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THEORETICAL AND EXPERIMENTAL ANALYSIS OF THE SQUIRREL-CAGE INDUCTION GENERATOR
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Marcelo Augusto dos Santos Silva
Teresa Cristina Bessa Nogueira Assunção
Jonathan Quideroli de Andrade
José Tarcísio Assunção
Federal University of São João Del Rei, Department of Electrical Engineering, São João Del Rei, Brazil
marceloaugusto01@hotmail.com
bessa@ufsj.edu.br
jonathan_quideroli@hotmail.com
tarcisio@ufsj.edu.br

Abstract: *The object of this study is the evaluation of the three phase squirrel cage induction motors operating as induction generator. It is presented a solution for the excitation of the three-phase induction generator from a single-phase source maintaining the features main operation of the induction generator interconnected to three-phase power supply. It is also evaluated its operation isolated system, where the generator depends on arrangement using capacitor-excited induction generator. Also, is presented some information about interrelationships between the load, the excitation capacitor, frequency stabilization, voltage regulation and the speed. The analysis is applied to a specific machine, leading to a comparison between calculated and test results.*

Keywords: *Generator, Capacitor, Voltage, Regulation, Speed.*

1. Introduction

The use of the induction generators (GI) instead of synchronous generators (GS) in alternative energy systems (wind power stations, micro and mini hydropower plants) has increased considerably (Ackerman, 2012). Studies have shown that the cost of GI is approximately 40% lower than of the GS, and in addition the GI has other advantages such as: small size and cost units, strength, there are no commutator or slip rings to service (compared to the dc motor), there are no brushes to replace, minimum of maintenance is required, self-protection against over load and short circuit, no need for separate DC field power, among others (Thodeet al, 1984; Pham, 1991; Filho et al, 2014).

In isolated power systems, the GI with excitation capacitor is quite popular; it does not require synchronism devices and/or controllers for parallel operation, so the capacitor bank may provide the reactive power needed the operation of the motor as generator, as well as to assert the operating speed. However, its isolated operation present problems related to variable voltage regulation and frequency, it depends of the engine load and needs of the self-excitation capacitors of the high power and cost. The price of the capacitor bank is still a limiting factor for the the use of isolated GI in systems with power lower than 50 kW (Rahim, 1990; Mahato et al, 2008; Trapp, 2008). An important application towards the generator connected to the electric network can be seen as an additional energy source to local concessionaire network. The goal of this solution is the use of alternative energy systems of low power, providing the installed power increase with small investment and high reliability. This proposal can provide, for example, the electric power own generation on rural properties with small investment and operational cost.

2. Computational and Experimental Analysis

In this study, two configurations were adopted to configure the behavior of the three-phase induction generator connected to a single-phase power system: The evaluated system is composed for a three-phase induction generator (GIT), it is connected to the single-phase electric grid by means of frequency inverter, where the system will be analyzed with and without harmonic filters and being auto excited for a capacitor bank.

The GIT experimental tests was conducted in the dynamometer of the bench of the denominated “Laboratório de Otimização de Sistemas Motrizes” – LOSIM, as is shown in Fig. 1.

This bench has two three phase squirrel cage induction motors, which are mechanically coupled by a torque and speed transducer. A5 cv three-phase induction motor, 4 poles, is used as primary machine controlled by a frequency inverter and, one 2 cv MIT, 4 poles, was employed as GI; which is connected electrically to the single-phase electric grid by means of mono-three phase frequency inverter. This mono-three phase frequency inverter is a three phase normal inverter operating with one of the phases disconnected.

Figure 1. Dynamometer Bench of the LOSIM/DEPEL/UFSJ

3. Computational Results

3.1. System Isolated Operation

3.1.1. Calculation of the Capacitor Bank

In isolated power grid the GI require self-excitation systems that are, in most cases, capacitor bank, which can be connected in delta or star, according to Fig. 2.

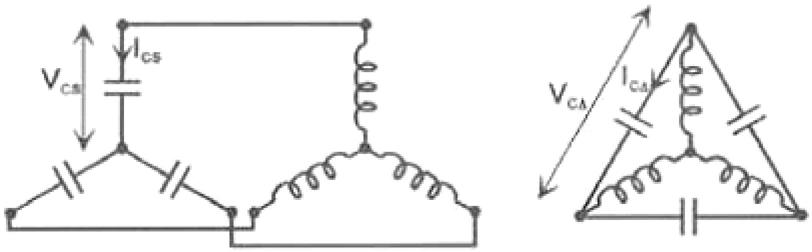

Figure 2. Capacitor Bank Connections. CHAPALLAZ (1990)

The capacitor bank was calculating by three ways, as follows: 1. Using the magnetization characteristic of the machine, usually provided by manufacturers on catalogs and nameplates; 2. Using the no-load motor eletric power; and 3. Motor mutual inductance, which is obtained from manufactures or experimentally (CHAPALLAZ, J. M, 1990).

3.1.2. Method of the motor magnetization curve

In Equation (1) is presented the capacitor calculation:

$$C = \frac{Q_G}{3 \times U^2 \times 2 \times \pi \times f} \tag{1}$$

Where: Q_G=capacitive reactive power [kVAR]; U = voltage [V]; f = frequency [Hz]; C = capacitance [μC].

The capacitive reactive power can be calculated according to the Eq. (2):

$$Q_G = \frac{sin\,(\varphi_G)}{sin\,(\varphi_G)} \times Q_M \tag{2}$$

Where: Q_M= motor reactive power [KVAR] according with the Eq. (3):

$$Q_M = \frac{P_N}{\eta_M} \times tan(cos^{-1}\varphi_M) \tag{3}$$

Where: P_N=motor nominal power [KW]; η_M=motor nominal efficiency; $\cos^{-1}\varphi_M$=motor power factor angle cosine.

The ratio $\frac{sin\ (\varphi_G)}{sin\ (\varphi_G)}$ was obtained using machines tests, 4 poles, 50 Hz, in the range of 0 a 25 [KW], but, can be used machines until 35[kW], in accordance with Fig. 3.

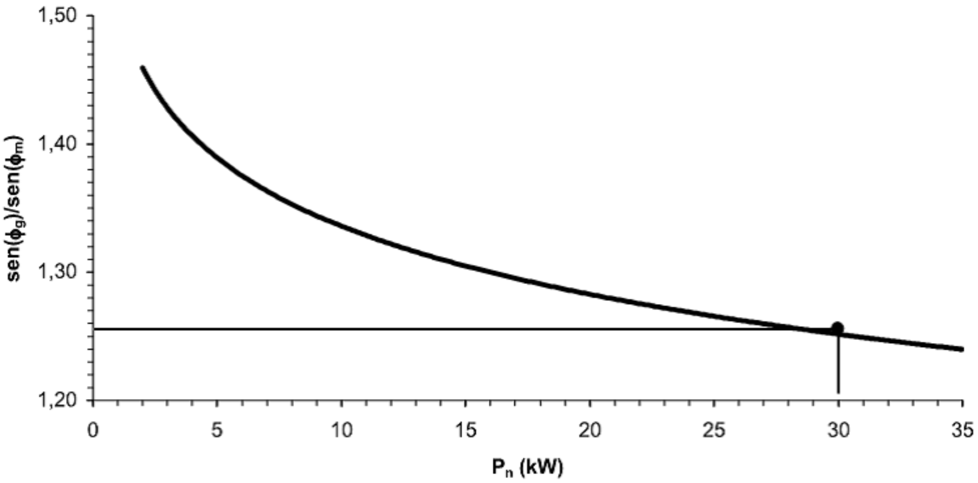

Figure 3. Generator and Motor $\sin(\varphi)$ Ratio

The self-excitation capacitance for 60 [Hz] frequency is calculated by Eq. (4):

$$C_{60} = C_{50} \times \left(\frac{50}{60}\right)^2 \quad (4)$$

Where: C_{60}= capacitance 60 Hz [µF per phase]; C_{50}= capacitance 50 Hz [µF per phase].

The electric power produced by machine is estimated by Eq. (5):

$$P_{ele} = \frac{\cos\varphi_G}{\eta_M \times \cos\varphi_M} \times P_N \quad (5)$$

Where: P_{ele} = generate electric power [kW].

The induction generator mechanic power and efficiency are calculated according to the Eq. (6) and Eq. (7):

$$P_M = P_{elG} + P_N \times \left(\frac{1}{\eta_M} - 1\right) \quad (6)$$

$$\eta_G = \frac{P_{elG}}{P_M} \quad (7)$$

Where: P_M =generated mechanic power [KW]; η_G= generator efficiency.

According to motor data available in Tab. 1, are presented in the Tab. 2 the results of the analyzed motor operating as generator.

Table 1. Motor Data.

P_M [kW]	Voltage [V]	Frequency [Hz]	Speed [rpm]	η [%]	cos φ
1.472	220	60	1755	84.2	0.81

Table 2. Generator Data.

Capacitance [µF]	P_{elG} [kW]	P_M [kW]	η [%]	cos φ
28.28	1.1	1.37	0.79	0.51

3.1.3. Method of the No-load Motor Electric Power

In this method is used the no-load motor electric power for the calculation of the reactive power for to keep the motor magnetic field. Matching the reactive powers of the motor and generator is possible the capacitance calculation, which is essential for the isolated operation of the generator, and with similar results as to the method of the motor magnetization curve.

3.1.4. Method of the Motor Mutual Inductance

Another way for the calculation of the capacitance is using the motor equivalent circuit parameters. In this case, the magnetization reactance or mutual reactance is equal to the capacitive reactance. Using the Eq. (8) is calculated the capacitance in ohms, whose value is as close as of the calculated by method of the motor magnetization curve.

$$C = \frac{1}{W \times X_L} \tag{8}$$

Where: w=angular frequency [rad/s]; X_L=inductive reactance [Ω]; X_C= capacitive reactance [Ω].

In Tab. 3 are presented the capacitance values according to methods studied in this paper.

Table 3. Capacitance Values with the generator operating in isolated power systems.

C_1[μF]	**C_2[μF]**	**C_3 [μF]**
28.28	39.42	28.98

Where: C_1 =capacitance value using the motor magnetization curve [μF];; C_2=capacitance value using the method of the no-load motor electric power [μF]; C_3=capacitance value using the method of the motor mutual inductance [μF].It must be highlighted that, the capacitance is calculated to provide the reactive power for the motor, which can be adjusted according to the system load, or even to the voltage stabilization due to the system load variation.

4. Computational Modeling and Simulation

4.1. Isolated Power System

A. Self-Excited System and No-Load

The simulation has been carried out using the digital computer simulation package Simulink.

For operation of the motor isolated of the power system is necessary that a capacitor bank be connected to the motor, as shown in the Figure 4. In the simulation, the motor and capacitor were magnetized by power supply using a small time period, around 2 seconds.

Figure 4 shows the motor speed and electromagnetic operating isolated of power system. As can be seen from Fig. 5, when the simulated system is connected to power system, the motor speed has been as high as expected than the synchronous speed. With the capacitor there is a sharp decrease of the speed, which is maintained because of the no-load system. This speed decrease depends of the capacitor that establishes the system speed and frequency. Electromagnetic torque transient behavior is approximately equal to the few thousandth seconds, because momentarily the system operates as motor and soon after it operates as generator. The most critical factor to consider in applying induction generators is the need for the system to supply all the reactive power necessary to provide excitation at all generating levels. This means that the machine can only be applied where there is a source of reactive power and it is of adequate capacity. In this case the capacitor bank was adjusted to 150 [μF], thereby causing adverse effects in the torque, because this motor operating as generator its torque can't be higher than 17 [N.m]. The torque peak time of the generator is small, thus avoiding the speed increase.

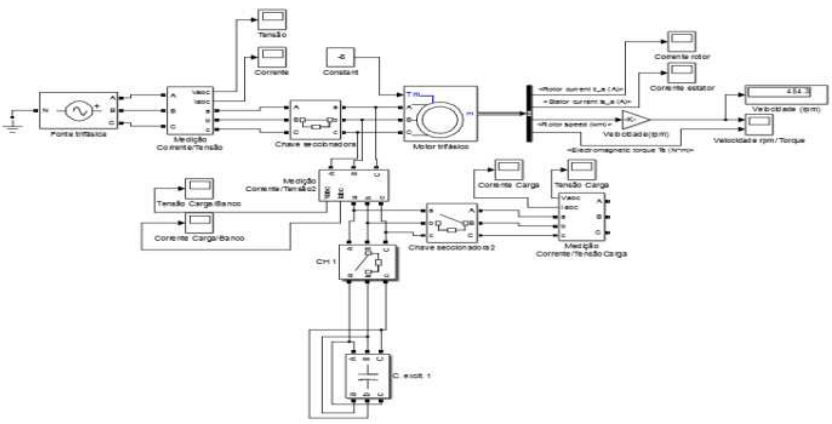

Figure 4. Isolate Power System – No-Load

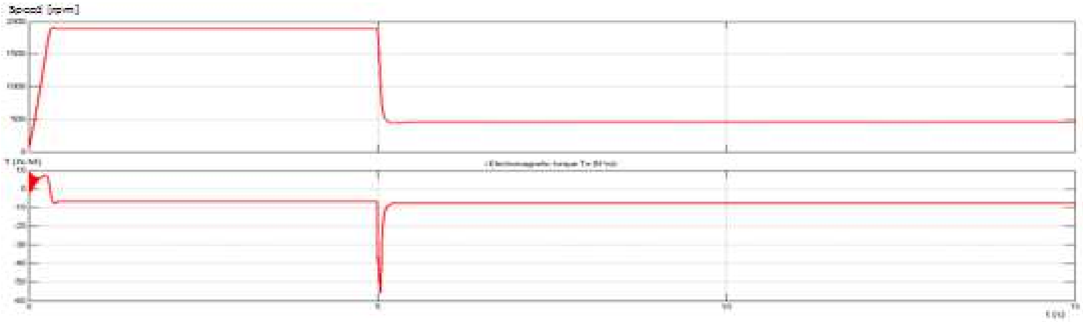

Figure 5. Speed and Torque x Time

Figure 6 shows the behavior of the voltage of the system without adjust of the capacitance, it is noted that from 1 to 5 seconds the system is connected to power supply with peak voltage of de 311 [V]. In a general way, with the system no-load and the capacitor value specified to the maximum value, the peak voltage is high, and it continues high in steady state. In Fig. 7 has been observed that after adjusting of the capacitor, the voltage reach acceptable values. However, in spite of adjust of the voltage level; there has been a clear variation of system frequency. With the connection of the capacitor in system there is the stabilization of the voltage, generator speed and as well the frequency regulation.

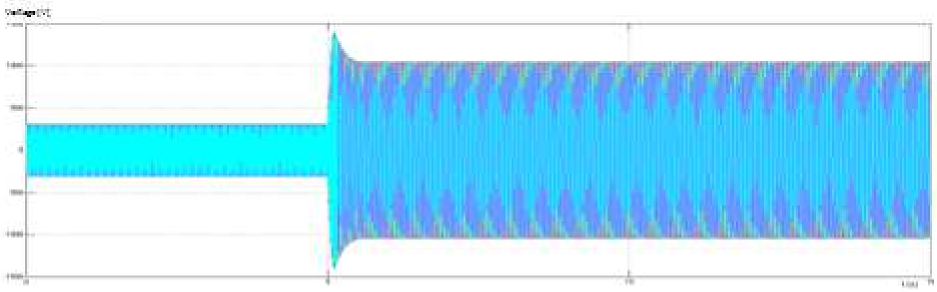

Figure 6. No-Load Voltage, without adjust of the capacitance

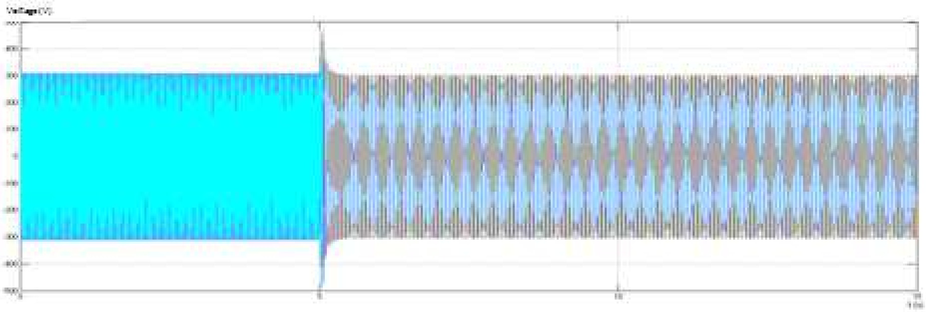

Figure 7. No-Load Voltage, with adjust of the capacitance

B. System with RL load

Figure 8 shows the system configuration with a RL load connected. The torque and speed behavior is presented in Fig. 9. It can be observed that due to load the speed is adjusted and the torque reach its nominal value.

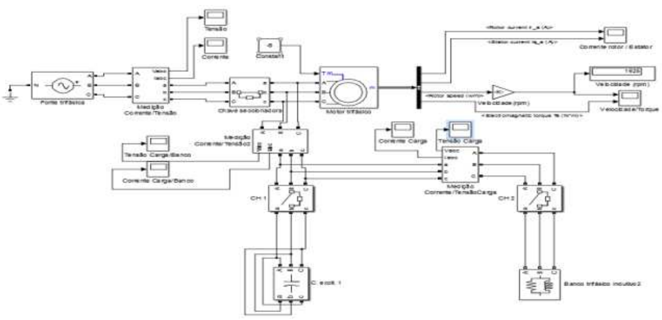

Figure 8. System with RL load

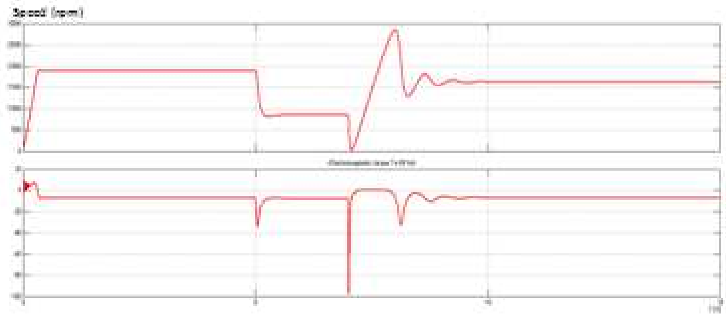

Figure 9. Speed and Torque x Time

In Figure 10 is presented the rotor and stator current, noting that there is a peak when there is the insertion of the RL load, but with the recovery of the speed the currents of the generator reach their nominal values.

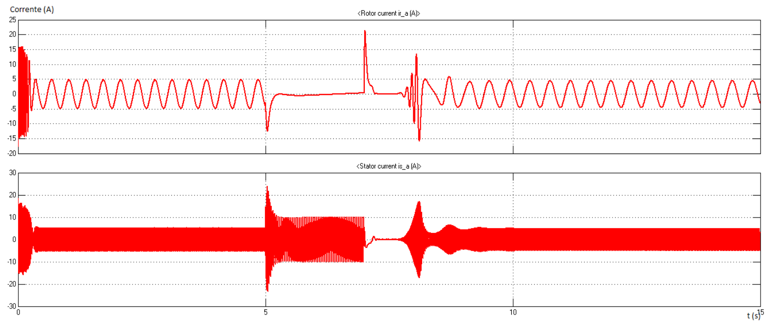

Figure 10. GI Rotor and Stator Current x Time

In Figure 11 the voltage behavior for a load RL can be seen.

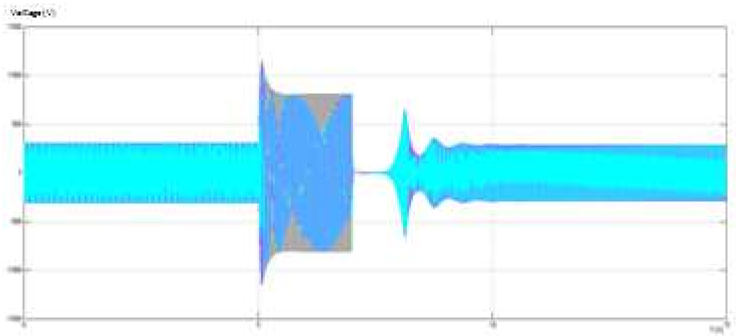

Figure 11. GI Voltage with RL Load

C. System with capacitive load

In Figure 12 is showed the system with capacitive load.

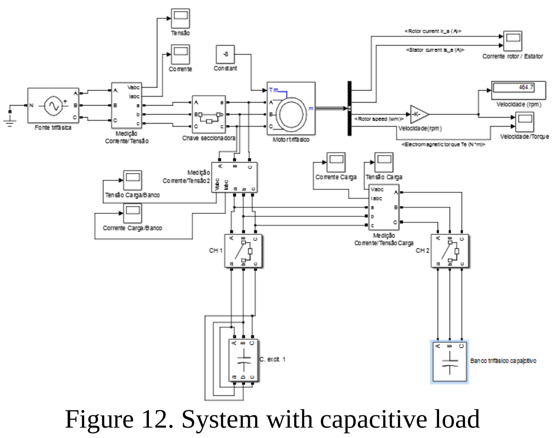

Figure 12. System with capacitive load

With a capacitive load connected to system is as if it was no-load and with a capacitor bank to control the voltage. In Fig. 13 is presented the variation of the GI voltage. In Fig. 14 is verified how behave the rotor and stator currents.

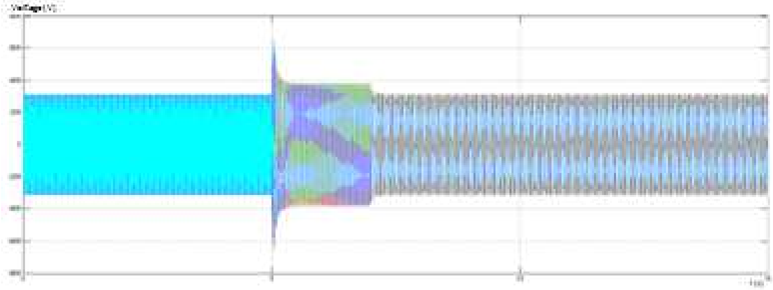

Figure 13. GI Voltage with capacitive load x Time

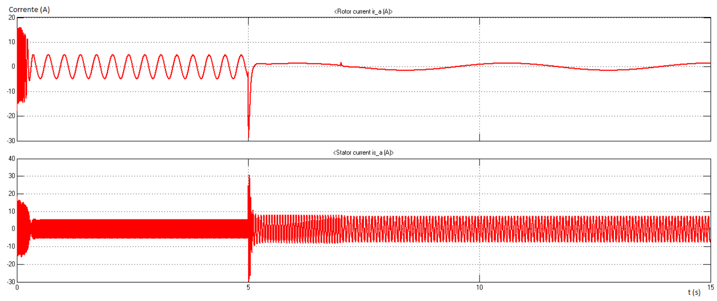

Figure 14. GI Rotor and Stator Currents with capacitive load x Time

4.2. Generator connected to the single-phase electric grid by means of frequency inverter

In Figure 15 is showed the configuration with the generator connected to the single-phase electric grid by means of frequency inverter. A RC filter is connected in frequency inverter output for to help in reduction of system harmonic components.

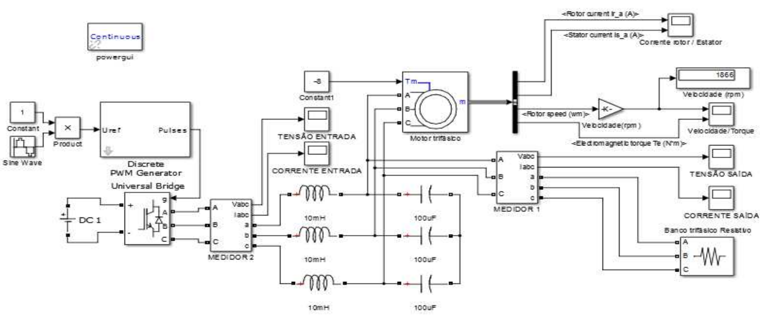

Figure 15. Generator connected to the single-phase electric grid by means of frequency inverter

The speed is within the limit value expected for a generator connected to the single-phase electric grid, as can be seen from Fig. 16. The electric grid assert the system frequency and speed, making the motor to operate as a generator with the speed greatest than synchronic speed, and the torque value is the nominal of the machine.

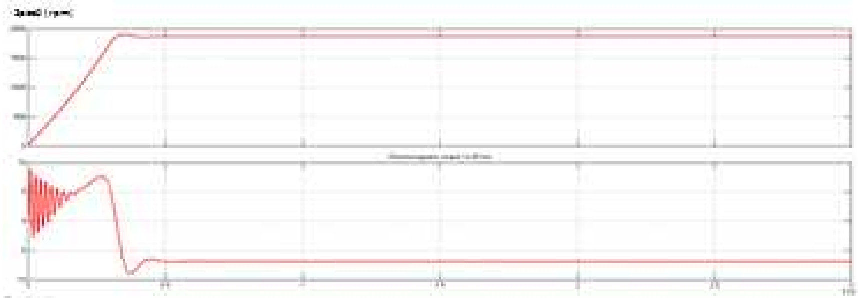

Figure 16. GI Speed and Torque x Time

In spite of filter connected the system is affected by harmonics due to the frequency inverter, but the harmonic distortion is in limit range required, can be observed in Fig. 17 and Fig. 18.

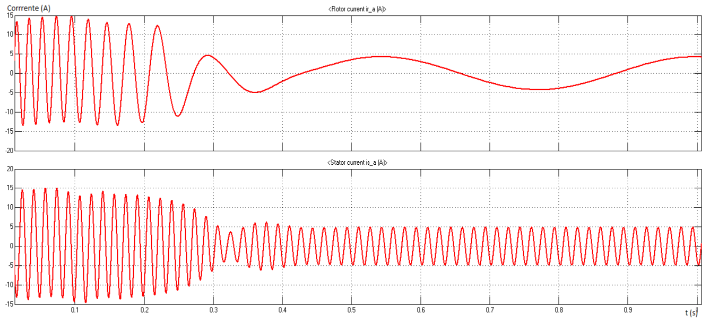

Figure 17. Rotor and Stator Currents x Time

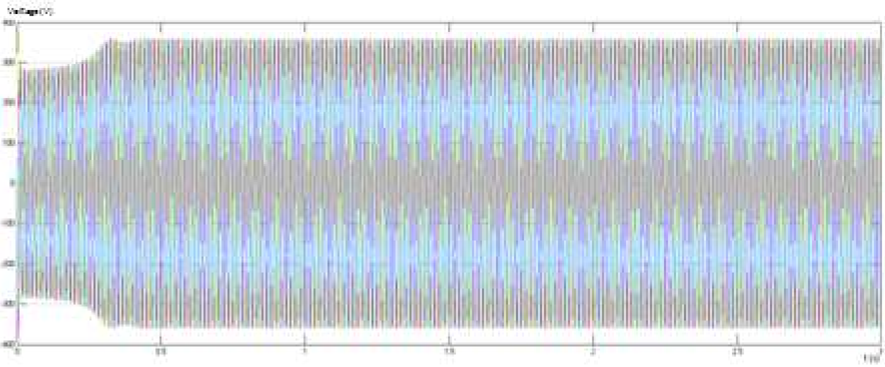

Figure 18. Load Voltage x Time

Now the analysis will be using the circuit of the Figure without the filter in frequency inverter output, and can be observed in the Fig. 19 the harmonic components of the stator and rotor currents. A filter appropriately dimensioned to system output soothing the effects relating to harmonics, which can be of higher amplitudes and can adversely impact the generation.

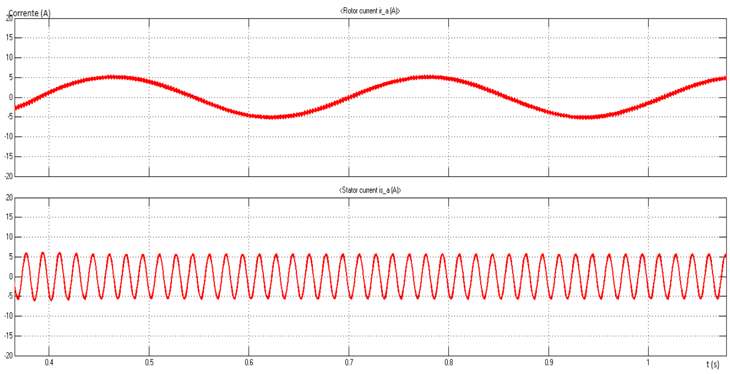

Figure 19. Rotor and Stator Currents x Time

5. Experimental Results

5.1. Generator connected to the single-phase electric grid by means of frequency inverter

In this configuration, the GI is connected to the single-phase electric grid by means of frequency inverter, and supplies power a three-phase resistive load. The control parameters of this test are the variation of operation frequency of a 5 CV motor (elementary machine) and the load voltage.

In Figure 20 and Figure 21 are shown the graphs concerned to active and reactive power, respectively, which are measured in the GI output terminals. The positive active power corresponds to the operation as a motor and the negative active power corresponds to operation as generator. All the reactive power is supplied by electric grid, because the GI not generates the reactive. In Fig. 22 is presented the frequency measured in the terminals of the GI, and it should be observed that in operation of the GI the frequency presents a variation within of the tolerance admitted by electric power system (60 ± 0,5 Hz). This GI frequency behavior as expected is kept by single-phase electric grid and does not need any complex controls of the frequency of an isolated generator.

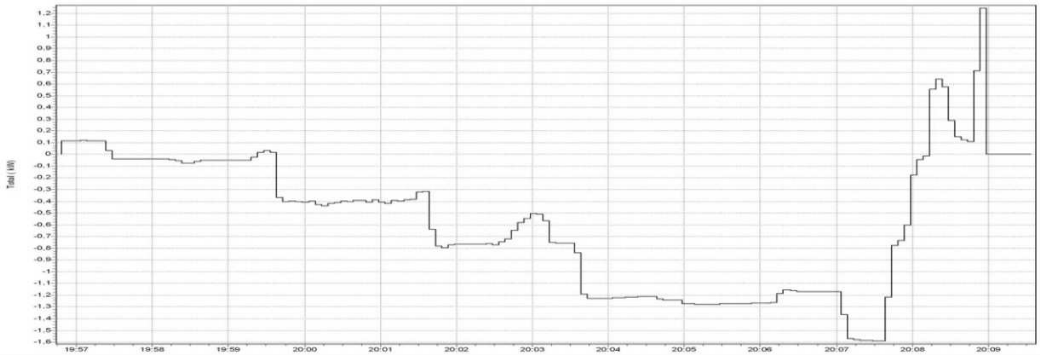

Figure 20. GI Active Power Connected to Grid and with Resistive Load x Time

Figure 21. GI Reactive Power Connected to Grid and with Resistive Load x Time

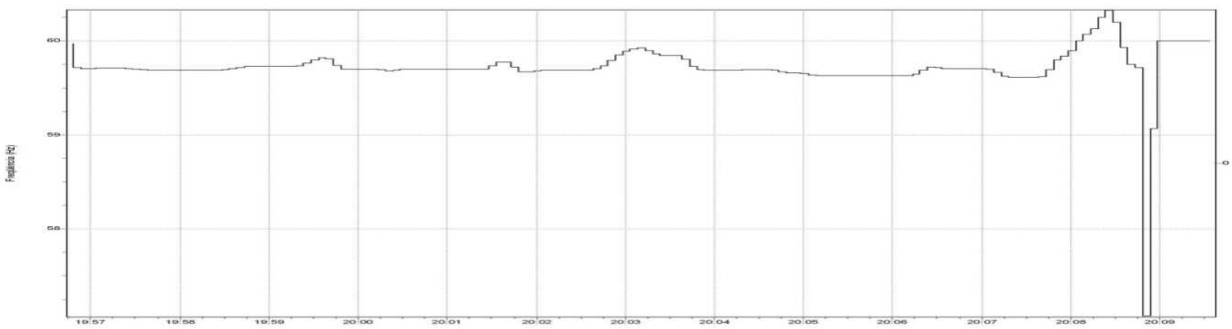

Figure 22. GI Frequency connected to grid and with resistive load

The voltage and current values of the generator terminals are presented in Fig. 23, and can be observed that the oscillations of the voltage and the variations of the current were absolute by normal.

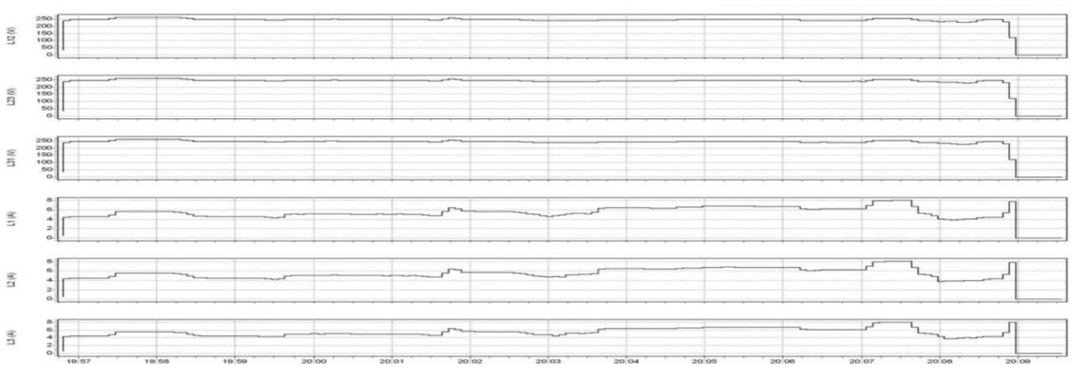

Figure 23. Voltage and currents on the generator terminals

5.2. Generator auto excited by capacitor bank

In this test, the three-phase induction motor of the 2 cv, 220V, 60Hz, 4 poles, of the experimental bench of the denominated “Laboratório de Otimização de Sistemas Motrizes” – LOSIM is disconnected of the electric grid and it will start to operate as a generator auto excited by capacitor bank. As expected, in this test is worth highlighting that, the generated frequency variation between 54 and 61 Hz and the voltage variation are above of the standard limit. The results of this test only confirm that in this configuration is needed to use voltage and frequency complex controls.

5.3. Generator connected to the single-phase electric grid by means of frequency inverter and with capacitor bank

In this case, the GI is connected to the single-phase electric grid by means of frequency inverter and it supplies a three-phase resistive load is associated with capacitor bank. As described in 4.1, the variation of frequency of the 5 CV motor (elementary machine) and of the load are the control parameters. The results are similar compared to 4.1, except that the reactive power of magnetization of the GI is now divided between the capacitor bank and the single-phase grid. It is necessary to emphasize that in this test were recorded several voltage trouble (overvoltage), such as shown in the Fig. 24, which probably are resulting of the interaction between the inverter harmonics and the capacitor bank.

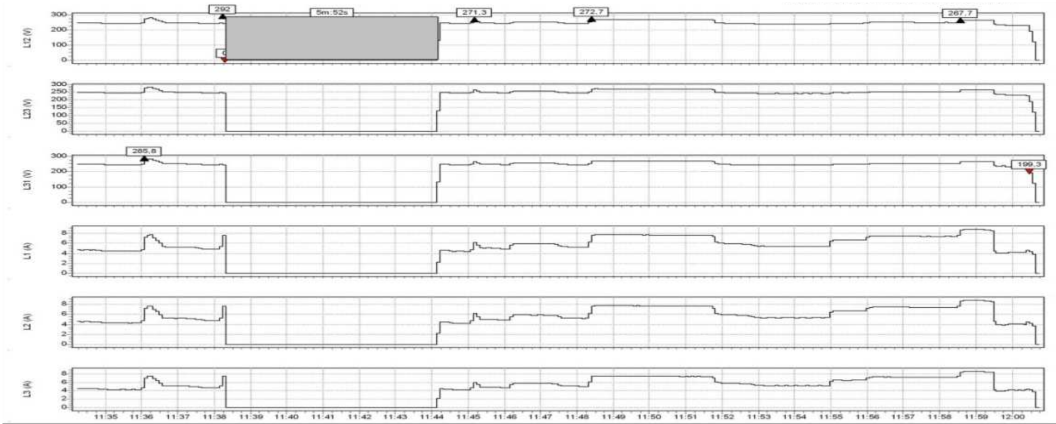

Figure 24. GI Voltages and Currents with Resistive Load and Capacitor Bank x Time

6. Conclusion

An analytical technique of the steady-state analysis of self-excited induction generator is presented in order to obtaintheperformancecharacteristicofthemachineusedinanisolateoperation. The search of the optimum value of the capacity makes possible the GI to obtain high performance while the voltage and the frequency are maintained within desired limits.

7. Acknowledgement

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8. References

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