Master's Degree Final Project

Master Degree in Industrial Engineering

CONTROL OF A HIGH FREQUENCY IGNITION SYSTEM BASED IN CORONA DISCHARGE WITH ARDUINO

MEMOIR

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ABSTRACT

The ignition systems have barely changed since the emergence of the first internal combustion engines. Nowadays environmental legislations are becoming stricter and it is getting more difficult for automotive manufacturers to comply their restrictions. For this reason, alternatives for the commonly used spark ignition are under investigation.

The corona effect is a phenomenon that takes place in high voltage electric systems connectors and it consists in the partial ionization of its surrounding fluid. It has been studied in several applications for different fields and, recently, it has been proposed as an alternative ignition system source.

The main objective of this research is to design and build a control system to create and maintain a corona discharge in the electrode of an ignition coil in order to study this phenomenon.

After some tests where the voltage and the current of the coil are analyzed, the results show which parameters have a greater influence on the generation of the corona effect in the electrode and the conclusions give a start point for future works.

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GLOSSARY

IC: Internal combustion

SIS: Spark Ignition System.

BDC: Bottom Dead Center

TDC: Top Dead Center

MBI: Mechanical Breaker Point Ignition System

CDI: Capacitive Discharge Ignition

DC: Direct Current.

AC: Alternate Current

TCI: Transistor-Controlled Ignition System

LIS: Laser Ignition System

HCCI: Homogeneous Charge Compression Ignition

CAI: Controlled Autoignition

CI: Compression Ignition

CDVG: Critical Disruptive Voltage Gradient.

EGR: Exhaust Gas Recirculation.

BMEP: Break Mean Effective Pressure.

IMEP: Indicative Mean Effective Pressure.

MCU: Microcontroller.

PWM: Pulse-width modulation

emf: Electromagnetic force.

1. INTRODUCTION

The climate change, which refers to the rise in average surface temperatures on Earth, is said to be due primarily to the human use of fossil fuels. One of the potential pollutant sectors is the automotive industry.

A typical passenger vehicle emits about 4.7 metric tons of carbon dioxide per year, in average. Governments and environmental organizations are increasing the restrictions on pollutant emissions of internal combustion engines to diminish their effects on this warning problem that affects the whole humanity.

Automotive manufacturers are having actual problems to create engines with pollutant emission within the limitations without reducing the delivered power. This is why new ignition systems are being developed as an alternative for the commonly used spark. As a general view, these systems have higher efficiencies and are less fuel consuming.

Although its technology needs further investigation before being worthy to commercialize, an example of these possible potential alternatives is the ignition system based on corona effect.

The objective of this project was to design and build a cheap and simple control system, with an Arduino board, able to create and maintain through time a Corona Discharge in the electrode of an ignition coil.

The experimental part of this project required knowledge on ignition systems, power electronics, Arduino coding and the corona phenomena. Thus, a previous research was done.

The aim of this experimental work was based on doing several tests and analysis in order to study the behavior of the voltage and the current of the ignition coil during the performance of Corona Discharge in its electrode.

Except for the Arduino board and the power electronics components, the equipment was provided by the *Machines and Thermal Engines Department* of the ETSEIB.

The scope of this project did not include the fabrication of any kind of engine or prototype.

The conclusions and results taken from this project were meant to guide future works on further studies of this alternative ignition system.

2. STATE OF THE ART

2.1. Technology overview

The first commercially successful Internal Combustion (IC) engine was created by the Belgian inventor Étienne Lenoir around 1859. It was a three-horsepower two-stroke cycle engine that used a mixture of coal gas and air as fuel, with a 4 percent of fuel efficiency. That inefficiency was because gas was not compressed before ignition while the intake of fuel, its combustion and the exhaust of the burned gas had to be completed in two strokes of the piston [1].

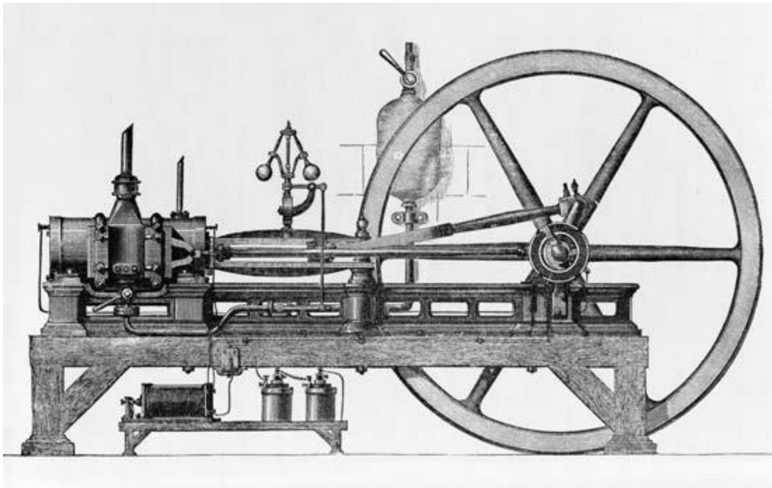

Figure 1. Étienne Lenoir's ICE

In 1876, the well-known German engineer, Nikolaus Otto, developed the first four-stroke engine, which cycle was given its name. With a higher efficiency than Lenoir's engine, its design is being currently used in gas fuelled engines. Those four strokes of the cycle are intake, compression, power and exhaust [2].

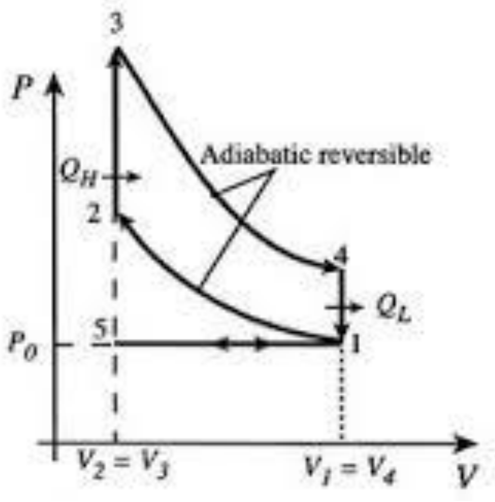

Figure 2. Ideal Otto cycle..

The *figure 2* above shows the different processes that take place in the Otto cycle ideally, with no useful work lost through turbulences or friction and no transferred heat to or from the gas. There are six stages in the four strokes cycle [3]:

1. *Intake stroke (5⇒1):* Gasoline vapor and air are drawn into the engine.
2. *Compression stroke (1⇒2):* The piston moves from the crank end or Bottom Dead Centre (BDC) to the head of the cylinder, called the Top Dead Centre (TDC) and the fuel-air mixture is compressed isentropically to point 2. As the volume of the cylinder changes from maximum to minimum (compression ratio of V1/V2) the pressure and temperature increase.
3. *Ignition phase (2⇒3):* When the piston is momentarily at the TDC and the fuel-air mixture is heavily compressed (minimum volume of the cylinder) the spark is fired up and heat (Q_h) is added into the system by with the combustion of the fluid. The volume is essentially maintained constant.
4. *Power (expansion) stroke (3⇒4):* The increased high pressure makes a great force to the piston pushing it go towards the BDC. The working fluid is expanded isentropically. This change of its volume (expansion ratio of V3/V4. In ideal cycle, it equals the compression ratio) turns into work done by the system on the piston.
5. *Blowdown (4⇒1):* The piston is in BDC momentarily and an expansion at ideally constant volume takes place. The heat I (QL) s removed and the gas returns to state 1.
6. *Exhaust stroke (1⇒5):* The exhaust valves open and as the piston moves from BDC to TDC, the gas mixture is driven out the engine to the atmosphere and the process starts again.

Both Lenoir's and Otto's engines, which have been the most relevant developments regarding IC engines history, used the same ignition system fundaments, the Spark Ignition System (SIS). Nowadays, the gas cars' ignition still work with the same principle.

Over time, spark plug designs have evolved as the engines technology have too. As small engines have better efficiency than bigger ones, the ignition system size had to be reduced too. However, the main work principle of those systems remains the same than the one used 60 years ago.

2.1.1. Spark ignition system

The main purpose of that ignition system is to provide enough electrical voltage to discharge a spark between the two electrodes of the spark plug to ignite the air-fuel mixture highly compressed during the compression stroke of the cycle in the engine's combustion chamber. It must be capable to produce as many as 30,000 volts to force electrical current across the spark plug gap.

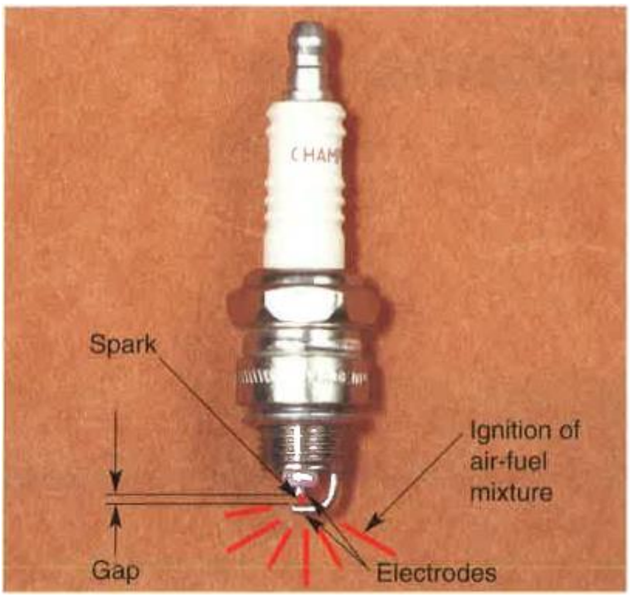

Figure 3. Spark plug

Phases of the ignition process

The voltage, current and duration of the spark depend on the gas through which the discharge takes place, its pressure, the gap length and shape and the electrical characteristics of the circuit used to supply the spark energy. Four phases can be identified in the ignition process [4]:

- *Prebreakdown phase:* The application of a high voltage in the gap of the plug, which initially offers an infinite impedance, accelerates free electrons in it towards the anode. Their energy ionizes the gap and reduces its impedance until *breakdown* is achieved. It usually lasts in about 1µs, although it depends on the electrical circuit design.
- *Breakdown phase:* As the current flow rises to 100A or higher, the ionization of the gas becomes greater and the voltage needed to maintain the arc starts to fall. That phase lasts for only 20-50 ns.
- *Arc phase:* With currents higher than 0,1A and lower voltages of about 100V, the energy transferred is greater than in the breakdown phase. However, has the duration is longer, there exist heat losses in the electrodes.
- *Glow phase:* The energy storage device dumps its energy into the discharge circuit. As the stored energy is finite, the power delivered falls resulting in fewer electrons that carry current.

Types of spark ignition systems

As said before, despite the technology around IC engines has been constantly evolving, the main fundaments of the ignitions have remained the same than the first models appeared. The two main SIS are:

- Magneto ignition system.
- Battery or coil ignition system

Magneto ignition system

Although there are several types of that ignition system, the main working principle of the Magneto ignition system, shown at *Figure 4*, is the following: It produces electrical current for ignition without outside primary source of electricity. As the magnets move past the coil, current is induced in the coils primary windings. This current causes a magnetic field to form around the primary windings. As the engine's piston gets close to the TDC on the compression stroke, the switching device opens and the magnetic field in the primary winding collapses rapidly, inducing a high-voltage current in the secondary windings. The high voltage current travels to the spark plug, where it arcs across the spark plug gap and ignites the air-fuel mixture.

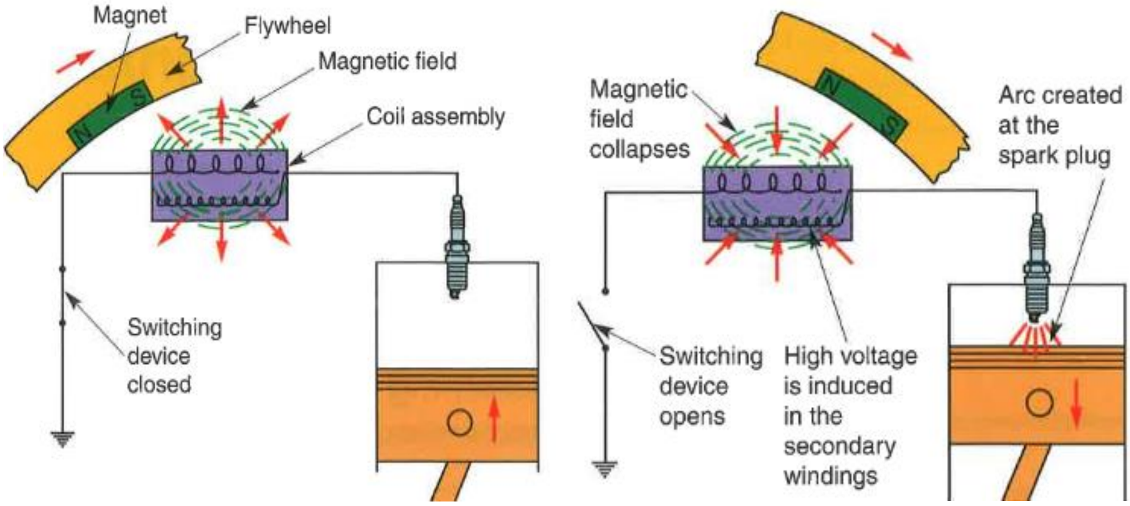

Figure 4. Basic operating principle of a magneto ignition system with switching device closed (left) and open (right).

- *Mechanical Breaker Point Ignition System*

The different Magneto Ignition Systems are classified by the type of switching device they use to control primary current to coil. The first of them, used until the mid-1980's, is the Mechanical Breaker point Ignition System (MBI). It controls the current in the ignition coil with a mechanical breaker point, which consists in a mechanical switch that is closed and opened once per firing event by a cam located on the distributor shaft. The number of cam lobes equals the number of cylinders.

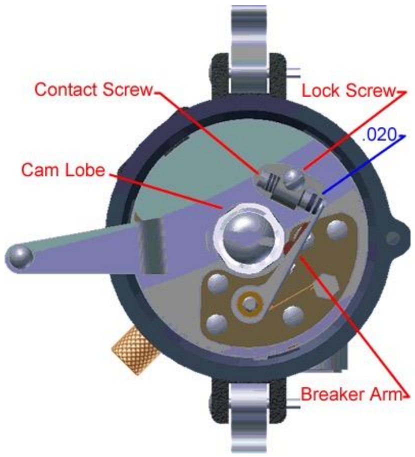

Figure 5. Main parts of the Mechanical Breaker point Ignition System.

- *Solid State Ignition System*

The MBI was used in IC engines until the development of the solid state ignition systems, applied in all late-model engines. They use electronic devices to control different ignition system functions. They have several advantages over mechanical systems such as:

- They have nearly no moving parts, so mechanical adjustments and maintenance are not required.
- No breaker contacts to burn, pit or replace.
- As they are electronic and automatic, they never need adjusting.
- They are hermetically sealed and unaffected by dust, dirt, oil and moisture.

The two existing solid state ignition systems are the Capacitance Discharge Ignition System and the Transistor-Controlled Ignition System:

A) Capacitance Discharge Ignition System (CDI):

The only moving parts of this solid state ignition system are the flywheel magnets. As they rotate, a low voltage alternating current is induced to the charge an exciter coil. That AC passes through a rectifier (d1) where it is converted into DC. It travels to the capacitor where it is stored. The spark occurs when, depending on the engine requirements, the pulse rotator rotates to induce a small electrical charge in the trigger coil that activates the silicon controlled rectifier (SCR). Then that stored voltage in the capacitor is driven to the ignition coil to be stepped up to a maximum of 30,000 V and be discharged across the spark plug gap. All these pointed parts can be seen in the *Figure 6*.

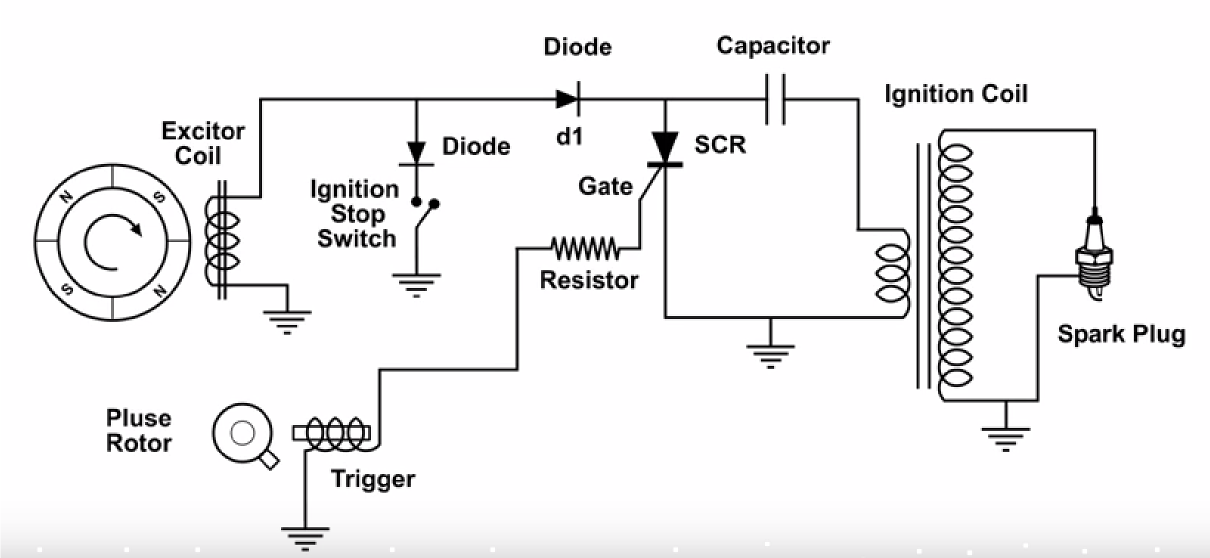

Figure 6. Main parts of the Capacitive Discharge Ignition system.

B) Transistor-Controlled Ignition System (TCI):

There are a variety of transistor-controlled circuits. The *Figure 7* below illustrates a typical circuit of this type of solid state ignition system. As its name says, in this system, the spark plug is controlled by a transistor. The ignition takes place when the flywheel rotates fast enough to turn on the transistor by sending a current signal to its base. When that occurs the transistor stops the current flow from the 12VDC source, which causes the primary winding magnetic field of the ignition coil to collapse across the secondary winding to fire the spark plug.

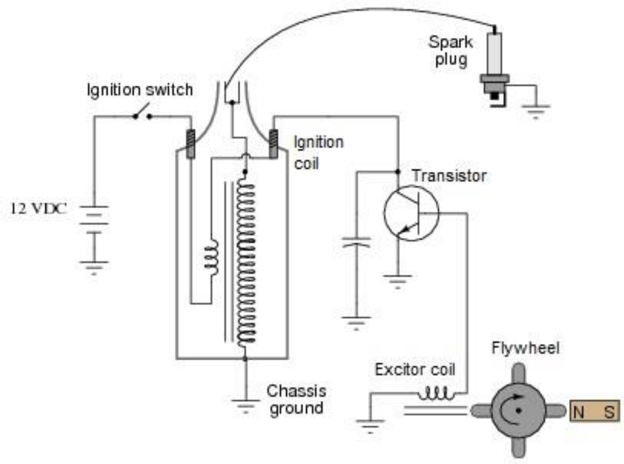

Figure 7. Main parts of the Transistor-Controlled Ignition System.

Battery ignition system

The Battery Ignition system has a low voltage primary circuit and a high voltage secondary circuit. Like the magneto system, it consists of a coil, solid state switching device and a spark plug. The main difference is that the source of the current for the primary circuit is supplied by a lead-acid battery instead of the flywheel magnets.

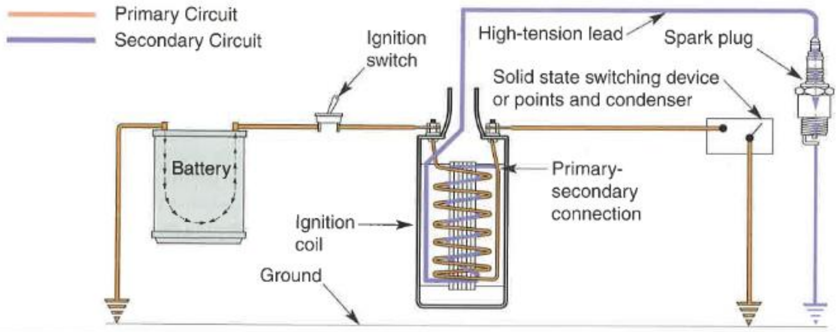

Figure 8. Battery ignition system.

When the ignition switch is turned on, current flows from the positive post of the battery to the ignition coil. While the switching device (MBI, CDI or TCI) is closed, which means that ignition is not required, that current builds up a magnetic field in the primary winding of the ignition coil. When spark plug is required the switching device is activated and the created magnetic field surrounding the coil collapses and induces a current in the secondary windings to create the necessary voltage to fire the spark plug.

Although it is the most commonly used type of ignition system in cars and light commercial vehicles, it has some advantages and disadvantages over the Magneto Ignition system:

Disadvantages:

- The battery needs an alternator/generator for recharging, which turns into mechanical losses. Otherwise, an engine equipped with a magneto system does not need this. Besides, the battery can discharge making it impossible to start the engine.
- It occupies more space than the magneto does.
- As the magneto ignition system has a solid connection with the crankshaft, at high speeds it guarantees a high intensity spark, which increases the engine efficiency. That is why it is mainly used in racing cars and two-wheel vehicles.

Advantages:

- Unlike magneto system, as it is not physically linked to the crankshaft, it can provide an intense spark at low speeds.
- For this exact reason, while the spark timing in the Magneto System depends on the speed of the crankshaft and it is difficult to vary, the great advantage of the Battery Ignition System is that this time can be changed depending on the needs of the engine making it more efficient [5].

2.1.2. Alternative gasoline ignition systems

Spark ignition engines are clearly dependent on repeatable and reliable ignition to produce good performance and low pollutant emissions. Current ignition systems such as TCI or CDI are very reliable and provide an adequate ignition energy. However, as the climate change issue is getting worse every year, current Pollutant Regulations are trying to slow it down by continuously increasing the restrictions of their emission limits. That fact forces the engines manufacturers to make actually big efforts to achieve those non-emission objectives with the current technology without reducing the power of their products.

The motivation of creating more efficient and less fuel-consuming engines has helped alternative gasoline ignition systems to appear. Although they are still in research stages, some of them seem to be reliable to substitute the currently used spark ignition system.

The main alternatives to SIS that are currently under investigation are [6]:

- Laser Ignition.
- HCCI (Homogeneous charge compression ignition).
- Microwave ignition.
- Corona ignition.
- High frequency ignition.
- Shock wave ignition.
- Plasma jet ignition.

A simple explanation of two of them was made:

Laser ignition system

Laser ignition, or laser-induced ignition is the process of starting combustion by the stimulus of a laser light source. Although there are some other mechanisms of laser ignition such as the photochemical mechanism and the resonant or thermal breakdown, because of its freedom in selecting the laser wavelength and ease of implementation, this kind of ignition system is mostly based in the non-resonant gas breakdown of a tightly focused pulsed laser beam[7].

The spark is changed by a laser beam that is passed through a convex lens and focused in the spot of the combustion chamber where the ignition is desired to be fired up.

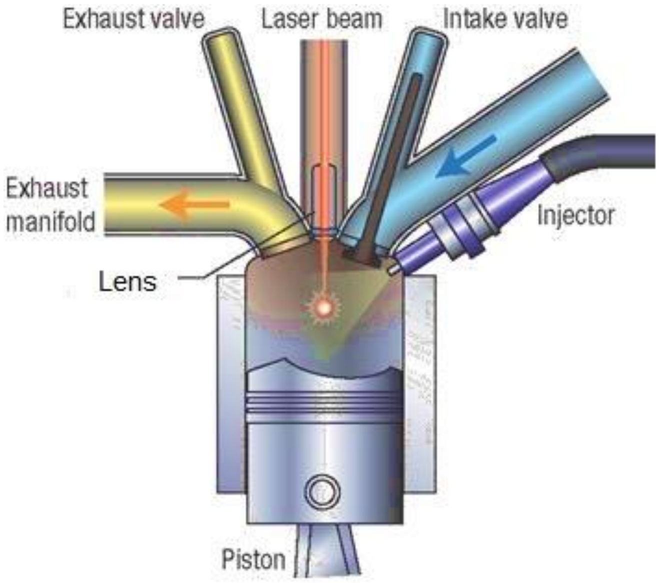

Figure 9. Laser ignition system.

An optical breakdown in air is produced by a short and intensive laser pulse. The needed irradiation levels are in a range between 10^{10} to 10^{11} W/cm^2. At such intensities, gas molecules are dissociated and ionized within the vicinity of the focal spot of the laser beam and hot plasma is generated. This plasma is heated by the incoming laser beam and creates a strong shock wave, which is used for the ignition of the fuel-air mixture.

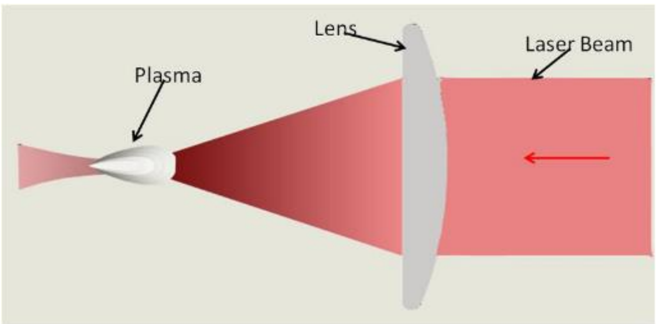

Figure 10. Plasma generation in a Laser Ignition System.

Usually, the laser source chosen for this kind of ignition system is the Nd:YAG laser. One photon emitted by it has an energy of 1.1 eV. The ionization energy of the nitrogen is approximately 14.5 eV, so that more than 13 photons from that laser source are required.

This project is not focused on the laser ignition system, so for further information, you can consult [8], [9] and [7].

The main advantages of the laser ignition system (LIS) over the SIS are:

- The ignition plasma positioning in the combustion cylinder can be chosen arbitrarily.
- With the LIS, leaner mixtures then with the spark plug can be ignited. That means lower combustion temperatures and, as a consequence, less NO_x emissions.
- The lifetime of a LIS is expected to be much longer than that of a spark plug as is carried no erosion effects.
- Higher pressures are possible. So that, efficiency increases.
- Precise ignition timing.
- Easier possibility of multipoint ignition.
- Etc.

On the other hand, it has two big disadvantages that stop it from being used in the current engines:

- It has high costs.
- It is a proven concept but there is no commercial system available yet.

Although that ignition system has some advantages over the SIS, the big amount of energy needed makes it a very expensive system that still needs more research in order to be used in conventional engines.

HCCI (Homogeneous charge compression ignition)

A lot of papers about this type of ignition system have been published over the last decade. The HCCI, also called Controlled Autoignition (CAI) has been often considered it a new combustion process. However, the SIS and the compression ignition (CI) have not been around much more time than it [10].

HCCI combines characteristics of gasoline engines and diesel engines. The first one combines homogeneous charge with spark ignition and the second one, stratified charge with compression ignition. The main working principle of this ignition system is the compression of a well-mixed fuel and oxidizer (normally air) until its auto-ignition. As in the SIS, fuel is injected during the intake stroke but, to ignite it, instead of using an arc discharge, the density and temperature of the mixture is raised by compression until a spontaneous exothermic reaction takes place.

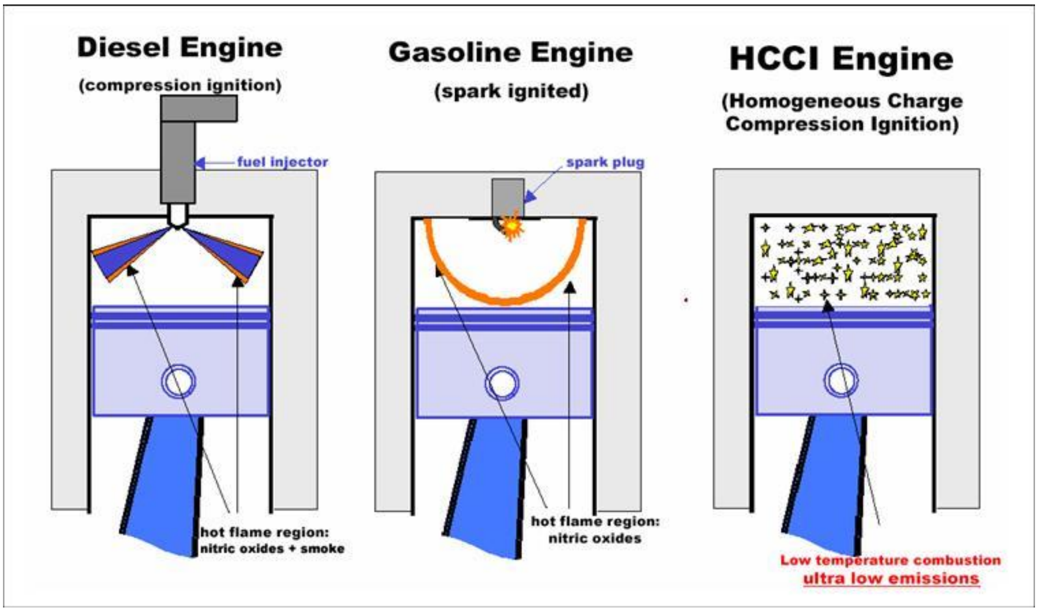

Figure 11. Comparison of cylinders in CI, SI and HCCI engines.

The main advantages of the HCCI engines over the SIS engines are:

- Higher efficiency due to an important reduction in pumping losses, what leads to big cuts in CO_2 emissions.
- The burning of the fuel is much faster.
- Combustion takes place at lower temperatures (<1300 ºC), what results in nearly no NO_x emissions.

On the other hand, one of the main reasons why this technology is not yet being used in current vehicles are the high compression ratios needed (above 12:1) that cause knocking issues during full-load operation due to high pressure rates and high heat release. Furthermore, at cold start, the compressed-gas temperature in an HCCI engine is reduced because the charge receives no preheating. Besides, HC and CO emissions are higher than a typical spark ignition engine because of incomplete oxidation in fast burnings.

3. CORONA DISCHARGE IGNITION SYSTEM

The working principle of this alternative ignition system is based on the Corona effect. This phenomena consists in an electrical discharge observed at the surface of a conductor of an AC high voltage system caused by the formation of electron avalanches, which occur when the intensity of the electric field exceeds a certain critical voltage value, called Critical Disruptive Voltage Gradient (CDVG). When this takes place, the surrounding air of the conductor ionizes and a glowing luminous discharge can be noticed at low light.

Figure 12.Glow light caused by corona discharge surrounding a high voltage coil.

3.1. Corona discharge formation

There are always a few free electrons in the air as a result of traces of radioactive materials in the Earth's crust and cosmic ray bombardment of the Earth from outer space. As current flows through the conductor an electric field is created. The electrons in the air surrounding its surface, which have an inherent negative charge, are accelerated toward the conductor on its positive half cycle of the AC current and away from the conductor on its negative half cycle.

For low intensities of the electric field, the collisions of the electrons with the air molecules such as O_2 and N_2 are elastic and no energy is transferred. However, if the electric field overcomes the CDVG, the collisions become inelastic, the velocity of the electrons increases and they have enough energy to push the electrons out of their orbit of the air molecules, which turn into a positive ion. This process is better known as air ionization.

The two electrons involved in the collision, which have lost most of their velocity, can be accelerated by the electric field of the conductor and are capable to ionize another air molecule in the next collision. The number of electrons is doubled in every collision until the number has grown enormously generating an intense electrostatic field. This process is the well-known electron avalanche.

The positive ions left in the wake of the electron avalanche are an attraction for the free electrons. When one of them is captured, the positive charge becomes a neutral molecule with a lower energy than that of the corresponding ion. This loss causes the emission of a quanta of energy, which is exactly equal in magnitude to the energy required to push an electron out of an air molecule's orbit. It is radiated as an electro-magnetic wave that, for air molecules such as oxygen and nitrogen, it can be seen as a soft violet colored light.

If a pointed tip and a metallic plate electrodes are faced one in front of the other the formation principle of the corona discharge is the same than in a conductor. In this case, the electric field would be greater close to the tip electrode. Thus, the ionization of the air mass between the two electrodes is lower near the metal plate.

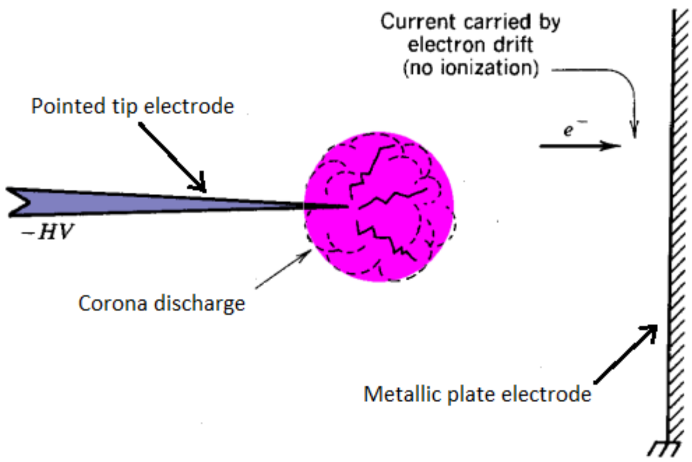

Figure 13. Sketch of a Corona discharge between a pointed tip and a metallic plate electrodes.

As long as current increases the ionization of the air mass between the two electrodes does so. When it is high enough to break the dielectric barrier, the arc discharge takes place and carries a big reduction of the voltage between the two terminals.

The increase of the current carries several types of electrical discharges, which are shown at the *figure* below. The non-self-sustained discharge and the self-sustained discharge take place before coronas.

In the non-self-sustained discharge first electrons are delivered from the tip electrode to the metal plate. The quantity increases with the applied voltage. This is why the characteristic curve shows an almost linear behavior. It requires an external ion source like thermionic emission, cosmic radiation or photoionization to increase the current to be sustained.

If the applied voltage reaches a certain value of voltage breakdown (V_b), electrons are able to start to ionize gas molecules and the electron avalanche forms, which is called the self-sustained discharge (or Dark discharge). As explained before, a glowing light surrounds the tip of the electrode due to the electromagnetic radiation of the molecules back to neutral, the corona discharge.

As electric field increases, the glowing area gets bigger too. Some call this the glow discharge and it is previous to the arc discharge [11].

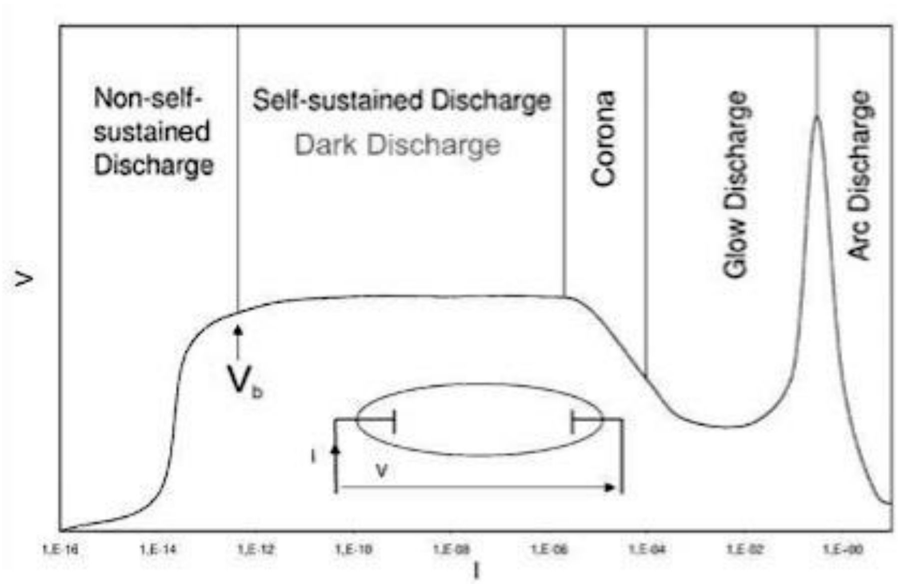

Figure 14. V-I characteristics of a discharge between two electrodes.

When the corona discharge takes place, the sudden increase of the voltage the glowing region starts to alter and it forms separate filaments, called streamers looking similar to the roots of a tree or a brush. This is called the Streamer Corona and is the potential event to be used for engines ignition. It can be seen in *figure 15.*

Figure 15. Streamers of the Streamer Corona.

There are different ways to classify all type of corona effects depending on the intensity of the electric field, on the distance from the electrode and its geometrical characteristics, the properties of the surrounding fluid, etc. The laboratory study made by *Hubbell Power Systems* classifies the corona effect in three types: plume discharge, brush discharge and glow discharge [12].

On the other hand, in an ignition system, if the corona discharge takes place between two electrodes and the electrode with the strongest curvature is connected to the positive output of the power supply, the phenomena is called positive corona. Thus, it is called negative corona if this electrode is connected to the negative output [13].

For most high voltage applications, Corona Discharge (CD) is an undesired side effect as it carries such important power losses. It can generate audible radio-frequency noises, particularly near electric power transmission lines and electromagnetic interferences. However, several studies prove that the use of corona as an ignition source has a lot of benefits regarding fuel efficiency and pollutant emissions.

3.2. Application to ignition system

Several methods and strategies have been employed in order to increase the fuel efficiency and to reduce pollutant emissions, such as the use of leaner air-fuel mixtures, EGR (exhaust gas recirculation), use of higher BMEP (brake mean effective pressure) and high turbocharger levels. However, the use of such lean, dilute air-fuel mixtures and high pressure levels is limited by the necessity of higher voltages, which are difficult to contain in the secondary winding of the ignition coil of the current SIS.

On the other hand, when complete dielectric breakdown takes place in a SIS, a very large current heats the fuel-air mixture between the electrodes to very high temperatures that are used to sustain the ionization of the gas long enough to initiate combustion. That results into great heat losses. Furthermore, the created high temperature plasma causes erosion of the electrodes.

Figure 16. Erosion of a spark ignition system electrode.

The corona discharge ignition system takes advantage of a high voltage and low current electric field to ionize the air-fuel mixture instead of heat. The ionization process is controlled by the electric field in such a way that complete dielectric breakdown does not occur. However, it is maintained at a high level enough to produce a flame front and originate combustion. Thus, this system carries no heat losses neither electrodes erosion problems [14].

One basic condition for the creation of a corona discharge is the existence of strongly inhomogeneous electrical fields. While in a homogeneous electrical field, an electrical breakdown happens instantaneously with reaching the ignition voltage, a stable discharge without electrical breakdown can be established in a current-limited circuit as corona is formed in the field-weak regions of a strong inhomogeneous field.

This condition can be achieved by enhancing the electric field with very asymmetric electrodes. It can be done by the use of tip electrodes forming a point-plane arrangement in the combustion chamber with electrical conductive engine components such as the piston, the cylinder head and walls and the valves as electrical ground potential.

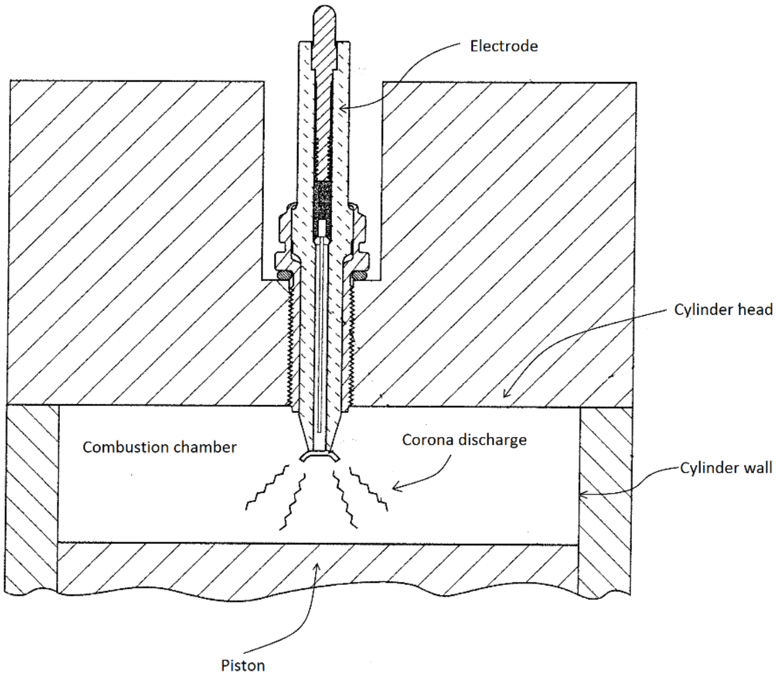

Figure 17. Sketch of the configuration a potential combustion chamber of a corona discharge system.

In the combustion chamber section of *figure 17* an asymmetrical electrode discharges corona to ignite the fuel-air mixtures. The rest of the components should be electrical conductive to increase the intensity of the electric field that ensures the generation of the streamers, which lead to a larger ignition volume than in the common SIS [15].

3.3. Current corona discharge ignition systems

Although they cannot be found in any engine of the current commercialized vehicles, at least two powertrain components manufacturers have developed an ignition system based in corona discharge.

In *BorgWarner* they have developed a prototype corona ignition system that they call "EcoFlash". It uses a high frequency alternating voltage with a frequency of a few megahertz for the generation of a strong electric field at the tip of the electrode. The signal generation is done in a control unit that contains the frequency generator and some DC-DC transformer stages that increase the voltage to hundreds of volts before it is transferred to the igniter through a coaxial high frequency (HF) cable.

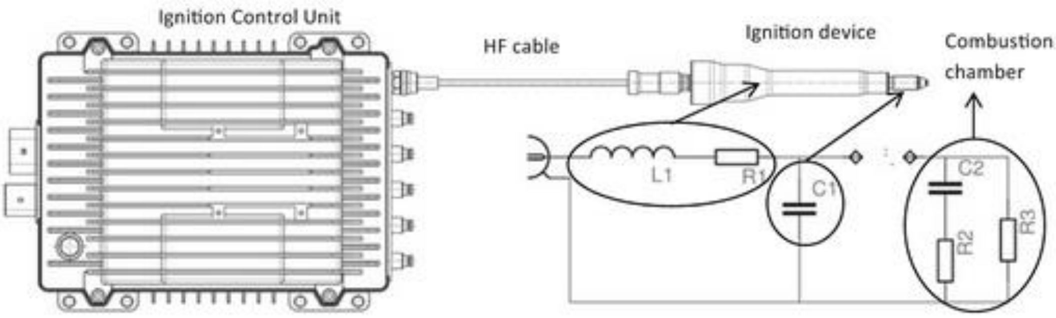

Figure 18. Corona Ignition System "EcoFlash" and equivalent circuit diagram of igniter and combustion chamber.

The system can have from 3 to 6 igniters capable to produce an extended corona discharge. Each of them has an integrated resonant circuit, made of an LC-oscillating-circuit, which increases the voltage by a factor of 100 to achieve an electrical field at the electrode tip up to 300 kV/mm [16]. As it can be seen in the *figure 19* below, the igniter has a 5 tip asymmetrical electrode and each of them delivers a discharge of Streamer Corona that would ignite the fuel-air mixture. In comparison with the plug of a SIS, it is obvious that the ignition volume is much bigger in the EcoFlash ignition. The combustion chamber is dimensioned by electric field simulation to ensure that its metal surface never reaches the threshold value that would fire up the spark discharge.

Figure 19.EcoFlash Igniter in comparison with a conventional spark ignition plug.

In *BorgWarner* they say the ECoFlash ignition system has several advantages over the conventional SIS:

- Higher fuel efficiency with a reduction of consumption up to 10%.
- Higher ignition volumes up to 1 cm^3.
- Capability of ignition of lean and diluted fuel-air mixtures.
- Short burn delays.

In general, they say the system significantly improves fuel economy and reduces pollutant emissions.

On the other hand, two years before, in 2012, *Federal-Mogul Powertrain* developed their own corona ignition system, which they call ACIS (Advances Corona Ignition System).

Like the rest of systems with corona effect as the working source, the ACIS uses a high energy and high frequency electrical field to produce repeatable controlled ionization creating multiple streams of ions of about 25 mm long in each tip of the electrode to ignite the fuel-air mixture throughout the combustion chamber.

Federal-Mogul has developed a two-piece and 4 electrode tip igniter compatible with current and future engine designs. A controller converts the 12 V DC electrical supply into a 72 kV electrical field with a resonant frequency up to 1 MHz in the tips of the igniter.

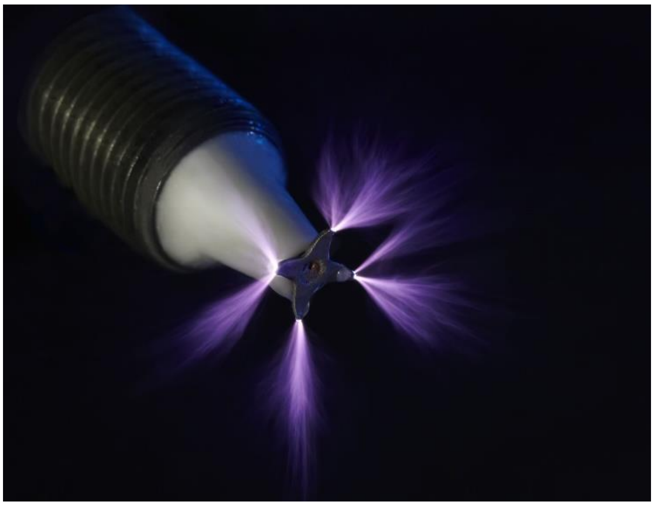

Figure 20. Electrode tips of the Federal-Mogul ACIS igniter.

The main advantages of this system over the common spark ignition system are quite similar to those that offers the *BorgWarner* corona ignition system [2]:

- Enables advanced combustion strategies such as lean burn, highly diluted mixtures and very high EGR (exhaust gas recirculation), leading to fuel economy/CO_2 improvements higher than 10% over a wide speed load range.
- Robust combustion initiated in as little as 30 µs.
- Faster burn and less delay: 5º less ignition advance than spark.
- More thorough combustion.

3.4. Benefits over the common ignition systems

Previous researches on this field studied the multiple benefits corona discharge has over spark ignition system.

One of the main benefits is the reduction in current consumption. As it has been seen before, corona needs less input power to fire up [17]. In the *figure 21* below it is shown as, for the same amount of released energy, the current consumed in case of the SIS is much higher than in the case of the corona ignition system.

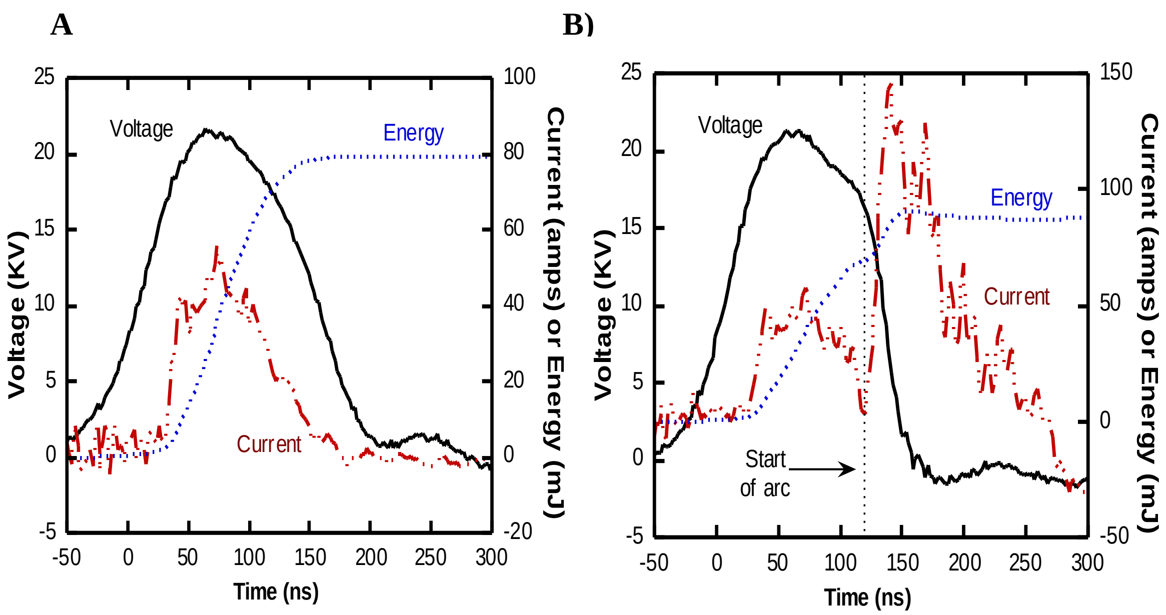

Figure 21. Current consumption of a corona ignition system (A) and a spark ignition system (B).

On the other hand, the use of corona discharge allow a descrease of both the delay and the rise times. As it is well-known, the delay time consists in the period needed to reach a 10% of the peak preassure. Moreover, the rise time represents the time needed to go from the 10 to the 90% of the peak pressure.

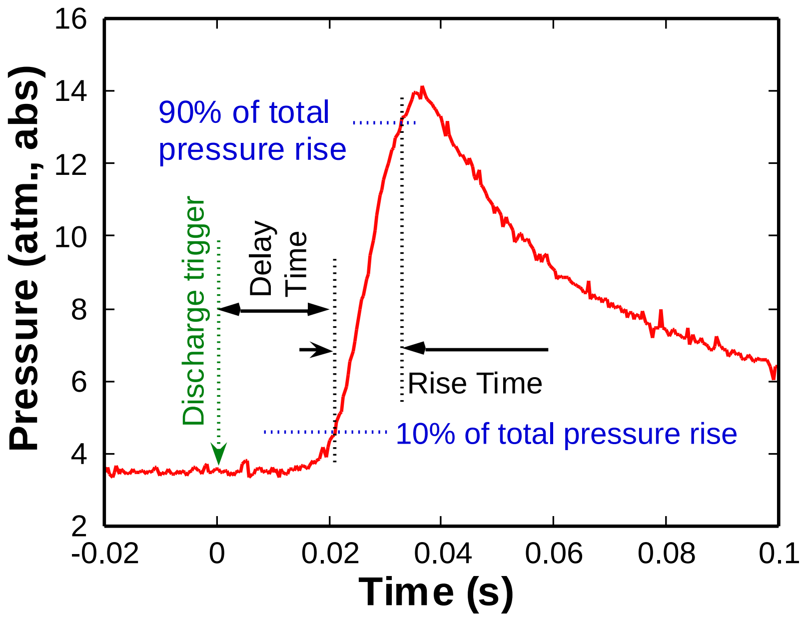

Figure 22. Representation of the delay and the rise times in the pressure-time graph of an ignition process.

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A study shows as these to parameters strongly depend on the geometry of the discharge electrode. However, it was shown that the delay time can be reduced by 2 times by using a tip electrode. The rise time though, did not change siginificantly.

As pointed by both *BorgWarner* and *Federal-Morgul'*s ignition systems, this reduction in the delay time leads to faster burn rates. This allows the use of advanced combustion strategies such as valve overlap increase in order to reduce the fuel consumption [17].

In the *figure 23.* below, this high fuel efficiency is shown for a load point of 2000 rpm and a 2 bar BMEP (Break mean effective pressure). The valve overlap technique with an spark ignition allows a fuel consumption reduction of about a 1,5%. With the use of a corona discharge, this reduction could be of 4,3% [15].

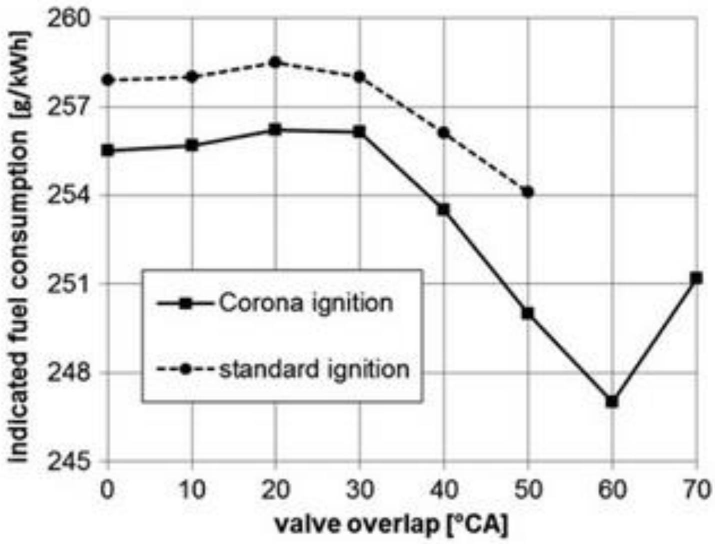

Figure 23. Fuel consumption of CD ignitionsystem and SIS with valve overlap strategy.

The most significant benefit of using corona discharges is the increase of the effective pressure that leads to higher effective work delivered by the engine. This is due to the higher ignition volume that can be achieved with this alternative ignition system. In the *figure 24* below the thermodynamic Otto cycle of an engine working at 3000 rpm is shown and it is quite obvious that its work is higher because of this increase in the effective pressure [17].

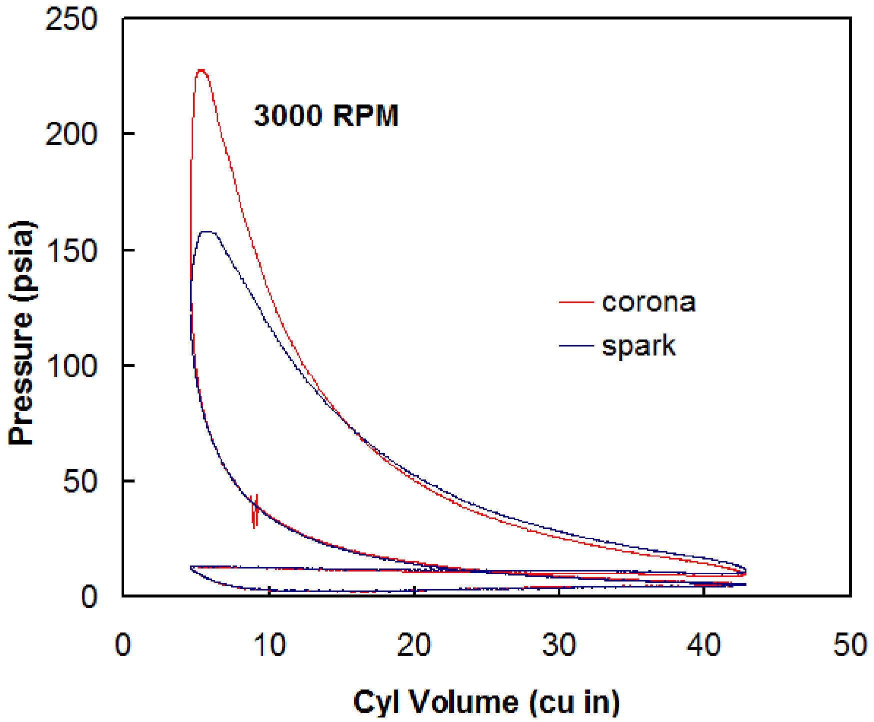

Figure 24. Comparison of the thermodynamic cycle of an engine working with SIS and one with CD ignition system.

4. ANALYSIS AND JUSTIFICATION OF THE EXPERIMENT

The aim of the experimental work done in this project was to design and build a simple and cheap control system capable to create a corona discharge in the electrodes of an ignition coil of an engine and to keep it through time.

To make it simple and cheap it was tried to use the maximum quantity of existent equipment in the laboratory as possible complementing it with economical electronic components.

The development of the experimental part started with the initial sketch of the system. It was mainly composed by the ignition coil of a car, which was already in the laboratory as it was used in other projects, a microcontroller (MCU) and a toroidal current sensor, as shown in *Figure 25.*

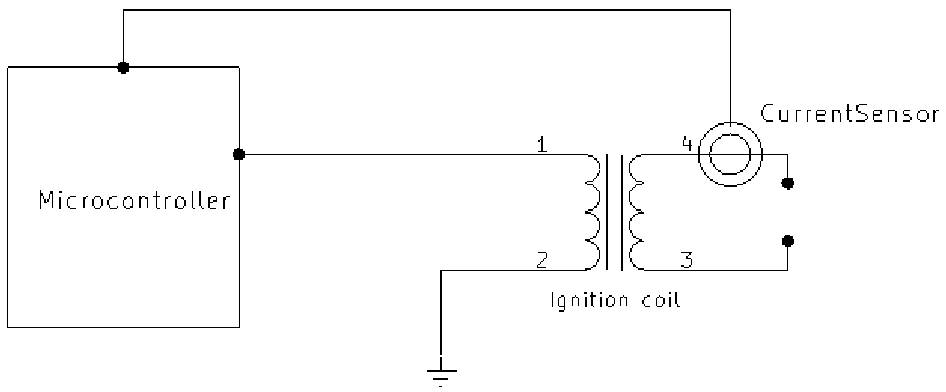

Figure 25. Intial sketch of the system.

The basic idea of this design was to send a high voltage and high frequency square wave with the microcontroller to the ignition coil to generate the CD. The toroidal current sensor would be placed in the output wire of the secondary winding as feedback of the control circuit to fight the electric field variation in the output wire of the coil.

This kind of AC current sensors consist in a toroidal wound coil wrapped around a core. When a current-carrying conductor passes through the center of it, a linear voltage proportional to the conductor current is induced in the sensor coil. See *figure 26* below.

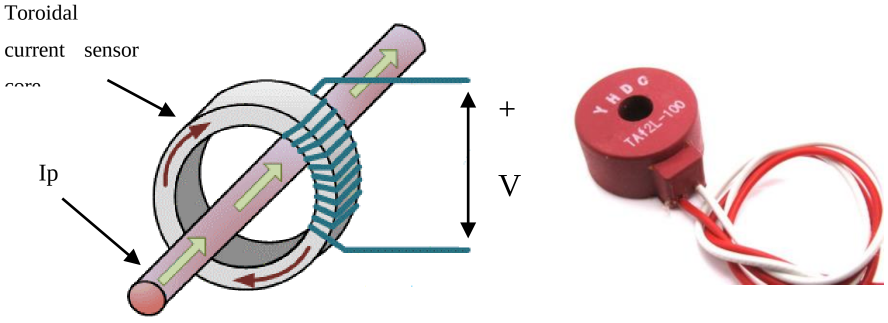

Figure 26. Sketch of a toroidal current sensor and the non-invasive AC current sensor TA12L-100.

That electric field variation could result in two undesired scenarios that the MCU would solve:

- It could make the current travelling through itself suddenly increase and, consequently, ionize the dielectric barrier until the spark fired up. In this case, MCU would reduce the input voltage until CD appeared again.
- Decrease this current and stop the CD in the electrodes. Then the MCU would raise its input voltage until corona effect appeared again.

Once the initial concept was set, the next step was to choose the MCU that would generate the signal to feed the ignition coil driven by the difference of voltage delivered by the current sensor.

The MCU Arduino Uno was chosen. It is classified as one of the “Entry Level” boards of this famous open-source software, what keeps the target of a simple and low-cost system.

4.1. Arduino UNO

The Arduino UNO is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins, six 5V analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, etc.

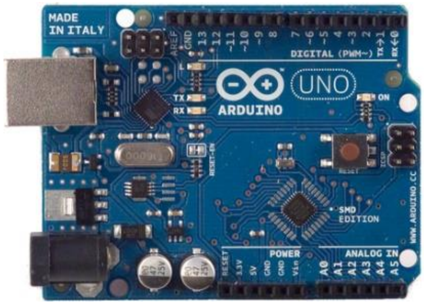

Figure 27. The microcontroller Arduino UNO.

Clock

One of the reasons why this board was chosen is because its clock is able to work at 16MHz frequency, which perfectly matches the fact that the corona effect tends to show up at high frequencies.

Inputs

The board has 6 analog inputs numbered from A0 to A5 that can read analog voltages from 0 to 5 V. So that, the difference of voltage in the current sensor could be read by plugging one of its poles in any of the Arduino UNO inputs and the other to the GND pin.

Outputs

This "Entry level" Arduino board has 14 digital outputs. 6 of them are said to be analog outputs. However it is not completely true. They are able to deliver a 0 to 5V fixed amplitude PWM.

The pulse-width modulation (PWM) is a square wave signal switched between ON and OFF that delivers a medium voltage product of the duty cycle and the maximum voltage the signal delivers. The duty cycle, the percentage of the signal period when it is ON (1).

D= Duty cycle.

τ= time in which the signal is positive.

T= Period of the signal.

$$D = \frac{\tau}{T} \quad (1).$$

In the Arduino UNO board, the ON state of the PWM generates 5V and 0V the OFF state. For example, a wave with a duty cycle of 60% would generate a medium voltage signal of 3V and 1,5V with 30%. *See sketch in figure 28 below.*

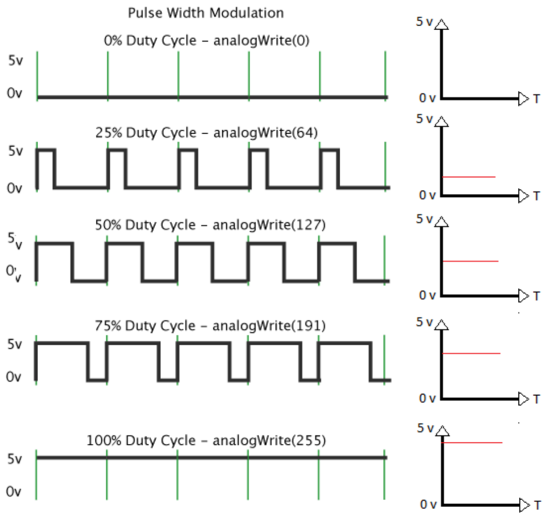

Figure 28. 5 PWM signals with different duty cycles and their equivalent medium voltage .

The next step was to find the way how to excite the ignition coil taking advantage of the PWM signal generated by the Arduino UNO. Although it gives a medium analog voltage, a maximum 5V signal is far from charging the coil enough to create the CD in its electrodes. Thus, a power stage was necessary.

4.2. Power stage

The ignition coil of an engine consists of a laminated iron core surrounded by two coils of copper wire. Unlike a power transformer, it has an open magnetic circuit meaning that the iron core does not form a closed loop around the windings. Thus, the energy stored in the magnetic field of the cores is the energy that is transferred to the spark plug.

The primary winding has relatively few turns of heavy wire and the secondary winding consists of thousands of turns of smaller wire in order to transform the 12V handed by the battery into thousands of volts necessary to fire up the spark [18].

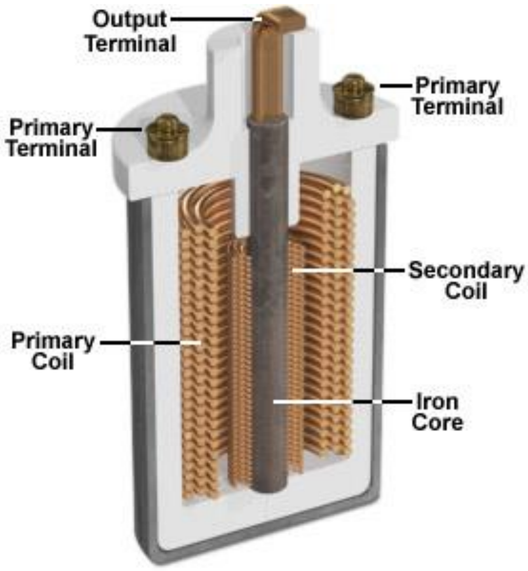

Figure 29. Components of an ignition coil.

The PWM signal generated by the Arduino board delivers, with a duty cycle of 100%, which creates 5V of medium voltage, a maximum intensity of 40mA. As said before, the ignition coil of an engine usually works with the 12V of the car battery. It is obvious that the microcontroller signal was not enough excite the coil and that an amplifying stage with electronic components was needed.

To carry out the electronic design it was important to understand the basic working principles of inductances. The first thing to consider is the fact that an electric current flowing through a conductor generates a magnetic field surrounding it.

Faraday's law

It is well known that the *Faraday's law* says that any change in the magnetic environment of a coil of wire will cause a voltage (electromotive force, ε) to be induced in the coil.

The magnetic flux through a surface is the surface integral of the normal component of the magnetic field passing through it (2).

$$\phi = \iint_S B \cdot dS \tag{2}$$

B= Magnetic field in T.

S= Surface whereby the magnetic field passes through.

That electromagnetic force (emf) is equal to the negative of the rate of change of magnetic flux times the number of turns in the coil [19].

$$E = -N\frac{\Delta\phi}{\Delta t} \quad (3)$$

ε= electromotive force. Induced voltage in V.

N=Number if turns.

φ= Magnetic flux in Wb

That induced voltage also depends on how quickly the flux through the coil is changing (Δt).

Lenz's law

The *Lenz's law* states that when an emf is generated by a change in magnetic flux according to *Faraday's Law*, the polarity of this induced voltage is such that it produces a current whose magnetic field opposes the change that produces it. That explains the negative sign in the emf equation.

The inductance of a coil characterizes the behavior of an inductor and is defined in terms of that opposing emf or its generated magnetic flux and the corresponding electric current. It also depends on the geometry of current path as well as the magnetic permeability of the nearby materials:

$$L = \frac{d\phi}{di}; \quad (4)$$

L= Inductance of the coil in H.

i= current through the coil in A.

After rearranging both *Lenz's* and *Faraday's laws*, the induced current in a coil comes up to be dependent on time (5):

$$\varepsilon \cdot dt = L \cdot di \quad (5)$$

After getting deeper into coils physics and basing on the current Transistor-Controlled Ignition System, the power stage could be set. The poor signal coming from the Arduino board would be amplified with a MOSFET.

MOSFET

The metal-oxide-semiconductor field-effect transistor (MOSFET) is a type of field-effect transistor (FET) very used in power electronics. It is a voltage controlled device whom current carrying ability changes by applying and electric field. They can be useful in multiple applications such as acting as an amplifier or as an electrically controlled switch.

The main advantage of a MOSFET over a regular transistor is that it requires very little current to turn on, while delivering a much higher current to a load.

There exist two different type of MOSFETs depending on their configuration: PMOS (p-type) and NMOS (n-type). Regardless of which type they are, they have 4 terminals like any other transistor: the Gate (G), the Source (S), the Drain (D) and the Body (B).

In this project the type of MOSFET chosen is the NMOS as they are considered to be faster than the PMOS and the system must be capable of working with high frequency signals. For this kind of transistors, the body and the source are usually connected to the ground, the drain to a fixed voltage and the gate to a variable voltage (V_G).

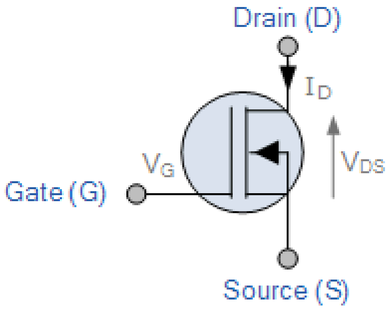

Figure 30. Symbol of an n-type MOSFET and its parts.

There are three regions of operation in MOSFETs:

- *Cutoff region*: The MOSFET works as an open circuit between the Source and Drain (I_D=0).
- *Triode (or Ohmic) region*: It works as a short circuit between Source and Drain (I_D=0).
- *Saturation region*: The transistor works as a variable resistance [20].

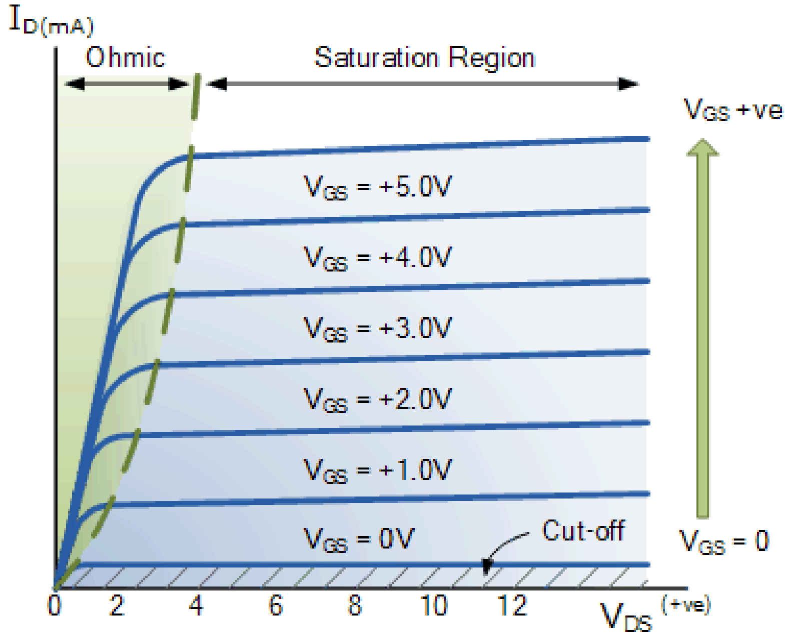

Figure 31. Operation regions of a MOSFET.

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After the introducing into MOSFETs it was easier to know how one of them would as an amplifier in the system.

Hypothesis: MOSFET and PWM from Arduino UNO to excite an ignition coil

The conclusion drawn from *Faraday's* and *Lenz's laws* was that the induced voltage in a coil changes with the amount of time that an electric current flows through them (6):

$$\varepsilon = L\frac{di}{dt} \tag{6}$$

The Arduino UNO does not allow to vary neither the current nor the voltage amplitude of the PWM signal, so the induced current of the coil cannot be changed by ranging the current flowing through it. However, what the board does allow to do is choosing the time the square wave is ON by setting the percentage of its duty cycle. This could be used to set the dt and be taken advantage of to control the voltage the coil is charged with.

The role of the MOSFET is to amplify the PWM signal, which is coming from the Arduino and does not have enough power to excite the primary winding of the ignition coil. It acts like a switch commanded by the ON/OFF wave coming from the board. The signal is brought to the Gate terminal, the Drain terminal is connected to a fixed voltage source and the Source terminal to the ground. If there was no coil, the activation of the transistor would give a voltage between the D and S terminals equal to the one given by the tension source.

Besides, a 220Ω resistor (usually called the gate resistor) is placed between the output Pin of the board to limit the instantaneous current that is drawn when the FET is turned on and that could damage the microcontroller. On the other hand, a 1kΩ resistor is connected between the Gate and the Source also as protection. MOSFETs include a parasitic capacitance between these two terminals that still stores charge when it is switched off. A resistor connected in parallel helps removing this maintained voltage. See the sketch in *Figure 32* below.

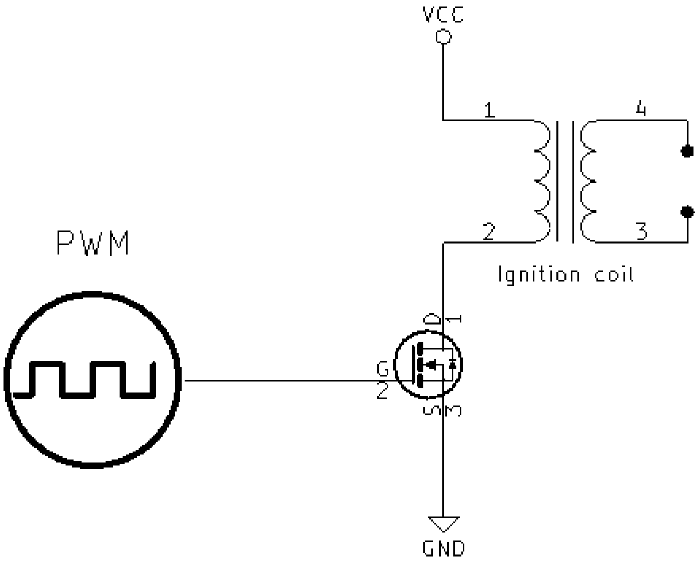

Figure 32. MOSFET and PWM signal to excite an ignition coil.

During the ON state of the square signal, the coil would be charged with the induced current. The shorter the time the PWM was in ON state, the lower the induced current would be (7).

$$\varepsilon_1 = L\frac{di}{dt} \tag{7}$$

The circuit can be treated as an RL circuit, where R would be the resistance of the wire from the voltage source to the ground.

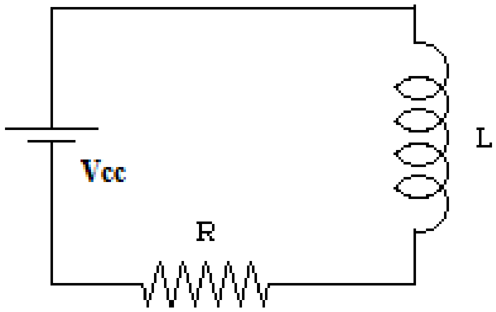

Figure 33. RL circuit example.

Where:

$$V_{cc} = IR + L\frac{di}{dt}; \quad (8)$$

V_{CC}= Voltage of the source;

I =Current flowing through the circuit.

This differential equation has a solution (9):

$$I(t) = \frac{V_{cc}}{R}(1 - e^{\left(-\frac{tR}{L}\right)}) \quad (9)$$

This equation shows that the current at t=0 s is equal to 0 and grows steadily to reach a final value of $\frac{V_{cc}}{R}$ at t=∞, which means that for longer times, the current that would charge the primary winding of the coil would be higher. This time can be identifies as the time the PWM signal is in ON state (t_{ON}), which depends on the duty cycle and the period of the wave (10).

$$t_{ON} = D \cdot T = D\frac{1}{f} \quad (10)$$

f= frequency of the PWM signal;

T= Period of the PWM signal;

Current in a coil

A coil needs a certain time to be charged with a specific current. After this, it reaches the saturation point. This phenomena takes place when its core is completely filled with magnetic field and it cannot take any more. In an ignition coil, when this happens, this field totally surrounds the secondary winding while useless current still flows through the primary.

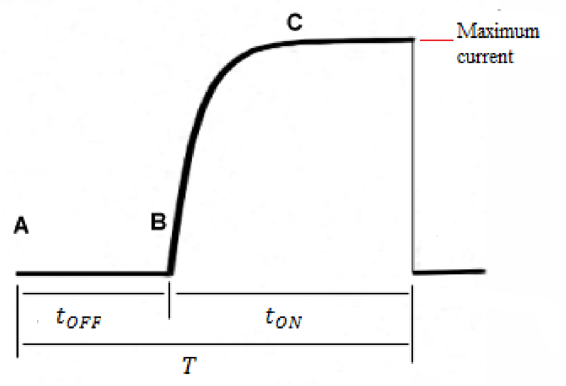

Figure 34. Graph of the current in a coil with a square wave as an input

In the *figure 34* the behavior of the current in the primary winding of a coil that is being charged with a square wave is shown. During the t_{OFF} of the PWM (from A to B) the coil suffers no change in its current. In B, when the ON state switches on, current starts flowing through the wires. It raises until its maximum current, in C. Thus, although the input wave is still switched on, the intensity does not change from this point, which means that its core got into saturation and that useless current is being delivered to the primary. When the t_{ON} switches off the current comes back to 0. In that moment, the secondary winding would be charged and, in SIS, the spark would fire up.

The longer the input voltage signal is ON, the easier for the coil to be in saturation point. It can be perfectly identified in the *figure 35* below, where the behavior of the current in the primary windings for different duty cycles of the input wave is shown.

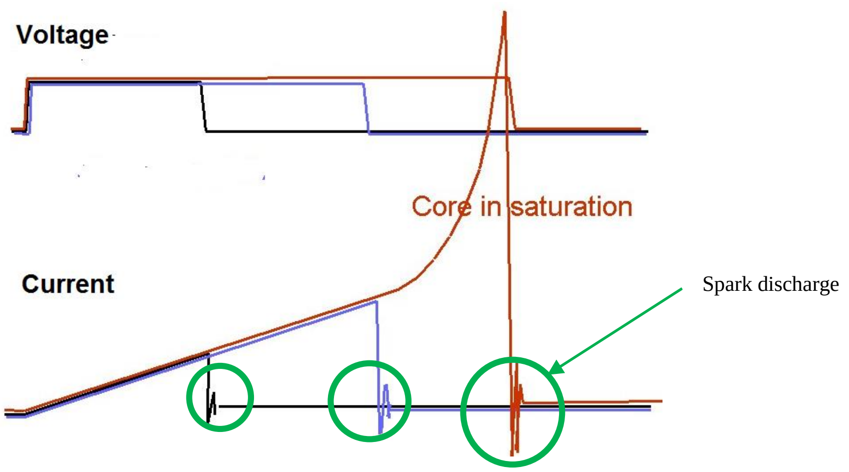

Figure 35. Behavior of the current in the primary winding for different pulse widths of the voltage signal in a SIS.

As said before, during the saturation of the core, although the secondary does not take any more magnetic field, the current is still flowing through the primary. When the voltage signal switches of, this “extra current” turns into the called *flyback current*, which flows back to the GND with the possibility of harming the electronic equipment. The MOSFET in this case. To avoid this, a “flyback diode” (D) is normally plugged in parallel with the coil. Its main function is to absorb this dangerous flowing back intensity.

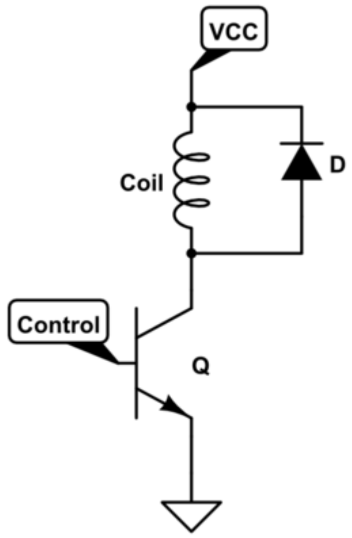

Figure 36. Exemple of a circuit with flyback diode in parallel with a coil.

The *figure 36* above shows as for higher currents, in case of a SIS, the spark discharge is greater. This is because the energy stored by an inductor is, ideally, equal to the amount of work required to establish the current through it, like shown in equation 11:

$$E = \int_{t_0}^{t_1} P(t) \cdot dt = \varepsilon \cdot I(t) \cdot dt = \frac{1}{2} L I(t_1)^2 - \frac{1}{2} L I(t_0)^2 \qquad (11)$$

E =Energy stored in the coil.

P= Power delivered by the coil.

Applied in the case of study, the energy stored would be:

$$E = \frac{1}{2}LI(t_{ON})^2 - \frac{1}{2}LI(t_{OFF})^2 \quad (12)$$

As it has been seen, the current during the OFF state of the wave is 0, so the expression would finally be:

$$E = \frac{1}{2}LI(t_{ON})^2 \quad (13)$$

Thus, the hypothesis is that for high duty cycles, which means a longer time with PWM wave in ON state, the current flowing through the coil and the stored energy are greater than with lower duty cycles.

Regarding the control system to ensure the Corona discharge, in case that a decrease of the current in the secondary winding of the coil was noticed, the Arduino had to increase the duty cycle and, consequently, the t_{ON} to increase the intensity back to CD. In case of noticing an increase of the current of the secondary, the microcontroller had to decrease the duty cycle to avoid the arc discharge to fire up.

The next step was to code the microcontroller to be able to deliver a PWM signal for any frequency within the range of 30 Hz to, at least, 60 kHz and a variable duty cycle.

4.3. Code

As said before, Arduino is an open-source prototyping platform based on easy-to-use hardware and software. All kind projects and prototypes can be found in the Internet and they are all free and accessible to everyone.

The Arduino UNO, as it is one of the simplest boards that Arduino has, basically allows sending PWM at different frequencies and with different resolutions. The code of the software is quite similar to Python and C languages. However, the key of programming with this board is to know the use of their timers and interrupts.

A timer is like a clock, and can be used to measure time events. It can be programmed by some special registers. The Arduino UNO board has 3 PWM timers controlling 6 PWM outputs:

- Timer 0: It is an 8-bit timer, meaning its counter can record a maximum value of 255. It drives the pins 5 and 6.

- Timer 1: It is a 16-bit timer, with a maximum counter value of 65535. It drives the pins 9 and 11.
- Timer 2: It is an 8-bit timer that drives the pins 10 and 3.

With them, both the resolution and the PWM frequency can be changed. However, they are related, meaning that if the resolution of the signal is increased, the frequency decreases and vice versa.

Resolution of a PWM

A PWM resolution of 255 means that the period of the square wave is divided in 255 values. This also affects the average voltage. Each resolution value is more or less 0,019 V (5V/255 resolution values).

For a signal with a duty cycle of 60% and a frequency of 50Hz, the ON state will last for 0,012 seconds corresponding to the value 153:

$$T = \frac{1}{f} = \frac{1}{50Hz} = 0{,}02sec \tag{14}$$

$$D = \frac{\tau}{T} = \frac{\tau}{0{,}02sec} = \frac{res_{ON}}{255} = 0{,}6 \tag{15}$$

$$\tau = 0{,}012\ sec$$

$$res_{ON} = 153$$

res_{ON}= value corresponding to PWM resolution in ON state;

The average voltage of the PWM would be:

$$V = 0{,}6 \cdot 5V = 3V$$

So, as conclusion, it can be said that the higher the resolution is, the more accurate the control of the Corona Discharge will be.

The first experiment was to check if it was possible to create the Corona Discharge in the ignition coil with the current system design. To do this, the code written to launch the Arduino board allowed to choose the duty cycle of the PWM signal and its frequency in a range of 30Hz to 2MHz with an 8-bit resolution, 255 values. It can be checked in the *Annex A.1*.

To write it, a PWM frequencies library called <*PWM.h*> was found in the Internet. It can be checked in the *Annex A.2*.

5. EXPERIMENTAL PART

5.1. Equipment

Voltage source

The source used for this experiment was already in the laboratory. It was build up with components from other equipment and it can deliver a voltage from 0 to 600 V and a maximum current of 10 A.

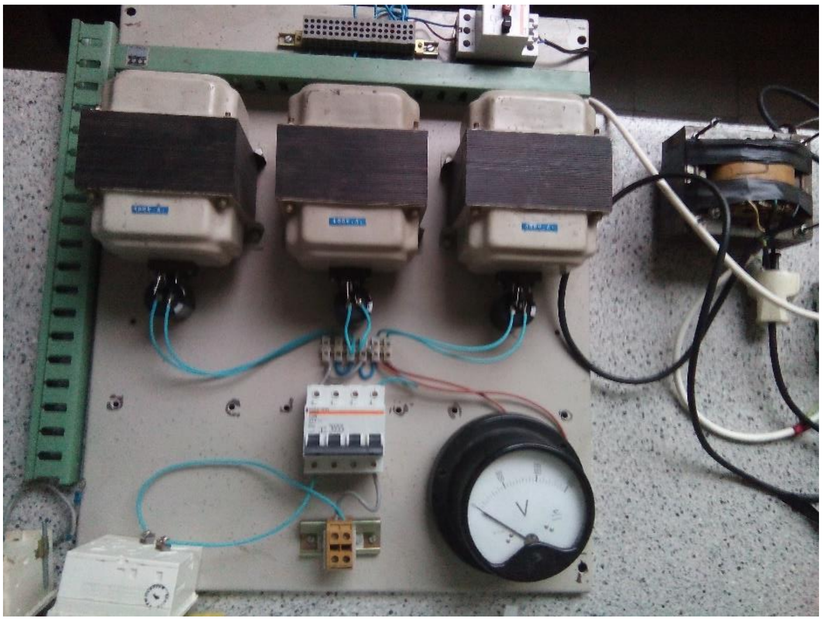

Figure 37. Picture of the voltage source used in the experiment.

Oscilloscope

The oscilloscope used to measure the voltage in the coil is a HAMEG HM 205-2 Digital Storage Oscilloscope with 2 channels. It was used to measure the voltage in the primary winding of the ignition coil and the intensity in the secondary winding.

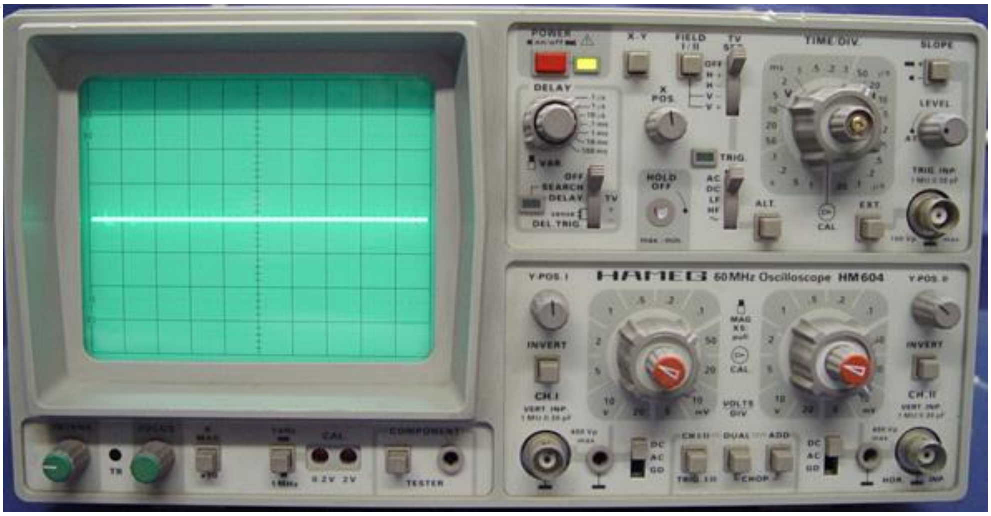

Figure 38. HAMEG HM 205-2 Digital Storage Oscilloscope.

MOSFET

The transistor used as a switch had to be chosen with a specific criteria: On one hand, the PWM average voltage (5V) had to be enough to activate the MOSFET. On the other hand, it had to be fast enough to switch up to high frequencies such as 60 kHz.

The chosen FET was the RFG50N06. Its Gate to Source threshold voltage is low enough (2V). Furthermore, it can switch frequencies until 3.5MHz, which is more than sufficient for the expected in this system. Its datasheet can be seen in the *Annex B.2*.

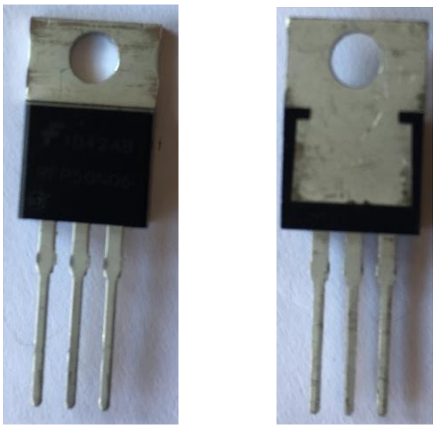

Figure 39. MOSFET RFG50N06 used in this project.

Radiator

As the MOSFET was meant to work at high frequencies it would probably heat up with the danger of harming itself. That is why a radiator is completely necessary. It tights to the transistor with a small screw and dissipates the produced heat. A 48x26x14 mm radiator was chosen.

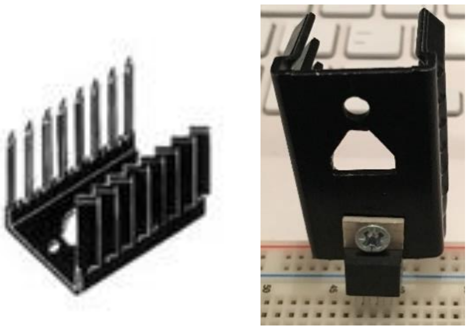

Figure 40. 48x26x14 Radiator and its assembly with the MOSFET.

Function generator

The PROTEK 9205C is a function generator capable of providing sine, triangle, square, pulse and ramp waveforms. It was used in the third experiment to deliver a sinusoidal wave to excite the ignition coil.

Figure 41. PROTEK sweep function generator 9205C used in the experiment #3.

Ignition coil

Two different coils were used in different experiments. They were two old FEMSA coils that were already in the laboratory. This kind of ignition coils was used in cars. Their characteristics, such as the transformation ratio or inductances, were unknown. However, this experiment was made based on a trial and error analysis.

Figure 42. Ignition coil used in the first experiment.

Figure 43. Ignition coil used in the 2nd and 3rd experiments.

Power amplifier

The ECLER PAM800 is an 800W dual channel power amplifier that was used in the third experiment to amplify the sine wave coming from the sweep function generator.

Figure 44. ECLER PAM800 dual channel power amplifier.

5.2. Experiment #1

To analyze the voltage in the primary winding of the coil is a safe and reliable way to check the behavior of the coil for different duty cycles of the PWM. Any change in the secondary would be reflected in the signal of the oscilloscope and, besides, no high and dangerous tensions to deal with would take place in the primary. The circuit for the first experiment was an open loop composed by the Arduino, the power stage and an ignition coil, without taking into account the feedback of the current sensor.

To avoid noises that could be produced due to the inductive and capacitive effects of high frequencies a shunt resistor was connected to work as the tip of the electrode. It had already been used in previous projects and it is usually used to measure currents. However, as this part was to check the hypothesis out, the current was not the main issue. The shut is made of six 2,2MΩ 10% tolerance resistors soldered in a hexagonal arrangement in two cooper plates and covered with kneaded rubber to minimize the effect of the electrical field gradient outside the electrode tip. Besides, a 0,25mm thickness copper foil worked as electrode.

Figure 45. The shunt resistor used in the preliminary experiment.

The voltage source was set to 12V as if it was a car battery and the oscilloscope connected between the two poles of the primary winding. See the circuit in the sketch below.

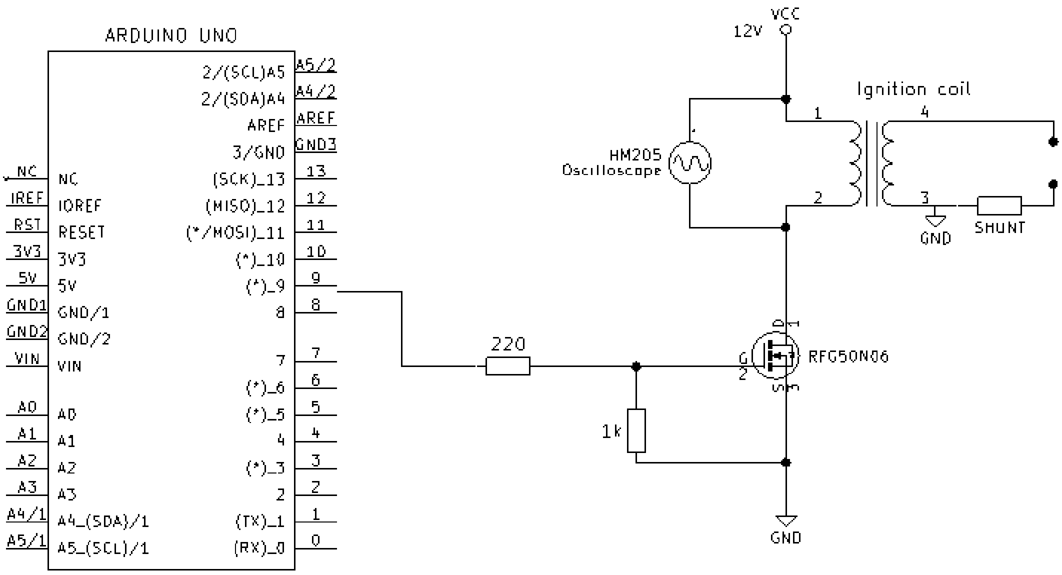

Figure 46. Open loop circuit of the experiment #1.

Test #1

The first test of the preliminary experiment was made with a PWM frequency of 5 kHz, which means a period (T) of 200µs, and a duty cycle (D) of 40%.

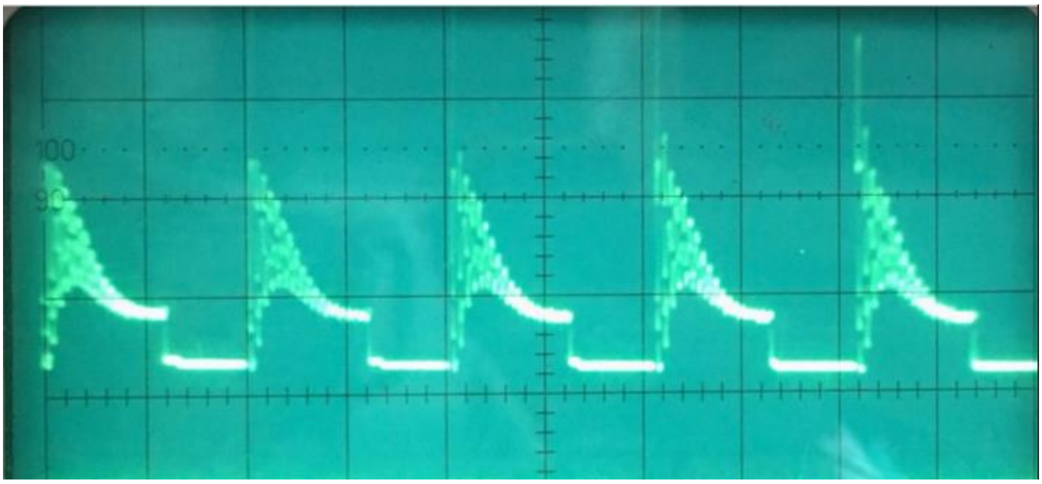

Figure 47. Oscilloscope's screen in test #1 Voltage signal of the primary winding of the coil.

X axis: 100 µs/division.

Y axis: 10V/division.

No Corona Discharge could be detected. However, a spark fired up every time the PWM signal was in OFF state.

The system was working as if it was a TCI (transistor-controlled ignition system). During the ON state of the PWM, the coil is being charged with magnetic field. This is called the dwell time. When the signal switches off, the arc discharge takes place in the secondary resulting on important fluctuations in the voltage of the primary. The *figure 48* is a detail of the picture of the oscilloscope screenshot and it points the different events that take place during a spark discharged.

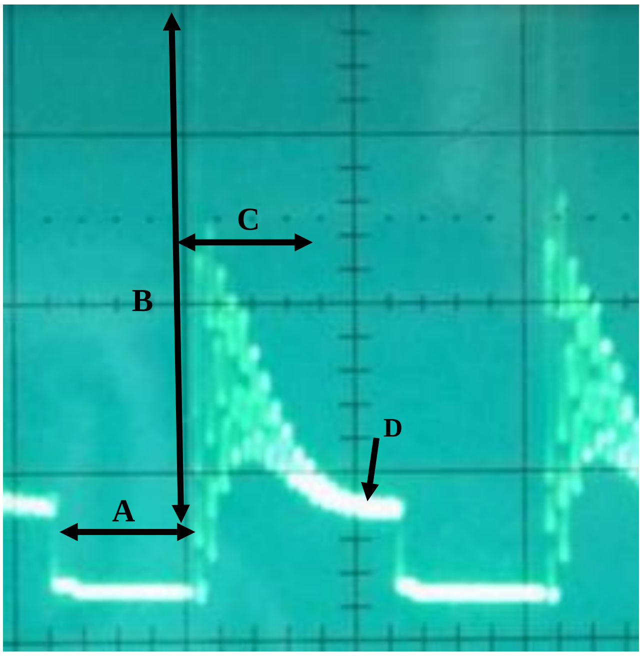

Figure 48. Different events in that take place during the spark discharge in test #1.

Dwell time (A): The coil gets grounded and the magnetic field is created across the primary winding.

- *Arc discharge (B):* The coil gets undergrounded and the magnetic field collapses across the primary windings making a voltage spike of tens of volts. It could not be measured correctly as it was out of the scope of the oscilloscope.
- *Spark duration (C):* Big fluctuations hit the primary winding due to the discharge in the secondary. It lasted for about 80 µs of the whole period.
- *Coil oscillation (D):* After the spark has fired up, there are some oscillations between the primary and secondary.

In the *figure 49* the small spark breakdown can be seen in the tip of the shunt electrode.

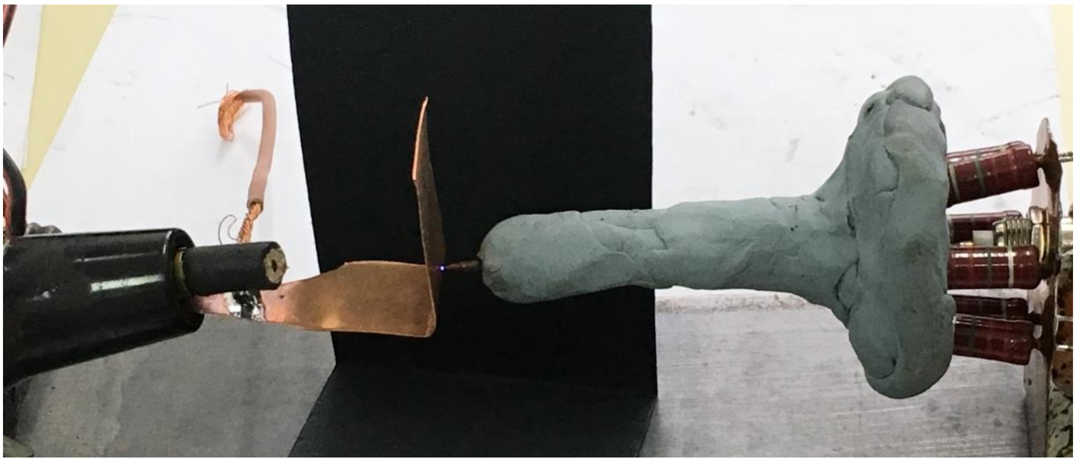

Figure 49. Spark in the tip of the shunt electrode in test 1#.

Test #2

The second test was made with the same 5 kHz PWM frequency than in the first test. This time, the duty cycle was increased to 70%. The energy stored was expected to increase from test #1.

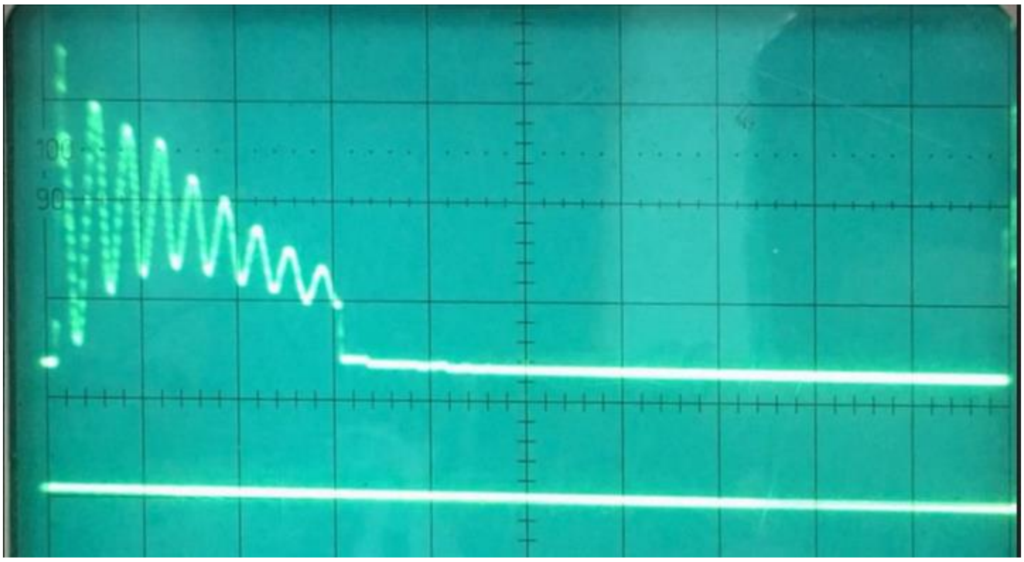

Figure 50. Oscilloscope's screen in test #2. Voltage signal of the primary winding of the coil.

X axis: 20 µs/division.

Y axis: 10V/division.

Spark discharge was observed. It was stronger than in test #1, as expected. The stored energy was greater indeed. It could be perfectly seen in day light. Its duration was about 60 µs of the whole period, which is shorter than in the other test. This is because it is working in a quite high frequency and the duty cycle is quite big, giving a short t_{OFF} time to fire up the spark before the primary gets grounded again.

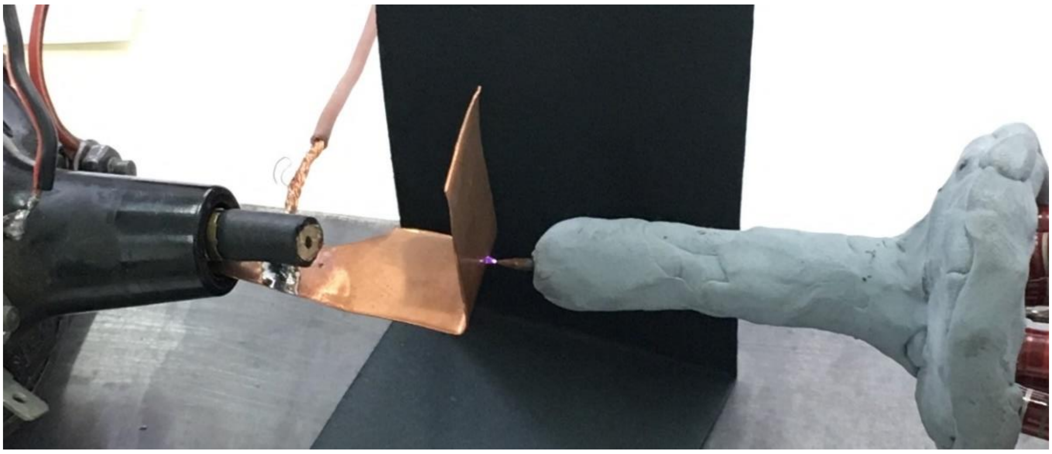

Figure 51. Spark in the tip of the shunt electrode in test #2.

It was interesting to see the shape of the spark. It was like a cone, which is because the ionization of the surrounding air was between a plane electrode and a sharp one. It can be seen in the detail below.

Figure 52. Shape of the spark in test #3.

Test #3

In this case, the frequency was increased until 6500 Hz. This was mainly to check if the program worked properly. So it did.

The duty cycle was set to a low 10%. It was supposed to mean a lower intensity than the other 2 tests.

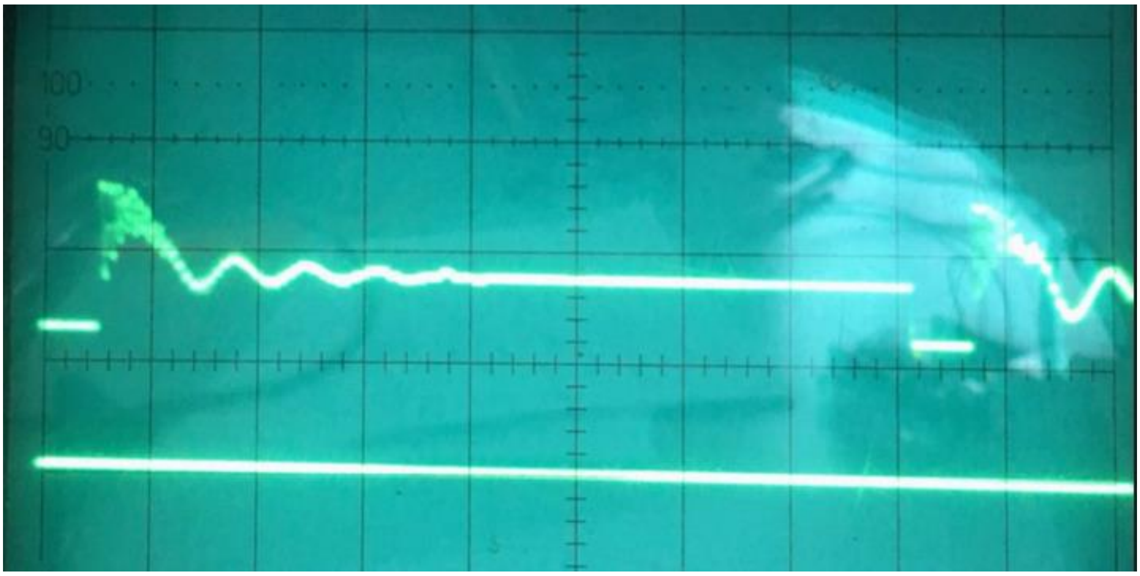

Figure 53. Oscilloscope's screenshot in test #3. Voltage signal of the primary winding of the coil.

X axis: 20 µs/division.

Y axis: 10 V/division.

Arc discharge took place once again. It was actually difficult to appreciate. It can be seen in the *figure 54* below.

The distance between electrodes was 5 mm.

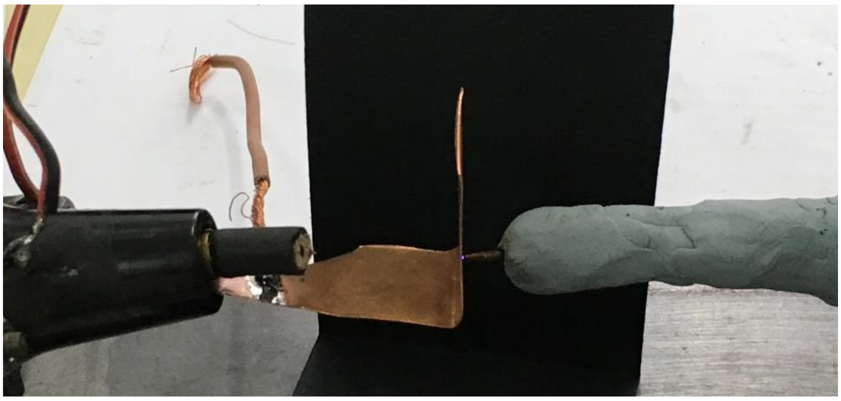

Figure 54. Spark in the tip of the shunt electrode in test #3.

In this case the coil oscillations after the spark (were more obvious than before. There is a notable difference between the two parts.

The spark discharge had a duration of about 20 µs, while the oscillations lasted in about 55 µs. The rest of the t_{OFF} time of the PWM the steady voltage induced (ε) in the coil, which rates about 6V takes place.

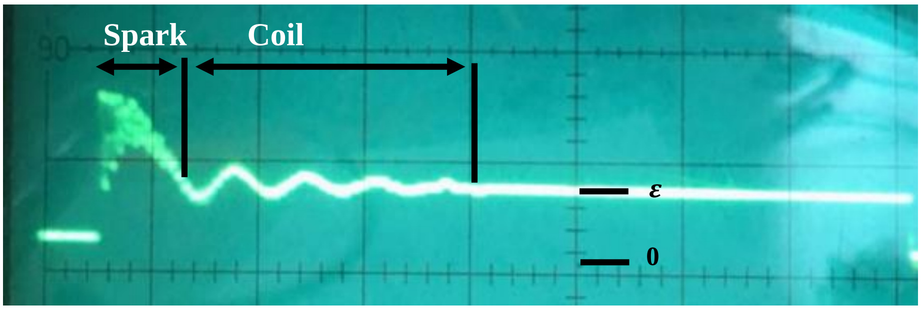

Figure 55. Detail of the voltage signal in the primary winding in test #3.

Test #4

The frequency was set back to 5 kHz and the duty cycle to 75%, which may seem a similar situation than in test #2. However, the main difference was that the distance between the two electrodes, which had been about 5 mm in the other 3 tests, was increased until 1,5 mm.

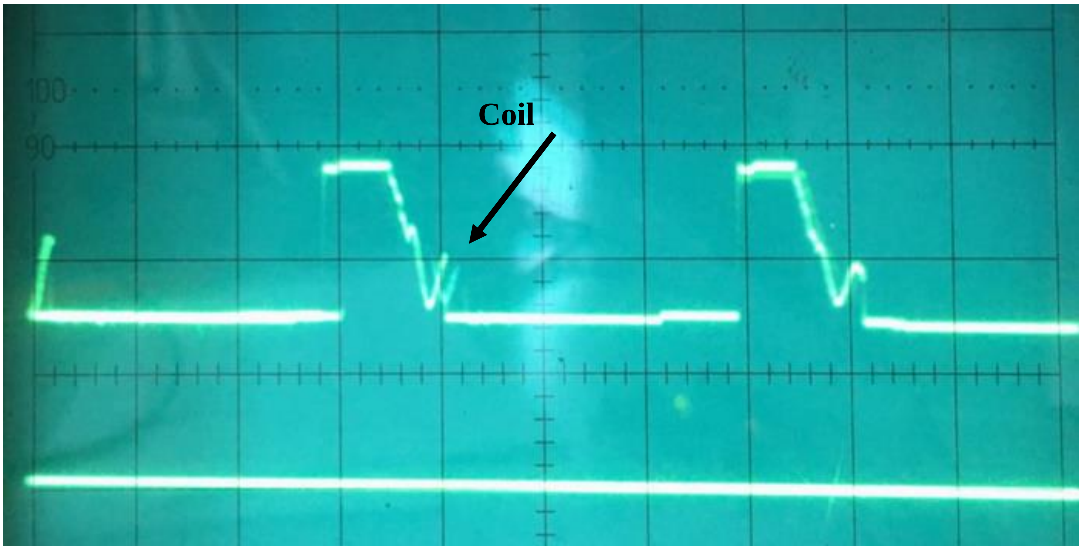

Figure 56. Oscilloscope's screenshot in test #4. Voltage signal of the primary winding of the coil.

X axis: 20 µs/division.

Y axis: 10 V/division.

A wave completely different from what had been seen before was obtained. The particular voltage peak that takes place when the coil is undergrounded in a spark discharge situation did not appear. However, the oscillations of the coil did so. Besides, the voltage was much higher than in the other tests, even more than the 12 V of the voltage source.

Maximum voltage: 14 V.

On the other hand, no arc was seen between the two electrodes. However, a sizzling sound could be heard, like if an ionization of the air surrounding them was taking place. No visual effect could be seen in daylight, so it was not sure that Corona Discharge was happening.

Results

The main objective of this preliminary experiment was to analyze the behavior of the coil for different duty cycles of the PWM wave and to check if the Arduino program worked properly.

The second target seemed to be accomplished. The microcontroller happened to change both the duty cycle and the frequency on user's command.

On the other hand, it was checked that the duty cycle has an influence on the behavior of the ignition coil. It was seen that, for the same frequency (or similar), the longer the PWM signal was switched on, the greater the energy stored in the coil and the bigger the discharge between the two electrodes.

In the first three tests, spark discharge took place but meanwhile, in the fourth test, the distance between the electrodes was increased. No spark discharge was noticed but an oscillating voltage signal and a sizzling sound that could have been caused by partial air's ionization, maybe the corona effect. This bigger distance between the tip of the shunt and the copper plate of the ignition coil increases the amount of air to be ionized making it more difficult for the spark discharge to fire up.

Voltage in the secondary winding

Although no images are posted, some measures of the voltage in the secondary winding were taken with a voltmeter. It never measured more than 400 V. This, added to the fact that the secondary reached the saturation state quite quickly, for example with a duty cycle of only 40%

in test #1, in 80 µs, drives to the conclusion that the old ignition coil used in this test was not working properly.

5.3. Experiment #2

As the ignition coil used in the first experiment did not seem to work properly, for this new experiment, the other FEMSA coil was used.

The aim of these new tests was to finally obtain the CD by setting higher frequencies than before and obtaining higher voltages in the secondary winding of the new coil, which was expected to raise it until thousands of volts.

The shunt resistor was taken out. Instead, a wire was plugged in the output terminal of the new ignition coil and its tip pointed directly to a chrome plate that was fixed in one of the primary terminals. The feedback of the current sensor was not included yet. It is shown in the *figure 57* below.

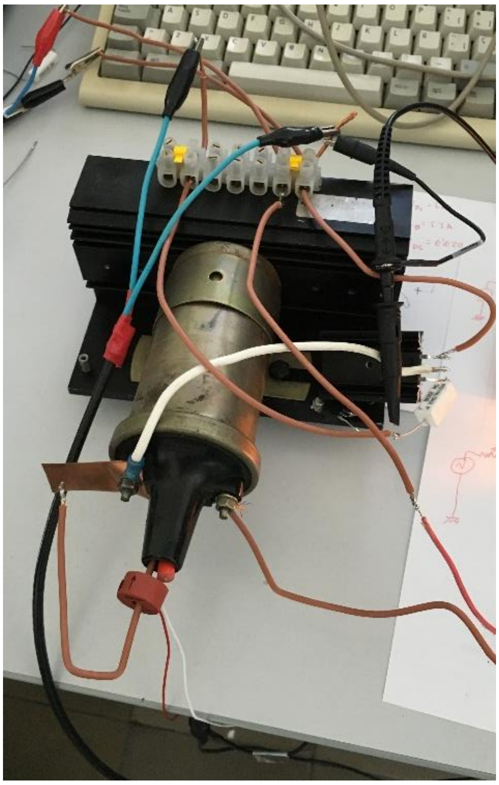

Figure 57. Connection of the ignition coil in the experiment #2.

The fixed voltage source was set to 20V in order to obtain voltages in the secondary winding of the coil.

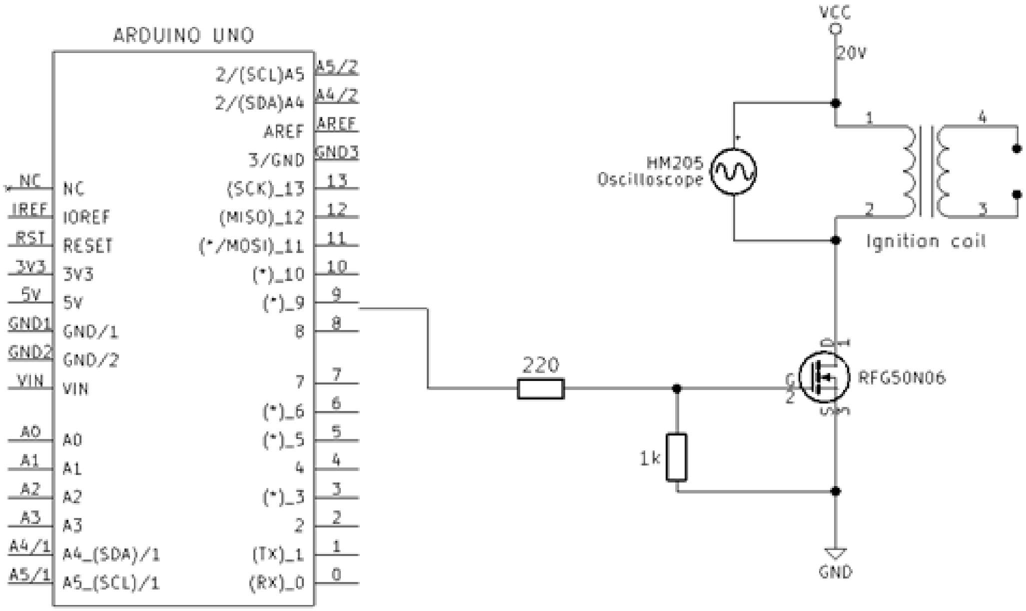

Figure 58. Open loop circuit of the experiment #2.

Test #5

In the first test of the second experiment, the PWM duty cycle was set at 60%. With the main objective of observing the corona effect, the frequency was increased until 25 kHz, which means a period of 40 µs. The electrode's gap distance was 10 mm.

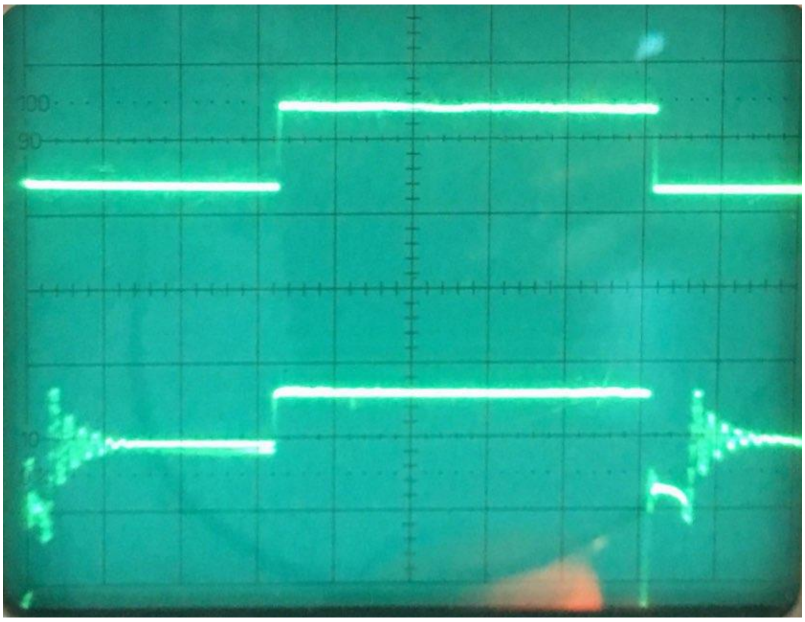

Figure 59. Oscilloscope's screenshot in test #5.

X axis: 5µs/division.

Y axis (channel 1): 20 V/division.

Y axis (channel 2): 5 V/division.

The voltage between the Drain and the Source terminals of the MOSFET was measured with the first channel of the oscilloscope in order to check that the fixed source was delivering the correct value of the voltage. It was set to 20 V so, it seemed to work properly indeed.

On the other hand, the probe of the second channel was connected between the terminals of the primary winding of the coil to analyze its behavior.

As is can be seen in the graph (this time inverted) in the *figure 59* above, a spark discharge fired up every time the input signal switched off.

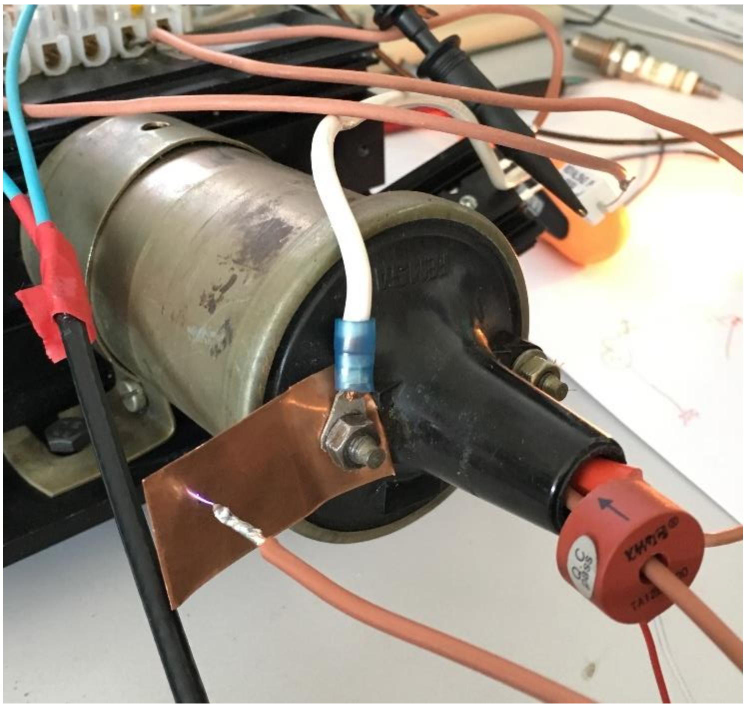

Figure 60. Spark discharge observed during the test #5.

The spark observed during the first test of the second experiment was quite strong, as it can be noticed in the *figure 60* above. Actually the cracking sound was a lot more intensive than in the other experiments. It was probably because the voltage of the fixed source was higher this time. Besides, the distance between electrodes was also bigger and so the amount of air to be ionized.

In the obtained voltage waveform it was is easier to identify the different events that take place during a spark discharge. In fact, it is closer to the typical voltage's waveform that can be seen in most of the current gasoline engines.

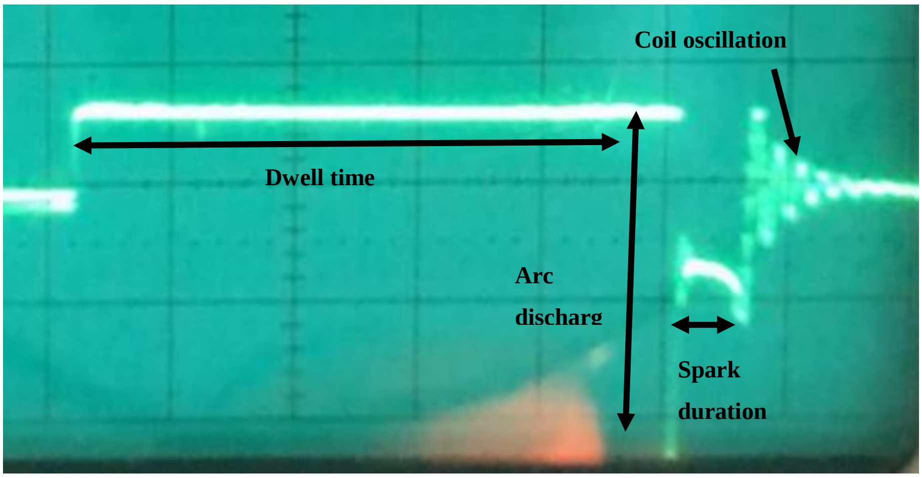

Figure 61. Different events that take place during the spark discharge in test #5.

Test #6

In this 6th test of the second experiment the aim was to set the same parameters than in the 5th but increasing the gap between the two electrodes from 5 mm to more or less 20 mm. This new distance was established by pulling the output wire of the coil manually and holding it while the system was working.

In addition, the toroidal current sensor was placed concentric to the wire of the output of the ignition coil (*see figure 62*) in order to analyze its voltage difference, which would detect any change in the current. Its signal was checked in the channel 1 of the oscilloscope replacing the connection between the Drain and Source terminals of the MOSFET.

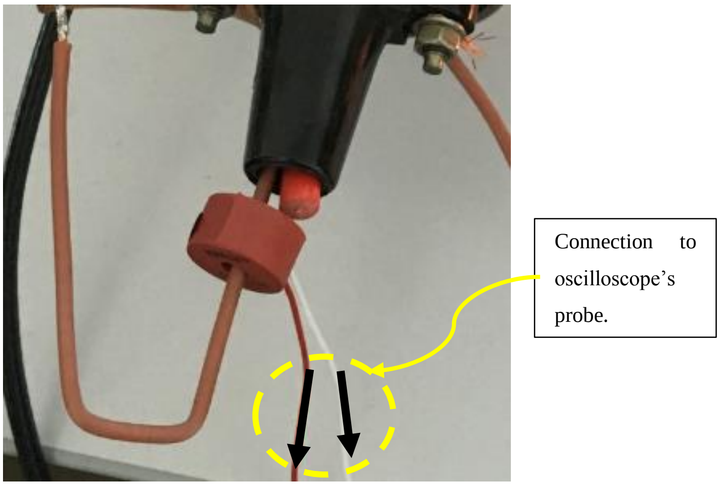

Figure 62. Placement of the toroidal sensor in the output wire of the coil.

As seen in test an increase of the gap distance makes the amount of air to be ionized much bigger reducing the probability of arc discharge.

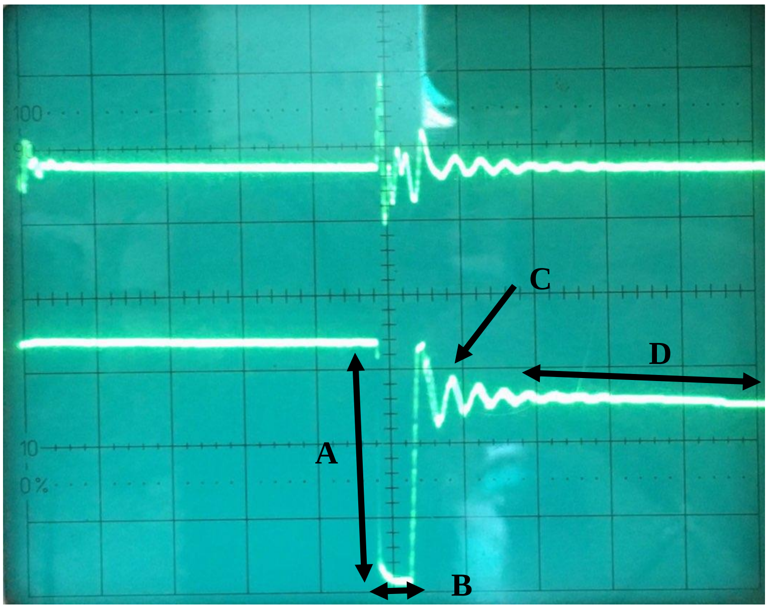

Figure 63. Oscilloscope's screenshot in test #5.

X axis: 5 μs/division.

Y axis (channel 1): 20 V/division.

Y axis (channel 2): 5 V/division.

There was no spark discharge, as expected. The air ionization's sizzling sound was heard again but no glow light in the tip of the electrode was noticed, what would have been an indicative that CD was taking place.

Regarding the signals seen in the oscilloscope, the channel 2 showed a big increase in the voltage at the right time the input signal switched off (A). It stayed steady for about 2.5µs (B) before going back to the initial voltage. After this event, the coil oscillations took place (C) and, finally the steady induced emf in the primary winding (D) that lasted until the input signal switched on again.

On the other hand, the channel 1 displayed that the output wire only suffered a change in the current flowing through it during the events A, B and C seen in the channel 2. It is interesting to point that, along these 2.5µs in which the voltage keeps steady (B), there are some oscillations showing some variations in the potential difference that cannot be noticed in the waveform of the voltage in the primary winding of the coil, probably due to the partial ionization of the air. It was thought that Corona Discharge took place.

Results

Several tests with different frequencies and duty cycles of the PWM were made and the same pattern was seen in all of them. For specific chosen parameters and an initial distance between electrodes of less than 10 mm, spark discharge always took place. Meanwhile, if this gap was increased little by little, the spark disappeared and the cracking sound of air ionization and a waveform similar to test #6's suddenly came out. CD took place.

With this results it is obvious that the corona effect depends on the distance between electrodes. It has been checked it is easier to observe for bigger gaps as the quantity of air that has to be ionized before the arc discharge takes also increases, driving to partial ionizations. However, the designed system should be able to create it for any distance.

In the *figure 64* there is a graph showing an example of the dependence of the distance between electrodes on the applied voltage for an specific electrode's tip diameter found in a journal article about a novel water treatment technique based on a combination of electrospraying and pulsed corona discharge.

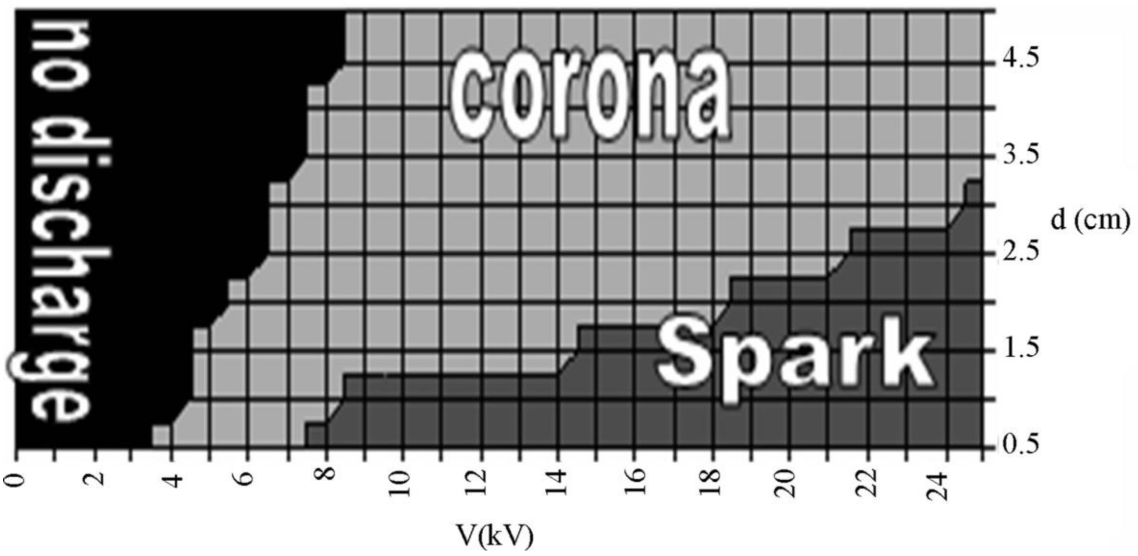

Figure 64. Dependence of the gap distance on the applied voltage.

In this experiment the effect of different discharge parameters were identified to avoid the spark region. It explains that the discharge phase transitions depend on the electric field distribution and on the three parameters: the applied voltage, the distance between the two electrodes and the discharge electrode diameter [21].

It can be seen that, for a greater distance between the two electrodes, the range of the corona discharge phase increases. It proves the fact that in the experiments #1 and #2, for bigger gaps, spark discharge stopped and the presumed corona effect appears instead.

After some tests in different conditions and parameters, it could be said that the main objective of this project could not be achieved. Nevertheless, an extra experiment was made.

5.4. Experiment #3

In this experiment, the Arduino board was dismissed. Instead, a function generator was used in order to deliver a frequency and a variable amplitude voltage sine wave. Regarding the power stage, the MOSFET was replaced by a power amplifier, which was already in the laboratory. It would allow to vary the power of the input waveform that would excite the primary of the ignition coil. The ignition coil was the same than in the second experiment.

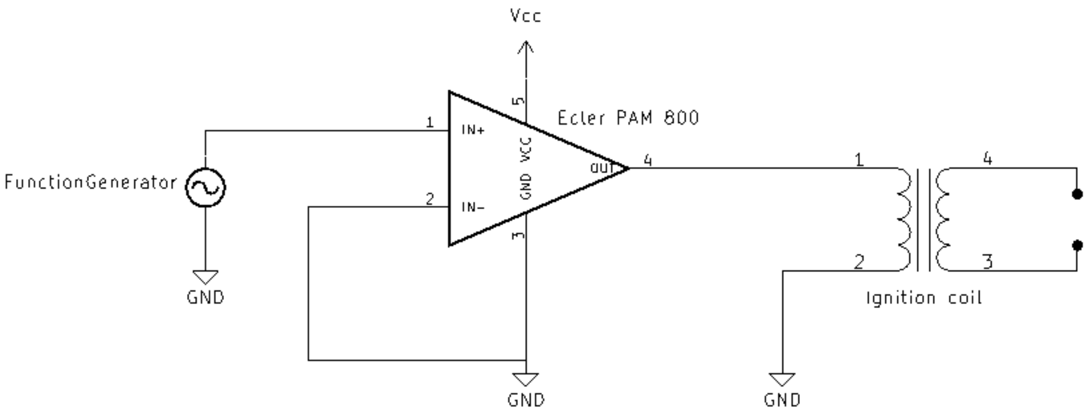

Figure 65. Sketch of the circuit for experiment #3.

The aim of this experiment was to test and analyze the behavior of the ignition coil with a sine wave as an input and to compare it with the two previous experiments.

With the power amplifier, higher input values could be generated, increasing the probability of obtaining the corona effect. Furthermore, a sine wave reaches its maximum voltage gradually instead of instantaneously like a square wave, which could help too.

The procedure would consist in starting with a specific frequency and voltage in the first test and, after analyzing the behavior of the system with the new input signal type, in the second the frequency would be kept steady while the voltage amplitude increased expecting to observe a change in the output. In other words, the CD occurring.

Test #7

The frequency of the function generator was set to 30 kHz (33 µs period) and the amplitude of the sine wave regulated manually through the power amplifier. The gap distance was 10 mm.

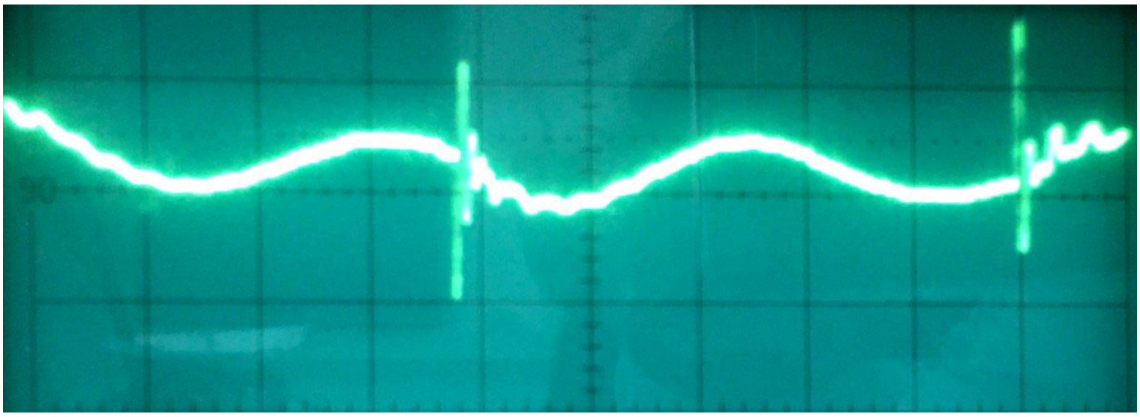

Figure 66. Screenshot of the oscilloscope in test #7.

X axis: 10 µs/division.

Y axis: 20 V/division.

In this test, a spark discharge could be observed between the two electrodes. The sine wave in *figure 66* displays the voltage difference measured with the toroidal current sensor in the output wire of the ignition coil. It showed an important change in the secondary winding current in every arc breakdown. It looked like it needed about a complete period and a half to charge the coil enough to ionize the air between the two electrodes and to fire up the spark.

The duration of the spark was much shorter than in the other experiments, where PWM was used as an input signal.

Another thing to take into account is that, while in square waves tests ON/OFF state was delivered, in this case the input waveform contains both negative and the positive values of the voltage. The spark discharge took place with any of them.

Test #8

In this new trial the frequency and the gap distance were kept at 15 kHz and 10 mm respectively. The amplitude of the signal was increased with the power amplifier.

The oscilloscope displayed the voltage difference measured with the toroidal current sensor and the input voltage signal in the primary winding of the coil.

Figure 67. Screenshot of the oscilloscope in test #8.

X axis: 20 µs/division.

Y axis (channel 1): 20 V/division.

Y axis (channel 2): 10 V/division.

The amplitude of the input voltage signal was the maximum that could be achieved with the power amplifier before the protection system was triggered, ± 30V

The cracking sound could be heard and no arc discharge was seen. A partial ionization of the air mass between the two electrodes was reached without increasing the gap distance. In other words, corona effect took place.

As it can be seen in the channel 2 of the oscilloscope's screenshot, the input signal is not a perfect sine wave. This was probably because the power amplifier was working close to its maximum limit power range, what possibly caused the fact that the CD did not appear in each semi period of the input wave.

In any case, every time the corona effect took place, the current suffered variations that were printed in channel 2 for both the positive and negative delivered voltages of the input waveform.

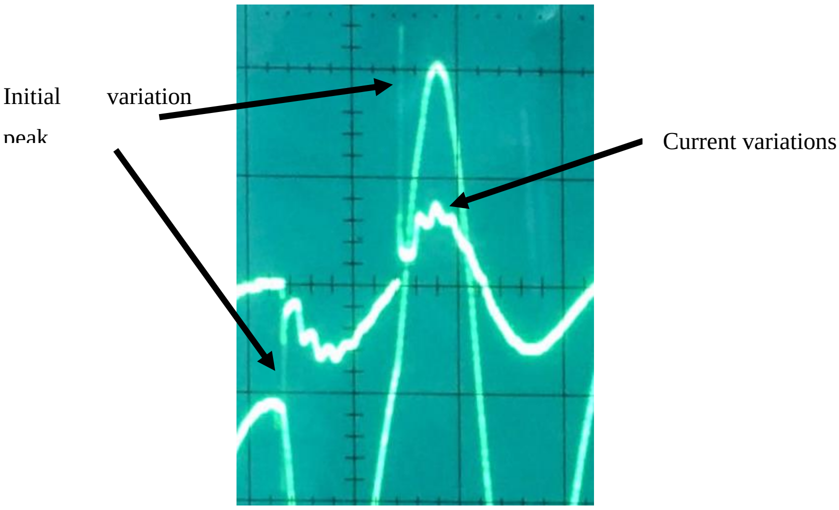

Figure 68. Changes in the current of the output wire during corona discharge.

The *figure 65* shows the different variations of the current flowing through the output wire during the corona discharge in the positive and the negative voltage inputs. It starts with an initial peak of voltage difference and goes on with some oscillations that last for about 5µs.

Results

It can be observed that the generation of the CD in the electrodes of the ignition coil did not have any influence on the input voltage signal but it remained a clean sine wave instead. It is because the dielectric barrier does not break completely, and the air that is not ionized has a great impedance.

In comparison with the experiments #1 and #2 it could be said that a sine wave makes it is more likely to obtain a corona discharge than a square wave as input signal.

In fact, it is well known that any repeating, non-sinusoidal waveform can be equated to a combination of sine waves. Following Fourier Series, a square wave is mathematically equivalent to the sum of a sine wave at that same frequency, plus an infinite series of odd-multiple frequency sine waves at diminishing amplitude, or harmonics.

As an example, the closed-form equation for a square wave of frequency f with a peak-to-peak amplitude of 2 may be approximated arbitrarily well by Fourier series:

$$x_{square}(t) = \frac{4}{\pi}\sum_{k=1}^{\infty}\left[\frac{\sin(2\pi(2k-1)f(t)}{(2k-1)}\right]$$
$$= \frac{4}{\pi}\left(\sin(2\pi f t) + \frac{1}{3}\sin(6\pi f t) + \frac{1}{5}\sin(10\pi f t) + \cdots\right)$$

The *figure 69* below shows the representation of a square wave as the combination of its fundamental sine wave and the next 2 harmonics (the 3rd and the 5th), both odd frequencies sine waves with a frequency $f = 2\pi$.

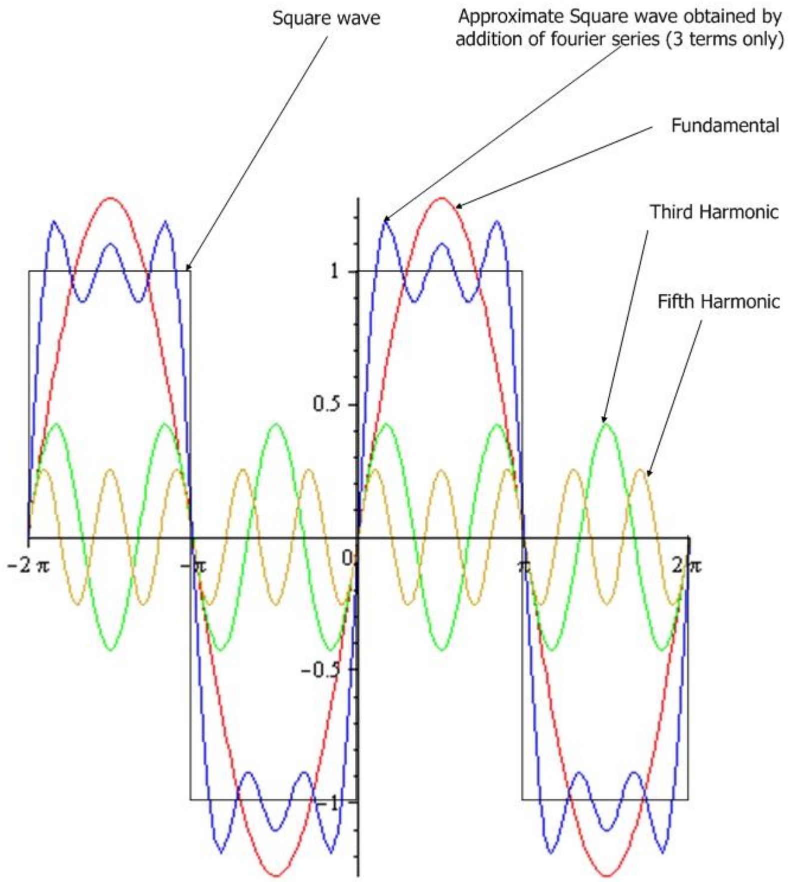

Figure 69. Square wave and the first three terms of its Fourier series.

Regarding this, in other projects, some mathematical and experimental analysis have been done on the induced emf in coupled circuits (transformers) excited by square waves and sine waves. They show that when considering sine wave excitation, they present higher gains than by square wave excitation. It is said to be due to the amplitude of its sine wave components (considering Fourier series), that are lower than the peak of the sine wave excitation. A transformer acts like a filter that eliminates some of these harmonics and the response in the secondary winding is normally lower than if it is direct sine wave excitation [22].

This statement stands the hypothesis made out of the experimentation of this project, which would say that using a sine wave as an input signal for the primary winding of an ignition coil to generate the corona effect is more suitable than delivering a PWM or a square wave.

6. BUDGET

This project is only a small part of the preliminary work that needs to be done before the definitive development of a corona discharge ignition system reliable and economical enough to be set in current vehicles. Thus, this budget only includes the costs of the lab equipment and instrumentation, the material and the labor of this research.

	Description	Cost per unit	Quantity	Total
Labor				
	Design	36 €/h	100	3,600 €
	Lab work	36 €/h	150	5,400 €
	Report	36 €/h	80	2,880 €
	Subtotal		330 h	**11,880 €**
Equipment				
	HAMEG Oscilloscope	-	1	0 €
	Arduino UNO	20 €/u	1	20 €
	PROTEK 9205C function generator	129 €/u	1	129 €
	ECLER PAM800 Power amplifier	-	1	0 €
	FEMSA Ignition coil	-	2	0 €
	Subtotal			149 €
Material				
	MOSFET RFG50N06	1.51 €/u	3	4.53 €
	48x26x14 Radiator	0.75 €/u	2	1.5 €
	Jumper wires 100mm	0.39 €/u	10	3.9 €
	Toroidal current sensor	5.93 €/u	1	5.93 €
	Oscilloscope probes	13.52 €/u	2	27.04 €
	Subtotal			**43 €**
TOTAL				**11, 923 €**

To fulfill this budget it has been considered that the equipment that was already in the lab, such as the oscilloscope, the power amplifier or the 2 ignition coils were completely amortized and that their cost was 0 €.

However, although the oscilloscope probes and the function generation were also found in the lab, as the first was completely new and the second has been hardly used, their whole cost have been considered.

Finally, a quite an economical project was developed.

7. ENVIRONMENTAL IMPACT

The investigation of the Corona Discharge as an ignition system is being done with the aim of finding an alternative to current SIS capable to reducing pollutant emissions such as CO_2 and NO_x and of increasing the fuel efficiency. Several studies have proven and quantified these improvements.

The development of this project is part of this investigation and as no engine nor a prototype were built, no combustion and pollutant emissions took place. Thus, this study has no specific impact on the environment and no environmental impact needs to be considered.

Hence, this chapter of the report only includes the possible improvements that this new injection system could lead to in base on other researches.

The European legislation that the automotive manufacturers must comply is the COMMISSION REGULATION (EC) No 692/2008. These standards have a thorough monitoring mainly on 5 specific pollutant compounds that are emitted by internal combustion engines and contribute in the global warming: Carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), which is exclusive for diesel engines, and carbon dioxide (CO_2).

The emission of HC in an internal combustion engine occurs because of incomplete combustions. The concentration of this compound in parts per million (ppm) represents the amount of unburned fuel that exits the engine with the exhaust gases.

Like hydrocarbons, CO emissions are a consequence of incomplete combustion. This highly poisonous odorless gas when there is an excess of fuel in its mixture with the air. During combustion, there is not enough O_2 to become CO_2, so CO is formed instead.

As explained before, the ignition volume of a CD ignition system is considerably increased over the common SIS. This leads to more thorough combustions reducing the emissions of HC and CO. For example, with the use of an 10% rate of EGR, which means that the ten percent of the exhaust gases are driven back to the combustion chamber, the emissions can be reduced about a 9,9 € for HC and a significant 36,4 % of CO emissions in a 2,000 rpm and 20 bar BMEP regime [23].

The generation of CO_2 emissions in a car engine are directly proportional to the amount of consumed fuel. Thus, an increase in the fuel efficiency of the engine can reduce the emissions of this gas. In 2015, the average CO_2 emissions rate was about 119.5 g/km. The target of the European Commission for 2021 is that the average emissions rate 95 g/km, which means a decrease of a 20%.

The CO_2 emissions reduction is not as significative as HC or CO's. With an EGR rate of 15%, the emissions decrease only in a 4% for a 2,000 rpm and 20 bar BMEP regime [23]. Higher burn rates drive to more complete combustions what makes it more difficult to decrease CO_2 emissions.

Nitrogen oxides are one of the main ingredients involved in the formation of ground-level ozone, which can trigger serious respiratory problems. Furthermore, it contributes to formation of acid rain and, in general to global warming. Regarding emissions in internal combustion engines, NO_x appears when high temperatures and high pressures combustion take place.

The use of an engine with a CD ignition system allows an important decrease in the combustion peak-in temperature, which leads to a reduction in NO_x that can be of a 73,3% in a 2,000 rpm and 8 bar BMEP regime [23].

Although this data is from a specific experiment and their values would vary for each type of engine and for different conditions, they give an idea of how favorable can be for the automotive manufacturers the application of the CD in their ignition systems to reach the values maximum pollutant emissions compelled by the regulation organizations.

8. CONCLUSIONS

The preliminary research of this project makes an approach on spark ignition systems development. It shows that they have evolved together with technology and mechanical systems have been progressively changed by electronically-controlled systems, such as transistor-controlled ignition system, which give a higher reliability and maintenance and fabrication costs reduction. However, current environmental legislation has become highly restrictive and it getting actually very difficult for automotive companies to manufacture internal combustion engines that create pollutant emissions below the limits established.

Several alternatives with higher efficiencies and less fuel consumption, such as laser ignition system, have come out to replace the common spark ignition system. Although most of them are really promising, for the moment they are too expensive and still in development stage.

Although it still needs a lot of experimentation, the ignition system based on Corona Effect has a lot of advantages on the current spark ignition such as:

- Higher peak pressures.
- Higher power delivered into the combustion chamber.
- Shorter ignition delay and rise times.
- Shorter burn times and faster heat release.
- Higher efficiency and les fuel consumption.
- Lower pollutant emissions.

The aim of the experimental part of this project was to develop a cheap and simple control system to create and maintain through time a corona discharge between the two electrodes of an ignition coil.

After it was found that the Arduino UNO is not suitable for creating the corona effect in an ignition coil. Thus, it only acted as a PWM signal generator. No feedback signal from the toroidal current sensor was delivered back to the microcontroller as expected. However, it could be said that it is a potential cheap alternative to control a spark ignition system.

After the two first experiments, it was found that the limits between arc and corona discharge regions strongly depend on the distance between the two electrodes of the ignition coil. As the gap distance increases, the discharge barrier gets bigger and it becomes easier to obtain the corona effect.

The main reason why the Arduino board is not suitable for generating corona is because it can only deliver PWM, a square wave. It was checked that the best waveform to use as an input to the primary winding of the ignition coil is a sine wave. A square wave is composed by different amplitude and frequency sinusoidal waves that generate less energy in the coil than a pure sine.

A feature that could not be studied in this project is the influence of the frequency on the generation of the corona effect.

9. FUTURE WORK

In this project, the control system was thought to work with a PWM input signal with a fixed frequency and a variable duty cycle and a fixed distance between electrodes.

The results showed that a sine wave is the most suitable waveform to use as an input for the primary winding of an ignition coil to generate the corona discharge instead of a square wave. Thus, it would be interesting to do a further investigation on the generation of corona by delivering this type of signal as input.

On the other hand, it has been seen that the distance between the electrodes also has an influence on corona generation. A deeper research on this aspect would probably part of future works.

Furthermore, in the last experiment of this project, corona discharge was reached by increasing the amplitude of the sinusoidal wave. Further experiments might be done on this field as it was not within the scope of this previous project.

During the experimental parts, different frequencies of the input signal were chosen arbitrarily and they were not considered within the scope of the project and it is obvious that they have a great influence on the corona phenomena generation.

A potential system to study all these features could be composed by a microcontroller able to generate a sine wave with variable frequency and amplitude that would drive an ignition coil plugged to a fixed discharge electrode and a movable ground electrode that would able a variable gap distance (d). A sketch can be seen in the *figure 70* below.

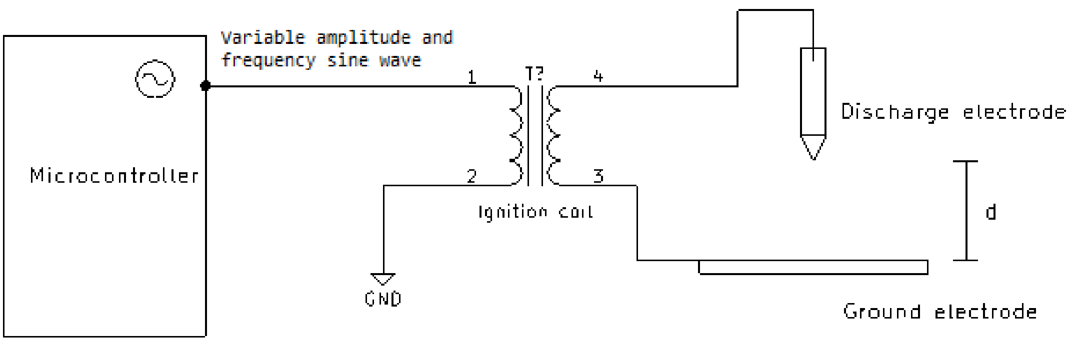

Figure 70. Sketch of a potential system for future work.

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