Cage Induction Generators for Wind Turbines with Power Electronics Converters in the Light of the New Grid Codes

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Acknowledgements
The authors would like to thank SINTEF Energy Research in the persons of John Tande and Kjell Ljokelsoy for providing the 55 kW machines and drive system that were used in the experiment. The authors also wish to thank Giuseppe Guidi for his contribution in the experimental set-up and during measurements.

Keywords
« grid code », «voltage sag», «DC link control», « back to back converters », « cage induction generator »

Abstract
An electrical system for wind turbines using cage induction generator with back to back converters for connection to the network is experimentally tested under short circuit conditions in a 55 kW generator set-up. 50% voltage sag is realized in the laboratory set-up to investigate the performance of the power electronic converters control under the newly introduced grid codes. Standard vector control techniques are implemented with the aim to maintain balance between generated power and power supplied to the grid. The robustness of the power electronics converter is experimentally analyzed under the short circuit for different settings of the converter nominal current and the converters are found to be robust against voltage sags.

Introduction
The emergence of new grid codes will pose wind turbine developers a new challenge: the ride through capability during voltage sags. This means that with a high penetration of wind power in the network, the wind turbines/wind farms should be able to continuously supply the network during voltage sags. One of such grid code voltage sag profile for ride through is shown in Fig 1(1) for illustration. These new grid codes which are being proposed in Norway (2) and several other countries (3) will most likely influence the topology of the electrical system (generator and network interface) of future wind turbines. To cope with this new challenge several industries have already directed research efforts to the development of ride through capability. (4) (5).

Among the technology choices, squirrel cage induction machines are a very attractive choice for wind power generation because they are robust, inexpensive and have low maintenance requirement and cost. As network interface, the use of back-to-back converters for variable speed operation is extensively
reported in the literature (6) (7) (8) showing their capability to achieve maximum energy capture in a wide range of wind conditions. There is however little reference to the control of back to back converters for low voltage ride-through capability of wind farms connected to the network (9) (10).

In this paper we analyze an electrical system for wind turbines with cage induction generators interfaced to the grid with back to back converters, and experimentally evaluate the ride through capability under short circuit in the power system for different setting conditions of the converters. A 55 kW motor-generator set of squirrel cage induction machines with a wind emulator to control the torque is used as model for the wind farm. This set-up is connected to the grid through back to back converters, as schematically shown in Fig. 2. The purpose of the experiment in this paper is to evaluate the role of the power electronics converter as a grid interface under short circuit conditions for the most common and inexpensive type of generator: the squirrel cage induction generator. Standard vector control techniques are implemented, aimed at keeping the DC link voltage constant or rising to a safe value to ensure power balance during the short circuit. Experimental results show a very stiff DC link control which proves the robustness of the back to back converters against voltage sags.

**Statement of the problem**

The system under study is represented in Fig. 2. If there is a fault in the power system, the voltage on the grid side converter will be reduced and the power transfer on the grid side will accordingly be reduced if the current out of the converter is not controlled. In the instant of the fault there will be a power unbalance between generator supply and grid supply because the power on the generator side remains at the same value as the instant prior to the fault. This power unbalance, if not controlled, will make the DC link voltage rise because of the excess of power generated that cannot be supplied to the grid due to the fault.
Then, to avoid that the DC link voltage rises over its threshold value and activate the protection of the converter, the power unbalance has to be controlled very fast during the fault. This can be done by reducing the electromagnetic torque of the generator and thus reducing the power generated, and by increasing the current out of the grid side converter, that is maximizing the power supplied to the grid during the fault within the physical limitations imposed by the converter settings. The reduction of electromagnetic torque is also conditioned by the physical limitations imposed by the system total inertia and the stresses the system will have to undergo when the reduction is made from nominal operating power to a very low value at a very fast speed. In this paper we make use of a combination of both strategies; first we maximize the power supplied to the grid without acting on the electromagnetic torque and keep the balance of power during the fault. In this condition the DC link voltage rises up to a safe value that does not trigger the protection system. Secondly, we impose a lower current limit on the grid side converter and in this case without the control of electromagnetic torque by the generator side converter, the DC link voltage rises to a voltage level that triggers the protection of the converter and the converter is disconnected from the grid. Then, we actively control the electromagnetic torque with the generator side converter and reduce the power generated. In this case the DC link voltage safely rises up to its threshold value and the whole wind generation system can safely ride through the fault.

Control strategy

Wind turbines are normally programmed to drop out when there is a 30% voltage drop. Local and remote faults on the grid produce voltage dips that cause wind turbines to trip. With the growing generating capacity of wind farms, utilities are concerned about the stability of the whole system and are proposing grid codes for wind that will request wind farms to ride-through grid disturbances, remaining on-line and supplying the system. Without power electronics solution as interface between wind generation and grid, compliance with low voltage ride-through will be a hard to accomplish goal. Given the choice of the power electronics solution, the control algorithm of the power electronics converters almost entirely determines the performance and is therefore critical to ensure ride-through. Looking upon this problem, we propose a control strategy for the power converters in the event of a voltage sag in the grid side. Standard vector control techniques are implemented and tested on both, generator and grid side converters. By doing so, on the generator side converter we get decoupled control of electromagnetic torque and flux and on the grid side converter we get decoupled control of active and reactive power. The control of the DC link voltage is made in a coordinated fashion between generator and grid side converters in a way that is explained in detail in the following subsections.

Control of the grid side converter:
The aim of the grid side converter is to regulate the DC link voltage $V_{dc}$ and maintain the balance between the DC link power and power supplied to the grid. This is done by actively controlling the direct axis current component of the converter. To do that the converter 3 phase currents and voltages are expressed in a two axis reference frame synchronously rotating at the grid frequency.

The voltage at the grid side is expressed as

$$V_{abc} = R_i_{abc} + L \frac{d i_{abc}}{dt} + V_{abc_{con.}}$$  \hspace{1cm} (1)

where $V_{abc}$, $i_{abc}$, $V_{abc_{con.}}$ are grid voltages, grid currents, and voltage of the front end converter, $R$, and $L$ are the resistance and inductance between the converter and the grid. Equation (1) is then transformed into a $dq$ reference frame rotating at the grid frequency $\omega$.

$$V_{dq} = R_i_{dq} + L \frac{d i_{dq}}{dt} + L \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} i_{dq} + V_{dq_{con.}}$$  \hspace{1cm} (2)
Aligning the $d$ axis of the Park reference frame with the grid voltage vector we have that $v_q = 0$. The angular position of the supply voltage vector is computed as

$$\theta_v = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right)$$

(3)

where $v_\alpha$ and $v_\beta$ are the components of the stator voltage in a stationary two axis reference frame (Clark transformation). The power balance between the DC link and the grid side converter output gives

$$V_{dc}i_d = \frac{3}{2}v_qi_d$$

(4)

where $V_{dc}$ is the DC link voltage and $i_d$ is the DC link current. In equation (4) $v_q$ is determined by the depth of the voltage sag, and the DC link voltage can be controlled by modulating the converter direct axis current component $i_d$.

The converter quadrature current component $i_q$ is used to modulate the flow of reactive power. In our case, the reactive power reference is set to zero, to obtain unity power factor and at the same time to have the full range of the IGBT available for boosting the direct current component $i_d$ during the fault. The DC link voltage is regulated at 650 V and the threshold value for which the protection is triggered is fixed to 740 V. Fig. 3 shows the block diagram of the control of the grid side converter.

**Control of the generator side converter:**

The cage induction generator is controlled using sensorless vector control, with currents and voltages referred to a $dq$ synchronous frame with the $d$ axis aligned along the rotor flux vector position. This allows decoupled control of electromagnetic torque and flux. To calculate the rotor flux vector, first the stator flux is evaluated by integrating the stator voltage:

$$\psi_s = \int (v_s - R_s \cdot i_s)dt$$

(5)
Drift of the open loop integration is avoided by forcing the stator flux vector to follow a circular trajectory on the $\alpha - \beta$ plane, as proposed in (11). Rotor flux is then evaluated as

$$\psi_r = \psi_s - L_a i_s$$  \hspace{1cm} (6)

Above, $\psi_s, \psi_r$ are stator and rotor fluxes, $L_a$ is the leakage inductance, and $i_s$ is the stator current. The $\alpha - \beta$ components of the flux are used to calculate the electrical angle $\theta_\psi$ of the rotor flux position used in the Park transformations in order to achieve field orientation.

The electromagnetic torque of the induction machine is calculated as

$$T_e = \frac{2}{3} P \frac{L_m}{L_r} \psi_d i_q$$  \hspace{1cm} (7)

where $P$ is the number of pole pairs, $\psi_d$ is the $d$ component of the rotor flux, $L_m, L_r$ are the magnetizing and rotor inductances respectively, $i_q$ is the torque producing current and is the one used to control the electromagnetic torque. This will in turn control the active power flow and thus the voltage level of the DC link. Fig. 4 shows the block diagram of the control of the generator side converter. During normal operation, the generator is speed controlled to a set point that can be calculated so as to maximize the power that can be transferred from the turbine. When severe voltage sag occurs on the grid side, the grid side converter may reach its current limit and will not be able to transfer the whole amount of power coming from the turbine to the faulty line. As a result of the power imbalance, the DC link voltage will increase from the normal operation set-point. The generator-end converter will sense this increase and will automatically regulate the torque so that the DC link does not increase above a safety value, allowing the system to ride through a short fault.

**Experimental case-study**

Figure 5 shows the experimental configuration and data acquisition system. Ratings of experimental devices and components are shown in Table I. A 55 kW, 380 V, 110 A, 50 Hz, 6 poles cage induction machine is utilized as generator in the experimental set-up. Two non commercial converters prototypes with 5 kHz switching frequencies are used. An inductor of 1mH is connected after the grid side converter as filter. The three phase short circuit is emulated using a short circuit device composed of three anti parallel thyristor stack connected in shunt to the line via a short circuit inductor of 0.5mH.
The whole set-up is then connected to the utility bus via three 0.2mH inductors that act as line impedance. The inductors were selected so as to produce the desired voltage sag and also to limit the short circuit current from the mains. One DSP is used for signal processing and control of each converter and communication between is achieved by means of a CAN bus. The DC link voltage is regulated to 650V. In the generator side, only two phase currents are measured, while the value of the DC link voltage is received from the line front-end system through the high speed CAN bus. At the grid side converter two line currents, two line voltages together with the DC link voltage are measured. The induction generator is driven by a second induction machine of 55 kW whose torque is controlled using a commercial frequency converter to have constant nominal torque. Fig. 6 shows the 55 kW motor-generator set-up used in experiments to emulate the wind turbine and wind generator. Fig. 7 shows the two back to back converters connected to the generator of Fig. 6. The IGBTs of the converters used in the experiment were rated for 110 A (rms) with no short time overload. In a second test the current limit of the IGBTs was set to 0.8 p.u. to test the performance of the generator side converter controller. The short circuit was emulated by sending triggering signals to the thyristors so as to produce a short circuit for 100 ms.

Fig. 5: Experimental configuration and data acquisition system

**Table I: Ratings of experimental devices**

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<th>Component</th>
<th>Specification</th>
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| Cage induction machines (M-G set) | Power rating: 55 kW  
                              | Rated speed: 990 rpm  
                              | AC voltage: 380 V  
                              | Current: 110 A  
                              | Drive: commercial ABB inverter |
| Line inductance                  | Utility side: 0.2 mH  
                              | Generation side: 1mH |
| Power converters (IGBT)          | Switching frequency: 5 kHz  
                              | DC link voltage: 647 V  
                              | DC link capacitance:  
                              | Current: 110 A |
| DSP: TMS320F2812                 | AC Voltage: 400 V  
                              | Current: 2000 A (short circuit) |
| Utility line                     | Inductance: 0.5 mH  
                              | Snubbers: C:220nF; R: 68Ohm  
                              | Max. Current: 2200 A |
Experimental results

Several short circuit trials have been made to achieve a voltage sag of 50%. We operated the short circuit device previously described by giving a triggering signal to the thyristors for a short circuit duration of 100 ms. The torque of the induction motor that drives the induction generator was set to give constant nominal the torque for all the tests. For the first experiment, the rating of the IGBTs was set to 110 A (1p.u.). With the parameters of the experimental system shown in Table I we measured the voltages and currents shown in Fig. 8. In the first graph of Fig. 8, the line voltages $V_{ab}, V_{bc}$ are shown. At the instant the short circuit is activated we can observe a voltage reduction down to 0.5p.u. In the second graph of Fig. 8, we have the DC link voltage $V_{dc}$ and the direct component $V_d$ of the line voltage. We can see that during the 100 ms of the short circuit the DC link voltage is very stiffly controlled to the preset value in the grid side converter controller. Imperceptible variations are observed during the short circuit, which means that a perfect decoupling of the generator from the grid was achieved; the generator did not sense there was a short circuit. This is the result of the balance between generated power and power supplied to the grid. Active and reactive powers $P, Q$ are shown in the third graph of Fig. 8. It is an important feature of the control that the power delivered to the grid tends to be constant, given by the product of $V_d I_d$ which gives approximately 50 kW using the VA appropriate base. The reactive power oscillates around zero which is expected because the control is programmed for unity power factor. In the last graph of Fig. 9, we can confirm this by observing the reactive current $i_q \approx 0$. We see also the direct component of the current out of the front end converter which increases up to its limit of 1 p.u. during the short circuit and thus tends to maintain constant the supply of power to the mains.

Among all the measurements, the DC link voltage is the most representative and relevant, because it shows the robustness of the converter control system during a 50% voltage reduction on the mains. This is a very desirable feature during severe short circuits because the capability to continue stable supply will strongly depend on the dynamics of the DC link.

Fig. 6: The 55 kW motor-generator set for the experimental set-up
Fig. 7: Back to back converters of the experimental set-up

Fig. 8: Experimental results on the 55 kW set-up for the 50% voltage sag during 100 ms: $I_{\lim}=1$ p.u.
A second experiment was performed in which the rating of the IGBTs was limited to 0.8 p.u.. This was done in order to test the performance of the generator side converter controller in handling the excess of mechanical power by reducing the electromagnetic torque and allowing increase of generator speed for a short time. In this case the generator was controlled in a variable speed fashion. The results of measurements are shown in Fig. 9. In the first graph of Fig. 9, the line voltages $V_{ab}, V_{bc}$ are shown, and we can observe a voltage reduction down to 0.5p.u during the fault. In the second graph of Fig. 9, we have the DC link voltage $V_{dc}$ and the direct component $V_d$ of the line voltage. During the 100 ms of the short circuit the DC link voltage rises. As soon as it reaches a safety threshold, active DC link control is activated on the generator side, reducing the amount of generated power in order to keep the DC link voltage under control. In general, the excess power from the wind will cause the generator to accelerate, according to its inertia. In this case, there was not significant change in generator speed during the 100 ms fault. The DC link was stiffly controlled and again, a perfect decoupling of the generator from the grid was achieved.

Active and reactive powers $P,Q$ are shown in the third graph of Fig. 9. Active power is reduced as expected due to the lower limit imposed to the IGBTs, and is given by the product of $V_d I_d$ which gives approximately 50 kW. Reactive power oscillates around zero which is expected because the control is programmed for unity power factor. We confirm this by observing the last graph of Fig. 9, where reactive current $i_q \cong 0$. We see also the increase of the direct component of the current out of the grid side converter which increases up to its limit of 0.8 p.u. during the short circuit, and in this way limiting the active power supply to the grid.

Fig. 9: Experimental results on the 55 kW set-up for the 50% voltage sag during 100 ms: $I_{lim}=0.8$ p.u.
Discussion

In this paper we are showing the results of the control for a maximum voltage drop of 50% for two different cases of converter settings, and could observe that the DC link was still very stiff and there were good margins to inject the excess current into the network. However, for voltage sags deeper than 50% the control of the grid side converter might not be able to inject more current into the network because the current limit of the IGBT will be reached. In this case, the generator side converter will sense a DC link voltage threshold and that will activate the control of the electromagnetic torque aimed at reducing it in order to compensate for the power unbalance with the network. In this case the excess of power generated will be stored in the kinetic energy of the rotor and can be aided by a coordinated pitch control of the blades to reduce the incoming power from the wind. When the sag approaches zero voltage, there can be some other possible solutions to counteract the excess of generating power from the wind turbine, especially if before the fault the wind turbine was operating near its nominal power. One of these solutions is to dimension the converters to withstand a certain level of over current and to have at the same time braking choppers in the DC link to dissipate the excess power. It may also help to maximize the generator losses during the fault, in order to be able to absorb as much power as possible from the wind turbine. This strategy will be fully exploited in future experiments.

Conclusion

It is found in the experiment that down to 50% voltage reduction the DC link voltage is very stiff during the short circuit. Considering that wind turbines generators will trip when they detect a 30% voltage drop, the results shown in this paper are very promising with respect to the ride through capability. In the electrical system analyzed in this paper, in spite of the additional cost of power electronics converters and control, with the new grid codes the achievement of ride through capability is of relevance. Therefore, the additional investment will certainly be justified in this new scenario. However, depending on the grid code to be adopted, it will be necessary to test the back to back converters for more severe voltage sags and this remains a subject for further investigation.

References