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ABSTRACT

The electromagnetic torque, antagonistic to the movement that to prime mover exerts on the shaft the contemporary synchronous generator, it is the fundamental cause of the enormous amount of energy consumed in thermoelectric plants, diesel - generators, hydroelectric plants, wind turbines, etc.; in this text, two old alternators from the 19th century are analyzed: Ferranti and Hasselwander, great British and German engineers respectively, while this text mentions about the homopolar generator, all today seen as museum objects due to their great historical value, however their behavior with respect to the harmful electromagnetic torque is much lower than in the current synchronous generator; based on the study of both electric generators, it is demonstrable that by modifying the magnetic circuit of the current synchronous generator it is possible to generate with less electromagnetic torque, which is equivalent, assuming constant rotation speed, to lower power consumption in the primary motor only by changing the magnetic circuit of the generator.

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I. INTRODUCTION

When electrical machines are studied today, the synchronous motor and the synchronous generator are practically very similar, however at the beginning of the 20th century several types of generators were successfully serving, but the design of Siemens was imposed technologically, leaving the vast majority as museum objects the other designs, the constructive feasibility and a very high efficiency make generators and synchronous motors today practically the same machine, protected by the Principle of Reversibility of Electrical Machines.

The very high efficiency of the current synchronous generator makes us believe that it is absurd to look for primary energy savings by modifying something of proven excellence and it would be very true scientifically to look for more efficiency by minimizing losses, which is already something very successful today technologically, large commercial synchronous generators exceed the 98% efficiency and even 99%, minimizing energy losses.

Among the set of energy losses of a synchronous generator, the antagonistic electromagnetic torque to the mechanical torque injected into the shaft is not counted as such, but it is consuming primary energy (renewable or not), brakes proportional to the load connected to its output, this brake is compensated with more primary power; although this phenomenon is inevitable, it is possible to minimize it.

At the beginning of the 20th century, energy consumption was not seen with the strategic and environmental importance it has today, it was not the amount of electrical energy required today necessary, and fuel costs were low, for all of which it lacked technical - economical importance the electromagnetic torque Vs the production cost and versatility of the Siemens generator commercially in use today.

The generators that present less antagonistic torque with connected load are:

- Homopolar generator
- Ferranti generator
- Hasselwander generator

As is known, none of these electric generators is used commercially today.

II. THE CURRENT CONTEXT

Today's synchronous generator is a much more technologically developed form of the synchronous generator designed by Siemens in the 19th century.

In a synchronous generator, when delivering power to a given load, there is a group of energy *losses:*

- Mechanical losses.
- I2R thermal losses.
- Losses due to parasitic currents.
- Additional losses.
- Magnetic losses due to dispersion.

A worthy example of the high efficiency achieved in minimizing the afore mentioned losses in synchronous generators is the Siemens SGen 2000P Series from 370MVA to 560MVA, which achieves efficiency above 99% [6].

Considering that the rotation speed of a synchronous generator is constant, the primary power consumption depends on the antagonistic torque exerted on its shaft, which is the electromagnetic torque exerted between the rotor and the stator, it is what determines the necessary mechanical power consumption at each moment, all of which is expressed as follows:

$$P_{Mec} = \omega T_{Total} \quad (1)$$

Being ω constant, the mechanical power consumption is a function of the torque,

$$T_{Total} = J_{Rotor}\omega + T_{friction} + T_{EM} \quad (2)$$

$$J_{Rotor} = mr^2 \quad (3)$$

Where J_{rotor} ω is the inertial torque [7] of the rotor, $T_{friction}$ is the frictional torque of the rotor and T_{EM} is the antagonistic torque exerted on the shaft due to its main magnetic circuit and the electric current it supplies to the load, called electromagnetic torque, the latter much greater quantitatively, that is why most of the mechanical power supplied to the shaft is consumed in overcoming this harmful torque, antagonistic to motor movement

III. THE ELECTROMAGNETIC TORQUE IN THE SYNCHRONOUS GENERATOR

The electromagnetic torque in rotating electrical machines is the interaction between the forces exerted rotor - stator, with a positive direction in electric motors, but negative or antagonistic in the specific case of the synchronous generator (Fig. 1), in both machines referred to the interaction between static and rotating magnetic fields.

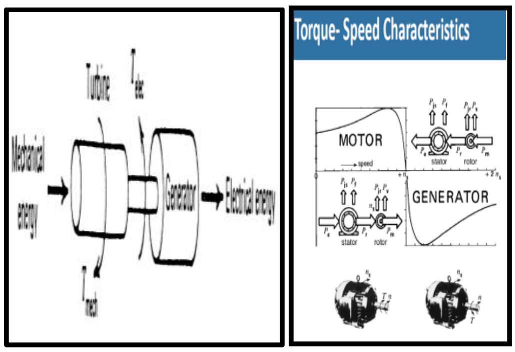

Fig. 1: The Electromagnetic Torque in the Synchronous Generator

The existing magnetic fields in the stator and rotor of the synchronous generator interact based on the mutual inductances
[8].

The mutual inductance $M_{R \leftarrow S}$ of the induced winding with respect to the field winding is the ratio of the magnetic flux through the N_R turns of the induced winding produced by the magnetic field of the current I_S through the field winding, that is:

$$\mathbf{M}_{R\leftarrow S} = \frac{N_R \Phi_{R\leftarrow S}}{I_S} = \frac{N_R(B_S \times (A_S))}{I_S} \quad (4)$$

$$\mathbf{M}_{R\leftarrow S} = \frac{\mu_0 \mu_{rel} N_R A_S}{\ell_S} \quad (5)$$

While the mutual inductance $M_{S\leftarrow R}$ of the field winding with respect to the induced winding is the ratio of the magnetic flux through the N_S turns of the field winding produced by the magnetic field of the I_R current through the induced winding, that is:

$$\mathbf{M}_{S\leftarrow R} = \frac{N_S \Phi_{S\leftarrow R}}{I_R} = \frac{N_S(B_R \times (A_R))}{I_R} \quad (6)$$

$$\mathbf{M}_{S\leftarrow R} = \frac{\mu_0 N_R A_R}{\ell_R} \quad (7)$$

for all of which the equivalent mutual inductance will be:

$$M = \begin{vmatrix} L_{Rotor} & M_{R\to S} \\ M_{S\to R} & L_{Stator} \end{vmatrix} \quad (8)$$

$$M = L_{Rotor} L_{Stator} - M_{R\to S}(M_{S\to R}) \quad (9)$$

The torque equation in a three-phase commercial synchronous machine [9] stated as a function of mutual inductance is:

$$T = -pMif\,(ia\overset{R}{S}en(p\varnothing) + ibSen\,(p\varnothing - 2\pi) + i\,Sen\,(p\varnothing + 2\pi)) \quad (10)$$

There are other methods of evaluating the electromagnetic torque, based on Park's equations [10] and it is expressed as:

$$T = i_q\Psi_d - i_d\Psi_q = i_q(i_d L_d) - i_d\,(i_q L_q) \quad (11)$$

Where $iq\Psi d - id\Psi q$ is a difference between vector products and flux linkages $\Psi = L_i$. The electromagnetic torque equation in a three-phase synchronous generator as a function of the magneto-motive forces (M.M.F) is:

$$T_{EM} = k.\bar{B}_{Stator}.\bar{B}_{Rotor}.Sin(\delta) \quad (12)$$

$$T_{EM} = k.(\overline{MMF}_{Stator}).(\overline{MMF}_{Rotor})Sin(\delta) \quad (13)$$

Once the basic issues on the subject have been expressed, each of the three types of electric generators with less electromagnetic torque will be analyze, to apply to the current electro-energy context in search of primary energy savings.

VI. THE HOMOPOLAR GENERATOR IN THE CURRENT CONTEXT

The homopolar generator (Fig. 2) is a direct current machine initially designed by Michael Faraday in 1831, consisting of a disc of electrically conductive material, rotating in a magnetic field perpendicular to it, where the energy is extracted between the edges of the disc and its center.

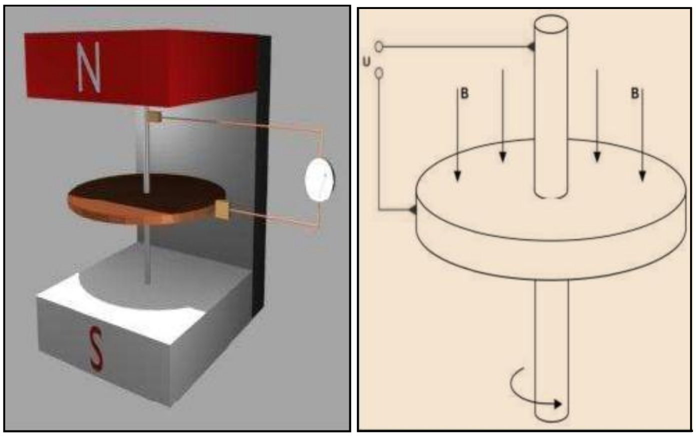

Fig. 2: Basic Homopolar Generator

It is characterized by very low voltage and very high current, a very pure direct current, the interaction between rotor and stator is very low despite the very high current values with which it is capable of contributing to the load.

This small relationship between the current and the antagonistic torque that this generator produces was exposed in Germany in September 2016, the German Electrical Union and the Swiss Electrical Union sponsored a great event in the Congress Center of Wurzburg, [11] Germany, where the Indian scientist Tewari defended his modification to the homopolar generator (Fig. 3), unfortunately despite the successful result, the physical argument is not scientifically validated because an absurd disproportion between the input and output energies is affirmed, although the low torque antagonistic is logical and probable.

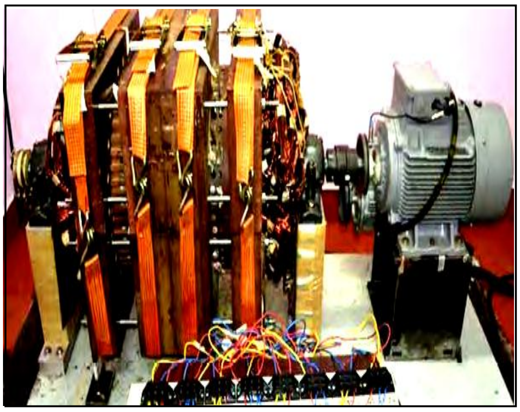

Fig. 3: Homopolar Generator Exhibited by Indian Scientist Paramhamsa Tewari at Conference in Würzburg, Germany in 2016

The homopolar generator continues to be scientifically investigated today.

V. THE FERRANTI GENERATOR IN THE CURRENT CONTEXT

The alternator designed by Zianni Ferranti (1864 – 1930) had an inductor with a ferromagnetic core and an induced core with an air core, axial magnetic flux and exciter mounted on the shaft, specifically in Fig.4 it can be seen that each 1MW synchronous generator is moved by 1500 HP (1.12MW) machines with approximately 89.4% efficiency, excellent for those times.

Given his personal friendship with Siemens and the economic superiority of the radial magnetic flux synchronous generator model proposed by his German colleague, which in turn also allowed the material to be used to build motors, Ferranti abandoned continuing to perfect his inventiveness, collaborating with Siemens on his technology, it still existing today.

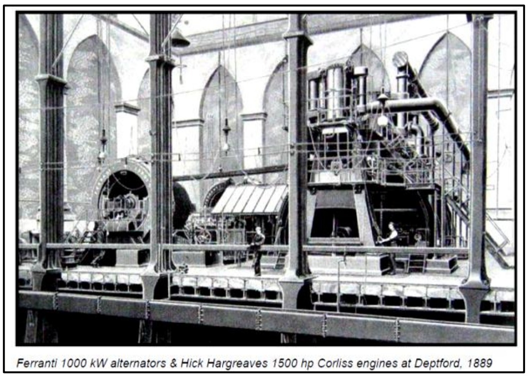

Fig. 4: Ferranti Alternator: First Thermoelectric Plant in the World (Deptford Station, London, Great Britain, 1889), Whose 1MW Synchronous Generators Were Designed by Zianni Ferranti

In the Electrical Machines Laboratory of the Technological University of Havana, successful tests were carried out (2004) with a design based on the old Ferranti generator (Fig. 5), but seeking to save primary energy [12] based on the lower antagonistic torque it presents.

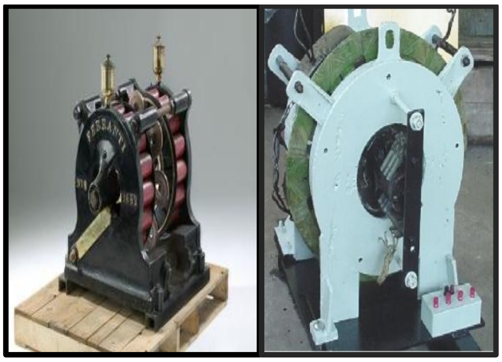

Fig. 5: Left: Ferranti generator (United Kingdom, 1882). Right: Low reversibility electric generator (Cuba, 2004)

There are 2 classic ways (there is a third: deforming the core) to vary the magnetic flux: varying the electric current (for example, the transformer) or varying it mechanically (for example, in electric generators); in both cases the electrical energy is produced in a unidirectional action: inductor to induced; once produced, the delivery of that electrical energy to perform work on the connected load creates a series of electrical, magnetic and mechanical losses, but fundamentally reflected in the presence of the electromagnetic torque resistant to rotation injected by the prime mover, main concern in this text due to the high cost of primary energy and the growing need for electrical energy.

Fig. 6: Low Reversibility Electric Generator (2004), on the Right Its Rotor

Constructively (Fig. 6) the low reversibility electric generator consists of a stator completely lacking in lamination, made of carbon steel (C20 and C45), 4 poles wound with AWG 15 wire, while the rotor consists of 3 windings at 120° offset from each other, with 4 poles each, rectangular wire (2.00 x 2.80 mm), the output is through 3 sliding rings (12.5kVA / 10kW / 230V, three-phase).

The calculation of its relative parameters is as follows:

$$\mathbf{Z_b = \frac{U_f}{I_f} = \frac{230V/\sqrt{3}}{31,8A} = 4,18\ ohm} \qquad (14)$$

$$\mathbf{X_{dp.u} = \frac{X_d}{Z_b} = \frac{2,17}{4,18} = 0,519} \qquad (15)$$

$$\mathbf{X_{qp.u} = \frac{X_q}{Z_b} = \frac{1,32}{4,18} = 0,316} \qquad (16)$$

Being its Short Circuit Ratio the following:

$$\mathbf{\frac{1}{X_d} = 1,93} \qquad (17)$$

Table 1: Experimental Calculation of Efficiency in Low Reversibility Electric Generator 12.5kVA, 10 kW, Cos ϕ = 0,8 Ind, 4 Poles, 1500rpm Constant

Nominal Power	*10 kW*
Seem Power	*12,5 kVA*
Mechanical losses	*0,32 kW*
Steel losses	*View not*
Cooper losses	*1,21 kW*
Other losses	*0,055 kW*
Total losses	*1,585 kW*
Efficiency	*86,32%*

Table 2: Comparative Table Between Current Commercial Generators [13, 14 Y 15] and the Low Reversibility Electric Generator at the Same Rated Power, Number of Poles and Rotation Speed

Potencia 100 % / 0,8 ind.	Stamford 2004	Stamford 2019	Low reversibility	Leroy Somer 2020
V_{nom}	230 / 115 Volt	380 / 220 Volt	230 / 127 Volt	230 / 115 Volt
S_{nom}	12,5 kVA	12,5 kVA	12,5 kVA	12 kVA
Cos φ	0,8 inductivo	0,8 inductivo	0,8 inductivo	0,8 inductivo
P_{nom}	10 kW	10 kW	10 kW	10,2 kW
Eficiencia	78%	81,50%	86,32%	84,4 % (FP=!)
Relación Corto Circuito	0,495	0,493	1,927	No dato
Xd (p.u)	2,02	2,03	0,519	No dato
Xq (p.u)	1,01	0,98	0,316	No dato
Paso Polar	Dos tercios	Dos tercios	1	Dos tercios
Flujo Magnético	Radial	Radial	Axial	Radial

Tables 1 and 2 show the prospects for developing this construction technology of the synchronous generator, because despite the obvious technical shortcomings with which the project was developed, there is approximately 5% better energy efficiency.

VI. THE HASSELWANDER GENERATOR IN THE CURRENT CONTEXT

The German engineer Friedrich August Hasselwander is credited as the author of the first three-phase synchronous generator (Fig. 7), this produced 2.8 kW, 4 poles, 960 rpm (32 Hz), and this generator was presented at the Frankfurt exhibition of 1891.

In 2020 an experiment was carried out to study the physical behavior of the Hasselwander generator at our university, for which there was a lack of a toroid with

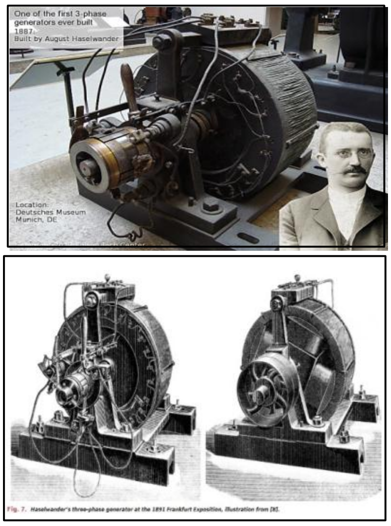

Fig. 7: Synchronous Generator Hasselwander: First Three-Phase Generator in the History

core had lamination in the direction convenient to the rotation of the inductor, for which a square transformer core was taken (Fig. 8), this results in the magnetic flux emanating from the rotor having additional dispersion losses, in addition of an excessive air gap.

Fig. 8: Experiment to Study Electromagnetic Torque in a Hasselwander Generator. Above: Side and Diagonal View. Below: The Rotor - Stator Assembly in a Demonstration Photo of Physical Layout

The behavior of the project is compared with a commercial alternator of 120 Watt power at 1800 rpm (Fig. 9), in the event of a controlled short circuit.

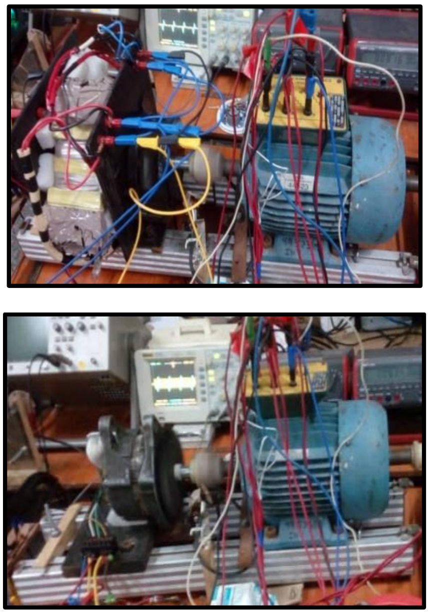

Fig. 9: Comparison before a controlled short circuit of a commercial generator Vs experimental generator. Above: With experimental generator. Below: With classic generator

The experiment presented the result shown in table 3.

Table 3: Comparative table of antagonistic torque and mechanical power of the LADA AAG (120W) automobile alternator and a rudimentary experimental generator in the event of a stable 18 Amp short circuit presented to the Scientific Council of the Faculty of Electrical Engineering (CIPEL / CUJAE) in 2020

*Not load: LADA I_{EXC} nominal = 2,5 A GSBR I_{EXC} = 12 A	NOT LOAD*	SHORT CIRCUIT OF 18 A
Mechanical power in the shaft of the synchronous generator LADA AAG (w)	109,03	213,63
Torque in the shaft of the synchronous generator LADA AAG (N-m)	0,58	1,139
Mechanical power in the shaft of the experimental synchronous generator (w)	18	71,88
Torque in the shaft of the proposed synchronous generator (N-m)	0,095	0,382

The table 3 shows the enormous torque difference in the prime mover at the same controlled short-circuit current value (18Amp) existing between both generators.

VII. CONCLUSIONS

In any of the 3 generators mentioned in this text, it is observed that the electromagnetic torque is less than its current commercial counterpart; of course, in all cases, it is necessary to perfect the disadvantages that they present and find the design of an only synchronous generator that optimizes the consumption of primary energy.

Saving in a technologically accessible future, for example, 10% of primary energy by changing the magnetic circuit of the current synchronous generator would bring in generator sets, whose internal combustion engine generally does not reach 40% efficiency, savings of perhaps 20% in fuel consumption, in wind energy limited by the Betz constant, would allow the diameter of the blades to be reduced to deliver similar power; it is not possible to speak of exact savings numbers because they are non-linear processes.

In addition, which is also very important, it would allow sustainable savings because modifying the electric generator does not harm the environment and would take advantage of all the existing infrastructure today.

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