BEHAVIOUR AND CONTROL OF DOUBLY FED INDUCTION GENERATORS IN WIND TURBINES DURING GRID FAULTS.

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Summary: This paper describes the influence of grid faults on a doubly fed induction generator and the attached converter. It also presents a control strategy to minimize these effects without using a crowbar. Therefore keeping the converter generator system controllable.

1 INTRODUCTION
Doubly fed induction generators (DFIG) are commonly used in wind energy turbines. While the mechanical loads introduced in the drive train due to wind turbulences have been examined (e.g in [12]). The influence of grid faults on the generator and the drive train is not very well understood. This paper examines the behaviour of the DFIG in case of grid faults, the effects of these grid faults on the wind turbine as well as possible control strategies.

2 MODULAR SIMULATION MODEL
In order to examine these effects, a modular matlab simulink model of the electrical system of a wind turbine has been developed at the IALB. The model can work in concert with a simplified matlab model of the mechanical part of the drive train developed at the IALB as well as a much more detailed multi body model of the mechanics. The modular model of the electrical system shown in Fig. 1 consists of a simplified mechanical model, a detailed model of the generator, a converter model, a detailed representation of the cable, the transformer and the grid.
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![Fig. 1 Model Components](image)

a. Generator Model

A standard model of a DFIG [4] neglects iron-saturation and skin-effect. Some models consider exclusively skin-effect [2] or iron-saturation [9]. In fact both saturation and skin effect are affected in case of transient events. Depending on the shape of the rotor current the rotor current is influenced by the skin effect. The amplitude of the currents affects in case of saturation the effective main inductance is reduced and therefore cannot be described as a constant parameter [5]. A mathematical model of the DFIG oriented on the main flux axis, describing the physical relationship between the magnetizing current $i_m$ and the main inductance in a direct way was presented in [10].

\[
\begin{align*}
\mathbf{u}_x &= R_S (i_m - i_x) + \frac{\mathrm{d}i_m}{\mathrm{d}t} (L_{\text{b} (i_m)} + L_{S_\sigma}) - L_{S_\sigma} \frac{\mathrm{d}i_y}{\mathrm{d}t} + L_{S_\sigma} \omega_m i_y \\
\mathbf{u}_y &= (L_{\text{b} (i_m)} + L_{S_\sigma}) \omega_m i_m - L_{S_\sigma} \omega_m i_x - R_S i_y - L_{S_\sigma} \frac{\mathrm{d}i_y}{\mathrm{d}t} \\
\mathbf{u}_x &= R_R (i_x) i_x + L_{R_\sigma (\text{skin})} \frac{\mathrm{d}i_x}{\mathrm{d}t} - L_{R_\sigma (\text{skin})} (\omega_m - p \omega) i_y + \frac{\mathrm{d}i_y}{\mathrm{d}t} L_{h (i_m)} \\
\mathbf{u}_y &= R_R (i_y) i_y + L_{R_\sigma (\text{skin})} (\omega_m - p \omega) i_y - L_{h (i_m)} (\omega_m - p \omega) i_y
\end{align*}
\]

In the equations (1.1) to (1.4) $u_x, u_y$ and $i_x, i_y$ describe the direct and the quadratur part of the stator voltage and stator current in main field coordinates, $u_{x, y}$, $u_{x, y}$ and $i_{x, y}$ describe the direct and the quadratur part of the rotor voltage and rotor current in main field coordinates. $R_S$ and $R_R$ represent the resistances of the stator and the rotor windings, $i_m$ the amplitude of the magnetisation current, $L_h$ the main inductance; $L_{S_\sigma}$ and $L_{R_\sigma}$ the stator-, rotor- leakage inductance, $\omega_m$ the main flux angular velocity, $\omega$ the mechanical angular velocity and $p$ the number of pole pairs.

As can be seen in the equations (1.1) to (1.4) the description of the saturation is separated from the description of the skin effect. This allows an easy calculation of the dynamic behavior because saturation and skin effect are described independently. The new model allows the simultaneous use of the well known methods for calculation the skin effect [2], [13] and the main flux saturation [5], [9]. With these results the influences on the torque and the resulting dynamic loads on the drive train of the wind turbines can be described in a higher level of detail while still retaining easy to use methods.
b. Converter Model
The modelling of the converter was based on the PhD thesis of H.Raffel [8] and has been extended by pulse-width-modulated signals both for the grid side as well as the generator side of the converter. Depending on the configuration of the complete system model it is possible to vary the influence of the converter on the whole simulation. At the lowest detail level, only the time delay is considered. At higher levels the switching behaviour of both the grid side and the generator side converter are taken into account. Based on the standard control in stator flux coordinates optimized controllers for both converters were developed.

c. Cable and transformer Model
For the modelling the cable was divided into multiple parts of equal size. Each of these parts has the basic structure of a series oscillator circuit. These parts or segments interact via action and reaction. Each Segment comprises an inductance $L_C$, a resistance $R_C$, as well as a capacitance $C_C$ and its parasitic resistance $R_{PC}$. The length of the simulated cable can be varied by the number of segments. By the parameterization of each segment an aerial line can be simulated as well as an underground cable. In a first step for the simulations the three-phase cable was approximated by three screened cables. In order to expand the model to the simulation of an unscreened three-phase cable the inductance, resistance and capacitance in each segment can be replaced by matrices also comprising the coupling factors between the phases. Additionally a transformer model was developed. An important challenge was to ensure the compatibility of this model with the rest of the separate models as well as the complete model as a whole. Starting from the basic model of a transformer [3] the model was extended in order to consider additional effects. As with every other sub-model here also the needed computing capacity increases with higher complexity of the model and a balance has to be found between the required complexity and the computing capacity. With the available computational power not all details (e.g. the capacitive couplings between phases) could be simulated. However all significant aspect up to ca. 1 kHz signal frequency are represented by the model [3].

d. Grid Model
Furthermore a compatible simulation model of a three-phase grid was derived. The model can be used to simulate symmetric as well as asymmetric grid conditions. As is shown in [15], [16] an asymmetric system can always be split into three symmetric systems. These are the direct system, rotating in the same direction as the original three-phase system, the inverse system, rotating in the opposite direction and the zero system, which does not rotate. In a three-phase grid the zero system is not present [15], [16]. Also a symmetrical system can be considered a special case, where there is only a direct system.
The sub model of the grid allows for the simulation of different grid fault and the introduction of harmonics at an arbitrary point. The grid model comprises sinusodial voltage sources for the fundamental frequency as well as higher frequency sources, which can be added with different amplification to the fundamental frequency, thereby simualting hamonic contents with different amplitudes. Furthermore the three fundamental phase voltages can be attenuated in order to simulate voltage drops.
3 **GRID FAULTS**

For this work the consideration of the many possible grid faults was reduced to some significant and characteristic cases. Among these are the single-phase and the three-phase voltage drops shown in Fig. 2. At a specific point in time the voltage of one or all three phases drops to a certain level and rises again to the original level after a predetermined amount of time (in the example in Fig. 2 after 200ms).

![Fig. 2 example grid fault](image)

4 **EFFECTS ON THE GENERATOR**

In order to evaluate the effects of grid faults on the generator, both simulations with the new modular model and measurements on a test stand were conducted.

a. Simulation

In this section the results of simulations of both a symmetrical and an asymmetrical voltage drop to about 60% of the original value are shown. The influence of the grid fault can be seen in the following figures.

![Fig. 3 Simulation of a symmetrical grid fault](image)

![Fig. 4 Simulation of an asymmetrical grid fault](image)
In Fig. 3 a) and Fig. 4 a) the time signals of the grid voltage, the rotor current and the shaft torque of the generator are shown for a symmetrical and an asymmetrical grid fault respectively. Fig. 3 b) and Fig. 4 b) show the spectrum of the rotor current both before (blue) and during the fault (red).

From the equations of the induced open-circuit voltage \( u_{R0} \) (1.5), (1.6) (cf. [14]) during the transition form one voltage level to the other the behaviour of the rotor current under load can be derived. Eq. (1.5) describes the rotor open-circuit voltage during a symmetrical grid fault.

Besides a stationary part comprising the slip frequency \( (\omega_m - p\omega) \), an additional, transient component with the mechanical frequency of the rotor exists,

\[
\begin{align*}
\frac{L_{h(S_{i_1})}}{L_{S_{i_1}}} \frac{p\omega}{\omega_m} U_2 e^{j(\omega_m - p\omega)t} - \frac{L_{h(S_{i_2})}}{L_{S_{i_2}}} \left( 1 - \frac{p\omega}{\omega_m} \right) (U_1 - U_2) e^{-j\omega(t - \frac{1}{\tau_s})} \\
\end{align*}
\]

In case of an asymmetrical grid fault, using the description by the symmetric components of the asymmetric fault, in addition to the stationary part of the direct system at the slip frequency \( (\omega_m - p\omega) \) and the transient part at the mechanical frequency, there appears a stationary part of the inverse system at the frequency -(\( \omega_m - p\omega \)). Under load transient multiples of the grid frequency occur in the stator current, caused by retroactive effects [7]. This in turn causes transient components at frequencies \( (n\omega_m + p\omega) \). In case of asymmetrical grid faults also at frequencies -(\( n\omega_m + p\omega \)) where \( n=2,3,... \)

\[
\begin{align*}
\frac{L_{h(S_{i_1})}}{L_{S_{i_1}}} \frac{p\omega}{\omega_m} e^{j(\omega_m - p\omega)t} + U_{S_{i_2}} \frac{L_{h(S_{i_2})}}{L_{S_{i_2}}} \left( 2 - \frac{p\omega}{\omega_m} \right) e^{-j(\omega_m + p\omega)t} \\
- \Psi_{S,A0} \frac{L_{h(S_{i_1})}}{L_{S_{i_1}}} \left( \frac{1}{\tau_s} + jp\omega \right) e^{-j\omega(t - \frac{1}{\tau_s})} \\
\end{align*}
\]

b. Test Stand

The test stand emulates the behaviour of a wind energy plant. An induction motor driven by a frequency converter provides the torque and simulates the wind driven rotor blades. The mechanical to electrical energy transformation is done by a 22 kW doubly fed induction generator. Additionally the drive train comprises a single stage spur gear box. Additionally a replication of the connecting cable was developed and implemented at the IALB [12].

At the machine lab of the IALB the dynamic of the voltage drop is limited to a fall time of about 15 ms. In order to compare the measurements additional simulations were done with this reduced dynamic. These are shown together with the measurement in the following section.

c. Measurements

Fig. 5 shows an exemplary result for a symmetrical voltage drop to 60 % of the original voltage. Shown are the measurements (red) in comparison to the corresponding simulation (black). As can be seen, both fit quite well and confirm the usability of the simulation model.

At the machine lab of the IALB the dynamic of the voltage drop is limited to a fall time of about 15 ms. Additional faults with a higher fault dynamic in the falling flanks of the voltage drop not obtainable at the test stand were therefore examined in simulation. Fig. 5 shows in black a simulation of the same case as above but with a fall time of 15 ms.
5 CONTROL STRATEGY

As has been shown, the grid faults lead result in high current peaks in the generator. Because the converter is usually not designed for such high current peaks, the converter has to be protected. This poses a challenge as switching off or using a crowbar gives up the control of the system. According to the grid codes of the energy supply companies, depending on the level of the voltage drop faults of 150 ms up to 1.5 seconds duration must be ridden through and the system must stay controllable [11]. A novel control strategy in order to reduce the current peaks and allow the converter to stay in active control of the system is presented here.

By means of an FFT-Analysis of the rotor currents during a grid fault the relevant harmonics were identified and dedicated controllers were developed in order to compensate for these. The basic controller concept is shown in Fig. 6. Shown in blue is the standard current controller. Drawn in red is the new control concept to eliminate the higher harmonics excited by the fault.
Thereby the fault ride through capability of the system is reached. A continuous control of the DFIG is possible for symmetrical and asymmetrical grid faults. This forms the basis for all further load reducing concepts, as it is necessary for the converter to stay active in order to implement any kind of control of the system.

6 RESULTS

Fig. 7 a) and Fig. 8 a) show the effects of the control in case of a symmetrical and asymmetrical voltage drop to 60 % of the original voltage with a fall time of 5 ms, respectively. Fig. 7 b) and Fig. 8 b) show the spectrum of the rotor currents both before (blue) and during (green) the fault. Comparing these to the uncontrolled results for the same fault shown in Fig. 3 and Fig. 4 it can be seen, that the additional frequencies induced by the voltage drop were successfully reduced by the new control. The time signals of the rotor current show significantly lower peaks in both cases.

7 CONCLUSION

In this paper a modular simulation model of the drive train of a wind turbine including the generator and converter with grid connection was presented. This model was used to examine the effects of grid faults on the converter / generator sub-system. Furthermore a new control strategy was developed in order to reduce these effects and thereby keep the generator controllable and connected to the grid during grid faults.
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8 REFERENCES


