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Capacitor Bank Sizing for Squirrel Cage Induction Generators Operating in Distributed Systems

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ABSTRACT The design of the capacitor bank to be placed with the squirrel cage induction generator, when operating with a direct connection to the distribution system, is performed from the value of the magnetization reactance of the machine. Based on the experimental procedures, the necessary reactive power is simulated according to the induction generator loading. Therefore, with the increase in generated active power, a larger portion of reactive is required. The simulation indicates the values of ideal capacitors. Thus, an analysis is made of which magnetization reactance factor is ideal for the capacitor bank design designated for the generator. The characteristic curve for capacitor bank sizing is related to the load torque loading depending on the active power generated. Thus, this work contributes to the analysis of the self-excitation curve of the three-phase induction generator that operates in parallel with the steady-state power distribution network. Obtaining the active power generated as a function of the absorbed reactive power required for induction generator magnetization can be found.

INDEX TERMS Electric machines, distributed power generation, generators, power generation, power generation economics.

I. INTRODUCTION

The sizing of capacitor banks for the three-phase squirrel cage induction generator, operating on an electric distribution network, is essential in order that payment is not charged for reactive excess on the contract of the generating unit with the local distribution electric utility. Therefore, in this study a contribution is sought through the sizing of the capacitor bank from a magnetizing reactance factor, according to the loading of the squirrel cage induction generator. In the present bibliography, one finds evaluations of capacitor banks on self-excited induction generator, i.e., operating in isolation [1]. In terms of the generator connected directly to the electric network at a constant speed, a detailed analysis is provided in [2], [3] of the power flow and the efficiency of the asynchronous induction generator connected to the electric network. In [4] a study is presented of the induction generator in steady state and the transient three-phase self-excited induction generator connected to the electric network, with emphasis placed on the dynamics of the generator. Another article directed toward the dynamics of the generator, however, without considering self-excitation is analyzed in [5].

The dynamic performance of an induction generator related to small hydroelectric connected to the grid considering self-excitation is presented by [6].

Regarding the induction generators operating in isolation and considering the capacitor bank to supply most of the reactive power of the isolated system, the following stand out [7]–[14].

In the studies in [7], [8], a self-excited induction generator voltage and frequency control is performed, a hybrid topology with switched capacitor bank and static distribution compensator (DSTATCOM) is proposed.

In [9], a structure voltage control of the self-excited three-phase induction generator is realized by means of the main capacitor bank and by a BOOST DC-DC converter.

It is highlighted in [10], [11] the importance of capacitor bank sizing in self-excited three-phase induction generators so that the minimum magnetization capacitance is adequately supplied. The voltage control must not provide reactive magnetization of the induction generator [12], [13], but the voltage control must be responsible for the reactive power demand that the isolated load requests.

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A technique of voltage and frequency control of the isolated induction generator is proposed in [14], in which a Capacited Excited Induction Generator (CEIG)-Matrix Converter (MC) is proposed.

The study of the minimum capacitance [15], [16] for effective voltage regulation in self-excited induction generators operating at variable speed driven by wind force is found. These studies aim to meet the generator excitation initialization requirements and the capacitor bank switching by converters seeking to maintain the steady state dynamics of the proposed isolated system.

In [17] proposes that the bank of capacitors used to self-excite the induction generator can improve the dynamic performance of induction generators operating by wind forces and connected to the grid. It is worth mentioning the importance of capacitor bank sizing.

The majority of the relevant studies concerning induction generators connected to the infinite bus are at variable speeds [18]–[27], with their focus on wind energy.

Noteworthy are the studies of the self-excited induction generator operating alone at variable speeds [17], [28]–[31], where its use depends directly on voltage control and frequency of the isolated load.

According to [32], in order that the squirrel cage induction generator is able to generate electricity, the induction generator needs elevated reactive energy. The asynchronous machine of the squirrel cage type is indicated for use as a generator at constant speeds, due to the low cost of the machine, and through its robustness can be operated while connected to the electric distribution network, independent of the primary source, should that be biogas, hydraulic force, natural gas, among others.

In light of the applicability of the squirrel cage induction generator, it becomes necessary a study into the sizing of the capacitor banks, when this generator is connected in parallel to an electric distribution system, aiming at the same load, while avoiding reactive power consumption from the network, but instead receiving energy from the capacitor bank.

By analyzing the load of the induction generator that is connected to the three-phase distribution network, it is possible to perform the ideal capacitor bank design for various charging situations. Facilitating any capacitor bank switching control techniques to be more effective. As far as the reactive is necessary to supply the magnetization reactance in the proper loads. In this work, the analysis is performed to analyze the reactive power required to generate 25%, 50%, 75% and 100% of the nominal active power. Subsequently, an analysis of the reactive power required for the generator is performed as a function of the loading of 15 to 100% of the active power of the induction generator.

II. INDUCTION GENERATOR OPERATING ON THE ELECTRIC NETWORK

In order that the asynchronous squirrel cage motor operates as a generator, the speed of the rotor should surpass the synchronous speed (of the electric distribution network) when acting as a generator, the end result is a negative slippage. This therefore means that the induction motor will produce a negative torque, and as such will operate as a generator [33]. With respect to producing energy, the induction generator should receive reactive energy, which may come from the power grid or from a capacitor bank, as illustrated in Figure 1. The equivalent circuit of the asynchronous machine acting as a generator is represented by Figures 2 and 3.

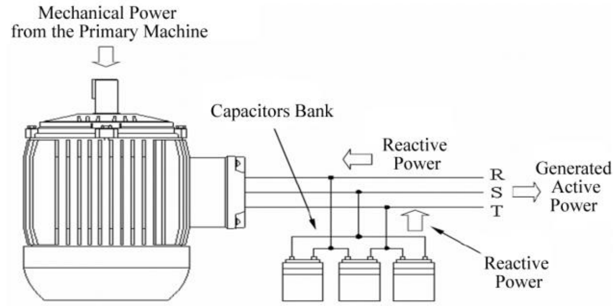

FIGURE 1. Capacitor bank connection on induction generator. Source: Extracted from [34].

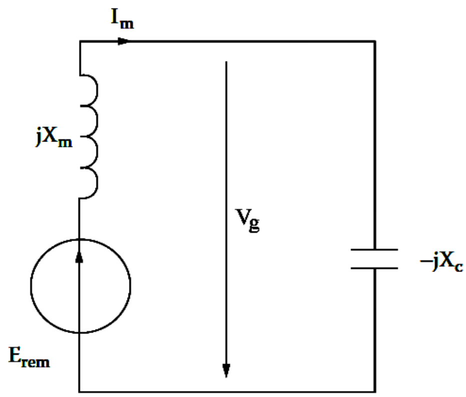

FIGURE 2. Simplified equivalent circuit for the induction generator with a capacitor bank. Source: Extracted from [35].

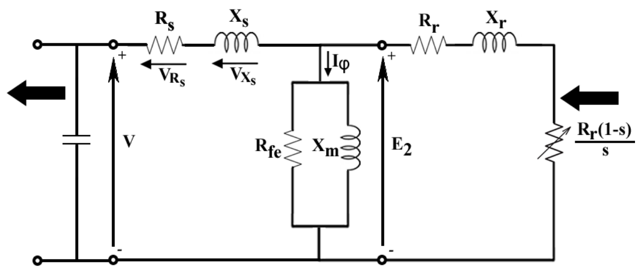

FIGURE 3. Single-phase equivalent circuit for the induction generator with capacitor bank. Source: Redesigned and adapted from [36].

The value of the voltage induced through air gap E2, is less than the voltage of the electric network (V). Here the machine is asynchronous operating as a motor, when operating as a generator the opposite happens, in order that it can maintain the same voltage as the electric network.

The data and parameters of the induction generator used in the experimental test and computer simulation are presented on Table 1.

TABLE 1. Data and parameters of the induction generator.

Data / Parameters	Values
Rated power	110/150 [kW/cv]
Rated voltage	380 [V]
Rated current	207 [A]
Connection	YY
Poles	4
Power Factor	0.87
Yield	0.95
Service Factor	1.15
Frequency	60 [Hz]
Stator resistance	0.0792 [Ω]
Rotor resistance	0.0457 [Ω]
Magnetizing reactance	3.6567 [Ω]
Core loss resistance	154.25 [Ω]
Stator dispersion reactance	0.4354 [Ω]
Rotor dispersion reactance	0.6528 [Ω]
Rotor inertia	0.8748 [kg.m²]

III. SIZING OF CAPACITOR BANKS

In cases where one does not know or have a magnetization curve ratio of the asynchronous machine, in order to find the value of the capacitor bank, one can calculate from the magnetizing reactance the minimum value that the three-phase reactive power will be, given by:

$$C_{\text{minimum}} = \frac{3}{\omega\, X_M} \tag{1}$$

Sizing by the magnetizing reactance should be used preferentially for squirrel cage induction generators with capacitor banks connected to the electric network. However, for generators that operate in isolation (self-excited), another technique should be applied in accordance with [36].

For the sizing of capacitor banks, the calculation for the minimum three-phase reactive power necessary to supply the magnetizing reactance of the induction generator is calculated by:

$$Q = 3\left(\frac{V_{phase}^2}{\frac{1}{\omega\, C_{\text{minimum}}}}\right) \tag{2}$$

However, the reactive power found through equation (2) is only to supply the reactive power requested by the magnetizing reactance, a new portion of reactive power is requested at the rate that generated active power increases. Therefore, in order to find this necessary addition of reactive power, one can simulate the generator with the plate data and parameters of the equivalent circuit. In this way, one finds the ideal value for the capacitor bank for the loading or generation of rated power.

Upon performing the sizing through the magnetizing reactance using (1), with the value present on Table I, along with the plate data of the induction generator, and applying (2) one obtains the three-phase reactive power minimum.

$$C_{\text{minimum}} = \frac{1}{377 \times\ 3{,}6567} = 7,2538 \times 10^{-4}\ [F]$$

$$Q = 3\left(\frac{V_{phase}^2}{\frac{1}{\omega\, C_{\text{minimum}}}}\right)$$

$$= 3\left(\frac{220^2}{\frac{1}{377 \times 7,2538 \times 10^{-4}}}\right) = -j39.707,95$$

$$Q = 39,708\ [KVar]$$

In accordance with the connection of the induction generator used (Table 1), a capacitor bank connected in delta (380V) should be used to perform the magnetization of the 40 kVar asynchronous generator. In the computer simulation, the results will be shown for the reactive power necessary for the sizing of the capacitor banks for 25%, 50%, 75% and 100% the active power generated, which is delivered to the distribution network.

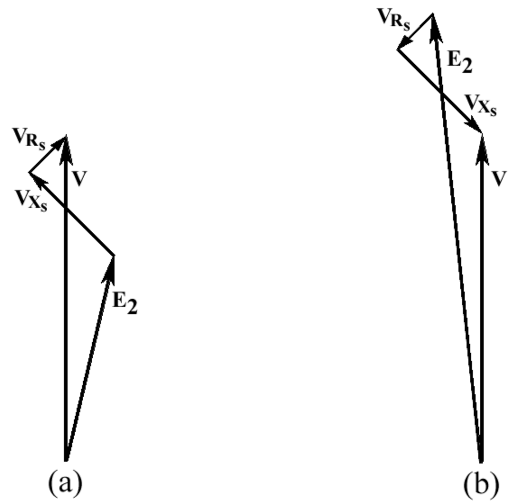

FIGURE 4. Induced voltage phasor diagram. (a) Motor action; (b) Generating action. Source: Redesigned and adapted from [36].

IV. MATHEMATICAL MODELING

The equations for the squirrel cage three-phase induction machine, on the domain dq0, are given through [33].

The electric equations are expressed by:

$$v_{qs} = r_s i_{qs} + \omega\lambda_{ds} + \frac{d\lambda_{qs}}{dt} \tag{3}$$

$$v_{ds} = r_s i_{ds} - \omega\lambda_{qs} + \frac{d\lambda_{ds}}{dt} \tag{4}$$

$$v'_{qr} = 0 = r'_r i'_{qr} + (\omega - \omega_r)\,\lambda'_{dr} + \frac{d\lambda'_{qr}}{dt} \tag{5}$$

$$v'_{dr} = 0 = r'_r i'_{dr} - (\omega - \omega_r)\,\lambda'_{qr} + \frac{d\lambda'_{dr}}{dt} \tag{6}$$

$$\lambda_{qs} = X_{ls} i_{qs} + X_m\left(i_{qs} + i'_{qr}\right) \tag{7}$$

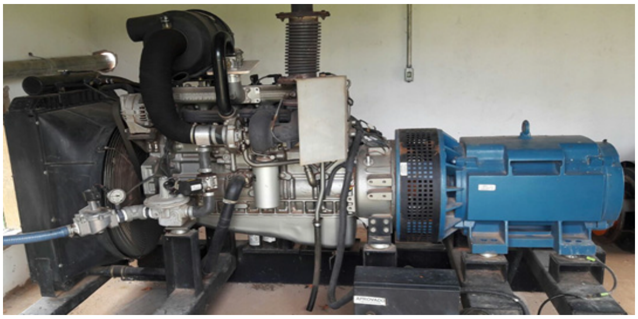

FIGURE 5. Experimental trial performed on the squirrel cage rotor induction generator of 150 hp.

$$\lambda_{ds} = X_{ls}i_{ds} + X_m\left(i_{ds} + i'_{dr}\right) \tag{8}$$

$$\lambda'_{qr} = X'_{lr}i'_{qr} + X_m\left(i_{qs} + i'_{qr}\right) \tag{9}$$

$$\lambda'_{dr} = X'_{lr}i'_{dr} + X_m\left(i_{ds} + i'_{dr}\right) \tag{10}$$

where,

$v_{qs}, i_{qs}, \lambda_{qs}$- Voltage, current and flux linkage stator for the quadrature axis (V, A, Wb).

$v_{ds}, i_{ds}, \lambda_{ds}$- Voltage, current and flux linkage stator for the direct axis (V, A, Wb).

$v'_{qr}, i'_{qr}, \lambda'_{qr}$- Voltage, current and flux linkage rotor for the quadrature axis (V, A, Wb).

$v'_{dr}, i'_{dr}, \lambda'_{dr}$- Voltage, current and flux linkage rotor for the direct axis (V, A, Wb).

r_s, X_{ls}- Resistance and leakage reactance for the armature windings (Ω).

r'_r, X'_{lr}- Resistance and leakage reactance for the rotor windings (Ω).

The mechanical equations are described by:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}\right) \tag{11}$$

$$\omega_m = \left(\frac{2}{P}\right)\omega_r \tag{12}$$

$$\frac{d}{dt}\omega_m = \frac{1}{J}\left(T_e - T_L\right) \tag{13}$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{14}$$

where,

T_e, T_L- Electromagnetic torque and the load torque (N.m).

ω_r, ω_m- Electrical angular velocity and the mechanical angular velocity (rad/s).

ω - Reference frame angular velocity (rad/s).

θ_m - Mechanical rotor position (radian).

J - Inertia of the rotor (Kg.m^2).

P - Number of poles.

V. EXPERIMENTAL AND SIMULATED RESULTS

A. EXPERIMENTAL TRIAL

An experimental reading was performed of the active power generated due to the necessary reactive energy absorbed from the squirrel cage rotor induction generator. Figure 5 shows the induction generator to the right, fed by a biogas combustion motor. The electric diagram of the installation is presented in Figure 6. Note that the capacitor bank is turned off, i.e., all

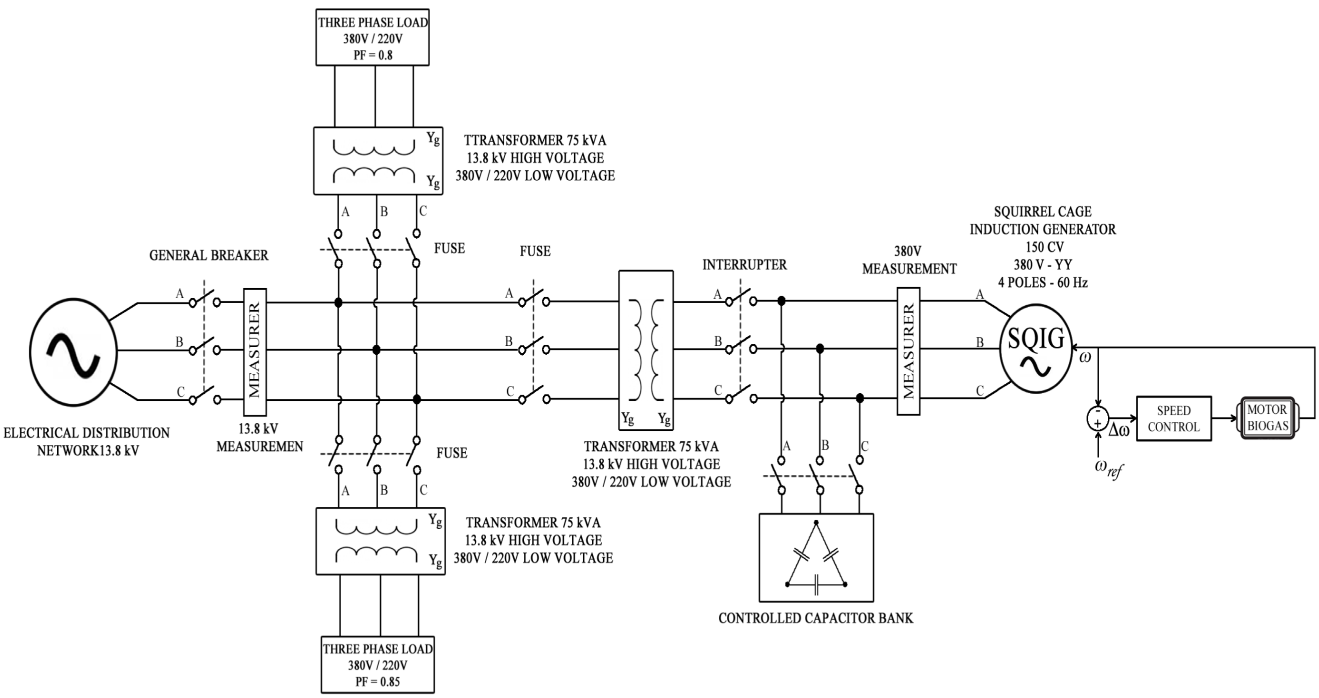

FIGURE 6. Electric diagram of the electric installation with the possibility of using the induction generator operating with the electric distribution network.

reactive energy from the asynchronous generator is supplied by the electric distribution network.

While the induction generator feeds to the electric distribution network approximately 40 kW, the generator needs approximately 43 kVar from the electric network, as noted from Figures 7 and 8.

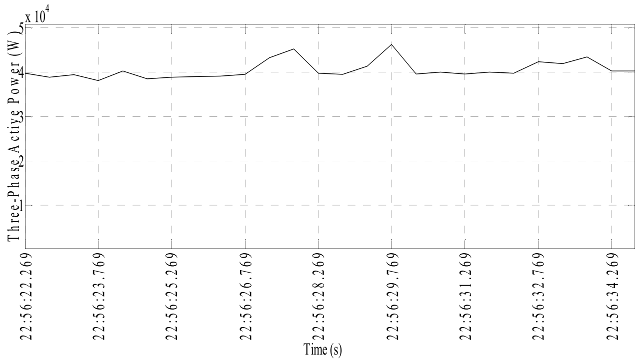

FIGURE 7. **Active power generated by the squirrel cage induction generator, experimental trial.**

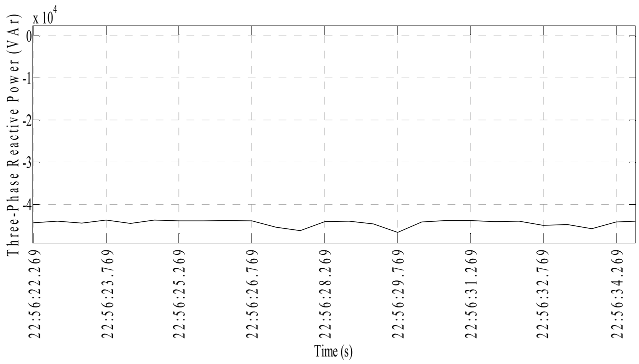

FIGURE 8. **Reactive power consumed by the squirrel cage induction generator, experimental trial.**

Figure 9 shows the frequency generated that is imposed by electric distribution network. Note that in order to generate active power at the same speed as the rotor of the induction generator, it needs to be above the electrical synchronous speed of the network.

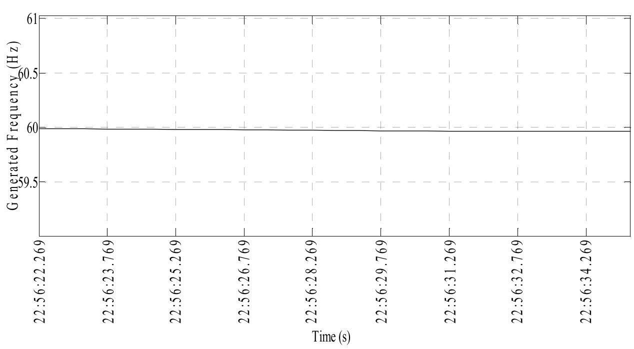

FIGURE 9. **Electric frequency of the squirrel cage induction generator, experimental trial.**

B. COMPUTER SIMULATION

The computer simulation was performed as presented by the electric diagram of the installation in Figure 6. For the load extracted from the experimental trial, the parameterization was performed from the computer simulation. Figure 10 and 11 respectively show the simulated active and reactive power.

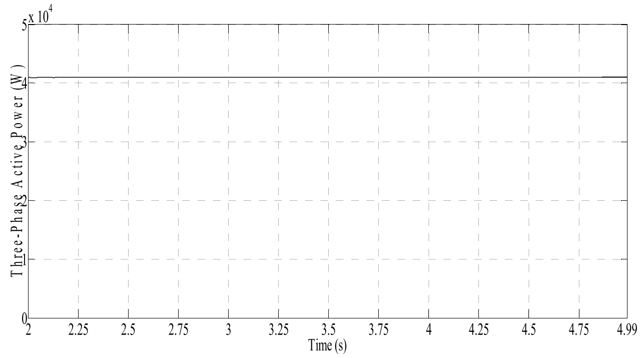

FIGURE 10. **Active power generated by the squirrel cage induction generator, computer simulation.**

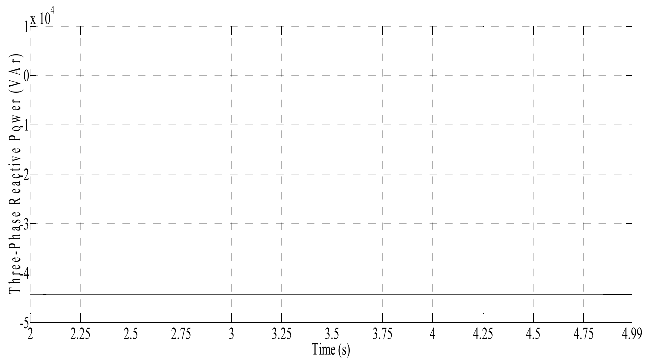

FIGURE 11. **Reactive power consumed by the squirrel cage induction generator, computer simulation.**

Noteworthy here is that the comparative values for the experimental and simulation results present a trustworthy validation. As previously stated, in order to generate active power the induction generator should be at an over synchronous mechanical speed. Figure 12 demonstrates the mechanical speed of the induction generator.

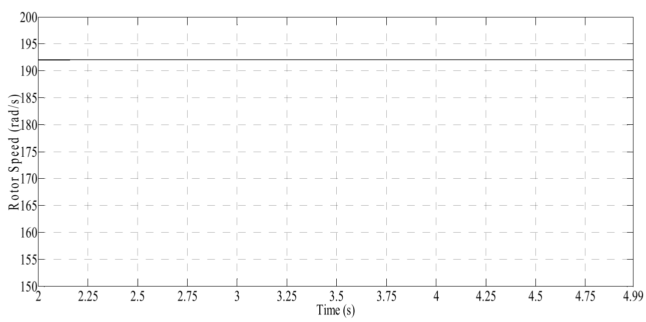

FIGURE 12. **Speed of the squirrel cage rotor, computer simulation.**

C. EVALUATION OF THE SIZING OF THE CAPACITOR BANK

In order to analyze the reactive power necessary from the capacitor banks, in accordance with the active power generated, two electric variables were plotted. Figures 13 and 14 show respectively, the relationship between the reactive power absorbed by the induction generator when generating 25% and 50% of its rated active power.

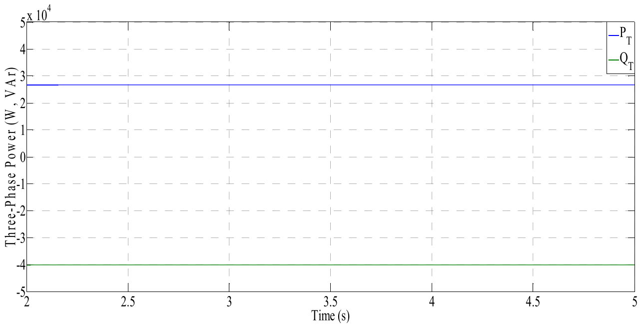

FIGURE 13. **Three-phase power at 25% of the generated active power, computer simulation.**

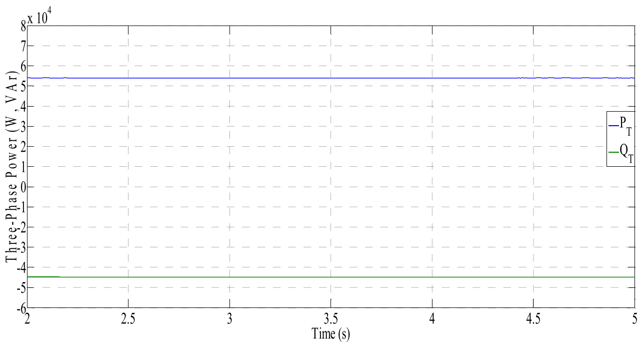

FIGURE 14. **Three-phase power at 50% of the generated active power, computer simulation.**

A comparison is given of the active and reactive power, as demonstrated in Figures 10 and 11. The induction generator has a load of approximately 38% of rated power. The value of the reactive power absorbed by the asynchronous generator, shown in Figures 13 and 14, is consistent with the reactive power value presented in the simulation for 25% and 50% of the active power generated in relation to rated power from the generator.

For the load used in the theoretical-experimental comparison, one should use the switching of the capacitor bank, which adds up to a three phase reactive power of 50 kVAr. The fact that the generator absorbs approximately 45 kVAr, the value of 50 kVAr on capacitor banks is the closest available on the market for performing the capacitor bank switching command, as illustrated in the electric diagram represented through Figure 6.

In light of the fact that the values are shown to be close to those of the experiments for 50% of generated active power, one obtains computationally, the relationship between the reactive power absorbed by the induction generator, when generating 75% and 100% of its rated active power, which are respectively included through Figures 15 and 16.

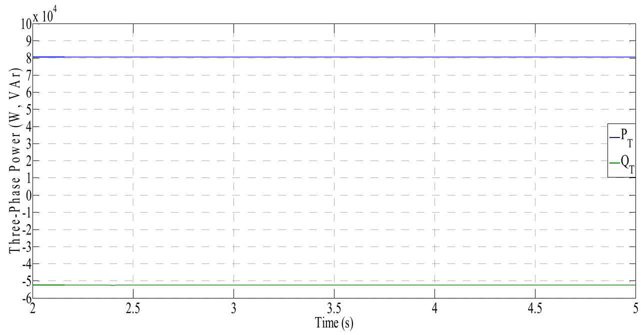

FIGURE 15. **Three-phase power at 75% of the generated active power, computer simulation.**

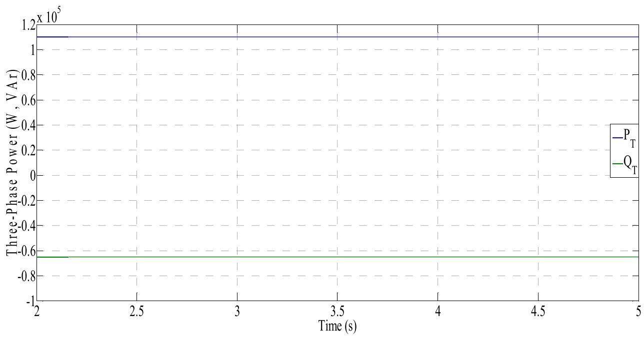

FIGURE 16. **Three-phase power at 100% of the generated active power, computer simulation.**

Note that one capacitor bank of power higher than 50 kVAr is necessary for 50% of the generated active power, and a capacitor bank of approximately 65 kVAr for rated operation.

Considering the period after the induction generator starts, the generated active power ratio and the reactive power absorbed by the induction generator are obtained. Figure 17 shows the ratio of active and reactive power as a function of a loading ramp up to 100%.

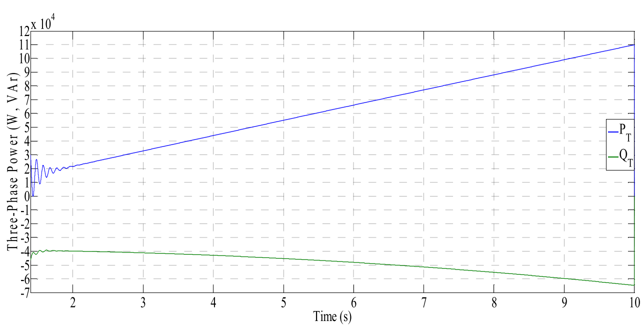

FIGURE 17. **Active and reactive power curve, ratio of active power generated by induction generator.**

From Figure 18, the power factor of the three-phase induction generator is plotted as a function of the load. Note that

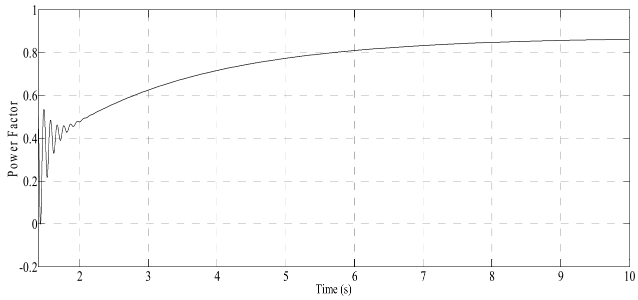

FIGURE 18. **Induction generator power factor according to load variation.**

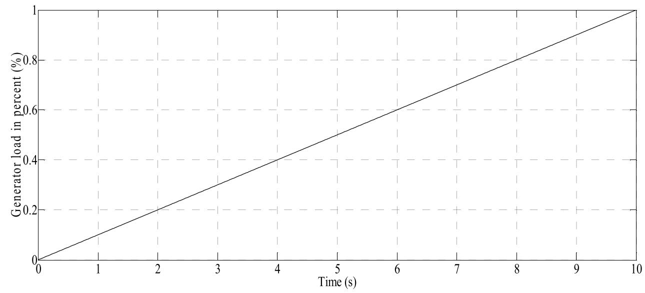

FIGURE 21. **Induction generator loading ramp.**

the power factor of the generator is changed according to the load of the three-phase induction generator.

All readings presented are restricted to the constructive characteristics of the induction generator. The readings were obtained from 380V measurement (the terminals of the three-phase induction generator) illustrated in Figure 6.

The rotor speed is shown in Figure 19 and the imposed load torque ramp is shown in Figure 20.

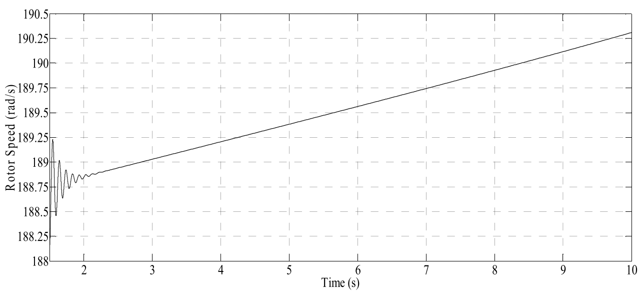

FIGURE 19. **Rotor speed in induction generator loading function.**

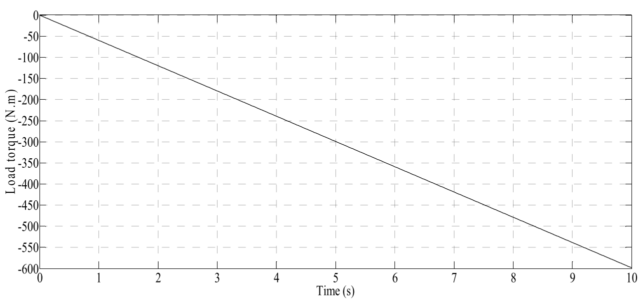

FIGURE 20. **Load torque ramp as a function of simulation time.**

The velocity curve shows that the results are correct because over time the loading increases, and necessarily the speed of the induction generator must be at super synchronous speed and increasing when the loading increases.

Figure 20 shows the torque ramp as a function of time, note that in 10 seconds the application of the initial to nominal torque is found. Thus it is also possible to present Figure 21, which is the loading ramp as a function of the simulation time.

Due to the start of the induction generator, it was considered an initial torque of approximately 15% in the time of 1.4s for capacitor sizing analysis which will be presented below.

The load torque is directly related to the torque required to generate power between 15% to 100% of the nominal active power of the induction generator.

Figure 22 shows the sizing curve of the capacitor bank to be switched (as shown in Figure 6) according to the three-phase induction generator loading.

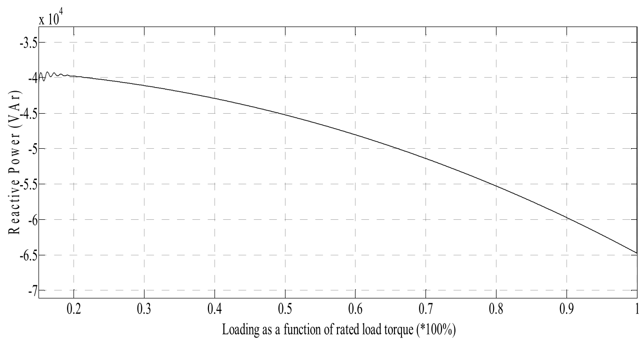

FIGURE 22. **Curve of the reactive power absorbed by induction generator as a function of load.**

The loading ramp in time can be performed at any simulation time, as long as respecting the loading limits of the squirrel cage induction generator. After obtaining the reactive power ratio absorbed by the induction generator as a function of the load given by Figure 22, the inclusion of the curve can be programmed in a supervisory system in any programming language.

Knowing the ratio of reactive power required to magnetize the induction generator, the curve can be included in the supervisory system and thus obtain the correct self-excitation without absorbing excess reactive power from the grid. This prevents companies investigating asynchronous generation from avoiding fines for exceeding contracted reactive power demand.

VI. CONCLUSION

From the data presented in this study, for the generation of rated active power from the induction generator, one should project a controlled capacitor bank of up to 65 kVAr. In this way, the switching command of the capacitor bank, can be performed according to the active power generated, thus avoiding the supply or consumption of surplus reactive power from the electric network.

In this way, one can calculate the approximate amount of reactive power needed to be sized by capacitor bank, which must be switched according to the load (generated active power) from the squirrel cage induction generator.

Under this analysis, the future perspective is for companies to know the characteristics of the reactive power curve absorbed as a function of the generated active power of the induction generator used. Knowing also the characteristic of the loads it is possible to perform the power factor correction itself by adding to the load curve (shown in Figure 22) the reactive power consumed by the loads.

Thus at the output or at the connection between the local load and the induction generator operating with the distribution grid, the power factor is close to the unit value. Without unnecessarily providing reactive power to the network that may come from capacitor bank oversizing. And without absorbing reactive power from the distribution grid due to capacitor bank undersizing.

From the market or industry perspective, the capacitor bank sizing analysis results in a more accurate system of supervision of the electrical parameters related to the energy bill. Being able to perform the logic of capacitor bank sizing and also of capacitor bank sizing with power factor correction in the capacitor bank switching.

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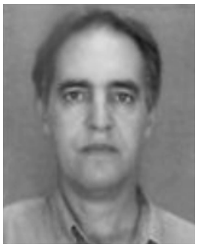

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