TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

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SUMMARY OF PH.D. THESIS

THEORETICAL AND EXPERIMENTAL STUDY OF THE GRID CONNECTED INDUCTION GENERATORS, USED IN WIND MICROSYSTEMS

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Giving the goal of the thesis, the study of the double fed induction generators to be used in wind plants, few major subjects were approached:

- The energy quality supplied to the grid or to autonomous consumers;
- Theoretical study of the influence of the geometry and of the saturation of the machine’s iron core on the induced voltage harmonics;
- Study of the induction generator when the is or isn’t supplied;
- Experimental study of the induction generator behavior for the considered cases.

The steps in achieving the goal of the thesis were:

- The choosing of two types of induction generator used in wind turbines;
- The determination of the induction machine parameters;
- The determination of the induced voltage harmonics at an induction generator with wound rotor by using:
  - Analytical method;
  - Numeric analysis using finite element method(Flux 2D);
  - Experimental tests in order to validate the obtained results.
- Simulation program of the double fed induction generator connected to the grid;
- Experimental validation of the behavior of the analyzed generator.

Chapter one – **STATE OF THE ART**

The first chapter analyses the state of the art in the field of the electrical energy production using wind energy. A presentation of the various types of small plants is followed by a review of the generators used in these plants and their behavior when connected to the grid. The chapter is closed by the analysis of the energy quality and of the voltage harmonics that arise.

Chapter two– **HARMONICS**

The second chapter, “Harmonics”, represents a study on the induction generators’ harmonics, emphasizing the definitions of the used harmonics indexes, the harmonics sources and the methods of analysis of these harmonics. Some general considerations on the space harmonics are presented. The geometrical dimensions and the construction elements of the induction generator are given in this chapter. Based on this an analytic approach of the space harmonics for the studied is made. After analyzing the harmonics due to the stator and rotor teeth saturation, the machine’s equations are written in phase coordinates, evincing in this way the induced voltages harmonics. The chapter contains an experimental check of the space harmonics by obtaining the waveforms of the induced voltages both in stator and rotor windings. Some considerations on time harmonics introduced by the voltage converters are made in a theoretical study that closes the second chapter.

**The harmonics sources**

The voltage and the current produced by the generators can have harmonics caused by:

- The presence of the harmonics in the magnetic field of the generators;
- Non linear load;

The magnetic field in the generator contains:

- Space harmonics;
- Time harmonics, due to the power supply source of the excitation.

Space harmonics of the induction machine field

The space harmonics of the induction machine are due to:

- The distribution of the magneto motive force of the alternative current windings;
- The presence of the slots on the machine’s armatures;
- The saturation of the magnetic circuit.
In order to perform the studies on the wound rotor induction machine, the data of the machine are needed.

a) Geometrical data and the description of the induction generator

The induction generator presented in the thesis has the following data: wound rotor, 3 pole pairs, 50 Hz, 3kW, 230/400V, Δ-Y connection, speed of n=1000 rot/min, 27 rotor slots and 36 stator slots. Transversal section through the machine is given in figure 2.4.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior diameter of the stator</td>
<td>D_e</td>
<td>199 mm;</td>
</tr>
<tr>
<td>Height of the stator yoke</td>
<td>h_S</td>
<td>12.8 mm;</td>
</tr>
<tr>
<td>Air gap</td>
<td>δ</td>
<td>0.38 mm;</td>
</tr>
<tr>
<td>Inner diameter of the stator</td>
<td>D</td>
<td>136.4 mm;</td>
</tr>
<tr>
<td>Stator tooth width</td>
<td>b_d_S</td>
<td>6.23 mm;</td>
</tr>
<tr>
<td>Active length of the machine</td>
<td>L</td>
<td>280 mm;</td>
</tr>
<tr>
<td>Pair poles number</td>
<td>p</td>
<td>3</td>
</tr>
</tbody>
</table>

The distribution of the stator winding for one pole pair is presented in figure 2. Due to the odd number of rotor slots, the rotor winding is a special one, its distribution being presented in figure 3.

b) Analytical approach of the space harmonics for the analyzed machine

Computation of the harmonics that appear due to winding distribution into slots

For the considered three-phase induction machine the stator armature mmf distribution when t = 0 (the current of the phase A is null) is presented in figure 2.7., while the rotor armature mmf distribution in figure 4.28.
The total mmf

The spectrum of the air gap mmf was obtained by combining the mmf of the two armatures.

Harmonics that appear due to the opening of the slots

Considering a number of \( m \cdot q \) slots of a pole, the ranks of the harmonics that appear due to the slots are:

\[
\nu = 2 \cdot k \cdot m \cdot q \pm 1 \quad k \in R
\]

For the analyzed machine in the stator results: \( \nu = 12 \cdot k \pm 1 \quad k \in R \)

The main harmonics due to the slots have the rankings:

\[
\nu = 11, 13, 23, 25, \ldots
\]

The rankings of the harmonics in the rotor are obtained with the formula:

\[
\nu = 9 \cdot k \pm 1 \quad k \in R
\]

The rankings of the harmonics in the rotor begin with:

\[
\nu = 8, 10, 17, 19, \ldots
\]

2.4. Induced e.mf. harmonics

The emf harmonics of the induction machine

The frequencies induced by the space harmonics of the stator mmf in the wound rotor windings are:

\[
f_{\text{rotor}} = \left[ 1 \mp \nu (t - s) \right] f_s
\]

The flux induced in the stator windings and the emf induced in the stator windings will contain harmonics whose rankings are given by:

\[
f_{\text{stator}} = \left[ 1 \mp (\nu + \gamma) (t - s) \right] f_s
\]

Where \( \nu = 6k \pm 1, k = 0, 1, 2, 3, \ldots \) și \( \gamma = 6h \pm v, h = 0, 1, 2, 3, \ldots \)
The calculation algorithm is presented in figure 2.2.

2.5. Experimental validation of space harmonics

The harmonic frequencies of the induced emf on a rotor and a stator phase are given:

\[ f_{\text{rotor}} = \frac{\omega_r}{2\pi} \quad f_{\text{stator}} = \frac{\omega_r}{2\pi} \]  \hspace{1cm} (2.58)

where \( \omega_r = p\Omega_\tau \), \( \Omega_\tau \) is the mechanical rotor speed.

The driven speed gives the frequency of the first harmonic, i.e. 55 Hz. The superior harmonics are given by expressions (12) and (13), i.e. 5th, 7th, 11th, 13th, 17th, 19th. These can be found in the represented spectra, in figures 17 and 18.

Chapter three – INDUCTION MACHINE

The third chapter, “The Induction Machine”, presents the theoretic background of the two operating regimes of the induction generator: with wound rotor and double fed induction generator. The numerical analysis, performed using the Flux 2D package, is presented in this section of the thesis. The amplitudes of the main harmonics are given in a series of tables, for a certain case being shown values bigger than 10% of the fundamental harmonic for the odd harmonics 3, 9, 19, as well as for some even harmonics 8, 10.

A Finite Element Method software, Flux 2D, was used for simulating the performances of the generator topologies. Once the basic structure of the machine was introduced, the mesh was generated and the field equations solved. Figure 8 presents the magnetic flux lines in the cross section of the machine.
The simulations were performed at different rotor speeds: \( n=1005 \text{rot/min} \), \( n=1010 \text{rot/min} \), \( n=1015 \text{rot/min} \), \( n=1020 \text{rot/min} \) and \( n=1030 \text{rot/min} \). The air gap flux density of the induction generator is given in figure 3.11. The considered rotor speed is 1005 rot/min.

Chapter four – **FINITE ELEMENT SIMULATION OF THE LINEAR ELECTRIC GENERATOR**

The fourth chapter, “The numerical analysis of the double fed induction generator”, has the starting point in expressing the induction generator equations with instantaneous values, and then with complex ones. The electrical equivalent scheme and the diagram of the currents in complex form are presented. The parameters of the machine are computed based on the experimental tests. The mathematical model of the machine and the computation of its parameters obtained after the experimental tests are presented.

**Modeling of double fed induction generator**

Double fed induction machine model for the stator reference system

In order to elaborate the mathematical of the induction machine in the synchronous reference system we must impose the condition:

\[
\omega_c = \omega_S
\]  

(4.60)

\( \omega_c \) is the reference system angular speed.

By using the induction machine voltages equations, the flux derivatives and by taking into account the magnetization inductivity, the electromagnetic torque and the movement equation, the Simulink diagram was created.

Rotor supply was done from a three phase power source with the following frequencies: 5 Hz, 7.5 Hz and 10 Hz. In order to meet the \( f_R = s \cdot f_S \), \( f_R \) being the rotor
frequency, \(f_s\) the stator frequency and \(s\) the sleep, a torque regulator was needed in the Simulink diagram. The three phase rotor power supply is considered to be written in respect with the stator.

**Operation of the double fed induction machine when the rotor is supplied at a frequency of 5Hz**

The shifting of the stator phases is considered to be \(\pi\).

\[
\begin{align*}
\mu &= 13.16177^* 4.066^* \sin(10^* \pi^* \tau + \pi) \\
\nu &= 13.16177^* 4.066^* \sin(10^* \pi^* \tau - 2^* \pi / 3 + \pi) \\
\omega &= 13.16177^* 4.066^* \sin(10^* \pi^* \tau + 2^* \pi / 3 + \pi)
\end{align*}
\]  

(4.70)

The waveform of the rotor voltage, torque and angular speed are given.

The stator current and rotor waveforms are presented.

The passing from the motor to the generator regime can be seen in the above presented figures.

**Chapter five – EXPERIMENTAL RESULTS**

The fifth chapter is dedicated to: experimental setup, composed by Dc machine-wound rotor induction generator assembly, electrical consumers system, of various phase shifting, connected at the stator terminals, frequency converter and the three phase transformer used to adapt the rotor voltages in order to connect the machine to the 50 Hz grid, electrical measures transducers and data acquisition and data processing system, using Labview environment. The chapter presents measurements performed on the machine operating as:

- Self excited induction generator at different values of the capacitors in the stator circuit, connected on the resistive loads, the rotor being short-circuited.
- Autonomous induction generator at a frequency of 50 Hz, connected on various loads, for different values of the voltage frequencies applied to the rotor that was rotated at the appropriate speeds;
- Induction generated connected to the grid at a frequency of 50 Hz supplied with various voltage frequencies in the rotor meaning double fed regime.

The description of the tests performed each of the operating regimes of the machine is completed by comments on the harmonics content and on the accordance between the computed values and those obtained from the data acquisition.

5.3.1. Tests of the self excited induction generator

a) in load operating regime

The harmonics spectrum for the stator voltage and load current of the self excited induction generated when the machine operates with a capacitor and a resistance of $C=70,18 \, \Omega$, $R_s=235,655 \, \Omega$ are:

![Figura 5.13 Stator voltage harmonics spectrum](image)

Self excited generator, $C=70,18 \, \mu F \, R_s=235,655 \, \Omega$

![Figura 5.21 Load current harmonics spectrum](image)

Self excited generator, $C=70,18 \, \mu F \, R_s=235,655 \, \Omega$

5.3.2. Tests of the autonomous rotor supplied induction generator

The supply from the convertor was done at various frequencies: 2.5 Hz, 5 Hz and 7.5 Hz. The waveforms when the rotor voltage frequency is of 2.5 Hz is presented.

a) rotor supplied from the converter at 2.5 Hz frequency

The induction machine rotor speed is 950 rot/min. The rotor current and stator voltage waveforms and harmonics spectrums are:

![Figura 5.25 Rotor current harmonic spectrum](image)

Double fed induction generator $f_r=2.5Hz$, $n=950$ rot/min

![Figura 5.27 Stator voltage harmonic spectrum](image)

Double fed induction generator $f_r=2.5Hz$, $n=950$ rot/min

5.3.3. Tests of the connected to the grid induction generator (double fed)

The supply from the convertor was done at various frequencies: 2.5 Hz, 5 Hz and 7.5 Hz. The waveforms when the rotor voltage frequency is of 5 Hz (n=900rot/min) are presented.

No load operating regime

a) rotor supplied from the converter at 5 Hz frequency

The induction machine rotor speed is 900 rot/min. The rotor current and stator voltage waveforms and harmonics spectrums are:

![Figura 5.37 Rotor current harmonics spectrum](image)

Double fed induction generator $f_r=5Hz$, $n=900$ rot/min, load

![Figura 5.39 Stator voltage harmonics spectrum](image)

Double fed induction generator $f_r=5Hz$, $n=900$ rot/min, load
**Load operating regime**

The supply from the convertor was done at various frequencies, for two load values.

*rotor supplied from the converter at 5 Hz frequency*

*a) rotor supplied from the converter at 5 Hz frequency*

The induction machine rotor speed is 900 rot/min, the obtained power is $P=320\text{W}$.

The stator current waveforms and harmonics spectrums are:

![Figure 5.44 Stator current waveform](image1)

![Figure 5.45 Stator current harmonics spectrum](image2)

The maximum value for the total harmonic distortion factor THD is limited by the normative at 5%.

1. By comparing the values of THD factor we can say that only for the load current (7.22%) in the case of the self excited induction generator the value indicated in the normative are passed. The THD factor is influenced by load and by capacitor value in case of self excited induction generator.
2. The value of THD factor is quite high for double fed induction generator for no load operating regime. In the case of the double fed induction generator connected to the grid for load operating regime the grid is very powerful and the THD factor became slow comparing with the one obtained for independent generator. Operating speed and voltage supply frequency influence the THD factor in case of double fed induction generator connected to the grid.

**Chapter six – CONCLUSIONS**

Chapter 6 presents the conclusions of the performed researches.

The study performed in this thesis gives solutions to a real problem in terms of power quality coming from micro wind systems.

From the analytical study made on the induction machine it can be said that in the air gap of the machine odd and even harmonics appear. The high harmonics are those that appear due to the opening of the rotor and stator slots, the others are small due to the windings distribution.

From the numerical study made with Flux 2D, the analytical study is validated the conclusion drawn from the analytic calculation, the main air-gap harmonics having the rankings 8, 10, 11, 13, 17, 19, 23, 25, 26, 28, 35 and 37.

The theoretical study is validated by the experimental one.

The main personal contributions considered in this these are:

1. **Identification (measurement)of the studied induction machine parameters.**
2. **The elaboration of the field model of the studied machine.**
3. **The elaboration of the circuit model used at the dynamic analysis of the double fed induction machine.**
4. **The elaboration and theoretical validation of the studied induction machine harmonics spectrum.**
5. **The experimental validation of the induction machine harmonics spectrum.**