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Scientific and technological research article

Magneto-dynamic method in wireless transmission of electrical energy

Método magneto - dinámico en transmisión inalámbrica de energía eléctrica

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ABSTRACT/*RESUMEN*
Wireless transmission of electrical energy was born at the beginning of the 20th century, but at commercial level it is relatively recent in recharging of mobile phone batteries and in electric vehicles (first decade of the 21st century), using the development of contemporary electronics, both authors working with synchronous generators note that there is a wireless transmission with certain advantages, this text presents experiments based on the mechanical rotation of stationary magnetic fields (magneto-dynamic method) very similar to the excitation in synchronous generators , there were some first tests in a British university in 2014 as the only reference of previous use. Experimenting on this topic has no historical precedents in Cuba, but any scientific achievement on the topic is highly valued because they are paths not usually used, being a fertile field for future research that could obtain potentially interesting results developed from laboratory experiments carried out.
Keywords: wireless energy, synchronous generator, sustainable charging.

La transmisión inalámbrica de energía eléctrica nació a principios del siglo XX, pero a nivel comercial es relativamente reciente en la recarga de baterías de teléfonos móviles y en vehículos eléctricos (primera década del siglo XXI), aprovechando el desarrollo de la electrónica contemporánea, por tanto los autores que trabajan con generadores sincrónicos señalan que existe una transmisión inalámbrica con ciertas ventajas, este texto presenta experimentos basados en la rotación mecánica de campos magnéticos estacionarios (método magneto-dinámico) muy similar a la excitación en generadores síncronos, hubo algunas primeras pruebas en una universidad británica en 2014 como única referencia de uso anterior. Experimentar sobre este tema no tiene precedentes históricos en Cuba, pero cualquier logro científico sobre el tema es muy valorado porque son caminos no habitualmente utilizados, siendo un campo fértil para futuras investigaciones que podrían obtener resultados potencialmente interesantes desarrollados a partir de experimentos de laboratorio realizados.
Palabras clave: *energía inalámbrica, generador sincrónico, carga sostenible.*

INTRODUCTION
A very brief preliminary historical account is made, followed by the main current technological advances in static wireless transmission of battery charging in mobile telephony and electric vehicles (EV), after which, with proposal for wireless transmission based on magneto - dynamic, similar to the synchronous generator is made in experiments in the Technological University of Havana.

This work constitutes applied research [1], specifically R&D, because although the solution to a specific problem is reached, it does not reach a degree of completion that allows its direct commercial application, but it does indicate the real possibility of applying technological changes in current commercial products in wireless battery charging with technical-economic improvements. The method used is a combination of empirical methods (observation, experimentation, measurement, etc.) with theoretical ones (analysis, synthesis, deduction, logic, etc.) [2], supported by prior experimental knowledge of electrical machines and very specifically of the synchronous generator compared to the wireless transmission and current reception of electrical energy through resonant electronic circuits, taking the observation of electromagnetic induction as a common element and considering magneto-dynamic transmission possibilities in future designs.

Historically, wireless energy transfer emerged at the beginning of the last 20th century with the famous experiments of Nikola Tesla [3-5], in the Wardenclyffe Tower, experiments unfortunately aborted in their beginnings due to the financial disinterest of J.P. Morgan, despite his indisputable previous success at the 1893 Chicago Fair and managing to light incandescent light bulbs at enviable distances in the first decades of the 20th century, but everything remained a myth and the anecdotes once again acquired scientific and commercial interest from the successful experiment of wireless energy transmission at the Massachusetts Institute of Technology (MIT) in 2007 in which it was possible to transmit with 40% efficiency at a distance of 2 meters [6, 7].

A good example of wireless charging in cell phones is the Samsung S23 [8], series (S23, S23Plus and S23Ultra), whose batteries are respectively characterized by tolerating 0.9Ah, 4.5Ah and 5Ah respectively, in the case of iPhone: iPhone 15, and iPhone 15 plus their batteries are 3.35Ah and 4.38Ah respectively, reaching approximately 50% charge in 30 minutes. There are commercially higher power wireless chargers (30W, 45W and even 80W), but the most commercially widespread is between 10 and 15W, being able to charge between 1 or 3 cell phones and with Qi2, that is, looking for the optimal angle between receiver and transmitter, allowing greater charging power than previous 5 and 7.5W models, however traditional 15W network outlet charging chargers cost much less as can be seen in figure 1 left.

Fig. 1. rigth) Cell phones with wireless charging on the United States market in July 2024 **left)** Fast charging chargers that connect with a charging cable

Land transportation is, after electricity generation, the largest global consumer of fuel, which is why the development of electric transportation has gained increasing importance due to environmental motivations and this growing number of electric vehicles has to compete in terms of performance solidly established in vehicles with an internal combustion engine, wireless charging is something impossible in a gasoline or oil vehicle, giving convenience to the user. In the field of wireless charging of electric vehicles (EV), one of the most positive results in 2024 according to Verified Market Reports, among those commercially possible for the consumer is Hevo's 12kW (figure 2), which competes with a wired charger level 2 on the market, capable of achieving a range of more than 560 km in 1 hour of charging.

As far as traditional wired charging of electric vehicles (EV) [9], is concerned for use in the garage of your home there are 120V and 230V chargers called level 1 and level 2 respectively, although in the first case the charging is slower so the second option with J1772 port and J3400 connector is generally preferred and thus achieve 40A or 48A in the case of EV Tesla, this installation allows very wide ranges of ambient temperature and rain or humidity.

Electric vehicle battery charging currently exists in 2 forms:

- Static charging (Wireless charging or not in a static vehicle).
- Dynamic charging (Wireless charging in a moving vehicle) [10].

The dynamic wireless charging is showing in figure 2 b), but this article only refers to the static charging of electric vehicles (or cell phones).

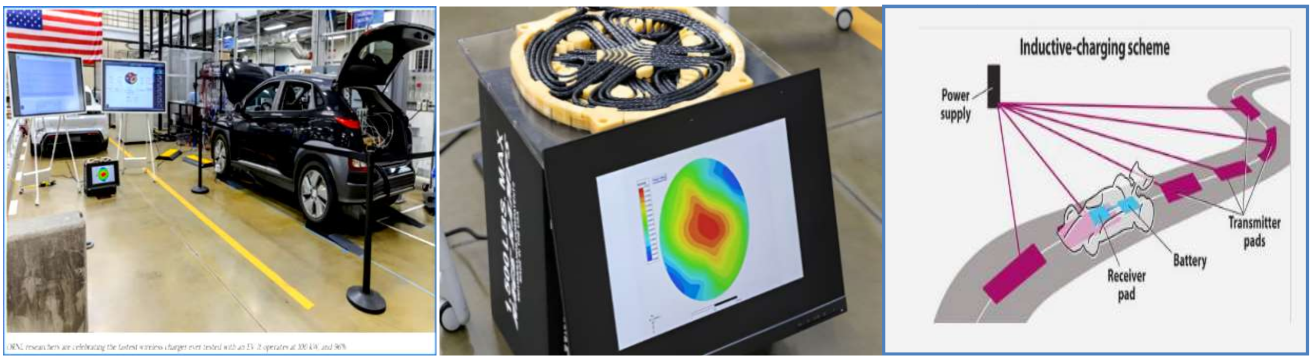

Fig. 2. rigth) Oak Ridge National Laboratory (ORNL) Wireless Charging Laboratory. Center: Hyundai Kona EV three-phase transmitter with more than 30 cm diameter windings **left)** On-road charging for Electric Vehicles

DEVELOPMENT AND THE USED METHODOLOGY

Resonant magneto-motive transfer of wireless energy

This work constitutes applied research, specifically R&D, because although the solution to a specific problem is reached, it does not reach a degree of completion that allows its direct commercial application, but it does indicate the real possibility of applying technological changes in current commercial products in wireless battery charging with technical-economic improvements. The methodology used is a combination of empirical methods (observation, experimentation, measurement, etc.) with theoretical ones (analysis, synthesis, deduction, logic, etc.), supported by prior experimental knowledge of electrical machines and very specifically of the synchronous generator compared to the wireless transmission and current reception of electrical energy through resonant electronic circuits, taking the observation of electromagnetic induction as a common element and considering magneto-dynamic transmission possibilities in future designs.

Generally there are 2 types of wireless transmission depending on the distance between transmitter and receiver, but the transmission of the highest electrical powers is carried out over short distances, at long distances very low power signals are received, in the vast majority of In all cases, the oscillations to be transmitted have electronic origin, taking advantage of the very high development of power electronics and communications. In figure 3, we have the circuit of a classic wireless battery charging [11], today, the efficiency is 94%, that is 106,4 w for every 100 w. In all synchronous generators there is a magneto-motive transfer of wireless energy (non-resonant and at a millimeter distance) from inductor to armature and a transfer in the reverse direction in the presence of load on their output terminals, as happens to a certain extent with mutual inductance between transmitter and receiver in wireless power transmission today.

The impressive development of current electronics has marginalized the magneto-motive transfer of wireless energy, and practically today it only serves as an excitation system in synchronous generators, but the electromagnetic induction that occurs in a synchronous generator has an extraordinarily low frequency (50 or 60Hz) and very exceptionally up to about 300 to 500Hz, the working spectrum of radio transmissions is very broad in relation to the transmission frequency.

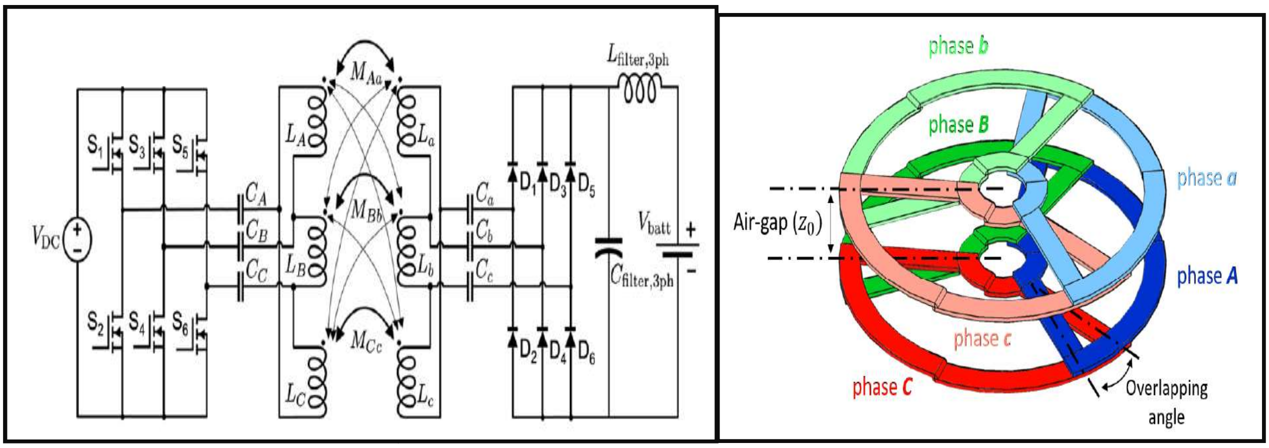

Fig. 3. Example of three-phase wireless battery charger for EV

When mutual inductance is studied in Electrical Circuits [12], we have that in the case of 2 adjacent or close coils:

- **Distance between the coils**: The closer the coils are to each other, the greater the mutual inductance, as the distance increases, the mutual inductance decreases.
- **Coil area**: Coils with larger areas tend to have greater mutual inductance because they can couple more magnetic flux.
- **Number of turns**: Increasing the number of turns in the coils increases the mutual inductance.
- **Orientation of the coils**: If the coils are aligned with their parallel axes the mutual inductance will be maximum; changing the orientation with a different angle reduces this effect.
- **Core material**: The presence of a ferromagnetic or ferrite core can significantly increase mutual inductance due to its high permeability.

Efficiency in wireless transmission by electromagnetic induction generally requires resonance [13], as an essential condition, it is using in the scheme shown in figure 4, and it is: See equation (1).

$$\eta = \frac{\omega^2 M^2 R_L}{\left(R_3 + R_L\right)\left[\omega^2 M^2 + \left(R_2 + R_S\right)\left(R_3 + R_L\right)\right]} \qquad (1)$$

Where R_S represents the internal resistance of the voltage source, R_2 resistance of the transmitting coil, R_3 resistance of the receiving coil, R_L resistance of the load, ω transmission frequency coincident with the resonance frequency, and M is the mutual inductance between transmitting coil and receiving coil.

The frequency (ω) and the mutual inductance (M) are fundamental in the wireless transmission of electrical energy as can be observed in equation (1), in studies and experiments carried out the mutual inductance between transmitting and receiving inductances in wireless energy behaves as shown in figure 5. Above in the case of alignment between both, while in the case where there is also an angle (30º, 45º and 60º in Fig. Below) the mutual inductance as a function of distance will be smaller.

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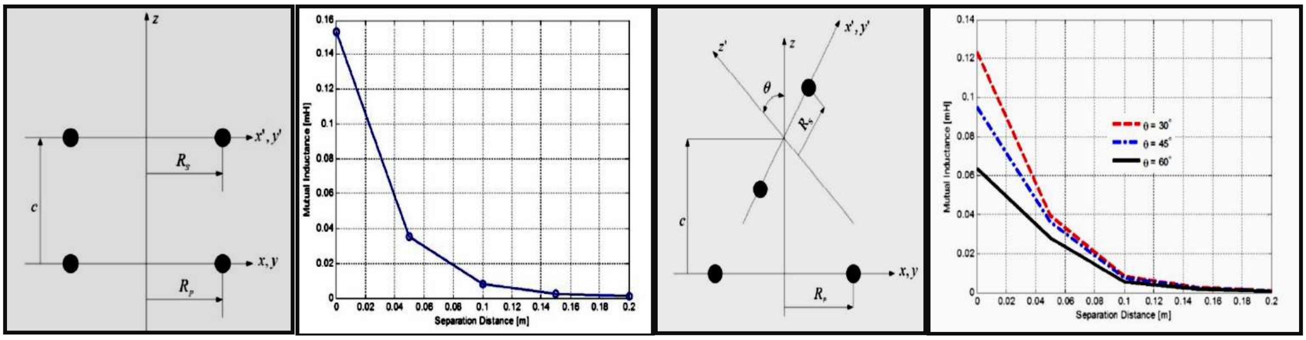

Fig. 4. First & second: Behavior between the transmitter and receiver coils (mutual inductance) as a function of the distance between them, in case of mutual alignment **Third and fourth:** Behavior between the transmitter and receiver windings (mutual inductance) as a function of the distance between them, in case of non-mutual angular alignment

In a synchronous generator, the wireless transmission of energy occurs from inductor to armature by the magneto-dynamic method based on Faraday's Law, so the possible energy in a synchronous generator is given by equation (2), [14, 15]:

$$E_{Gen} = U \times I \times t = \left(k\phi\omega\right) \times \frac{Q_{ab}}{t} \times t = k\phi\omega \times Q_{ab} \Rightarrow Joules \qquad (2)$$

That is, according to equation (2), the electrical energy (E_{Gen}) produced by a synchronous generator is conditioned by the shape of its magnetic circuit (k), by the amount of magnetic flux that cuts the armature (ϕ), by the angular velocity (***ω***) and by the amount of electrical charges (Q_{ab}) possible to move (which is conditioned to the number of turns, the quality of the conductor and its diameter), of that electrical power possible to generate ($P_{loadMax}$) in a synchronous generator, the maximum to be extracted is a function of the Thévenin Theorem of Maximum Power [16], that is, proportional to the voltage (U) in the load squared and inversely to its internal impedance (z): See equation (3).

$$P_{load_{\max}} = \frac{U^2}{Z} \textit{Thévenin Theorem of Maximum Power} \qquad (3)$$

While the mechanical power (generally at constant rotation speed) in its shaft ($P_{MecShaft}$) has to be greater than the sum of mechanical ($P_{LossesMec}$) losses (inertia, friction and beating) and the brake imposed by the antagonistic electromagnetic torque proportional to the connected load, which is the majority in the consumption of mechanical energy input to the shaft. See equation (4).

$$P_{Mec_{Shaft}} > \sum P_{Losses_{Mec}} + T_{Load}\,\omega \qquad (4)$$

If we observe in table 1, it is visible how the magnetic flux density (B) is greater for higher nominal power and the excitation power increases as a function of the nominal power, but always invariably the excitation power is a minimum fraction of the nominal power (maximum 5%), of course there are several differences in relation to commercial wireless energy transfer both in cell phone charging and in charging batteries in electric vehicles:

- With the exception of the air gap, the magnetic flux passes through ferromagnetic materials.
- The air gap is very small.
- The speed of changes in the magnetic flux is very slow relatively.

Table 1. Basic comparative parameters in some commercial synchronous generators (50Hz) [17]

Example (50 Hz)	1	2	3	4	5	6
Seem Power (kVA)	10	60	62,5	175	200	325
Voltage (V)	320	220	380	400	3150	230
Phase current (A)	15	158	95	253	37	815
Power Factor	0,8	0,8	0,8	0,8	0,8	0,8
Speed (Radians/s)	157,1	104,7	78,5	104,7	31,4	52,4
Number of Poles	4	6	8	6	20	12
Magnetic Flow (Maxwell x 10^6)	1,02	2,4	1,87	4,37	1,86	4,54
Density agnetic Flow (Gauss)	6500	6300	6800	7750	7300	8800
Excitement Power (W)	391	1323	1150	1783	3330	3840
Excitement/Nominal Power (%)	4,9	2,8	2,3	1,3	2,1	1,5

When analyzing the efficiency in wireless transmission (equation 1) of electrical energy, evidently, the efficiency depends very strongly on the speed of change of the magnetic flux (***ω***) and the mutual inductance between receiver and transmitter (M), where the latter depends on the distance between transmitter and receiver, the permeability of the medium between them, and the relative angle between transmitter and receiver. In the synchronous generator, only a maximum of 5% of its power is consumed to create the main magnetic flux through the excitation system, however in commercial wireless charging the nominal charging power quantitatively has values very similar to the input power, but in a synchronous generator the connected load creates an antagonistic torque mechanically slowing the rotation of the primary motor, although this occurs due to the physical proximity between inductor and armature and the magnetic circuit used; in wireless transmission this physical proximity does not exist, nor does the permeability of the medium through which the flow passes is high, as in the case of the synchronous generator, the case of the experiment at MIT in 2007, cited at the beginning of this article, is incomparable, the difference in the speed of change (***ω***) is abysmal. See equation (5).

$$9{,}9Mhz \;/\; 60Hz \;=\; 165{,}000 \textit{ times} \qquad (5)$$

EXPERIMENTS CARRIED OUT

In experiments carried out at the Technological University of Havana, the transmitter consisted of the rotation of8 permanent neodymium magnets properly oriented in alternate way: North – South – North – South (figure 5), and at a distance of 20 mm a coil with a laminated ferromagnetic core, forming a resonant circuit with a capacitor at its end.

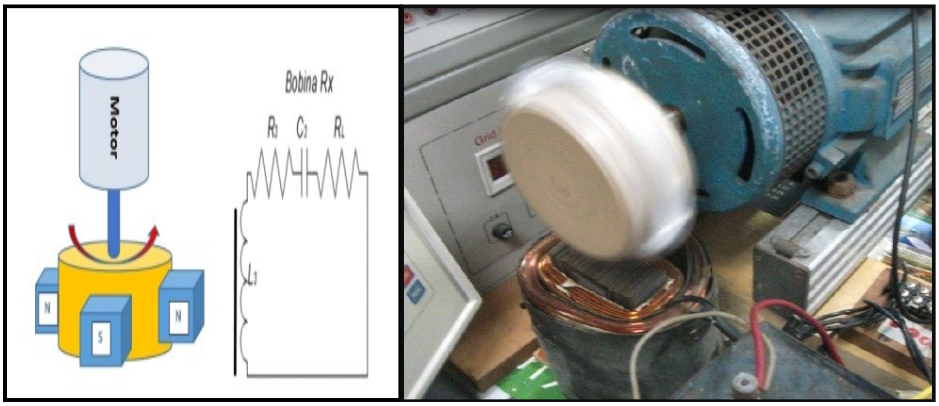

Fig. 5. Wireless transmission experiment carried out at the Technological University of Havana. Left: Basic diagram. Right: Experiment with controlled rotation of the 8 permanent neodymium magnets and receiving coil underneath physically and connected to a capacitor seeking to work in resonance.

Each neodymium permanent magnet with the following physical dimensions: Width: 12mm, Length: 20mm, Height: 8mm, Type N45 and Magnet Bearing Force: 10.5kg; while the receiving coil had L = 48.3mH and the capacitor C = 168Mf, measured with an LCR meter model XJ2811C and an error of 0.25%, for a theory resonance frequency of: See equation (6).

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{\left(48,3\times10^{-3}\right)168\times10^{-6}}} = 55,87\,Hz \qquad (6)$$

The experimental results was obtained with the help of a RIGOL oscilloscope model DS1022and a standard resistance of 0.1 Ohm, Class 0.01. The table 2, shows the short circuit current Vs frequency, in which it can be seen that the calculated resonance frequency and the one actually obtained coincide, demonstrating that in this way wireless electromagnetic induction is obtained similar to the commercial method.

Table 2. Primary motor speed (rpm), receiver: LC circuit frequency Vs Short Circuit Current, Series Resonance in wireless electric energy transmission experiment carried out at the Technological University of Havana, I_{SC} = f (Freq)

Test	Speed Motor (rpm)	Frequency receiving LC circuit Oscilloscope(Hz)	Frequency rotatory magnetic field (rps)	Frequency average (Hz)	Difference of Frequency (Hz)	Shortcircuit current (A)
1	344	22,73	22,96	22,845	0,115	0,038
2	425	29,4	28,37	28,885	0,515	0,044
3	495,8	31	33,06	32,03	1,03	0,053
4	563,9	34,72	37,59	36,155	1,435	0,063
5	622,2	41,67	41,48	41,575	0,095	0,088
6	707,4	48,08	47,16	47,62	0,46	0,173
7	781,2	52,08	52,08	52,08	0	0,382
8	802,2	54,35	53,48	53,915	0,435	0,478
9	824,4	55,56	54,96	55,26	0,3	0,529
10	857,4	56,82	57,16	56,99	0,17	0,472
11	887,4	59,52	69,16	59,34	0,18	0,388
12	925,8	62,5	61,42	61,96	0,54	0,286
13	961,8	64,1	64,12	64,11	0,01	0,24
				47,136	0,407	

In table 3, shows the experiment looking for parallel resonance, this is open circuit voltage Vs speed of the motor that rotates the neodymium permanent magnet system; a higher speed could be sought and the value of the capacitor used could be changed, but there are no good mechanical conditions for better R&D work, nor a greater number of permanent magnets; this experiment could also be done based on electromagnets and feeding through sliding rings.

Table 3. Primary motor speed, receiver LC circuit Frequency Vs Open Circuit Voltage, parallel resonance in wireless transmission of electrical energy experiment carried out at the Technological University of Havana, E = f (Freq)

Test	Speed Motor (rpm)	Frequency receiving LC circuit Oscilloscope(Hz)	Frequency rotatory magnetic field (rps)	Frequency average (Hz)	Difference of Frequency (Hz)	Open circuit Voltage (V)
1	308	20,66	20,53	20,6	0,07	0,512
2	397,4	26,32	26,49	26,41	0,08	0,742
3	495,8	31,25	33,06	32,16	0,9	1,07
4	619,8	40,98	41,32	41,15	0,17	1,97
5	735	49,02	49	49,01	0,01	4,48
6	785,4	53,19	52,36	52,78	0,42	7,42
7	803,2	54,35	53,48	53,92	0,44	8,36
8	833,4	55,56	55,56	55,56	0	9,32
9	867	58,14	57,8	57,97	0,17	7,18
10	882	59,52	58,8	59,16	0,36	5,98
11	925,8	61,1	61,71	61,41	0,3	4,53
12	943,2	62,79	62,88	62,84	0,04	3,74
13	987	65,44	65,8	65,62	0,18	3,07
				49,122	0,242	

Evidently, the LC receiver circuit in parallel resonance behaves in a wireless transfer of magneto-motive energy in a very similar way to a commercial wireless transfer of electromagnetic energy, the difference between the theoretical calculation of the resonance frequency and the value obtained experimentally (55.87Hz Vs 55.56Hz) can be considered negligible (0.6% error) in the resonance analysis. The behavior with load (active resistance R_L=5ohm) of the series LC resonant circuit shown above is shown in figure 10, the influence of the load parameters slightly shifts the resonance frequency previously reached in no-load characteristic.

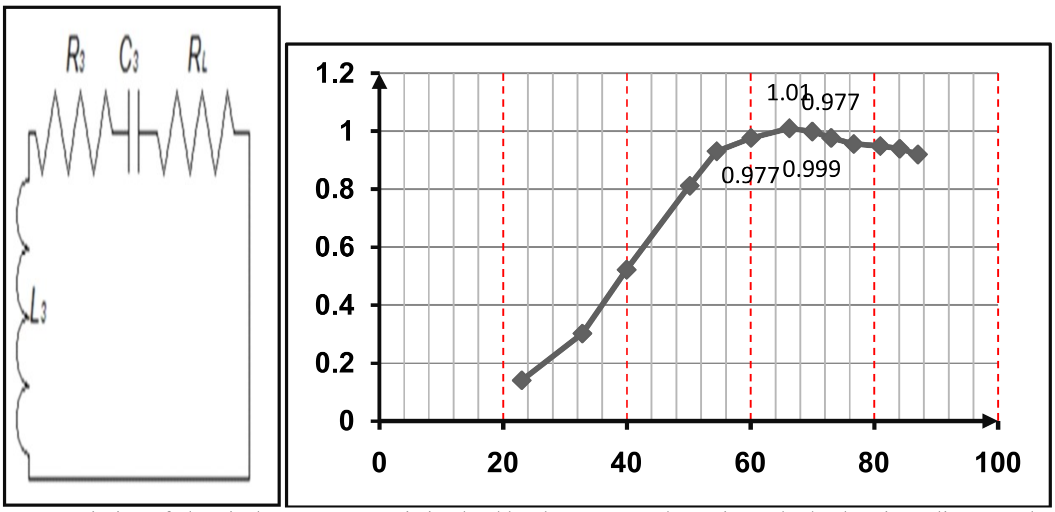

Fig. 6. Wireless transmission of electrical energy to a resistive load by the magneto-dynamic method: Electric outline. Graph V_{Load} Vs Freq. Parameters in the experiment

The first successful transmission of this century with wireless power carried out in 2007 at the MTI worked with a 9.9MHz transmission frequency, while today commercial wireless battery charging in electric vehicles is carried out at approximately 85kHz, but these experiments did not even reach 100Hz transmission frequency, if we return to equation (1), that expresses the efficiency of wireless transmission, observe that the most influential parameters are the frequency and the mutual inductance, very dependent on the distance, angle and permeability of the medium between the transmitter. and receiver, the most influential resource to use in a future design is the frequency, which would be given by the number of magnets, electromagnets or combination of both used.

The transmission frequency in the proposed case of magneto-dynamic transmission is given by the equation (7).

$$f = \frac{rpm}{60} \times pairpoles \qquad (7)$$

Evidently, the magneto-dynamic resonant method causes energetically in the receiving LC circuit a similar effect as the transmission with power electronic circuits that is used commercially today, but with the advantage that, unlike the current method where the variation of the magnetic flux with the required magnetic energy, it is done by consuming from an external source, now the required magnetic energy is extracted from powerful permanent magnets that do not consume from an external source, and where rotation with a large air gap creates very weak antagonistic electromagnetic braking torque.

Possible example with appropriate conditions R&D
Permanent neodymium magnets (type S-05-04-N) [18-20] are rotating in a non-magnetic disk of diameter 35cm (0,35m).
Exterior length: π x 0,35 = 1.1m.
Total bearing force: 0.86Kg X 400 units = 344Kg (N45).
Approximate total energy 1meter height holding that weight (figure 7), (344kg are approximately a third of 1 ton): See equation (8).

$$E_{Magn} \approx E_{Grav} = mgh = (344kg)\left(9,81\frac{m}{s^2}\right)(1m) = 3,37kJ \qquad (8)$$

The E_{Grav} physically is a similarity that is made to facilitate an approximate calculation of the potential magnetic energy in rotation, assuming a receiver-transmitter distance equal to 25cm.

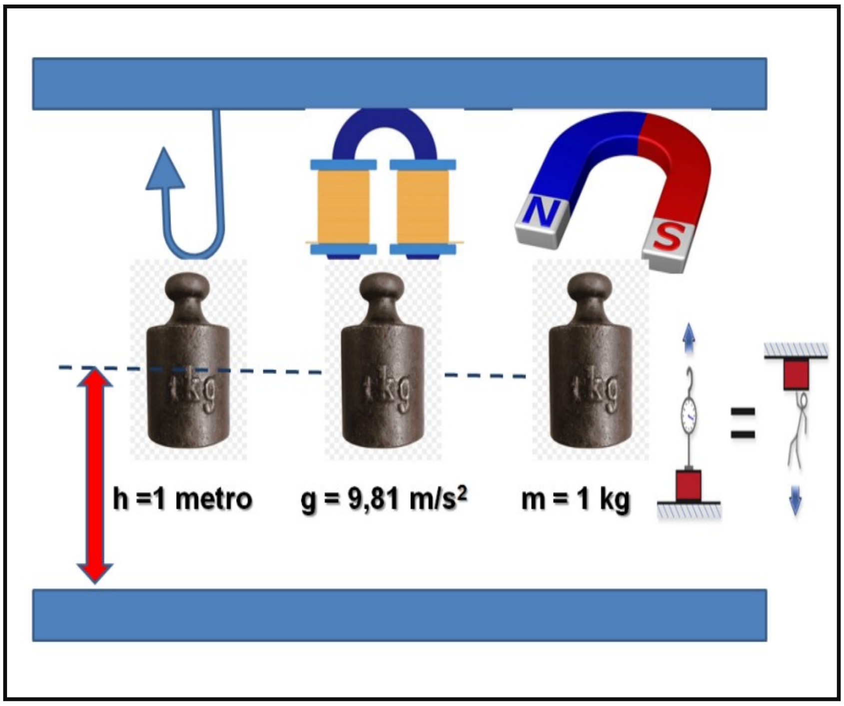

Fig. 7. The potential energy of the permanent magnet based on its bearing force (without extra influences) is assumed to qualify and quantify the magnetic energy in Joules

With Speed =3600 rpm = 377rad/s and 400 units of 0.6g each is a total of 240g, to which we must add the disk that carries the 400 permanent magnets for rotation, which weighs 0.33kg, in total 0.57kg, the electromagnetic torque antagonistic to the movement developed by an armature 25cm away cannot develop an appreciable brake. See equation (9), [21].

$$\begin{aligned}
&J = mr^2 = 0,57\left(\frac{0,35}{2}\right)^2 = 0,017 \\
&J\omega = 0,017\left(377\right) = 6,58 \\
&T_{Fric+Bat} \approx 0,07\left(6,58\right) = 0,37 \\
&T_{EM} \approx 0,1 \\
&T_{Total} = J\omega + T_{Fric+Bat} + T_{EM} \approx 7,05 \\
&P_{Motor} > \omega\left(T_{Total}\right) = 377\left(7,05\right) = 2,66kW \\
&P_{Motor} \cong 3kW \\
&f = \frac{rpm}{60} \times pairpoles = \frac{3600}{60} \times \frac{400}{2} = 12kHz
\end{aligned} \tag{9}$$

In other words, with an approximate consumption of 3kW (with margin to cover all possible losses), a magnetic field formed by 400 poles moves, developing a potential energy equivalent to 3,37kJ, rotating at 3600rpm for a frequency of 12kHz. In the table 1, we can observe that a mini hydro-generator of 200kVA uses a power of excitement of 3,3kW and in this case we are moving an energy magnetic potential of 3,37kJ and to a speed of change of flow of 12kHz, consuming 3kW approximately in that rotation, if we assume to achieve 7,5% of 200kVA (160kW) for all the implications that have 25cm of gap they will be 12kW like current EV wireless charging. The 12kHz is an easy resonant frequency to find commercial values of L and C in the receiving block, solving in the equation, with the value of C we solve for L or vice versa. See equation 10.

$$f = \frac{1}{2\pi\sqrt{LC}} \rightarrow f^2 = \frac{1}{4\pi^2 \times LC} \therefore LC = \frac{1}{\left(2\pi f\right)^2} \tag{10}$$

With the current technologies applied to magneto-dynamic wireless transmission, very promising results can be achieved, since it is possible to rotate with precision at these speeds and even higher a certain number of permanent magnets that could also be greater and that can be designed specifically for this end.

RESULTS ACHIEVED

Despite technological shortcomings for the execution of the experiments, it has been demonstrated that the transmission of wireless electrical energy by the dynamic magnet method is physically possible, so its future development is already being carried out successfully [22], at Griffith University, Australia.

CONCLUSIONS

The importance of wireless transmission of electrical energy for recharging batteries will grow in the future due to the comforts it implies for the user who just by parking in the indicated place, can recharge their vehicle's batteries or charge their cell phone without the need for connectors for that purpose. The possible development in a future, maybe be able to bring near to the dream that Nikola Tesla could not reach due to the lack of support of J. P. Morgan with the transmission of wireless energy.

The development of this magneto-dynamic resonant wireless charging option for batteries is yet to be born, it is potentially demonstrated in the body of this article that it is physically and mathematically a reality, a possible successful development in wireless charging of electric vehicles (EV) allowing this technology be applicable in wireless mobile charging too. The great development of the permanent magnet achieved today allows it to be manufactured specifically with the bearing force and physical form required for an optimal future design, and just like a computer hard disk, high rotation speeds can be achieved mechanically of excellence; while the control of the load current can be obtained by varying the distance between transmitter and receiver through a servo - mechanism for this purpose.

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CONFLICT OF INTERESTS

Los autores declaran que no existe conflicto de intereses.

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