Conclusions. 1. At low-frequency impact of the external source on the oscillator, energy exchange between them has the character of pulsations. Maximum of the modulation of the forced vibrations’ spectrum forms on the condition that impulse of energy transfer from the source to the oscillator is either in phase or in anti-phase with the vibrations’ amplitude of the latter.

2. In the mode of steady-state oscillations, interference effects in the processes of energy exchange of the oscillator with the interacting systems are suppressed by the damping processes and are not to be taken into consideration.

MODELLING OF DOUBLY FED INDUCTION GENERATOR
BY USING OF ATP-EMTP PROGRAM

© Rosolowski E., Jedut L., 2007

This paper presents the simulation results of a grid-connected windmill driven doubly fed induction generator (DFIG) together with some machine performance results. The model was prepared by using of widely known ATP-EMTP program. The construction of a dynamic model of a DFIG is similar to a wound rotor induction machine. The transient current, electromechanical torque, and active and reactive power are derived taking into account the generator rotor speed change. The simulation results obtained from the analysis are also included. The presented model is considered as a first step to preparing the program tools for investigation of the influence of wind driven generators on local grid protection and automation.

**Introduction.** Wind energy is one of the fastest growing industries at present and will continue to grow worldwide, as many countries have planned future development in this area. As a result of traditional energy sources consumption and increasing environmental concern, in recent years the efforts have been made to generate electricity from renewable sources, such as wind energy. Institutional support on wind energy sources, together with the wind energy potential and improvement of wind energy conversion technology, has led to a fast development of wind power generation. During the recent few years the performances and therefore the complexity of the variable-speed drives have considerably increased.

The grid-connected wind generators have relatively big influence on the local distributed network if the power quality or relaying and automation is concerned. Thus the analysis of the transient phenomenon of wind power generator due to connection to utility grid are important [6, 8].

Variable speed wind turbines with DFIG is worldwide the most popular installed variable speed wind turbines. The paper presents the model of grid-connected doubly fed induction generator, which was prepared by using of ATP-EMTP program. Some simulation results illustrate the model performance.

**The generator mathematical model.** DFIG is a wound slip-ring induction machine (brushless realizations are also applied [2]), in which the rotor is supplied from voltage or current source with regulated frequency and form. This source device is composed of power electronic converter supplied from the grid to which the generator is connected (Fig. 1). Phase and frequency of the sinusoidal source are on-line determined taking into account the rotor velocity to meet the network frequency by the machine main electromagnetic flux. We can notice that if rotor windings are supplied with dc current, the generator is synchronous-like.

![Fig. 1. Structure of the considered model](image-url)
The main advantage of using doubly fed induction generators in wind power station is that they provide direct connection to grid – without additional converters in the main circuit [2, 8].

DFIG can be represented in ATP-EMTP program by using of the standard Universal Machine model: UM-4 (for wound machine) [1]. Structure of the model connection is presented in Fig. 1. Mathematical model of electrical part is based on the machine equivalent scheme as in Fig. 2 (for one coordinate) [3, 5].

![Fig. 2. Equivalent scheme of DFIG for α coordinate](image)

Model of the wind turbine and generator mechanical part is represented by the equivalent electrical network, which, in simple case, is composed of a current source, capacitor and resistor (Fig. 1). The network represents the generator dynamics modeled by a single equation of motion [2, 5]:

$$J_m \frac{d\omega_r}{dt} + D_m \omega_r = T_m - T_c$$

where, on the basis of duality principle, mechanical variables are represented by adequate electrical quantities:

- inertia constant $J$, kg m$^2$ ↔ capacitance $C$, F;
- friction coefficient $D$, N m/(rad/s) ↔ conductance $1/R$, 1/Ω;
- torque $T$, N m ↔ current $i$, A;
- angular velocity $\omega$, rad/s ↔ voltage $u$, V.

Therefore, the instantaneous value of voltage $\omega_r$ [V] (Fig. 1) is equivalent to the rotor angular velocity [rad/s]. The current at the machine input represents the torque shaft, which is balanced with the electromagnetic torque:

$$T_c = \frac{3}{2} p (\Psi_d I_q - \Psi_q I_d)$$

where $p$ – number of machine pair of poles; $\Psi_d$, $\Psi_q$, $I_d$, $I_q$ – electromagnetic flux and current, respectively, in d and q coordinates.

As the rotor position is concerned, in the no-sensor application, this variable can be estimated on the bases of measured quantities: the rotor current $I_r$ and the stator current $I_s$ and voltage $U_s$. The adequate
relation can be derived from the machine vector diagram (Fig. 3). We can note that the space vector coordinates: \( \alpha_r, \beta_r \), is related to the rotor position which is determined by the angle:

\[
\theta = \delta_1 - \delta_2
\]  

(3)

The angle \( \delta_1 \) may be directly determined from the measured rotor 3-phase currents, from which one can obtain the space vector components:

\[
I_{rav} = (2I_{ra} - I_{rb} - I_{rc})/3
\]

\[
I_{rfb} = (I_{rb} - I_{rc})/\sqrt{3}
\]  

(4)

and, finally:

\[
\delta_2 = \arctg \frac{I_{rfb}}{I_{rav}}
\]  

(5)

For determination of the angle \( \delta_1 \) (Fig. 3) we can use adequate components of the measured stator quantities [2, 5]:

\[
\delta_1 = \arctg \frac{I_{rB}}{I_{ra}}
\]  

(6)

where

\[
I_{ra} = \left( I_{sa} (X_m + X_s) - U_{sB} \right)/X_m
\]

\[
I_{rB} = \left( U_{sB} - I_{SB} (X_m + X_s) \right)/X_m
\]  

(7)

and: \( I_r = I_{ra} + jI_{rb} \); \( X_m = \omega_1 L_m \); \( X_s = \omega_1 L_s \); \( I_{sa}, I_{SB}, U_{sa}, U_{sB} \) – the stator current and voltage space vector components, calculated from the measured quantities, similarly as in (4).

Finally, the rotor current generated by the converter is determined as follows (in \( \alpha, \beta \) coordinates):

\[
I_{ra} = \frac{S_e}{U_s} \left( d_1 \sin \gamma - d_2 \cos \gamma \right), I_{rB} = -\frac{S_e}{U_s} \left( d_1 \cos \gamma + d_2 \sin \gamma \right)
\]  

(8)

where

\[
d_1 = \frac{2}{3} + \frac{X_s}{X_m} \left( \frac{2}{3} - \frac{U_{sB}^2 X_m}{S_e X_s} \right), d_2 = \frac{X_s U_{sB}^2}{X_m S_e X_s}
\]

\[
\gamma = \omega t + \varphi_e - \theta, \varphi_e = \arctg \frac{Q_e}{P_e}
\]

\( P_e, Q_e \) are assumed as the generator load (power delivered to the grid): \( S_e = \sqrt{P_e^2 + Q_e^2} \).

From the current components as in (8) we can determine 3-phase rotor currents:

\[
\begin{bmatrix}
I_{ra} \\
I_{rb} \\
I_{rc}
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
\sqrt{3}/2 & -1/2 & 0 \\
- \sqrt{3}/2 & -1/2 & 0
\end{bmatrix}
\begin{bmatrix}
I_{rav} \\
I_{rB} \\
I_{rav}
\end{bmatrix}
\]  

(9)

It is assumed in (9) that there is no zero-sequence current in the rotor windings (they are isolated from the earth).

**Studied system** model prepared by using of ATP-EMTP program is presented in Fig. 4. The presented scheme was arranged by using of the graphical editor ATPDraw [7]. For simplicity the phase current sources in the rotor circuit was represented by controlled current sources. Included also the sinusoidal current source stabilizes of the model during starting period and is switched-off after 0.1s.
Fig. 4. Scheme of the studied mode

In the scheme reproducing the mechanical part of the power station, the three current sources are placed, which are introduced consecutively in time for change the windmill input torque. Graphical schedule of this torque is presented in Fig. 5a.
The control procedure for determination of a needed current in the rotor circuit was realized in the form of MODELS module [1] (block DFIM in Fig. 4). There are four 3-phase signals at the input of this block: voltage and current at both sides of the generator and the 3-phase current source control signal at the output.

Simulation of the studied system was performed with the generator which parameters are presented in Table. Parameters of the equivalent circuit was obtained by using of WindSyn program [4]:

\[ L_m=0.015064 \text{H}, \quad R_s=0.013315 \Omega, \quad L_s=0.000317 \text{H}, \quad R_r=0.040974 \Omega, \quad L_r=0.000317 \text{H} \]

The simulation was accomplished for the following scenario: the windmill torque \( T_t \) was change as in Fig. 5a, and the output active \((P_e)\) and reactive \((Q_e)\) power profile was as in Fig. 5b (curve 1 and 3, respectively).

During simulation the angular velocity changes according to Fig. 5c (per unit values). Notice that at start this velocity was greater than the rated value, i.e. 1 what is adequate to 1500 r.p.m. The windmill torque is then equal to zero so, taking into account a small power delivered to the grid, we can observe insignificant decreasing of the rotor velocity. From the moment of \( t=1 \text{s} \) increasing the power passed to the network what results in decreasing the rotor velocity, which next increasing after growing the wind turbine

### Parameters of the analyzed generator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power ( P ), [kW]</td>
<td>670</td>
</tr>
<tr>
<td>Rated voltage ( U ), [V]</td>
<td>690</td>
</tr>
<tr>
<td>Rated power factor ( \cos \phi )</td>
<td>0.9</td>
</tr>
<tr>
<td>Rated load efficiency</td>
<td>0.906</td>
</tr>
<tr>
<td>Maks. shaft torque, p.u.</td>
<td>1.58</td>
</tr>
<tr>
<td>Number of polar pairs</td>
<td>2</td>
</tr>
<tr>
<td>Initial slip</td>
<td>2.3%</td>
</tr>
<tr>
<td>Inertia constant ( H ), [kgm²]</td>
<td>58.0134</td>
</tr>
<tr>
<td>Rated turbine torque ( T_m ), [Nm]</td>
<td>2485.94</td>
</tr>
<tr>
<td>Friction coeff. ( D ), [Nm/(rad/s)]</td>
<td>2.53</td>
</tr>
</tbody>
</table>
torque (from $t=4s$). The actual electric power measured at the generator is changing according to curves 2
and 4 (respectively for $P$ and $Q$).

We can see that changing of the rotor velocity (due to variation of the windmill torque and/or the
generator power) leads to adequate correction of the rotor supplying current: its magnitude and frequency
(Fig. 6a). When the rotor velocity crossing the rated value (amount of 1.0 for $t=1.5s$ – Fig. 5c), the rotor
current and voltage waveforms change direction. One can also observe adequate frequency changing of
this waveforms.

**Conclusions.** Considering the important growth that wind power made up with doubly fed induction
generators have had during the last few years, analysis and simulation of those kind of energy source can
become an important future research works. Therefore, the paper presents developed a complete model of
DFIG connected to the network. The model was prepared by using of ATP-EMTP program. Some
simulation results are also presented. They confirm the supposition that the simplified model is correct and
can be used in the future research related to wind generation, especially to the problem of connection of
such sources with the network. The proposed dynamic model of wind governed generator is aimed to
assess the impact of varying levels of wind penetration on the protection and control system of the
network.

speed generators, Taylor & Francis Group, LLC, Boca Raton, FL, 2006. 3. Dommel H.W.,
Electromagnetic Transients Program. Reference Manual (EMTP theory book), Bonneville Power
Administration, Portland 1986. 4. Furst G., Induction and synchronous motor simulation using ATP/U.M.
5. Haginomori E., Applied ATP-EMTP to highly-sophisticated electric power systems. Funded Research
Laboratory (Kyushu Electric Power Co. Inc). Summary of EMTP seminars, 2003, available in:
http://www.kifkit.net/index2_e.html. 6. Lubośny Z., Wind Turbine Operation in Electric Power Systems,
Modeling and control of a wind turbine driven doubly fed induction generator // IEEE Transactions on