Effect of Wind Turbine Output Current during Faults on Grid Voltage and the Transient Stability of Wind Parks

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Abstract— **This paper deals with the effectiveness of fault-induced current injection into the system by wind turbines. First, a brief review of the grid code requirement on wind turbines to support voltage profile during fault is reviewed. Based on first principles, analytical expressions quantifying the effectiveness and the limits of the voltage support effort are formulated. This has then been extended to include the limits imposed on output current by the transient stability requirements of the wind park, in which stability constrained current limits through the link wind park – the point of the interconnection and the boundary conditions for stable operation have been derived. Using sample computations, the effect of the violation of this stability limit during fault on the wind park has been analyzed. Finally, a control scheme has been proposed, which on the basis of the voltage dip experienced by the network, reduces the real part of the wind park output current with the objective of enhancing the transient stability margin. Again the effectiveness of the proposed scheme has been demonstrated using sample computations.**

*Index Terms—***Grid fault, voltage support, doubly-fed induction machine, wind power, wind generation control, transient stability.**

I. INTRODUCTION

THE transient stability problem in conventional synchronous generators is a thoroughly investigated and now fully understood phenomenon. On the other hand, the conceptualization of stability as it relates to wind generation systems following a grid fault is still an evolving issue. The nature of the problem and the threats posed to system security in both cases are fundamentally different. Unlike the classical synchronous generators, in modern wind generation systems irrespective of the type of machine used, a grid fault does not directly lead to loss of synchronism.

The transient processes in modern wind turbines are much faster than those of the conventional synchronous generators. The role of the inertial response, which is central to the behavior of conventional synchronous generators following a disturbance, is largely supplanted by the response of the controllers in wind generation systems. The impact of the wind generation plants on the rest of the system in a post fault scenario, therefore, is primarily determined by the action of their control systems. But the power electronic devices contained in the control circuitry are particularly sensitive to overloading and if a disturbance leads to supply interruption, it is probably as a result of the converters blocking operation due to excessive current.

The role of wind power in the generation mix is in all probability will continue to increase. In the near to medium term wind farms with hundreds or even thousands of megawatts installed capacity are set to be built offshore. As the wind portfolio in the overall generation mix increases, so does its impact on the transient stability behavior of the entire system. Additionally, the anticipated large offshore wind farms will often be connected to the grid through long submarine cables which on economic grounds are likely to operate (at least intermittently) at maximum capacity without considerable reserve margin. The long transit route (together with operation at high stress level) makes the offshore wind farms susceptible to dynamic problems. On the other hand the control system in modern wind turbines provides some unconventional methods for overcoming some of the problems caused by grid faults. Accordingly further research and investigations aimed at fully understanding the nature of dynamic phenomena underlying wind turbines in interaction with the grid and possible countermeasures to contend with the ensuing problem is necessary.

This paper will primarily focus on the effect of the forced current injection into the network by the wind park (WP) on the voltage profile at the point of common coupling (PCC) during a grid fault. WP are obliged to feed current into the network in support of system voltage during faults. First, grid code requirements spelling out these and other related requirements will be reviewed briefly. Then, analytical expressions quantifying the limits of the voltage support capability of WP at PCC will be derived. Similar expressions that relate the real current injected by the WP to its impact on the voltage at PCC by taking into account the reduced nature of the voltage profile during fault will be presented. This will form the basis for the formulation of the boundary condition for the current transfer limit between WP and PCC. The results thus obtained will help elucidate the concept of transient stability as it relates to wind generation systems. They will also show what the violation of the current transfer

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limit entails in terms of network voltage. The sample simulations demonstrate that the impact of severe fault on the machine is pole slippage rather than outright loss of synchronism observed in conventional synchronous generators.

Furthermore, the results of the simulation will lay the conceptual groundwork for a control approach in which the real current injected by the WP is reduced depending on the level of voltage dip at PCC. This control measure, among other things, achieves to: a) secure the stability of the wind generation system, b) enable the supply of more reactive current to raise the voltage profile during fault, and c) improve the transient stability of the synchronous generators in the network to which the WP is connected [1]. Simulation results to corroborate the enumerated advantages of the proposed control scheme together with evaluation of the scope of its application will be provided.

II. VOLTAGE SUPPORT REQUIREMENTS AND GRID CODES

The major requirements imposed on wind farms by grid codes [2], [3] in relation to their behavior following grid faults concern fault ride-through (FRT) capability and voltage support during fault. As a general rule, separation from the grid following a fault is allowed only as a safeguard measure by the system protection as spelt out in grid codes. The German grid code, for example, stipulates that if the local voltage at PCC remains low despite voltage recovery elsewhere in the grid, the safeguard is permitted to initiate separation of wind turbines in three steps starting from 1.5 s after the fault. Up until this point wind turbines have to stay connected even if the voltage at PCC drops to a value as low as zero.

Furthermore, according to the grid code currently in force wind turbines are required to perform voltage control for voltage values outside a pre-specified dead band. As a result of the typically long distance between wind farm and grid the effect of voltage support measures are bound to be limited, as will be discussed later in this paper. Fig. 1 shows the control characteristic defined in the German grid code.
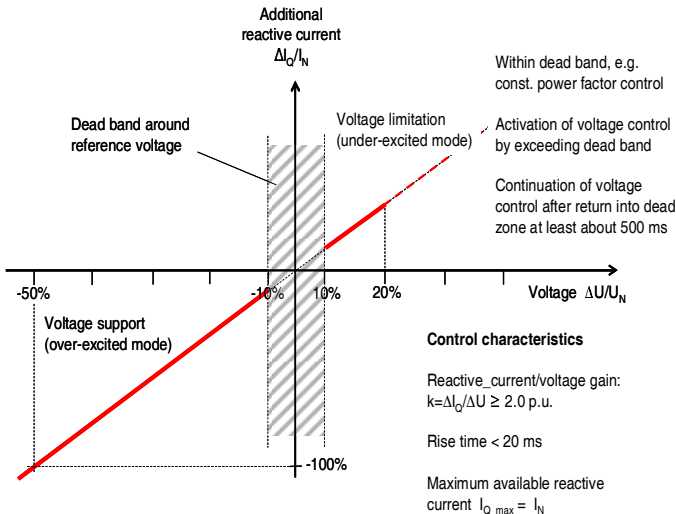

Fig. 1. Voltage control characteristic.

III. INFLUENCE OF WT CURRENT ON VOLTAGE AT PCC

To analyze and quantify the effect of the current injected by the WP on the voltage at PCC, a simplified schematic diagram of the link between WP and PCC, shown in Fig. 2, has been used. The external network is represented by its Thevenin equivalent, and in line with the usual practice, the equivalent Thevenin impedance ($\underline{Z}_G$) is computed from the short circuit capacity $S_{SC\_G}^{''}$ of the network at PCC.
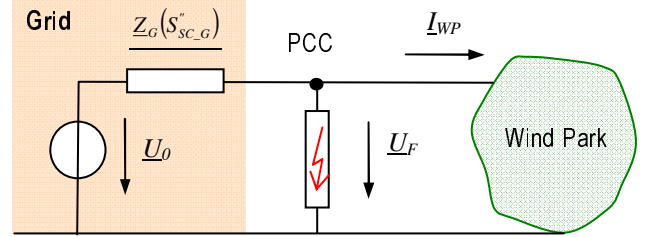

Fig. 2. Schematic diagram of a WF connected to the grid.

Assuming that $\underline{Z}_F$ represents fault impedance (or any load impedance in a general case) the voltage at PCC can be shown to be:

$$\underline{U}_F = \underline{U}_0 \frac{\underline{Z}_F}{\underline{Z}_G + \underline{Z}_F} - \underline{I}_{WP}\underline{Z}_F \frac{\underline{Z}_G}{\underline{Z}_G + \underline{Z}_F} \qquad (1)$$

Please note that the current $\underline{I}_{WP}$ is directed into the machine in line with the consumer-oriented sign convention. To quantify the voltage boosting effect of the WP at PCC, a complex voltage factor as defined in (2) is introduced:

$$\underline{\eta}_{WP} = \frac{\underline{U}_F}{\underline{U}_{F0}} \qquad (2)$$

Where $\underline{U}_{F0}$ corresponds with the voltage at PCC without the effect of the current injected by the WP. The voltage at PCC, as a result, can be re-written as:

$$\underline{U}_F = \underline{\eta}_{WP}\underline{U}_{F0} \qquad (3)$$

Alternatively, the voltage factor can be brought into relationship with the ratio of the output current of the WP $\underline{I}_{WP}$ and the short circuit current at the terminals of the external network $\underline{I}^{''}_{SC\_G}$ as follows:

$$\underline{\eta}_{WP} = 1 - \underline{I}_{WP}\frac{\underline{Z}_G}{\underline{U}_0} = 1 - \frac{\underline{I}_{WP}}{\underline{I}^{''}_{SC\_G}} \qquad (4)$$

For streamlined notation, the voltages, currents and the impedance are all expressed in polar co-ordinates as follows (with the voltage $\underline{U}_{F0} = U_{F0}$ taken as the phase reference):

$$\underline{I}_{WP} = I_{WP}e^{j\varphi_{WP}} \qquad (5)$$

$$\underline{Z}_G = Z_Ge^{j\varphi_G} \qquad (6)$$

$$\underline{U}_0 = U_0e^{j\varphi_0} \qquad (7)$$

Substituting $(5) - (7)$ in to (4), we obtain:

$$\underline{\eta}_{WP} = 1 - \frac{I_{WP}}{I^{''}_{SC\_G}}e^{j(\varphi_{WP}+\varphi_G-\varphi_0)} \qquad (8)$$

For the special case of both the fault impedance $\underline{Z}_F$ and the equivalent impedance of the network $\underline{Z}_G$ having the same phase angle, we have $\varphi_0 = 0$, leading to:

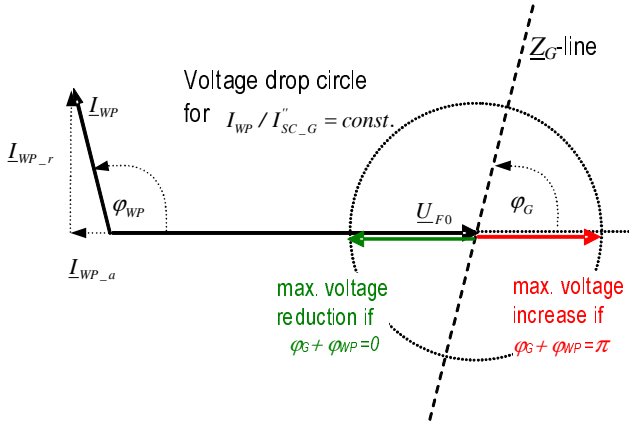$$\underline{\eta}_{WP} = 1 - \frac{I_{WP}}{I''_{SC\_G}} e^{j(\varphi_{WP} + \varphi_G)} \qquad (9)$$

Fig. 3. Voltage at PCC in relation to current injected by WP.

Fig. 4. Voltage increase at PCC as affected by WP

The preceding equations are summarized in Fig. 3. On the basis of

Fig. 3 some quick remarks with regard to the effect of the WP current on the voltage at PCC can be made. Assuming that the transmission network comprises of a pure inductive elements, maximum voltage increase occurs when the WP injects leading (capacitive) reactive current in to the PCC, i.e. when the WP operates in the overexcited mode, whereas maximum voltage reduction takes place when the WP absorbs pure inductive current (i.e. during operation in an under-excited mode). With regard to the phase position of the WP current, the condition for maximum voltage support is given by the relationship $\varphi_{WP} + \varphi_G = \pi$, while $\varphi_{WP} + \varphi_G = 0$ results in maximum voltage reduction.

The voltage support factor can also be expressed in terms of WP nominal apparent power S_{WP_N}. Thus,

$$\underline{\eta}_{WP} = 1 - \frac{I_{WP}}{I''_{SC\_G}} e^{j(\varphi_{WP} + \varphi_G)} = 1 - i_{WP} \frac{S_{WP\_N}}{S''_{SC\_G}} e^{j(\varphi_{WP} + \varphi_G)} \qquad (9)$$

where i_{WP} represents the WP current in per unit on the base of the WP nominal current whereas S''_{SC_G} is the short-circuit capacity of the grid (SSC) at the PCC.

In Fig. 4 it is arbitrarily assumed that the WP injects 1.0 p.u. current with the most favorable phase angle in terms of supporting the voltage, i.e. $\varphi_{WP} = \pi - \varphi_G$. The family of curves (Fig. 4) shows the voltage support provided by the injected current in relation to the distance of the fault location from the PCC, with SCC of the network as a parameter. It follows from the figure that the level of voltage support that can be provided depends on the strength of the network on which the machine is operating. The voltage support that can be achieved by injecting current from the WP into the network becomes more and more marginal as the network (to which the wind park is connected) becomes stronger (i.e., increasing SCC).
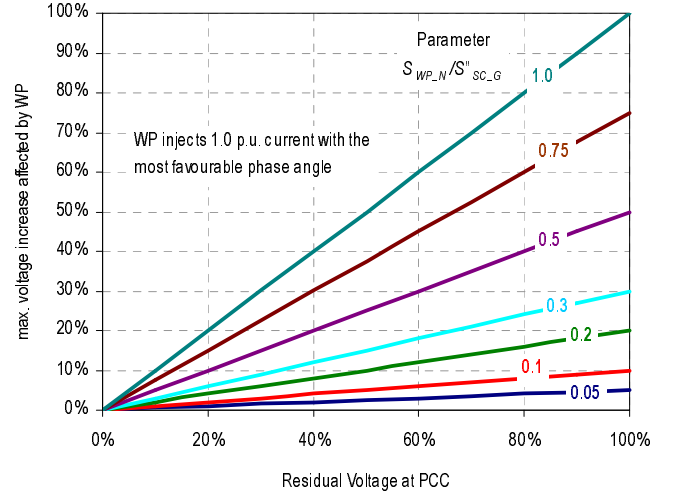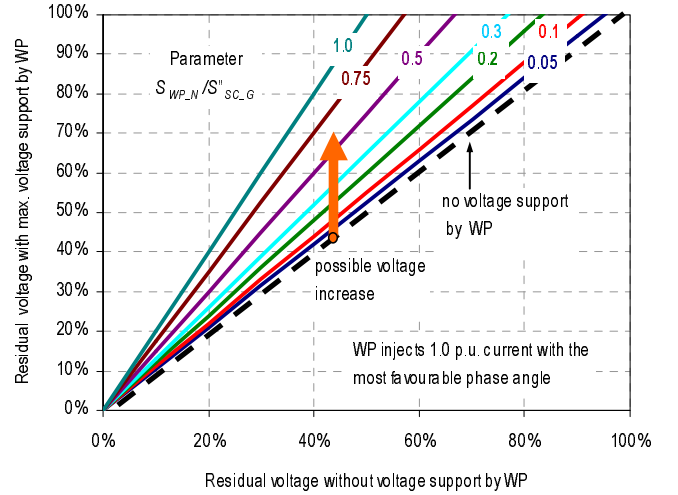

Fig. 5. Achievable voltage boost at PCC.

Fig. 5 compares the same basic relationship from a different perspective, namely the voltage dip experienced at PCC for different levels of fault severity with and without voltage support. The dashed line represents the voltage without any support by the WP. For direct comparison, in each case the reactive current injected remains at 1.0 p.u. In reaffirmation of the results obtained in Fig. 4, it can be concluded that the voltage support is most effective if the network is weak, and for a strong network (for small S_{WP_N} / S''_{SC_G}) the voltage boost that can be achieved remains marginal. Moreover the voltage support is highly contingent on the location of the fault. For faults not far away from PCC, i.e. low residual voltages, the voltage boost induced by the WP is insignificant. For example, for a fault reducing the PCC voltage to 20 %, the current injected by the WP (in this example 1.0 p.u.) can raise the voltage to 30 % ($S_{WP\_N} / S''_{SC\_G} = 0.5$), whereas for a fault reducing the voltage to 60 %, the same injected current can raise the voltage by 30 % to a post fault voltage of 90 %.

IV. CONSTRAINTS ON CURRENT SUPPLY BY WIND TURBINES DURING SHORT CIRCUIT

In the previous section, the role of WP current to boost or reduce the voltage at PCC during a contingency situation was discussed. Due to the inductive character of the high voltage grid the best voltage boosting effect can be achieved by injecting capacitive (leading) reactive current. In this section, limitations arising from the active component of the injected current will be discussed.

1) Current magnitude limitation

The output current of wind turbines during fault is limited primarily by the semiconductor devices as they are particularly sensitive to overloading. The amplitude can obviously be reduced by decreasing either the real or the reactive part of the current. However, the voltage support requirement precludes the reduction of the reactive current, and, as a result, the wind turbine control switches from active current priority (which was the case during normal operation) to reactive current priority when the voltage falls below a certain threshold. The active current reduction procedure by keeping the reactive current unchanged is illustrated in Fig. 6, in which $\underline{I}_1$ is the current violating the limit.
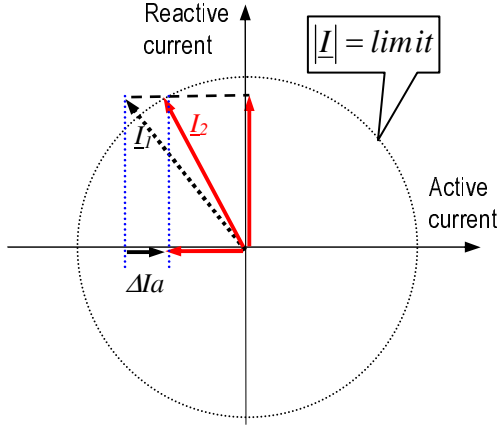

Fig. 6. Real current reduction to maintain current within limit.

Reducing the active current output for the duration of the fault does not significantly affect the overall balance between generated and consumed power adversely, as the loads also draw less power as result of the reduced voltage.

2) Current limitation due to stability

The stability requirement may necessitate the further reduction of the wind turbine output current, especially when the converter rating is relatively high. Fig. 7 shows the equivalent circuit on the basis of which the analytical expressions describing the constraints imposed by stability requirement will be derived.
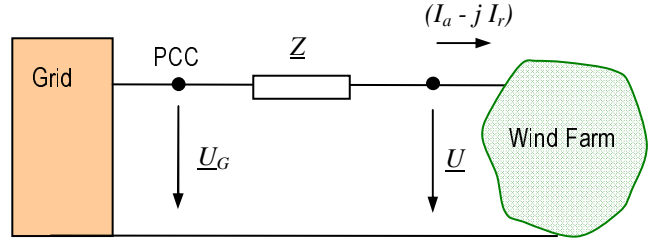

Fig. 7. Voltage at PCC in relation to current injected by WP.

The voltage at PCC is given by the following basic expression:

$$\underline{U} = \underline{U}_G - \underline{Z}\left(I_a - jI_r\right) \tag{10}$$

where I_a and I_r the active and reactive components of the current, respectively. Note that I_a and I_r do not necessarily correspond, in the general case, with real and imaginary components of the current. In polar form (with $\underline{U}$ as the phase reference), (10) can be re-written as:

$$U = U_G\, e^{j\varphi_G} - Z\, e^{j\varphi_z} \cdot I\, e^{-j\varphi} =$$
$$= U_G\, e^{j\varphi_G} - j \cdot Z \cdot I \cdot e^{j(\varphi_z - \varphi - \pi/2)} \tag{11}$$

Now, we define two additional variables to enable a simpler notation:

$$\left(\varphi_z - \varphi - \pi/2\right) = -\varphi^* \tag{12}$$
$$\beta = \varphi_z - \pi/2$$

Incorporating (12) into (11) and re-arranging, we obtain for the voltage at PCC:

$$U = U_G e^{j\varphi_G} - j \cdot Z \cdot I_a^* - Z \cdot I_r^* \tag{13}$$

with

$$I_a^* = \left(\cos\beta\, I_a + \sin\beta\, I_r\right)$$
$$I_r^* = \left(\cos\beta\, I_r - \sin\beta\, I_a\right) \tag{14}$$

Eq. (14) corresponds with rotating coordinate transformation from I_{real}, I_{imag} axis to I_{real}^*, I_{imag}^* axis with the angle difference between the two axes being β. Fig. 8 summarizes the relationships (13) and (14) in form of a phasor diagram.
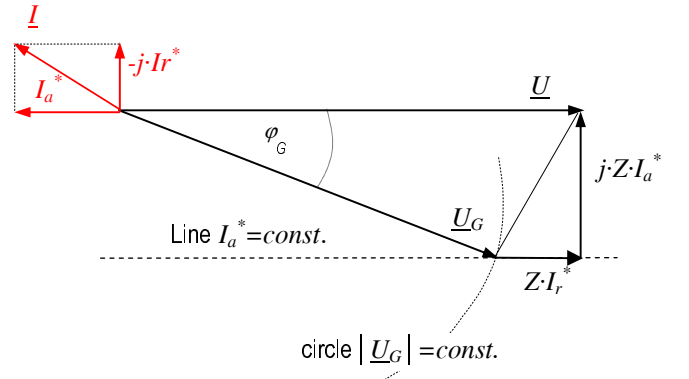

Fig. 8. Locus of voltage at PCC in relation to current injected by WP.

As is well known, the steady state stability limit for power transfer via the link WP – PCC is given by $|\varphi_G| \le \pi/2$. During transients in conventional synchronous machines, on the other hand, even if the angle φ_G exceeds this limit transient stability can still be maintained under circumstances. On account of

their fast response time, the controllers in modern wind generation systems in effect create a quasi stationary situation. Consequently, the above-mentioned steady state limit can still be considered valid for such basic discussions for a short initial period following a fault. It then follows from the phasor diagram (Fig. 8) that for φ_G =-π/2 we have for the voltage: $U = -Z \cdot I_r^*$.

Now, taking both conditions together, i.e. φ_G =-π/2 and $U = -Z \cdot I_r^*$, eq. (13) leads to:

$$0 = -jU_G - jZ \cdot I_a^*,$$

which directly results in the following expression for the stability limit:

$$I_{a\_max}^* = -\frac{U_G}{Z} \qquad (15)$$
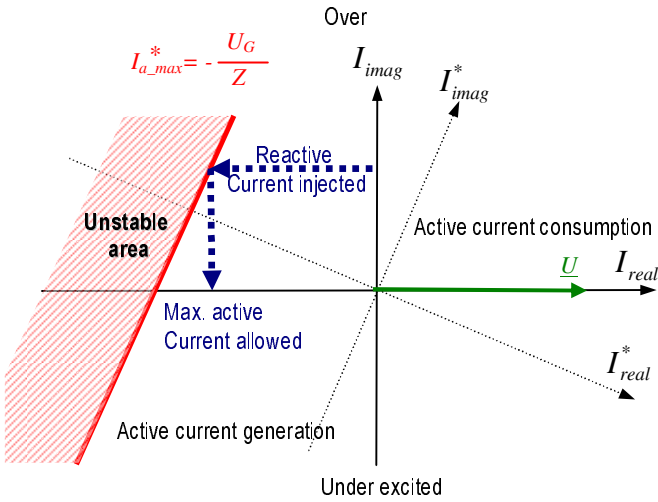
Fig. 9. Boundary between stable and unstable operating points.

Fig. 9 is the illustration of eq. (15) in the complex plane, which shows the stable and unstable operating regions and the boundary separating them. A typical current phasor is indicated in the diagram as an example. (Please note that the consumer-oriented sign convention has been used, and as a result the phasor corresponding to the machine operation as on overexcited generator lies in the 2. quadrant).
For further discussion of the relationship embodied by
Fig. 9, assume now that the current exceeds the stability limit and strays into the unstable region. Meeting the stability requirement and moving the phasor back into the stable region can theoretically be accomplished by reducing either the reactive or the real current. However, the control system under fault conditions is switched to reactive current priority as stipulated in grid codes and as a result under the given circumstances this is not an option, and the only available course of action is to reduce the real current. If the current is not reduced the wind turbine starts getting unstable and can experience a significant pole slippage. As a result of the fast response time of the converters, however, chances are that it will catch up with the system and return to synchronism much

faster than the typical settling time of conventional synchronous generators.

3) Magnitude and stability constrained current injection

Fig. 10 combines both the magnitude limitation and the constraint imposed by stability requirement. Both the magnitude and the phase angle of the output current determine which of the two constraints is at risk of being violated first.
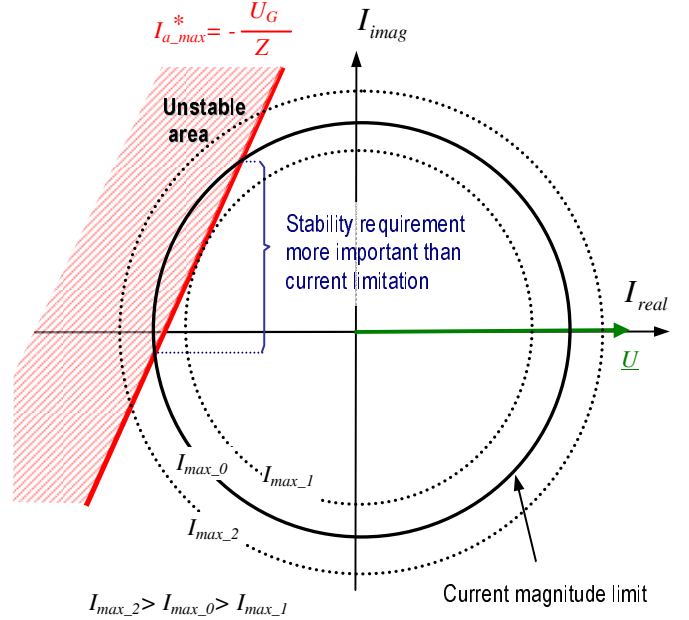

Fig. 10. Real current reduction to maintain current within limit.

Based on Fig. 10 and within the context of the requirement to fulfill both the current magnitude and stability requirements concurrently, the following observations can be made.
– The corollary of increasing the reactive current and the gain of the voltage controller (as required by grid code) is active current reduction. This will, generally, have a positive effect on the transient stability.
– The grid code specifies the necessary reactive current injection during faults in an indicative range. Some turbine manufacturers choose to fulfill only the minimum requirement and accordingly set this value as maximum (e.g. 1.0 p.u.). It follows from the preceding bullet that a cap on the reactive current apart from the magnitude limit can have an adverse effect on the stability. Because, as a result of the limit put on the reactive power, now there is room for the supply of more real current. This may shift the operating point to a region where the stability can become a problem. To put it more pointedly, putting an additional limit on the reactive current (before the magnitude limit is reached) can have a negative effect on the transient stability of the wind park.
– Converters with higher current limits (I_{max_2} in Fig. 10) tend to cause an unstable WP behavior. Conversely, a

smaller converter current limit (I_{max_1} in Fig. 10) can under circumstances preclude the stability constraint altogether, i.e. for every current value within converter limit the WP remains stable. It should however be borne in mind that lower converter limit also entails lower availability of reactive current to support the voltage in the event of fault, and as a result, not an optimum solution, when the requirements of the system are considered holistically.

V. VOLTAGE DEPENDENT ACTIVE CURRENT REDUCTION DURING A GRID SHORT CIRCUIT

The stability phenomenon and the risks associated with it for the WP are the subject of further discussion in this section. For this purpose, a typical wind park arrangement (Fig. 11) with real-world data has been simulated. The fault in this example is adjusted to reduce the voltage at PCC to about 20 %. The resulting plots are shown in Fig. 13. The WT values are measured on the 33-kV side of the transformer. The curve shows voltage (a) and phase angle (b) both at the WP terminal and at PCC. Plots of additional variables of interest are also shown in the figure.
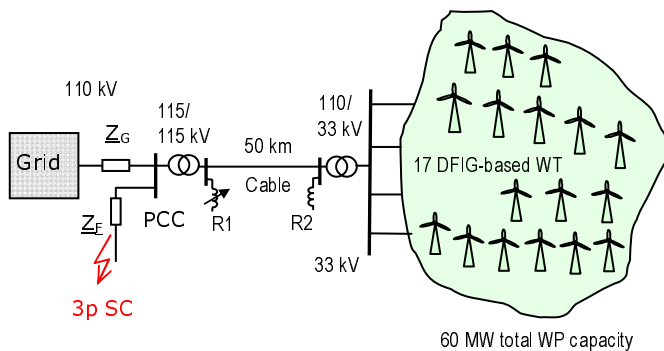

Fig. 11. Test network

Fig. 13 reveals that the phase angle of the voltage undergoes changes over a wide margin. Once the fault is cleared, the angle settles fairly quickly at stable operating point. This is due to the fast converter control. Returning to the behavior of the voltage angle, Fig. 13 shows (for the fault simulated in this example) the machine is in fact on the verge of experiencing complete pole-slippage vis-à-vis the grid. As can be observed in Fig. 13 the angle traverses from 180^0 all the way to -180^0 within a space of only a few milliseconds. The change over such a wide margin so quickly is bound to cause stress on the machine and needs to be avoided. As shown earlier in

Fig. 9, shifting the operating point from an unstable to stable region or increasing the stability margin can be accomplished by reducing either the real or the reactive current, of which only the real current reduction remains an option.
As a next step, a control structure - denominated "voltage dependent real power reduction" – which can fulfill this objective has been proposed. The structure of the proposed controller is shown in

Fig. 12 [1]. The controller, depending on the level of the voltage dip experienced, reduces the active power output of

the WP. The objective of this control measure is to reduce the risk of pole slippage or loss of synchronism by the machine. With all the assumptions remaining unchanged, the improvements in terms of performance during fault by using this control scheme is shown in Fig. 14. The parameters of the controller are given in [1].
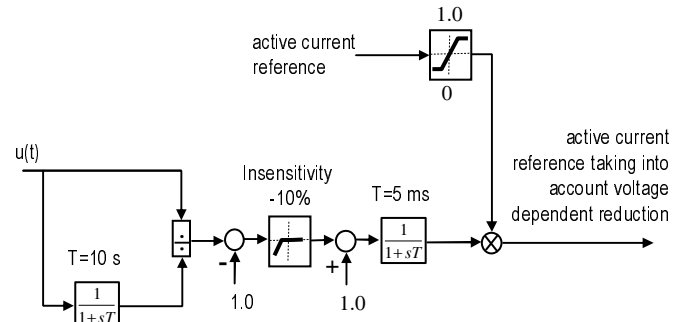

Fig. 12. Model of a control structure for voltage dependent active current reduction

It is evident that the voltage angle now undergoes only modest changes and is nowhere near loosing synchronism or experiencing pole slippage. The voltage recovery takes place also faster. The real and reactive power oscillations are also much more damped.

VI. CONCLUSIONS

In this paper the effect of forced current injection into the network by the wind park on the voltage profile and on the transient stability of the wind park has been studied. While reactive power support helps stabilize the network voltage in the post fault scenario, the amount of support provided depends on the strength of network to which the wind park is connected. In a strong network the impact of the injected reactive current in terms of boosting the network voltage is only marginal.

In addition to the magnitude limit dictated by the converter rating, the current in-feed of the wind park during fault is also constrained by the need to preserve the transient stability of the wind park. The fact that wind turbines during fault switch to reactive current priority mode has a positive impact in terms of improved transient stability performance. On the other hand, limiting the reactive current in-feed before the magnitude limit is reached may reduce the stability margin. Converters with higher current limits tend to cause an unstable WP behavior, while a smaller converter current limit can under circumstances lead to an operation without stability constraints.

To improve the transient stability performance of the wind park, a control structure has been proposed, which on the basis of the voltage dip experienced, reduces the active power output of the turbines during a contingency situation. Using simulations on a representative wind park configuration, it has been demonstrated that the control approach significantly reduces the risk of loss of synchronism in the event of grid faults.
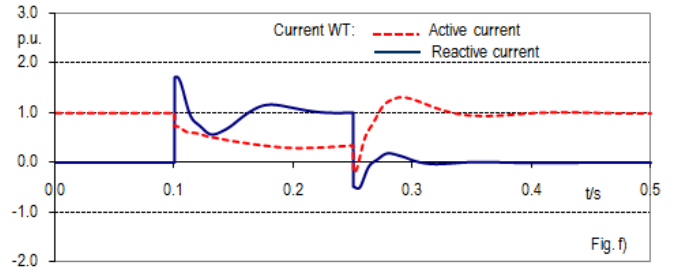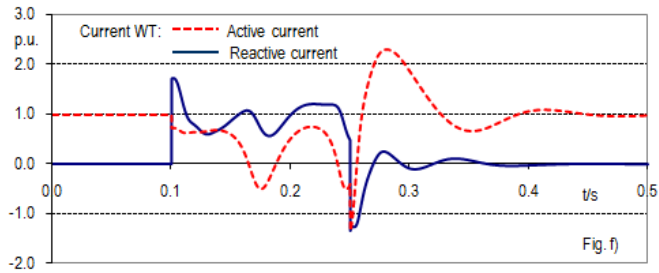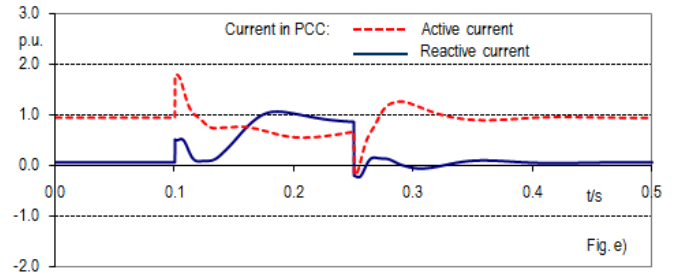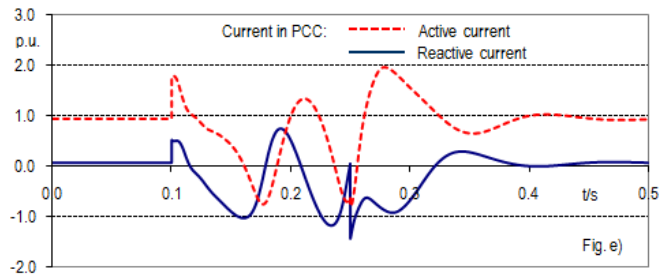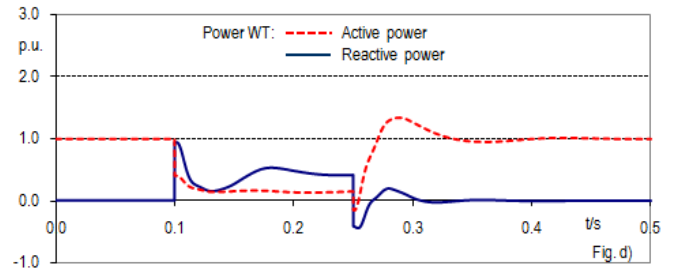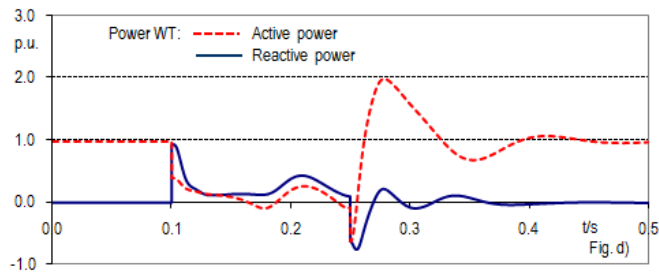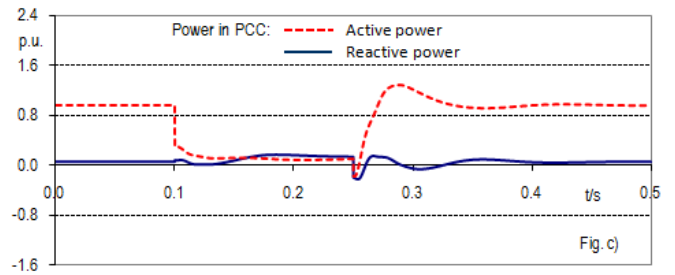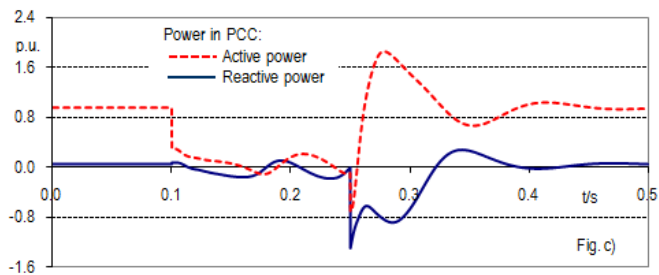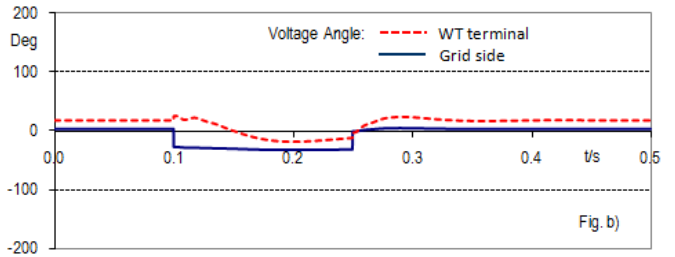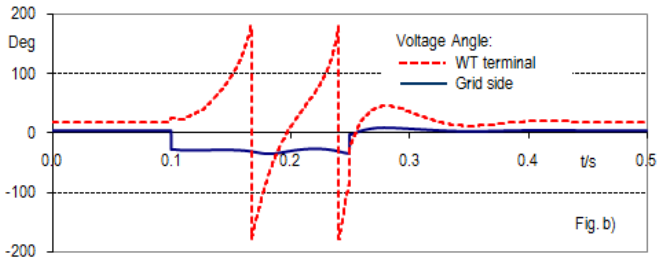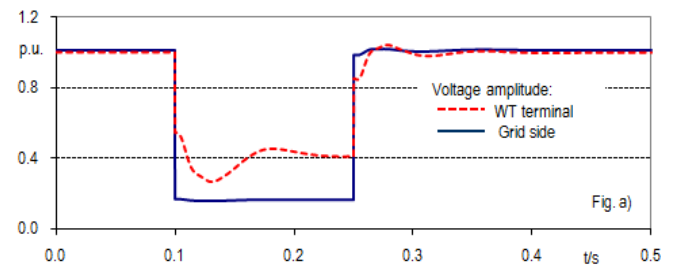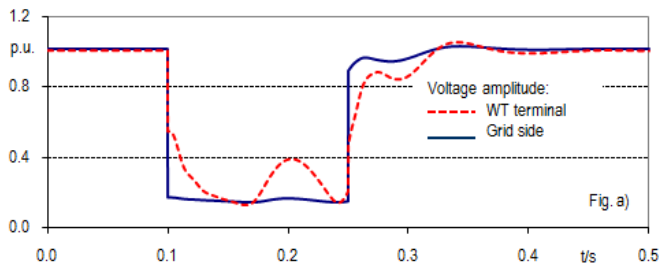
Fig. 13. Unstable operation during the fault; results without voltage dependent active current reduction (WT quantities at the 33-kV terminal).

Fig. 14. Stabilization of Wind Park with voltage dependent active current reduction (WT quantities at the 33-kV terminal)

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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, modeling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and 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 in the same university 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.

Stephan Engelhardt (1967) received his Dipl.-Ing. degree in electrical engineering from the University Hannover, Germany, in 1997. Since 1997 he is with SEG GmbH & Co. KG, Kempen/Germany, presently head of the group Converter Technology and responsible for system designs and simulations, control strategies and patents. He is a member of IEEE.

Jörg Kretschmann (1958) received his Dipl.-Ing. degree in electrical engineering from the Technical University Berlin, Germany, in 1986. In the period of 1986 to 1988 he worked for engineering department of AEG-Kanis in Essen, manufacturing of synchronous generators up to 200 MVA. Since 1988 he is with SEG GmbH & Co. KG, Kempen/Germany, as a designing engineer for speed-variable applications: uninterruptible power supply, shaft alternators, DFIG for wind turbines. His main field is simulation of power converter systems, design of power components, passive grid-filter.

Jens Fortmann (1966) received his Dipl.-Ing. degree in electrical engineering from the Technical University Berlin, Germany, in 1996. From 1995 to 2002 he worked on the simulation of the electrical system and the control design of variable speed wind turbines at the German wind turbine manufacturers Suedwind and Nordex Energy. Since 2002 he is with REpower Systems AG, Germany as project manager for the simulation and implementation of new technologies for improved grid compatibility of wind turbines like voltage control and ride-through of grid faults. He is member of IEEE.

Friedrich W. Koch (1969) received his Dipl.-Ing. degree in electrical engineering from the University of Siegen, Germany in 1998. From 1998 to 2000 and 2005 to 2006 he worked as engineer, project manager and finally as head of group in the field of industrial and power plants for the SAG GmbH. In between from 2000 to 2005 he worked on his PhD in the Department of Electrical Power Systems at the University of Duisburg - Essen, Germany. Since 2006 he is with REpower Systems AG, Germany as head of the group "Grid Integration / Simulation".