ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA

Wireless Power Transmission

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Madrid
July 2016

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WIRELESS POWER TRANSMISSION

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Entidad Colaboradora: Universidad Pontificia Comillas (ICAI); Colorado School of Mines.

RESUMEN DEL PROYECTO

Introducción

La transmisión de energía sin cables se basa principalmente en el fenómeno de la inducción, descubierto por Michael Faraday en 1831. Mediante este proceso somos capaces de transmitir energía, desde cualquier fuente de alimentación, a diferentes dispositivos sin el uso de ningún tipo de cable conductor.

A día de hoy estos sistemas inalámbricos están formados por una bobina transmisora, conectada directamente a una fuente de alimentación, y por una bobina receptora, encargada de recibir y transformar los campos magnéticos en corriente eléctrica. Todos estos elementos a su vez, están rodeados de una serie de elementos de electrónica de potencia encargados de transformar las diferentes corrientes en función de las necesidades del sistema.

Este método tiene una infinidad de aplicaciones, especialmente es muy útil para aquellas situaciones en las que los cables son los culpables de ciertas incomodidades o peligros. En este proyecto vamos a estudiar un amplio abanico de aplicaciones, desde aplicaciones en el área sanitaria hasta aplicaciones en el área del transporte. Nos centraremos principalmente en el estudio de la implantación de este método en los vehículos utilitarios. Para ello, analizaremos su uso en dos situaciones totalmente distintas, con el vehículo en movimiento y estacionado.

Nuestro principal objetivo será el de analizar si es rentable el uso de este sistema para distintas aplicaciones. Para ello, simularemos y analizaremos posteriormente el impacto que tendría en la sociedad actual.

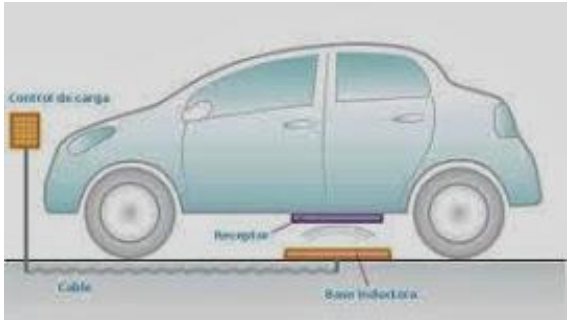
Metodología

Las simulaciones las realizaremos mediante el programa informático Matlab/Simulink. Nuestro proyecto va a estar separado en dos partes claramente diferenciadas.

En la primera parte del proyecto analizaremos la idea del vehículo en movimiento. Para ello, simularemos de forma experimental, la cantidad de flujo magnético que recibiría un vehículo autoritario a la hora de circular sobre un carril, caracterizado por la implantación de sistemas de transmisión eléctrica inalámbrica.

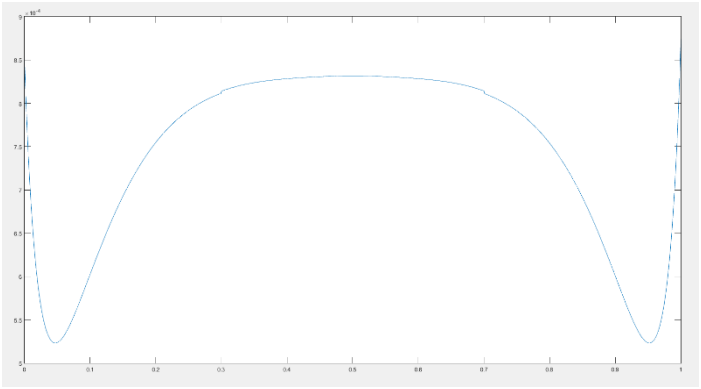
Con el objetivo de representar con la mayor fiabilidad posible nuestra potencia de carga recibida, diferenciaremos las diferentes cantidades de flujo magnético captado por la bobina receptora, en función de la posición en la que esté respecto a la bobina transmisora.

En la segunda parte del proyecto nos encargaremos de analizar la idea del vehículo cuando está estacionado. Para ello, simularemos y analizaremos cómo sería la implantación de este sistema, cuando es combinado con otros sistemas de carga. Usaremos diferentes códigos de Matlab/Simulink que nos ayudarán a analizar de forma clara y precisa los diferentes estados de carga de las baterías presentes en un coche eléctrico.

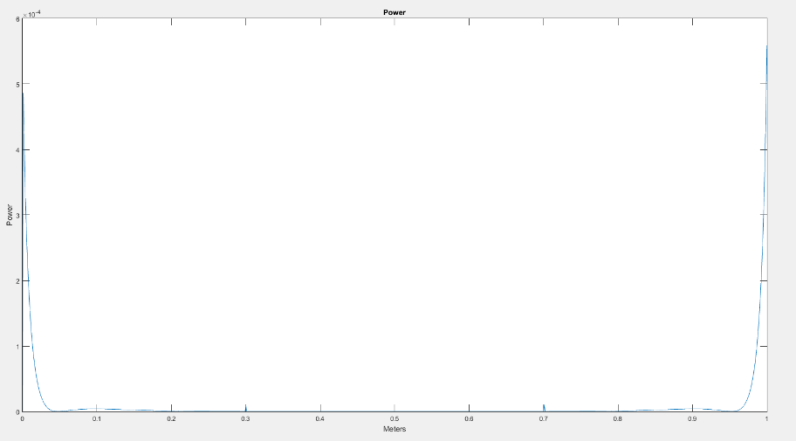


Resultados

Los resultados que hemos obtenido para nuestra primera parte del proyecto, es decir, la del coche en movimiento es el siguiente:



En esta gráfica podemos ver el flujo que le llega a la bobina receptora, quedando clara constancia de que la mayor cantidad de flujo se recibe cuando la placa receptora está inmersa en el campo magnético de la capa transmisora. Si traducimos esta gráfica a un sentido más económico obtenemos el siguiente resultado:

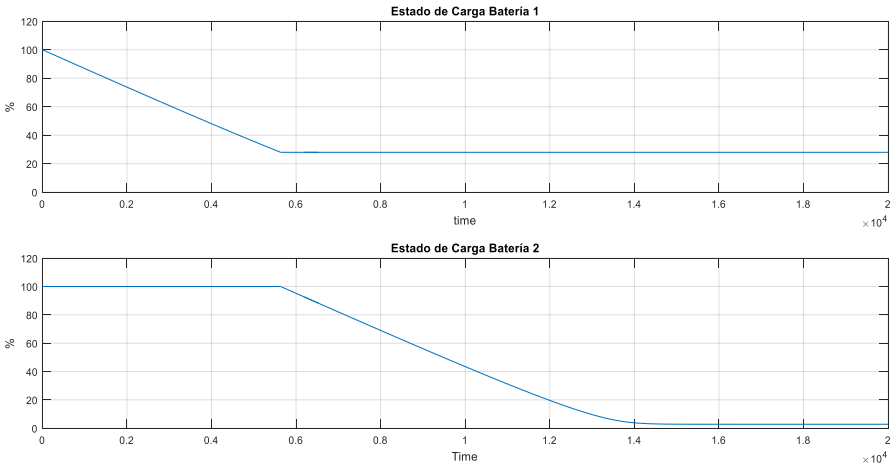


Por lo tanto, en esta gráfica observamos la potencia total que se le suministraría al motor de un vehículo eléctrico en caso de usar este método, como forma de carga. Como podemos ver en la parte central de nuestra bobina donde el flujo era mayor, nuestra potencia es prácticamente nula, ya que nuestro flujo es constante.

Para la segunda simulación, no ha sido necesaria el cálculo de la corriente convertida por la bobina receptora, ya que debido al uso del núcleo de hierro y al

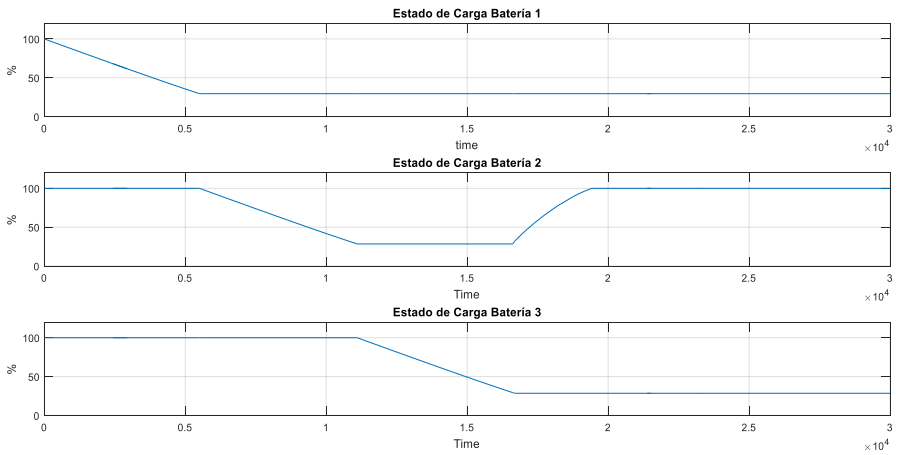
mecanismo que pone prácticamente en contacto ambas bobinas, no obtenemos pérdidas en la transmisión inalámbrica. Por lo tanto, en estas simulaciones hemos puesto en marcha este sistema combinado con otros sistemas de carga:

1ª Combinación: Manguera Convencional y Conexión Inalámbrica



En esta simulación podemos observar el tiempo total de descarga de dos baterías conectadas a la misma carga.

2ª Combinación: Manguera Convencional, Conexión Inalámbrica y Sistema Renovable



En esta simulación al igual que en la anterior podemos ver una serie de baterías conectadas a la misma carga. La única diferente que hay es que en esta simulación hemos incorporado un sistema forma de carga renovable cuando el coche está en movimiento. Lo podemos observar en el estado de carga de la batería 2.

Conclusiones

Después de haber simulado y haber hecho un pequeño análisis de cómo sería el impacto de este método en la sociedad podemos decir que el principal problema al que se enfrentan este tipo de tecnologías es la distancia de transmisión.

Como hemos visto en la primera simulación, la potencia que recibiría un coche en caso de usar el sistema de carga inalámbrica, es prácticamente nula. Por lo tanto, a efectos de un consumo particular podemos decir que es algo inviable.

Sin embargo, con la segunda simulación, sí que hemos obtenido buenos resultados. Ya que la potencia que obtendría el vehículo, sería prácticamente la misma que la que se obtendría con la manguera convencional, mientras que con este método podríamos suplir todos los problemas que se presentaban anteriormente.

Como conclusión decir, que sin duda alguna la transmisión inalámbrica va a ser una clave en el desarrollo de tecnologías futuras, pero a día de hoy podemos decir que es muy complicado hacer frente al gran problema que presente la disipación del campo magnético en el aire.

WIRELESS POWER TRANSMISSION

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ABSTRACT

Introduction

The wireless power transmission is mainly based on the phenomenon of induction discovered by Michael Faraday in 1831. Through this process we are able to transmit power from any power supply, to different devices without using any wire.

Today these wireless systems consist of a transmitter coil, connected directly to a power supply, and a receiver coil, in charge of receiving and transforming the magnetic fields into electricity. All these elements are surrounded by a number of power electronics elements responsible for transforming the different currents according to the system needs.

This method has many applications, especially is very useful for those situations where wires are to blame for certain discomforts or dangers. In this project we will study a wide range of applications, from applications in the health area to applications in the area of transport. We will focus primarily on the study of the implementation of this method in commercial vehicles. To do this, we use two completely different situations, with the vehicle in motion and stationary.

Our main objective will be to analyze whether it is cost-effective the use of this system for different applications. To do this, we are going to simulate and after that we are going to analyze the impact on today's society.

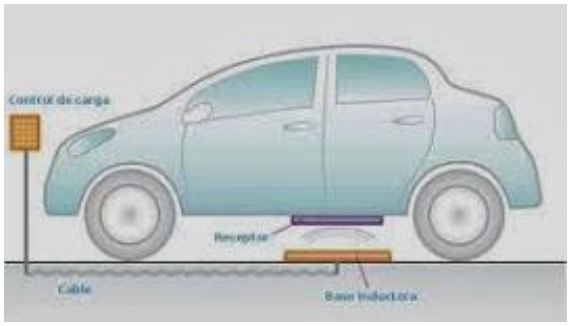
Methodology

The simulations will be conducted by the Matlab / Simulink software. Our project will be separated into two distinct parts.

In the first part of the project we will discuss the idea of moving vehicles. To do this, we will simulate experimentally, the amount of magnetic flux that the coil would receive in an authoritarian vehicle when it´s driving on a rail, characterized by the introduction of wireless power transmission systems.

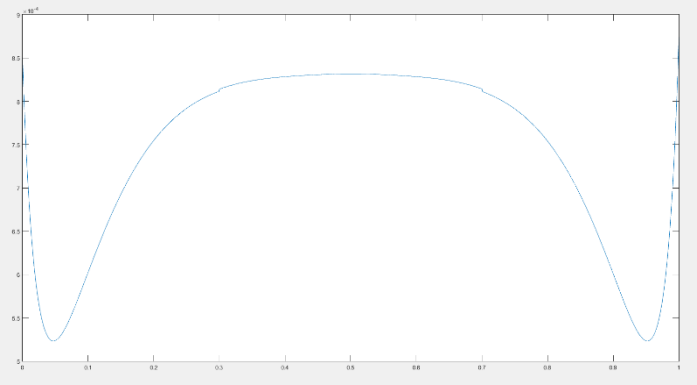
In order to represent, with the greatest reliability, the power received by our load we will differentiate the amounts of magnetic flux captured by the receiver coil, depending on the position in respect of the transmitter coil.

In the second part of the project we'll analyze the idea of the vehicle when it´s parked. To do this, we will simulate and analyze how would be the implementation of this system, when it´s combined with other charging systems. We will use different Matlab / Simulink codes to help us to analyze clearly and precisely the different states of charge of these batteries in an electric car.

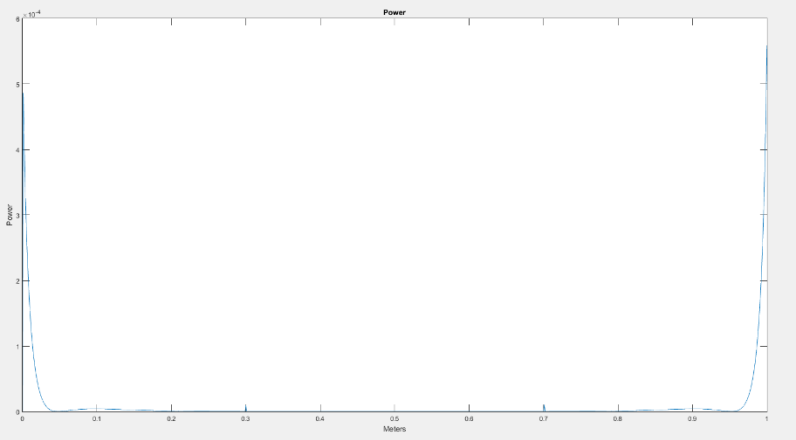


Results

The results that we have obtained for our first part of the project, ie, the car in motion is:



In this graph we can see the flow that reaches the receiver coil, leaving clear evidence that the greatest amount of flow is received when the receiving plate is immersed in the magnetic field of the transmitting plate. If we translate this figure to a more economic sense, we get the following result:

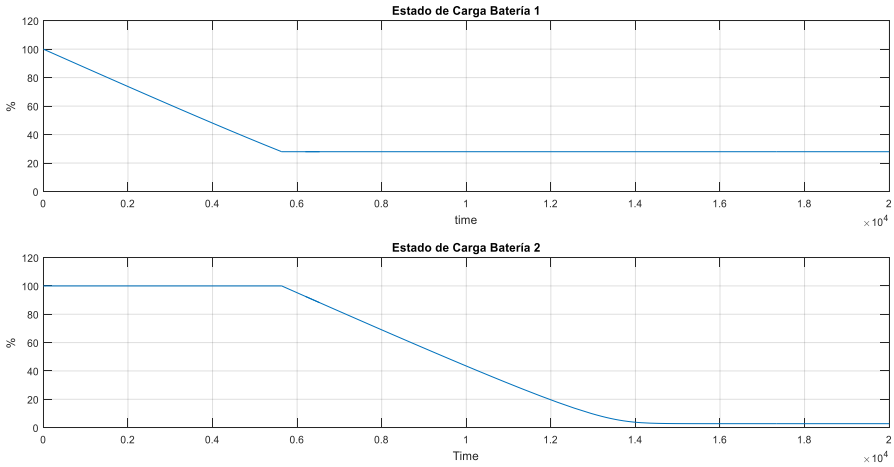


Therefore, in this graph we observe the total power that would supply the motor of an electric vehicle if we use this method as a way of loading. As we can see in the central part of our coil where the flow is bigger, our power is practically nil, as our flow is constant.

For the second simulation, the calculation of the current converted by the receiver coil it´s not necessary, since due to the use of the iron core and the mechanism which makes practically the contact of both coils, so we don´t get wireless

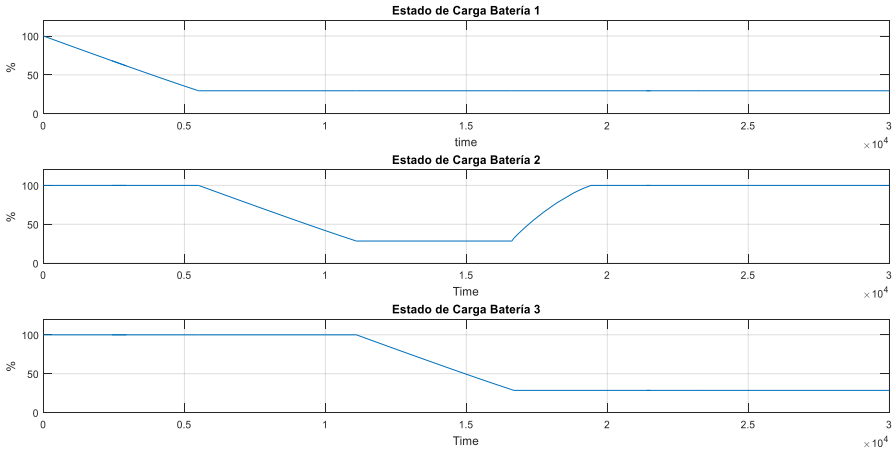
transmission losses. Therefore, in these simulations we have implemented this system with other charging systems:

First Combination: Conventional Hose and Wireless Connection



In this simulation we can see the total discharge time of two batteries connected to the same load.

Second Combination: Conventional Hose, Wireless Connection and Renewable System



In this simulation as in the above we can see a series of batteris connected to the same load. The only different is that is in this simulation we have incorporated a form of renewable charging system when the car is moving. We can observe in the state of charge of battery 2.

Conclusions

After having simulated and having done a little analysis of what would be the impact of this method in the society, we can say that the main problem of these technologies are the transmission distance.

As we saw in the first simulation, the power that the car would receive in case of using the wireless charging system, it is practically nil. Therefore, for the purposes of a particular consumption we can say that it is unworkable.

However, with the second simulation, we have obtained good results. Since the power to get the vehicle would be practically the same as the power that we obtained with a conventional hose, while this method could supply all the problems presented above.

In conclusion, we can say without any doubts that the wireless transmission will be a key in the development of future technologies. But nowadays we can say that it is very difficult to deal with the big problem of the magnetic field dissipation in the air.

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Chapter 1: Fundamentals

1. FUNDAMENTALS

To generate the wireless power transmission, we need two coils, a transmitter coil and a receiver coil. The process is the following one:

1. We need to connect the transmitter coil to a generator (battery)

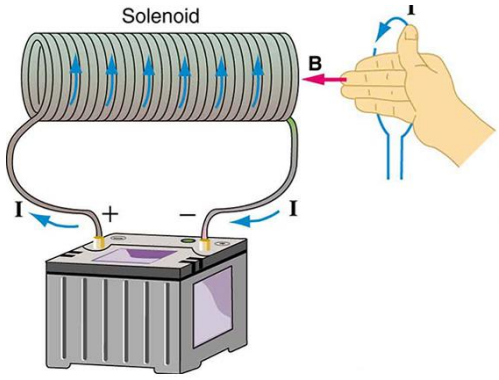

Fig. 1: Connection of a solenoid to a battery [1]

2. That battery generates a current across the coil

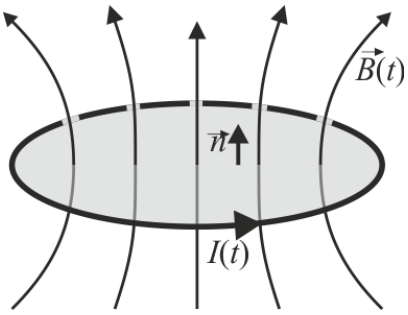

Fig. 2: Magnetic field generation [2]

3. That current at the same time creates a magnetic field. To determine the direction of the magnetic field we need to use the right-hand rules.

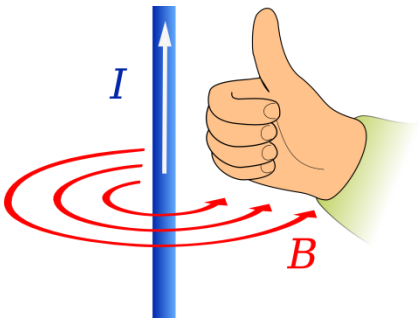

Fig. 3: Right-hand rule [3]

4. The magnetic field has this form:

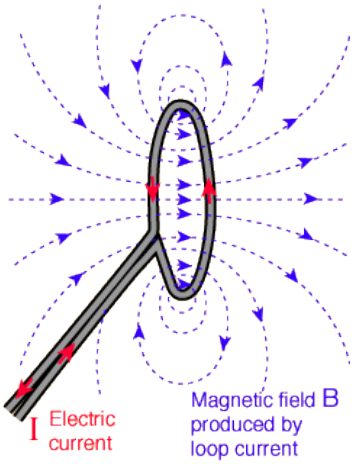

Fig. 4: Magnetic field on a current loop [4]

5. So if we approach the other coil, our magnetic field cross the new coil and creates an induced current.
6. That current is used to generate electricity.

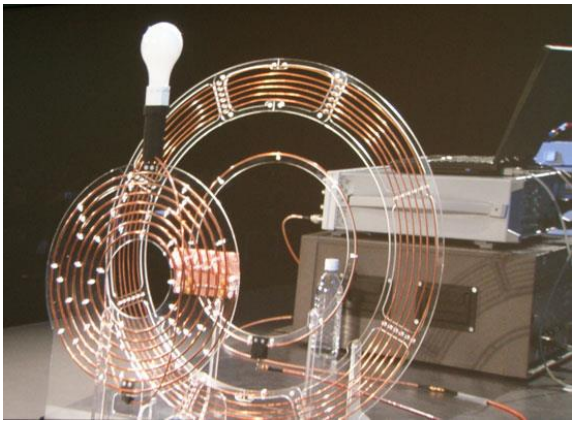

Fig. 5: MIT's experiment in order to prove that current can generate electricity [5]

Chapter 2: Scientific explanation

2. SCIENTIFIC EXPLANATION

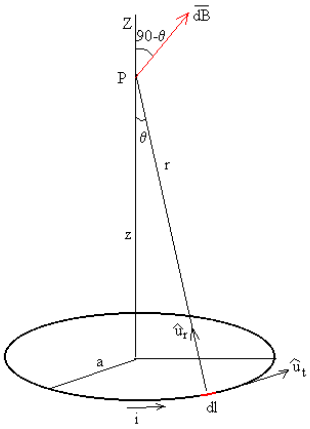

Fig. 6: Electric field in a circular coil with a radius 'a' [6]

When a current goes over the entire coil, generates a magnetic field. We are going to applicate the 'Biot's Law' to calculate this magnetic field:

$$dB = \frac{\mu_0}{4\pi} * \frac{u_t * u_r}{r^2} * dl$$

We have to notice that the vectors u_t and u_r are perpendiculars, so we can simplify this formula to:

$$dB = \frac{\mu_0}{4\pi} * \frac{u_t * u_r}{r^2}$$

So the vector magnetic field dB has two components:

1. dB*cos(90-Q): along the axis of the coil
2. dB*sin(90-Q): perpendicular to the axis of the coil

But we have to notice that if the dl portions create a magnetic field perpendicular to the axis of the coil, it should cancel because the symmetry ($dB * \cos(90 - \theta) = 0$). So we finally obtain:

$$B = \int dB * \cos(90 - \theta) = \frac{\mu_0}{4\pi r^2} * \sin\theta * \oint dl = \frac{\mu_0}{4\pi r^2} * 2\pi a \sin\theta = \frac{\mu_0}{2(\sqrt[2]{z^2 + a^2})^3}$$

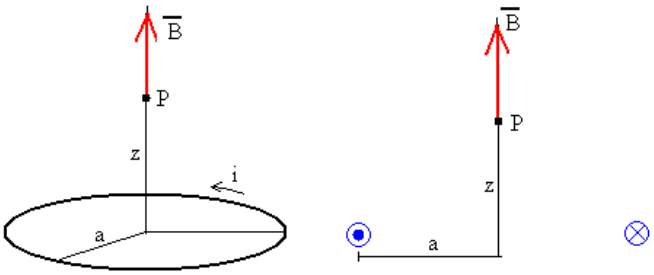

Fig. 7: Magnetic field at the axis [6]

Chapter 3: Modelling and design configurations

3. MODELLING AND DESIGN CONFIGURATIONS

We have two different ways of modelling it:

1. A basic model with two coils

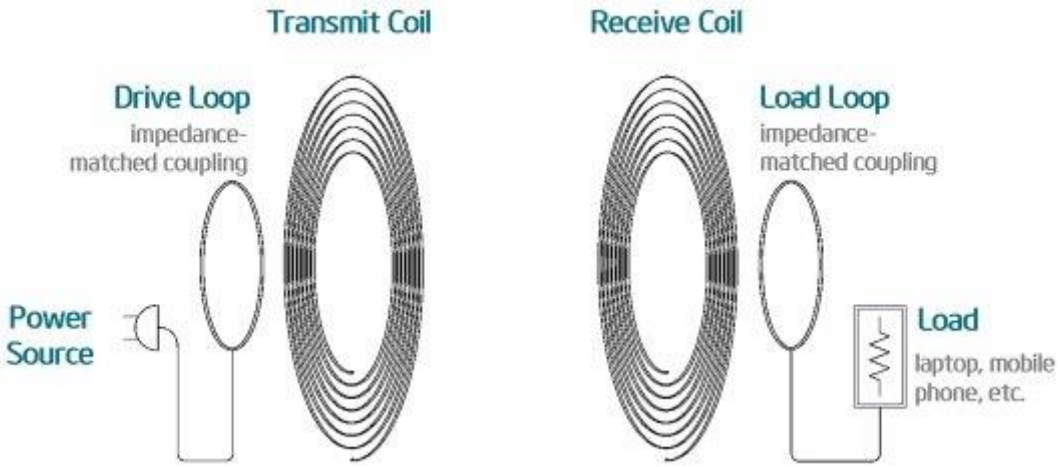

Fig. 8: Wireless power transmission system using two coils [7]

2. A model using a Tesla coil

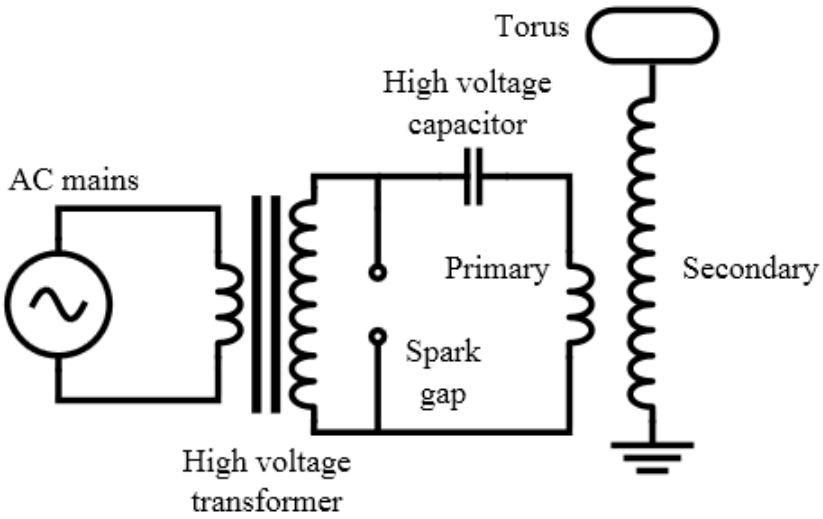

Fig. 9: Wireless power transmission system using a Tesla coil [8]

But this project is principally based on the basic two coils model as it's the most used model nowadays.

Chapter 4: Limitations

4. LIMITATIONS

4.1. Distance and Capacity

As we all know, one of the principal problems of this model is the distance. The energy needs a transmission medium. Therefore, analyze these problems is going to be one of the targets of this project. According to previous reports we know that:

- MIT's (Massachusetts Institute of Technology) introduced the Coupled Magnetic Resonance System in 2007, which used a magnetic field to transfer energy for a distance of 2.1 meters.
- Chun T. Rim, a professor of Nuclear & Quantum Engineering at KAIST, and his team showcased, on April 16, 2014 at the KAIST campus, Daejeon, Republic of Korea, they developed the "Dipole Coil Resonant System (DCRS)" for an extended range of inductive power transfer, up to 5 meters between transmitter and receiver coils [9].

We will now study why does this happen.

- Magnetic permeability

In physics we call magnetic permeability to the ability of a substance to attract and pass through magnetic fields, which is given by the relationship between the ratio existing magnetic induction and the magnetic field strength on the inside of the material.

The degree of magnetization of a material in response to a magnetic field, is called absolute permeability and is usually represented by the symbol μ

- *Relative permeability*

$$\mu = \frac{B}{H}$$

To compare other materials, we define the absolute magnetic permeability (μ) as the product of the relative magnetic permeability (μ_r) and vacuum magnetic permeability (μ_0):

$$\mu = \mu_r * \mu_0$$

We can classify the materials according to their relative magnetic permeability:

- Ferromagnetic: materials whose value of relative magnetic permeability is greater than 1. These materials attract the magnetic field inward. Therefore, they "adhere to the magnets"
- Paramagnetic or nonmagnetic: materials whose relative permeability is about 1 (behave as vacuum). These materials are found in nature. They do not show ferromagnetism, and their reaction to magnetic fields is very despicable.
- Diamagnetic: materials with less than 1 relative magnetic permeability. Diamagnetic materials repel the magnetic field, causing it to pass through the outside of the material. In general, this action is very weak, and is not comparable to the effect of the magnetic field on ferromagnetic materials. An example of diamagnetic material is copper.

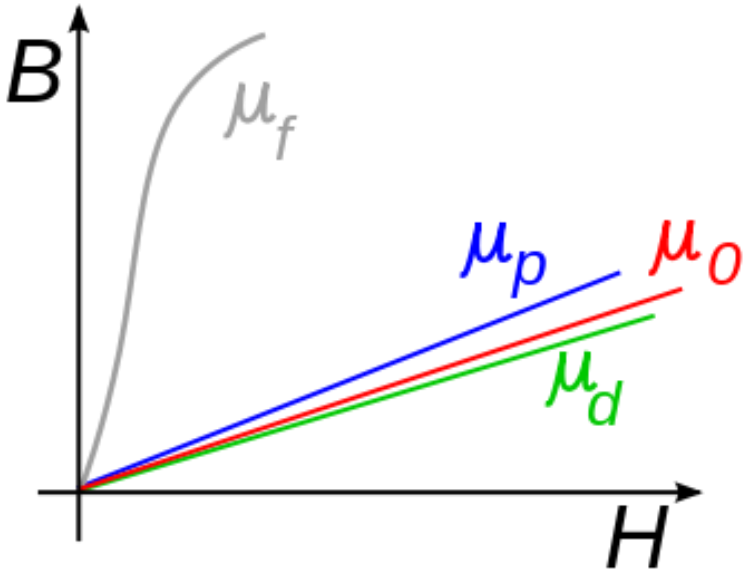

Fig. 10: Comparison of different permeability where μ_f is the permeability of ferromagnetic materials, μ_p is the permeability of paramagnetic materials, μ_0 is the permeability of free space and μ_d is the permeability of diamagnetic materials [10]

This project is basically based on paramagnetic materials, because our conductor is going to be the air.

4.2. Health Effect

There is no question that, above certain values, of electromagnetic fields can trigger biological effects. According to experiments conducted with healthy volunteers, short-term exposures to the levels present in the environment or at home do not produce any harmful effects. Exposure to higher levels that could be harmful is limited by national and international guidelines. The controversy arises today centers on whether low levels of long-term exposure can produce biological responses and influence the welfare of people [11].

Fig. 11: New about the danger of electromagnetic fields [11]

4.2.1. The International Project CEM

In response to the growing concern of society about the potential health effects of exposure to a growing number and variety of sources of electromagnetic fields, the World Health Organization (WHO) launched in 1996 a large multidisciplinary research project. International Electromagnetic Field Project or "International EMF Project" brings together current knowledge and available resources of agencies and international and national key scientific institutions.

In the last 30 years, approximately 25,000 articles have been published on the biological effects and medical applications of non-ionizing radiation. Although some people think that more research is needed, scientific knowledge in this field are now wider than those for most chemicals. Based on a thorough review of the scientific literature, the WHO concluded that the existing results do not confirm that exposure to low-intensity electromagnetic fields cause any health consequences.

4.3. Materials

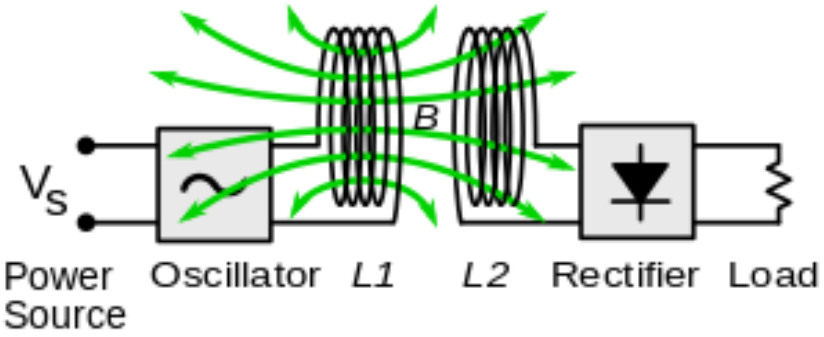

Fig. 12: Inductive wireless power system [12]

In our project we will not need a DC / AC converter input, because our system will be connected directly to the grid. Therefore, to generate the electric field, only we need power source and a coil. However, at the output of the second coil we can place an AC/DC converter to change the signal reached our load AC to DC, as we shall see below:

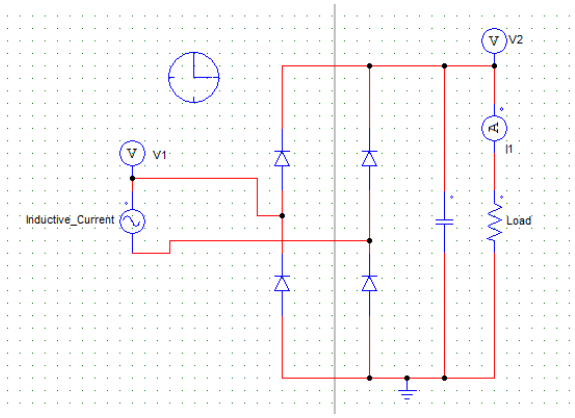

Fig. 13: Electronic scheme of and AC/DC converter obtained with PSIM

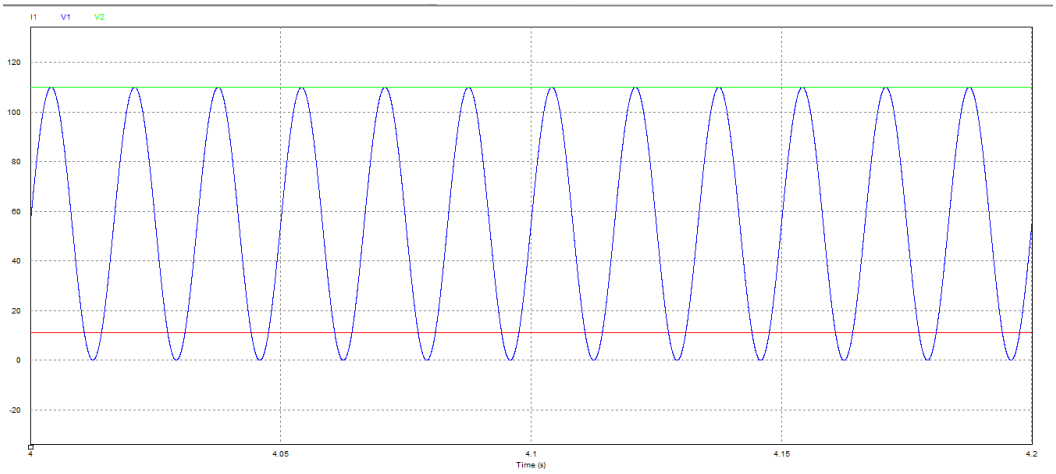

Fig. 14: Current, voltage1 and voltage2 obtained in the electronic circuit of figure 13 obtained with PSIM

Chapter 5: Survey of commercial or experimental solutions in the market

5. SURVEY OF COMMERCIAL OR EXPERIMENTAL SOLUTIONS IN THE MARKET

5.1. Effects of the wire transmission in our society

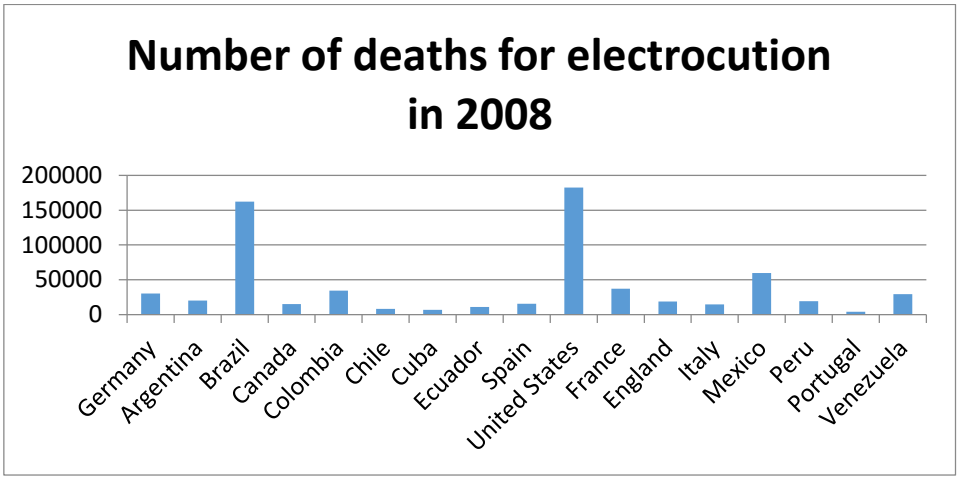

Fig. 15: Number of deaths for electrocution in 2008 [13]

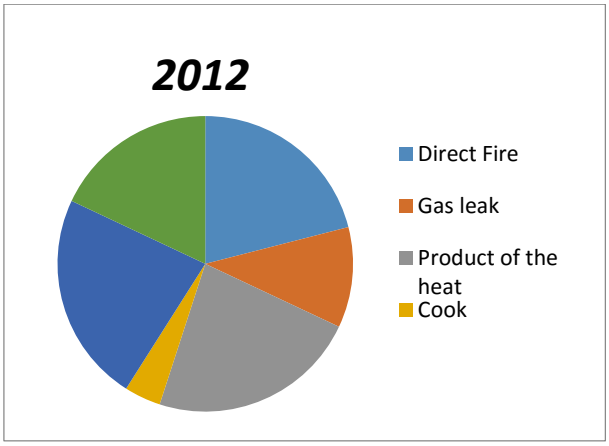

Fig. 16: Fire causes in 2012 [14]

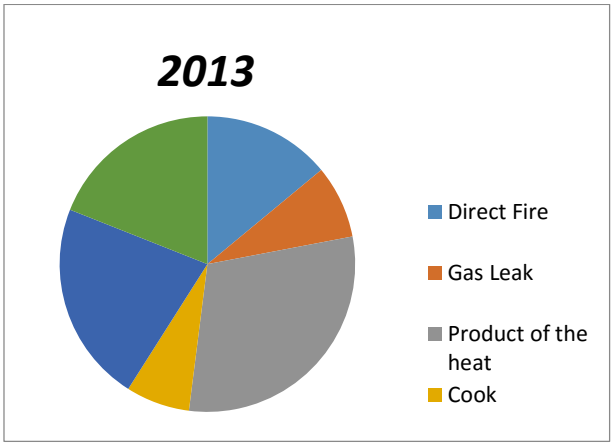

Fig. 17: Fire causes in 2013 [14]

Therefore, thanks to the wireless power transmission studied in this project we will be perfectly allowed to solve all these problems.

5.2. Analysis of a normal house

We are going to analyze a normal apartment (basic degree of electrification=5750 W), in order to calculate the number of wires that we need to transmit this amount of power.

Fig. 18: Plane of an apartment [15]

Loading elements:

- Plugs: 30/40
- Lighting spots: 10/15

5.3. Costs of installation

To make the installation we are going to use the H05V-K & H07V-K wires:

- Wire of 1.5 mm^2: lighting (23.22 €)
- Wire of 2.5 mm^2: plugs (42.50 €)
- Wire of 4 mm^2: washing machine, drier.. (58.58 €)
- Wire of 6 mm^2: kitchen and oven (86.09 €)

The prices are based on 100 meters of wire.

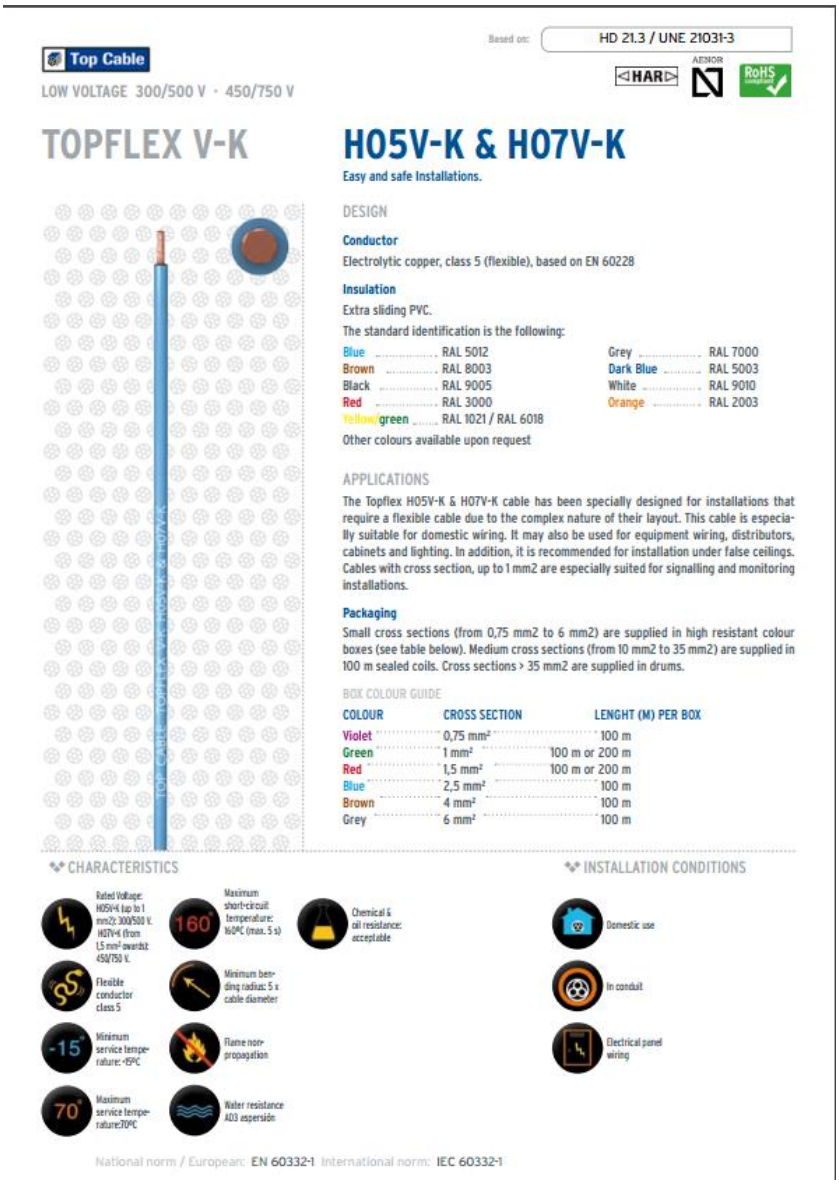

Fig. 19: Catalogue of the wire prices [16]

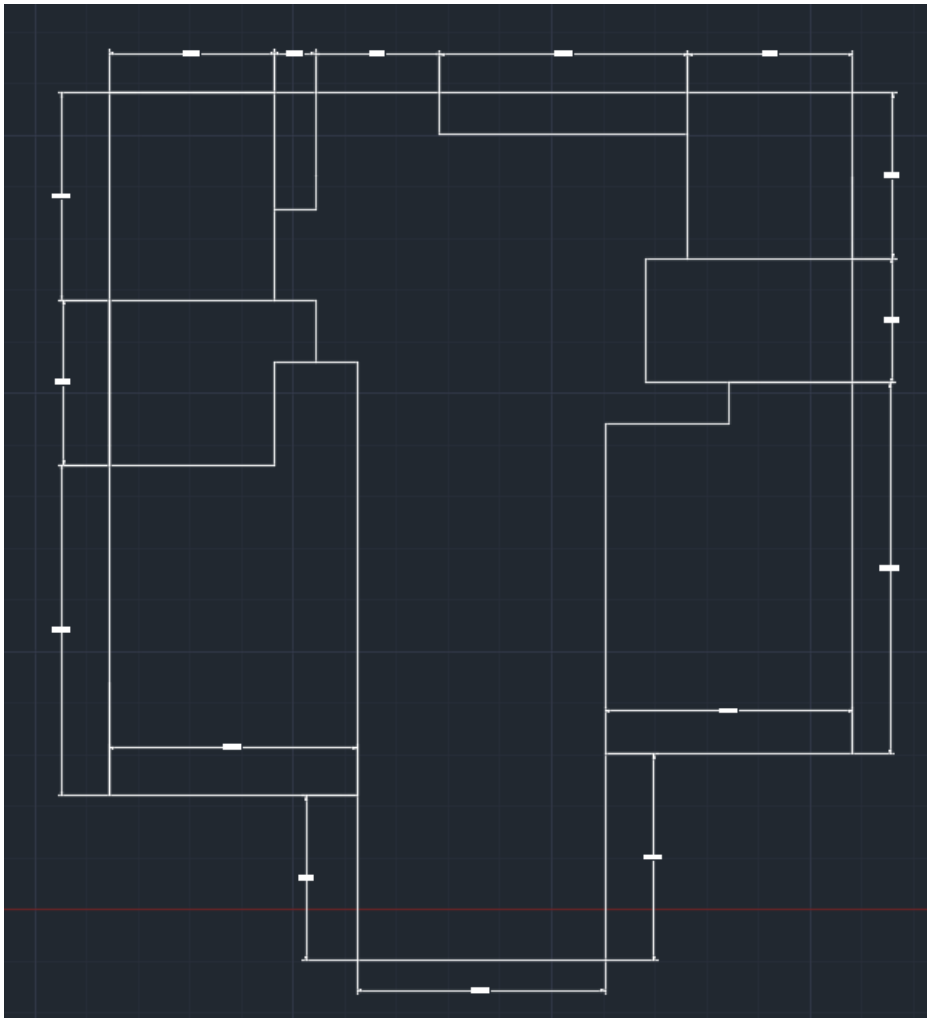

Fig. 20: Plane of a house with proportional distances obtained with AutoCAD

Therefore, the amount of wires that we need to use in this installation is:

	Type of Wire			
	1.5 mm^2	2.5 mm^2	4 mm^2	6 mm^2
Quantity (m)	50	40	10	10
Price (€)	11.61	17	5.85	8.609
Total	43.06			

Table 1: Meters of wire needed in the installation [17]

We need to add the price of the wiring installation:

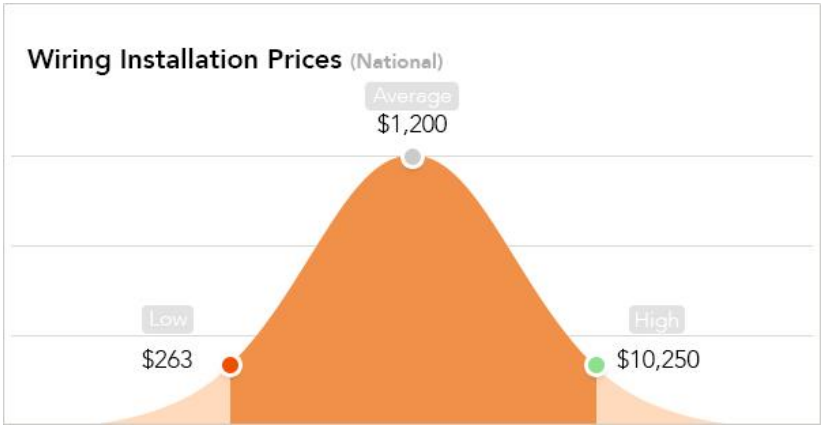

Fig. 21: Price of the wiring installation [16]

Finally, we must consider the maintenance and service life of the wires that we are going to install. Since the average of the life of the wires is around 40-50 years.

5.4. Analysis of the price of Copper

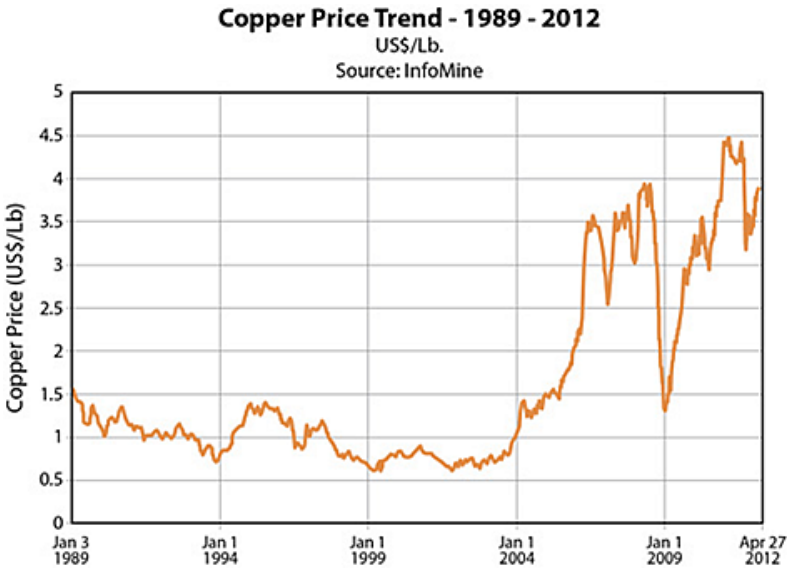

Fig. 22: Copper price trend in the last few decades [18]

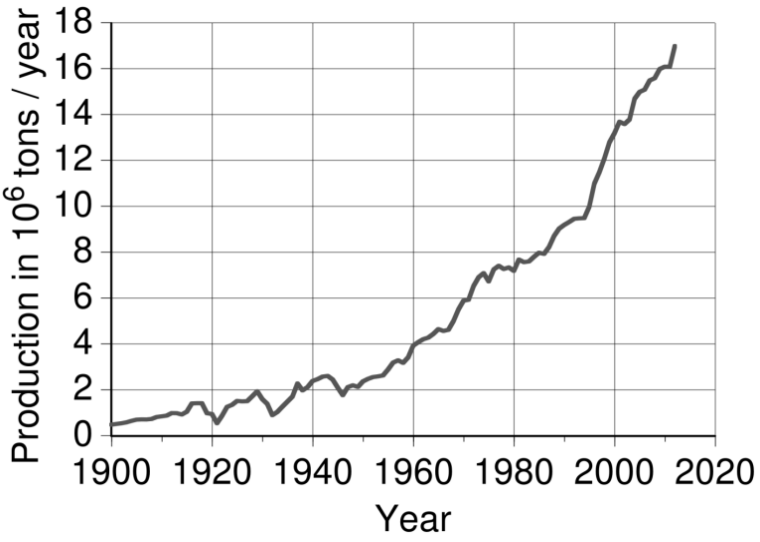

Fig. 23: Trend of production of copper in the last few decades [18]

During the last years the price and the production of the copper have been increasing considerately as we can see in both graphics. This increase is due to the rise of the amount of wires presents in our society. With this project our objective is to reduce the number of wires. Therefore, we can also reduce the huge environmental impact that the copper factories make when we try to obtain the copper [18].

Chapter 6: Applications

6. APLICATIONS

6.1. Electronic portable devices

Fig. 24: Energy distribution in a living room [19]

Using a central generator in the middle of a common room, we can distribute energy to other devices, as you can see in the picture. With this method we can delete the need to have wires all around the room. So we can reduce considerately the number of:

- Deaths from electrocution
- Fires

This system generates enough energy to power televisions, computers, mobile phones...

6.2. Electric Vehicles

All public transportation systems have the need to perform various stops to pick up the users of these services. The estimated time at each stop could be used to charge the batteries of these vehicles and thus reduce fuel consumption. In the same way the time lost waiting for the traffic lights could be used by car drivers to charge their car.

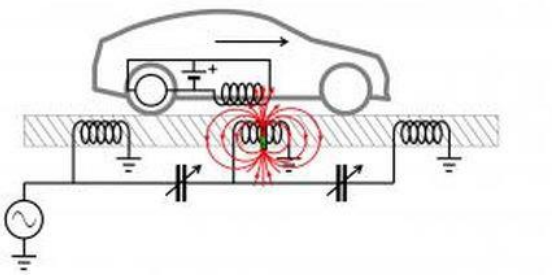

Fig. 25: Wireless power transmission in a car [20]

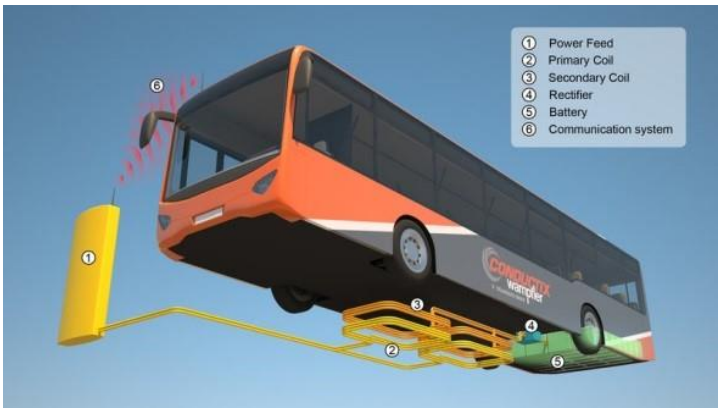

Fig. 26: Wireless power transmission in a bus [21]

Finally, we can create some kind of energy exchange system between trains and train tracks in order to energize the system without any fuel or connections through pantographs.

Fig. 27: Train track [22]

This method can be very efficient because the train is at all times in contact with the train tracks, so we would not have the problem of energy loss by the distance between source and receiver.

6.3. Medical applications

The use of pacemaker or any electronic device that serves to improve the proper functioning of a human organ is something very common in our society nowadays. These devices need to be continuously connected to a power source to function properly. This connection is done by cumbersome systems, very uncomfortable for the patient.

Therefore, through our system, which simply involves placing a receiver coil in our apparatus, we could eliminate the need for continuously conveying a connection system, as you can see in the picture below.

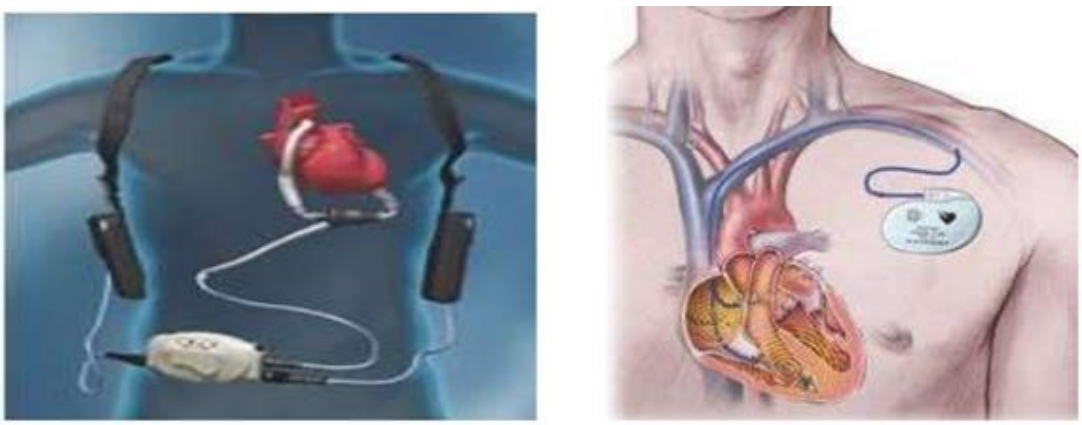

Fig. 28: Medical application of the wireless power transmission [23]

Chapter 7: Simulink analysis

7. SIMULINK ANALYSIS

We are going to analyze the behaviour of the magnetic field in a coil. Therefore we are going to change different parameters and analyze their impact in the magnetic field.

We know that the magnetic field that is produced by a solenoid is:

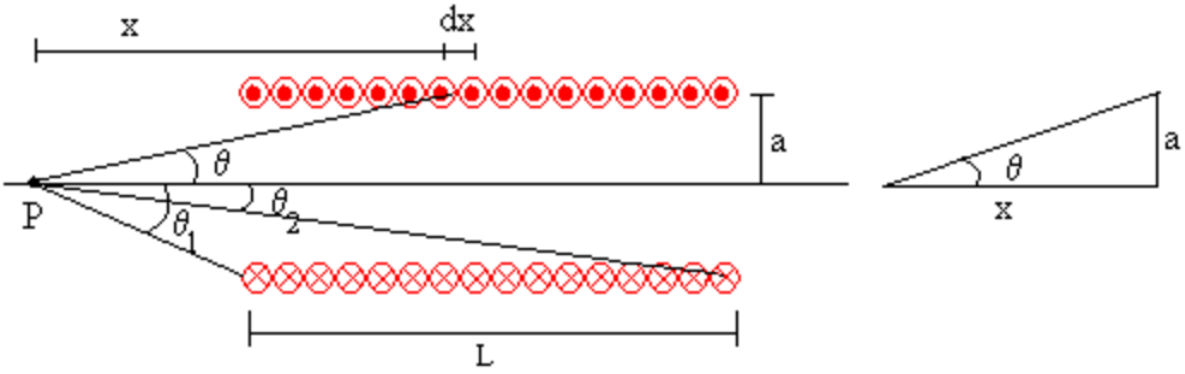

Fig. 29: Electromagnetic field produced by a solenoid [24]

$$B = \frac{\mu_0 * i * N}{2 * L} * (\cos(\sigma 2) - \cos(\sigma 1))$$

Where:

- μ_0= magnetic permeability
- I= current (A)
- N= number of turns
- L= length of the solenoid
- σ= angle(radians)

So the parameters that we are going to maintain constants are:

- μ0= $4*\Pi*10^{-7}$ $N*A^{-2}$
- I= sine wave (Amplitude=1, Frequency=1)

Therefore the paremeters that we are going to change are:

1. Distance
2. Number of turns
3. Lenght

Applying the formula in a Simulink Model, we obtain:

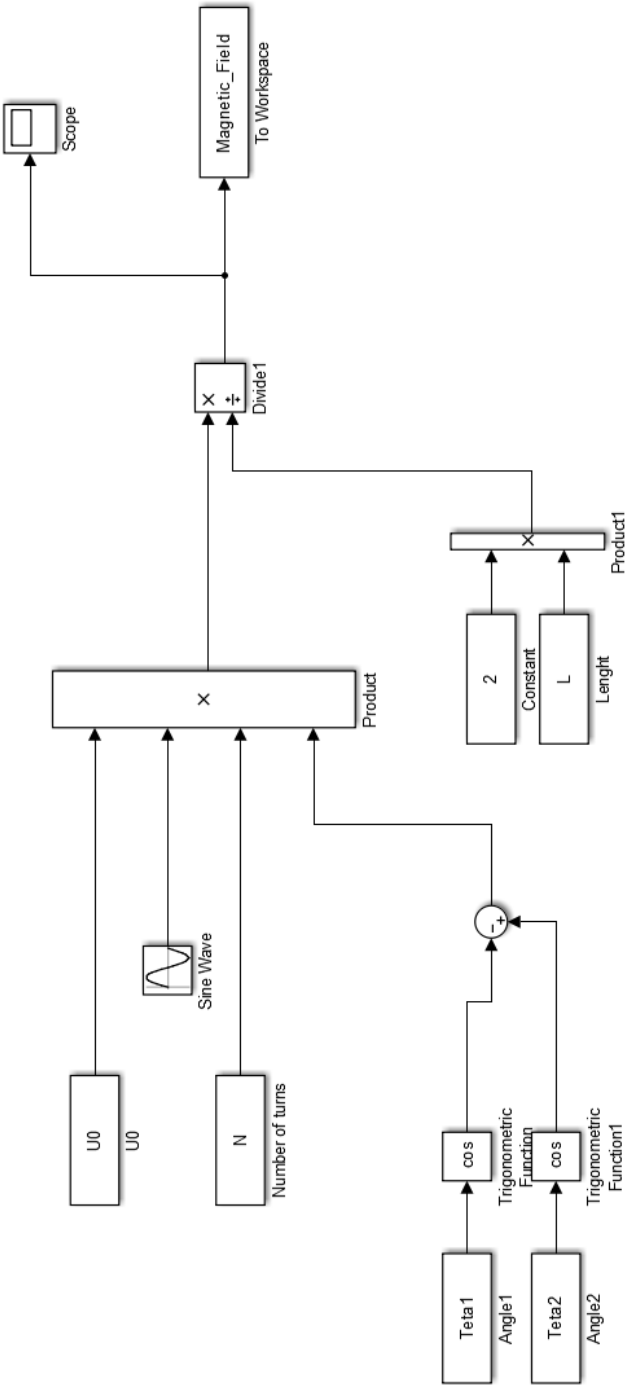

Fig. 30: Simulink model of the magnetic field produced by a solenoid

7.1. Distance

7.1.1. Magnetic Field: 0.1, 0.2, 0.3, 0.4, 0.5 m

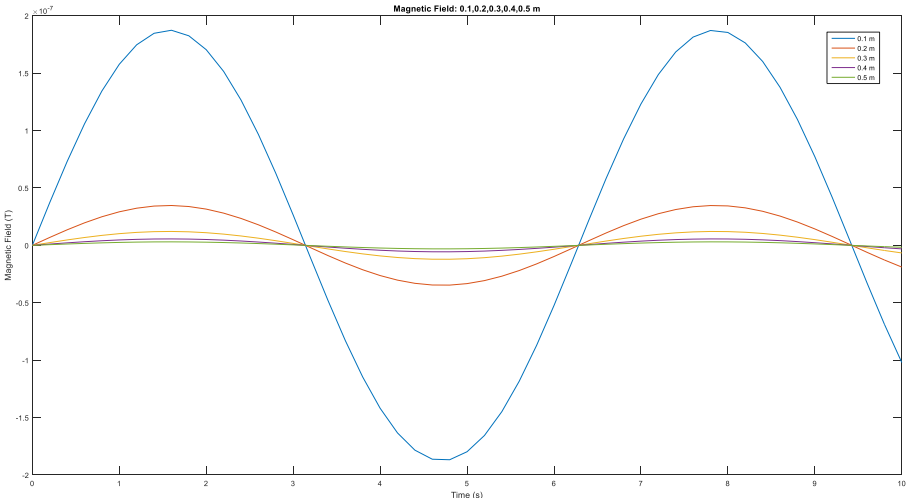

Fig. 31: Magnetic field at different distances

7.1.2. Magnetic Field: 0 m

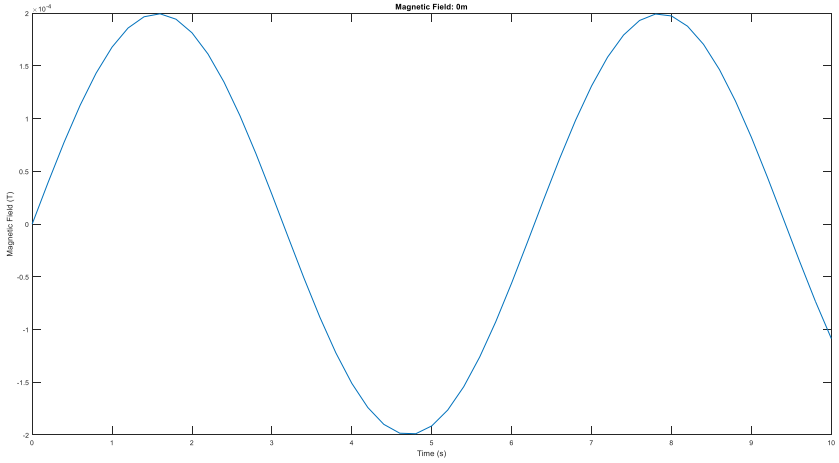

Fig. 32: Magnetic field at the origin

	X= 0 m	X= 0.1 m	X= 0.2 m	X= 0.3 m	X= 0.4 m	X= 0.5 m
Rms	1.3698e-04	1.2865e-07	2.3844e-08	8.3250e-09	3.8604e-09	2.0974e-09
Maximum	1.995e-04	1.874e-07	3.473e-08	1.212e-08	5.622e-09	3.055e-09

Table 2: RMS value and maximum value of the magnetic field at different distances

7.2. Number of turns (200)

7.2.1. Magnetic Field: 0.1, 0.2, 0.3, 0.4, 0.5 m

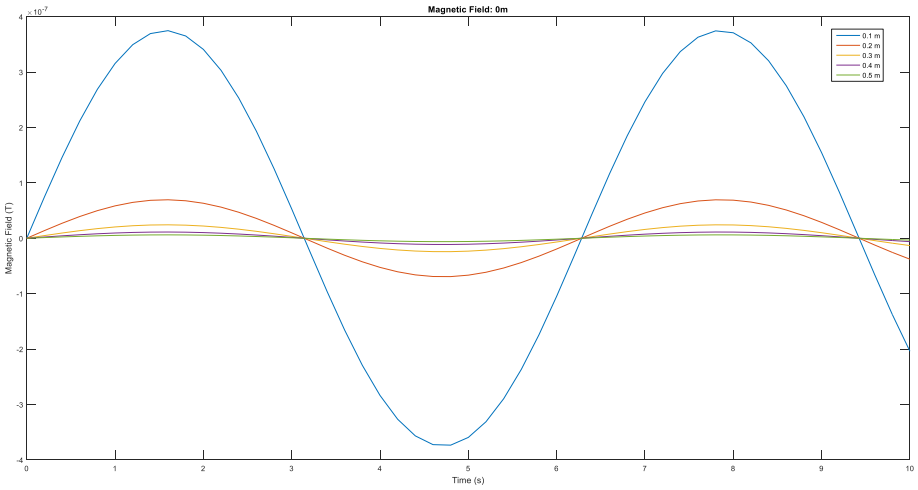

Fig. 33: Magnetic field with 200 turns at different distances

7.2.2. Magnetic Field: 0 m

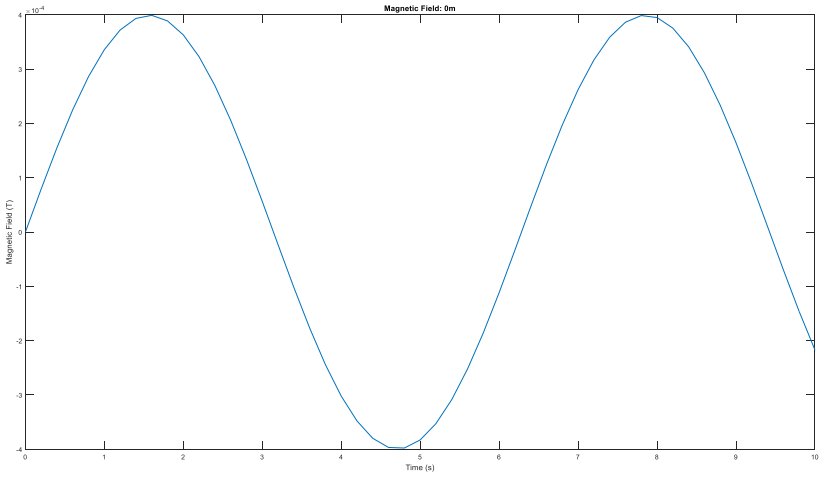

Fig. 34: Magnetic field with 200 turns at the origin

	X= 0 m	X= 0.1 m	X= 0.2 m	X= 0.3 m	X= 0.4 m	X= 0.5 m
Rms	2.7396-04	2.573e-07	4.7687e-08	1.6650e-08	7.7208e-09	4.1948e-09
Maximum	3.99e-04	3.748e-07	6.946e-08	2.424e-08	1.1244e-08	6.11e-09

Table 3: RMS value and maximum value of the magnetic field with 200 turns in different distances

7.3. Lenght (0.2 m)

7.3.1. Magnetic Field: 0.1, 0.2, 0.3, 0.4, 0.5 m

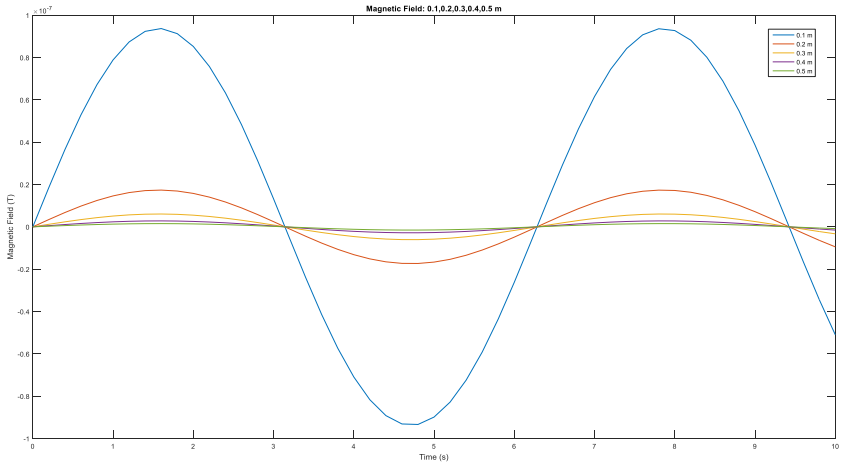

Fig. 35: Magnetic field with a length of 0.2m at different distances

7.3.2. Magnetic Field: 0 m

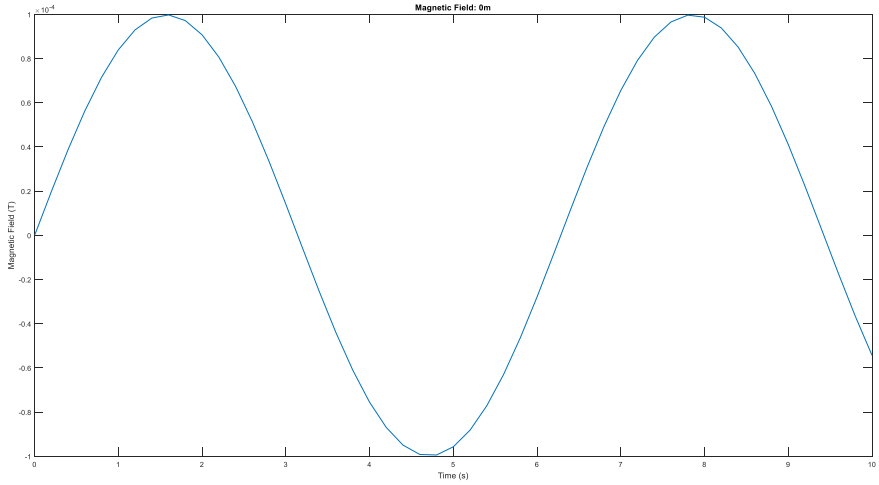

Fig. 36: Magnetic field with a length of 0.2m at the origin

	X= 0 m	X= 0.1 m	X= 0.2 m	X= 0.3 m	X= 0.4 m	X= 0.5 m
Rms	6.8491-05	6.4325e-08	1.1922e-08	4.1625e-09	1.9302e-09	1.0487e-09
Maximum	9.975-05	9.639e-08	1.736e-08	6.062e-09	2.811e-09	1.527e-09

Table 4: RMS value and maximum value of the magnetic field at different distances with a length of 0.2m

Chapter 8: Electric vehicles

8. Electric Vehicles

8.1. First method: moving car

We will simulate the effect of adding a supply plate magnetic fields on our streets. For that:

1. We will put the supply plate on the asphalt of the streets.
2. We will place our receiving plate in our car.

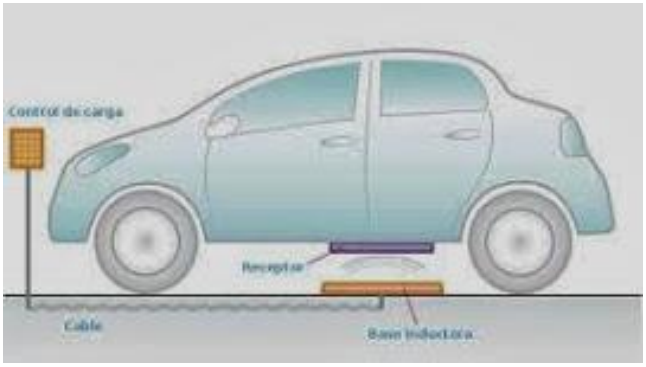

Fig. 37: Adding of a supply plate in the street [25]

The first thing we will do is simulating our electric field as a function of the distance that will put our car, we will do it in a range between 0-0.5 meters. To do this we will use our formula of magnetic field we have previously used, but in this case we use a position vector as input. In order to perform the different simulations depending on our position we will use a for loop in our Matlab script, which send the data to our Simulink.

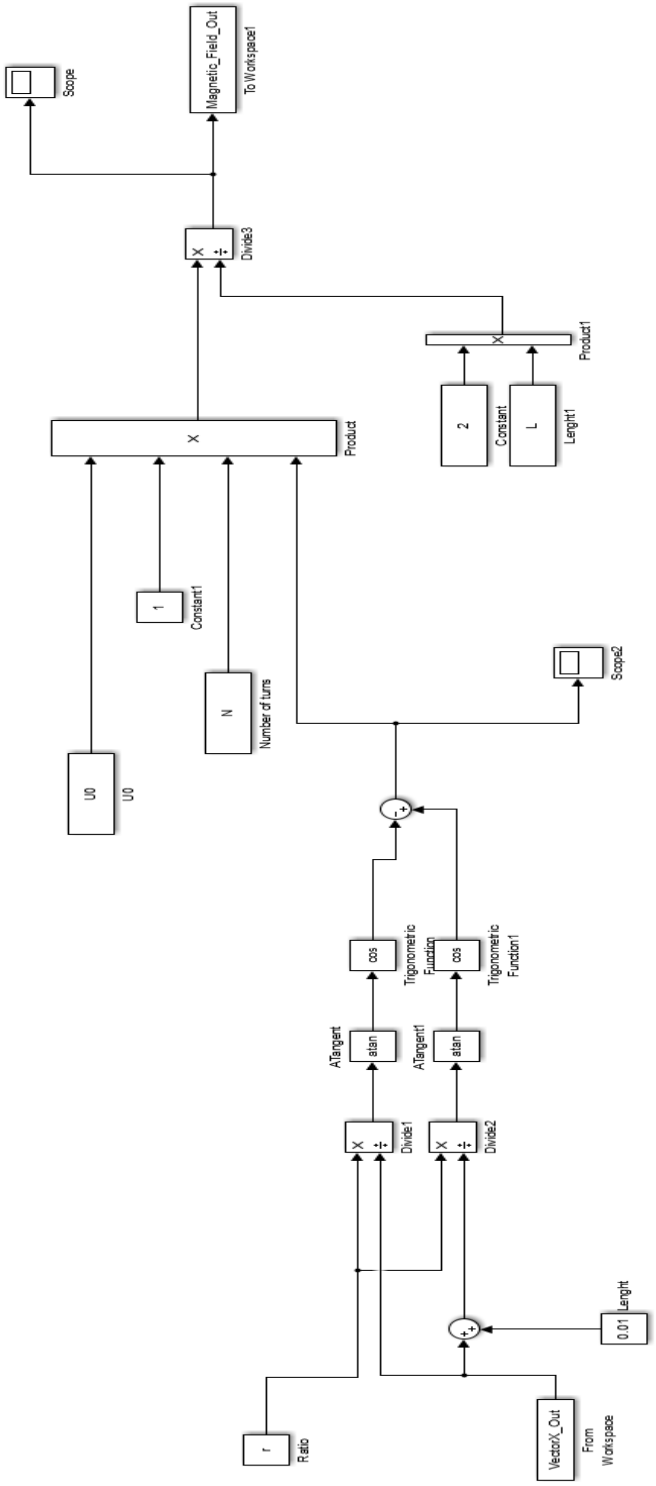

Fig. 38: Simulink model of a magnetic field in the axis of a solenoid at different distances

```
N= 100;
L = 0.2 ;
U0 = 4*pi*10^(-7) ;
r = 0.005;

Position= [];
Position(1)=0 ;

Result= [];
Result(1)= 3.1351647*10^(-04);

W= [];
W(1)=0;

VectorX_Out= [0 0.001];


for i= 2:501

   Position(i)= Position(i-1)+0.001 ;
   sim('Magnetic_Field');

   W(i)= Position(i) ;

   time = i/1000-0.001;
   VectorX_Out= [time W(i)];
   Result(i)= Magnetic_Field_Out(i);

end

time= 0:0.001:0.5 ;
plot(time,Result)
title('Values of the Magnetic Field in different locations')
xlabel('Meters')
ylabel('Magnetic Field')
```

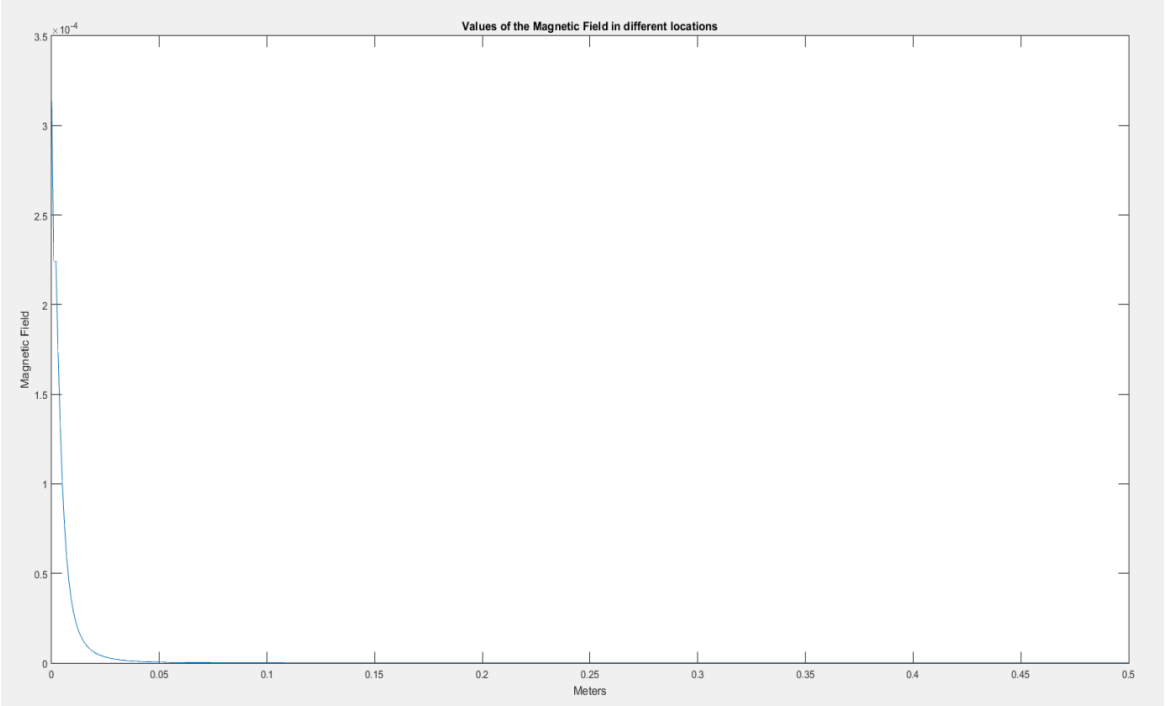

Fig. 39: Values of magnetic field in different locations (0, 0.5m)

As we can see our magnetic field decreases dramatically as we are moving away from the supply plate.

For out prototype we are going to use a coil with the following characteristics:

- Number of turns = 100
- Length = 0.01 m
- Ratio = 0.5 m

Let's assume a distance between the supply plate and the plate attached to our car 0.3m. To perform the calculations of the magnetic field we will use the following formulas:

$$\mathrm{B} = \frac{\mu_0}{4\pi} * \oint \frac{u_t * u_r}{r^2} * dl$$

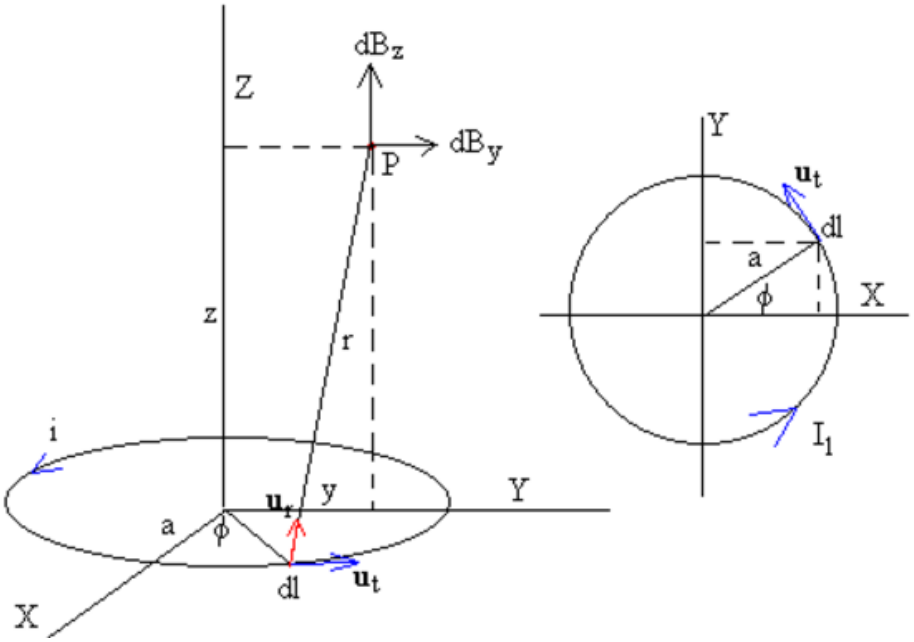

Fig. 40: Values of magnetic field in different locations of the y axis and the z axis [24]

$$B_y = \frac{\mu_0}{2\pi}\frac{a}{(2ay)^{\frac{3}{2}}}\left(-\sqrt[2]{2mK(m)} + \frac{2-m}{2-2m}\sqrt[2]{2mE(m)}\right)$$

$$B_z = \frac{\mu_0}{2\pi}\frac{a}{(2ay)^{\frac{3}{2}}}\left(a * \frac{m}{2-2m}\sqrt[2]{2mE(m)} + y\sqrt[2]{2mK(m)}\right.$$

$$\left. - y\frac{2-m}{2-2m}\sqrt[2]{2mE(m)}\right)$$

$$m = \frac{2}{1+b} = \frac{4ay}{a^2+z^2+y^2+2ay}$$

$$E(m) = \int_0^{z/2} \sqrt{1 - m\sin\phi^2}\, d\phi$$

$$K(m) = \int_0^{z/2} \frac{d\phi}{\sqrt{1 - m\sin\phi^2}}$$

So our Simulink model is going to be like:

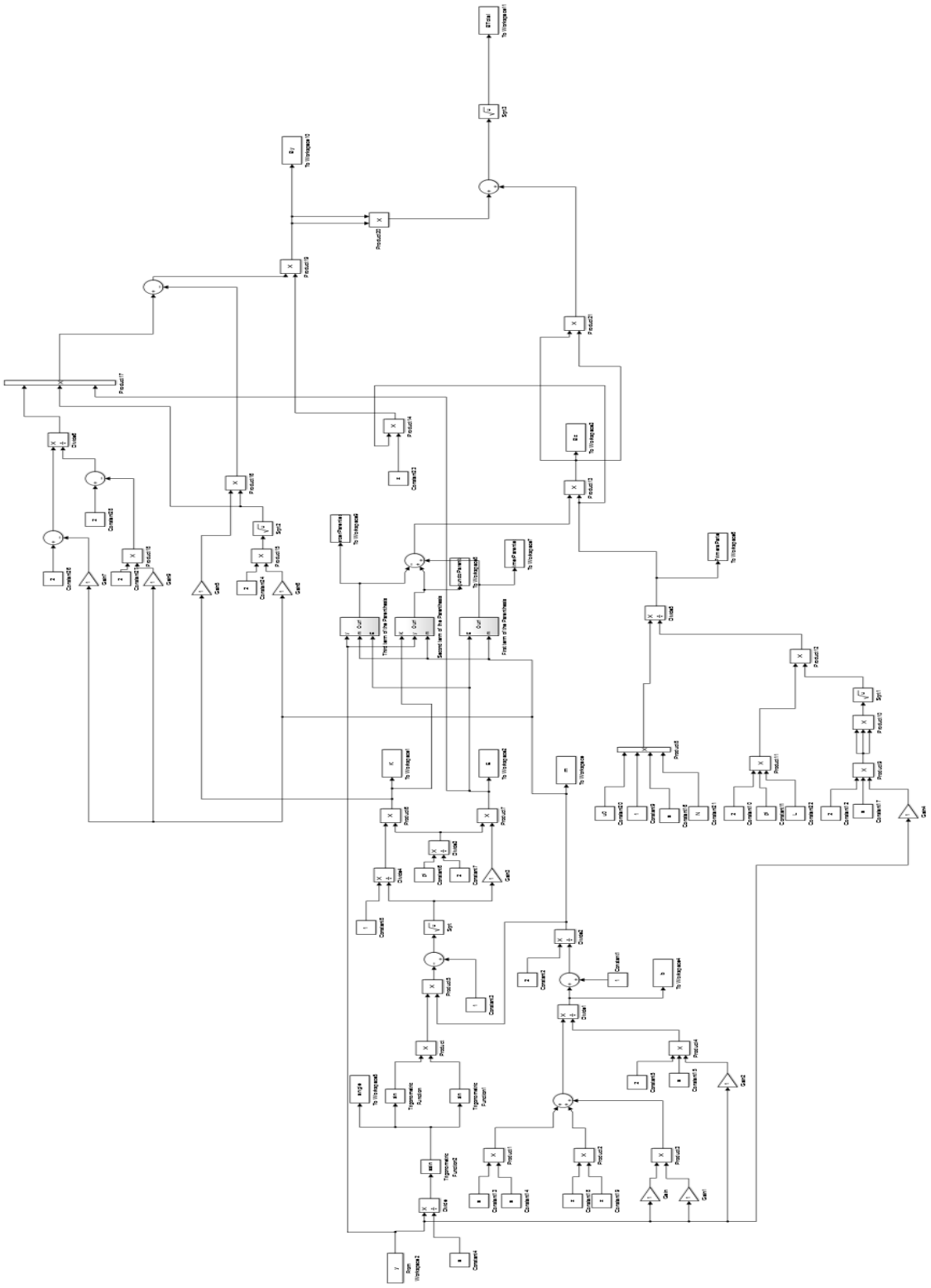

Fig. 41: Simulink model of the electromagnetic field at different distances in the space

```
N= 100;
L = 0.01 ;
u0 = 4*pi*10^(-7) ;
a= 0.5;
z= 0.3;

Position= [];
Position(1)=0 ;

Result= [];
Result(1)= 0.009239971672034;

Bz1(1)= 7.92321610567*10^(-3);

W= [];
W(1)=0;

y= [0 0.001];

for i= 2:501

   Position(i)= Position(i-1)+0.001 ;
   sim('Magnetic_Field_OutofAxis');

   W(i)= Position(i) ;

   time = i/1000-0.001;
   y= [time W(i)];
   Result(i)= BTotal(i);
end

time= 0:0.001:0.5 ;
plot(time,Result)
title('Values of the Magnetic Field at 0.3 m')
xlabel('Meters')
ylabel('Magnetic Field')
```

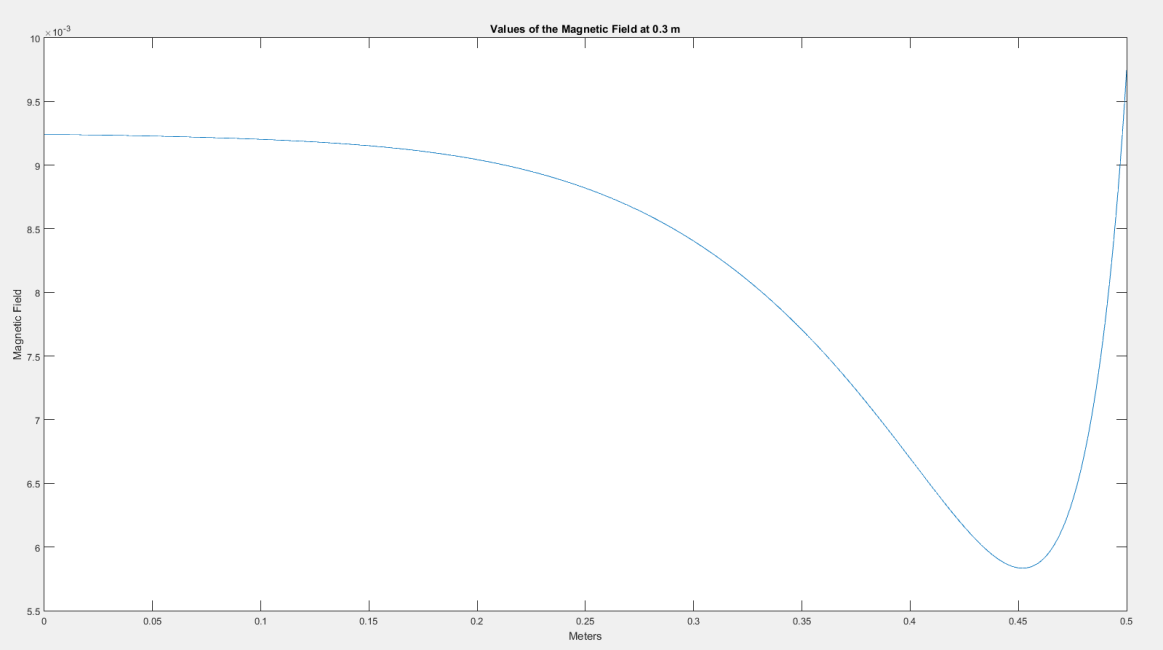

Fig. 42: Values of magnetic field at 0.3m obtained with Simulink

Finally with the previous result (0-0.5 m) we can calculate the other side of the coil (-0.5,0 m)

```
FirstPart= fliplr(Result);
Total = horzcat(FirstPart,Result) ;

time= -0.5:0.001:0.501 ;
plot(time,Total)
title('Values of the Magnetic Field at 0.3 m')
xlabel('Meters')
ylabel('Magnetic Field')
```

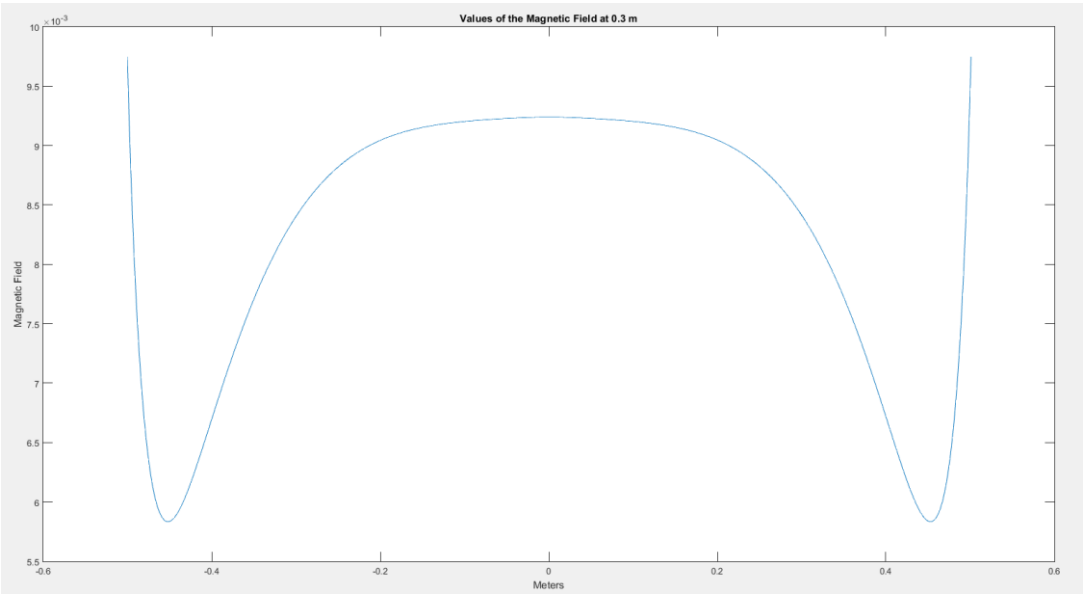

Fig. 43: Values of magnetic field at 0.3m obtained with Simulink

Therefore this is the magnetic field generated by our coil 0.3 m high

But our goal is to calculate the power that will be able to sumisitrar the car, so we have to analyze the flow that our car is going to receive form the coil. The plate will be square to facilitate flow calculations and the dimensions will be **a = 0.3 m**. We'll have three possible positions:

$$\phi = \int B * dS$$

1) First Stage

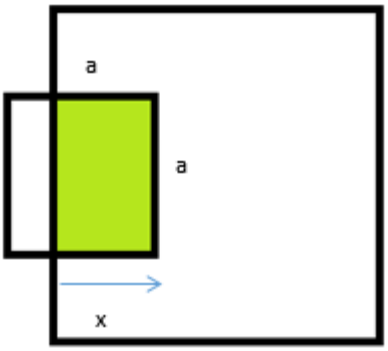

Fig. 44: Geometrical disposition of the first stage

$$S = a * x \qquad 0<x<0.3\ m$$

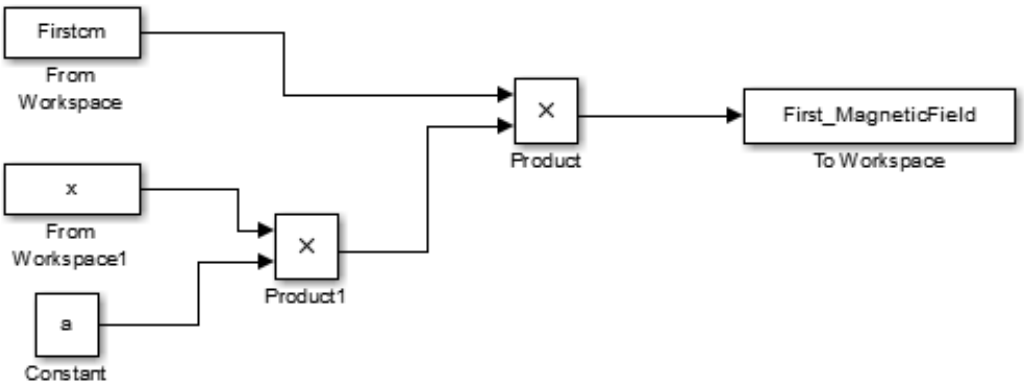

Fig. 45: Simulink model for the first stage

```
Firstcm = Total(1:300);
a = 0.3 ;

Position= [];
Position(1)=0 ;

Result= [];
Result(1)= 0;

W= [];
W(1)=0;

x= [0 0];


for i= 2:301

   Position(i)= Position(i-1)+0.001 ;
   sim('FirstPart_LastSimulation');

   W(i)= Position(i) ;

   time = i/1000-0.001;
   x= [time W(i)];
   Result(i)= First_MagneticField(i);
end

time= 0:0.001:0.3 ;
plot(time,Result)
```

2) Second Stage

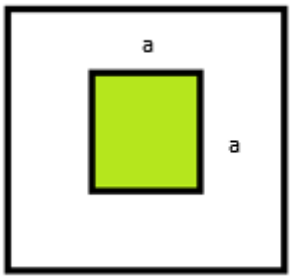

Fig. 46: Geometrical disposition of the second stage

$$\phi = B * a^2$$

```
Secondcm = Total(301:701);
a = 0.3 ;

Second_MagneticField(1) = 0.000810940832093241;


for i= 2:402

   Second_MagneticField(i)= Secondcm(i-1)*a^2;

end

time= 0:0.001:0.4 ;
plot(time,Second_MagneticField)
```

3) Third Stage

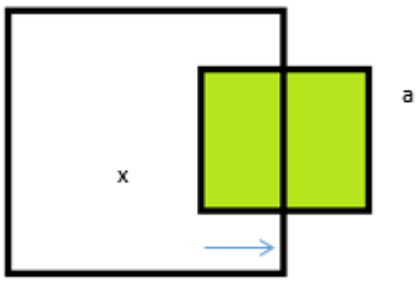

Fig. 47: Geometrical disposition of the third stage

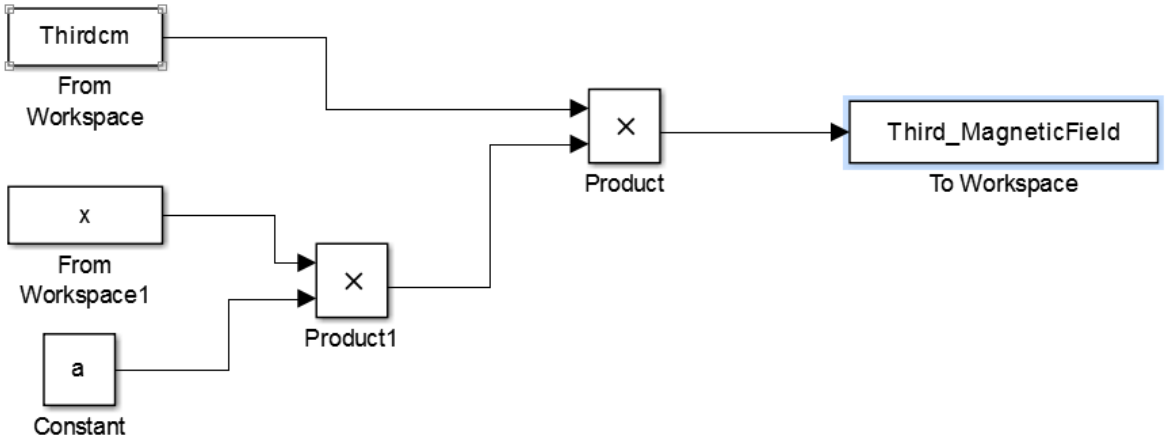

Fig. 48: Simulink model for the third stage

```
Thirdcm = Total(702:1002);
a = 0.3 ;

Position= [];
Position(1)=0 ;

Result= [];
Result(1)= 0;

W= [];
W(1)=0;

x= [0 0];


for i= 2:301

   Position(i)= Position(i-1)+0.001 ;
   sim('ThirdPart_LastSimulation');

   W(i)= Position(i) ;

   time = i/1000-0.001;
   x= [time W(i)];
   Result(i)= Third_MagneticField(i);
```

```
end

time= 0:0.001:0.3 ;
plot(time,Result)
```

Once we have the flow in different positions, we apply a series of commands to unite all results. So our final flow will be:

```
First_Part = First_MagneticField(1,:);
Second_Part = Second_MagneticField(:,1);
Second_Part = Second_Part' ;
Third_Part = Third_MagneticField(1,:);

Totalcm = horzcat(First_Part,Second_Part,Third_Part) ;

time = 0:0.001:1;
plot(time,Totalcm)
```

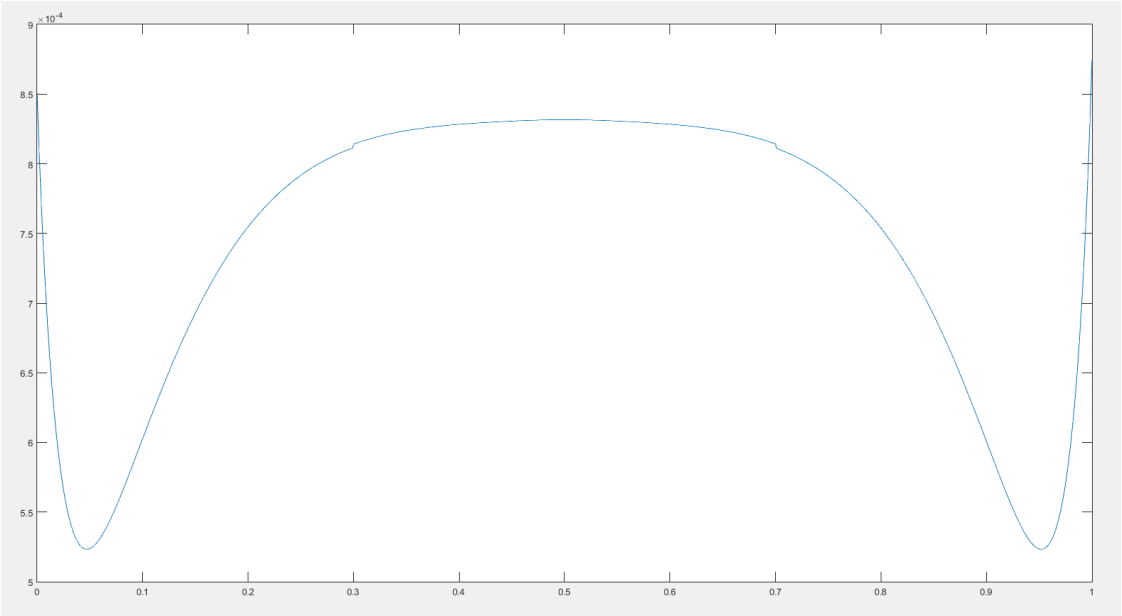

Fig. 49: Total flow seen by the receipting coil

Once we have the total flow we need to calculate the electromotive force:

$$Ve = \frac{d\phi}{dt}$$

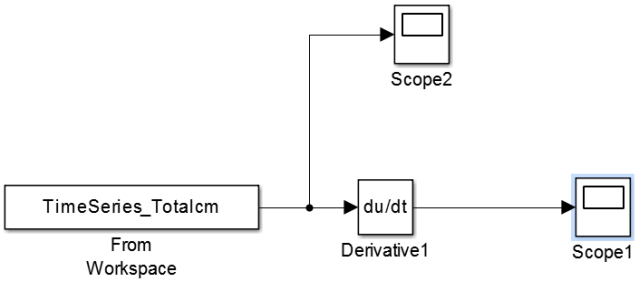

Fig. 50: Simulink model for the total electromotive force

```
Totalcm = horzcat(First_Part,Second_MagneticField,Third_Part) ;

time= 0:0.001:1 ;

TimeSeries_Totalcm = timeseries(Totalcm,time);
```

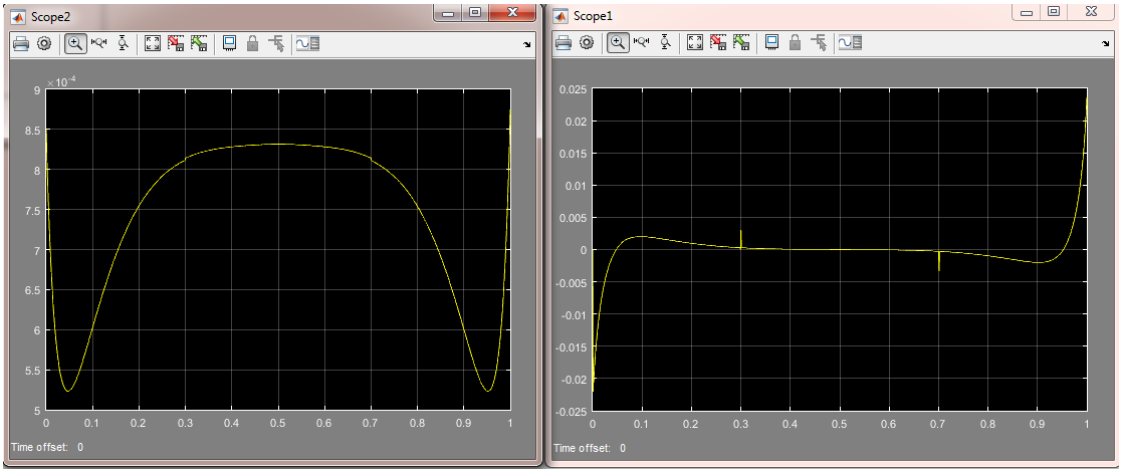

Fig. 51: Comparison of the total flow and the electromotive force

So now that we have electromotive force we can calculate the induced current in our circuit. To do this we must calculate the equivalent load resistance of our motor (R). For our experiment, as we have done with the input current, we give a nominal value of 1 and perform calculations based on this parameter.

$$i = \frac{Ve}{R}$$

Thus in our case the induced current will have the same value as the voltage induced in our circuit.

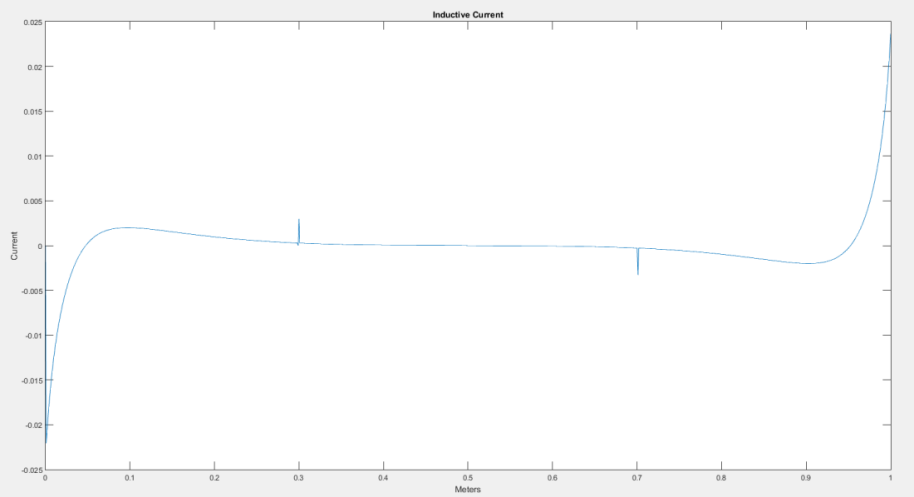

Fig. 52: Induced current

Finally, to calculate the final power to be able to supply our circuit, we can apply different formulas:

- $P_R = i^2 * R$
- $P_R = V_E * i$

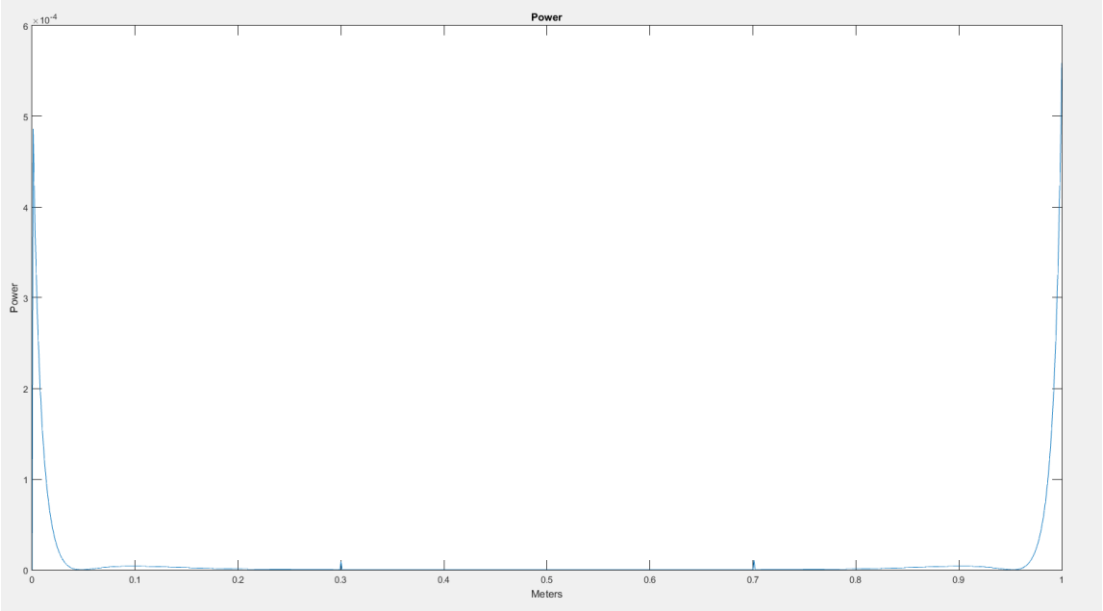

Fig. 53: Total power

As we knew from the beginning, when the coil is fully inserted into the magnetic field, the magnetic flux variation is practically nil, therefore our electromotive force is zero. This is what we see in our end graphics power.

8.1.1. Conclussions of the first method

As we have seen in the last simulations, if the distance is 30cm the power obtained by the engine will be really small, around 10^{-4}. So, we can affirm that charging the car using wireless transmission lanes or using the traffic lights are futuristic ideas. The problem is that we need to improve the amount of energy sent out by the transmission plate, decrease the air losses and increase the output voltage in the reception plate by power electronics.

Fig. 54: An ideal electric re-charging lane [26]

So, due to the inefficacy of this method we have to say that nowadays is not an achievable one.

The rest of the project will consist in an application of this same wireless power transmission method but from a different point of view. This new method will include the analysis of a wireless power transmission method while the vehicle is parked. In this case, we will be able to achieve a union of both the transmission and the reception plate. Even more, we will be able to reinforce this union by means of an iron core in order to improve the connection of the coils by their magnetic field.

8.2. Second method: parked car

This new method consists in the usage of a transmission coil and a reception coil. But, respecting the other method, in this one the car will be parked. Therefore, this sytems can solve the big problem that present the current charging method of the electrical cars using a conventional hope.

One of the main problems of charging the electrical cars nowadays is the charging stations. As we can see in figure number 55 this system has a few inconvinientes:

Fig. 55: Electrical car being charged [27]

1. It is strictly necessary to install a lot of charging stations in order to provide the daily consume of all the electric cars
2. These charging stations generate a huge visual contamination that would be lethal in the traditional places of the country
3. In order to connect the charging station and the electrical car, a charging hope is used. This type of system facilitates it being robbed
4. As the hopes are used worldwide it would be necessary a universal charger

All these disadvantages have caused the appearance of new charging systems for our electrical cars when we are away from home.

One of the main ideas that has being lately presenting is creating a supply system for the batteries that works this way: once the vehicle gets into the charging station its discharged battery is changed for a new one. This method will mean a big installation for the batteries' distribution company and a big warehousing capacity. Moreover, this method will imply a big cost, as the new batteries will be sold for $60 more or less. So, this method seems a dismissed idea currently.

Fig. 56: Replacement of batteries in an electric car [28]

8.2.1. Design

If we put together all these disadvantages with the problem that we had before respect the distance between the plates, we will be able to come up with a new system based in this new power transmission method.

This system will consist on a mechanism through which will be placed on top of a special base when the car is parked in public places. Using a mechanism, the transmission plate will be raised to a level where it makes contact with the car's plate. So, we will eliminate the distance problem and all the disadvantages that this has for the usage of the charging stations and the rest of the systems.

8.2.1.1. First part: transmission plate

The transmission plate will me mainly constituted y the transmission coil. This coil will be directly connected to the electrical network by a wire that will come from any light point. As we can see in figure number 57 and figure number 58 the coil will be protected by a metallic cover in order to avoid possible damages and thefts.

This system will need a mechanism that will be activated once the vehicle was placed on top of the plate. At that exact moment, the coil and the iron core will be elevated until they join the receipting coil. This mechanism will have two main objectives:

1. Make this system a universal one for all of the cars, as the users will have no problem regarding the underneath of the car
2. Facilitate the transmission of the power thanks to the iron core. Without this mechanism the union of both coils will be impossible

-

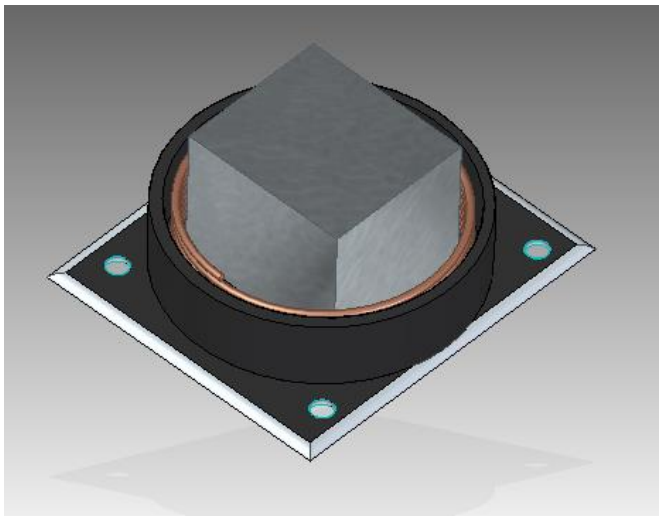

Fig. 57: Transmission plate obtained with SolidEdge

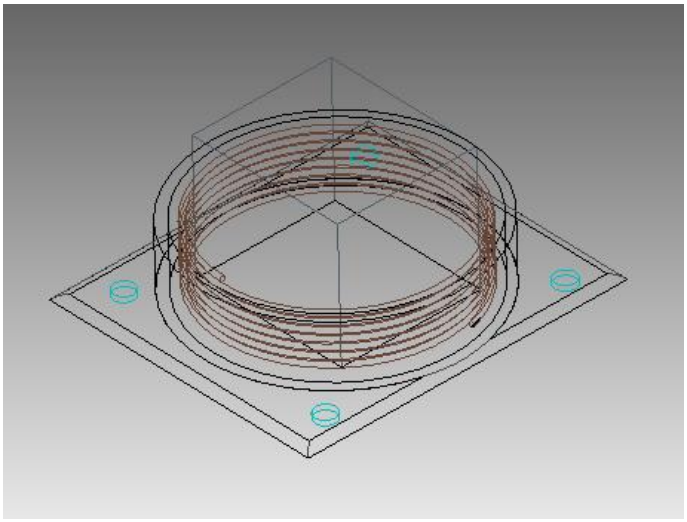

Fig. 58: Transmission plate obtained with SolidEdge

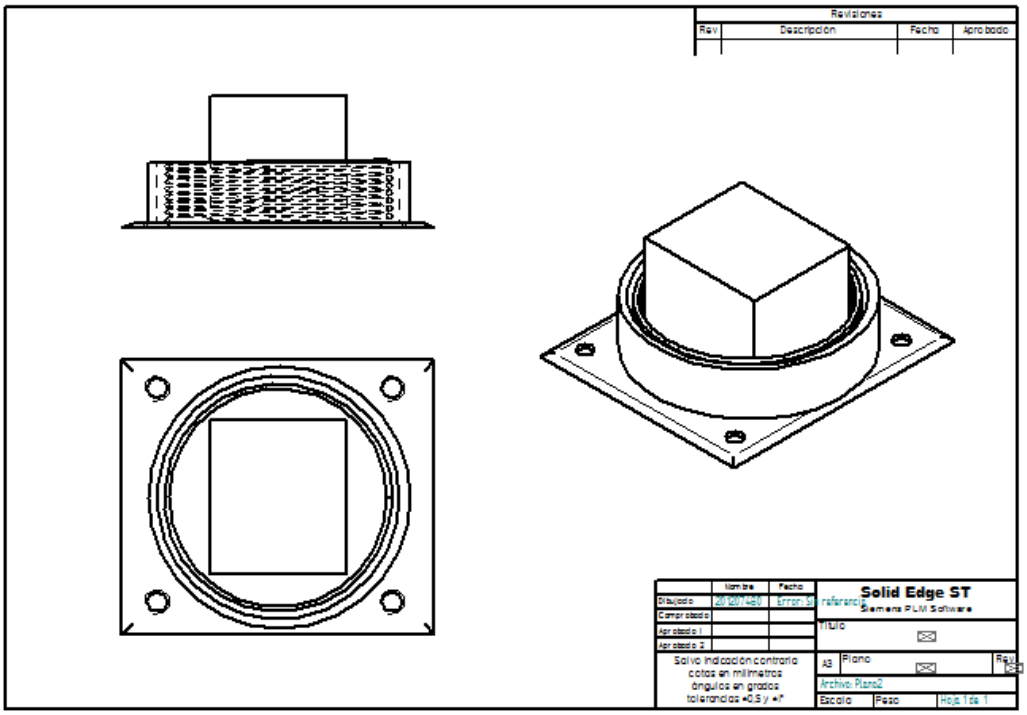

Fig. 59: Plane of the transmission plate obtained with SolidEdge

8.2.1.2. Second part: receipting plate

The receipting plate in mainly made of the receipting coil. This receipting coil joins the transmission coil by the iron core. By means of electromagnetic camps an electric current will be induced. This current will be the charging source for the batteries of our electric car. As we can see in figure number 60 and figure number 61, the coil will be protected by a metallic cover that will serve as protection. Both parts, the coil and the cover will be embedding into the underneath of the car so that they don't harm the car's aerodynamics.

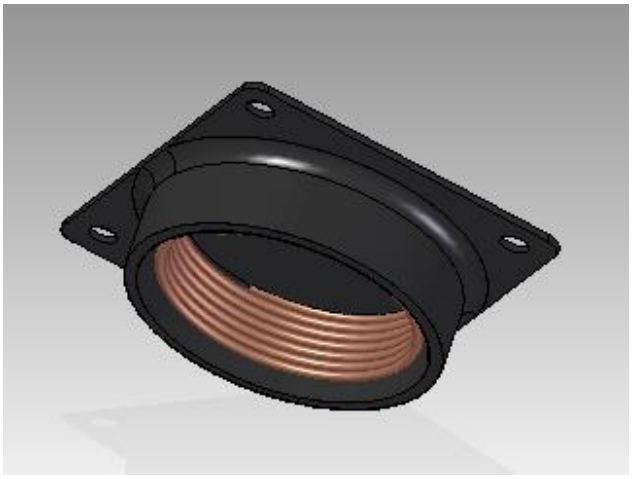

Fig. 60: Reception plate obtained with SolidEdge

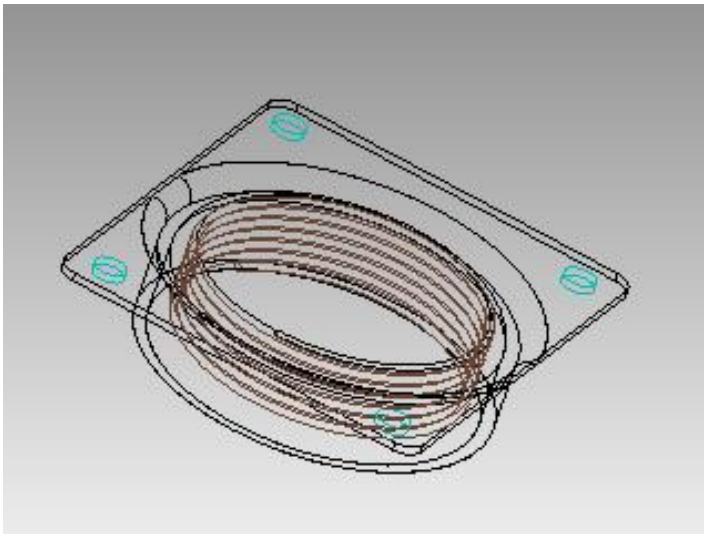

Fig. 61: Reception plate obtained with SolidEdge

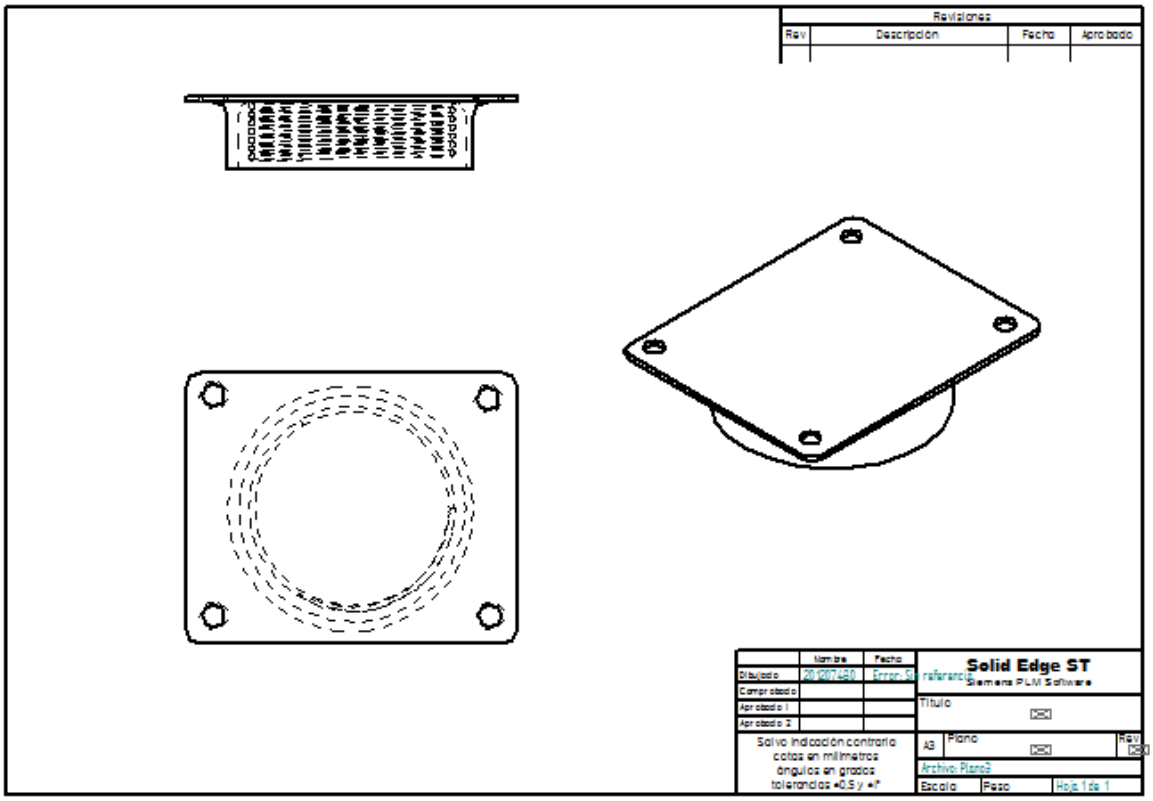

Fig. 62: Plane of the reception plate obtained with SolidEdge

8.2.1.3. Third part: iron core

This part of the system is mainly used to improve the amount of electrons that arrive to the receipting coil. The placement of the iron core highly increases the amount of current that arrives to the receipting coil as it improves the auto induction coefficient of each coil and, therefore, the mutual induction coefficient too.

As we already know, the auto induction coefficient for a coil us:

$$L = \frac{N^2 * S}{l} * \mu_0$$

L= auto induction coefficient (H)

N= number of turns

S= surface of the iron core (m^2)

l= length of the turns (m)

μ_0= permeability of the vacuum

Therefore, if we add and iron core or any other core of the materials in table number 4, our auto induction coefficient will be of the same way:

Fig. 63: Solenoid with an iron core [29]

$$L = \frac{N^2 * S}{l} * \mu_0 * \mu_r$$

As we can see in the formula above the only element that modifies the value of the auto induction coefficient is the permeability of the material that is used as core. Now we can find a table with some elements and their chemical properties, including their permeability.

Material	Permeability	Saturation's induction (T)	Excess's induction (T)	Conductivity (IACS)
Overcooked OFHC Copper	1	1	1	99
Overcooked 99.99% iron	20000	2.15	0.01	17
Overcooked 99.9% iron	1900	2.11	0.08	16
Overcooked 0.8% C Steel	1000	2.10	0.25	15
Overcooked 0.8% C T+R Steel 500ºC	450	2.10	0.50	15
Overcooked 0.8% C T+R Steel 200ºC	450	2.10	0.68	15

Table 5: Chemical properties of some elements

We will use an iron core as it is the one with the highest permeability.

Once we have calculated the auto induction coefficient of both the coils we will calculate the value of the mutual induction coefficient. We will use this formula:

$$\mathrm{M} = \mathrm{K} * \sqrt{(\mathrm{L1} * \mathrm{L2})}$$

M = mutual induction coefficient

K = coupling coefficient

L1, L2 = auto induction coefficient of each coil

Because of the disposition of our system its coupling is perfect so, K=1. This phenomenon is because all the flux generated by one of the coil is completely absorbed by the other coil thanks to their same disposition and the iron core that joins them. Therefore, we can clearly see how the iron core in our system improves the coil induction.

8.2.2. Simulation

In order to simulate our system, we will use a group of batteries to represent our electric car prototype. We will do two types of simulations:

1. In the first simulation we will represent the combination between the usual charging method with a hope and our system
2. In the second simulation we will represent the same thing as in the first one but we will also add a third new system based in different renewable energies. This system will be able to work while the car is in movement

In the Annex A we will find information about the different types of batteries that are currently available in the market.

The battery is the main block of the Simulink model. Now all of the parameters available in the Simulink block will be explained.

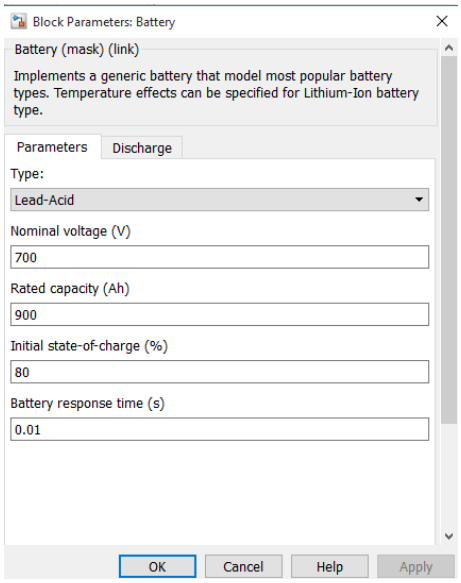

Fig. 64: Parameters of the battery block in Simulink

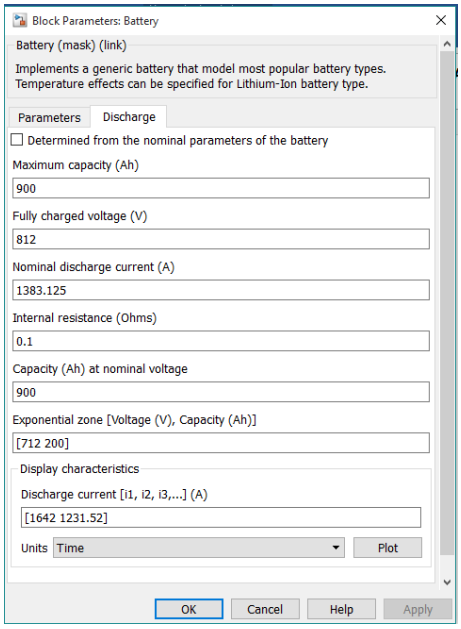

Fig. 65: Parameters of the battery block in Simulink

- Type: the type of battery is determined by the chemical reaction that takes place during its charge and discharge. Therefore, depending on the type of battery chosen, the charge behavior will be different. The batteries included are Lead-Acid, Lithium-Ion, Nickel-Cadmium and Nickel-Metal-Hydride.
- Nominal voltage (V): the nominal voltage of a battery indicates the voltage at which the device is designed to operate. It is usually known as the 'normal' voltage of the battery. In figure number 67 the nominal voltage represents the end of the linear zone of the discharge characteristic.
- Rated capacity (Ah): the rated capacity of a battery represents the energy capacity of the battery working under normal circumstances. This number depends, not only in the chemical reaction that takes place in the battery, but also in the number of cells that are working in parallel in a battery cell. A rated capacity of 900Ah means that, if the battery is fully charged, it will take nine hours to discharge it when it provides a current of 100A. Moreover, it will take 18 hours to fully charge the battery if the charging current is 50A. This parameter is quite important as it represents 'how much current can the battery provide', but also 'how long can a battery provide that current' [30].
- Initial state-of-charge (%): the initial state of charge of a battery represents, as a percentage, the amount of energy that is available to be provided by the battery at the beginning compared to the maximum energy that could be given.

100% indicates that the battery is fully charged and 0% that it is empty. This parameter is used as an initial condition for the model but it doesn't influence on the battery's discharge.

- Battery response time (s): the battery response times measures the time that it takes the battery to start providing the necessary amperage as they cannot provide it instantaneously. Therefore, it represents the voltage dynamics.
- Maximum capacity (Ah): the maximum capacity of a battery represents the maximum amount of electric charge (A) that can be provided by a battery during a specific amount of time (h) at a rated voltage. It is usually equal to 105% of the rated capacity of the battery [31].
- Fully charged voltage (V): the fully charged voltage indicates the value of the battery voltage when it is fully charged. This value is different than the no-load voltage.
- Nominal discharge current (A): it represents the current at which the battery is designed to be discharged. As it is a nominal value, the discharge current of the battery can differ from it. It is important to note that, if the discharge current increases, the amount quantity of charge that can be extracted from the battery decreases.
- Internal resistance (Ω): this parameter indicates the resistance within the battery. It is normally a different value when charging and discharging the battery [32]. It is usually constant during the charge and the discharge cycles and does not depend on the amplitude of the current.
- Capacity (Ah) at nominal voltage: this parameter indicates the capacity that can be extracted from the battery at its nominal voltage.
- Exponential zone [Voltage (V), Capacity (Ah)]: as it is shown in the figure number 67 the exponential zone represents the region of the discharge curve in which the voltage drops exponentially. As the discharge curve depends on the battery it is necessary to indicate both the voltage and the capacity in order to set the exponential zone of the discharge curve. The value of the voltage has to be between Vnom and Vfull while de value of the capacity has to be between Qnom and 0 [31].

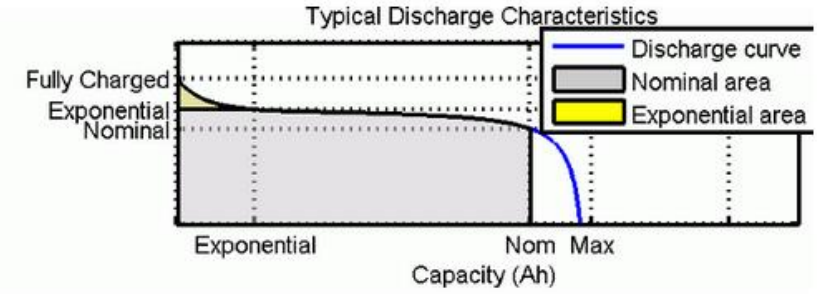

Fig. 66: Typical discharge characteristics of a battery [31].

- Discharge current [i1, i2, i3…] (A): this parameter allows to specify different values for the discharge current. Once chosen, the discharge curves can be plotted using Simulink as it is shown in figure number 68 [31].

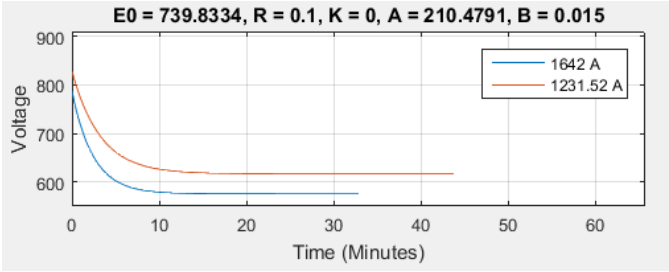

Fig. 67: Discharge characteristics for the different values of current [31]

8.2.2.1. First simulation

As it has been explained before in this first simulation we will represent the combined used between those two methods of charge. In order to do so we will mix the conventional method with the wireless one. The idea of doing it this way comes from realizing that, doing so, we will save up the installation of the new charging system for the particular users. By doing this, all the batteries will be charged in any socket, making this system cheaper.

In order to represent this system, we will distinguish the different batteries associated to the different charging methods. Doing it this way we will clearly distinguish both system, so that we will be able to analyze better how the discharge and charge of the batteries will be. However, if this project is implemented in real life it will be necessary to change the model and study again all the simulation with only a charging and discharging battery.

So, with this system we will be able to charge our battery by two different methods. The Simulink model that we will use is shown in figure number 69.

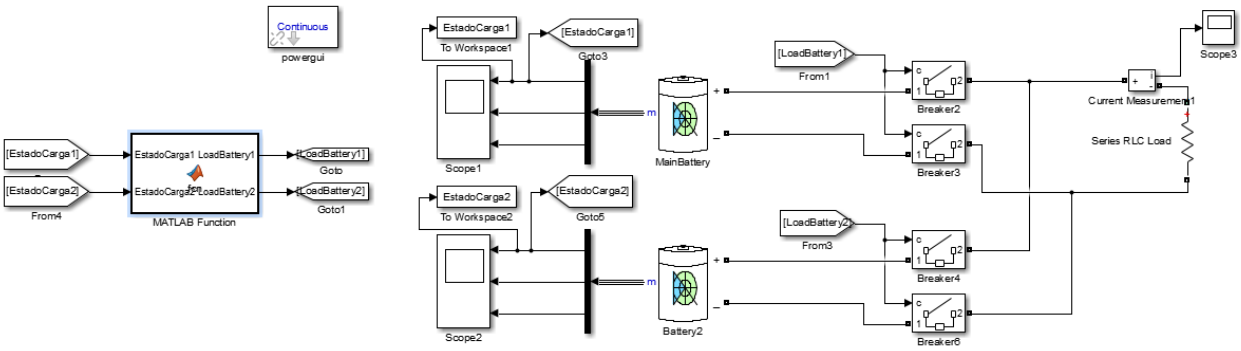

Fig. 68: Simulink model for the first simulation

As we can see in the model, the engine is represented as an impedance and it is connected in series to the two batteries. These batteries are in charge of providing the necessary current so that the engine can perfectly work. In order to control the state of charge of the batteries we have designed a system that provides us with that information. With all this and the breakers we have designed a function that helps us adjusting a controlling the charge and discharge of the batteries.

The Matlab code that we have used is the following one:

```
function [LoadBattery1, LoadBattery2] = fcn(EstadoCarga1, EstadoCarga2)
%#codegen
LoadBattery1= 0;
LoadBattery2= 0;
if(EstadoCarga1 >=30)
   LoadBattery1= 1;
   LoadBattery2= 0;
else
   if(EstadoCarga2 >=30)
      LoadBattery1= 0;
      LoadBattery2= 1;
   else
      LoadBattery1= 0;
      LoadBattery2= 0;
   end
end
end
```

In the Matlab code we can see how the working of our system will be. When the MainBattery reaches the 30% charging level we give way to the second one. When we do this change, we open the connection of the main battery and we close the connection of the secondary one. The states of charge that we have experimentally obtained are shown in figure number 70.

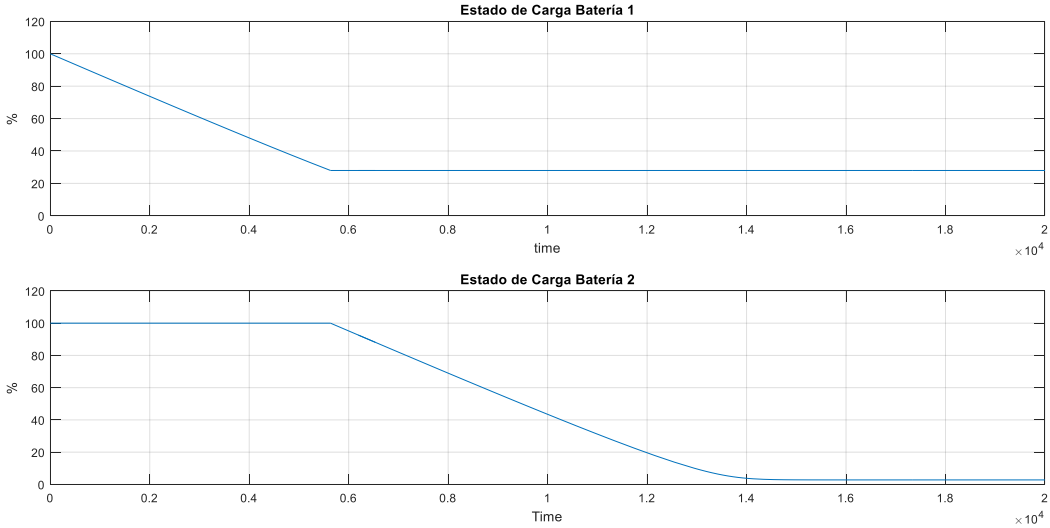

Fig. 69: States of charge obtained with the Simulink model

8.2.2.2. Second simulation

In the second simulation we will represent how will be the combined use of the three charging systems. We will mix the system that we already had in the first simulation with different renewable systems. The renewable systems will be the following ones:

- **Photovoltaic solar panel**

The photovoltaic solar panels are mainly made of silicon, a really common material in the earth. The silicon is characterized for being a semiconductor material, this means that the number of electrons around its core are not a lot. When the solar panel is exposed to the sun, the electrons star rustling uncontrollably, jumping from one atom to the other. In order to generate electrical current, we need the electrons to flow in the same direction so we need to dope the silicon. This doping process includes two reactions:

1. We dope the superior plate by adding phosphorus to it. This is done because the phosphorus has a high level on electrons in its layers

2. We dope the inferior plate: we need to add gold to it because gold has a short level of electrons in its layers

Thanks to this method we are get a negative plate and a positive one. The working method of the photovoltaic planes is the same method as the one that is takes place in the batteries.

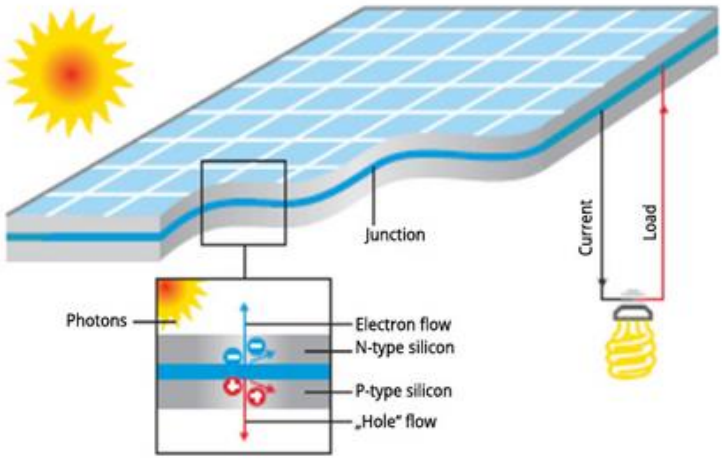

Fig. 70: Photovoltaic plate [33]

We will represent the photovoltaic plates in Simulink using the model shown in figure number 72.

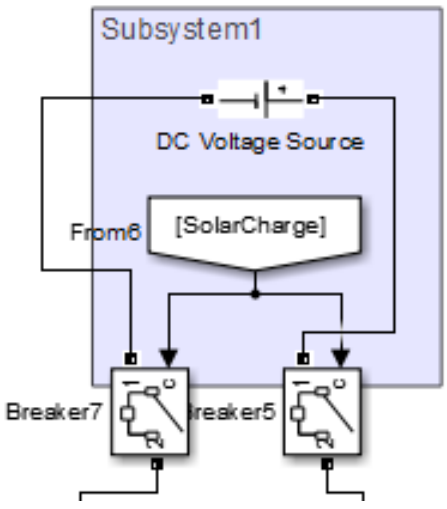

Fig. 71: Photovoltaic plate in Simulink

- **Regenerative brake**

The regenerative brake uses a method that lets us use the kinetic energy that is generated in the stoppage of the car or in its speed reducing. Once the car starts braking the kinetic energy is converted into electrical one by an alternator. This alternator spins freely when the car starts braking so that it works as a generator. The electrical energy is directed to a converter where it is converted into direct current. This direct current is directly used to charge our battery. We will represent the regenerative brake in Simulink using the same model as the one used for the photovoltaic planes.

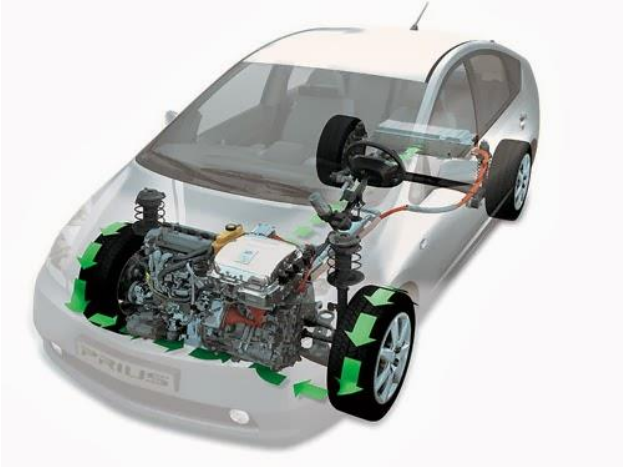

Fig. 72: Car with a regenerative brake [34]

In order to represent this system, we will distinguish the different batteries associated to the different charging methods. Doing it this way we will clearly distinguish both system, so that we will be able to analyze better how the discharge and charge of the batteries will be. However, if this project is implemented in real life it will be necessary to change the model and study again all the simulation with only a charging and discharging battery.

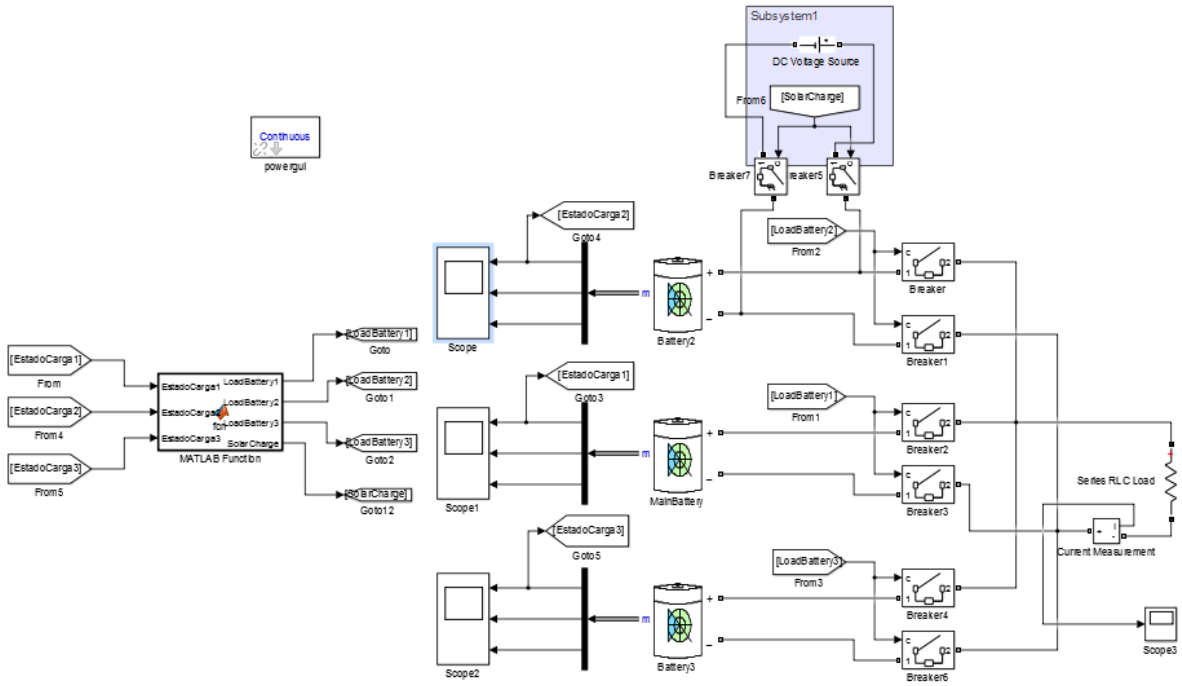

Fig. 73: Simulink model

As we can see the Simulink system is really similar to the one used in the first simulation. The only difference with the other simulation is the third battery. This battery is connected to a subsystem that consists on the charge with the renewable energies. In this case, we have only represented the solar panel system but we could combine the different systems explained above in order to charge our battery.

The Matlab code used is the following:

```
function [LoadBattery1, LoadBattery2, LoadBattery3, SolarCharge] = fcn(EstadoCarga1, EstadoCarga2,
EstadoCarga3)
%#codegen
LoadBattery1= 1;
LoadBattery2= 0;
LoadBattery3= 0;
SolarCharge= 0;

if(EstadoCarga1 >=30)
   LoadBattery1= 1;
   LoadBattery2= 0;
   LoadBattery3= 0;
   SolarCharge= 0;
else
```

```
if(EstadoCarga1 <30 && EstadoCarga2 >=30)
   LoadBattery1= 0;
   LoadBattery2= 1;
   LoadBattery3= 0;
   SolarCharge= 0;
else
if(EstadoCarga2 <30 && EstadoCarga3 >=30)
   LoadBattery1= 0;
   LoadBattery2= 0;
   LoadBattery3= 1;
   SolarCharge= 0;
else
   if(EstadoCarga3 <=100)
   LoadBattery1= 0;
   LoadBattery2= 0;
   LoadBattery3= 1;
   SolarCharge= 1;
   end
end
end
end
end
```

With this code we will be able to start with the MainBattery so that it stars discharging. Once this battery has a state of charge of 30% the second battery start to acct. this battery works until its state of charge is 30% when some changes are produced. The first change is that we star to function with the third battery. The second change that takes place is that, while we use the third battery, we start to charge the second one with our renewable system. Therefore, with this, we are able to obtain higher autonomies for our electrical car. The results that we have obtained are the following ones:

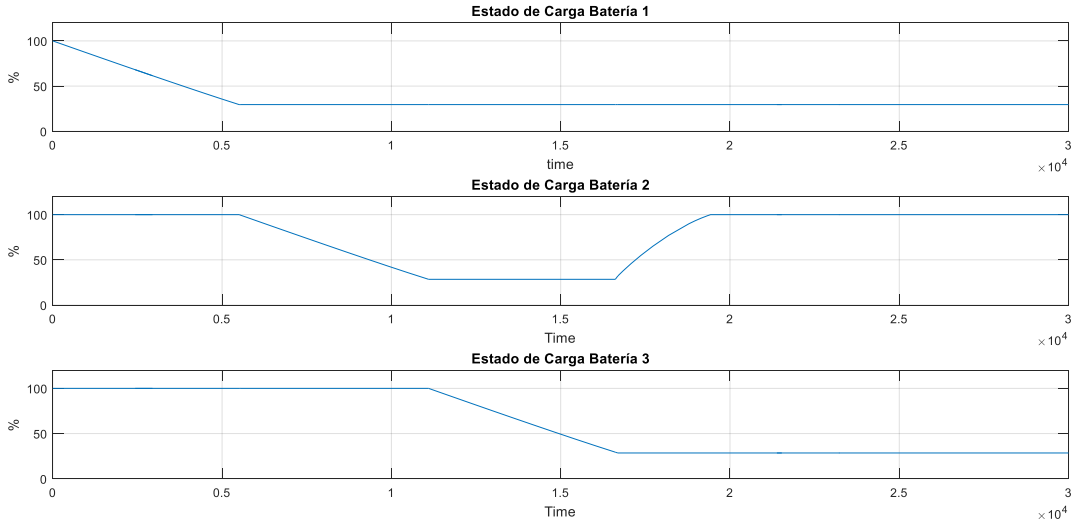

Fig. 74: Results obtained with the Simulink model

Chapter 9: Conclussion

9. CONCLUSSION

The realization of this project has awakened in me a certain interest in the transmission of electricity without wires. As we have seen there are endless applications and very different, because nowadays the use of electricity is essential in any activity we conduct.

Even though I have spend a lot of time doing this project it is a practically new topic and there is almost no information about it. So, my complete dedication to it cannot be shown in this paper. I'm sure that the wireless power transmission will be the future of electricity, therefore it is an honor for me to have investigated and tried to simulate this great discovery.

Finally thank the collaboration of Professor Salman Mohagheghi because without him none of this could have been possible.

Chapter 10: Bibliography

10. BIBLIOGRAPHY

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Annex A

11. ANNEX A: TYPE OF BATTERIES

A battery is an electromechanical that allows to release energy in order to power a load whenever the user wants to do so [35]. In order to release that energy an electrolysis, which is a chemical reaction, occurs inside the battery. During an electrolysis electrons flow from a negative electrode to a positive one, generating an ionic bond because of the electrostatic attraction of those two electrodes. The flow of electrons is shown in figure number 76. As a result of this reaction water is produced and it tends to weaken the electrolytes. Also, hydrogen and oxygen are released so it is necessary a good ventilation in order to avoid explosions.

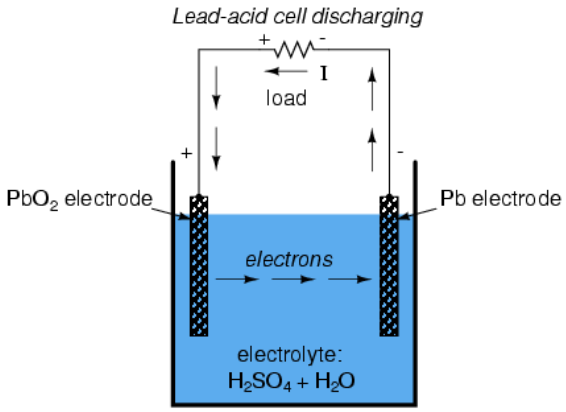

Fig. 75: Example of the reaction that takes place in a Lead-Acid battery **[36]**

Several parameters are used to describe the battery; the main ones will be now explained.

- Nominal voltage is the value of the voltage such that the battery works in ideal conditions. It depends on the number of battery cells connected.
- State of charge: how full a battery is. It depends mainly on the temperature as hot batteries show a higher voltage than cold ones when they are fully charged.
- Depth of discharge (DOD): it's a parameter used to describe how deeply discharged is a battery. 0% means that the battery is completely full while 100% means its empty.
- Battery storage capacity: amount of energy charge in a battery that will allow one ampere of current to flow for one hour measured in Ampere-hour (Ah). It main seem that the quantity of current delivered depends only on this

parameter but it does not, the speed at which the current is released from the battery is also an important parameter.

As it has been mentioned before the battery are set in cells so that the necessary amount of current and voltage is obtained. The energy released by the batteries in direct current (DC) so it is necessary an inverter to convert the energy from DC to AC.

One way of classifying the batteries it's by the chemical reaction that takes place in them. So, the following types can be found:

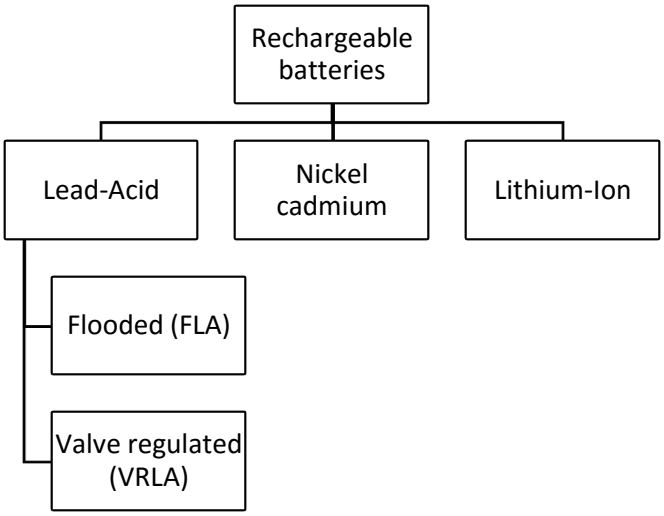

Fig. 76: Types of rechargeable batteries

11.1. Lead-Acid batteries

Lead-Acid batteries were invented in 1859 by the French physicist Gaston Planté and they are the oldest in the market. Their electrodes are mead of lead metal and lead oxide with a diluted sulphuric acid solution as the electrolyte. While the battery is discharging its electrodes turn into lead sulphate.

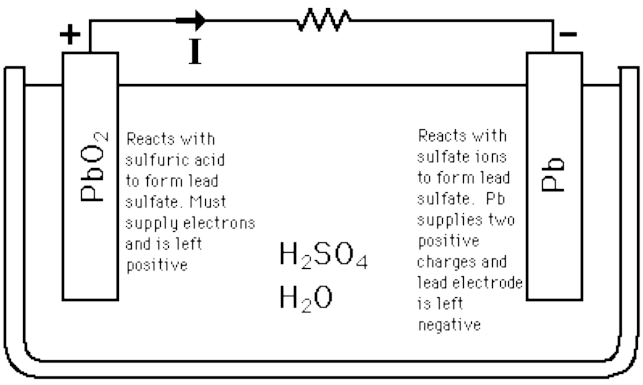

Fig. 77: Reaction that takes place in the lead-acid batteries. **[37]**

The best thing about these type of batteries is their low price, small self-discharge rates and high efficiency. Their main disadvantage that they have a really short life, 1200-1800 cycles, which makes replacement necessary. Moreover, these batteries cannot be completely discharged as this can lead to sulfation. As they are made of lead this has a negative impact on the environment which is making some companies replacing them from other types.

We can distinguish two categories of lead-acid batteries: flooded lead-acid (FLA) and valve regulated lead-acid (VRLA).

11.1.1. Flooded Lead-Acid batteries

Its positive electrode is made of lead dioxide but its negative one is made of thinly divided lead.

These types of batteries are the cheapest ones but they need a strict maintenance, which make them a long-term cost. They are used in different applications such as solar and wind electric systems.

11.1.2. Valve-Regulated Acid batteries

Their electrolyte is made of a gel instead of a liquid one. Its main advantage is that no ventilation is required thanks to some valves they have, eliminating therefore the maintenance cost. They are less robust and with a shorter life than other type of lead-acid batteries.

As no ventilation is required they are used in small places like motorbikes, electronics…

11.2. Nickel-Cadmium batteries

Nickel-Cadmium batteries use nickel oxide hydroxide as the positive electrode and metallic cadmium as the negative one, with an alkaline potassium hydroxide KOH as electrolyte.

These batteries have a higher resistance to temperatures than lead-acid and a longer life (>3500 cycles). They charge and discharge really quickly.

Even though its main disadvantage is their high price we can find others like losing energy while they are not being used (1% daily more or less), low efficiency (60-70%) and its memory effect. The memory effect of the batteries is a really complex process for which, if a Ni-Cd battery is recharged repeatedly after being discharged for example, 30% , it will become incapable of delivering more than 30% of its capacity [38].

Their main use is portable electronics (such as solar garden lights) and toys. Ni-Cd batteries are also used in photographic equipment, emergency lighting and wireless telephones.

11.3. Lithium-Ion batteries

Its positive electrode is made of lithium metallic oxide while its negative electrode is made of a carbon material. Lithium salt in an organic solvent is used as electrolyte.

Their advantages are a lot like high energy density, high efficiency (80%-90%), lower self-discharge rate (2% monthly) and long lifespan (3000 cycles).

They need to be packed in a special package so its makes them very expensive. They also have a short life, 3 years approximately.

Because of their high energy/weight ratio these batteries are being used in the mobile phone market and in the electric vehicles.

11.4. Comparison of batteries

In the following table we can found a comparison between the three main types of batteries. The most important characteristics are the ones shown.

Cell type	Lead-Acid	Nickel-Cadmium	Lithium-Ion
Voltage (V)	2.0	1.2	3.0
Power density	Moderate	Moderate	Very high
Specific energy (Wh/kg)	30-40	50-60	130-200
Self-discharge (%per month)	4-8	20-30	1-2
DOD (V/cell)	1.75	1.0	3.0
Life cycles	1200-1800	>3500	3000-3200
Weight comparison for the same capacity	4	2	1
Size comparison for the same capacity	3.5	1.8	1
Cost	Moderate	Moderate	High

Table 6: Comparison of the different types of batteries