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A Proposal of Expansion and Implementation in Isolated Generation Systems Using Self-Excited Induction Generator With Synchronous Generator

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ABSTRACT This work presents a theoretical and experimental study of the self-excited three-phase induction generator in steady state, operating with a synchronous generator for use in isolated generation. Through the remoteness of many locations or because of the absence of an energy distribution network, difficulties exist in the supply of electric energy. The proposal contemplated herein can be applied in order to provide a well-adjusted voltage and reduce project costs in the expansion and implementation of isolated systems. That is, when taking into consideration acquisition costs of the asynchronous squirrel cage rotor machine in relation to the synchronous generator. The main contribution of this study is the making of the synchronous generator into a voltage regulator of the isolated system, in such a manner that the synchronous generator supplies the minimum of active power necessary, where a lower power generator is able to play the role of being the sole voltage regulator.

INDEX TERMS Induction generator, isolated generation, self-excited, synchronous generator, voltage control, voltage regulation.

I. INTRODUCTION

The study of of induction generator (IG) operation in parallel with the salient-pole synchronous generator (SPSG) for isolated generation applications presented herein, arises from the focus given to the development of power generation for isolated regions or those far from the power distribution network. It is fundamental to such regions that there exist simple techniques for reducing costs, when it comes to aspects such as equipment durability, low demand of technical labour maintenance and a reduction of project costs for the implementation of isolated energy generation systems or under its other denomination as islanded generation.

In this manner, the inclusion of asynchronous generation produces lower cost projects, since the acquisition and maintenance costs of the squirrel cage asynchronous machine (due to its constructive simplicity, robustness and excitation absence), are much lower than the synchronous machine [1]–[4].

The expansion for generation capacity in these remote areas can be realized through the employment of induction generators operating in conjunction with already existing synchronous generators. The only requirement is that one has control of the mechanical power, such as found in groups of diesel or combustion generators. If the mechanical power is not controlled, it is necessary to implement power electronics in order to dissipate the unused active power [5], [6], a subject which is not touched upon in this work.

Highlighted also in this study is the fact that although the application for distributed generation exists, the use of the three-phase induction generator is employed for the delivery

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of active power to the distribution network. When faced with loss of power supplied by the electric network, the generator stops generating power, this is due to the absence of reactive power, and consequently its demagnetization. Therefore, the idea arises of carrying out self-excitation, which guarantees the operation of the induction generator even under eventual outages on the part of the power network.

When there is no supply or power from the energy utility, the induction generator can operate in isolation and take control of the terminal voltage in a direct manner. This is obtained through the control of the excitation on the synchronous generator and frequency control performed by the first machine, whether hydraulic or thermic. The most interesting point in this situation is that with the possibility of an outage occurring from the power utility, there is a diesel synchronous generator at the ready to meet essential load needs, which makes the application of this theme extremely viable.

The disadvantage of the three-phase induction generator is its demand for reactive power, as it in itself cannot generate it. In the case of isolated systems the reactive energy source can come from capacitor banks or a diesel motor synchronous generator [7]–[9].

Various already published papers employ the static synchronous compensator (STATCOM) for the voltage and frequency control of the synchronous generator. These operate in parallel with the self-excited induction generator in isolated systems [5], [9], [10], as well as solely on the self-excited induction generator in the control of voltage and/or frequency [3], [11]–[17].

There exist various techniques employed for voltage control on the self-excited induction generator, among which one can highlight the shunt saturable reactor [18], Static Synchronous Series Compensator (SSSC) [19], Series and Parallel compensation [20], [21] and inductors switched by thyristors [22]. An experimental analysis of induction generators operating in parallel with synchronous generators in isolated systems is presented in [23], based on the influence of the use or not of the capacitor bank, observing the behavior of the synchronous generator excitation current.

When the subject arrives at controllable mechanical power, this study comes into its own, through presenting technical and financial advantages over those techniques already cited. Therefore, guaranteeing in this way a cost and maintenance reduction, as this only uses power electronics for the voltage regulator of the synchronous generator, in order to provide voltage control, in a manner different to the other aforementioned regulators. This makes the isolated generation system much simpler and robust, by providing validity to supply and greater reliability. Besides the fact that in short circuit and blackouts, only the generators suffer with these contingences, as converters for voltage control are not necessary, thus avoiding loss or partial burnout of this type of electronic equipment.

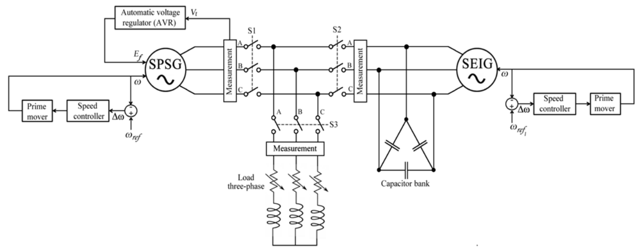

FIGURE 1. Schematic diagram of the synchronous generator and self-excited induction supplying an inductive load.

TABLE 1. Nameplate data and the parameters for the electrics and mechanics of the synchronous generator.

Parameter	Value
Nominal power	2 [kVA]
Nominal voltage	380 [V rms]
Nominal (full-load) current	5.2 [A rms]
Frequency	60 [Hz]
Nominal frequency	377 [rad/s]
Synchronous mechanical speed	1800 [rpm]
Nominal power factor	0.80
Nominal efficiency	0.85
Moment of inertia	0.0494 [kg.m^2]
Constant of inertia	0.438 [s]
Direct axis reactance, X_d	1.850 pu
Saturated direct axis reactance, X_{ds}	0.945 pu
Quadrature axis reactance, X_q	1.436 pu
Direct axis transient reactance, X'_d	0.370 pu
Direct axis subtransient reactance, X''_d	0.220 pu
Quadrature axis subtransient reactance, X''_q	0.200 pu
Direct axis short circuit transient time constant, T'_d	2.40 [s]
Direct axis short circuit subtransient time constant, T''_d	0.02 [s]
Quadrature axis short circuit subtransient time constant, T''_q	0.02 [s]
Leakage reactance, X_l	0.077 pu
Stator dc resistance, R_s	0.056 pu

II. MATHEMATICAL MODELLING

The references [24], [25] present the equations for the synchronous machine with salient poles and for the squirrel cage rotor induction machine.

III. THEORETICAL-EXPERIMENTAL ANALYSIS

The computer simulation and the experimental testing are performed based on the electrics diagram in Fig. 1, where the salient pole synchronous generator is connected in parallel with the self-excited induction generator coupled to an inductive load. Phase voltage and current readings are obtained in the locations indicated on the electrics diagram, with the aim of calculating the terminal voltage and the generated/consumed powers.

These currents can be decomposed into positive sequence, negative and zero according to Fortescue's transform, in Fig. 1.

TABLE 2. Nameplate data and the parameters for the electrics and mechanics of the three-phase induction generator.

Parameter	Value
Nominal power	3 [hp]
Nominal voltage	380 [V rms]
Nominal (full-load) current	4.96 [A rms]
Frequency	60 [Hz]
Nominal frequency	377 [rad/s]
Synchronous mechanical speed	1800 [rpm]
Ratio of start-up to nominal current	6.8
Nominal power factor	0.85
Nominal efficiency	0.793
Moment of inertia	0.0075 [kg.m2]
Constant of inertia	0.059 [s]
Protection	IP55
Category	N
Stator resistance, R_s	0.0441 pu
Stator reactance, X_{ls}	0.0257 pu
Rotor resistance, R_r	0.0399 pu
Rotor reactance, X_{lr}	0.0548 pu
Magnetizing reactance, X_m	1.2316 pu

TABLE 3. Electrical values for the parameters of the capacitor bank.

Parameter	Values	
	Capacitor B1	Capacitor B2
Nominal power	1,0 [kVAr]	1,5 [kVAr]
Nominal voltage	380 [V]	380 [V]
Frequency	60 [Hz]	60 [Hz]
Nominal frequency	377 [rad/s]	377 [rad/s]
Connection	Δ	Δ
Reactance	433,2 [Ω/phase]	288,8 [Ω/phase]
Capacitance	3x6,0[μF]	3x9,0 [μF]

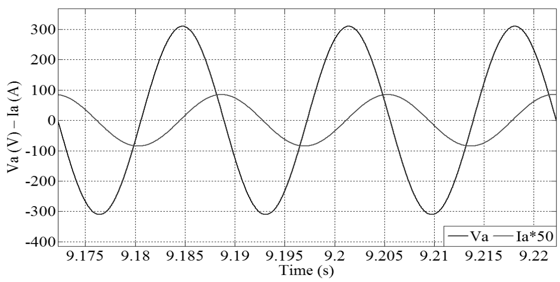

FIGURE 2. Phase voltage and current of the synchronous generator.

Tables 1, 2 and 3 present respectively, the parameters for the synchronous generator, induction generator and capacitor bank.

The results from the trial experiment, performed in the laboratory and with computer simulation for the theoretical-experimental analysis, are presented in the following.

A. COMPUTATIONAL SIMULATION

Represented in Fig. 1 is the computer model used for the theoretical study of the induction generator operation, where it operates concomitantly with a salient pole synchronous generator. First, close the S1 and S2 switches, in this manner, the synchronous generator operates with the induction generator empty. Shortly after, close the S3 switch, and the generators go on to supply an inductive load from an isolated system, the simulation has a ten second duration.

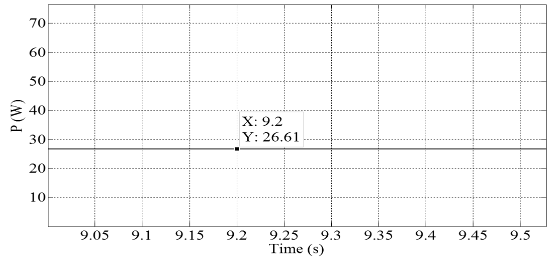

FIGURE 3. Active power per phase, delivered to the load by the synchronous generator.

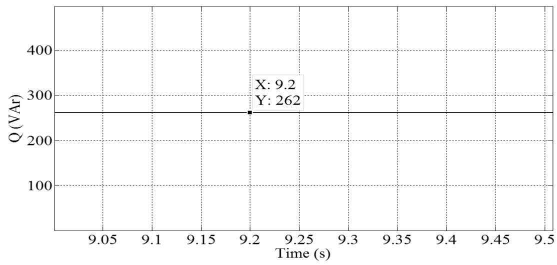

FIGURE 4. Reactive power per phase, delivered to the load by the synchronous generator.

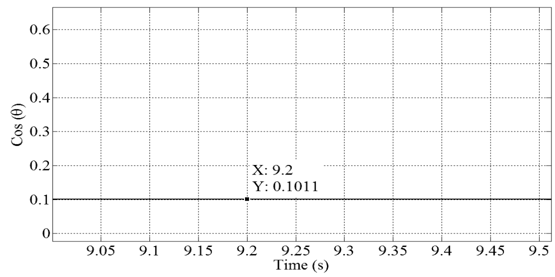

FIGURE 5. Power factor from the synchronous generator.

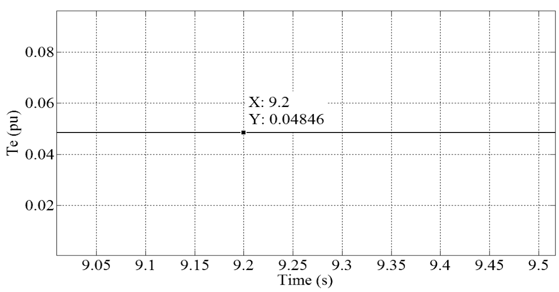

FIGURE 6. Electromagnetic torque developed by the synchronous generator.

The results of the simulation for the synchronous generator are presented by Figures 2 to 7.

Figures 8 to 12 present the simulation results for the self-excited induction generator.

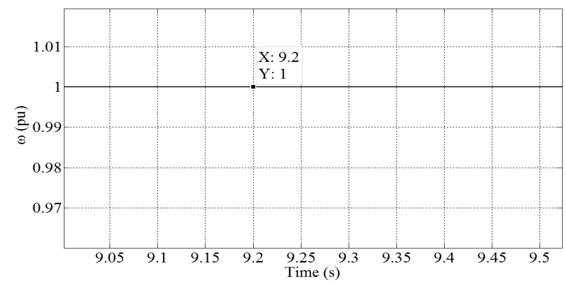

FIGURE 7. Mechanical velocity of the synchronous generator rotor.

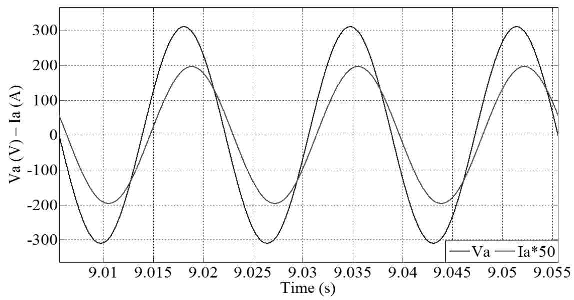

FIGURE 8. Phase voltage and current from the self-excited induction generator.

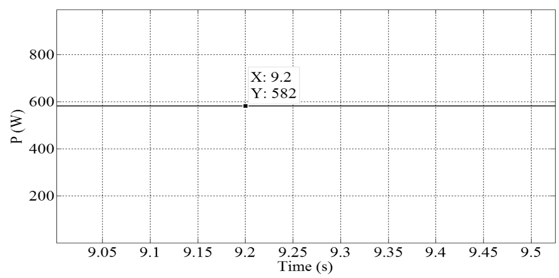

FIGURE 9. Active power per phase, delivered to the load by the induction generator.

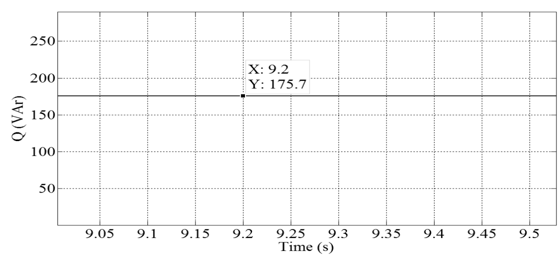

FIGURE 10. Reactive power per phase, supplied by the capacitor banks.

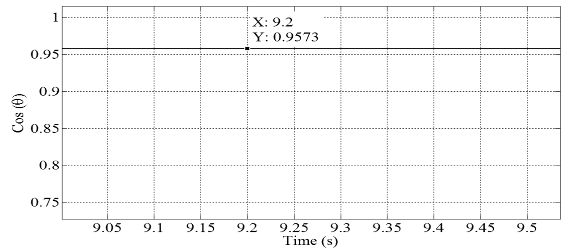

FIGURE 11. Power factor for the self-excited induction generator.

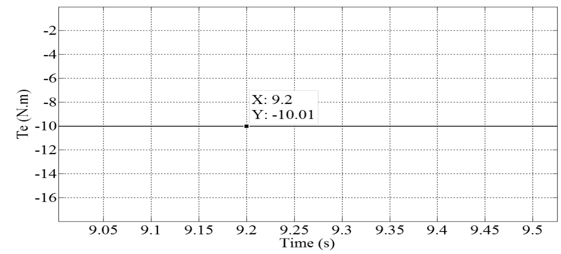

FIGURE 12. Electromagnetic torque developed by the self-excited induction generator.

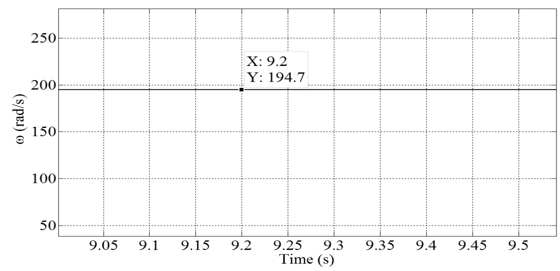

FIGURE 13. Mechanical velocity of the induction generator rotor.

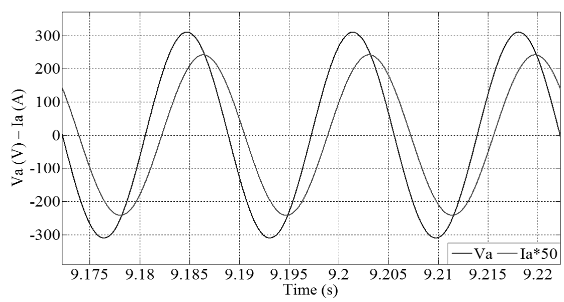

FIGURE 14. Phase voltage and current on the inductive load.

Note that the reactive power surplus from the induction generator capacitor banks flows to the load. Since the design of the capacitor bank is rated to voltage with nominal loading.

The results for the simulation on the load terminals are presented by Figures 14 to 17.

B. EXPERIMENTAL PROCEDURE

The trials were performed on a test bench. This bench was composed of a synchronous generator and a self-excited induction generator, both driven by direct current motors, as shown in Fig. 5. The diagram that represents the experimental procedure for the motor-generator groups is presented in Fig. 18.

Initially, the direct current motors are started up, at this moment the synchronous generator remains at the no load synchronous speed, and the induction motor goes over to a supersynchronous speed, thus operating as an induction generator. Therefore, after the S1 and S2 switches are closed

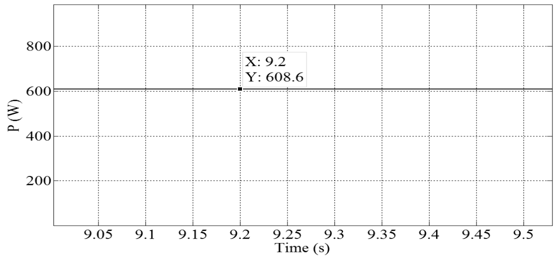

FIGURE 15. Active power per phase, consumed by the inductive load.

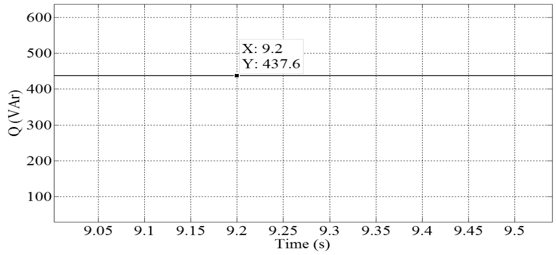

FIGURE 16. Reactive power per phase, consumed by the inductive load.

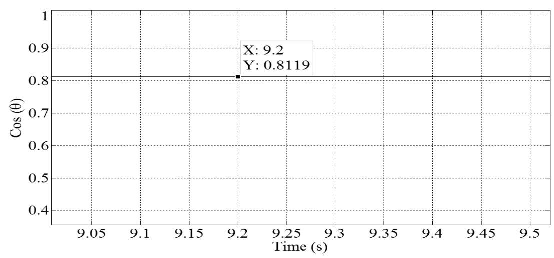

FIGURE 17. Power factor for the inductive load.

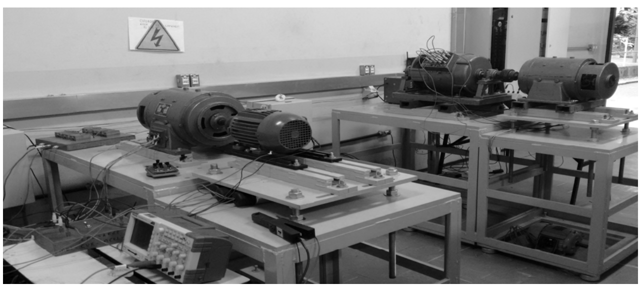

FIGURE 18. Mounting of experiment test bench.

and the generators are operating in parallel, switch 3 is closed, which supplies the load. The control of the terminal voltage is carried out through means of the excitation circuit control of the synchronous generator. The shaft torque provided by the primary machines is controlled in such a way that the induction generator supplies the maximum active power and the synchronous generator supplies the minimum power to the load.

The values for voltage, current and power factor are calculated taking into consideration harmonic distortion. Due in principal to the harmonic content caused by the spatial harmonics from the synchronous generator (constructive features), and by the magnetic saturation of the

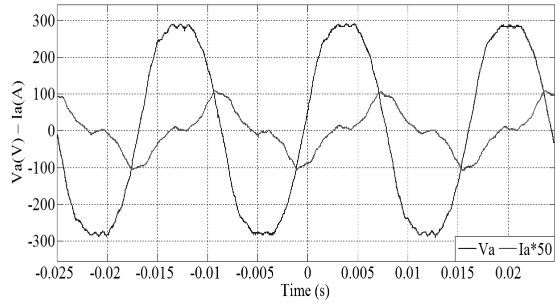

FIGURE 19. Voltage and current waveforms on the synchronous generator, supplying a three-phase load.

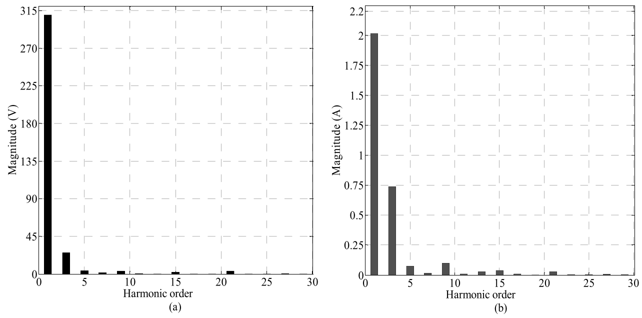

FIGURE 20. Harmonic spectrum of voltage and current waveforms on the synchronous generator. (a) Spectrum of voltage; (b) Spectrum of current.

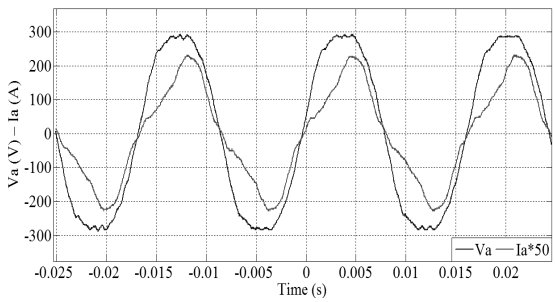

FIGURE 21. Voltage and current waveforms on the induction generator, supplying a three-phase load.

induction generator. The harmonic components for voltage and current (at peak values), can be seen in the harmonic spectrum presented below.

Presented in Fig. 19 are the waveforms for voltage and current on the salient pole synchronous generator, while its harmonic spectrum is presented in Fig. 20.

The voltage and current waveforms on the terminals of the induction generator are presented in Fig. 21. The harmonic spectrum is presented in Fig. 22.

Presented in Fig. 23 are the waveforms for voltage and current on the load, while harmonic spectrum is presented in Fig. 24.

C. THEORETICAL-EXPERIMENTAL RESULTS AND DISCUSSIONS

Through the voltage and current phase waveforms that were presented in the simulation and the experimental procedure,

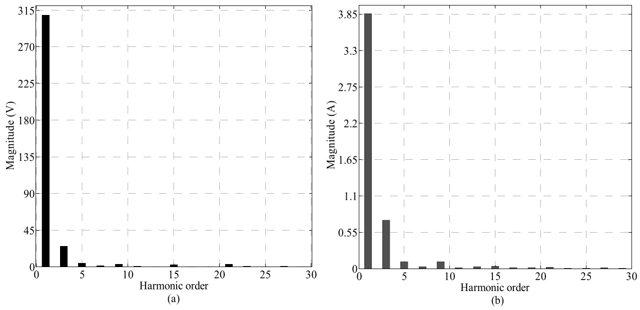

FIGURE 22. Harmonic spectrum of voltage and current waveforms on the induction generator. (a) Spectrum of voltage; (b) Spectrum of current.

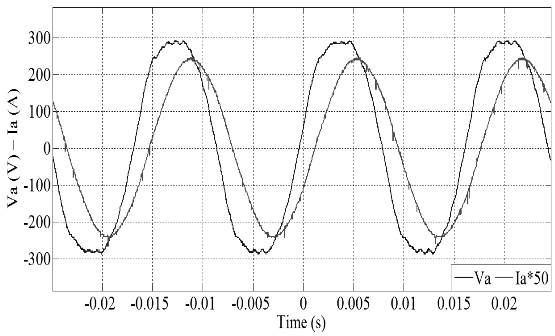

FIGURE 23. Voltage and current waveforms on the load.

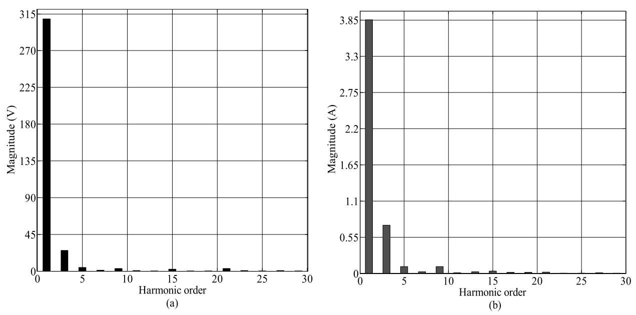

FIGURE 24. Harmonic spectrum of voltage and current waveforms on the load. (a) Spectrum of voltage; (b) Spectrum of current.

one obtains the results for the electrical parameters by means of a power analysis computer program. The mechanical velocity is obtained in the simulation and converted into rpm, in experimental fashion the velocity is obtained through the reading of the rotation of the generator rotors.

In order to calculate the voltage and current rms values, power factor and power generated from the experiments, while considering harmonic pollution, one uses the energy quality theory, which can be found in [26]–[28].

Tables 4, 5 and 6, present respectively, the comparison between the digital simulation and the experimental test, for the synchronous generator analysis on the induction generator load.

As seen on Table 4, the synchronous generator supplies the minimum of active power necessary, where it is responsible for the control of reactive power for the regulation of the voltage of the isolated system. The advantage found in this

TABLE 4. Theoretical-experimental comparison for the analysis of the synchronous generator.

Parameter	Simulated data	Experimental data
Active power	26,61 [W]	28,7 [W]
Reactive power	262 [VAr]	332 [VAr]
Power factor	0,1011	0,086
Irms	1,201 [A]	1,5218 [A]
Vrms	219,3 [V]	219,9784 [V]
Speed	1800 [rpm]	1804 [rpm]

TABLE 5. Theoretical-experimental comparison for the analysis of the induction generator.

Parameter	Simulated data	Experimental data
Active power	582 [W]	582 [W]
Reactive power	175,7 [VAr]	182 [VAr]
Power factor	0,9573	0,955
Irms	2,773 [A]	2,7769 [A]
Vrms	219,3 [V]	219,2647 [V]
Speed	1859 [rpm]	1857 [rpm]

TABLE 6. Theoretical-experimental comparison for the analysis of the load.

Parameter	Simulated data	Experimental data
Active power	608,6 [W]	608,6 [W]
Reactive power	437,6 [VAr]	437,6 [VAr]
Power factor	0,8119	0,8119
Irms	3,419 [A]	3,4135 [A]
Vrms	219,3 [V]	219,6185 [V]

is that one can have a larger induction generator and smaller synchronous generator, which will be responsible for only the control of reactive power. In such a setting, the fine control of the terminal voltage is performed on the load (as noted on Table 6). The aim is that the isolated system proposed herein has the smallest synchronous generator possible, as the synchronous machine already has a higher price than that of the squirrel cage asynchronous machine, thus decreasing the cost of implementation or expansion of a given island system.

Note on Table 5 that the excess reactive power on the capacitor banks of the induction generator flow to the load, this occurs due to the capacitor used being a little larger than necessary for self-excitation, as the values for the capacitor banks found on the commercial market possess restricted values. Any excess of reactive power in the design of the capacitor banks will be absorbed by the load if this is inductive, on the other hand it will be absorbed by the synchronous generator.

IV. CONCLUSION

The proposal behind this work-study is validated through the results seen from simulations and tests performed in practical laboratory tests, this methodology is a new suggestion for implementation in isolated generation on the user market that makes use of island systems.

Any variation in the loading, the terminal voltage of the synchronous generator and induction set, will be controlled by means of the voltage regulator of the synchronous generator and the frequency, through the adjustment of the speed regulators of the primary machines of both generators.

The application of induction generators operating concomitantly with synchronous generators possesses significant economic viability. The generator powers can be higher or lower than one another, the only demand made is that a portion of the apparent available power from the synchronous generator is reserved, in order to consume reactive power or supply it for voltage control.

The underpinnings of this work proved, the synchronous generator possesses the possibility of supplying the smallest portion of active power possible, thus leaving the greater part of the active power portion for the induction generator. A fact that makes the synchronous machine a generator or absorber of reactive power, thus developing the role of the system terminal voltage controller. In this manner, one can increase the capacity of electric energy generation of the asynchronous generator at the minimum level of the synchronous generator.

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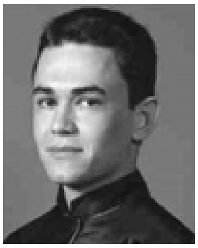

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