Variable Frequency Operation of DFIG based Wind Farms connected to the Grid through VSC-HVDC Link

C. Feltes and I. Erlich, *Senior Member, IEEE*

Abstract--**High voltage DC transmission using voltage source converters is a quite new technology for the interconnection of offshore wind farms. It facilitates variable frequency operation in the wind farm grid, which can be used for improving the performance of the wind turbines. In this paper a new approach for the coordinated control of voltage source converter based HVDC and wind turbines equipped with doubly-fed induction generators is introduced. Variable frequency can be used to reduce the machine slip. Thus a lower rated converter is sufficient for the same speed range. Alternatively, the slip-limiting operation can be used for extending the speed range while keeping the converter rating at the same level. The basics of variable frequency operation of doubly-fed induction generators are discussed, and the performance is evaluated by a simulation model in MATLAB/Simulink.**

Index Terms—**Wind power, control system, coordinated control, doubly-fed induction generator, VSC-based HVDC.**

I. INTRODUCTION

RECENTLY there has been a huge development in the wind energy sector all over the world. Latest statistics show that Germany is the world's leading wind energy producer with an installed capacity of 19,299MW and 18,054 wind turbines [1]. This makes approx. 6.8% of Germany's annual energy production. Since the best onshore locations are already occupied, future trends in wind energy development will be to replace the old, small-rated units or to go offshore. The former will only allow a small increase in installed capacity, while the latter seems to be more promising. Approximately 20-25GW offshore wind power is expected in the German North and Baltic Sea by 2030 [2].

Some offshore wind farms will be located far away from the shore. The HVAC transmission for such a long distance is not economical due to the large charging currents of the sea cables. Therefore, a HVDC link is more appropriate, because there are no charging currents in the steady state allowing for higher transmission voltages and power ratings. Mainly, there are two HVDC technologies available in the market which differs in their converter technology. Conventional HVDC transmission using line-commutated thyristor valves is characterized by very high transmission voltage and power. and it also has low transmission losses. On the other hand it has some restrictions. Due to the low degree of controllability and the converter's reactive power consumption, weak networks cannot be connected to this system.

Voltage source converter (VSC) based HVDC transmission, using self-commutated valves (IGBTs, IGCTs and GTOs) is only available for low voltage and power ratings. It is more expensive and has high transmission losses [3]. But there are also some significant advantages, which make it suitable for the connection of off-shore wind farms:

- Independent and fast control of active and reactive power
- Contribution to voltage stability and transient stability of the connected AC networks through AC voltage control
- Black start capability
- Connection to weak or even passive networks is possible
- Power flow direction can be changed instantly
- Smaller footprint of the converter stations requires smaller offshore platforms
- Variable Frequency operation in the wind farm grid offers new control options for the connected wind turbines

Additionally, new soft-switching topologies for VSC-based HVDC can significantly reduce the converter losses and make this kind of transmission more economical and reliable [4]. The operation of a wind farm connected to a VSC-based HVDC differs from that of the wind farms connected through conventional AC transmission.

This paper describes a new approach for the coordinated control of the HVDC system and the connected wind turbines equipped with doubly-fed induction generators (DFIG). Since VSC-based HVDC and DFIG are well-known technologies, several control strategies have been developed. In this paper the state of the art controls are used and slightly modified for coordinated control at variable frequency in the wind farm grid. A sliding frequency can be used to extend the speed variability of the connected wind turbines and to improve their wind power usage.

There are some approaches using this option for wind farms consisting of squirrel cage induction machine (SCIM)

C.Feltes is with the University Duisburg-Essen, 47057 Duisburg, Germany, (e-mail: christian.feltes@uni-duisburg-essen.de).
I. Erlich is with the University Duisburg-Essen, 47057 Duisburg, Germany, (e-mail: istvan.erlich@uni-duisburg-essen.de).

1-4244-1298-6/07/$25.00 ©2007 IEEE.

based wind turbines [5], [6]. But in a large offshore wind farm the distribution of the turbines over a wide area and the resulting differences in wind speed make it difficult to utilize the frequency control for a real power enhancement. The frequency control can only track a group optimum, which may be far away from the individual optima of the wind turbines. Additionally, saturation effects of the generators and transformers for low frequency as well as field weakening effects for high frequency further limit the resulting speed range.

DFIG based wind turbines are already designed for variable speed operation and their control aims to adjust the generator speed to the point of best wind power usage within their speed limits. The speed range of a DFIG is determined by the converter rating and is typically about ±30% of the synchronous speed. Fig. 1 shows a typical tracking characteristic of a DFIG wind turbine. It is obvious, that the real tracking curve is far away from optimal tracking due to limited speed range.

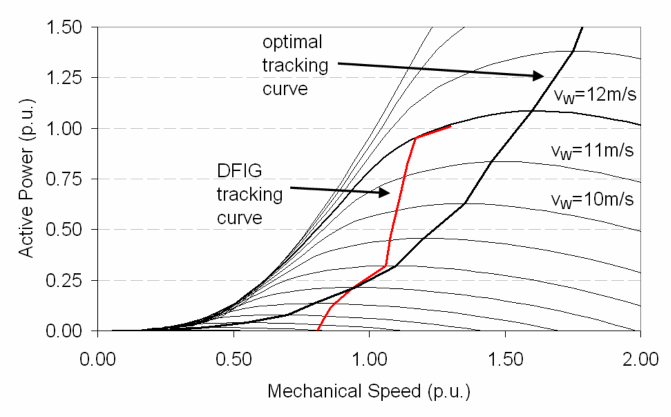

Fig. 1. Tracking characteristic of a typical DFIG

To converge to the optimal tracking curve, the speed range of the DFIG has to be extended. But higher generator speeds also mean higher mechanical stress on the rotor blades and the gearbox. Additionally, an extension of speed range at fixed stator frequency causes a higher machine slip and thus higher rotor power flows through the machine converter.

A variable frequency operation of the wind farm grid can be used to avoid the necessity for a higher rated converter, because the machine slip can be limited. The frequency control shifts the allowable generator speed range taking into consideration the mean mechanical speed of all connected wind turbine generators. Using a modified tracking characteristic, which considers frequency dependence, the tracking point of each turbine is determined by its individual optimum in the shifted speed range. Since the frequency range of the wind farm grid is limited, the resulting power tracking will not be optimal, but enhanced without the need for a bigger converter.

Alternatively, the sliding frequency can be used to limit the machine slip for the given speed range without modifying the DFIG tracking curve. This approach leads to a reduction of rotor power and a smaller load for the wind turbine frequency converter. Therefore, control strategies can be used to limit maximum or mean slip of the connected wind turbine generators. The performance of these approaches is discussed in chapter IV. As rotor power is limited, the grid side converter can be down-rated which helps to cut down the cost without overloading the converter. Additionally, this approach does not require any modifications in the mechanical part of the wind turbine and is therefore preferred.

In this paper the basics of the DFIG variable frequency operation are explained. The advantages as well as the limitations of this operation are derived based on the simulation results. Section II and III describe the HVDC and the DFIG system as well as their control strategies. In section IV variable frequency operation is discussed and section V describes the simulation model in MATLAB/Simulink and presents some results. Finally the advantages and restrictions of the variable frequency operation are concluded in section VI.

II. VSC-BASED HVDC SYSTEM

With VSC-based HVDC transmission, large wind farms can be connected over long distances. Latest systems can transfer up to 1100 MW at a DC transmission voltage of ±300 kV [3]. The transmission lengths are only restricted through the cable resistances. Fig. 2 shows a sample configuration of a wind farm connected to the main grid through a VSC-HVDC.

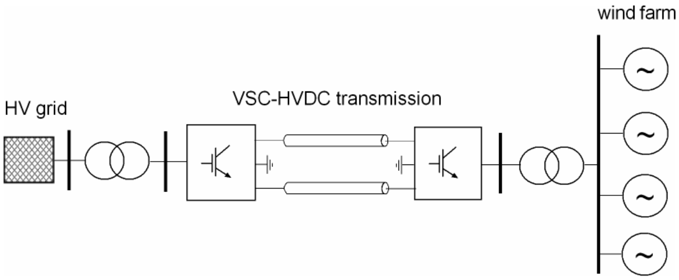

Fig. 2. Wind farm connected through VSC-HVDC

The mostly used VSC-system is based on a two-level topology (Fig. 3). Each converter consists of 6 semiconductor switching devices, commutating inductors, harmonic filters and the DC-circuit capacitors.

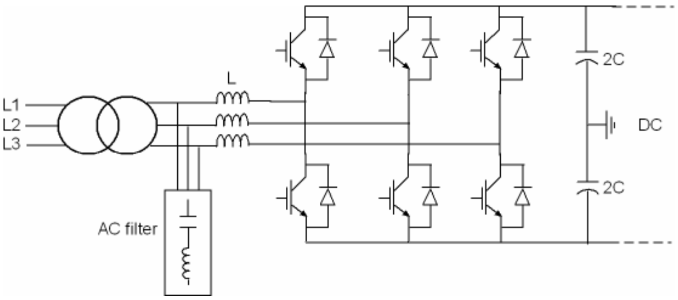

Fig. 3. Two-level VSC

This topology is the simplest VSC-configuration as it requires a simple control, but it has high switching losses, especially at low power transfer. For that reason, in some existing test systems an AC transmission is connected in parallel and used for power transfer at low wind speeds. At higher wind speeds it is switched off and power transfer is done through the HVDC link [5].

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 variable frequency operation of the DFIG wind farm.

A. Receiving End Converter

The function of the receiving end converter is to feed in the active power transmitted by the sending end converter while maintaining the DC voltage at the desired level. Additionally, the reactive power channel can be used to support the grid voltage during faults and also in steady-state [7]. The control structure for the receiving end converter is shown in Fig. 4.

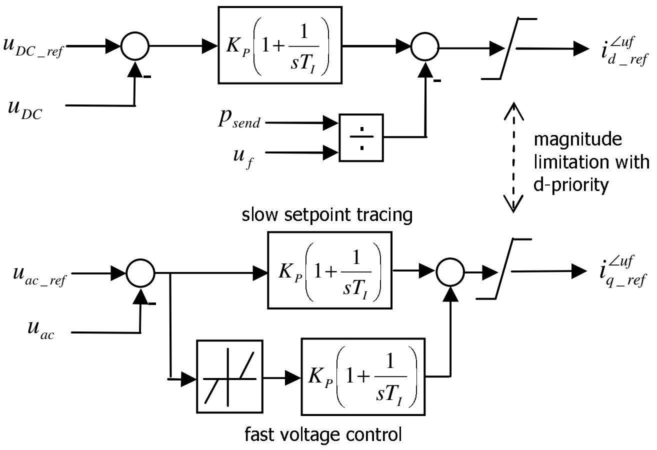

Fig. 4. DC and AC voltage control of receiving end VSC

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 PI controllers. The controller in the upper branch is slow and only responsible for set-point tracing in steady-state operation. The second controller is very fast and is activated when the voltage error is bigger than 0.1 p.u. i.e. during grid faults. The magnitude of the current outputs is limited. In steady-state operation the DC voltage control or the d-component of the current has higher priority.

The decoupled control of active and reactive current is achieved by a feed-forward current control with a very good dynamic response [8]. This control is based on a vector control approach with its rotating reference frame aligned to the filter voltage u_f . 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. 5). The magnitude of the output voltages is limited by maximum modulation degree and DC voltage.

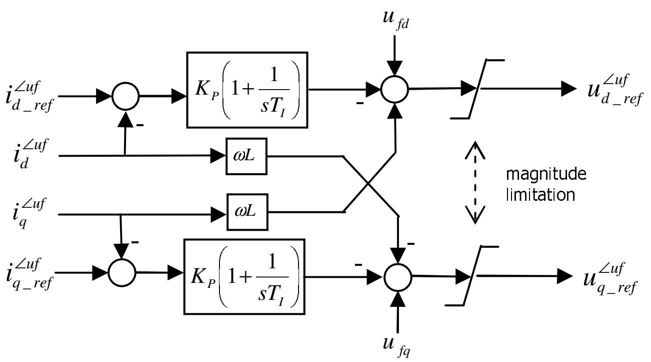

Fig. 5. Feed-forward decoupled current control

B. Sending End Converter

The sending end converter 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 changes in the generator slip of the connected DFIG wind turbines. Thus, active power transfer through the low-rated converter in the rotor circuit of the DFIG can be limited without a reduction of total power.

As the power control is performed by the wind turbines, a simple voltage magnitude controller can be used for the sending end converter, thus fulfilling the aforementioned requirements. The frequency can be directly regulated without the need for a closed loop structure. Fig. 6 shows the control structure of the sending end converter. Since no current control is used, a current limitation can only be achieved by blocking the IGBTs during a heavy fault in the wind farm grid.

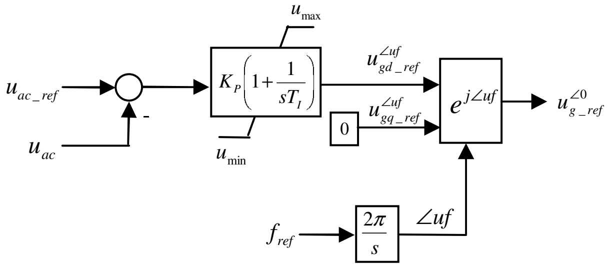

Fig. 6. Sending end converter control

III. 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. 7. 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. A line inductor and an AC filter are used at the grid side converter to improve the power quality.

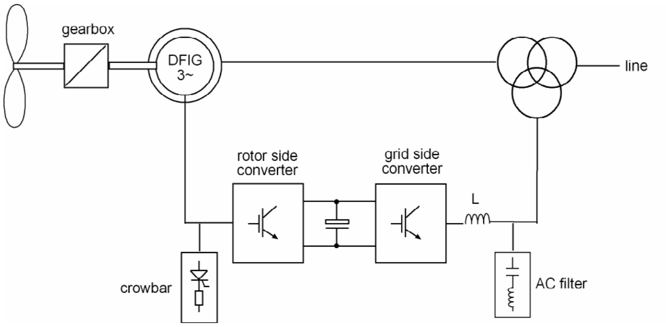

Fig. 7. System configuration of DFIG

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 [8] similar to that used for the receiving end converter 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 [10].

IV. VARIABLE FREQUENCY OPERATION

When the wind farm is connected through a VSC-based HVDC system, the DFIG wind turbines can be operated at variable stator frequency. Thus the power sharing between stator and rotor circuit can be actively changed according to the following relationships:

$$P_G = P_S + P_R \tag{1}$$

$$P_S = \frac{P_G}{1-s} = \frac{\omega_S}{\omega_R} P_G \tag{2}$$

$$P_R = -s \cdot P_S = \frac{-s}{1-s} P_G = \frac{\omega_R - \omega_S}{\omega_R} P_G \tag{3}$$

$$s = \frac{\omega_S - \omega_R}{\omega_S} \tag{4}$$

$$\omega_R = 2\pi \cdot p \cdot n_R \tag{5}$$

where

P_G, P_S, P_R: Generator, stator and rotor active power

ω_S, ω_R: Stator and rotor angular frequency

s, p, n_R: Slip, no. of pole pairs, rotational speed

In fixed stator frequency operation the slip can only be influenced by changing the mechanical rotor speed, while in variable frequency operation changing the stator frequency offers a new degree of freedom. The slip can be regulated independent of rotor speed within certain limits. For evaluating these limits, the following active power characteristics (Fig. 8) of a typical DFIG wind turbine are considered.

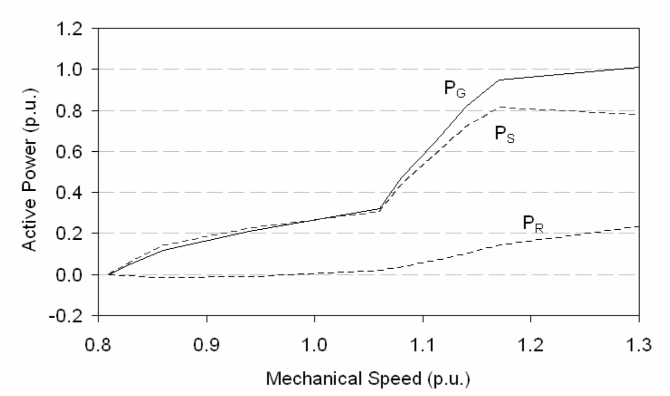

Fig. 8. Typical power spreading in a DFIG wind turbine with fixed stator frequency

Obviously, at fixed stator frequency the rotor power strongly increases above synchronous speed. With a variable stator frequency the active power can be redistributed (Fig. 9) to reduce the rotor power. This leads to an unloading of the grid side converter while keeping the total power constant. Consequently, a higher load is induced in the stator. Common DFIGs have relatively big tolerances in their machine ratings, and therefore this overload can be assumed as uncritical for the stator windings. But there is also an impact on the rotor circuit that includes the slip-rings and the machine converter and thus is more sensitive to over-currents.

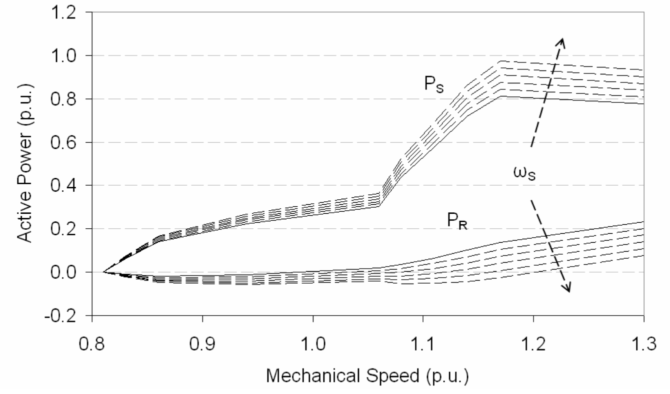

Fig. 9. Variable power spreading of DFIG with sliding stator frequency between 1 and 1.2 p.u.

The relation between stator power and rotor current can be derived from the machine equations [10]: In an arbitrary reference frame ($\angle K$) the stator active and reactive power p_S and q_S are defined by:

$$p_S = u_{Sd}^{\angle K} i_{Sd}^{\angle K} + u_{Sq}^{\angle K} i_{Sq}^{\angle K} \tag{6}$$

$$q_S = -u_{Sd}^{\angle K} i_{Sq}^{\angle K} + u_{Sq}^{\angle K} i_{Sd}^{\angle K} \tag{7}$$

where

$\underline{u}_S, \underline{i}_S$: Stator voltage and current

In a rotating reference frame aligned to stator voltage:

$$u_{Sd}^{\angle us} = \left|\underline{u}_S\right| \tag{8}$$

$$u_{Sq}^{\angle us} = 0 \tag{9}$$

With stator resistance $r_S \approx 0$ (valid for big machines), the stator flux linkage $\underline{\psi}_S$ is given by:

$$\psi_{Sd}^{\angle us} = l_S i_{Sd}^{\angle us} + l_h i_{Rd}^{\angle us} \approx 0 \tag{10}$$

$$\psi_{Sq}^{\angle us} = l_S i_{Sq}^{\angle us} + l_h i_{Rq}^{\angle us} \approx -\frac{\left|\underline{u}_S\right|}{\omega_S} \tag{11}$$

where

l_S, l_h : Stator and main inductance

And thus, the rotor current $\underline{i}_R$ is:

$$i_{Rd}^{\angle us} = -\frac{l_S p_S}{l_h \left|\underline{u}_S\right|} = -\frac{\omega_S l_S p_G}{\omega_R l_h \left|\underline{u}_S\right|} \tag{12}$$

$$i_{Rq}^{\angle us} = \frac{l_S q_S}{l_h \left|\underline{u}_S\right|} - \frac{\left|\underline{u}_S\right|}{\omega_S l_h} \tag{13}$$

The current magnitude is:

$$\left|\underline{i}_R\right| = \sqrt{\left(\frac{\omega_S l_S p_G}{\omega_R l_h \left|\underline{u}_S\right|}\right)^2 + \left(\frac{l_S q_S}{l_h \left|\underline{u}_S\right|} - \frac{\left|\underline{u}_S\right|}{\omega_S l_h}\right)^2} \tag{14}$$

It is assumed that reactive power balance in the wind farm grid is mainly supported by the VSC-converter, and the DFIG wind turbines are operated close to unity power factor. Thus, rotor reactive current $i_{Rq}^{\angle us}$ is nearly the excitation current of the generator, which is typically about 30% of the machine rated current i.e. the second term in (14) gives a small contribution to the rotor current magnitude at operation close to rated power. The current magnitude therefore is mainly determined by the active current $i_{Rd}^{\angle us}$ which is proportional to the stator frequency at a fixed power tracking point. In case of an increase in grid frequency, it can be reduced by increasing the stator voltage.

The approach in [11] therefore used a stator flux linkage control, where the voltage change was proportional to the frequency change. As a conventional HVDC was used, the DFIG had to apply this flux control, demanding reactive current from the DFIG converter and strongly limiting the possible frequency range. However, in this approach the frequency is not varied in a wider band.

In the current configuration, the voltage control of the VSC-based HVDC converter can fulfill this function. The frequency range is then determined by the maximum voltage of the devices as well as the allowable rotor currents. These parameters slightly vary for different DFIG and VSC-HVDC types, but a frequency range of ±20% seems to be realistic for common devices.

As explained before, a variation of frequency can be used for different purposes. Fig. 10 shows the structure of a frequency control for the VSC-HVDC converter, which can be used to limit the machine slip of the connected wind turbines leading to reduced rotor power. This slip reduction can be applied for maximum or mean slip to fulfill different requirements.

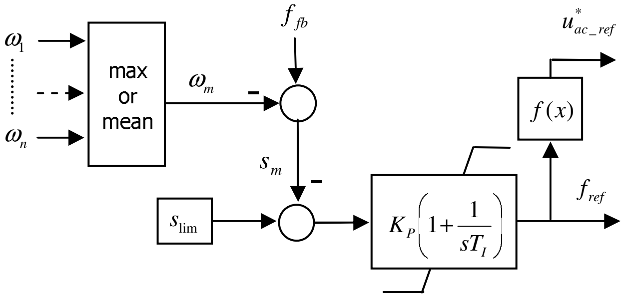

Fig. 10. Frequency control for slip limiting operation

The rotational speed of all wind turbines is measured and the values are transmitted to the HVDC control to determine the actual maximum (or mean) generator speed ω_m. Under the consideration of the measured grid frequency f_{fb} the resulting slip s_m is calculated. A PI-controller regulates the frequency in the wind farm grid to limit s_m to the desired value $s_{\lim}$. The frequency reference value f_{ref} is also used to set the reference voltage of the HVDC terminal according to the function $f(x)$. In the simplest case $f(x)$ is a direct assignment.

When this control is used to limit the maximum slip considering maximum speed, a slip limitation can only be performed at supersynchronous operation. But since rotor power in subsynchronous operation mode is small (Fig. 8), this approach shows the best behaviour concerning limitation of rotor power. However, the voltage of the rotor side converter is directly proportional to the slip and thus, machine slip also has to be limited for subsynchronous speed to protect the converter against over voltages. This can be realized by limiting the mean slip instead of the maximum slip, but at the cost of a small decrease in power limiting performance.

When it is desired to use the frequency control to extend the speed range of the wind turbines, the tracking characteristic of the DFIG also has to be extended to consider the additional grid frequency dependence. Additionally, an online optimization algorithm can be implemented in the frequency control of the HVDC converter to determine the reference frequency for maximum power output of the wind farm. The different wind speeds at the single wind turbines and the modified tracking characteristics should also be considered. This optimization is beyond the scope of this paper and will be treated in later research.

V. SIMULATION

All the simulations in this paper are carried out in MATLAB/Simulink using SimPowerSystems Toolbox. The investigated wind farm has a total installed capacity of 200 MW (40x5 MW) and is connected through a 250 MVA IGBT-based VSC-HVDC to the high voltage grid. The DC transmission voltage is ±150 kV and the cable length is

150 km. The high-voltage grid has a short circuit level of 2 GVA. Different control scenarios including wind speed changes are simulated to show the performance of the variable frequency control in the wind farm grid. Since the detailed models of the DFIG and HVDC include PWM triggered converters, the wind farm is represented through a single equivalent turbine to reduce simulation time to an acceptable level. The equivalent 200 MW turbine is connected through 8 parallel medium voltage cables of 10 km length to the VSC terminal.

A. *Wind Speed Variation*

An increase of wind speed above its nominal value accelerates the rotor of the wind turbine. The pitch control is slow and it takes time to reduce the mechanical torque again, so that the generator can brake and finally recover its nominal speed. During this process the variable frequency control can be used to limit the generator slip and thus the rotor power. This leads to an unloading of the grid side converter.

Fig. 11 shows the wind and generator speed (a), grid frequency (b) and rotor (c) and stator active power (d) at a wind speed ramp from 12 to 20 m/s for fixed frequency operation, slip limiting operation to $s_{\mathrm{lim}} = -0.17$ (nominal slip) and to $s_{\mathrm{lim}} = -0.1$. Fig. 11(a) shows that the generator is accelerated above nominal speed for several seconds. When the slip limiting control is used, the wind farm frequency (Fig. 11(b)) changes proportional to generator speed. As result the rotor power is reduced to a small value (Fig. 11(c)), even during this strong gust. For $s_{\mathrm{lim}} = -0.1$ it is also reduced at steady state. As can be gathered from Fig. 11(d), this leads to increased power flow through the stator circuit, which may be critical in case $s_{\mathrm{lim}} = -0.1$.

When the frequency control is operated at constant voltage, the grid and rotor side converter active currents are proportional to rotor and stator active power. But when the grid voltage is changed with frequency, the rotor current can be limited as shown in Fig. 12. Simulations are run at $s_{\mathrm{lim}} = -0.1$ for a) $u = const.$, b) $\Delta u = 0.5\Delta f$ and c) $\Delta u = \Delta f$. Case a) shows a high overshoot in active rotor current that could be harmful for the converter. In cases b) and c) the rotor currents can be reduced to a lower level. Case c) gives the best results, since it is utilizing the full voltage range of ±10%.

Another way of unloading the machine side converter during variable frequency operation is to choose a different machine design. It can be seen that slip limiting operation mode strongly reduces the rotor voltage but increases the rotor currents. A higher turn ratio between rotor and stator windings can reduce the rotor currents without inducing rotor voltages that are beyond the converter limits.

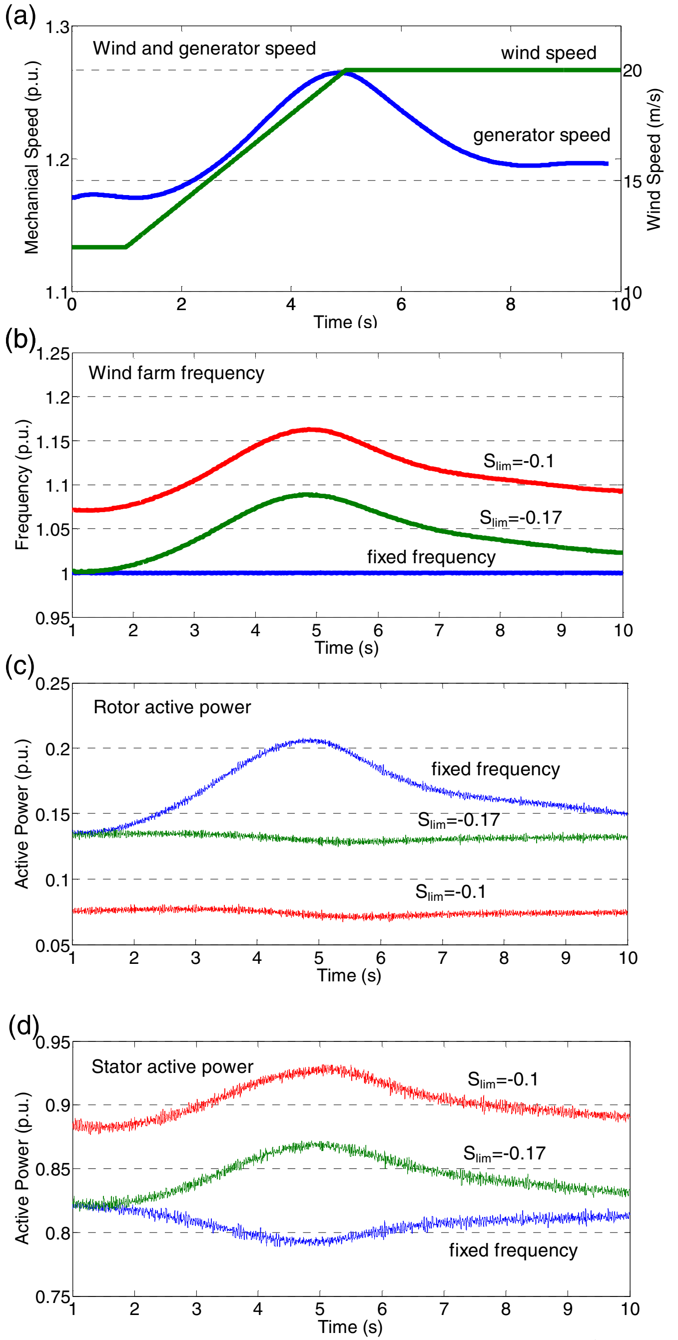

Fig. 11. Wind speed change from 12 to 20 *m/s* with a gradient of 2 *m/s*^{2}: a) wind and generator speed; b) wind farm frequency; c) rotor active power; d) stator active power

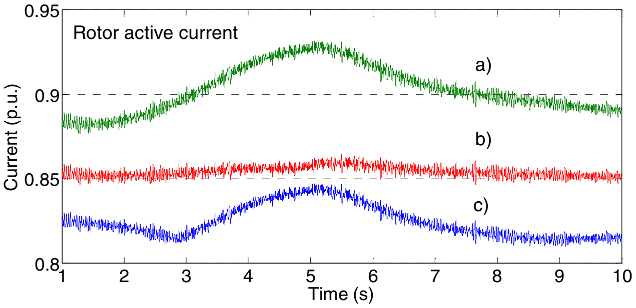

Fig. 12. Rotor active current $i_{Rd}^{\angle us}$ for different voltage control strategies at $s_{\lim} = -0.1$ a) $u = const.$, b) $\Delta u = 0.5\Delta f$, c) $\Delta u = \Delta f$

VI. CONCLUSION

A coordinated control of a DFIG wind farm and a VSC-based HVDC link was discussed in this paper. Simulation results have shown the merits as well as the limitations of variable frequency operation in DFIG based wind farms. The slip-limiting control allows a lower rating of the grid side converter while maintaining the same generator speed range. This control can strongly reduce the rotor power at the cost of higher stator loading and higher rotor currents. By either choosing a different machine design or varying the stator voltage with frequency, the rotor currents can be limited. Hence no higher rating machine side converter is required. Variable frequency operation in the wind farm can also be used for an extension of the DFIG mechanical speed range, without the need for a higher converter rating in the DFIG rotor circuit. Further research is necessary to evaluate the possible extra gains and to develop a yield-optimizing control strategy for DFIG and VSC-HVDC, considering the wind distribution in a large offshore wind farm. Furthermore, an easier modelling approach for DFIG and VSC-HVDC can be used in future, to enable simulation of multi-turbine arrangements. This way it is possible to evaluate the impact of the frequency control on the single turbines with different deviations from mean mechanical speed and accordingly different machine slip.

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VIII. BIOGRAPHIES

Christian Feltes (1979) received his Dipl.-Ing. degree in electrical engineering from University of Duisburg-Essen/Germany in 2005. Since January 2006 he is doing his Ph.D. studies in the Department of Electrical Power Systems at the same University.

His research interests are focused on wind energy generation, control, integration and dynamic interaction with electrical grid.

Istvan Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modelling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE.