Direct field oriented control of induction motor fed by wind turbine generator under saturation effect
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Abstract—In this paper, we present the voltage build up process and the terminal voltage control of an isolated wind powered induction generator driven by a variable speed wind turbine using rotor flux oriented vector control. A description of the studied system is provided, and a simulation study is presented. The model used for the autonomous induction generator is a diphase one obtained by application of the Park transform. This model permits, when adopting some simplifying hypotheses, taking account the saturation effect. Wind powered isolated induction generators have an input, wind, that is not controllable, but they can be set to operate within a given variation of speed. Unlike a grid connected induction generator, in an isolated case, there should be a control system that keeps the DC bus voltage at a constant value when the speed of the rotor varies. The paper presents the control system to maintain the DC bus voltage at a constant value. This DC voltage is utilized for feeding an induction motor used as charge. The obtained results demonstrate a good performances of regulation for the DC voltage as input of the induction motor and the speed, torque and fluxes as its outputs.

Key words—Wind energy system, Induction generator, Saturation, Induction motor, Direct field oriented control.

I. INTRODUCTION

As a result of increasing environmental concern, more and more electricity is generated from renewable energy. The main advantage of electricity generation from renewable sources is the absence of harmful emission and the infinite availability of the prime mover that is converted to electricity [1, 2]. One of the best ways of generating electricity from renewable energy is to use wind turbines. A tendency to erect more and more wind turbines can be observed in power industry. Wind energy technology has developed extremely rapidly and many commercial wind turbines in the market have capacity of 2MW or more. Also the cost of wind-generation electricity has fallen steadily. Wind turbines in USA produce about 1% of total generation [2]. Also, wind power meets 3% of the total electricity demand in Europe [3], and this development will continue to grow in coming years. It seems that in the near future wind turbines may start to influence the behavior of electrical power systems. As a result of such developments, extensive research is being carried out on the subject of wind generation.

Self-excited induction generators are good candidates for wind powered electricity generation, especially in remote areas, because they do not need an external supply to produce the excitation magnetic field (emf). It is well known that when capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced across its terminals. The induced emf and current in the stator will continue to grow until steady-state condition is reached [2, 3]. However, self excitation has its own problems and can cause overvoltages, torque and machine speed fluctuations, etc. [4]. The impact of magnetizing inductance, minimum speed and capacitance requirement on self excitation has been examined by Seyoum [4]. The transient and steady state performance of self-excited isolated induction generators for different loading scenarios have been investigated and critical factors identified through various studies [2, 5].

In this paper, we present a study of the vector control of an autonomous induction generator taking the saturation effects into account. The output voltage of the induction generator passes by the association rectifier–filter–inverter for feeding a three phase induction motor. To use the induction machine in a reliable manner as an autonomous generator that converts wind energy, the machine has to be connected to a rectifier and all the system controlled. The control system is required to keep the DC voltage at a constant value whatever the rotor speed and the load as long as the available power of the wind is sufficient.

We show that the use of the oriented vector control presented in this paper leads us to feed the load with voltage of effective value and frequency fixed whatever the speed of turbine in a given speed range.

In section II, we propose a wind- turbine model. For the induction generator, it’s a diphase model obtained by application of the Park transform. Assuming some simplifying hypotheses, the saturation effects is formulated by a variable magnetizing inductance function of the current that we approximated by a polynomial function of 12th degree. This approach is simple and sufficiently accurate.

The third section concerns the control of the system. To control the flux in the induction machine and the DC voltage at the rectifier output, we use a rotor flux oriented vector control. The vector control algorithm consists of two parallel loops. The first one control the flux and leads to the d axis current reference and, by the same way, the reactive power flow in the system. The second loop control the DC voltage at the rectifier output and leads to the q-axis current reference. This permits the active power to flow from the generator to the DC circuit. In this system control, an additional level of complexity is introduced by the generator saturation. The induction motor (considered as a load of the rectifier) is controlled by a direct field oriented control.

The fourth section presents simulation results of the overall system, using the MATLAB-SIMULINK package.

II. THE TURBINE-GENERATOR SYSTEM MODEL

Fig. 1 shows the wind turbine induction generator system configuration considered in this study. The wind energy generation system consists of a horizontal axis turbine connected to a cage-machine rotor through a gear system. The induction machine is driven at super-synchronous speed and it feeds a constant impedance load at a terminal voltage, \(V_c\). The models for the different components of the wind turbine-generator system are given in the following subsections.
The linear model of the induction machine is widely known and used. It leads to relative accurate results when the operating point studied is close to the conditions of the model parameter identification. It’s often the case when studying the motor, operating at rated voltage. As the air gap of induction machines is generally narrow, the saturation effect is not negligible in this structure. So, to improve the accuracy of simulation studies, especially when the voltage is variable, the non-linearity of the iron has to be taken into account in the machine model.

This becomes a necessary condition to study an autonomous induction generator because the linear model is not able to describe the behaviour of the system. Thus, only approaches that take account the saturation effect can be utilised. This effect is not easy to simulate using three phase classical models. So, we adopt diphase approaches to take account globally of the magnetic non-linearity. This needs some simplifying hypotheses. Indeed, the induction is considered homogenous in the whole structure. Moreover, the use of the diphase model supposes that the saturation effect is considered only on the first harmonics and does not affect the sinusoidal behaviour of the variables. In our approach, we adopt the diphase model of the induction machine expressed in the stator frame. The classical electrical equations are written, in the synchronous frame, as follows [10, 11]:

\[
\begin{align*}
\mathbf{V}_\text{sd} & = \mathbf{R}_r \mathbf{i}_\text{d} - \mathbf{L}_m \mathbf{i}_\text{q} - \mathbf{L}_\text{sd} \mathbf{j}_\text{d} - \mathbf{L}_\text{sq} \mathbf{j}_\text{q} \\
\mathbf{V}_\text{sq} & = \mathbf{R}_r \mathbf{i}_\text{q} - \mathbf{L}_m \mathbf{i}_\text{d} - \mathbf{L}_\text{sq} \mathbf{j}_\text{d} - \mathbf{L}_\text{sd} \mathbf{j}_\text{q} \\
\mathbf{L}_m \frac{\mathbf{d}\mathbf{i}_\text{d}}{\text{dt}} & = -\mathbf{i}_\text{d} - \mathbf{L}_\text{sd} \frac{\mathbf{d}\mathbf{i}_\text{q}}{\text{dt}} \\
\mathbf{L}_m \frac{\mathbf{d}\mathbf{i}_\text{q}}{\text{dt}} & = -\mathbf{i}_\text{q} - \mathbf{L}_\text{sq} \frac{\mathbf{d}\mathbf{i}_\text{d}}{\text{dt}}
\end{align*}
\]

(4)

Where \( \mathbf{R}_r \), \( \mathbf{i}_\text{d} \), \( \mathbf{R}_r \) and \( \mathbf{i}_\text{q} \) are the stator and rotor phase resistances and leakage inductances, respectively, \( \mathbf{L}_m \) is the magnetizing inductance and \( \mathbf{i}_\text{d} \) and \( \mathbf{i}_\text{q} \) are the stator and rotor pulsations, respectively. Besides, \( \mathbf{V}_\text{sd}, \mathbf{i}_\text{sd}, \mathbf{V}_\text{sq} \) and \( \mathbf{i}_\text{sq} \) are the d–q stator voltages and currents, respectively. \( \mathbf{i}_\text{md} \) and \( \mathbf{i}_\text{mq} \) are the magnetizing currents, along the d- and q-axis, respectively, given by

\[
\begin{align*}
\mathbf{i}_\text{md} & = \mathbf{i}_\text{sd} + \mathbf{i}_\text{rd} \\
\mathbf{i}_\text{mq} & = \mathbf{i}_\text{sq} + \mathbf{i}_\text{rq}
\end{align*}
\]

(5)

ird and irq represent the d–q rotor currents.

The saturation effect is taken into account by the expression of the magnetizing inductance \( \mathbf{L}_m \) with respect to the magnetizing current defined as

\[
\mathbf{i}_m = \sqrt{\mathbf{i}_\text{md}^2 + \mathbf{i}_\text{mq}^2}
\]

(6)
To express $L_m$ with respect to $i_m$, we use a polynomial approximation of degree 12 [12, 13].

\[
\begin{align*}
L_m &= f(I_m) = \sum_{j=0}^{n} a_j |I_m|^j \\
\frac{dL_m}{di_m} &= \sum_{j=0}^{n} \frac{d}{di_m} a_j |I_m|^{j-1}
\end{align*}
\]

(7)

Fig 4. presents magnetizing inductance function of the magnetizing current. This figure demonstrates the non linearity nature of the induction generator.

C. Study of an induction generator connected to a capacitance bank

The stator windings of the induction machine are linked to a capacitance bank connected in parallel to a resistive load (Fig. 1).

As the stator and rotor pulsations are unknown, it is necessary to re-write the electrical equations in the rotor frame where only the mechanical pulsation, known, is considered. In this case, with no load, the diphase stator voltages and currents are linked by the following expression:

\[
\begin{align*}
\frac{d}{dt} [V_{sd}] &= \left[ \begin{array}{cc}
\frac{1}{c} & 0 \\
0 & \frac{1}{c}
\end{array} \right] [V_{sd}] + \left[ \begin{array}{c}
0 \\
\omega\sigma
\end{array} \right] [V_{sd}] \\
\frac{d}{dt} [V_{sq}] &= \left[ \begin{array}{cc}
\frac{1}{c} & -i_{chd} \\
0 & \frac{1}{c}
\end{array} \right] [V_{sd}] + \left[ \begin{array}{c}
0 \\
\omega\sigma
\end{array} \right] [V_{sq}]
\end{align*}
\]

which becomes, when the induction generator is loaded:

\[
\begin{align*}
\frac{d}{dt} [V_{sd}] &= \left[ \begin{array}{cc}
\frac{1}{c} & 0 \\
0 & \frac{1}{c}
\end{array} \right] [-i_{sd} - i_{chq}] + \left[ \begin{array}{c}
0 \\
\omega\sigma
\end{array} \right] [V_{sd}] \\
\frac{d}{dt} [V_{sq}] &= \left[ \begin{array}{cc}
\frac{1}{c} & -i_{chd} \\
0 & \frac{1}{c}
\end{array} \right] [V_{sd}] + \left[ \begin{array}{c}
0 \\
\omega\sigma
\end{array} \right] [V_{sq}]
\end{align*}
\]

(8)

(9)

III. THE PROPOSED CONTROL STRATEGY

A. Control strategy of Wind turbine-generator system

To lead to a generated voltage with a constant magnitude and frequency, the induction machine must be connected to a rectifier and an inverter. Both have to be controlled. In this part, we will study the vector control of the system consisting of a wind turbine, an induction generator, a PWM rectifier and a PWM inverter (Fig. 5). The goal of the control is to maintain the DC bus voltage at a constant value when the rotor speed is varying. To control the flux in the generator and the DC voltage at the rectifier output, we use a rotor flux oriented vector control.

The vector control algorithm consists of two loops that operate in parallel (Fig. 6). The first one allows us to control the flux and leads to the d-axis current reference. It controls, by the same way, the reactive power flow in the system. The second loop enables us to control the DC voltage at the rectifier output and then to reach the q-axis current reference. This permits the active power to flow from the generator to the DC circuit. In this system control, an additional level of complexity is introduced by the saturation of the generator. We will show that the control of the flux implies a constant saturation level of the generator and, then, leads to a model of the machine, which becomes linear at an operating point. The flux variations around this point are negligible.

B. Direct Field Oriented Control of Induction Motor

For the induction machine, we adopt the following model, developed in the synchronous reference frame ($d, q$) with $\psi_{sd} = 0$ [14, 15]:

\[
\begin{align*}
\frac{du_{sd}}{dt} &= (R_s + sL_s)I_{sd} + sL_m \psi_q - \omega_s L_{sq} \\
\frac{du_{sq}}{dt} &= (R_s + sL_s)I_{sq} + \omega_s L_{sd} \psi_q + \omega_s L_{sq} I_{sd} \\
\psi_r &= \frac{L_m}{1 + s\tau_r} I_{sd} \\
\omega_r &= \frac{L_{sq}}{L_r} \psi_q \\
C_r &= \frac{3}{2} L_m L_r \psi_q I_{sq}
\end{align*}
\]

(10)

With: $\sigma = 1 - \frac{L_m^2}{L_s L_r}$, $\tau_r = \frac{L_r}{R_s}$

where:

- $i_{sd}, i_{sq} = \alpha$ -axis $\beta$ -axis stator current
- $\psi_{sa}, \psi_{sb} = \alpha$ -axis $\beta$ -axis rotor flux
- $v_{sa}, v_{sb} = \alpha$ -axis $\beta$ -axis stator voltage
- $\Omega = $ mechanical rotor speed
\[ L_s = \text{stator self inductance per phase} \]
\[ L_m = \text{magnetising inductance per phase} \]
\[ R_s = \text{stator phase resistance} \]
\[ R_r = \text{rotor phase resistance} \]
\[ P = \text{number of pole pairs} \]
\[ \sigma = \text{total leakage factor} \]
\[ T_s = \text{sampling interval} \]

The block diagram of the direct field-oriented induction motor drive system is shown in fig 7.

**IV. SIMULATION RESULTS**

**A. Simulation Results of Wind turbine-generator system**

The simulation conditions are given in the appendix.

Simulation results using the vector control strategy with different cases are given. Both the inverter and rectifier are modeled in the same way. The switches are considered as ideal, and their states are given by logical functions that take value 1 when the component is closed and 0 when it is open.

First, the rotor speed of the induction machine is increased till the synchronous speed. Once this last is reached, the flux and Vdc reference values are applied. These are:

\[ \Phi_r = 0.8 \text{Wb}; \quad V_{dc-ref} = 515 \text{V}. \]

The DC voltage regulation is obtained using the proposed vector control algorithm. In Fig. 17, we can see the stator voltage waveform. The increase of the rotor speed implies an increase of the voltage. Fig (10) presents the a, b, c currents and the DC voltage is presented in fig (11), we can see that the generated voltage reaches the reference one with high precision. The DC voltage is controlled with the torque via the current isq.
B. Simulation Results of Direct Field Oriented Control Of Induction Motor

Simulations using Matlab-Simulink software package have been carried out to verify the effectiveness of the proposed IM indirect field oriented control.

The induction motor used for the simulation studies has the following parameters:

Type: three-phase, 0.75kW, 220/380V, squirrel-cage induction motor.

\[
\begin{align*}
R_s &= 10\Omega; R_r = 6.3\Omega; L_s = 0.6560H; L_r = 0.6530H; \\
L_m &= 0.613H; J = 0.02Kg.m^2; B = 0N.m.s/rad; \\
p &= 2; T_s = 5N.m; \Omega = 146\text{Rad}/s.
\end{align*}
\]

The validity of the control scheme is demonstrated through the results shown in figure 12.

Fig. 12 shows the step response of speed at 10 sec and with 12 sec a time rating load 5Nm. We can notice the good performances of the control; the real speed converges to the reference one with a high precision. The electromagnetic torque allure is presented, it can concluded that the electromagnetic torque developed by the motor increased at t =12 sec to 5 Nm for compensate the load torque. The d q rotor fluxes, this figure demonstrates the perfect decoupling between the d and q axis. The d stator current conserved a constant value while q stator current followed the increasing and the decreasing of electromagnetic torque. These results demonstrate the good performances of the regulation.

\[
\begin{align*}
\Omega (\text{rad/s}) & \quad \quad \quad \quad \quad \quad \quad \quad C_b (\text{Nm}) \\
50 & \quad \quad \quad \quad \quad \quad \quad \quad 10 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \quad \quad \quad \quad \quad \quad \quad \quad 15 \quad \quad \quad \quad \quad \quad \quad \quad 20 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 5 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \quad \quad \quad \quad \quad \quad \quad \quad 5 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \quad \quad \quad \quad \quad \quad \quad \quad 10 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \quad \quad \quad \quad \quad \quad \quad \quad 15
\end{align*}
\]

\[
\begin{align*}
I_d (A) & \quad \quad \quad \quad \quad \quad \quad \quad I_q (A) \\
5 & \quad \quad \quad \quad \quad \quad \quad \quad 10 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \quad \quad \quad \quad \quad \quad \quad \quad 5 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \quad \quad \quad \quad \quad \quad \quad \quad 10 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \quad \quad \quad \quad \quad \quad \quad \quad 15
\end{align*}
\]

\[
\begin{align*}
\Psi_{id}, \Psi_{iq} (\text{Wb}) \\
0.5 & \quad \quad \quad \quad \quad \quad \quad \quad 1 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0.5 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0 \\
0 & \quad \quad \quad \quad \quad \quad \quad \quad 0
\end{align*}
\]

Fig.12. Drive response of induction motor under load disturbance.

V. CONCLUSION

In this paper, the vector control of an induction generator used in an autonomous speed wind system is presented. An analytical model of the autonomous induction generator, taking the increasing and the decreasing of electromagnetic torque. These results demonstrate the good performances of the control. The diphase model of the induction machine enabled us to define a vector control for the generator operation of this machine. As the flux is maintained at a constant value, the machine model can be considered linear around an operating point. Then, the adjustment of the torque is independent of the flux. This avoids having a complex algorithm of control when taking into account saturation.

This control enables us to maintain the saturation level of the generator constant and to control the DC voltage through the torque in the same way as it was done for the motor operation. Finally, the use of the control leads us to feed the load with voltage of effective value and frequency fixed whatever the speed of the turbine.

The direct vector control of the induction motor used as charge presents a good performance of regulation of speed. We can say that the associations of the wind turbine and induction generator permits feeding the induction motor with a sufficient voltage and frequency.

VI. APPENDIX

Parameters of the system used in simulation:

Parameters of the turbine:

\[
\begin{align*}
R &= 3.36m \\
\rho &= 1.225kg/m^3 \\
V_w &= 6m/s
\end{align*}
\]

Parameters of the Induction generator:

\[
\begin{align*}
R_s &= 1.2\Omega; R_r = 1.8\Omega; L_s = 0.115H; L_r = 0.115; \\
J &= 0.07Kg.m^2; \Gamma_s = 0.001N.m.s/rad; \\
p &= 1; \Omega = 314\text{Rad}/s.
\end{align*}
\]

Parameters of the IM:

Type: tree-phase, 4Kw, 220/380V, squirrel-cage induction motor.

Parameters of the PWM converter:

Supply’s voltage and frequency: 220 V(rms), 50 Hz.

Line’s inductance and resistance 0.002 H, 0.08 Ω.

Output capacitors 0.0025 F.

PWM carrier frequency 1 kHz.

VII. REFERENCES


