Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems, Chalkida, Greece, May 8-10, 2006 (pp281-286)

Autonomous Induction Generator Voltage Control

VASILE HORGA, MIHAI ALBU, MARCEL RĂŢOI and CORNELIU BOŢAN*
Electrical Engineering Faculty,
*Faculty of Automatic Control and Computer Science
Technical University of Iaşi
Blvd. D. Mangeron, no.51-53, 700050, Iaşi
ROMANIA

Abstract: - The paper presents results referring to the voltage control of an autonomous induction generator. The possible applications are for isolated systems with water or wind turbine or engine. The induction generator is excited using a PWM inverter connected to a single capacitor on the DC side. The voltage control is carried out with an adequate flux control based on rotor field oriented control.

Key-Words: - Autonomous induction generator, Rotor field oriented control, DC line voltage control

1 Introduction

Autonomous generator systems have acquired nowadays a wide spreading as an alternative to the traditional power plant, for isolated consumers, for automotive power supply etc. These systems operate in various conditions and under a large number of demands. The interest and the strong requirements imposed to these systems explain the large number of research works in this domain [1- 4]. The general structure of an autonomous generator plant is presented in Fig.1.

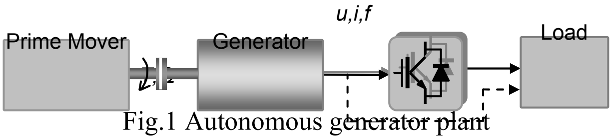

Fig.1 Autonomous generator plant

The prime mover (PM) ensures the mechanical energy for the generator and is either water or a wind turbine, or an engine. In the last case, the available power is rough constant but the speed is influenced by load. The speed and power have large variations in the case of water turbine, and especially in the case of the wind turbine. In each situation there is a small reserve of power and this affects the system behavior.

Note that in the experimental plants, a DC or AC motor with adequate control system is frequently used. This fact allows the changing of the conditions of the experiments. An important direction of our research activity is just to carry out an experimental set-up, which allows a suitable modeling of the real working conditions.

The generator of autonomous systems can be a permanent magnet machine (rarely used due to its high cost), a synchronous or an induction machine. The present papers refers to an induction generator (IG), frequently used because of its low cost, robustness and because it does not need an external power supply to produce the magnetic field.

Different types of static converters can be used in the structure of an isolated generator system, depending mainly on the type of the generator and of the load (AC or DC).

The main requirement of the control of the generator system is to ensure constant output voltage and frequency, independent of the input speed and load. There are certain isolated rural applications where the demands are not very strict, but in many cases and especially if it is necessary to carry out a grid connection, an accurate regulation has to be obtained. First, it is possible to control only the generated voltage (this allowing the connection of certain AC loads directly to generator). Another possibility is to control the voltage on the DC side of the converter. For an AC load, the DC-AC part of the converter can also be controlled. It is useful to combine the control at different levels of the system in order to ensure high performances. A supplementary problem that needs to be solved in the case of IG refers to the self-excitation and the start of the operation in generator mode. This can be ensured by the inverter with only one capacitor connected to the DC side or a three-phase capacitor.

The present paper refers to the theoretical aspects and experimental results for a structure based on rotor field oriented control intended to maintain the voltage constant on the DC side.

2 Induction generator system

Fig.2 shows the experimental set-up. The main part of the system consists of a standard three-phase squirrel cage induction machine (4kW, 380V, 8.6A, 50Hz, 1430 rpm) that operates in self-excitation generator mode.

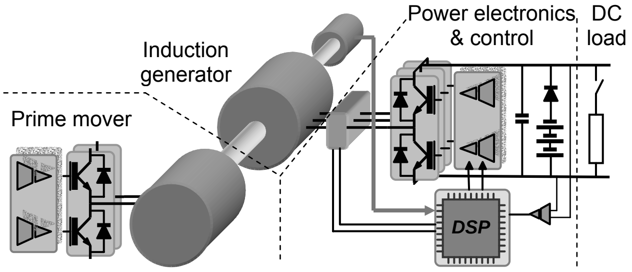

Fig 2. Experimental setup

The PWM converter is used for AC-DC energy conversion and to control the output voltage magnitude of the IG. An external battery, a capacitor bank (1000μF) and a DC load are connected on the DC line. The speed is measured with an encoder. For the currents and the voltages measure Hall transducers are used. A TMS320C31 Motion Control Development Board is being used to control the IG system [5].

For this autonomous generator, the PM is a DC machine that must operate at different speeds. The speed of the DC motor can be varied in open loop by means of a four-quadrant DC-DC converter.

The PWM converter connected to IG is a standard three-phase bridge with bi-directional power flow capability. In order to control the PWM converter in different modes, the three-phase structure was conceived especially for laboratory studies. IGBT transistors are used for the power stage of the three-phase bridge.

The IG must often operate in isolated areas driven by wind turbine, micro-hydro plants, engine etc. As the remanent magnetic flux of the IG is insufficient for the system start-up, an auxiliary battery must be connected to the DC link to provide the initial reactive energy. A 24V battery charging the capacitor bank through a diode is used on the laboratory stand. After the start-up operation of the IG, the voltage on the DC link increase over 24V and the diode disconnects the battery. In the normal operation mode, the IG supplies itself with the necessary amount of the reactive energy. This energy is stored in the capacitor from which is taken by the PWM converter that, in this case, acts as a controlled reactive current source. To compensate the losses produced by the reactive current, an active energy is necessarily taken by the IG from the PM. Thus, the PWM rectifier also acts as a controlled active current source for these losses and for the DC load connected to the DC link. Part of the mechanical power supplied by the PM arrives as an active power into the DC load. Few mechanical and electrical losses appear. The electrical losses appear in the IG windings and in the PWM rectifier.

It is obvious that the PWM converter must control the phase of the fundamental harmonic of the AC current in the induction machine. If the DC load is not connected, the phase displacement between the sinusoidal waveform of the current and the generator voltage is approx. 90º (electrical degrees). If the DC load is connected and tends to rated value, the phase angle between current and voltage waveforms tends to 180º. It is recommended to operate at the rated load to maximize the efficiency of the system.

The output DC voltage of PWM rectifier is greater than the peak value (amplitude) of the IG electromotive voltage. On the other hand, the electromotive voltage is proportional to the IG speed and the linkage flux. Consequently, at a certain speed of the IG, imposed by the PM, the linkage flux must be adjusted in order to maintain the peak value of generator voltage under the reference of the DC voltage.

3 Control of Induction Generator

Field oriented control schemes transform the control problem of the induction machine into the classical control problem of a separately excited DC machine and create independent flux and torque control loops. The stator current phasor is decomposed into two orthogonal components, one along the rotor flux, the other in quadrature with it, when the rotor flux position is known [6]. The in-phase component is the reactive current and the quadrature component is the active current. The rotor flux position should be known on this purpose. Therefore, the accurate instantaneous position of the rotor flux is crucial for the success of the field-oriented structures. In the indirect control schemes the flux position is determined indirectly through the rotor speed and the slip estimation. The absence of the flux sensors and the ability to operate at low speeds has increased the popularity of the indirect control strategy.

The machine model describes an electrical and magnetic symmetric machine with three phase windings. A phasor, $\underline{y}$, is assigned to each of the three phase variables system:

$$\underline{y}=\sqrt{\frac{2}{3}}\left(y_a+\underline{a}y_b+\underline{a}^2y_c\right)=y_d+j\,y_q \qquad (1)$$

Within the rotating reference frame with ω_e, the squirrel cage induction machine can be modeled as:

$$\begin{cases} \underline{u}_s^e = R_s \underline{i}_s^e + \dfrac{d\underline{\psi}_s^e}{dt} + j\omega_e \underline{\psi}_s^e; & \underline{\psi}_s^e = L_s \underline{i}_s^e + L_m \underline{i}_r^e \\ 0 \;= R_r \underline{i}_r^e + \dfrac{d\underline{\psi}_r^e}{dt} + j(\omega_e - \omega_r)\psi_r^e; & \underline{\psi}_r^e = L_m \underline{i}_s^e + L_r \underline{i}_r^e \\ J\dfrac{d\Omega}{dt} = p\dfrac{L_m}{L_r}\underline{\psi}_r^e x \underline{i}_s^e - m_r - D\Omega; & \omega_r = p\Omega \end{cases} \quad (2)$$

Symbols *u, i, ψ* denote voltage, current and flux linkage, respectively index *s* denotes parameters and variables associated with stator, index *r* is used for parameters and variables associated with the rotor, and index *m* refers to a parameter associated with the magnetizing flux. The *e* superscript denotes the rotating reference frame synchronous with the fluxes.

If the position of the rotor flux is known and the rotating reference frame is synphasic with this one, then the system (2) becomes:

$$\begin{cases} \dfrac{d\psi_r^e}{dt} + \dfrac{1}{T_r}\psi_r^e = \dfrac{L_m}{T_r} i_{sd}^e; \quad \omega_{sl} = \dfrac{L_m}{T_r}\dfrac{i_{sq}^e}{\psi_r^e}; \quad T_r = \dfrac{L_r}{R_r} \\ \theta_s = \int(\omega_r + \omega_{sl})dt; \quad m_e = p\dfrac{L_m}{L_r}\psi_r^e i_{sq}^e; \omega_{sl} = \omega_e - \omega_r \end{cases} \quad (3)$$

and

$$\begin{cases} u_{sd}^e = \sigma L_s \dfrac{di_{sd}^e}{dt} + \left(R_s + R_r \dfrac{L_m^2}{L_r^2}\right) i_{sd}^e - \omega_e \sigma L_s i_{sq}^e - \dfrac{L_m}{L_r^2} R_r \psi_r^e \\ u_{sq}^e = \sigma L_s \dfrac{di_{sq}^e}{dt} + \left(R_s + R_r \dfrac{L_m^2}{L_r^2}\right) i_{sq}^e + \omega_e \sigma L_s i_{sd}^e + \omega_r \dfrac{L_m}{L_r}\psi_r^e \end{cases} \quad (4)$$

Taking into account only the permanent magnetic state, Eqs. (4) become:

$$\begin{cases} u_{sd}^e = \sigma L_s \dfrac{di_{sd}^e}{dt} + R_s i_{sd}^e - \omega_e \sigma L_s i_{sq}^e \\ u_{sq}^e = \sigma L_s \dfrac{di_{sq}^e}{dt} + R_s i_{sq}^e + \omega_e L_s i_{sd}^e \end{cases} \quad (5)$$

Note that the Eqs. (2)-(5) can be used to represent the electric machine operating in both modes - motor and generator [1].

A regulation concept capable of incorporating the AC machines as a motor or a generator can only be achieved in a reliable and economically manner on a digital basis; the high signal processing effort for variables estimation, regulation and signal modulation/demodulation (Park transformation) preclude an analog system. The control algorithm must perform several stages in the digital signals processing, namely:

a) computing the instant position of the rotor flux;
b) computing the actual values of the stator currents in the new coordinates frame;
c) computing the reference values of the active and reactive components of the stator currents according to the control strategy;
d) computing and modulating the new commands and send them to the inverter.

The first two requirements lead to the induction machine model, described by Eqs. (3). The third requirement proves the fact that a vector control structure follows two objectives: the magnetic control of the machine and the electromagnetic torque control. In the motoring mode, the electromagnetic torque and the speed are controlled variables and an additional motion equation is needed [7]. During the generator operation, the machine speed is given by the PM (engines) and the torque (current) control is used to govern output power. In this mode, the field oriented control technique is used for controlling energy flow rate so that at different speed and load conditions the rated DC voltage is maintained [8]. The control structure is based on the inverse dynamic model of the induction machine and it is presented in Fig. 3.

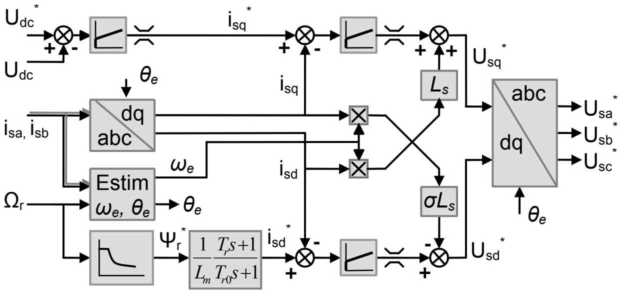

Fig.3 Control structure

As the transfer function of the reactive component is not a proper one, it is replaced with a lead-lag structure for practical implementation:

$$\frac{i_{sd}^{e*}}{\psi_r^*} = \frac{T_r s + 1}{L_m(T_{r0}s + 1)} \quad (6)$$

When a voltage fed inverter is used, the orthogonal components of the stator current will be indirectly controlled through the stator voltage components. In this case two supplementary current loops are needed. On the basis of the equivalent model of the vector controlled induction machine, the equations of the decoupling and performance regulators can be computed. Eqs.(4) are used to design current regulators and the decoupling regulator of the control voltages. The tuning of the PI current regulators can be done by using the resulted open loop transfer function:

$$H(s) = K_{Ri}\frac{T_{ii}s + 1}{T_{ii}s}\frac{K}{Ts + 1}; \quad K = \frac{1}{R_s}; T = \frac{\sigma L_s}{R_s} \quad (7)$$

The time constant of the electric circuit, T, is compensated by the integral time constant of the PI regulator. Thus, one obtains:

$$H_0(s) = \frac{1}{\tau s + 1}; \quad \text{where } \tau = \frac{T}{K_{Ri} K} \tag{8}$$

The tuning parameters of the current regulators can be calculated for an imposed time constant, τ, of the current loop:

$$K_{Ri} = \frac{\sigma L_s}{\tau}; \quad T_{ii} = T = \sigma T_s \tag{9}$$

PM speed may vary at any time. Variation in PM speed affects the rotor speed of the induction generator, and the variation in rotor speeds affects the generated voltage unless there is well-designed control system to regulate the generated voltage.

In motoring application, all control scheme use constant flux for rotor speeds lower than the rated speed. The flux will be reduced inversely proportional to the speed when the induction motor is operated above its rated value which is the flux weakening mode. In the generator mode the aim is to have a constant generated voltage. Of course, the frequency of the generated frequency is dependent on the rotor speed but once it is rectified the DC voltage depends only on the magnitude of the AC voltage.

The self-excited IG relies on the DC line capacitors to provide excitation energy through the power converter. By controlling reactive current, i_{sd}^*, one can change the flux level of the induction machine. On the other hand, the no load generated terminal voltage can be approximated by [2]:

$$E = C\omega_r \psi_r^e \tag{10}$$

where C is a constant. If the product of the rotor speed and the flux linkage remains constant, the terminal voltage will not change. However, there is a problem of core saturation in practical applications. Since the maximum value of the flux linkage is determined by the saturation of the core, the flux linkage required at any speed is calculated based on this maximum flux linkage:

$$\psi_r^* = \frac{\omega_{r\min}}{\omega_r} \psi_{r\max}^* \tag{11}$$

When the rotor speed decreases to a value lower than $\omega_{r\min}$, the flux linkage should theoretically increase to a value greater than $\psi_{r\max}^*$. In this case it is maintained constant.

Active current, i_{sq}^*, is determined by the needed power pumped to the DC line load. Therefore, a DC bus PI voltage regulator can be used to determine them.

4 Experimental results

The control algorithm of the IG was implemented on the experimental set-up presented in section 2. This section will shows the experimental results related to the behavior of the IG system in three different cases: the start-up of the system, the control of the DC voltage for a variable speed of the prime mover and the DC voltage control for a step variation of the load. In all diagrams the variables are represented in a per unit system.

Fig.4 shows the experimental waveforms for the no-load start-up transient. The speed of the PM is around the rated value when the start-up command is applied. Initially, the AC and the DC voltage have a slow rate of growing due to remanent magnetism of the IG and the low reactive energy in the capacitor. At a certain value of the DC voltage, the magnetic flux reaches a value that allows a rapidly build up of the IG voltage.

Fig.5 shows the transient waveforms when the speed of the DC motor was varied in large limits at light DC load. It is clear that, in those terms, the voltage controller can stabilize the DC voltage.

Fig.6 shows the transient behavior when a resistive load is suddenly applied to the DC output. Because of the small power reserve of the PM and roughly control of the AC voltage, the DC voltage has a small decrease with the load.

In Fig.7 it can be observed an increasing of the current phase displacement when the load is applied.

5 Conclusions

One of the serious problems with the IG is its poor voltage regulation. It is well-known that the output voltage of the IG collapse with a little increase of the load power which means that the maximum power that can be supplied from the stand alone IG without voltage regulation is very small as compared to its rated power (10% of the IG rated power [3]).

This paper has provided a solution for an IG by applying the field oriented control. The proposed system is implemented as an output voltage control scheme for a stand alone IG driven by variable speed PM such as wind turbine, micro-hydro plants, engine etc. The variable speed IG system is suited to applications as a simple, rugged, maintenance free, high reliability and low cost DC power source.

A laboratory prototype for the IG system has been implemented to validate the proposed method. The results of the paper suggest that the controlled IG can generate enough active power, compared with its rated value, if the PM is able to sustain this power.

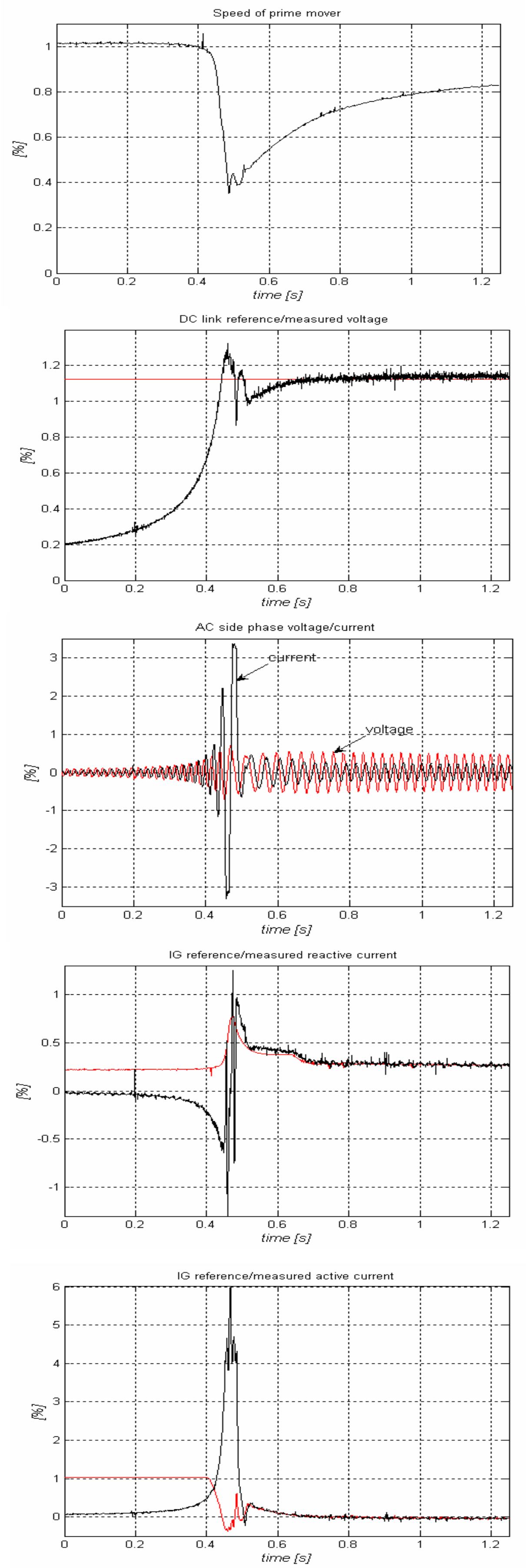
Speed of prime mover
[%]
1
0.8
0.6
0.4
0.2
0
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
DC link reference/measured voltage
[%]
1.2
1
0.8
0.6
0.4
0.2
0
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
AC side phase voltage/current
current
voltage
[%]
3
2
1
0
-1
-2
-3
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
IG reference/measured reactive current
[%]
1
0.5
0
-0.5
-1
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
IG reference/measured active current
[%]
6
5
4
3
2
1
0
0 0.2 0.4 0.6 0.8 1 1.2
time [s]

Fig.4.

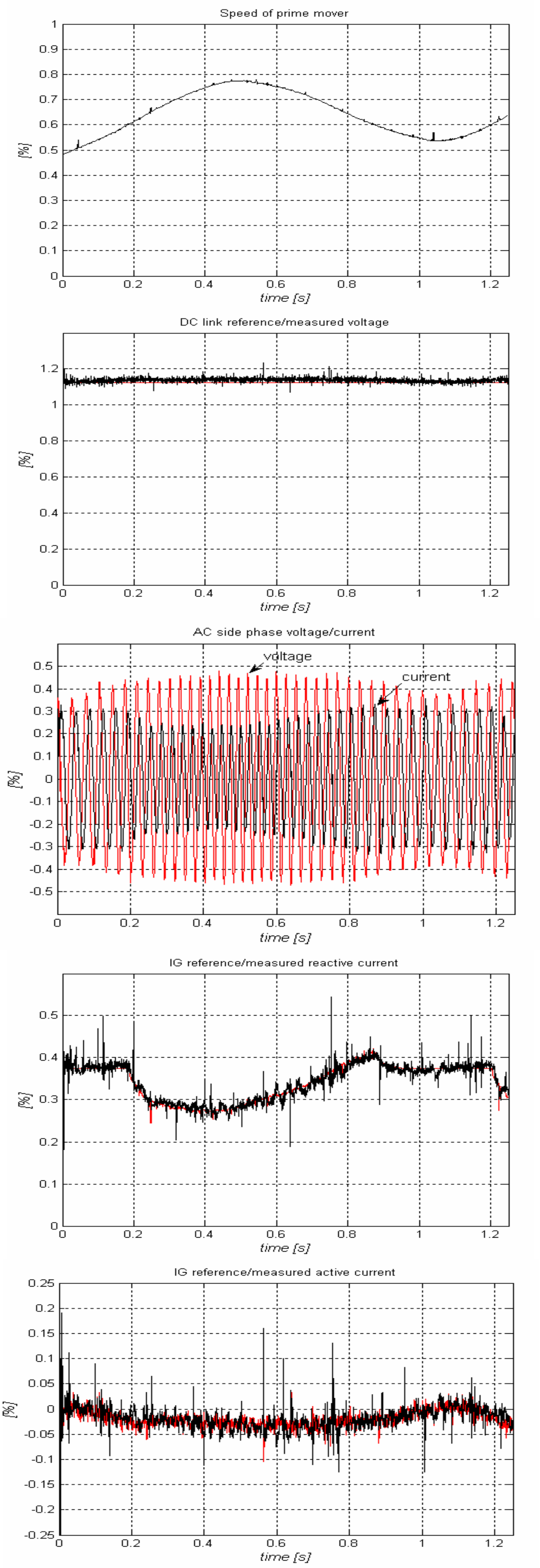
Speed of prime mover
[%]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
DC link reference/measured voltage
[%]
1.2
1
0.8
0.6
0.4
0.2
0
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
AC side phase voltage/current
voltage
current
[%]
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
IG reference/measured reactive current
[%]
0.5
0.4
0.3
0.2
0.1
0
0 0.2 0.4 0.6 0.8 1 1.2
time [s]
IG reference/measured active current
[%]
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0 0.2 0.4 0.6 0.8 1 1.2
time [s]

Fig.5.

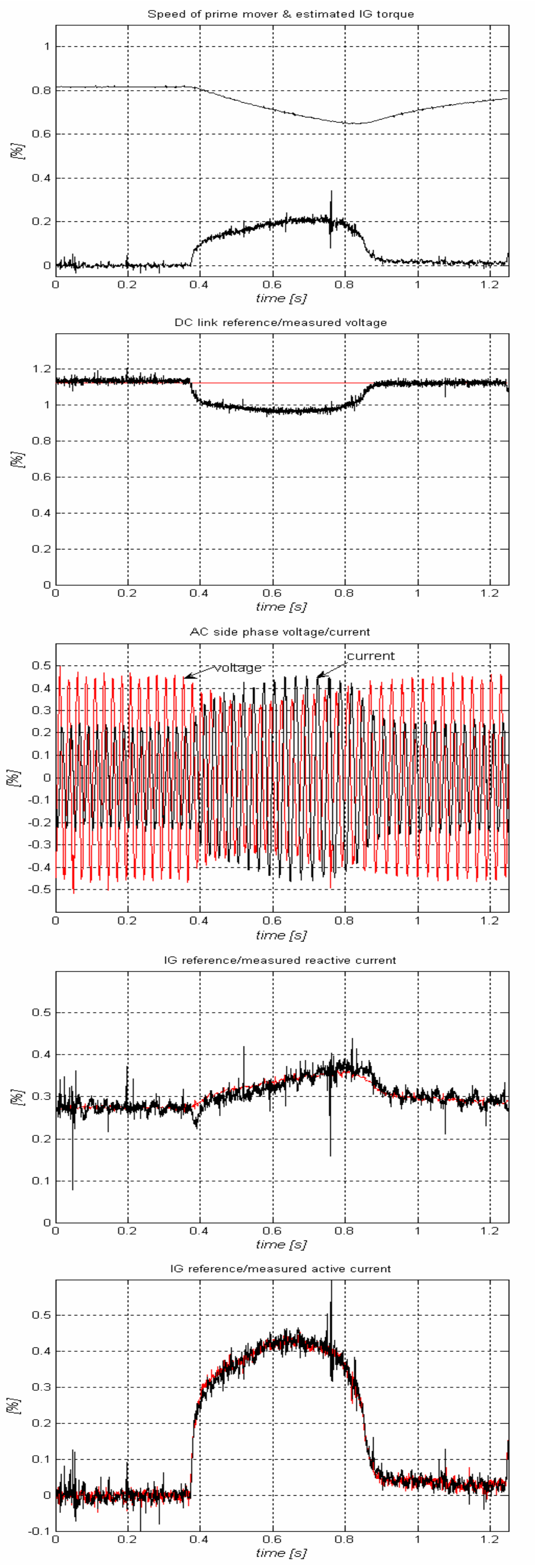

Fig.6

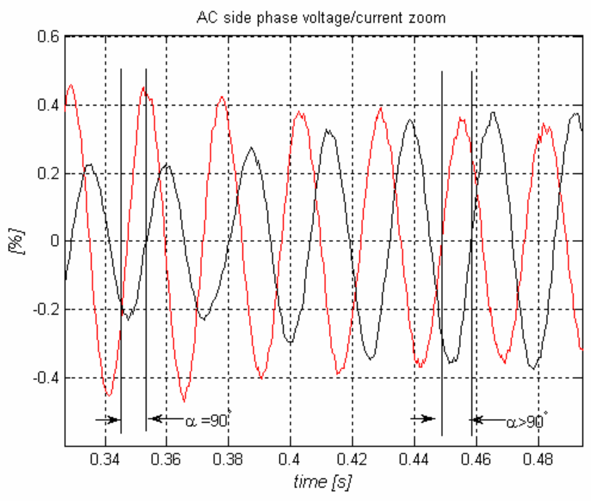

Fig.7.

References:

[1] D.Seyoum, M.F. Rahman, C.Grantham, Inverter Supplied Voltage Control System for an Isolated Induction Generator Driven by a Wind Turbine, *Conf.Rec. IEEE-IAS Annual Meeting, 2003*, pp.568-575.

[2] D.Seyoum, F. Rahman, C. Grantham, Terminal Voltage Control of a Wind Turbine Driven Isolated Induction Generator, *Applied Power Electronics Conference and Exposition, APEC'03*, 18th Annual IEEE, 2003

[3] T.Ahmed, K.Nishida, M.Nakaoka, A Novel Stand-Alone Induction Generator System for AC and DC Power Applications, *Industry Applications Conference, IAS Annual Meeting Conf.Rec.* 2005, pp.2950-2957.

[4] G. Sousa, F.Martins, J.Rey, J.Bruinsma, An Autonomous Induction Generator System with Voltage Regulation, *IEEE Int. Conf. on Power Electronics and Drive Systems*, 2001, pp.94-98.

[5] A.Onea, V.Horga, C.Boțan, Digital Motion Control Development Shell. In: *Advances in System Theory, Mathematical Methods and Applications*, WSEAS Press, 2002, pp.87-89

[6] P.Vas, *Vector Control of AC Machines*, Clarendon Press, Oxford, 1990.

[7] A.Onea, V.Horga, M.Albu, C.Boțan, Indirect Vector Control of Induction Motor with Floating Point DSP, *The Bulletin of the Polytechnic Institute of Jassy, Tome* XLVII (LII), Fasc.1-4, 2—2, pp.88-98.

[8] J.Liu, J.Hu,L.Xu, Design and Control of the Kilo-Amp DC/AC Inverter for Integrated Starter-Generator (IGS) Applications, *Conf.Rec IEEE-IAS Annual Meeting*, 2004, pp.2754-2761.