HV grid side is nearly the same as in the first scenario and characterized again by the grid voltage support of the HVDC converter. On the wind farm side the behaviour is the opposite to the case before. Voltage is reduced instead of current and the current is kept nearly constant. The variations in the current result from errors in the calculation of the transition voltage and from software switching actions inside the controller. In this case the WF active power is reduced much faster. I.e. that this FRT approach leads to a smaller overshoot in the HVDC voltages to approx. 120 %. The generator torque shows some oscillations that are very small and well damped. After fault clearance the WF voltage is increased with a ramp function to its pre-fault value leading to a smooth power up.

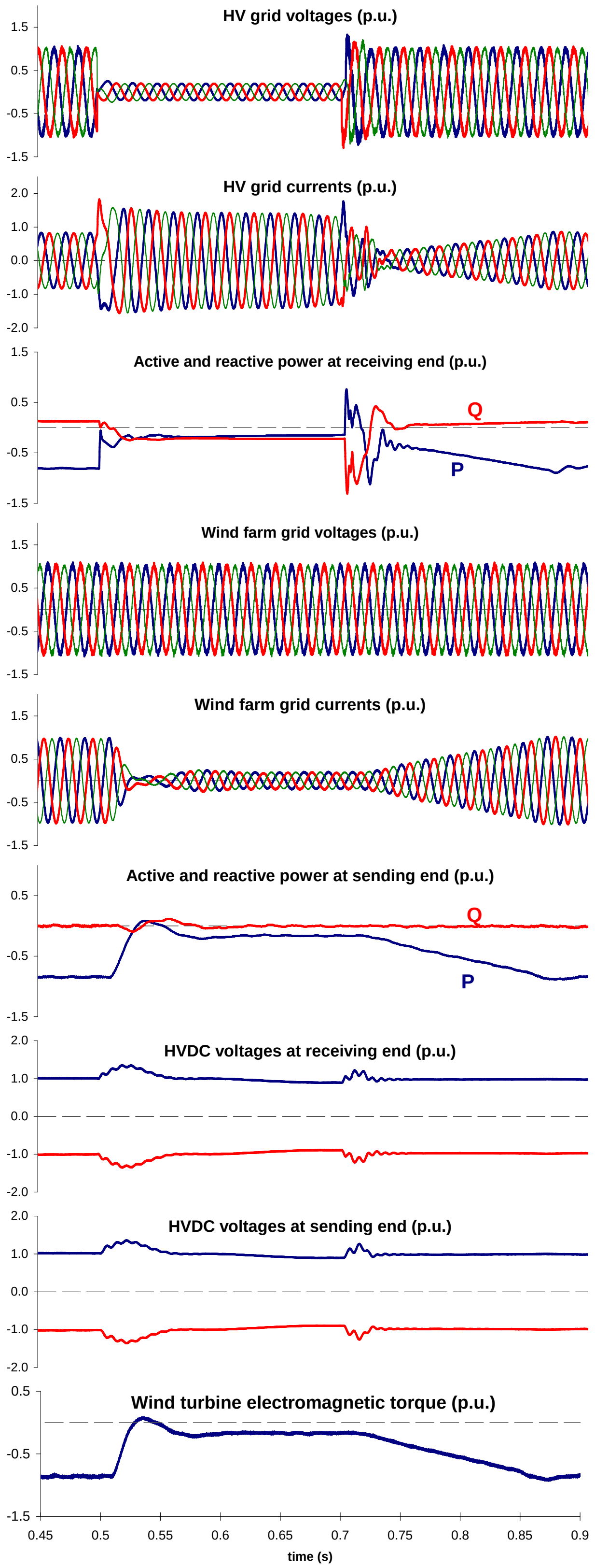

Figure 11: Simulation results for a three-phase fault in the HV grid with coordination of HVDC and WF with output power reduction through current control

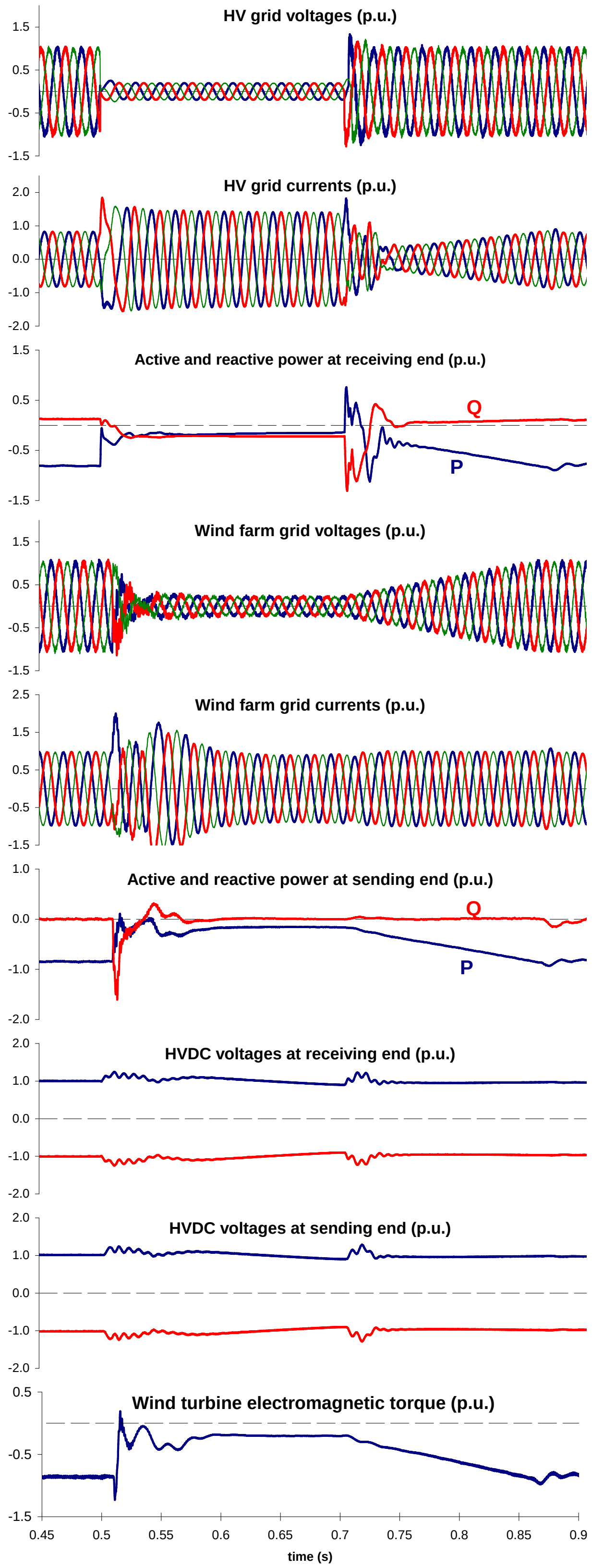

Figure 12: Simulation results for a three-phase fault in the HV grid with coordination of HVDC and WF with output power reduction through voltage control

7 Conclusion

This paper deals with two solutions for securing FRT of a wind farm connected to the grid through VSC-based HVDC transmission. The first described method is using full communication between HVDC and WF and reducing the output power of the WTs through power setpoint adjustment, when a fault occurs in the connected HV grid. The control recovers the power balance between sending and receiving end of the HVDC and limits the HVDC voltage to 135% of its nominal value. This short-time voltage overshoot is acceptable for the HVDC cables, but it has to be considered in the converter design.

The second FRT method initiates a voltage drop in the WF grid after fault detection in the HV grid. This method even allows a faster reduction of the WF output power and limits the HVDC voltage to 120%. Through directed demagnetization of the WT generators this approach prevents the typical DFIG short circuit currents with DC components and reduces the mechanical stress to the generator and the drive train. Compared to a real three-phase short circuit the impact on the DFIG converter is also reduced to a minimum. Additionally, this approach does not require communication between HVDC terminals and WTs and only small modifications in the control of existing DFIG-based WTs.

REFERENCES

[1] I. Erlich, U. Bachmann: Grid code requirements concerning connection and operation of wind turbines in Germany, Power Engineering Society General Meeting, 2005. IEEE, June 12-16, 2005 Page(s): 2230 - 2234

[2] I. Erlich, W. Winter, A. Dittrich: Advanced Grid Requirements for the Integration of Wind Turbines into the German Transmission System, IEEE-PES General Meeting Montreal 2006, panel paper 06GM0837

[3] E.ON Netz GmbH: Netzanschlussregeln Hoch- und Höchstspannung, April 2006

[4] ABB: Technical description of HVDC Light technology, rev. 2, Februar 2006, [online], Available: http://www.abb.com

[5] Y. Jiang-Hafner, M. Hyttinen, B. Paajarvi: On the short circuit current contribution of HVDC Light, in Proc. 2002 IEEE Transmission and Distribution Conference and Exhibition 2002: Asia Pacific.

[6] Yin Ming, Li Gengyin, et al.: Modeling of VSC-HVDC and its Active Power Control Scheme, in Proc. 2006 IEEE International Conference on Power System Technology

[7] S. Ruihua, Z. Chao, et al.: VSCs based HVDC and its control strategy, Proc. 2005 IEEE Power Engineering Society Transmission and Distribution Conf.

[8] C.Feltes, I.Erlich: Variable Frequency Operation of DFIG based Wind Farms connected to the Grid through VSC-HVDC Link, in Proc. 2006 IEEE Power Engineering Society General Meeting

[9] I. Erlich, H. Wrede, C. Feltes: Dynamic Behavior of DFIG-Based Wind Turbines during Grid Faults, in Proc. 2007 IEEE Power Conversion Conference - Nagoya, 2007. PCC '07

[10] R. Pena, J. C. Clare, G. M. Asher: Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation, in Proc. 1996 IEE Electric Power Applications

[11] I. Erlich, J. Kretschmann, J. Fortmann, et al.: Modeling of Wind Turbines based on Doubly-Fed Induction Generators for Power System Stability Studies, IEEE 2007 Transactions on Power Systems, Volume 22, Issue 3, Pages 909-919

[12] M.S. Vicatos, J.A. Tegopoulos: Transient State Analysis of a Doubly-Fed Induction Generator under Three Phase Short Circuit, IEEE 1991 Transactions on Energy Conversion, Vol. 6, No.1