Advanced Grid Requirements for the Integration of Wind Turbines into the German Transmission System

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***Abstract*--In Germany 18 GW wind power will have been installed by the end of 2005. Until 2020, this figure will reach the 50 GW mark. Based on the results of recent studies and on the experience with existing wind projects modification of the existing Grid Code for connection and operation of wind farms in the high voltage grid will be necessary. The paper discusses main issues of the suggested requirements by highlighting major changes and extensions. The topics considered are fault ride-through, grid voltage maintenance respective voltage control, system monitoring and protection as well as retrofitting of old units. The new requirements are defined taking into account some new developments in wind turbine technologies which should be utilized in the future to meet grid requirement. Monitoring and system protection is defined under the aspect of sustainability of the measures introduced.**

***Index Terms*—Grid Code, fault ride-through, voltage control, wind power**

I. Introduction

In many countries in the world energy policies are focused on the increased utilization of wind energy due to the fact that wind power can provide a considerable input to electricity production. Besides, wind represents a natural resource which is renewable, environmentally benign and is available nearly in every country. In Germany the installed wind turbine capacity already reached 18 GW (see Figure 1). By the year 2020 a total wind power capacity of nearly 50 GW is expected, which is more than 50% of the German peak load. In the future wind power increase will be realized mainly offshore where wind farms with several thousand megawatts should be built. Figure 2 shows the expected wind power in-feed points in the northern part of Germany and as a result the dominating power flow directions within the grid.

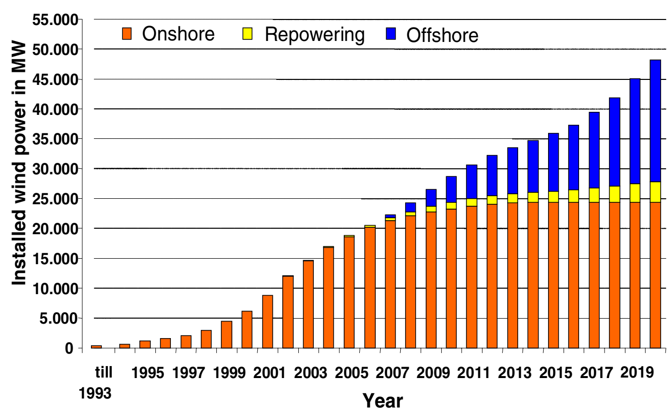

Fig. 1. Development of wind power utilization in Germany

Most of the wind turbines are connected to the medium voltage grid. However, the expected large offshore wind farms will always be connected to the 400-kV network. Due to the required bundling of cable routes wind power in-feed will be concentrated to selected, strong 400 kV nodes. However, for security reasons the capacity of 400 kV stations is limited to 3000 MW. Another concern focuses on the transportation of wind power to the load centres in the South for which new lines are indispensable in the near future.

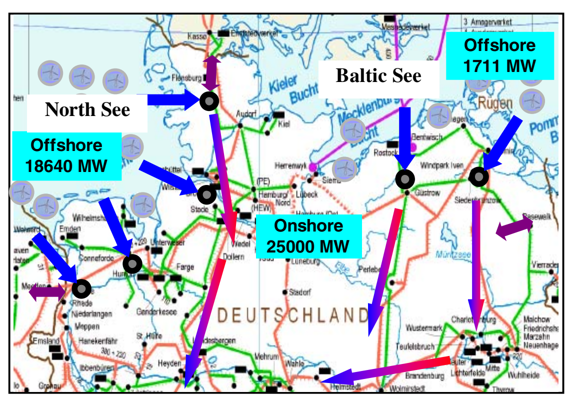

Fig. 2 Expected wind power generation by the year 2020

Despite several improvements, wind power forecast is still fraught with uncertainty. Therefore power system operation with increasing wind power penetration is becoming more and more difficult. Besides, the substitution of conventional power

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plants by wind turbines and the unidirectional power flow in the grid may impact system stability considerably.

It is obvious that for secure power system operation wind turbines have to meet grid requirements. In Germany the first Grid Code for wind turbines was introduced in 2003 [1]. However in 2005 German transmission grid operators, together with wind turbine manufactures and several research institutes conducted detailed investigations about further development of wind power utilization in Germany and the consequences on system stability, operation and grid extensions [2]. The results of this so-called “dena-study” underline the need for updating the existing Grid Code. The main concerns are:

- Fault Ride-Through (FRT) requirement to keep wind turbines on the grid during faults by introducing new technologies.
- Even in case of tripping wind turbines have to guarantee reconnection and continuation of power generation in the shortest possible time.
- Wind turbines have to provide ancillary services like voltage and frequency control with particular regard to island operation.
- Definition of technical standards for grid connectivity and operation of large offshore wind farms.
- The establishment of mechanisms for ascertaining and continuous monitoring of the fulfilment of grid requirements
- Establishing intelligent system protection devices to ensure a minimum loss of wind power and to guarantee fast recovery of normal operation.

After the year 2015, the wind power share on the German electricity production will increase considerably also due to the intended shutdown of nuclear power plants. As a result, the stability margin of the system is going to be less, affecting the security of the whole European power system. The European UCTE system is designed to withstand 3000 MW sudden generation losses. Therefore the substitution of conventional power generation by wind requires some new methods applied to wind turbines and wind farms for further secure system operation. On the one hand wind turbines have to provide some services still offered by conventional generators, and on the other hand, new features of modern wind turbines such as control and FRT properties have to be utilized for maintaining system security.

Special focus is directed to the old wind power plants built before 2003 and not capable of fulfilling Grid Code requirements. The objective is to enable these plants after a minimum retrofitting to withstand voltage dips and thus to avoid tripping following network faults.

II. Grid Requirements and Capabilities of Wind Turbines

The first German Grid Code concerning wind power was released in 2003. However, due to the experiences acquired in the recent years and in face of further developments, it has become necessary to update the current Grid Code.

Avoiding voltage collapse within the grid requires intelligent protection devices and schemes, which separate wind turbines selectively from the grid even when their contribution to system behaviour is going to be adverse. Wind turbines have to identify island operation and to manage the situation properly. In addition to the regular certification following grid connection requests, it will be necessary to establish mechanisms for controlling the effectiveness and indeed the sustainability of the measures introduced.

From the technical point of view, wind turbines are able to withstand voltage dips without tripping. However, to ensure this, the technical challenges on the wind turbines increase with the depth and duration of the voltage dips. On the other hand modern protection devices guarantee fast separation of grid faults so that the low voltage period usually remains short. Longer durations are always indicative of escalating faults which may require counteractions under different system aspects.

Wind turbines have to withstand not only the most likely unbalanced fault but also three-phase short circuits near the grid connection node. Consequently, zero voltages in all three phases in the connection points have to be considered. However, depending on the network and wind farm configuration, it does not necessarily lead to zero voltages at the wind generator terminal side. The German Grid Code contains FRT requirements concerning grid connection nodes only. At least with the request for connection, wind farm operators have to provide evidence of the fulfilment of these requirements for their particular case. For single wind turbines it may be sufficient to present a certificate, but large wind farms always need to be investigated by simulations which include steady state as well as dynamic studies. Besides, fulfilling grid requirements will be monitored continuously in the future.

Subsequent to protection relay actions wind turbines can remain connected to small islands. As a result large voltage and frequency deviations may occur. Therefore, wind turbines have to identify island operation and separate from the grid upon violation of voltage and frequency limits.

The majority of wind turbines use Doubly Fed Induction Machines (DFIM) as generator. The stator of theses machines is connected to the grid directly, whereas the three phase rotor winding are supplied through a voltage source converter. By varying the voltage magnitude and frequency, the active and reactive power generated can be controlled and thus the optimal rotor speed can be adjusted to each particular wind speed. Because of the limited speed variability required for wind turbines the converters have to be designed for 20-30% of the total generator power only. Figure 3 shows the structure of DFIM wind turbines. A short circuit within the grid results in currents and torques shown in Figure 4. Depending on the distance to the short circuit location, the peak current may account to about 5…8 times the rated stator current. As a consequence, the mechanical drive and shaft system is subjected to a considerable stress. Moreover, the current passing through the converter may lead to overloads leading to increased DC voltage there. Most of the manufacturers protect the converter against these effects by the so-called Crow Bar (CB). When the CB is fired converter and rotor are decoupled and the rotor circuits are closed through the CB resistances. However, this measure is protecting the power electronics, but does not change the behavior of currents and torque considerably. While the CB is switched on, the wind turbine acts as a reactive power consumer further reducing the voltage level in the grid. After the fault is eliminated, the voltage jumps back to the normal value, which can lead to a second CB firing with consequences for the voltage.

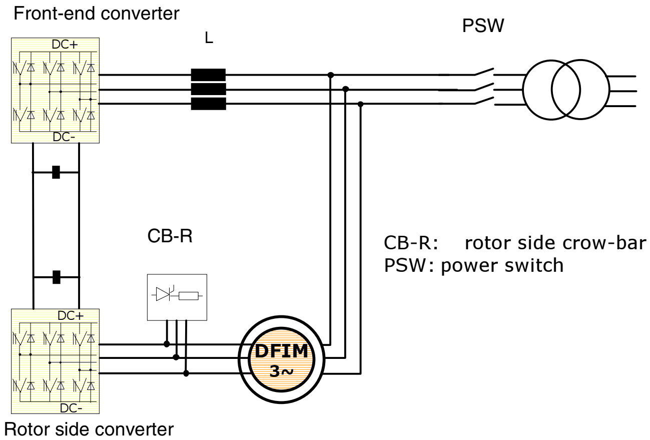

Fig. 3. Structure of the DFIM with rotor Crow Bar

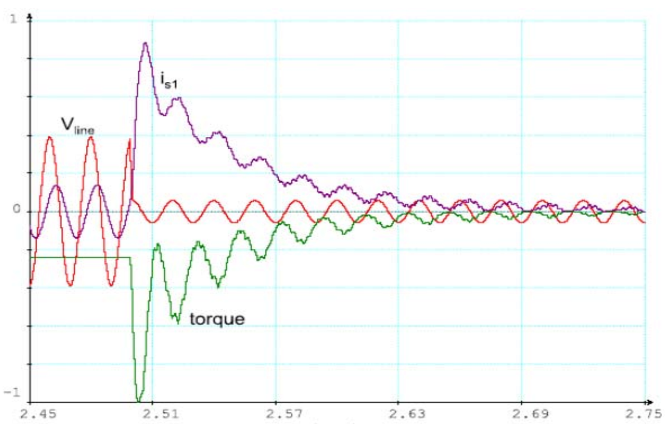

Fig. 4. Behavior of DFIM on grid short circuit (no CB firing)
Voltage related to 2.5*rated (amplitude), current to 7.0*rated (amplitude), torque to 4.2*rated, P, Q to 1.8*rated

FRT of wind turbines is necessary for two reasons:
- To be able to continue with active power in-feed immediately after the fault clearance.
- Wind turbines have to provide voltage support during and after the fault period to reduce the size of the voltage dip area within the grid.

Wind turbines equipped with rotor CB are able to stay on grid during faults. However, they do not supply reactive power into the grid as necessary for keeping the voltage high. On the contrary, wind turbines act in this case as a reactive power consumer.

An alternative approach for FRT is shown in Figure 5.

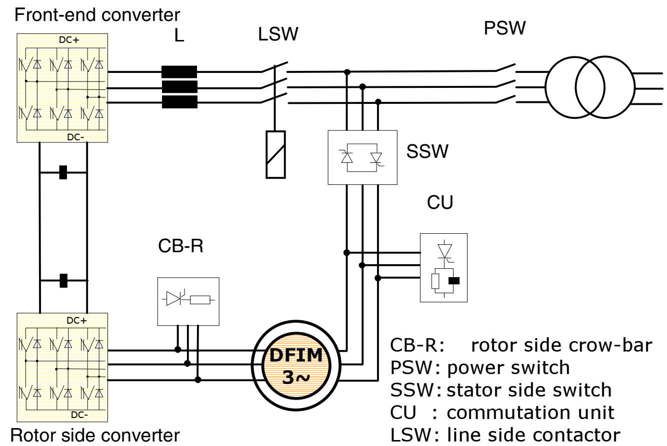

Fig. 5. DFIM structure with stator side FRT

According to this schema thyristor switches are installed on the stator side, which are able to interrupt the short circuit currents after 10 ms at the latest. Thus the current is interrupted before the peak current is reached. Therefore the mechanical stress on the rotor shaft is reduced considerably. At the same time, with stator switching, the commutation unit (CU) is fired and the rotor-side converter is stopped. Thus the generator will experience a forced demagnetization through the applied back-voltages on stator side (CU) and rotor side (DC link). However, the front-end converter remains connected to the grid and is controlled now to supply the maximum reactive power available for the desired short period of time to the grid. After demagnetization, the rotor side converter is restarted and controlled for resynchronisation through the stator thyristor switches. Even if the voltage is low the stator is synchronized with the grid. Thus the wind turbine is able to supply active and reactive power again within the margin of the maximum converter currents. Following resynchronisation it makes sense to use the rotor side converter for reactive power generation again. Figure 6 shows the FRT cycle experienced by the proposed approach.

As can be seen, the duration of stator interruption is very short. It takes about 200-300 ms only. Even during this period the wind turbine supplies reactive power to the grid by using the front-end converter. After resynchronisation reactive power generation can be further increased.

The stator side FRT provides several advantages for grid as well as wind turbine. However, it is slightly more expensive due to the additional hardware requirements.

Based on the experience with the new FRT methods, the new term“Short Term Interruption” (STI) is introduced as an alternative measure to rotor crow bar firing..

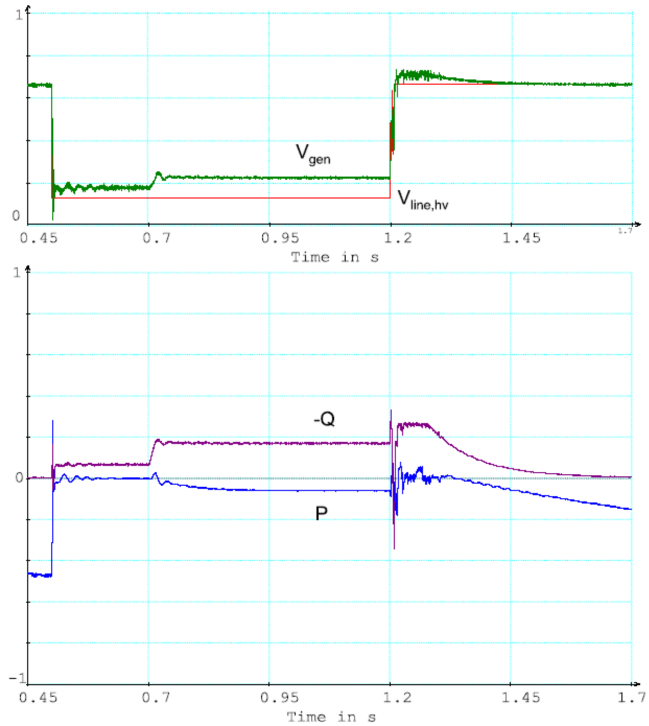

Fig. 6. FRT cycle by stator side approach
Voltages related to 1.5*rated; active/reactive power related to 2*rated

III. Suggested Changes in the German Grid Code

According to the experience with the dena-Study and the application of the previous Grid Code to different large wind farm projects, a revision of the existing rules for connection and operation of wind turbines on the transmission grid will be necessary. In the following the main aspects of the suggested changes are discussed with focus on the new and innovative issues.

A. Fault Ride Through (FRT)

In accordance with the previous Grid Code, FRT requirements are described based on a time voltage diagram (Figure 7) which does not contain characteristic voltage behavior but border lines. According to the proposed requirements wind turbines have to stay on the grid at voltages within the areas 1 and 2 shown in Figure 7 [3]. However, if wind turbines face overloads, stability or other kind of technical problems in area 2, they can interrupt the connection to the grid when resynchronization takes place at least after 2 s (STI). Besides, they must be able to increase the active power after resynchronization by gradients of at least 10% of the nominal power per second. Wind turbines with much faster STI cycles, as described in the previous section, can initiate stator STI already at higher voltage levels under the following conditions:

- The interruption time is T_{STI}<< 2 s
- Reactive current in-feed continues also during the interruption period, e.g. by the grid side front-end converter or by other equipments

However, utilities will always require verifications by simulation or measurement with regard to the effectiveness of the proposed measures.

Wind turbines remaining on grid during faults have to return to total active power in-feed with gradients of about 20% P_{nom}/s. Often, active power generation is reduced by the converter control temporarily during the low voltage period. This allows the further increase of reactive power generation. After the fault period, a fast return to normal active power generation is essential to ensure power balance within the grid and thus frequency stability.

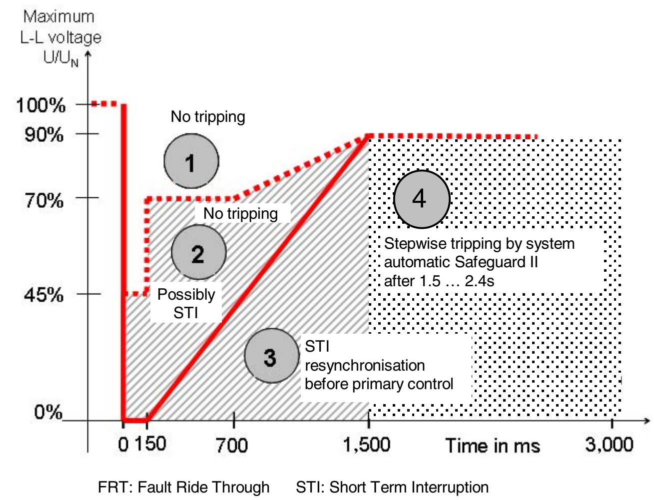

Fig. 7. Definition of FRT requirements

Grid faults resulting in voltage sags in area 3 are affecting wind turbines considerably. Therefore, short disconnection from the grid 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 which will be discussed below.

The main differences to the existing grid code can be summarised as follows:

- Zero voltage for about 150 ms at grid connection point has to be considered in the future.
- The total duration of the low voltage period referred in the Grid Code 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 without tripping
- Wind turbines have to ensure that after FRT power generation continues 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. Voltage Maintaining

Conventional synchronous generators are usually equipped with exciter and voltage control. Besides, energy is also stored in the magnetic fields within the machine, particularly in the rotor circuits. Therefore, synchronous generators are able to supply high short-circuit currents to the fault location during considerable time intervals. High generator short-circuit currents keep the voltage within the grid relatively high and thus the low voltage area caused by the fault is reduced. In consequence, less consumer, wind turbines or other distributed generator units are affected. However, many conventional power plants will be replaced by wind power in the future. Therefore, wind turbines have to provide voltage support during faults and, to some extent, also during normal operation. Voltage support is required when the terminal voltage exits the dead band of 10% around the current operating point. The minimum reactive current/voltage gain required is 2.0 p.u. According to this, a reactive current of 1.0 p.u. will be supplied at voltages below 50%. Furthermore, the rise time required for this control is less than 20 ms. To ensure variable voltage support during normal operation utilities can require continuous voltage control too as practised by conventional synchronous generators. Fast continuous voltage control guarantees also maximum available reactive current in-feed during faults and some smoothening of voltage flicker may be caused by the fluctuating wind power. Large offshore wind farms are candidates for continuous voltage control. Besides, wind farms have to provide a contribution to stabilizing power system electromechanical oscillations that require the design of voltage controller taking power system stability aspects into account.

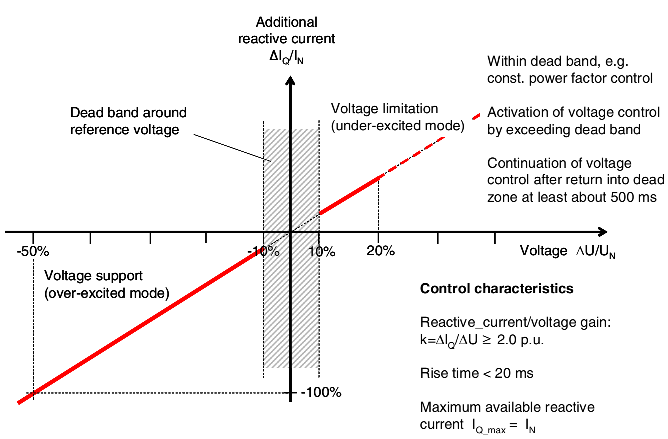

Fig. 8. Characteristic of voltage control

C. System Monitoring, Control and Protection

Following major disturbances power system may experiences large excursions in voltages and frequency. Beyond specific limits, system stability can not be guaranteed and generators as well as consumers may risk damage. In this case disconnection from the grid seems to be the best strategy. According to the new Grid Code wind turbines have to stay on grid within the frequency range of 47.5 Hz and 51.5 Hz. Beyond these limits separation without any time delay is required. However, wind turbines have to reduce power in-feed already at frequencies about 50.2 Hz as shown in Figure 9.

When the wind turbine terminal voltage increases up to 120% of the maximum permanently allowed terminal voltage (e.g. 690 V x 1.05 x 1.2 = 870 V) disconnection with a time delay of 100 ms is necessary. This requirement refers to the minimum line to line voltage. When the voltage falls below 85% of the grid nominal voltage and the reactive power flow is directed to the wind farm, i.e. the wind farm is consuming reactive power, the wind turbines have to be disconnected after 0.5 s delay.

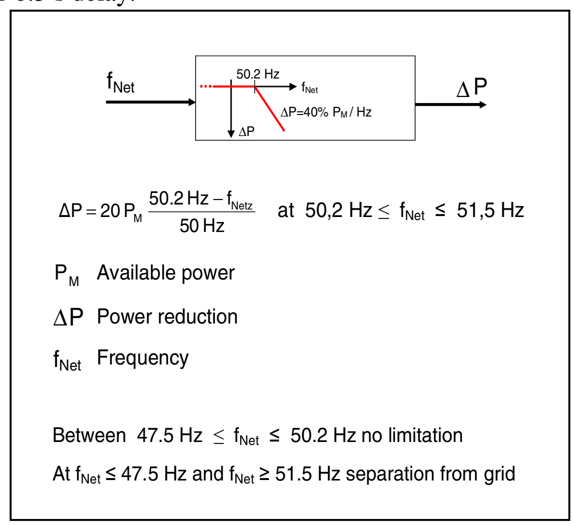

Fig. 9. Frequency characteristic of wind power generation

The conditions of this rule are referring to the connection points. However, disconnection has to be taken at the wind turbines directly in order to ensure fast restoration. The voltage considered is the maximum line to line voltage at the connection point. Taking into account the direction of reactive power flow, the conditions also provide for monitoring of the voltage support requirements. Assuming that the voltage at the wind turbine terminal nodes falls further below 80% of the minimum permanently allowed voltage (i.e. 690 V x 0.95 x 0.8 = 525 V), disconnection of wind turbines is required in time steps of 1,5 s, 1,8 s, 2,1 s and 2,4 s. In each time step 25% of the wind farm units have to be tripped if the voltage doesn't increase again to about 80% in the meantime. The grid code contains also requirements concerning backslide relations of the voltage relays too. Besides, it is recommended to build voltage and frequency functions in one joint relay.

After disconnection, due to violation of voltage and frequency limits, resynchronisation can take place not until the voltage increases again to about 105 kV in 110-kV-networks, to about 210 kV in 220-kV-networks and to 370 kV in 380-kV-networks. In this case the maximum power gradient allowed is about 10% per minute of the contracted grid capacity.

Figure 10 provides an overview of the voltage and frequency monitoring and protection functions respectively.

In the subsequent protection switching actions, wind farms might remain separated from the grid. However, stable operation of islands presupposes that the balance between generation and consumption as well as voltage and frequency control capabilities of the remaining generator units. Because of power balance is unlikely to be maintained within the island and wind turbine usually can not provide the required control service, separation from the grid is recommended. Wind turbines as a rule will be tripped by voltage and frequency relays due to violations of the corresponding limits. However, when the circuit breakers connecting the wind farm to the grid trip, shut down signals have to be sent to the wind turbines too. Then, island operation has to be terminated within 3 s.

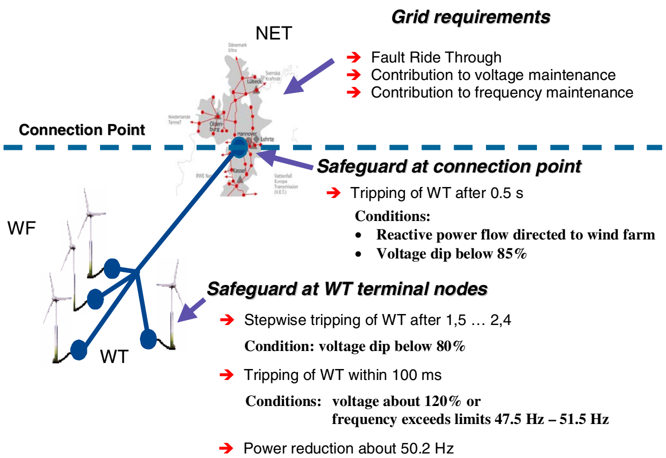

Fig. 10. Overview of system monitoring and system protection functions

D. *Improving Old Plant's Behaviour*

According to studies carried out considering the prospective increase of wind power and the reduced share of conventional generators [2], just simple line faults may endanger the security of the whole European power system in the near future. Three phase short circuits will result in voltage dips in wide areas of the network as shown in Figure 11 for a section of the German grid. Subsequently, old wind power plants without any FRT capabilities will be tripped and thus the system will experience loss of a large amount of generation capability.

In case of the most likely single line to ground faults, system security may be guaranteed by alignment of voltage protection relays evaluating the maximum line to line voltage for developing corresponding decisions. Furthermore, a time delay of approximately 250 ms would protect tripping also for three phase short circuits. However, the technical feasibility of the proposed measures is still not proven by the manufacturers.

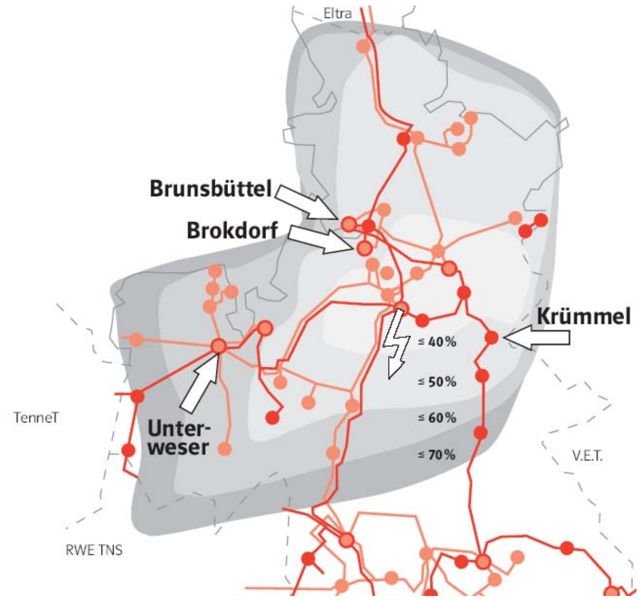

Fig. 11. Voltage dip during a three phase short circuit in the German grid

IV. Conclusions

Due to the German energy policy considerable increase in utilization of wind energy is expected in the next decade. However, the transport and distribution of wind power will alter the capacity limits of the German grid and will result in new congestions. With increasing share, wind turbine behaviour during faults and also in normal operation will become significant. In accordance with the results of the dena study available since April 2005, modification of the existing rules for wind turbines are necessary. The proposed changes and extensions discussed in this paper aim, on the one side, at better adaptation of grid requirements to wind turbine capabilities and, on the other side, at the introduction of extended more specific control and protection rules.

For maintaining power system stability, it is indispensable to prevent the loss of considerable wind power generation following grid faults. Therefore, the new FRT requirements consider more realistic grid behaviour and also innovative FRT solutions for modern wind turbines. To ensure power system stability retrofitting of older wind turbines without FRT capability is necessary. For this purpose, some suggestions are made by the German utilities which are currently under examination by wind turbine manufacturers. The implementation of the described measures will improve and stabilize wind turbines behaviour and results in decreasing loss wind power following disturbances.

V. References

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

[2] „dena-Netzstudie", www.deutsche-energie-agentur.de, Februar 2005

[3] P. Erickson, T. Ackermann, H. Abilgaard, J.-M. Rodriguez, W. Winter. "System operation with high wind penetration", IEEE power & energy, Volume 3, Number 6, Nov/Dec 2005

VI. 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.

Wilhelm Winter received the M.Sc. degree and the Doctor degree in Power Engineering from the Technical University of Berlin in 1995 and 1998 respectively. From 1995 to 2000 he was with Siemens, working in the department for protection development and in the system planning department. He was involved in large system studies including stability calculations, HVDC and FACTS optimizations, Modal Analysis, transient phenomena, real-time simulation and renewable energy systems. .He was responsible for the development of the NETOMAC Eigenvalue Analysis program. Since 2000 he has been working at E.ON Netz, responsible for system studies, system dynamics and the integration of large scaled wind power.

Andreas Dittrich (1958) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1985. Until 1994, he worked with the Department of Automatic Drive Systems at the Technical University of Dresden, where he received his PhD degree in 1988. Since 1994, he works as manager software engineering with Integral Drive Systems AG Zürich, Switzerland, where his main technical focus is on control system and converter software design for high power drives in energy conversion, motor control and traction applications.