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An Innovative Method to Increase Energy Efficiency of PMSM-Type Synchronous Motors

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This paper proposes reduction in the consumption of active electrical energy (kWh) by 67%, while maintaining the same mechanical work speed (RPM) at variable torque loads of water and similar fluids using the "Fan Affinity Law" in an innovative way in PMSM-type synchronous motors. The work is carried out comparatively between brushless asynchronous motors with starting loop (motor with a short-circuited loop) versus brushed asynchronous motors and PMSM-type synchronous motors without the need to use Variable Frequency Drives (VFD), simplifying the technology (electronics) and saving costs in an innovative way (*R*+*D*+*i*). The case study was developed on a design applied to a centrifugal air extractor/blower with PMSM/IPM type synchronous motor. The study focused on a specific bibliographical review of ecodesign and energy efficiency in refrigeration and ventilation systems, taking into account a couple of personal works and other general ones by various authors.

***Keywords*:** Energy efficiency, Single-phase active energy, kWh, Electricity saving, Fan Affinity Law

Introduction

Synchronous motors are a type of alternating current motors, in which the rotation of the shaft is directly related to the frequency of the supply current 50 Hz; the speed of rotation of the shaft is exactly equal to the synchronous speed of the rotating magnetic field of the stator. Its turning speed is constant and depends on the frequency of the voltage of the electrical network to which it is connected and the number of pairs of motor poles, and this speed is known as "synchronous speed". This type of motor contains electromagnets or permanent magnets in the rotor (depending on the type of synchronous motor in question) that create a magnetic field that rotates over time at the synchronous speed established by the stator magnetic field.

Historically, Friedrich August Haselwander's three-phase synchronous machine is recognized as one of the first inventions. In order to establish electricity, a way was needed to transmit power with as little loss as possible. This low-loss transmission is directly related to the voltage level: the higher the voltage, the lower the losses.

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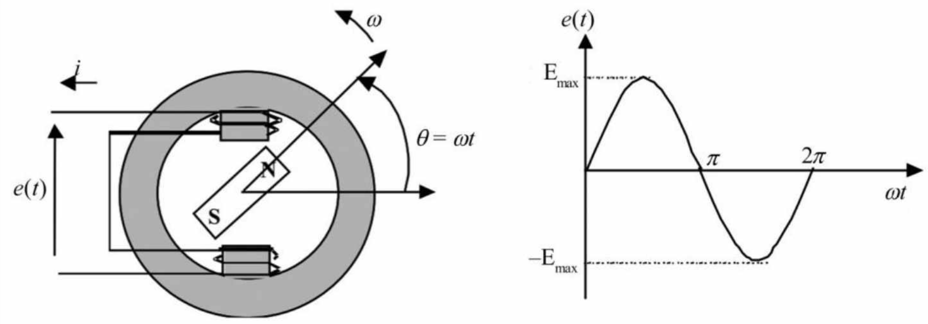
Haselwander addressed this problem early on. His first such generator came online in October 1887. He seamlessly integrated his invention into existing DC and AC systems. The patent application was filed in July 1887 and in 1889, the patent was granted.

In 1891, Haselwander was able to show his generator with a three-phase stationary ring armature and a four-pole rotor at the 1891 International Electrotechnical Exhibition in Frankfurt. But the prototype remained, which he then gave to the Deutsches Museum in Munich while he was still alive, where the system still stands today.

Consider a single-phase generator, as shown in Figure 1. The generator rotor consists of a permanent magnet (ferrite or neodymium) that generates a magnetic field B (1 Tesla = 10,000 Gauss) or constant magnetic induction vector and is rotating (thanks to an external driving machine) at an angular speed (ω), if we measure the voltage $e(t)$, the sinusoidal curve, as shown on the right of Figure 1, is observed.

Figure 1: Generator Uncoupled from the Grid



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The rotation of the rotor axis causes the flux linked by the stator coil to be variable so that the voltage generated at its terminals is due to the temporary variation of said flux, which is known as the Lenz-Faraday Law:

$$e = -N\frac{d\Phi}{dt} \qquad ...(1)$$

Faraday's Law states that any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil. No matter how the change occurs, the voltage will be generated. The change could be brought about by changing the strength of the magnetic field, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field, rotating the coil relative to the magnet, etc. The sense of the induced emf is given by Lenz's Law.

The magnetic flux (represented by the Greek letter fi: Φ) has the form:

$$\Phi = B.A.cos(\omega t) \quad ...(2)$$

The induced voltage is:

$$e(t) = K.B.\omega.sen(\omega t) = E_{max}.sen(\omega t) \quad ...(3)$$

where

ωt, is a design constant of the machine (it depends on the area of the section "A", the number of turns "N" and in general the geometry of the winding).

B is the magnetic field generated by the rotor.

ω is the mechanical speed of the rotor.

In the same way, other formulas to calculate the maximum voltage generated from the area (A) and the number of turns (N) of the copper winding (winding) of the stator with a magnetic field generated by permanent magnets of ferrite or neodymium are:

$$E_{max} = \omega.N.B.A \quad ...(4)$$

Being:

ω = Angular velocity (rad/s);

N = Number of turns;

B = Magnetic field (Tesla); and

A = Area (m^2).

Since the generator is a reversible machine and can be used as an alternating current generator or as a synchronous motor, when connected to the 220 V and 50 Hz electrical, home or commercial network. The speed of rotation of the axis is imposed by the network and the mathematical expression that relates the speed of the machine with the mentioned parameters is:

$$n = \frac{120.f}{p} \quad ...(5)$$

where

f = Frequency of the network to which the machine is connected (Hz);

p = Number of poles that the machine has; and

n: Machine synchronous speed (revolutions per minute).

Like the asynchronous induction machine, the stator of the synchronous machine is powered by alternating currents. This causes a rotating magnetic field to be produced which induces a magnetomotive force in the three-phase stator windings, given as:

$$F_e = \frac{3}{2}.F_m.\cos(\omega t - \theta) \qquad ...(6)$$

where

F_e is the magnetomotive force of the stator;

F_m is the maximum force equivalent to $N.I_{max}$ ("N" the number of turns of the stator coil and the "I_{max}" maximum value of the supply current);

ω is the synchronous speed; and

θ is the angle that determines the position of the air gap point where the magnetomotive force is being calculated.

A three-phase power supply provides a rotating magnetic field in a synchronous motor in the same way, as it does in an asynchronous induction motor (no difference). The clarification of the previous equation on a three-phase stator is because the consulted bibliography does not refer to single-phase synchronous stators, although their experimental behaviors are analogous. Industrial power requirements make it necessary for motors to be supplied with three-phase voltages.

The previous expression implies that the maximum of the magnetomotive force, when cos $(\omega t - \theta) = 0$, moves through the air gap at the speed $\theta = \omega$, that is, at the synchronous speed. This synchronous speed corresponds to the network frequency.

The synchronous machine rotor, is powered by permanent magnets (ferrite), which make the magnetomotive force constant and are fixed to it. Under these conditions, the rotating magnetic field of the rotor tends to align with the rotating magnetic field of the stator, causing the shaft to rotate at synchronous speed.

The expression of the instantaneous torque of the machine is given as:

$$T(t) = K_T.F_e.F_r.sen\,\delta \qquad ...(7)$$

where

K_T is a design constant of the machine;

F_e is the magnetomotive force of the stator;

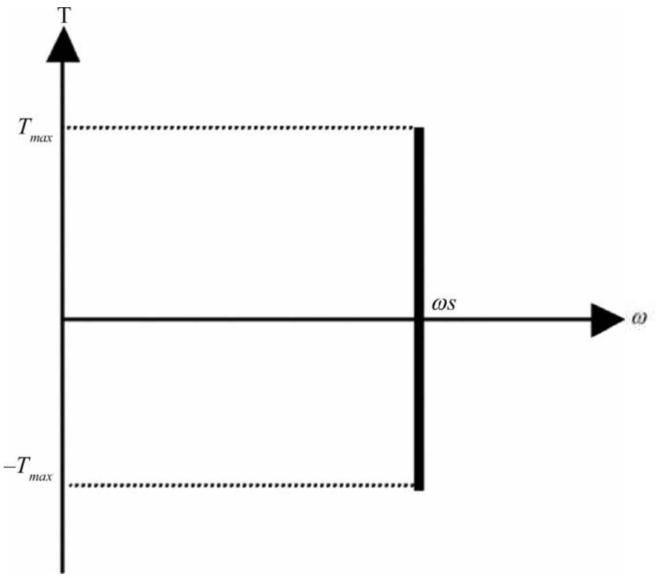
F_r is the magnetomotive force of the rotor; and

δ_r, delta is the angle between the magnetomotive forces of the stator and rotor.

It is feasible to verify that the existence of an average torque is subject to the condition that the angle between the magnetomotive forces (=delta) is constant, which is true since both magnetic fields rotate at synchronous speed.

In accordance with the above, in the case of the synchronous motor, the characteristic, torque speed is shown in Figure 2.

Figure 2: Torque Speed Characteristic of the Synchronous Motor



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$$\omega_s = 2.\pi.\frac{f}{p} \qquad \text{...(8)}$$

where

ω_s = Synchronous speed, in this case: 314.159 rad/s;

f = Network frequency, in this case: 50 Hz; and

p = Number of pairs of rotor poles, in this case: $p = 1$.

From Figure 3, it can be seen that the motor does not have starting torque, therefore it requires additional mechanisms that allow starting until it reaches synchronous speed. This is achieved through the "non-soft" start of the engine (at the beginning of its ignition), with the torque at 0.057 Nm; this is due to the need for the nominal active power of the starting static torque required by the mass of the load (radial blades connected to the

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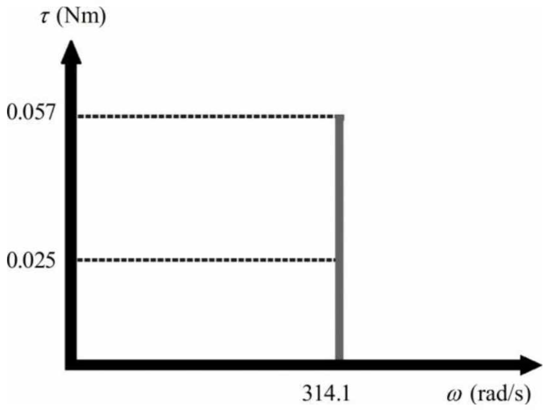
Figure 3: Torque-Speed Curve



Note: Synchronous Speed = 313.159 rad/s of the rotor as a function of the minimum torque of $\tau = 0.025$ Nm and the maximum torque of $\tau = 0.057$ Nm. Remembering that the rotation speed of a synchronous motor is directly proportional to the frequency of the network in which it is connected of 50 Hz, being: 314.159 rad/s, $\tau = 3000$ RPM.

rotor shaft) that must be accelerated. "Non-soft" starting does not save energy due to the initial power demand of the motor at start-up; but this only lasts for an instant (2-3 s); once the synchronous speed of 3000 RPM is reached, it is manually switched to Energy Efficiency mode. The change of mode to Energy Efficiency is achieved through the mechanical contacts or SPDT switch, for which the demand for single-phase active energy drops and the torque drops to 0.025 Nm maintaining 3000 RPM (now the motor works smoothly and the decibels drop).

Above a certain size, synchronous motors are not self-starting motors. This property is due to the inertia of the rotor; it cannot instantaneously follow the rotation of the stator's magnetic field. Since a synchronous motor does not produce an inherent average torque at rest, it cannot accelerate to synchronous speed without some complementary mechanism.

Large motors running on a commercial power frequency include a squirrel cage induction winding that provides sufficient torque for acceleration and also serves to damp oscillations in running motor speed. Once the rotor approaches synchronous speed, the field winding is energized and the motor is synchronized. Very large motor systems may include the so-called "pony" motor (or starting aid) that accelerates the unloaded synchronous machine before the load is applied. Electronically, controlled motors can be accelerated from zero speed by changing the frequency of the stator current with a Variable Frequency Drive (VFD).

We can identify starting problems and torque limitations by saying that single-phase synchronous motors can rotate freely in any direction, unlike the shaded-pole type, which provides a uniform starting direction, but this design will only work satisfactorily if the rest charge is close to zero and has very little inertia (as in the hands of a clock). Even by shaded pole motor standards, the power output of these motors is usually very low. Therefore, it is difficult to have a starting torque to overcome the stationary inertia of the stopped rotor blades and make them accelerate at the speed of the rotation frequency of the mains supply. Because there is often no explicit starting mechanism, the rotor of a motor running on a constant frequency power supply must be very light so that it can reach operating speed within one cycle of the mains frequency.

Within the family of synchronous motors, we must distinguish:

There are basically three types of synchronous motors: (a) reluctance motors; (b) hysteresis motors; and (c) permanent-magnet motors. We are particularly interested in the PMSM/IPM type motor (Permanent Magnet Synchronous Motor/Interior Permanent Magnet) or synchronous motor with permanent magnets (ferrite or neodymium) or with permanent magnets inside the rotor.

A PMSM uses permanent magnets embedded in the steel rotor to create a constant magnetic field. The stator has windings connected to an AC supply to produce a rotating magnetic field (as in asynchronous motor). At synchronous speed, the rotor poles are locked in the rotating magnetic field. PMSMs are similar to brushless DC motors. Neodymium magnets are the most commonly used magnets in these motors. Although in recent years, due to the rapid fluctuation in the prices of 14,000 Gauss Neodymium (Nd2Fe14B) magnets, many researchers have been looking for an alternative in 4,000 Gauss ferrite magnets. Due to the inherent characteristics of currently available ferrite magnets, the magnetic circuit design of these machines needs to be able to concentrate the magnetic flux; one of the most common strategies is the use of radial type rotors. Today, newer machines using ferrite magnets have lower power density and torque density than machines using neodymium magnets (but are less expensive).

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Most PMSMs require a VFD to get started. However, some incorporate a "squirrel cage" rotor for starting; these are known as online-booting or auto-booting PMSMs. They are typically used as higher-efficiency replacements for induction motors (due to the lack of slip), but must be carefully specified for the application to ensure synchronous speed is achieved and the system can withstand torque ripple during starting.

PMSMs are mainly controlled by "direct torque control" and "field oriented control". However, these methods suffer from relatively high torque and stator flux waves, and additionally require the use of VFDs which require complex and expensive electronics.

The use of VFD associated with PMSM motors makes the process much more complex and expensive (considering if they are neodymium magnets). Costs increase and become less competitive compared to other types of technologies.

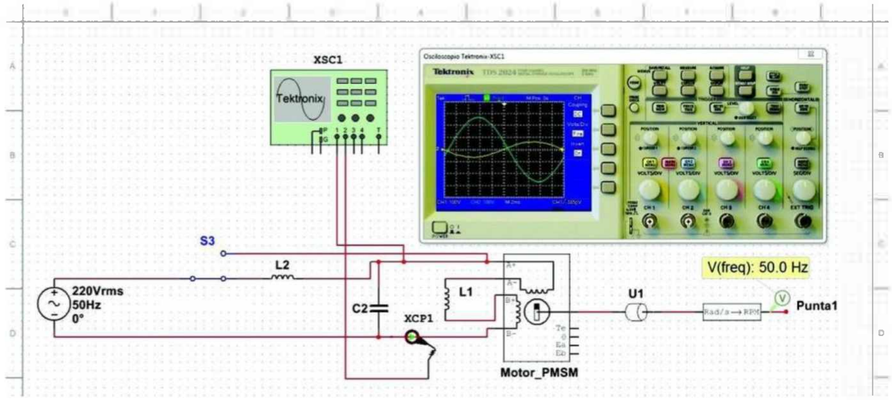
It is not the important to specify what a VDF consists of, but has only been cited to show in that this work it has been possible to eliminate it.

Methodology

Simulation by NI Multisim 14.0 Software (Canale, 2010a)

With the SPDT switch off, the THDv (voltage) is 20.5%, and it has a THD greater than 5%, which is not acceptable by the IEEE 519 standard. Voltage and current are observed on the oscilloscope. With the SPDT switch connected to the RCL circuit, the inductive-capacitive type low-pass circuit design that works analogously to a resistive-capacitive one has a THDv (voltage) less than 5%, which is acceptable, as per IEEE 519 Standard, The harmonics in the oscilloscope are reduced in the voltage waveform (Figure 4).

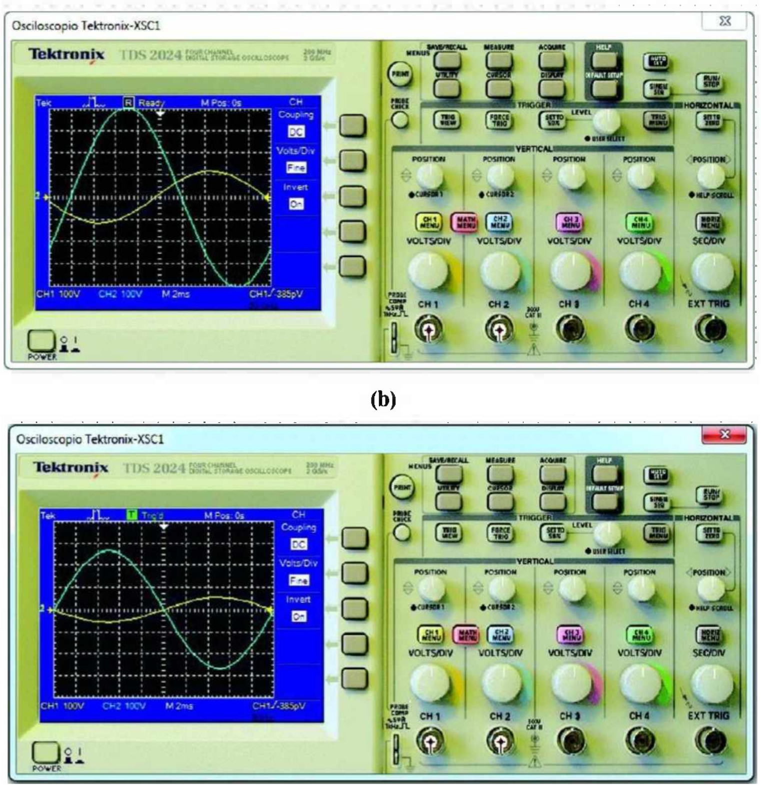
Figure 4: Computational Simulation of the Energy Efficient LC Circuit (Behaving like an RLC Circuit)



Note: Design of the LC circuit simulated by computer software, the circuit is turned on and off through the SPDT switch (S3), powered by a 220 (VAC) and 50 Hz single-phase alternating current emf source. It consists of a capacitive reactance (C2) and an inductive reactance (L2), which are responsible for processing the binomial expression of impedance. The capacitive reactance is obtained from a 3 μF capacitor connected in parallel to the two phases, and whose function is the power factor correction (cos de fi). The inductance of 1.5 Henry is connected in series to one of the phases of the emf source and whose function is to limit the passage of current or intensity (Amps) so that the single-phase active energy consumption decreases. Although the PMSM-type synchronous motor is simulated with a bipolar stepper motor (which would require a two-phase half-step driver), it still behaves analogously to a PMSM-type synchronous motor if it is powered by a current. Single-phase AC: it has an internal resistance (L1), so the entire system behaves like an RCL circuit (simultaneously filtering current and voltage harmonics: THD). The system is connected to a load (U1) that represents the impeller blades and there is a converter from Rad/s to RPM (Point 1: Punta 1) that displays the speed (frequency) in Hertz.

What is important is what happens in both cases, SPDT connector circuit “off” or “on”, in the probe (Point 1) that records the detail of the analyzer tip converting radians over seconds to revolutions per minute (Rad/s to RPM and in frequency (Hz), on the mechanical work done by the rotor on the centrifugal radial blades (load). It is observed that it rotates at 3000 RPM which is equivalent to 50 Hz, product of the frequency of the synchronous motor, regardless of whether the SPDT switch is “off” or “on” in Energy Efficiency (EE) mode; since in both cases, the frequency of the alternating current is always 50 Hz. For this reason, the motor, although its torque decreases, does not decrease its speed (Figure 5).

Figure 5: Phase Shift Between the Total Voltage and the Total Current of the LC Circuit



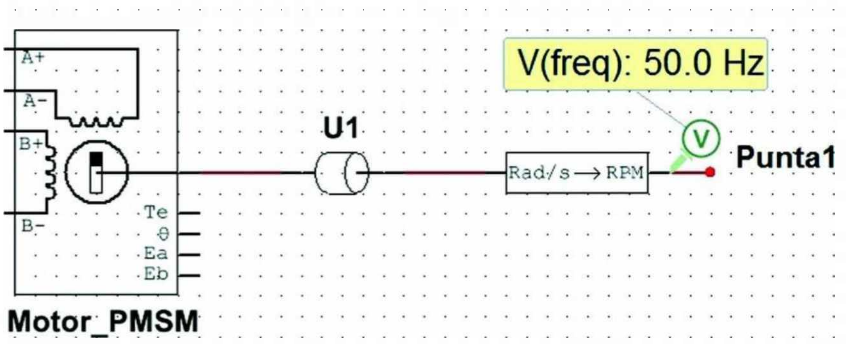
(a)

(b)

Note: The oscilloscope displays the phase shift between the total voltage and the total current of the LC circuit. It is an inductive circuit with a phase shift of 79.82º (with the energy efficiency circuit “off”), the voltage leads the current. When the energy efficiency circuit is “on” the phase shift between voltage and current is 90º and the voltage (Volts) continues ahead of the current (Amps). It is clearly observed how the voltage 220 V and the current 0.45 A in the image (a), decrease in intensity in the image (b) to 110 V and 0.10 A.

Enlargement of the analyzer tip converts revolutions per minute (RPM) to frequency (Hz), on the mechanical work done by the motor (from the frequency of the synchronous motor, fed with the single-phase power supply of 220 VAC and 50 Hz, without losing speed in the rotation of the rotor shaft, that is, without reducing the ability to perform mechanical work on the radial blades. It is observed that it rotates at 3000 RPM which is equivalent to 50 Hz (Figure 6).

Figure 6: Enlargement of the Analyzer Tip



In general terms, this innovation required taking into account the classical physical principles and the fundamental laws of electricity and magnetism such as the behavior of Ohm's law in alternating current and the Faraday-Lenz law and other known alternating current laws (Tipler and Mosca, 2006; Resnick *et al.,* 2007; Sears and Zemansky, 2009; and Serway and Jewett, 2008), to cite some examples that represent classical concepts on the theoretical and physical foundations of motors that explain their electromagnets operation, additionally, bearing in mind a bibliography on alternating current electrical machines published in Spanish (Fitzgerakd *et al.,* 2003; 1975; Chapman, 1987; Vargas-Machuca, 1990; Harper, 2006; Aller, 2008; Fraile, 2008; Mohan *et al.,* 2009; and Contreras and Sanchez, 2010) and another in English (CanMOST; NEMA; Best Practices on Motors; Thompson, 1895; EASA, 2003; Wildi, 2007; US Department of Energy; and IEEE, 2016). Likewise, attentive to the new and extensive specific bibliography on the approach to environmental problems and the so-called "carbon footprint", for Energy Efficiency (EE), the study has focused on a specific bibliographical review of ecodesign and EE in refrigeration and ventilation systems, taking into account a couple of personal works (Anderson, 2019a; 2019b; 2022a; 2022b; 2022c; 2022d; and 2022e) and other general ones and by various authors (Tesla, 1887; Zitron, 2007; Technological Institute of Canary Islands, 2008; Soler and Palau, 2009; Canale, 2010a; 2010b; 2013a; 2013b; 2014; 2015; Undersecretary of Energy Saving and Efficiency, 2017; and https://www.ni.com). Of the seven (7) levels of the so-called Ecodesign Strategic Wheel addressed by Eng. Guillermo Canale in the Ecodesign Postgraduate course of the Department of Industrial Design of the National University of La Plata, the one on which the central focus has been decided is on the structure level of the product and the reduction of the impact during use and the lowest consumption of active single phase energy of 220 V and 50 Hz available in the distribution system of the domestic and commercial electrical network in the Argentine Republic (nonindustrial three-phase). For which a high EE fan motor has been developed that saves single-phase active energy – kilowatthour (kWh) – and was originally intended for residential and commercial use.

Prototype Manufacturing Stage

The activities carried out for the construction of said prototype, of a centrifugal air blower for civil and commercial (nonindustrial) use, are the following:

According to National Association of Electrical Manufacturers (NEMA), the synchronous motor that was decided to be built is of PMSM/IPM type with ceramic magnets inserted tangentially in the rotor. The magnets are of ceramic ferrite with a magnetic field of 2,000 to 4,000 Gauss or 0.2 to 0.4 Tesla, the cheapest in the market, interacting with a stator of 482 Ω impedance (Z). In the future, it is planned to replace ferrite magnets with neodymium rare earth magnets (Nd2Fe14B) between 11,000 and 14,000 Gauss or 0.2 to 0.4 Tesla magnetic field strength, which is a key factor to increase EE.

The activities carried out for the construction of the prototype were: (a) coupling a synchronous or self-excited PMSM/IPM type motor obtained from the rotor-stator of a 65 W nominal power dishwasher electric pump connecting it to; and (b) the six radial blades of the impeller obtained from a rotor of a shaded-pole asynchronous motor (frager's turn or short-circuited turn) of a hair dryer. In this preliminary experimental stage, it was only thought of obtaining an experimental (verifiable) prototype, before obtaining a scalable minimum product for industrial production for single-phase commercial use.

The control that is achieved with the design of an LC circuit consisting of a capacitive reactance and an inductive reactance are responsible for processing the binomial expression of impedance ($Z = A + jB$). The capacitive reactance is obtained from a 3 μF capacitor connected in parallel to the two phases of the 220 V and 50 Hz single-phase Alternating Current (AC) emf (electromotive force) source and whose function is the power factor correction (cos de phi). The inductance is obtained from a coil analogous to a 48 Ω magnetic ballast connected in series to one of the phases of the emf source (electromotive force), whose function is to limit the passage of current or intensity (amp) that passes through it (due to its inductive reactance).

Finally, the conventional prototyping of a 220 V and 50 Hz 2-pole PMSM/IPM synchronous motor with a volute made of Glass-Fiber Reinforced Plastic (GFRP) composite material was completed, and six (6) blades of 105 mm in diameter, with the exact dimensions of a microwave fan.

Therefore, the invention belongs to the technical field of starting control in PMSM/ IPM electric motors and provides a method for the motor-system to control the starting of the outer radial blades of the centrifugal fan/air extractor and its subsequent EE.

The starting method includes: (1) a start at rated motor power of 17.7 W active power; and (2) a pass through to the EMI-LC filter activated by the SPDT switch at 6.6 W of power active in total that make up the RLC set (capacitor + inductor coil + motor stator).

Work Materials

The work materials used correspond to the following test bench.

The basic equipment used for analysis of non-sinusoidal voltages and currents is the oscilloscope. The waveform graph on the oscilloscope provides immediate quantitative information about the degree and type of distortion; sometimes cases of resonance are identified through the visible distortions that are present in the voltage and current waveforms. No harmonic distortion is observed.

The Crest Factor (CF) is an indication of harmonics caused by the nonlinear load connected to the power control of the inductive-reactor in series to one of the phases, which demands a distorted or non-sinusoidal current. For current and voltage measurement, the CF value is 1.9.

The magnification of the image observed in the oscilloscope, the wave signal, is perfectly sinusoidal when it is not connected to the EE system. No harmonics (THD) is observed. Peak voltage 600 ($voltios_{pico}$) y 216 (V_{rms}) and 50 (Hz).

The basic equipment used for analysis of non-sinusoidal voltages and currents is the oscilloscope. The waveform graph on the oscilloscope provides immediate quantitative information about the degree and type of distortion; sometimes, cases of resonance are identified through the visible distortions that are present in the voltage and current waveforms. No harmonic distortion is observed.

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The CF value data was calculated with the following formula:

$$CF = \frac{V_{peak}}{V_{rms}} = CF = \frac{420\left(Volts_{peak}\right)}{2} = 210\left(Volts\right) \rightarrow \frac{210\left(Volts\right)}{107.8\left(Volts_{RMS}\right)} = 1{,}948 \qquad \text{...(9)}$$

After its simulation in three dimensions (3D), we proceeded to the physical construction of the product and its parts. 3D simulation is generally used as a procedure, among other things, to save money and experimental time, to correct variables such as dimensions, volumes, sizes, assemblies between parts and pieces, form and function relationships, aspects that are not only functional and aesthetic, but also ergonomic, etc. This is analyzed in the next stage of manufacturing the prototype.

The central idea of technological innovation (*R+D+i*) of EE is inspired by line no. 15 of invention patent no. 381968 of the electrical engineer Nikola Tesla, dated May 1, 1888 (inventor of the alternating current system that today is used throughout the world), in effect as cited in point No. 15 of the aforementioned patent: "15: Such solution, mainly, requires speed uniformity in the motor regardless of its charge within its normal working limits" (Tesla, 1887: US381968A) (Technological Institute of the Canary Islands, 2008).

But the patent of the invention, here it was innovated, not in conventional asynchronous induction motors (as originally proposed by Tesla), but in PMSM/IPM type synchronous motors (PMSM/IPM), to increase the EE of motor performance without the need to use complex electronics such as VFDs or variable speed drives frequently used in induction motors.

A synchronous machine is an alternating current rotating electrical machine whose permanent speed of rotation is linked to the frequency of the voltage at the terminals and the number of pairs of poles. The speed variation problem has been solved by altering the "scalar control" of the Command Law; that is, keeping the voltage/frequency relationship (V/Hz) non-constant. The principle was solved by electromechanical means, physically more resistant to work and with less generation of harmonics than an electronic design with Triac, which constitutes a study prior to the development of another prototype, antecedent of this development, where the use of electronics was analyzed (Anderson, 2019a; 2019b; 2022a; 2022b; 2022c).

How motors produce torque due to flux in their rotating field? When operating below its base speed, torque is delivered by keeping the voltage/frequency ratio (V/Hz) applied to the motor constant. This is what VFDs do to regulate speed while maintaining torque. So if the motor speed is reduced, because the voltage drops, the frequency must drop for the voltage/frequency ratio to remain constant. If the Volts/Hertz (V/Hz) ratio increases by reducing the frequency to slow the motor, the current will increase and become excessive. If, on the other hand, the Volts/Hertz ratio is reduced by increasing the frequency to increase the speed of the motor, the torque capacity will be reduced.

But in the design proposed here, the Volts/Hertz ratio is not constant and we reiterate that the decrease in torque does not affect the normal operation and/or work of the motor; on the contrary, it reduces vibrations, decibels (not measured), and consequently reduces the temperature rise of the parts and/or mechanical parts of the electrical machine due to the transformation of electromechanical energy into thermal energy. This results in an improvement in EE.

As the motor operates with a light load (air flow), the V/Hz ratio can be reduced to minimize the motor current, and because a lower voltage is applied, the magnetizing current is reduced and consequently, a lower current is produced as well. The lower torque is still tolerable by the engine.

As stated, reducing the V/Hz ratio with increasing frequency to increase motor speed will reduce torque capacity. Indeed, although the motor torque decreased, what is truly surprising is that for the load (propellers connected to the motor shaft), the rotational speed (RPM) of the six (6) blades connected to the rotor shaft did not decrease (confirming what Nikola Tesla stated in point no. 15 of his patent: US381968A from 1887); therefore, the ability to perform mechanical work (J) on fluid air did not decrease (although he was referring to asynchronous and non-synchronous induction motors, such as the one proposed in this development). This is technological innovation.

The motor presents a drop in the rated power of the motor of 17.7 W with the EE circuit "off", when "turned on" it was reduced to 6.3 W, in the total circuit RCL, without losing speed in the rotation of the rotor (6 radial blades), that is to say, without diminishing the capacity to carry out mechanical work (J) on the blades of the centrifugal turbine. This is known as EE.

Since the motor is running with a light load (air fluid), the V/Hz ratio can be reduced to minimize motor current; and because a lower voltage is applied, it is also possible to reduce the magnetizing current and consequently produce a lower torque which is still optimal for normal motor operation (pushing it to the limit of its operable physical capabilities, as described in his patent of Nikola Tesla). Maintaining the non-constant voltage/frequency relationship, although with a decrease in torque.

For this reason, with the aim of obtaining a voltage wave attenuator (V) and current intensity (amp), which works as a limiter of the electric current as well as a low-pass Electro Magnetic Interference (EMI) filter. (LPF), the EE circuit was designed with passive elements whose topology is inductive-capacitive: LC.

In the design proposed, the inductor "L" is connected in series and the capacitor "C" is connected in parallel", forming an LC design for the LPF, which reduces the ripple effect in the input average voltage ($Vavg$).

The innovation lies in the fact that the analysis of first-order linear filter circuits has a cutoff frequency ($\omega c = 1/LC$) of the inductive-capacitive type that works by analogy to a resistive-capacitive one, that is, ($\omega c = R/L$). We can assume that in the inductor the inductive reactance operates simultaneously as a resistance that reduces the flow of electric current (amp) with the consequent voltage drop (V) from the output to the load and as an energy storage tank in the form of a magnetic field that is returned to the grid for consumption; while in the capacitor the capacitive-reactance stores the energy in the form of an electric field, both linear circuits filter the harmonics present in the sinusoidal wave of the alternating current.

The importance of using an inductive reactance has double meaning: (a) as a passive component of the Low Pass Filter (LPF), since it reduces the ripple effect in the output voltage acting as a harmonic filter and subsequently; (b) produces a drop in the average input voltage (*Vavg*), that is, it produces a voltage drop from 220 V to 110 V, which in the calculation of the active power formula will produce a drop in the engine power (no loss of rpm or loss of engine speed), that is, without affecting its ability to perform mechanical work (J).

Results and Discussion

This stage of proof or testing will end up confirming (affirming) as "true" point no. 15 of Nikola Tesla's invention patent, as anticipated in the introduction.

The load on the motor shaft is the centrifugal blades, whose value is expressed in ù, which is the angular velocity measured in radians/second: 314.159 Rad/s; equivalent to 3000 RPM obtained by the converter from (Rad/s) to (RPM). 3000 RPM corresponds to a frequency of 50 Hz.

The formula for the average active power (*Pmed*) in a general RCL circuit of AC is equal to the product of the effective voltage (*Vrms*), by the effective intensity of the electrical current (*Irms*), multiplied by the factor power or cos phi: cos (ϕ).

Exactly, according to some classical authors of physics, electricity and magnetism: "$Pmed = \frac{1}{2}.VI\cos(\phi) = Vrms.Irms.\cos(\phi)$" (Sears and Zemansky, 2009, p. 1076). Values were taken with the corresponding instruments of true effective value or RMS.

Then, the stability of the frequency (Hz) of the AC, which in the Argentine Republic is 50 Hz, ensures a constant rotation at 3000 RPM of the motor shaft. If the pair of poles of the synchronous machine is equivalent to two (2) poles (north-south) in the stator, being $p = 2$, the number of poles used in the design of the prototype—according to authors in the field of electrical machines—has the following formula:

The rotor and the stator always have the same number of poles (...); the number of poles determines the synchronous speed of the motor: $ns = 120.f/p$

where

ns = Motor speed (r/min)

f = Source frequency (Hz)

p = *Number of poles* (Wildi, 2019, p. 379)

Characterized by the following formula:

$$ns = \frac{120.f}{p} = \frac{120.50}{2} = \frac{6000}{2} = 3000\,\text{RPM} \qquad \text{...(10)}$$

As mentioned earlier:

F: Frequency of the network to which the machine is connected (Hz)

Q: Number of poles that the machine has

ns: Synchronous speed of the machine or revolutions per minute (RPM)

Calculation with which the constant data of the revolutions per minute (r/min or RPM) is obtained, according to the frequency of the current in the Argentine Republic: $ns = 120.50$ Hz/2 = 3000 r/min, or 3000 RPM. The rotor, unlike asynchronous machines, rotates without slip at the speed of the rotating field.

The 3000 rev/min or 3000 RPM, as indicated above, is a consequence of the frequency of AC. As the motor is PMSM type; the poles (north-south) of the rotor magnets are aligned with the poles (south-north) of the stator (through which the single-phase alternating current flows), synchronously following the rotation speed.

We had previously argued that the centrifugal motor presented here does not decrease its rotor RPM when active power consumption is reduced; decreasing the active power (W), ergo, your active energy consumption (kWh) decreases. But it had been noticed that the same did not happen with the torque, since it descends to the minimum limit, without affecting the capacity of the rotor blades to carry out mechanical work (J) in the air.

In the International System of Units (SI), the unit of torque (also called torque) is the physical quantity: Newtons.meters (abbreviated: Nm). Torque is the moment of a force exerted on the power transmission shaft (rotor). According to certain authors, from the rotation power formula, we know that: "$P = \tau.\omega$" (Tipler and Mosca, 2006, p. 265).

where each algebraic symbol means:

P is the power (measured in W);

τ is the engine torque (measured in Nm). Represented by the letter of the Greek alphabet: tau; and

ω is the angular velocity (measured in rad/s). Represented by the letter of the Greek alphabet: omega.

In both situations (without inductive reactance and with inductive reactance connected in series to one of the phases), the angular speed ω (represented by omega), or speed of rotation measured in radians/second (rad/s) is the same, 314.159 rad/s. Equivalent to 3000 (RPM) obtained by the alternating current frequency of 50 Hz.

Analyzing the power values at the motor input, only of the motor and not of the total RCL circuit, we obtain the following values with the EE circuit: "off" and "on". Solving the torque-motor (tau) or torque, we obtain the following values, 0.057 Nm with the key "off" and 0.025 Nm with the key "on".

According to the Fan Affinity Law specified in the UNE 100-230-95 Standard, the power absorbed by a fan with an asynchronous motor varies with the cube of its speed. This means that for a small variation in rotational speed, the power changes considerably. This has great implications from the point of view of EE since by reducing the rotational speed of the centrifugal fan blades by 23.7% (measured in revolutions per minute), the mechanical power (measured in watts) supplied to the fan is reduced by 56%. Power (W) and speed (RPM) variables are determined according to International Standards ISO 5801-96(E) and WD 13348-1998.

Considering that the Fan Affinity Law applies to asynchronous motors and does not apply to synchronous motors, such as the one used in the project, the EE advantage is significantly higher (and impossible to compare since there is no International Standard establishing such benchmarks). Given that in the conventional asynchronous motor (single-phase induction) the speed of rotation of the blades should be reduced by 23.7% for a reduction of 56% of the active power (W) of the motor, here the speed is not reduced because the motor is synchronous and keeps the 3000 RPM as a consequence of the frequency of the alternating current, 50 Hz.

That, on the other hand, induced the motor to operate by reducing the V/Hz ratio and decreasing the torque of the motor and its capacity to provide constant output power. As motors produce torque due to flux in their rotating field, when operating below its base speed, the torque is carried out by keeping the voltage/frequency ratio (V/Hz) applied to the motor constant. This is how the VFDs regulate speed, thus maintaining the torque. So if the motor speed is reduced, because the voltage drops, the frequency must drop so that the voltage/frequency ratio remains constant and the core of the motor does not saturate, generating harmonic distortion (THD).

Table 1 shows the data of the PMSM/IPM type synchronous motor calculated by formulas and data extracted by laboratory instruments (with the Energy efficiency system "off") with their respective formulas, values and physical units.

Table 1: Data of PMSM/IPM Type Synchronous Motor

Denomination	Formula	Worth	Units
Active power	$P = V_{rms} . I_{rms} . Cos\,\phi$	17.7	(W) : Watts
Effective voltage	$V_{RMS} = \frac{V_{pico}}{\sqrt{2}}$	220	(V) : Volts
Effective current	$i_{RMS} = \frac{I_{pico}}{\sqrt{2}}$	0.456	(A) : Amps
Power factor (cos phi)	$Cos\phi$	0.17	(nls)

Table 1 (Cont.)

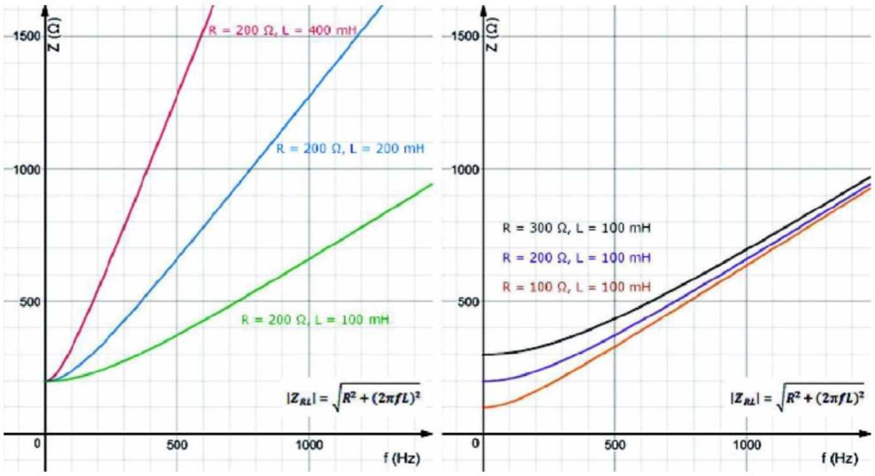
Denomination	**Formula**	**Worth**	**Units**
Reactive power	$Q = X_L.I_{RMS}{}^2$	98.73	(VAr) : Volt-Amp Reactive
Apparent power	$S = V.I$	100.32	(VA) : Volt-Amps
Total impedance RL	$Z_{RL} = \frac{V_{RMS}}{I_{RMS}}$	482.4	(Ω) = Ohms
Endurance	$R = \frac{P}{I_{RMS}2}$	85.12	(Ω)
Inductive reactance	$X_L = \sqrt{Z^2 - R^2}$	474.83	(Ω)
Angular frequency (pulsations)	$\omega = 2.\pi.f$	314,159	(Rad/s) : Radians/ Seconds
Grid frequency	f	Fifty	(Hz) : Hertz
Inductance	$L = \frac{X_L}{2.\pi.f}$	1.51	(H) : Henrys
Phase shift between total voltage and total current	Inductive circuit, the voltage leads the current.	79.82 (°) 1.39 (Rads)	(°) : Degrees (Rad) : Radians
Impeller blade speed	$ns = \frac{120.f}{p}$	3000	(RPM) : Revolutions per minute

PMSM type motors provide a shaft rotation at a fixed speed in synchrony with the power supply frequency regardless of the fluctuation of the mechanical load—greater or less—that produces resistant torque. The voltage (V) and intensity (amp) of the current decrease when the inductive reactance ($Z1$) acts together with the capacitor ($C1$), and anyway, the motor runs at synchronous speed as long as the mains frequency is constant, in this case 50 Hz for any torque up to the motor's operating limit (Figure 7).

This joint effect is achieved by the combined work of the impedance ($Z1$) in series with one phase plus the capacitor ($C1$) in parallel with the two phases.

A perfect inductor would not generate Joule losses, limiting the current through the inductor without generating lower performance. In reality, an inductor has some internal resistance, and consequently Joule losses are minimized but not eliminated. But used in the design of the EE system for the motor, its reactance limits the current available with

Figure 7: ZRL Impedance of the Series RL Circuit Against Frequency *f* for a Given Inductance and Resistance



minimal power losses in the inductor. The ballast is also commonly known as a reactance, since due to the alternating current, the coil presents an inductive reactance.

Impedance (*Z*) is a measure of opposition that a circuit presents to a current when a voltage is applied. Impedance extends the concept of resistance to AC circuits, and has both magnitude and phase, unlike resistance, which only has magnitude. When a circuit is supplied with Direct Current (DC), its impedance is equal to the resistance, which can be interpreted as the zero phase angle impedance.

By definition, impedance (*Z*) is the relationship (quotient) between the voltage phasor and the current intensity phasor.

In electronics and electrotechnics, the opposition offered to the passage of alternating current by inductors (coils) and condensers (capacitors) is called reactance; it is measured in ohms and its symbol is Ω. Together with electrical resistance, they determine the total impedance of a component or circuit in such a way that the reactance (*X*) is the imaginary part of the impedance (*Z*) and resistance (*R*) is the real part, according to the following equality: $Z = R + jX$, binomial representation.

When alternating current flows through one of the two elements that have a reactance, the energy is alternately stored and released in the form of a magnetic field, in the case of coils, or an electric field, in the case of capacitors.

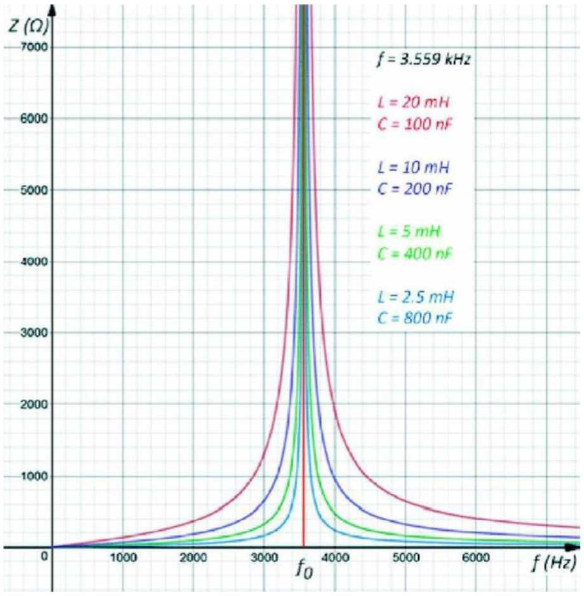
However, actual coils and capacitors have an associated resistance, which in the case of coils is considered to be in series with the element, and in the case of capacitors in parallel. In those cases, as already indicated above, the impedance is *Z*.

When the inductive reactance ($Z1$) value, $Z = 48\ \Omega$ is activated with the key ($S3$), said reactance is in charge of processing the binomial expression of the impedance $Z = A + jB$; where A = Resistance is the real part and j is the imaginary unit, and where $B = X$ is the reactance in ohms, it causes the voltage at the input to the motor to drop from 220 V to 97 V and the current drops from 0.6 A to 0.105 A. But the synchronous speed of the motor shaft connected to the six (6) radial blades of the impeller does not lose speed, which demonstrates EE.

The incorporation of the inductive reactance ($Z1$) in one of the phases, improves the power factor or cosine of fi, from 0.22 to 0.41 and without the capacitor ($C1$), which means a considerable increase or improvement of EE. With the capacitor connected, this value rises from 0.17 to 0.81.

The testing was carried out on a test bench, designed for this purpose, with two (2) oscilloscopes, one analog and the other portable digital, to observe and measure the waveform quantitatively and qualitatively (signal harmonic distortion: THD), peak-to-peak voltage (Voltsp-p) waveform signal meter, true RMS of the average voltage (Vavg), with a digital multimeter that measures voltage (*Vrms*), a frequency meter that measures alternating current oscillation (Hz), an amperometric clamp meter that measures amperes (A), a cosine phi meter (cos ϕ), a wattmeter that measures power active in watts (W) (Figure 8).

Figure 8: ZLC Impedance Versus Frequency *f* of Several Ideal Parallel LC Circuits for Given Inductance and Capacitance



Note: The Resonant Frequency of 3.559 kHz is the same for all LC Circuits

Table 2 shows the values of PMSM/IPM type synchronous motor calculated by formulas and other data obtained by laboratory instruments (with the Energy Efficiency System "on") with their respective formulas, values and physical units.

Table 2: Values of the PMSM/IPM Type Synchronous Motor

Denomination	**Formula**	**Worth**	**Units**
Active Power	$P = V_{rms}.I_{rms}.Cos\,\phi$	6.3	(W) : Watts
Effective Voltage	$V_{RMS} = \frac{V_{pico}}{\sqrt{2}}$	110	(V) : Volts
Effective Current	$I_{RMS} = \frac{I_{pico}}{\sqrt{2}}$	0.106	(A) : Amps
Power Factor (cos phi)	Cos ϕ	0.8	(nls)
Reactive Power	$Sen\phi.\frac{P}{\cos\phi}$	4,725	(VAr) : Volt-Amp Reactive
Apparent Power	$S = \sqrt{P^2 + Q^2}$	7,875	(VA) : Volt-Amps
Total Impedance RL	$Z_{RL} = \frac{V_{RMS}}{I_{RMS}}$	482.4	(Ω) = Ohms
Endurance	$R = \frac{P}{I_{RMS}2}$	85.12	(Ω)
Inductive Reactance	$X_L = \sqrt{Z^2 - R^2}$	474.83	(Ω)
Capacitive Reactance	$X_c = \frac{1}{2.\pi.f.C}$	1,061	(kΩ) : Kilohm
Total LC Impedance	$Z_{LC} = 2.\pi.f.L - \frac{1}{2.\pi.f.c}$	857.97	(Ω)
Angular Frequency (pulsations)	$\omega = 2.\pi.f$	314,159	(Rad/s) : Radians/ Seconds
Grid Frequency	f	fifty	(Hz) : Hertz
Inductance	$L = \frac{X_L}{2.\pi.f}$	1.51	(H) : Henrys

Table 2 (Cont.)

Denomination	Formula	Worth	Units
Capacitance	$C=\frac{1}{\omega.X_c}$	3	(μF) : Microfarads
Phase Shift Between Total Voltage and Total Current (V_T) (I_T)	Inductive circuit, the voltage leads the current	90 (°) 1.5708 Rad	(°) : Degrees (Rad) : Radians
Impeller Blade Speed	$ns=\frac{120.f}{p}$	3000	(RPM) : Revolutions per minute
Resonant Frequency	$f=\frac{1}{2\pi\sqrt{L.C}}$	74.77	(Hz) : Hertz

Conclusion

The non-soft start of the motor, at the beginning of its ignition, is due to the need for the nominal active power of the static starting torque required by the mass of the load (radial blades connected to the rotor shaft) that must be accelerated. Non-soft start does not save energy due to the initial power demand of the motor at start-up time; but this only lasts for an instant (2-3 s); once the synchronous speed of 3000 RPM is reached, it is manually switched to EE mode. Mode change to EE is achieved via mechanical contacts or SPDT switch.

Regardless of whether the SPDT switch is in "off" or "on" mode in EE mode, in both cases, the AC frequency always acts at 50 Hz. For this reason, the motor, although its torque decreases, does not decrease its speed or its ability to perform mechanical work on the radial blades (as long as the motor torque does not decrease the torque below the minimum limit required to keep the rotor running at sync speed).

Indeed, the electromechanical design hypothesis is clearly oriented in the right direction, since the harmonics decrease (the sinusoidal signal of the alternating current is rectified, as observed in the shape of the voltage wave observed in the oscilloscope), although the signal indicates that the load is still nonlinear and requires a Low-Pass EMI Filter (LPF) with passive elements in its construction.

Additionally, other information that resulted from the analysis of the data is that there is no harmonic alteration of the frequency of 50 Hz, since the electromechanical design of the passive LPF "LC" acts in a double sense as:

- A voltage reducer producing a voltage drop from 220 V to 110 V and current from 0.45 amp to 0.1 amp raising the power factor to 0, 17 (cos ϕ) to 0.81

(cos ϕ) which in the calculation of the active power formula in AC circuits will produce a drop in motor power without loss of rotor speed (RPM), that is, without affecting its ability to perform mechanical work (J). Meanwhile, active power (W) and energy consumption measured in kilowatt-hours (kWh) decrease by 56%, with no drop in RPM of the centrifugal blades connected to the synchronous rotor shaft.

- As a ripple reducer of the output voltage or LPF of EMI allowing the total harmonic distortion values to be maintained at: $THDv < 5\%$ (normal situation) and $THDi < 10\%$ (normal situation), according to the IEEE 519 standard., reducing the ripple in the output voltage acting as a harmonic filter.

Reiterating that, while the active power (W) decreases and the consumption of active energy measured in kilowatt-hours (kWh) also decreases, the same does not happen with its working speed (as is the case with any conventional centrifugal fan/extractor) connected to an asynchronous motor.

From the experimental conclusions, evidently the PMSM/IPM type synchronous motor does not lose speed, since it works at 100% of its maximum speed of 3000 RPM, with only 35.6% of its maximum active power, using only 6.3 W of the 17 nominal with which it operates at start-up, although it is built to work up to an operating limit of 50 W.

By way of comparison, a single-phase induction motor, of those normally used in refrigeration or ventilation equipment, is a "frager" type brushless asynchronous motor (in short circuit) and works with a maximum speed of 1690 RPM with 100% of its maximum active power of 19 W, which means 44% less speed when compared to the highly energy efficient motor developed here. In contrast, the PMSM/IPM type synchronous motor designed for this project (with the EE system "on") works at 100% of its maximum speed of 3000 RPM with only 35.6% of its active power maximum, using only 6.3 W.

So we can ensure that the synchronous motor saves 67% of active energy (kWh), doing 56% more mechanical work on air fluid with the same active power (W).

It should be clarified that in other countries where the frequency of AC is 60 Hz, the efficiency of this electromechanical design would be higher, taking the motor speed from 3000 RPM to 3600 RPM, much more than the 1690 RPM of the same asynchronous motor at 60 Hz but with a 64.4% higher consumption of active energy. That is to say that if in the country where the single-phase alternating current is 60 Hz, the asynchronous motor of 19 W of active power would have a speed of 1690 RPM; but in the same country of 60 Hz, the PMSM/IPM type synchronous motor with 6.3 W would have a speed of 3600 RPM with the same six (6) radial blades (the same weight and diameter of the impeller or impeller vanes of the air fluid).

Another advantage of the PMSM/IPM type synchronous motor, if we apply the so-called "Fan Affinity Law", specified in the UNE 100-230-95 Standard, the way in which the power variables are affected (W) and speed (RPM) is determined according to international standards ISO 5801-96(E) and ED 13348-1998- is as follows: the asynchronous motor, with a power of 19 W at 1690 RPM speed of the impeller blades would require 106 W of active power to equal the 3000 RPM of the PMSM/IPM type synchronous motor. This means that normally any refrigeration single-phase induction asynchronous motor would require 16.8 times more active power to match this highly energy efficient design.

Therefore, this experimentally proposed design reduces active power (W) and active energy consumption (kWh) by 67%, performing 56% more mechanical work (J) on fluid air (with a 50% reduction in carbon footprint).

That is why we say that the experimental prototype presented here is more EE, because it performs more mechanical work (J) on the impeller blades in the air fluid, with less power (W), consuming less electrical energy measured in kWh than the brushless asynchronous motor (of the frager or conventional induction type used in centrifugal fans/extractors), but at higher RPM than conventional asynchronous motors used in air conditioning equipment. ventilation, extractors and blowers. The advantage is double.

Therefore, based on the experimental results, it can be seen that centrifugal fans can be developed that save electrical energy (kWh) without the need to resort to: (a) the use of variable speed drives (VFD) or frequency, or (b) the Fan Affinity Law. The latter would change everything that is known in the world about the Fan Affinity Law and would imply a new bibliographic review and experimental development (new comparative studies such as the one developed here), since it is estimated that new and substantial comparative advantages could be created and developed that lead to energy saving and efficiency (never studied before, creating new fields and lines of research), which would bring enormous global savings in the cost of electrical energy with simpler technology, although rudimentary and limited, but effective, economical, rustic (electromechanical and not electronic) and resistant to extreme working conditions.

The added value proposition comes hand in hand with EE, which determines the reduction of the "carbon footprint"; where we went from consuming 202 kWh per year equivalent to 0.1 tons of CO_2 to 97 kWh per year equivalent to 0.05 tons of CO_2 (which means a 50% reduction in the carbon footprint) that our development of the prototype leaves on Planet Earth (to the small scale of the prototype experienced). Therefore, the relationship with the carbon footprint is directly proportional to the power of the motor and to future prototypes with greater power (the relationship in industrial three-phase motors has not been studied).

Obtaining this experimental minimum viable product is estimated to be scalable to higher single-phase power either for commercial use and to a three-phase model (star-delta connection) for industrial use (although the latter has not been tested).

Therefore, we could well describe this technological innovation as a hertzian engine.⏮

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