Interaction of Large Wind Power Generation Plants with the Power System

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Abstract - **This paper surveys the impact of increasing level of wind generation on the performance indices of the interconnected system and what this entails in terms of improved control and protection schemes for wind turbines. After a brief review of the mathematical model of the doubly-fed induction generator (DFIG) and its control structure, simulation results are shown to quantify the effect of wind generation on system frequency, voltage profile and behavior during a short-circuit. The results were correlated with the outcome of a recent more comprehensive study. This study carried out by a consortium of major German utilities and research institutes summarised the experiences to-date with existing wind plants and worked out the necessary modifications on the existing Grid Code, which stipulates conditions for connection of wind farms to the high voltage grid. The paper then discusses some of the proposed major changes and extensions that include fault ride-through, voltage profile maintenance and the need for voltage control, system monitoring and protection as well as retrofitting of older units. The new requirements are defined taking into account some new developments in wind turbine technology, which should be utilized in the future to meet the enhanced grid requirements.**

Index terms –Wind power, wind generator control, frequency stability, voltage stability, grid code, fault ride-through

I. INTRODUCTION

In many countries, wind energy is viewed as a low-cost pathway to achieving reductions in greenhouse gas emissions and addressing other environmental concerns associated with conventional power generation technologies. Unlike many technologies known today, the breakthrough for wind energy has been brought about not by advances in science and technology per se. Rather, the favorable condition accorded to wind energy by some economically important countries created conducive frameworks for its development, and this in turn stimulated the market. The huge market thus emerged has spurred the technological advances that are available today. The German 'feed-in' law of 1990 can be cited as one such proactive intervention with a lasting impact. This law obliged power utilities to purchase all renewable energy based electricity generated within their service territory at a price set by the government. Furthermore, utilities were not only required to incorporate wind and other renewable energy based generation plants into their grids but also to upgrade their distribution and transmission facilities as required to accommodate the newly installed plants. Additional incentives followed this law to encourage the growth of a vibrant domestic wind power industry.

As a result of this and similar measures by other countries, wind today is the world's most dynamically growing energy source. In 2003, 2004 and 2005, the installed worldwide wind energy capacity grew by 26%, 20% and 25%, respectively. Whilst by the end of the year 2002 in all 31,117 MW were installed, this figure went up to 47,305 MW and 59,084 MW by the end of the years 2004 and 2005, respectively. The 50,000 MW mark was surpassed by mid-2005. According to the World Wind Energy Association (WWEA) forecast, an aggregate installed wind energy capacity of 100,000 MW is expected to be reached in the year 2008.

Another remarkable development to be observed since the mid 1990s is the increasing interest to locate wind turbines in the high seas. Offshore wind resources are enormous. The wind energy potential in the seas of the European Union with water depths of up to 50 meters, for example, is easily several times larger than the total European electricity consumption. Consequently, in addition to the current large number of onshore sites, many offshore sites are in the planning or implementation stages. The installed capacity of the offshore plants in the North and Baltic seas (off the northern coast of Europe) is expected to reach 2 - 3 GW by 2010 [1]. This figure is projected to rise to 20 – 25 GW by 2030.

It is already clear that the interconnected European network (UCTE) will have to accommodate a significant wind power component in the years to come and wind, in all probability, will feature prominently in the generation mix in many parts of the world. The task at hand, therefore, is the efficient integration of both on- and offshore wind power plants into the existing interconnected power system by maintaining the current level of system security.

This paper surveys the systemic issues caused by the increasing share of wind power, experiences to date in dealing with these issues and the measures being adopted to guarantee system security in the face of new challenges arising from a surge in wind power generation.

II. MODELING AND SIMULATION

Nearly all turbines currently in use employ one of the following machines as generators: the squirrel-cage induction generator, the synchronous generator or the doubly-fed induction machine (DFIM).

Whilst the conventional squirrel-cage induction machine may often be encountered in older wind farms, modern multi-megawatt-machines invariably use the synchronous or the doubly-fed induction machines. These machines are collectively referred to as variable speed machines. They experience less mechanical stress arising from wind speed variation on account of the fact that the rotor absorbs the drive-train torque variations by acting as a flywheel and thus storing energy temporarily.

The synchronous machine is connected to the grid via a converter. The interposing converter releases the machine

from the rigid synchronous operation regime which otherwise would have been necessary in a grid parallel operation. The power electronic equipment in the doubly-fed induction machine provides a rotor voltage that is adjustable both in magnitude and in phase angle. The rotor mechanical speed is then given by the difference between the speeds of the rotating field due to the rotor voltage (which is determined by the rotor voltage frequency) and that of the rotating field due to the stator voltage (which is determined by the grid frequency). The rotor speed can thus be varied (by adjusting the frequency of the rotor voltage using the power electronic equipment) to match the optimum operating point in the power-efficiency curve corresponding to the actual wind speed. The practical speed range lies around ±30% of the synchronous speed. This capability of the machine to change its speed as necessary can lead to an increase in an annual energy production of up to 5%.

The DFIM typically employs a gear box that is maintenance-intensive and thus potentially unreliable. On the other hand, the converter of the doubly-fed machine handles only the power needed to control the rotor speed (up to one-third of the machine rating), whereas the converter for the synchronous machine needs to be designed for the full machine rating. It is this feature of the machine, which gives it an edge over the synchronous machine at the moment. Figure 1 depicts the structure of a DFIM-based wind power generating system including the front-end and rotor side converters.

Fig. 1. Structure of the DFIM based wind generating system

A. Generator model

The system of equations below is based on the DFIM. However, only minor modifications are needed to bring these equations in conformity with equations needed for the other machine types.

The mechanical/electrical energy conversion process is described by the equations of induction machines given by equations (1)-(5) [2], [5]:

$$\underline{u}_S^{\angle K} = r_S \underline{i}_S^{\angle K} + \frac{d\underline{\psi}_S^{\angle K}}{dt} + j\omega_K \underline{\psi}_S^{\angle K} \tag{1}$$

$$\underline{u}_R^{\angle K} = r_R \underline{i}_R^{\angle K} + \frac{d\underline{\psi}_R^{\angle K}}{dt} + j(\omega_K - \omega_R)\underline{\psi}_R^{\angle K} \tag{2}$$

$$\underline{\psi}_S^{\angle K} = l_S \underline{i}_S^{\angle K} + l_h \underline{i}_R^{\angle K} \tag{3}$$

$$\underline{\psi}_R^{\angle K} = l_h \underline{i}_S^{\angle K} + l_R \underline{i}_R^{\angle K} \tag{4}$$

$$\frac{d\omega_R}{dt} = \frac{1}{T_m}\left(m_W + \left(\psi_{Sd}^{\angle K} i_{Sq}^{\angle K} - \psi_{Sq}^{\angle K} i_{Sd}^{\angle K}\right)\right) \tag{5}$$

All values are in per unit and ∠ K stands for a rotating reference frame whose angular speed can be chosen arbitrarily. The nomenclature of the symbols used in the above equations and the equations to follow are given at the end of the paper.

Equations (1) and (2) resolved into real and imaginary parts together with the equation of motion (5) constitute the 5th order model of the doubly-fed induction machine. The terminal voltage u_S forms the link to the rest of the network.

The quasi-stationary model is derived under the assumption that in a reference frame rotating at the synchronous speed ω₀ the transformer voltage in the stator winding (in Eq. 1) can be neglected against the much greater speed voltage, i.e.

$$\frac{d\underline{\psi}_S^{\angle \omega_0}}{dt} \approx 0$$

(The superscript ∠ 0, which should have appeared in place of ∠ K to indicate the synchronously rotating reference frame, has been abandoned from this point onwards for ease of notation). The assumption that the speed voltage is much bigger than the transformer voltage is tantamount to neglecting the DC component of the stator transient current, permitting only the representation of the fundamental frequency component.

This simplification is necessary for large system modelling to ensure compatibility with model of the rest of the system, particularly the transmission network. The use of the 5th order model for a network of any practical size would still be quite a challenging computational task despite the immense computing capability available today. A detailed modelling (using the 5th order model) might only be necessary when the main objective is the development and testing of single units, in which case the fifth order model of the machine, with the rest of the network considered as an infinite bus, may be used.

The time frame and the dynamic phenomena on which this paper focuses are such that the use of the quasi stationary machine model is considered to be adequate. Thus, with the stator flux linkages from (1) by neglecting the transformer term, it follows for Eq. (3):

$$\underline{u}_S = r_a \underline{i}_S + j\omega_0 l'\underline{i}_S + j\omega_0 k_R \underline{\psi}_R \tag{6}$$

where $l' = l_S - \frac{l_h^2}{l_R}$ and $k_R = \frac{l_h}{l_R}$

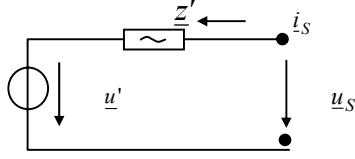Eq. (6) corresponds to the equivalent circuit given in Fig. 2 below.

Fig. 2. Quasi-stationary equivalent circuit of a DFIM

Re-writing (2) in a state-space form and eliminating the rotor current using (3) and (4) yields:

$$\frac{d\underline{\psi}_R}{dt} = (\underline{T}_{L0}^{1} + j\frac{\omega_0 k_R^2 r_R}{\underline{z}'})\underline{\psi}_R + \frac{r_R k_R}{\underline{z}'}\underline{u}_S + \underline{u}_R \tag{7}$$

where $\quad \underline{z}' = \omega_0 \cdot l'$

and $\quad \underline{T}_{L0}^{1} = \frac{r_R}{l_R} + j(\omega_0 - \omega_R)$

The equation of motion, expressed as a function only of the rotor flux linkages, then becomes:

$$\frac{d\omega_R}{dt} = \frac{1}{T_m}\left(m_W + k_R\left(\psi_{Rd} i_{Sq} - \psi_{Rq} i_{Sd}\right)\right) \tag{8}$$

Whereas for the DFIM a variable $\underline{u}_R$ is provided by the converter, $\underline{u}_R$ is zero for the SCIM. Because $\underline{u}_R$ is a complex quantity, it represents two control variables. Usually the field-oriented approach is employed, which allows the control of active and reactive power on the stator side independently. In general, however, the system represents a multi-variable control task, to which different methods can be applied.

Eq. (7) together with the modified version of the equation of motion (8) constitutes the quasi-stationary model of the induction machine.

In the simulation process, the determination of the rotor flux linkages $\underline{\psi}_R$ and thus the stator current $\underline{i}_S$ requires the numerical integration of (7) and (8) and the solution of the load flow equations of the network on which the machine is operating in an alternating procedure.

B. *Mechanical input power*

The kinetic energy of the mass of air m moving at the speed v_w is given by:

$$E_k = \frac{1}{2} m v_w^2 \tag{9}$$

The power associated with this mass of streaming air is the derivative of the kinetic energy with respect to time.

$$P_0 = \frac{\partial E_k}{\partial t} = \frac{1}{2}\frac{\partial m}{\partial t} v_w^2 = \frac{1}{2} q v_w^2 \tag{10}$$

The mass flow rate q is given by the expression:

$$q = \rho A v_w \tag{11}$$

ρ and A are the air density and the cross-section through which the air mass is streaming, respectively.

Only a fraction of the total kinetic energy passing through the turbine blades can be extracted and converted to rotational power at the shaft. That fraction of power depends on the actual wind speed, the rotor speed, the blade position (pitch-angle) and the quality of the turbine. This factor is denominated as the aerodynamic efficiency or power coefficient Cp. Thus,

$$C_p = \frac{P_{wind}}{P_0} \tag{12}$$

Wind turbine manufacturers give the specific value of Cp for a turbine usually as a function of the pitch-angle (β) and tip-speed ratio (λ). The tip-speed ratio is defined as:

$$\lambda = \frac{\omega_{tur} R}{v_w} \tag{13}$$

R is the radius of the turbine and ω_{tur} is the rotational speed of the turbine.

The mechanical power extracted from the wind can thus be given as:

$$P_{mech} = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v_w^3 \tag{14}$$

It is interesting to note that the mechanical power changes as the cube of the wind speed.

C. *The control system*

The DFIM encompasses two control structures, the fast electrical control and the slower pitch-angle control as shown in Fig.3 [3]. Depending on the wind speed the turbine operates in full or partial load mode. When the wind speed increases beyond the value needed for the rated power, the output power is limited by the pitch-angle control of the turbine blades. In part-load mode, the turbine is adjusted for the maximum available power by turning the blades fully into the wind. The optimum rotor speed is adjusted to follow a characteristic diagram to track the maximum power points. This maximum power is then passed on to the fast electrical converter control as the power reference through the control block with the transfer function $F_1(s)$. The speed is kept at the optimum level by the speed control denoted as $F_2(s)$ providing the reference pitch-angle to the blade drive mechanism, denoted by $F_3(s)$. The mechanical torque is then computed based on the Cp characteristic of the turbine.

The fast electrical control consists of two decoupled control channels, which act via a converter unit on the rotor circuit. The fact that the frequency and the amplitude of the rotor voltage can be varied independently from one another permits a decoupled control of P and Q. The reactive power can be set at any value within the capabilities of the machine, usually described by the active and reactive current operating chart. The reference value for the reactive power, however, is usually set to zero.

The mechanical torque and the two components of the rotor voltage are input variables to the electromechanical DFIM model. It will be recalled that the DFIM itself is represented by its reduced 3rd order model.
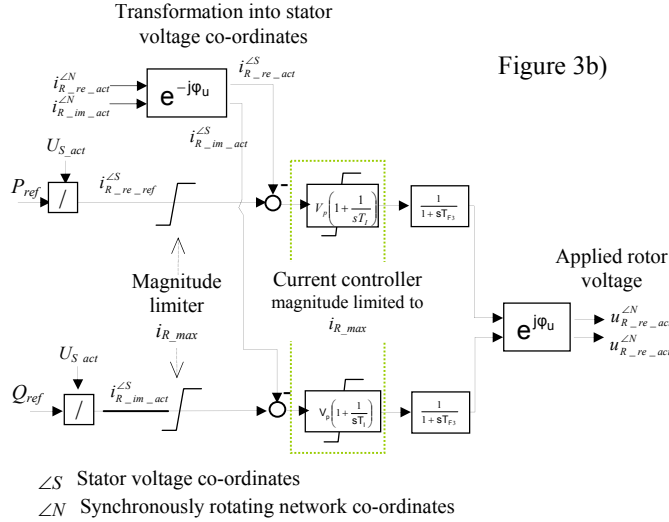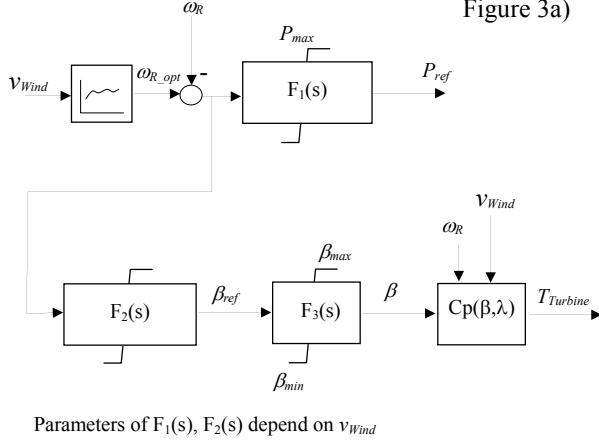

Figure 3a)

Parameters of $F_1(s)$, $F_2(s)$ depend on v_{Wind}

Figure 3b)

$\angle S$ Stator voltage co-ordinates
$\angle N$ Synchronously rotating network co-ordinates

Fig. 3. Control schema of DFIM; 3a) Determination of P_{ref} and pitch angle control; 3b) Current control

III. IMPACT OF WIND POWER GENERATION ON SYSTEM PERFORMANCE DURING A DISTURBANCE

Large offshore and onshore wind farms, which are now supplanting the conventional power plants, have introduced a new set of challenges into power system operation and control. The mere fact that the power generated by large offshore wind farms has a unidirectional flow may impact system stability adversely. Of the diverse problems attributable to increased wind power generation, in this paper two issues, namely frequency stability and behavior of the DFIM during a short-circuit current, are singled out for detailed discussion as instructive examples.

A. Frequency stability

As the baseline scenario, the response of the power system in terms of frequency variation following a sudden load increase (or loss of generation) without wind power was simulated. The simulation was then repeated as the share of wind power increases in stages from no wind power to approximately 50% of the overall power. In each case, the loss of generation is assumed to be 2.5% of the total. This amount of generation shortfall causes a frequency drop of 1 Hz in the UCTE system, which would leave the frequency relays just on the verge of operation. A larger loss of generation was not considered, since this would lead to load shedding and therefore necessitate the consideration of the frequency relays in the simulation.

The result in terms of frequency response is given in Fig. 4. The curve reveals that the inclusion of wind power in the generation mix leads to a sharper frequency drop in the first few seconds following the disturbance, and this all the more so as the share of the wind power increases.

The faster initial frequency drop is due to the fact that the DFIM is coupled indirectly to the grid via the converter. The converter (through the variable frequency rotor voltage provided by it) in a way decouples the rotating masses of the DFIM from the rest of the network leading to a smaller overall inertia. By contrast, the synchronous generators in conventional power plants are connected directly to the grid without any cushioning effect by the converter, which leads to a higher effective inertia of the whole system.
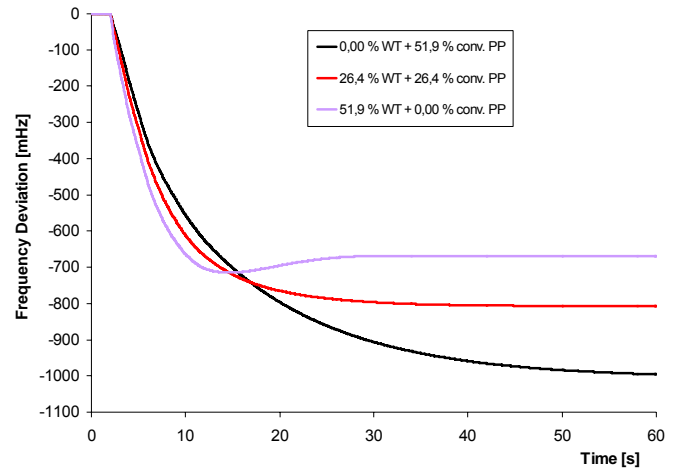
Fig. 4. Frequency deviation after a 2.5 % loss of generation

In the later phase of the disturbance, the frequency characteristic exhibits the opposite behavior, viz. the larger the share of the wind power the higher the settling value for the frequency, if the loss of generation is assumed to be sustained. This follows from the fact that the power absorbed by the loads decreases, if the load is primarily supplied by conventional plants. Because the conventional plants (by virtue of their voltage control capability) would maintain the voltage and with it the power absorbed by the load constant. The wind generation plants on the other hand maintain a constant reactive power output (but not the generator terminal voltage), which leads to lower voltage and thus to lower power absorption by the loads.

The fact that wind generating plants would cause a lower frequency dip in the later phase of the disturbance is not of

much practical importance as this magnitude of frequency decline normally would call for faster remedial measures anyway. From operational point of view, of much more significance is the fact that larger wind power in the system causes a sharper initial frequency drop following a sudden loss of generation or load increase.

B. Performance of the DFIM during a short-circuit

Figure 5 shows a typical short circuit current characteristic following a fault in the network. Depending on the distance of the machine from short circuit location, the pick current may reach a value of 5…8 times the rated stator current. Consequently, the mechanical drive and shaft system are subjected to a considerable stress. Moreover, the current passing through the converter may lead to excessive voltage in the DC link. Most DFIM manufacturers equip the machine with the crow bar (CB) to protect the converter against these effects. When the CB is fired, the converter is disconnected from the rotor, which in turn is short-circuited through the CB resistance. This measure is sufficient to protect the power electronics, but does not change the current and torque behavior in the machine considerably. For as long as the CB is switched on, the wind turbine acts as a reactive power consumer reducing the voltage level in the grid still further. After the fault is cleared, the voltage jumps back to the normal value, which can lead to a second CB firing with consequential adverse effect on voltage profile.
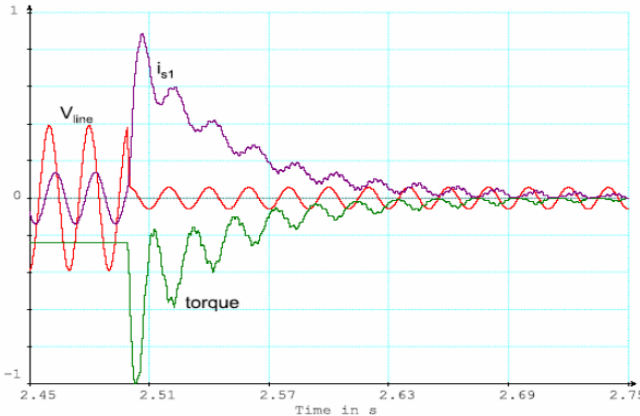
Fig. 5. Output values (in p. u.) of a DFIM during a grid short circuit (without CB firing)

IV. TECHNICAL STANDARDS FOR CONNECTIVITY AND IMPLICATIONS FOR THE GRID CODE

As pointed out in the previous section, wind generation plants introduce a new set of problems into the operation and control of power systems. The number of wind power in-feed points will continually increase in the years to come and with it parts of the network, where this impact will make itself felt. Apart from the overall share of wind power, many large off- and onshore wind farms already possess generating capabilities on a scale of conventional power plants. This together with the prominence that wind power has attained in relation to the aggregate system-wide power, therefore, underscores the need for wind farms to be in a position to undertake tasks necessary for maintaining system frequency and voltage profile within the prescribed tolerance band. It

should be borne in mind that until recently these tasks were considered to be the exclusive responsibility of conventional power plants. In addition, in the past wind plants were allowed to disconnect from the network during a disturbance, leaving the task of contending with the emergency and its aftermath to the conventional plants. This may have been an acceptable scenario for small, scattered plants. But the current portfolio of wind generating plants makes this untenable vis-à-vis the interests of the rest of the system.

In Germany, the requirements on wind generating plants in parallel operation with the system were formulated in the first grid code, which was enacted in 2003 [4], [6]. However, the fast-paced developments experienced during the past few years already rendered many of the provisions not to be on par with the operational requirements only two years later. In 2005 German transmission grid operators together with wind turbine manufactures and several research institutes conducted detailed investigations on future development of wind power utilization in Germany and the consequences of this on performance indices of the system together with what will this entail in terms of grid extension or reinforcement. The results of this so-called "dena-study"[1] recommended the updating of the existing Grid Code. The major propositions to this effect, which will most likely find their way into the revised edition of the Grid Code are summarized below.

A. Fault ride-through capability

The study calls for a more stringent requirement with regard to fault ride-through (FRT) capability. How wind generating plants are expected to acquit themselves during a disturbance is summarized in a voltage versus time curve shown in Fig. 6. Wind turbines are required to stay on the grid within areas 1 and 2 (shown in Fig. 6). If a wind turbine faces overloads, stability or other kinds of technical problems in area 2, it can disconnect itself from the grid provided a resynchronization can take place after 2 s at the latest (STI). Moreover, it must be able to increase the active power output following the resynchronization by gradients of at least 10% of the nominal power per second. Wind turbines with much faster STI cycles can initiate stator STI already at higher voltage levels, if:
- The interruption time $T_{STI} << 2$ s
- The reactive current in-feed continues during the period of interruption, using the grid side front-end converter or other auxiliary equipment.

Wind turbines remaining on grid during faults have to return to full active power in-feed with a gradient of about 20% of the nominal power per second. Often, active power generation is reduced by the converter control temporarily during the low voltage period. This opens up a possibility for further increasing the reactive power generation. After the fault, a fast return to normal active power generation is essential to ensure power balance within the grid and thus maintain frequency stability.

Grid faults leading to a voltage scenario depicted in area 3 affect wind turbines considerably. Therefore, STI is allowed in this area. However within the next 2 s resynchronisation is always required. Assuming the voltage remains low for longer than 1.5 seconds, tripping of wind turbines by system protection is reasonable.
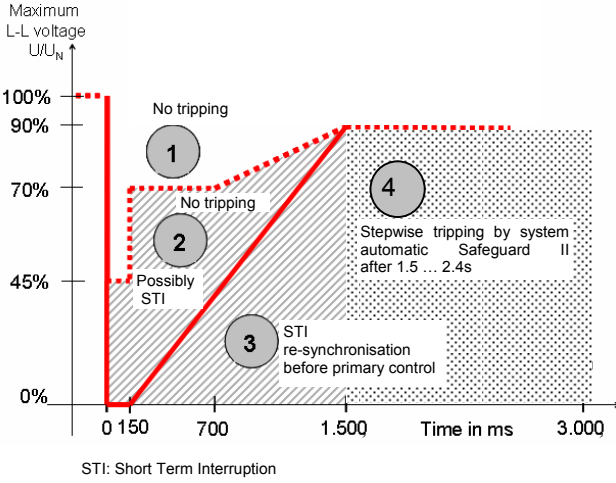
STI: Short Term Interruption

Fig. 6. Definition of FRT requirements

Fig. 7. Voltage control strategy for large wind farms

The main differences to the existing grid code can be summarised as follows:
- Zero voltage for up to 150 ms at grid connection point has to be considered in the future.
- The duration of the low voltage period is reduced to 1.5 s.
- STI is introduced and always required when low voltage period is shorter than 1.5 s and FRT is not possible
- Wind turbines have to ensure that after FRT power generation resumes within the shortest possible time. For this purpose, the required minimum power gradients are defined
- In case of large disturbances with long lasting voltage sags, measures for preventing voltage collapse are considered.

B. Ancillary services, voltage and frequency control

With the number of conventional plants being replaced by wind power continually increasing, wind turbines have to provide voltage support during faults and, to some extent, also during normal operation in the future.

Normally, voltage support is required only when the terminal voltage exits the tolerance band of ±10% around the nominal operating point. The minimum reactive current/voltage gain recommended is 2.0 p.u.

Furthermore, the rise time required for this control is less than 20 ms. However, to ensure variable voltage support during normal operation, utilities can require continuous voltage control in the manner practised currently by conventional synchronous generators.

Fast continuous voltage control guarantees also maximum available reactive current in-feed during faults and some smoothing of the voltage flicker caused by the fluctuating nature of wind power. Large offshore wind farms are obvious candidates for such voltage control. The proposed control strategy is summarized in Fig. 7. Besides, wind farms have to provide a contribution to the damping of electromechanical oscillations in power system, which require the design of voltage controllers taking power system stability aspects into account.
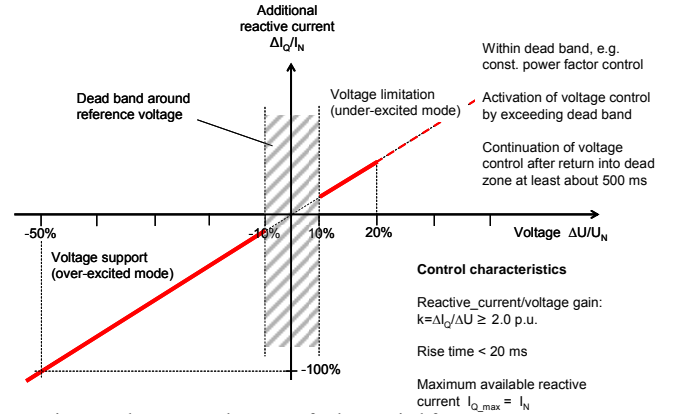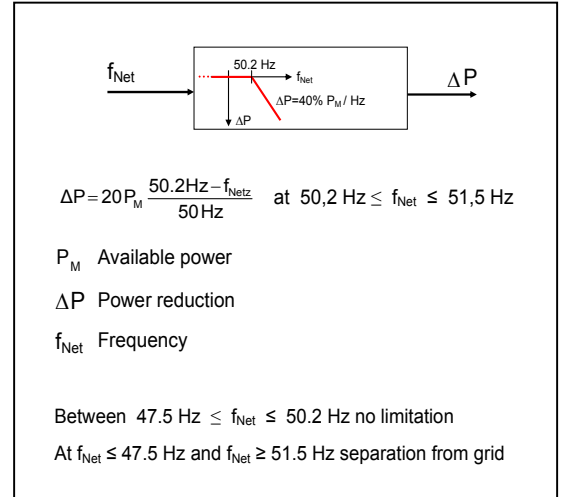

Fig. 8. Frequency characteristic of wind power generation

According to the new grid code wind turbines have to stay on the grid within the frequency range of 47.5 Hz - 51.5 Hz. Outside this range, disconnection without any time delay is necessary. In addition, wind turbines have to reduce power in-feed already at frequencies of about 50.2 Hz as shown in Figure 8.

When the wind turbine terminal voltage increases to 120% of the maximum permanently allowed value (e.g. 690 V x 1.05 x 1.2 = 870 V) disconnection with a time delay of 100 ms is necessary. If the voltage falls below 85% of the grid nominal voltage and the reactive power flow is directed towards the wind farm, i.e. the wind farm is a reactive power consumer, disconnection has to take place after 0.5 s delay.

The voltage values mentioned-above refer to those at the point of connection. However, disconnection has to take place directly at the wind turbines in order to ensure faster restoration. Considering the direction of reactive power flow as an additional criterion enables the monitoring of the voltage support requirements. For the case where the voltage at the wind turbine terminal falls below 80% of the minimum

permanently allowed value (i.e. 690 V x 0.95 x 0.8 = 525 V), disconnection of wind turbines is required to take place in time steps of 1,5 s, 1,8 s, 2,1 s and 2,4 s. In each step 25% of the units have to be tripped off if the voltage does not re-bounce to about 80% in the meantime. The grid code contains also requirements concerning the release time of the voltage relays too. Besides, it is recommended to design relays which combine voltage and frequency monitoring functions in one.

Following the disconnection as a result of violation of voltage and/or frequency limits, resynchronisation cannot take place until the voltage increases again to about 105 kV in 110-kV-networks, 210 kV in 220-kV-networks and 370 kV in 380-kV-networks. The maximum power gradient allowed after re-synchronisation is about 10% of the contracted capacity per minute.

V. Conclusion

Wind power in Germany with an installed capacity of over 18 GW has achieved a significant share in the overall generation mix. The importance of wind will be further enhanced when the planned shutdown of nuclear plants takes place by 2015. As a result, behaviour of wind farms during normal operation and faults will correspondingly impact the overall system performance. The reduction of the stability margin of the system caused by increased wind power generation will even affect the security of the whole European power system. First and foremost, therefore, it is necessary to prevent the loss of considerable wind power generation following grid faults. Generally, the main issues to be addressed are:

- Fault Ride-Through (FRT) capability to keep wind turbines on the grid during faults.
- Establishment of intelligent system protection devices to ensure a minimum loss of wind power during fault, when disconnection of some units proves to be necessary.
- Guaranteeing of supply restoration by wind turbines in the shortest possible time in cases where tripping had taken place.
- The provision of ancillary services including the capability for island operation.
- The establishment of mechanisms for ascertaining and continuous monitoring of the adherence to these and the other grid requirements.

The dena study, which has been quoted repeatedly in this paper, proposes the modification of the currently applicable rules for wind power connection to the grid to take these needs into account. The proposed changes and expansions aim on the one hand at better adaptation of grid requirements to wind turbine capabilities and on the other hand at the introduction of extended, more specific control and protection rules. The recommendation even goes to the extent of proposing the retrofitting of older wind turbines so as to enable them to comply with these requirements retroactively.

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VII. List of Symbols Used

Variables and constants		*Subscripts/superscripts*	
u	voltage phasor	S	stator
i	current phasor	R	rotor
Ψ	flux linkages	*	complex conjugate
ω	angular velocity	σ	leakage
m_T	turbine torque	h	main field
T_m	inertia constant	0	synchronous
l	inductance		
r	resistance		
x	reactance		

VIII. 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 senior member of IEEE.

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 at the same university in the area of the simulation of power system dynamics and obtained his PhD degree in 1988. After graduation, he joined the Addis Ababa University, Ethiopia as the member of the academic staff where he served in various 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.