Transients in doubly-fed induction machines due to supply voltage sags

Y. Plotkin [1], C. Saniter [1], D. Schulz [2], R. Hanitsch [1]

[1]Institute of Energy and Automation Technology, Technical University of Berlin,
Einsteinufer 11, D-10587 Berlin
<yuriy.plokin@iee.tu-berlin.de >, <christoph.saniter@iee.tu-berlin.de>,
<rolf.hanitsch@iee.tu-berlin.de>

[2]University of Applied Sciences Bremerhaven,
Research and Coordination Center Wind Energy,
An der Karlstadt 8, D-27568 Bremerhafen
<dschulz@hs-bremerhaven.de>

Abstract — Transients in doubly-fed induction machines (DFIM) caused by supply voltage sags are investigated. They are explained in a comprehensible way by decomposing the stator and rotor fields into stationary and rotating components. This method is similar to the well known analysis for synchronous machines.

I. Introduction

Increasing the share of electric power generated by renewable energy sources is an important political goal in Europe and in many other countries in the world. It reduces the environmental pollution caused by traditional power plants as well as the dependence on fossil fuels, which have limited reserves.

Electric energy, generated by wind power plants is the fastest developing and most promising renewable energy source in Europe. Off-shore wind power plants provide higher yields because of better wind conditions. The power output of a wind turbine is proportional to the cube of the wind speed (see Eq.1). Its theoretical limit is 59.3% of the wind power input (Betz).

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot c_p \qquad (1)$$

with

ρ - air density
A – rotor swept area
v - wind velocity
c_p - power coefficient

The power coefficient depends on the pitch angle and the rotor speed to wind speed ratio (tip-speed ratio).

In Fig.1 the power output is plotted against the rotor's angular velocity at a constant pitch angle. Each curve represents a different wind speed.

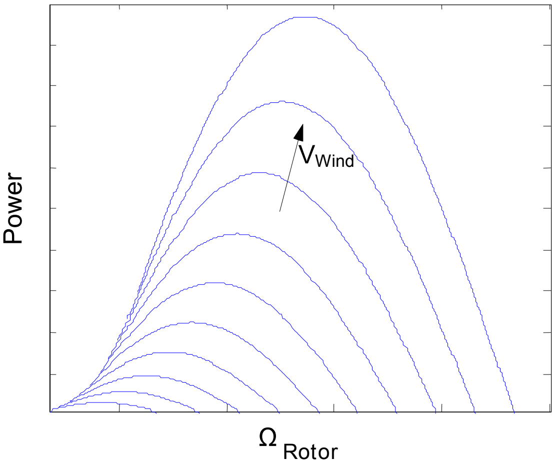


Figure 1. Extracted wind power at a constant pitch angle.

It can be seen from the Fig.1, that the rotor speed must be adapted if the wind speed changes, in order to extract the maximum power. Thus, variable-speed and pitch-controlled wind power plants are dominating the market nowadays. They are replacing the grid-connected induction generators which use the stall effect to limit their power output. Additionally, modern wind power plants allow power factor control (normally cosφ=1), which is impossible with uncontrolled turbines.

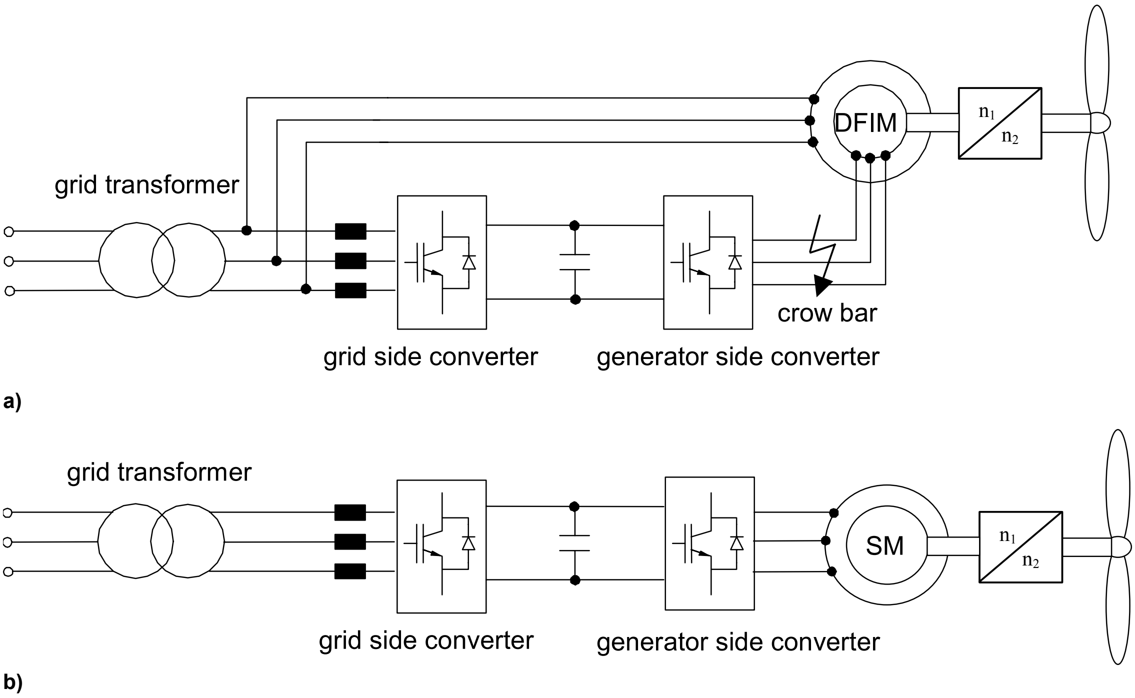


Figure 2. Generator types in wind power plants
a) doubly-fed induction machine
b) synchronous machine

II. Major Wind Power Plants Configurations

The two most common modern wind power plant configurations are:

a) Wind power plants with a synchronous generator and two full-sized converters or
b) doubly-fed induction generators with two converters in the rotor circuit.

Schematic representations are shown in Fig. 2.

In order to enable variable speed operation synchronous generators are decoupled from the power grid with its fixed frequency (50 or 60Hz) through two back-to-back frequency converters, which have a common dc-link. The main disadvantage of this topology is that the frequency converters are designed to handle the full generator power output. This inevitably means higher costs.

Speed and power factor control for a doubly-fed induction generator is achieved by controlling the rotor currents [7]. The power delivered to, or taken from, the rotor can be calculated using Eq.2.

$$P_r = P_\delta \cdot s \tag{2}$$

with

P_r - rotor power

P_δ - air gap power

s - slip

By limiting the speed range to +/- 30% of synchronous speed, the power rating of the frequency converters is reduced advantageously to only 30% of the generator's rated power. This results in substantial cost savings.

III. "Ride-through" capability during voltage sags

Due to increasing contributions of wind farms to the overall power generation, the necessity of their participation in grid stabilisation arises [1,2,4,6]. Especially under fault conditions they must perform similarly to conventional power plants. In recent years, grid codes have emerged in many countries, forcing wind farms to stay connected and maintain operations for a certain period of time during voltage sags. The level of the voltage sags during which safe operation has to be guaranteed differs greatly, e.g. down to zero voltage in Australia or 15% in Germany. Such a voltage sag is not critical for wind power plants using synchronous generators that are connected to the grid through converters [5]. The current into the grid is controlled by the grid side converter. In the case of a grid fault, the excessive power produced by the generator is controlled through a chopper circuit, to keep the dc-link voltage constant. Thus, the operation of a synchronous generator during voltage sags remains undisturbed.

Such fault conditions are very demanding for wind energy converters using doubly-fed induction generators (see Fig. 2a) [2,3]. High voltages are induced in the rotor winding during voltage sags. These voltages put the rotor side converter at risk. The rotor is short-circuited with a so-called crow bar in order to protect the converter. However, this may lead to a significant initial torque, which may destroy the gear box. Additionally, undesired torque pulsations can be observed.

IV. Transients of DFIM during voltage sags

Field components are analysed in order to understand the effects taking place in a doubly-fed induction machine during voltage sags. This method is similar to the short circuit analysis for synchronous machines. The time domain simulation program “Simplorer” was used to verify the theoretical predictions. Simplorer allows any power electronic circuit model to be built up and include its respective control. Additionally, models for all major machine types are provided.

The simulations were carried out under the following conditions:

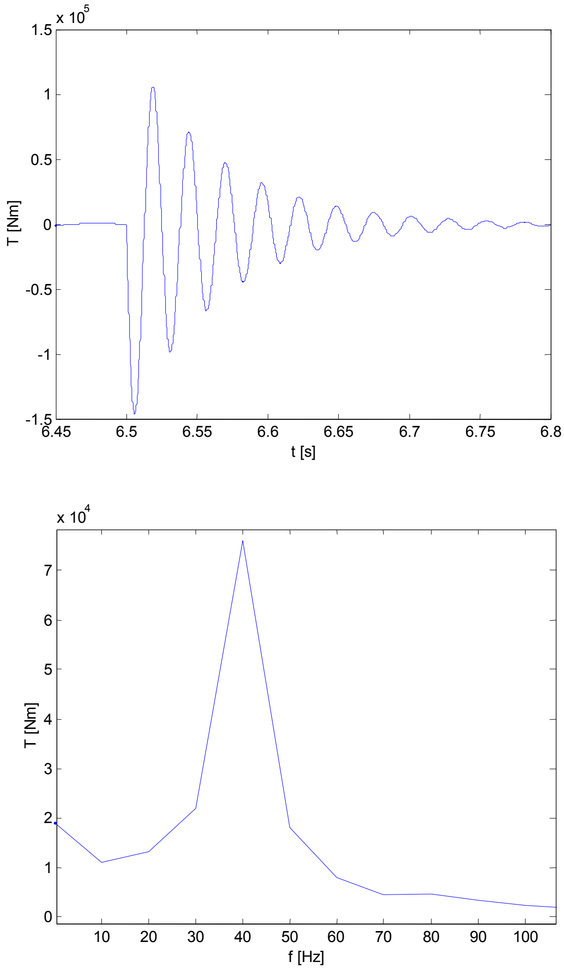
- The machine is operating at a sub-synchronous speed of 40Hz
- The rotor terminals are short circuited at the same moment as the voltage sag occurs to simulate the crow bar operation.

Firstly, a voltage sag down to 0% (short circuit) was investigated.

Sinusoidal currents flowing in the stator windings form a spatially rotating field. After the short circuit has occurred on the stator terminals, the stator currents retain their phase angle and begin to decay. Thus, a spatially stationary field that is decaying with time results. A similar process is observed in the rotor, with one significant difference: the decaying rotor currents form a field, which is stationary relative to the rotating rotor. Thus, two superimposing field components interact: the first one, stationary with respect to the stator and the second one, stationary with respect to the rotor rotating at some angular velocity. These field components form a torque which is alternating with the angular frequency of the rotor (first torque component, shown below).

The stationary stator field components induce voltages and currents in the rotor windings, resulting in a non-pulsating torque that is opposing the rotation (second torque component, shown below). The torque is proportional to the rotor angular velocity and to the amplitude of the stationary stator field. This effect is similar to the one which takes place when deliberately braking an induction motor using dc currents in the stator winding.

Parameters of a 1.5 MW wind plant generator were assigned to the DFIM model from the Simplorer-library. These parameters were used to simulate short circuiting of the stator - and rotor terminals. Simulation results clearly show both torque components described above (Fig. 3a). One can recognise an alternating component (fist torque component) with a decaying offset (second torque component). Fourier-analysis over a short time span shows that the frequency of the alternating component is directly related to the rotor angular frequency (see Fig. 3 b).



a)

b)

Figure 3. Torque transients upon short circuiting stator terminals.
a) time domain
b) frequency domain

The next step was to investigate a voltage sag down to 10%. A field component at grid frequency with 10% of the nominal amplitude remains as opposed to the case of the short circuit. The remaining 90% of the stator field become stationary and decay as described above. The rotating stator field component and the field component that is stationary with respect to the rotor form the third torque component at slip frequency.

Simulation results confirm these theoretical considerations (see Fig. 4). Fourier analysis of the torque yields three components: a small direct torque component, one component at angular frequency of the rotor, and a third component at slip frequency

$$f_{grid} = 50Hz = f_{mech} \cdot Z_p + f_{slip} = 20Hz \cdot 2 + 10Hz \quad (3)$$

where Z_p is the number of pole pairs.

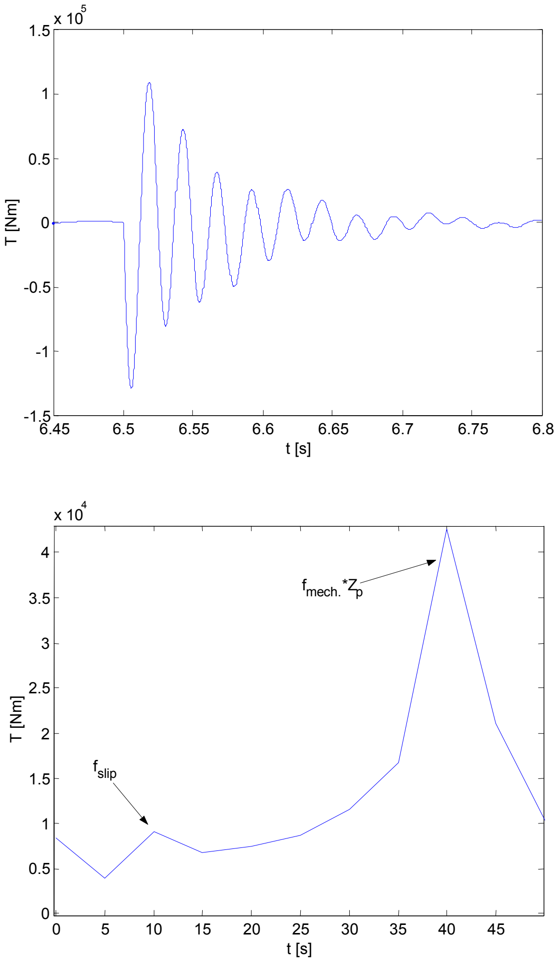


Figure 4. Torque transients after a voltage sag of 90%
a) time domain
b) frequency domain

The voltage induced in the rotor windings has a very high magnitude. Therefore, it is necessary to protect the rotor side converter by using a crow bar circuit. Torque amplitudes are very high, and may become critical for gear boxes.

V. Summary

Grid codes have emerged in many countries, requiring the "ride through" capability for wind plants. This is very demanding for wind plants with doubly-fed induction generators because of transients that occur after voltage sags.

High voltages are induced in the rotor windings. They are dangerous for the rotor side converter. Thus, a crow bar circuit is used for protection. The inherent torque pulsations may reach significant amplitudes and are dangerous for the gear box. Torque transients were investigated and explained in a comprehensible way by decomposing the field into rotating and stationary components. The presented simulation results confirm the theoretical predictions.

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