Design, Characterization, and Validation of a 1-kW AC Self-Excited Switched Reluctance Generator

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Abstract—The switched reluctance machine (SRM) has certain advantages such as robustness and the absence of permanent magnets which have encouraged its use in recent years. One of its applications is as a self-excited generator. This behavior is produced when a capacitor is series or parallel connected to each single phase forming a nonlinear pseudoresonant circuit. This application can be used in isolated sites with a wind turbine for energy generation. This paper describes a novel method used for the specific design of a 1-kW self-excited SRM for wind power applications based on torque considerations. The machine volume, dimensions, finite-element analysis, model verification, simulations, and experimental results are all presented.

Index Terms—Finite-element (FE) analysis (FEA), self-excited generator, switched reluctance generator.

NOMENCLATURE

\( \alpha_{pp} \)  
Angular pole pitch.

\( \lambda \)  
Phase-linked flux.

\( \omega \)  
Angular velocity in the rotor.

\( \phi \)  
Tooth core flux.

\( \theta = \omega t \)  
Angle position of rotor.

\( B \)  
Flux density.

\( D \)  
Rotor diameter.

\( D_s \)  
Bore diameter and stator diameter.

\( E_{cycle} \)  
Energy per cycle.

\( f_s \)  
Electrical frequency.

\( h_r \)  
Rotor pole height.

\( h_s \)  
Stator pole height.

\( i \)  
Phase current.

\( i_{max} \)  
Maximum phase current amplitude.

\( K_{ap} \)  
Ratio between scanned energy area and potential energy area.

\( l_g \)  
Air gap.

\( L_s \)  
Stack length.

\( L(\theta, i_f) \)  
Incremental inductance.

\( L_f(\theta, i_f) \)  
Phase self-inductance.

\( N \)  
Number of turns per coil.

\( N_p \)  
Number of phases.

\( N_r \)  
Number of rotor poles.

\( N_s \)  
Number of stator poles.

\( P \)  
Rated power.

\( P_{pitch} \)  
Linear pole pitch.

\( R \)  
Load resistance.

\( R_f \)  
Phase resistance.

\( S \)  
Tooth flux crossing area.

\( T \)  
Torque.

\( t_r \)  
Rotor pole width.

\( t_s \)  
Stator pole width.

\( V_c \)  
Capacitor voltage.

\( Y_r \)  
Rotor yoke height.

\( Y_s \)  
Stator yoke height.

I. INTRODUCTION

The switched reluctance machine (SRM) is an electromechanical structure with salient poles in the rotor and stator. It has certain advantages such as the absence of windings and permanent magnets in the rotor (it consists solely of the axis and the stack) which keep the cost of the materials low [1], [2]. A further advantage is its robustness, which enables its use as a generator in places with demanding operating conditions.

The torque on machines of this nature is produced by the tendency of the rotor to move to a position where phase inductance is maximized because the magnetic reluctance of the flux path is at its lowest [3], [4]. The phase inductance in this type of machine depends on the rotor position and the current in the active phase. This is a disadvantage because it produces nonlinear characteristics that make the machine difficult to model, characterize, and control. Simulation is an important tool which can be used to understand various major features in the design and effective implementation of the machine. Several simulation computer-aided designs (CADs) have been used for this proposed SRM: electric circuit simulators such as SPICE [5], [6], programming languages such as C, Fortran, or mathematical software such as Matlab [7] or Matlab/Simulink [8], [9].

The SRM has two operating modes: the “motor” mode, the most commonly used in this kind of machine, and the “generator” mode. In the former mode, the phase is excited when the inductance increases, while in the latter, the phase is excited when the inductance decreases. Possible applications are its use as a generator in dc systems using a wind turbine, in cars and aircraft [10]–[14] and as an ac self-excited switched reluctance generator (ACSRG) [15], [16], which is the focus of this paper. If the machine is working as a self-excited generator...
with a wind turbine, the rotor speed varies with the wind speed, and then, the oscillating circuit should hold its oscillating conditions. To avoid detuning, the capacitance should be modified accordingly [17].

An ac power generator incorporating switched reluctance generator is referred to in a U.S. patent [18]. However, the ac low-frequency wave shape is obtained by a high-frequency switched converter. Furthermore, self-excitation is only achieved in steady state, and an auxiliary power source is needed to initiate the generation operation. In our case, the ac wave shape is naturally obtained by the LC nonlinear oscillation without any switching elements. Additionally, an auxiliary power source for initiating the generation operation is unnecessary. The energy is obtained from the remnant magnetic field stored in the stator and rotor sheets. Another patent [19] claims a switched reluctance generator system with self-excitation. It has two buses named the excitation bus and power bus. Again, to initiate the generation mode, an external power source must be connected to the excitation bus to energize it. As a result, the switched reluctance generator system is self-excited after the generating action is initiated even during load faults and is furthermore capable of resuming normal generating operation following the occurrence of a short-circuit fault. A single phase with the same structure as that used in this paper is studied in [20], considering its operation under faults. The circuit needs to be described using mutual inductance among the coils because some coils are disconnected under faults. In our case, all the coils are included, and the symmetry is held. All the coils forming a phase are considered as a single entity whose parameters are defined at phase terminals. This simplifies the circuit equations.

Fig. 1 shows the electric model for an ACSR. The circuit equations are given by

\[
\begin{align*}
V_c - R_f \cdot i & = l(i, \theta) \cdot \frac{di}{dt} + i \cdot \omega \frac{\partial L_f(i, \theta)}{\partial \theta} \\
\phi(i, \theta) & = L_f(i, \theta) \cdot i \\
C \frac{dV_c}{dt} & = -(i + i_{\text{load}}) 
\end{align*}
\]

(1) (2) (3)

where \(l(i, \theta) = \frac{\partial \phi}{\partial i}\) represents the incremental inductance or the local slope over the linked flux curve.

In a nonlinear situation, the electromechanical interactions are given by

\[
T = \frac{d}{d\theta} (W_c - W_{\text{mag}}) \quad (4)
\]

\[
T_{\text{ext}} + T = J \frac{d\omega}{dt} + B \omega. \quad (5)
\]

The motor mode frame of reference shown in Fig. 1 was used to derive (5), where \(T_{\text{ext}}\) is the external torque coming from the turbine, \(W_c\) is the net electrical energy injected to the phase, \(W_{\text{mag}}\) is the stored magnetic energy, \(J\) is the inertia, and \(B\) is the viscose coefficient. In this case, a capacitor and resistor are parallel connected to each phase forming a nonlinear pseudoresonant RLC circuit, with variable inductance (dependent on the current and the rotor position) [21]. The nonlinear behavior of the magnetic saturation is responsible of the steady state that the oscillation reaches [22]. If the coincidence of the mechanical frequency of the rotor and stator teeth is close to the oscillation frequency of the resonant circuit, the energy in the circuit increases until a limit cycle is reached [21], [23]. The voltage produced has harmonic contents, being unsuitable for grid connection. However, using a simple ac–dc converter such as a diode bridge, it can be used to supply low-demand loads in isolated sites such as battery chargers. Various design methods oriented to a machine working in motor mode have been proposed in the literature. In this case, the design is based on torque considerations yielding the machine volume. In ac generator mode, an additional point of the design is the available energy area. Based on this consideration, a 1-kW ACSR has been designed.

Design procedures for SRMs are well established in the literature [4], [24]. However, they are focused on machines supplied from a dc bus, with unipolar phase-linked flux. In our case, the flux is bipolar because the phase current is alternative.

This paper first presents the design procedure of a 1-kW ACSR prototype, including sizing, finite-element (FE) analysis (FEA), and prototype validation. The rotor is inside the stator, although the procedure is easily adaptable for the opposite arrangement. The experimental results are then described and compared with the FE results. Finally, some conclusions are presented.

II. Prototype Design

The procedure followed for the prototype design is achieved in two stages: sizing and FE simulation. They are partly shown in [25]. The design objective is to validate this machine application as a self-excited ac generator. Sizing optimization is outside the scope of this paper.

A. Sizing

Selection of the Number of Phases: When an SRM is designed to operate in motor mode, various considerations are taken into account to select the number of phases. The machine must start independent of its initial position. Thus, a single-phase machine cannot start if the rotor and stator are aligned [24]. However, when operating in generating mode, this consideration can be ignored because the generator is a load pulled by the wind mill. Considering that the least number of phases implies easier modeling and control, the generator has been designed with a single phase \((N_p = 1)\), obtaining the generation behavior with only one capacitor section parallel connected to this phase.
Selection of the Number of Poles: With a single-phase machine, the number of rotor poles and stator poles is the same \( N_r = N_s \). The number of poles is related to the maximum velocity in the machine, in other words, to the rotor current frequency and the machine’s application. A high number of poles means higher production costs because there are more coils. Taking into account that the optimum speed for a 1-kW wind turbine is between 300 and 500 r/min, a six-pole design has been chosen, \( N_r = N_s = 6 \), or three pole pairs, both in the rotor and stator. The behavior of this machine implies an ac cycle every two teeth coincidences; thus, 20 Hz of electrical frequency is obtained when the rotor with \( N_r = 6 \) is rotating at 400 r/min. The next step is machine sizing.

Diameters and Stack Length: The ACSRG design is based on the rated power of 1 kW. The external volumetric limitations are given by the size of the nacelle where the generator will be located \((250 \times 250 \times 60 \text{ mm})\), the relationship between torque, power, and velocity, and the fact that torque is proportional to rotor volume as shown in (6). The constant of proportionality is based on the tangential force density on the rotor surface of \( 3.81 \times 10^4 \text{ N/m}^2 \). This value is typical for tangential force density in high-performance servomotors, as shown in [3]. Mathcad was used to implement the design providing an ordered procedure to determine each value for the different dimensions of the rotor and stator

\[
T \propto \pi \cdot (D/2)^2 \cdot L_s. \quad (6)
\]

The stack length \( L_s \) is defined as a multiple or submultiple of the rotor diameter \([24]\) given by (7). With \( k = 0.5 \), \( T \propto \pi \cdot (D/2)^3 \) is obtained. The rotor diameter is selected according to the external dimensions, bearing in mind that the machine could be fitted inside the nacelle

\[
L_s = k \cdot D. \quad (7)
\]

Accordingly, the value of the rotor diameter is \( D = 120 \text{ mm} \), and using (7), the stack length is \( L_s = 60 \text{ mm} \).

The air gap chosen is the minimum possible without hindering the production process. Considering the standard values for the air gap on machines of this size, \( l_g = 0.3 \text{ mm} \) is selected.

The bore diameter or stator inner diameter \( D_s \) is defined as \( D_s = D + 2l_g \), whereby \( D_s = 120.6 \text{ mm} \).

Stator and Rotor Pole Pitch: The angular pole pitch (\( \alpha_{pp} \)) is the angle between two rotor poles or stator poles \([24]\). This value is determined as shown in \([25]\). With \( N_x = N_s = N_r = 6 \), the angular pole pitch of the rotor and stator is \( \alpha_r = \alpha_s = 60^\circ \). On the other hand, the linear pole pitch is dependent on the diameter and is calculated using (8) where \( D_s \) is the rotor diameter or stator diameter, obtaining \( P_{pitch} = 62.83 \text{ mm} \) in the rotor and \( P_{pitch} = 63.14 \text{ mm} \) in the stator

\[
P_{pitch} = \frac{\pi D_s}{N_x}. \quad (8)
\]

Pole Width: Aligned and unaligned positions should yield far different values of phase-linked flux. In the unaligned position, the pole tips are separated by \( 20 \cdot l_g \), and as the rotor is wider than the stator pole by two air gaps, the stator pole width is calculated using (9) and the width of the rotor pole by (10)

\[
t_s = \frac{2\pi (D_s/2)}{2N_s} - 21l_g = \frac{P_{pitch}}{2} - 21l_g \quad (9)
\]

\[
t_r = t_s + 2 \cdot l_g, \quad (10)
\]

Turns Per Coil and Its Resistance: An operating speed of \( n = 400 \text{ r/min} \) is assumed, involving an electrical frequency of \( f_s = 20 \text{ Hz} \). This information is used to calculate the energy per cycle using (11) with \( P = 1 \text{ kW} \) and global efficiency \( \eta = 0.7 \) considering copper, iron, and electronic postprocessing losses.

\[
E_{cycle} = 71.43 \text{ J is obtained}
\]

\[
E_{cycle} = \frac{P/\eta}{f_s}. \quad (11)
\]

In terms of flux and current, the energy per cycle is given by

\[
E_{cycle} = 2 \cdot \lambda_{max} \cdot i_{max} \cdot K_{ap} \quad (12)
\]

where \( K_{ap} \) is the ratio between the leaf-shaped area in Fig. 2 and the rectangular area that confines it. \( K_{ap} \) relates specifications and electromagnetic parameters. Fig. 2 shows the semicycle trajectory of the \( \lambda-i \) variables when the machine is operating in steady state. The confining rectangle defines the machine size because it corresponds to the maximum linked flux and the maximum phase current. FE simulations suggest \( K_{ap} = 0.5 \). \( i_{max} \) is the current amplitude, and \( \lambda_{max} \) is the linked flux amplitude. From (12), the product \( \lambda_{max} \cdot i_{max} = 71.43 \). It should be noted that the maximum values of current and flux are not simultaneous. Assuming \( i_{max} = 10 \text{ A} \), the maximum linked flux is \( \lambda_{max} = 7.14 \text{ Wb} \).

On the other hand, the equation that defines the flux density in a stator tooth surface \( S \) is

\[
\lambda_{max} = N \cdot B_{max} \cdot S \cdot N_s \quad (13)
\]

where

\[
S = L_s \cdot t_s = 1525 \text{ mm}^2. \quad (14)
\]

From (13) and (14), \( N = 350 \) turns per coil is obtained to meet the specifications.

The coils are designed with rectangular section. The wire diameter is 0.9 mm. Each coil has 350 turns of two copper wires connected in parallel, with a copper filling factor of 0.5.
With a current density of $\delta = 5$ A/mm$^2$, the current phase is $I = 6.34$ A$_{\text{rms}}$. The resistance of each winding is determined using the equations for copper wire resistance. This provides a value of $R = 1.15$ $\Omega$. If the six coils are series connected, the total resistance is $R_{\text{total}} = 6.95$ $\Omega$ at 20$^\circ$C.

**Rotor Pole Height, Stator Pole Height, and Yokes:** The heights of rotor and stator yokes ($Y_r, Y_s$) and rotor and stator teeth heights ($h_r, h_s$) are calculated using the procedure shown in [25] and using (15)–(18). Fig. 3 depicts some of these variables:

$$h_r = \alpha_{pp} \cdot \frac{(\alpha_r - \beta_r - \beta_s)D/2}{2}$$

$$h_s = \left(\frac{D_s}{2} + 1 \text{ mm}\right) \tan\left(\frac{2\pi}{2N_s}\right) - \frac{t_s}{2} - 1 \text{ mm} + 3 \text{ mm}$$

$$Y_r = 1.2\frac{t_r}{2}$$

$$Y_s = 1.2\frac{t_s}{2}$$

TABLE I: SRM Design Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight</td>
<td>27.32Kg</td>
</tr>
<tr>
<td>Coil weight</td>
<td>1.005Kg</td>
</tr>
<tr>
<td>Air gap</td>
<td>$l_a = 0.3$mm</td>
</tr>
<tr>
<td>Stack length</td>
<td>$I_s = 60$mm</td>
</tr>
<tr>
<td>Stator inner diameter</td>
<td>$D_s = 120.6$mm</td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>$D = 120$mm</td>
</tr>
<tr>
<td>Rotor pole width</td>
<td>$t_r = 25.4$mm</td>
</tr>
<tr>
<td>Rotor pole width</td>
<td>$t_s = 26$mm</td>
</tr>
<tr>
<td>Stator pole height</td>
<td>$h_r = 41$mm</td>
</tr>
<tr>
<td>Rotor pole height</td>
<td>$h_r = 41$mm</td>
</tr>
<tr>
<td>Stator yoke</td>
<td>$Y_s = 16$mm</td>
</tr>
<tr>
<td>Rotor yoke</td>
<td>$Y_r = 16$mm</td>
</tr>
</tbody>
</table>

Table I gives a summary of the main SRM dimensions, and Fig. 4 shows the prototype. A scheme with the dimensional drawing can be seen in [25].

**B. FEA**

The FE method is a powerful electromagnetic simulation technique based on numerical analysis. Three-dimensional FEA (3-D-FEA) of the Opera tool from Vector Fields Software (3-D-FEA) provided by the Opera tool from Vector Fields Software was used to model the machine. Although 3-D-FEA takes a longer simulation time compared to 2-D-FEA, it has the advantage that end effects are included in the results leading to better accuracy particularly in the unaligned position. In this design, 3-D-FEA allows electromagnetic characteristics to be determined before manufacturing. Further, the data represented in Figs. 5–7 are used as tables for building a simulator.

A magnetic steel sheet has been used of $\varepsilon = 0.5$ mm thickness and 4 W/kg at 1.5-T 50-Hz grade M400-50A. Fig. 5 shows, for a single coil, the FE results obtained for linked flux as a
Fig. 6. Incremental inductance $l(i, \theta) = \partial \psi / \partial i$ versus rotor position for single tooth and different current values.

Fig. 7. FE results of torque versus position for single tooth and different current values.

function of phase current for different rotor positions between the aligned position (0°) and unaligned position (30°). For coil currents above 10 A, the machine saturates and is therefore not useful. However, analysis has been carried out for higher currents to expand the simulator bounds.

Fig. 6 shows the incremental inductance for several phase current values and rotor–stator positions. The incremental inductance represents the local slope of the flux-current curve at the instantaneous point of operation.

Fig. 7 shows, for a single tooth, the torque as a function of rotor position for different current phase values. It is shown that a peak torque of 29.58 N·m can be achieved with a phase current of $I = 27.66$ A. It is also noted that there is no torque in the aligned positions (0°) and at unaligned positions (30°).

Figs. 8 and 9 show the magnetic flux density distribution when the rotor is in aligned and unaligned positions, respectively. In both cases, the coil current is 6.91 A. On the left side of Figs. 8 and 9, there is a color-coded scale indicating the magnetic flux density. These figures show that, in the aligned positions, the magnetic flux density achieves values higher than 2.1 T, being higher than in the unaligned positions where the maximum value is about 1.2 T.

III. MODEL VALIDATION

Once the 3-D-FEA data are accepted, the machine is built and characterized. Some dimensions not relevant for 3-D-FEA simulation have been modified from a round shape to a square shape for manufacturing purposes. Thus, Fig. 3 outlines a square shape unlike the round shape shown in Figs. 8 and 9 used for 3-D-FEA simulation. This section describes the procedure followed to obtain the experimental flux-current curves equivalent to those shown in Fig. 5. The experiment uses the circuit depicted in Fig. 10.
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Fig. 10. Circuit used to obtain flux versus current experimentally.

The linked flux is calculated using (19). \( V_c \) is measured with a high-voltage differential probe and the phase current \( i \) with a hall probe. These signals are sent to a Dspace 1103 controller board where (19) is evaluated. The linked flux obtained by this method is affected by temperature variations in the value of the \( R_f \) phase resistor. To cancel this error, an algorithm is implemented for updating the resistance every oscillation cycle. This algorithm is described in [26]

\[
\phi = \int (V_c - R_f \cdot i) dt.
\]  

(19)

The circuit in Fig. 10 operates as follows: The capacitor is preloaded to dc voltage through a large resistor \( R \) by a dc variable voltage source. The phase is parallel connected to the capacitor by a triac. The selected voltage should be sufficient to reach the desired current through the generator phase.

When the triac is switched on, the stored capacitor energy is partly transformed into magnetic energy stored in the phase following a resonant oscillation that ends when the triac current goes to zero and naturally switches off.

The experiment is repeated for every desired rotor position. The experimental results give lower figures than the 3-D-FEA results, due to the unavoidable mechanical tolerances of a prototype. However, the differences are within 4%, as shown in Fig. 11. The measured data appear as FE data scaled down by 0.96.

![Fig. 11. Comparison between FEA analysis and experimental results of linked flux for aligned and unaligned positions for a single coil.](image)

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IV. EXPERIMENTAL AND SIMULATION RESULTS

This section describes the experimental measurements and simulations carried out to verify the machine’s operation as a self-excited generator. An ac capacitor set was arranged by dc-type electrolytic capacitors [17]. The equivalent capacitance obtained was 55 \( \mu \)F.

The coils can be connected in several arrangements: six series-connected coils, six parallel-connected coils, two parallel-connected groups of three series-connected coils, or three parallel-connected groups of two series-connected coils. In our case, the coils are connected in two groups of three series-connected coils where flux lines follow short flux paths. Both groups are then parallel connected. This configuration is used to divide the current between the two groups in parallel and to work with half of the achievable voltage when the six coils are series connected. This arrangement has been
selected for safety reasons and provides convenient values for output current, voltage, and power. The coil groups were parallel connected to the ac capacitor. Using this configuration, sustained oscillation is achieved with rotating speeds between \( n = 600 \text{ r/min} \) and \( n = 750 \text{ r/min} \). To shift the resulting rotor speed down to the optimum speed expected for a 1-kW wind turbine (between 300 and 500 r/min), the \( K_{ap} \) factor derived from Fig. 2 and assumed to be 0.5 should be decreased leading to more linked flux or turns per coil and a higher stator size.

The linked flux was measured using (19) being the same technique implemented in the model validation. To improve the power drawn, the experiments were carried out using the configuration in [27] where the triac is the control element used to delay the current setting and increase the energy area. Fig. 14 shows three experimental and two simulation results of the linked flux versus phase current. The limit curves for the aligned and unaligned positions are superimposed. In the first experiment (green curve), the rotor operated at 735 r/min, and the load resistor was 200 \( \Omega \). To compare results when the speed and load are changed, additional experiments were performed. In the second experiment, the load resistance was 180 \( \Omega \), and the speed was maintained. In the third experiment, the rotor ran at 710 r/min, and the load was maintained. The first and third experimental conditions were also simulated.

The figure shows that the second and third experiments yield less scanned area because the first experiment was tuned to be optimum. Comparing the experimental and simulation results, it can be verified that both match. This validates the 3-D-FEA modeling.

Figs. 15 and 16 present the experimental and simulation results when the machine turns at 735 r/min and the load is
Fig. 16. Phase voltage (in volts) and phase current (in amperes) in the ACSRG at 735 r/min with load $R_l = 200\ \Omega$.

Fig. 17. Torque versus time in the ACSRG at $n = 735\ \text{r/min}$ with load $R_l = 200\ \Omega$.

200 Ω. Fig. 15 shows the capacitor voltage, the capacitor current, and the load current waveforms. The capacitor voltage shows harmonics that cause its deformation. The voltage amplitude is $V_c = 670\ \text{V}$, and the load current amplitude is 3.35 A. The average power converted, obtained by the integration of the scanned area in Fig. 14, is 1115 W. The average load power measured at the load terminals is 978 W. These results indicate 87% efficiency in the energy transformation. Fig. 16 shows the experimental phase voltage and phase current. It can be observed that both signals are zero after the zero crossing of the current due to the control strategy implemented using a triac [27]. The phase current amplitude is 13.7 A. The phase voltage and capacitor voltage have the same amplitude. In this experiment, the copper losses are 91 W. Iron losses due to hysteresis can be calculated using the method described in [28]. Applying this method to the stationary state represented in Fig. 14 yields 45.5 W. Even with resistive loads, Fig. 15 shows a power factor $PF < 1$, because of the wave shape distortion. By applying fast Fourier transform (FFT) to the capacitor voltage in Fig. 15, $V_{cl\text{rms}} = 427.8\ \text{V}$ is obtained for the first harmonic and $V_{cr\text{rms}} = 436\ \text{V}$ for all harmonics, leading to a power factor $PF = 0.96$.

Fig. 17 shows the instantaneous output torque of the ACSRG and the equivalent torque in a three-single-phase stacked machine. The waveform is derived from instantaneous power and rotor speed. The instantaneous power is derived in turn from the rate of the scanned area in Fig. 14. The resulting average torque is 18.78 N·m. In the single-phase ACSRG, the torque has a high torque ripple that results in noise in the couplings because the torque is periodically positive and negative. With an equivalent three-phase ACSRG, the torque ripple is reduced, and the noise in the couplings can be practically eliminated [29]. Fig. 17 shows that most of the negative torques would be canceled, improving the average torque and lowering the torque ripple. Although it is outside the scope of this paper, some experiments carried out with the single-phase machine where the phase current is driven so as to avoid negative torque led to the noise in the coupling to be unappreciable.

Table II shows the main results of the three experiments. The experiments verify that the machine works as an ac self-excited generator achieving an output power fairly close to that specified at the design stage, although at a higher rotor speed than expected. However, the electromagnetic efficiency shows higher values compared to the global efficiency used in (11). Global efficiency is conservatively low to take into account further power postprocessing.

Self-excitation holds even after a short circuit because, in this case, the remnant flux density used to start the auto-oscillation reaches its maximum value. The experiments lead to the conclusion that, in isolated sites, stabilized dc energy distribution would be preferable. This can be accomplished by ac–dc converters. Due to the low magnetic coupling among phases, better efficiency could not be expected in multiphase machines. However, the inverter can save some electronic devices because they can be shared among nonconsecutive driven phases. Assuming local ac–dc conversion, a three-single-phase stacked generator would reduce the torque ripple compared to a single-phase generator.

### V. Conclusion

This paper has presented the design procedure for a 1-kW ACSRG. The output voltage shows harmonics limiting its use to low-demand loads. One possible application is as a battery charger in isolated sites where a wind turbine drives the ACSRG.
The design is based on torque and energy considerations. An FE simulation was performed to determine the system’s principal electromagnetic curves. This information is used to verify the correct design of the machine and can be additionally used to build a simulator.

In addition, once the machine has been built, its thermal profile is determined showing the operating temperature under different current phase conditions. The maximum operating temperature sets the upper limit of power losses and, indirectly, its rated power.

The machine was validated by comparing FE data with the flux versus current obtained experimentally. Differences between both data are below 4%, so it can be concluded that the machine meets the proposed specifications reasonably well. In contrast to generators, power losses are quite similar in both unloaded and loaded cases. This is because the oscillating cycle can be maintained independent of load circumstances. The thermal experiment has set bounds of 201 W for total losses. To shift the resulting rotor speed down to the optimum speed expected for a 1-kW wind turbine (between 300 and 500 r/min), the \( K_{ap} \) factor derived from Fig. 2 and assumed to be 0.5 should be decreased leading to more linked flux or turns per coil and a higher stator size.

Finally, some results show the machine working as an ac self-excited generator. The energy transformed is well understood by observing the cycle size of the linked flux versus the current trajectories for different load conditions. The influence of the load and the speed on the drawn power is also analyzed. The results verify that the generator almost achieves the 1-kW power specified at the design stage.

REFERENCES

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