Interaction of Large Offshore Wind Parks with the Electrical Grid

I. Erlich, Senior Member, IEEE, C. Feltes, F. Shewarega, Member, IEEE, and M. Wilch
University Duisburg-Essen

Abstract--**This paper deals with the impact of increased wind power generation on the behavior of the interconnected system in steady state as well as during and after a contingency situation. The issues specifically considered are performance during a severe short-circuit and frequency stability after a sudden loss of generation. The results of the short-circuit simulation are then evaluated vis-à-vis the grid code requirements placed on wind generating plants. Using a large interconnected system encompassing several conventional synchronous generators, the effect of increased wind power generation on the frequency stability of the system after a loss of generation has been discussed. It was found out that at the conceptual level there are a range of options which would place wind generating plants in a position to support system frequency in an emergency situation.**

Index Terms--**Control system, Doubly-fed induction machine, Frequency stability, Grid interaction, Power system stability, Wind power.**

I. INTRODUCTION

THE rapid expansion of wind power generation experienced in the recent past seems set to continue well into the future. In terms of energy, however, wind still accounts only for less than 1% of the electricity used globally. Then again there are already a number of countries where the share of installed wind power in relation to the aggregate capacity is quite significant. For example, as at the end of 2006 wind accounted in Demark, Spain and Germany for 20%, 9% and 7%, respectively, of the overall installed capacity. Some large offshore parks are already operational and others with much larger capacity are on the horizon. As a result, not only the role of wind in the international energy portfolio but also its singular impact on the interconnected system is already significant and will continue to increase in the coming years.

The reliable integration of this considerable wind power into the interconnected system is therefore the focus of the current research effort. Wind power in-feed will influence not only the power flow pattern and the task of maintaining constant frequency in the grid but also the dynamic behaviour of the whole system. As a result, the responsibility of ensuring reliable system operation will no longer be borne by the conventional synchronous generators alone. In the last couple of years some power utilities released codes, which wind farms need to fulfil upon connection to the rest of the system and adhere to afterwards during the synchronous parallel operation with the system. The overall trend is that wind farms in the future will increasingly be treated pretty much the same way as the conventional power plants with duties to participate on system control tasks to the fullest extent possible. Furthermore, in a post-fault scenario wind turbines have to remain on the grid for as long as feasible to help guarantee the continuity of the power supply and the rapid return of the system to normal operation.

II. IMPACT OF WIND ON STEADY STATE SYSTEM OPERATION AND GRID CODE REQUIREMENTS

The sustained and large-scale expansion of wind power has given rise to essentially new set of problems both in steady state system operation and in contingency situations. From the perspective of transmission system operators the most significant set of problems are associated with the fact that the primary source of energy (wind) is a random variable depending on the weather. Accordingly, the power in-feed from wind plants can only be forecast and the forecast can only be accurate to a limited degree. The result is that at times the power in-feed can vary against expectations over a wide range within a short period of time. E.on (one of the leading utilities in Germany) in its Wind Report 2005 [1] cites the following scenario that took place in its system. On 24.12.2004 at 9:15, the wind power in-feed was at its peak for that year with 6,024 MW. Ten hours later it dropped to less than 2,000 MW, and two days later the combined in-feed of all wind plants was a mere 40 MW. Handling such a huge difference in supply levels represents a major challenge from the system perspective, and this challenge is set to become even more daunting when one considers that the installed wind capacity in the German system is projected to rise to 48,000 MW in 2020 [2]. Additional issues of concern are the lack by wind turbines of active voltage support, participation on reactive power management and frequency control both in steady state and following a grid fault.

To involve wind units in the task of ensuring reliable system operation, grid operators have come up with grid codes in the recent past, which spell out preconditions for connection and operational directives after connection. These

---

J. I.Erlich (e-mail: istvan.erlich@uni-duisburg.de),
C. Feltes (e-mail: christian.feltes@uni-duisburg.de),
F. Shewarega (e-mail: fekadu.shewarega@uni-duisburg.de) and
M. Wilch (e-mail: michael.wilch@uni-duisburg.de)
are with the University of Duisburg-Essen, Duisburg, Germany

978-7-900714-13-8/08/ ©2008 DRPT

requirements are expected to address some of the problems related to power quality, grid stability, control capabilities and the performances of the wind turbines under contingency situations [3]. The grid codes have also given impetus to turbine manufacturers to consider these requirements in the development of the next generation of turbines or in the manufacture of equipment for upgrading forerunner models to attain grid code compliant operational capability.

In this paper, the grid code issued by E.on in 2003 and revised in 2006[4] will form the basis for the discussion.

A. Wind turbines and steady state real power balance

Traditionally, maintaining or restoring the generation and load real power balance over a given time frame has been accomplished by controlling generator outputs. But wind turbines are typically set for maximum output during normal operation and this control option is available only in the direction of output reduction. Taking account of this fact, the Grid Code stipulates requirements with regard to curbing the output whenever the need arises. Individual wind farms are thus to reduce their output in the frequency range between 50.2 Hz – 51.5 Hz as per the following relationship:

$$\Delta P = 20 \cdot P_M \cdot \frac{50.2Hz - f_{grid}}{50Hz} \qquad (1)$$

where ΔP = necessary power reduction, P_M = current output power, f_{grid} = actual value of the frequency.

Isolation from the network is permissible only for frequency values outside the range 47.5 Hz - 51.5 Hz. Apart from this, wind generation plants are explicitly exempted from the basic requirement of providing primary control power for now.

B. Voltage profile and reactive power balance

1) Basic requirements

The requirements with regard to voltage and reactive power are defined at the point of common connection (PCC) with the rest of the system. As a basic requirement, each wind farm must maintain a power factor between cos φ = 0.95 (under excited) and cos φ = 0.925 (overexcited) at PCC. Furthermore, the permissible operating range in terms of voltage versus reactive power is constrained to within the envelope shown in Fig. 1.

2) Methods for meeting these requirements

The fact that the voltage and reactive power prescriptions are to be fulfilled at the PCC (and not at the terminals of the machine) increases the available range of options for reactive power management. Fig. 2 shows a typical configuration of an offshore wind farm. The wind turbine, the cable link, the transformer tap-setting can all be used individually or in combination to maintain an operating point that is in conformity with the grid code requirement. There is also the additional possibility of deploying var generation devices at the PCC if all else proves unsatisfactory.

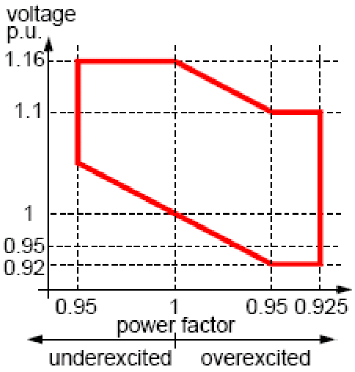

Fig. 1. Permissible voltage versus reactive power range

Assuming that the doubly-fed induction machine (DFIM) is used, as is currently the more common practice, the output reactive power can be controlled using the rotor side converter. The line side converter can also be used to supply reactive power, which, however, is normally the case only following grid faults.

The cable link itself represents a reactive power source that can be incorporated into the reactive power management process. Reactive power generation using the cable, however, is constrained by several factors. In order to increase the transmission capacity and reduce transmission losses, long AC cables always need compensation using shunt reactors, typically in both ends. Additionally, the capacitive current switching capability of circuit breakers imposes caps on using the cable for reactive power generation. The degree to which the cable would be available as a var source is determined by the required transmission capacity, transmission loss considerations and the circuit breaker switching capability in combination. Finally, the transformer tap-setting can also be included in the control of the voltage at PCC.

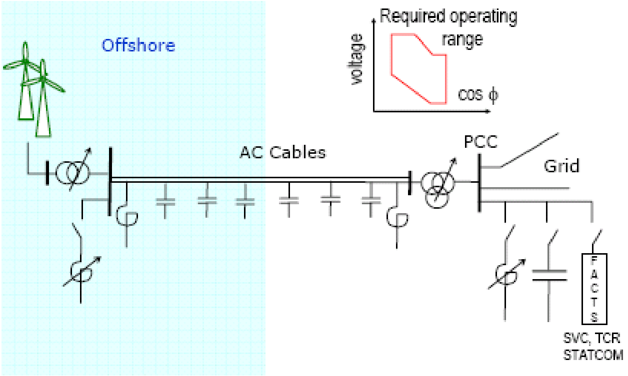

Fig. 2. Typical offshore wind farm configuration

In [5] an optimisation algorithm based on particle swarm optimisation technique has been proposed to find the optimum deployment and management of the reactive power sources. The approach is premised on the availability of a variable var generating capability at the PCC. The objective function is the loss optimum delivery of the power generated by the wind turbines to the PCC. The equality constraints are the real and reactive power balances together with a voltage at PCC corresponding to a set point value consistent with the grid code. The inequality constraints are the voltage, power, transformer tap-setting and line flows all remaining within the permissible or physically possible bounds. The two boundary scenarios with respect to reactive power generation are covering the reactive power demand fully by means of a var generation device installed at the PCC on the one hand and producing the reactive power demand in its entirety using the DFIM on the other. The paper presents some initial results aimed at corroborating the capability of the approach to provide a workable solution. But as the work underlying the paper is still in progress, no conclusive statement as to the best way for meeting the reactive power requirements at the PCC is made. However, each wind farm configuration will probably represent a unique scenario requiring a separate analysis.

III. EVALUATION OF GRID CODE REQUIREMENTS RELATED TO GRID FAULT

Prior to the advent of the grid codes, wind power plants were not duty bound to assist in the stabilisation of the grid frequency or the voltage during fault, which, of course, is considered to be a routine task when it comes to conventional power generation plants. But even more serious was the fact that wind power plants were permitted to disconnect from the grid even in the event of minor, brief voltage dips unlike large thermal power stations for which such a measure is possible only following serious grid faults [1]. It is easily conceivable, therefore, that minor disturbances in the extra-high voltage grid can instigate a chain of events that can lead to a sudden outage of all wind power plants in the affected region. Given the current status of wind, this would entail a significant loss of generation capable of putting the stability of the entire system at peril.

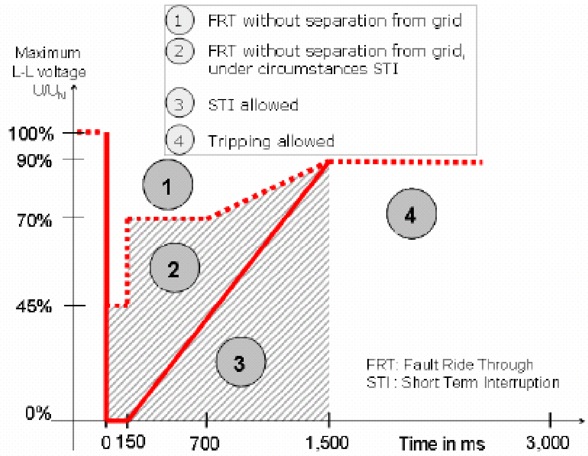

Fig. 3. Boundary conditions for fault ride-through

A. *Grid code requirements*

The grid code thus stipulates that only under certain circumstances shall wind power plants be disconnected from the grid following a grid fault. They must rather be operated in such a way as to provide voltage back-up to the grid.

The timeframe and the circumstances under which wind plants can be disconnected from the network are summarized in Fig. 3. In the area above the dotted line (area 1), fault related voltage dips must not lead to the disconnection of the wind generation plant from the grid. Only when the voltage dip persists for longer than 1500 ms (area 4), immediate disconnection is permitted. Similarly, a short interruption is permitted in the event of a voltage versus time scenario corresponding to any of the points in area 3.

In the area between the dotted and solid lines (area 2) all generating plants should negotiate through the fault without interruption. But if the internal configuration of any generating plant does not allow it to comply with this requirement, a short disconnection is permitted with the proviso that a minimum reactive power in-feed is guaranteed whatever the source of the reactive power. If the interruption occurs as a result of the machine becoming unstable or by the action of the protection system, a resynchronisation must take place within 2 s of the event and the active power ramp-up rate upon synchronisation must be no less than 10% of the rated power per second.

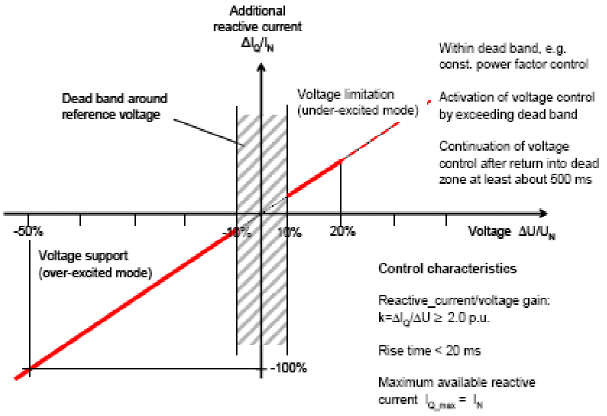

Fig. 4. Voltage support characteristic

In addition to the more specific requirement during severe grid faults, wind generation plants are also enjoined with a requirement to support the network voltage profile when the voltage deviates ±10% from its rated value. The prescribed voltage control characteristic in terms of reactive power injection is shown in Fig. 4. The voltage control must be activated within 20 ms of the recognition of the voltage variation. The voltage control must continue for a further 500 ms after the return to the voltage to the dead band. In a broader context, in future a continuous voltage control may prove to be necessary, particularly for offshore wind farms.

B. *Assessment of the scope of grid code requirements*

The extents to which the grid code requirements translate into operational values at the terminals of the machine are illustrated using a simulation. The test network (Fig. 5) resembles planned/existing offshore wind farms both in structure and the data used. As such, the results can offer a glimpse into the effectiveness of the grid requirements currently in force with regard to voltage support and reactive power supply for typical fault scenarios. Assessment of the currently specified extreme conditions under which wind turbines can be permitted to disconnect, the duration of the allowable down time and ramp-up rates after re-synchronisation are also possible.

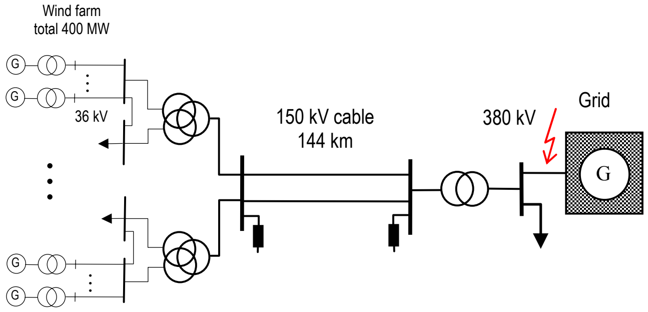

Fig. 5. Simulated offshore wind farm

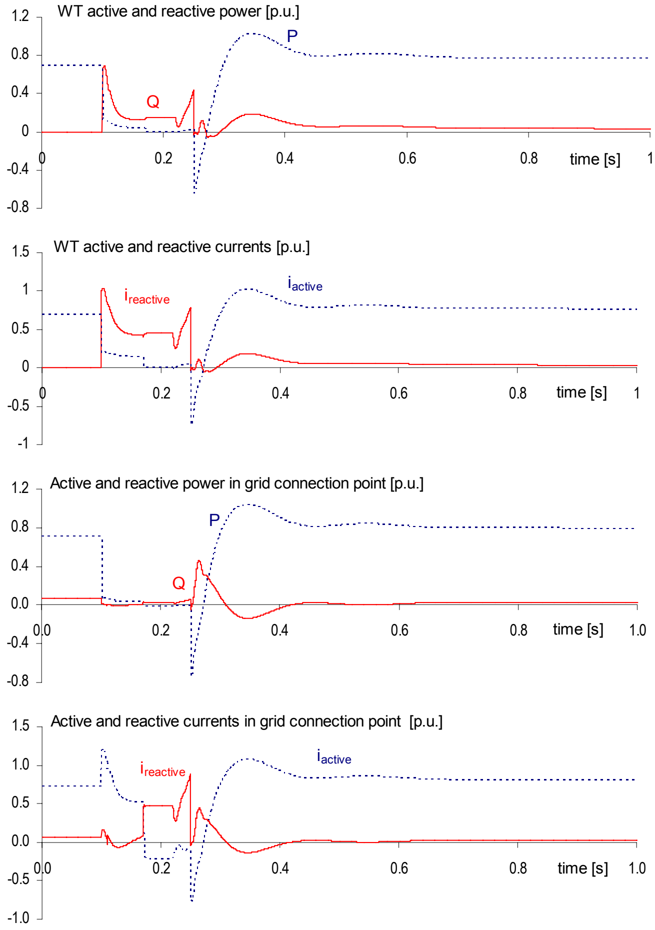

Fig. 6. Response of the offshore wind farm to three-phase grid fault

Plots of the voltage, real and reactive power as well as active and reactive currents for a three-phase fault (at the location indicated in Fig. 5) are shown in Fig. 6.

The introduced fault reduces the voltage at PCC to 0.1 p.u. As can be observed in Fig. 6, the WT terminal voltage remains at about 35% of the steady state value, which may not necessarily lead to compulsory crowbar firing. However, in this case the crowbar is deliberately activated to observe the crowbar's effect on operational values. The wind turbine control, especially the rotor side converter, is tuned to provide a strong voltage support. In addition, the line side converter is controlled for forced reactive current generation to the extent that a temporary overload of the converter bridge is permitted. During the fault the active power supplied to the grid is small as a result of the voltage dip. But the impact of this shortfall is tempered by the fact the voltage dip also reduces the power absorbed by the loads connected to nodes experiencing voltage dip. But significantly more important during this phase is the supply of the reactive current to support the network voltage. In the initial phase extending to about 20 ms, the WT discharges the stored magnetic energy so that the reactive current reaches its first peak of about 1.0 p.u. But this current decays quickly.

As the crowbar is activated, the DFIG itself becomes a reactive power consumer. However, since the line side converter in this phase supplies reactive current the WT as a whole remains a reactive current supplier. On the grid side a considerable reactive current is observed first when the WT active power in-feed goes to zero. It should be noted that the active current (as opposed to the reactive current) does not effectively support the grid voltage during faults. As can be seen from the simulation results the wind farm is able to supply about 50% reactive current during this stage. After voltage recovery the WT control brings back the voltage very fast near the reference value without considerable oscillations.

In summary, in spite of the additional features that enable a swift voltage recovery, the DFIM cannot achieve the same level of reactive power output as that of the conventional plants during fault. The results obtained underline the necessity of dynamic system investigations to ascertain that the requirements are fulfilled. Under circumstances, meeting Grid Code requirements may even go to the extent of necessitating the change of the control concept for the wind turbines. Also, recent trends tend to favour the use of the chopper rather than crowbar to enable the machine attain fault-ride through capability.

IV. FREQUENCY STABILITY AND INCREASED WIND POWER GENERATION

The doubly-fed induction machine is fed with a rotor voltage supplied by a converter. The capability of the converter to inject fast a rotor voltage of variable amplitude and phase angle uncouples the mechanical speed of the wind power generator from the grid frequency. In other words, the DFIM does not contribute considerably towards the overall inertia of the system. By contrast, a conventional synchronous generator is DC excited and the excitation winding is fixed along the rotor axis resulting in the direct coupling of the rotor inertia with the grid.

To characterize the impact on the system frequency of the reduced overall inertia as a result of increased wind power generation, a simulation was conducted in which the conventional generation allocation was decreased in stages in favor of wind plants, with everything else (including the overall generated power) remaining unchanged. The loads at various buses were concurrently increased by a total of 2.5% of the overall system-wide load to emulate the specified amount of loss of generation.

Figure 7 shows the frequency behavior for three levels of wind power portfolios in the system, namely wind accounting for 0%, 26.4% and 51.9% of the overall generation. All wind generation plants are assumed to maintain constant P and Q reference values. The result, as expected, is fairly straightforward. As the share of the wind power increases, so does also the initial drop in frequency. It can also be observed that the initial steep decline is followed by a quick kink and finally by a higher settling value. This behavior becomes more pronounced as the share of the wind power increases. With the generation comprising only of conventional plants, however, the frequency drop goes on longer and for the test network used a steady state deviation of 1 Hz is reached after approximately 60 s.

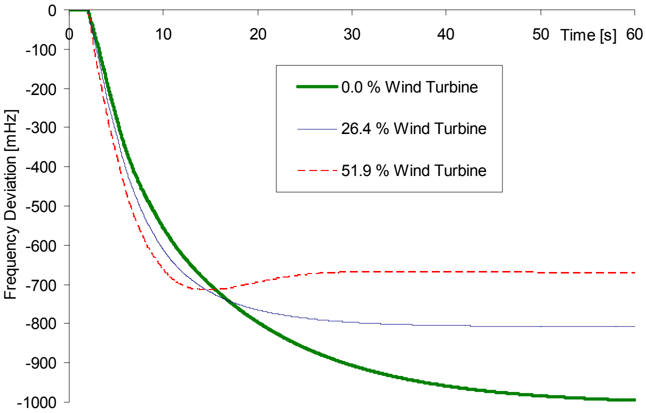

Fig. 7. Frequency deviation after a loss of 2.5 % generation; P and Q control

Just like the initial steep decline, the faster transition into the steady state in the presence of larger wind power is also caused by the smaller inertia together with the fast-acting electrical active power control of the DFIM. By comparison, the governor control of the conventional power plants is much slower.

It can thus be concluded that the increased share of wind power in the system leads to a higher frequency gradient. As the share of wind power goes on to increase, the task of maintaining constant frequency will become all the more involved. Whereas the primary control reserve in conventional plants is maintained at the expense of a part-load operation, which only leads to the reduction in efficiency, setting aside such a reserve power for wind turbines would directly lead to the loss of utilizable renewable energy and would thus be a more expensive option. In [6] the available ways and means by which wind turbines could be incorporated into the overall system frequency control task have been explored. The basic options proposed are the adjustment of real power (P) and voltage (U) references in response to the frequency deviation. The former, i.e. the frequency dependent P control, uses sophisticated control system to utilize the inertia of the rotating masses as a temporary sink or source of energy to be drawn from/supplied to the grid in response to frequency deviation.

The other option calls for the voltage control of the DFIM. Since wind generators are replacing conventional generators whose terminal voltages are controlled, it might in future prove to be necessary that wind turbines also resort to voltage control instead of reactive power control. The method proposed to improve frequency stability is therefore to include an additional feature in the voltage controller with the frequency deviation as an input. This signal is then used to adjust the voltage reference in order to utilize the voltage dependency of loads to counter the frequency fluctuation. Fig. 8 shows the frequency behavior when such a control scheme with a 200 mHz dead band is adopted. This result reveals the effectiveness of the frequency dependent voltage control to provide frequency support.

Ideally, the voltage controllers of wind turbines replacing voltage controlled conventional power plants should focus on voltage control alone. However, with no reserve control power at the disposal of wind generation plants, frequency support in contingency situations may necessitate tolerating a temporarily lowered voltage.

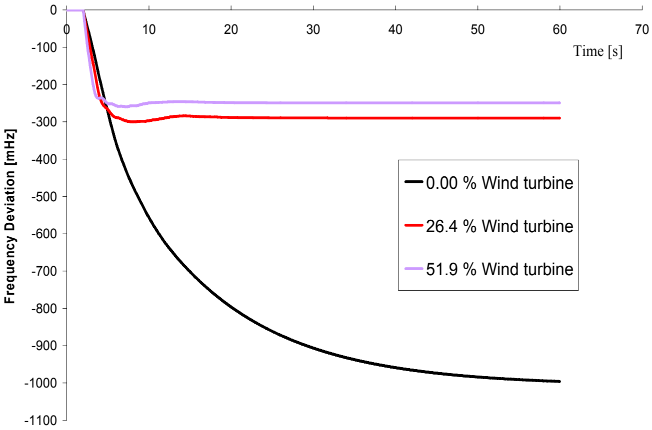

Fig. 8. Frequency deviation after a loss of 2.5 % generation; P plus static and dynamic frequency dependent voltage control

In summary, wind turbines are capable of participating in system frequency control tasks fully. When the situation demands the reduction of output, wind plants are already entrusted with specific tasks. As a possible option to compensate for the lack of capability in terms of output increase, wind plants can be equipped with appropriately designed control structures to utilize the cushioning effect that the voltage dependency of loads offers to maintain frequency.

V. Conclusion

The dependence of wind on the prevailing weather conditions means that the installed capacity does not guarantee firm dispatch-able energy. As a result, traditional power stations with sufficient capacities must be held on hand to fill the gap. Following the emergence of wind as a major power technology during the last several decades, in addition to devising ways to overcome this drawback, the proper integration of wind turbines into the system by maintaining the existing reliability and performance standards has become an issue of immense interest.

In this paper, three phenomena were singled out for in-depth discussion, namely behaviour of the wind generation plants in steady state, fault-ride through capability and frequency stability.

Wind generation plants reduce the overall inertia of the system due to shielding by the converter. Wind plants also achieve a much faster real power rate of response as a result of the electrical control of the real power. On the other hand, in spite of the additional features that enable a swift voltage recovery, wind generators cannot achieve the same level of reactive power output as that of the conventional plants during fault.

The smaller inertia of wind turbines has another implication in that it leads to a steeper drop in frequency following a loss of generation. Wind generators with frequency dependent voltage control are able, not only to maintain the grid voltage, but also to provide a considerable contribution to frequency stability by utilizing the voltage dependency of the loads. The need for voltage control of wind generation plants therefore needs to be balanced against the advantage that a softer voltage characteristic offers in terms of frequency stability.

VI. References

[1] E.on Netz, Wind Report 2005, http://www.eon-netz.com/frameset_reloader_homepage.phtml?top=Ressources/frame_head_eng.jsp&bottom=frameset_english/law_eng/law_windenergy_eng/law_windenergy_eng.jsp

[2] Dena Grid Study I, http://www.dena.de/en/topics/thema-reg/projects/projekt/grid-study-i/

[3] 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

[4] E.ON Netz GmbH, Byayreuth, Grid Code, High and extra high voltage, http://www.eon-netz.com/Ressources/downloads/ENENARHS2006eng.pdf

[5] Wilch, M.; Pappala, V.S.; Singh, S.N. & Erlich, I. , "Reactive Power Generation by DFIG Based Wind Farms with AC Grid Connection"., IEEEPowertech, July 2007 Lausanne, Switzerland

[6] Erlich, I.; Rensch, K. and Shewarega, F. , "Impact of Large Wind Power Generation on Frequency Stability", *Power* Engineering *Society General Meeting* , June 2006 Montreal, Canada

VII. Biographies

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 IEEE.

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.

Fekadu Shewarega (1956) received his Dipl.-Ing. Degree in electrical engineering from the Technical University of Dresden, Germany in 1985. From 1985 to 1988 he pursued his postgraduate studies in the same university and obtained his PhD degree in 1988. After graduation, he joined the Addis Ababa University, Ethiopia as an associate professor where he served in various teaching and administrative capacities. Currently he is a member of the research staff at the University Duisburg – Essen. His research interests are focused on power system analysis and renewable energy technologies. He is a member of IEEE and other professional associations.

Michael Wilch (1979) received his Dipl.-Ing. degree in electrical engineering with emphasis on Power Generation and Transmission from the University of Duisburg-Essen in 2006. He is currently a PhD student at the Institute of Electrical Power Systems of University Duisburg-Essen. His research interests include integration of large amounts of wind power into existing power systems.