Universidad de Valladolid

ESCUELA DE INGENIERÍAS INDUSTRIALES

UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

Máster en Ingeniería Industrial

Desarrollo de una unidad de control para un sistema de ignición de superficie caliente usado en motores de combustión interna.

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TFM REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO: Development of a fast-acting control unit for a hot surface ignition system used in internal combustion engines

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FECHA: 30/03/2016

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Resumen

Un nuevo Sistema de ignición para motores estacionarios ha sido desarrollado. Consiste en el uso de una bujía incandescente que se comporta como una resistencia PTC. La temperatura de la bujía incandescente es la encargada de regular el comienzo de la combustión, por ello es necesario efectuar un control preciso sobre su temperatura.

En este proyecto, un nuevo controlador es diseñado y construido, intentando mejorar el rendimiento del anterior. Para la programación del controlador se usara un microcontrolador. Además se construirá un circuito para el procesamiento de señales, de tal forma que el controlador pueda funcionar independientemente, requiriendo solamente el uso de la fuente de alimentación correspondiente.

Se cree que este sistema puede mejorar la relación ente eficiencia y emisiones de NO_x, además de reducir los costes de mantenimiento. Pero en primer lugar, se necesita un controlador que sea capaz de mantener la temperatura de la bujía constante.

Palabras claves

Controlador de temperatura, motor de gas natural, Arduino, procesamiento de señales y sistema de ignición.

Hochschule Karlsruhe
Technik und Wirtschaft
UNIVERSITY OF APPLIED SCIENCES

Master's Thesis

Development of a Fast-Acting Control Unit for a Hot Surface Ignition System Used in Internal Combustion Engines

Winter Semester 2015/16

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Task of Thesis

A new ignition system, which works in stationary Natural Gas engines, has been developed. This new system uses a glow plug, whose behaviour is like a PTC resistor and thus its resistance has a relationship with its temperature. This temperature enables adjust the start of combustion, therefore a control over this temperature is totally necessary with the purpose of selecting when the combustion starts.

In this thesis, a new controller is built, trying to improve the performance of the previous one. One of the goals to be improved is to operate the controller at bigger frequencies, allowing for a faster correction of the error. The controller will be programed using a microcontroller, and the circuit, which the microcontroller requires, will be built with the aim of operating this new controller with the only necessity of the external power supply.

It is believed that this new system can improve the trade-off between efficiency and NO_x emissions. Furthermore, the maintenance costs will be reduced. But first of all, a controller, which will able to keep the temperature steady, is necessary in order to reduce the cycle to cycle variation.

Declaration of Originality

I hereby declare that this thesis and the work reported herein was composed by and originated entirely from me. Information derived from the published and unpublished work of others has been acknowledged in the text and references are given in the list of sources.

Place and Date Signature

Mario del Río Carbajo

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I dedicate a special gratitude to my family and my girlfriend Belén, who have always supported me with their trust, love and sacrifice.

Karlsruhe, April 2016 Mario del Río Carbajo

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List of Abbreviations

Abbreviation	Description
A	Analog
AC	Alternating Current
ADC	Anolog-To-Digital Converter
CLK	Clock
CPU	Central Processing Unit
CS	Chip Select
D	Drain (terminal)
D	Digital
DAC	Digital-to-Analog Converter
DC	Direct Current
DCCT	Direct Current Current-Transformer
D_{in}	Data in
D_{out}	Data out
EEPROM	Electrically Erasable Programmable Read-Only Memory
FAS	Fast Adaptive Saturated (controller)
G	Gate (terminal)
GMR sensors	Giant Magneto Resistance sensors
GND	Ground
HIS	Hot Surface Ignition
I/O	Input(S)/Output(S)
I2C	Inter-integrated Circuit
IC	Integrated Circuit
IDE	Integrated Development Environment
LCD	Liquid Crystal Display
LSB	Lest Significant Bit
MISO	Master Input Slave Output
MOSI	Master Output Slave Input
NOx	Nitrogen Oxide
Op amp	Operational amplifier
PID	Proportional-Integral-Derivative Controller
PTC	Positive Temperature Coefficient
PTC	Positive Temperature Coefficient
PWM	Pulse-Width Modulation
RAM	Random Access Memory
REF	Reference

ROM	Read-Only Memory
S	Source (terminal)
SAR	Successive-Approximation Register
SCL	Serial Clock Line
SDA	Serial Data Line
SHA	Sample-and-Hold Amplifier
SHDN	Shutdown Input
SPI	Serial Peripheral Interface
SS	Select Signal
TTL	Transistor-Transistor Logic
USB	Universal Serial Bus

List of symbols

Symbol	Unit	Description
τ	[s]	Variable of integration for the integral part of the PID controller
C(S)	[-]	Actual output of the controller
CA50	[º]	Timing of 50% mass fraction burnt
e(t)	[Ω]	Resistance error for
I_HSI	[A]	Actual current value of the glow plug
Kd	[-]	Derivative gain of the PID controller.
Ki	[-]	Integral gain of the PID controller
Kp	[-]	Proportional gain of the PID controller
Qconduction	[W]	Heat from the conduction process
Qconvection	[W]	Heat from the convection process
R	[Ω]	Resistance
R(S)	[Ω]	Set point for the controller
R_HSI	[Ω]	Actual Resistance Value for the glow plug
R_set	[ºC]	Set point for the glow plug
R1	[Ω]	Resistance use for amplifier configuration
R2	[Ω]	Resistance use for amplifier configuration
RDS(on)	[Ω]	Resistance between drain and source when the Mosfet is on
t	[s]	Time
TGP	[ºC]	Temperature of the Glow Plug
Tsample	[s]	Time required for the ADC to read a value
U_HSI	[V]	Actual constant voltage value of the glow plug
U_set	[V]	Constant voltage value to fed the glow plug
V1	[V]	Voltage in the negative input terminal of the operational amplifier
V2	[V]	Voltage in the positive input terminal of the operational amplifier
VDD	[V]	Power supply for integrated circuit
Vin	[V]	Input Voltage of a certain process
Vout	[V]	Output Voltage of a certain process
λ	[-]	Air-fuel ratio

1 Introduction

The conventional ignition system (spark ignition),which is used in natural gas engine, sets restrictive limits regarding to the air-fuel relation and requires high level of maintenance due to electrode wear. With the aim of solving this problem, a new ignition system has been developed. Due to its larger mixture volume, working with lower air-fuel ratio is possible. As a consequence, the trade-off between engine efficiency and NO_x is improved.

The solution for this system is based on the use of a glow plug, whose temperature is controlled by a power supply working along with a PID controller. The glow plug consists of an electrically conductive solid ceramic with PTC-behaviour, which it is depicted in Figure 1, and thanks to its almost quadratic correlation between resistance and temperature, allows to know its temperature by measuring the resistance.

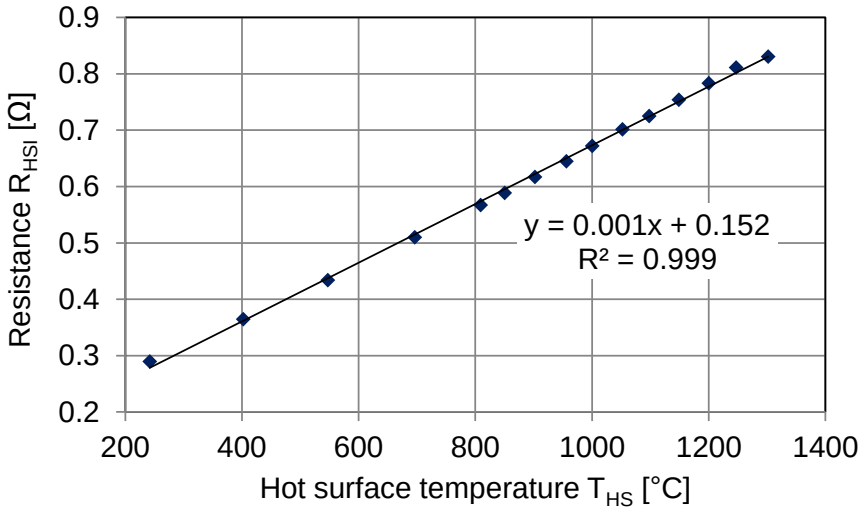


Figure 1: Correlation Resistance-Temperature for the glow plug [1]

One of the keys for the good performance of this system is to keep this resistance value steady while the engine is working. Previous experiments showed that by fixing the voltage value, the glow plug was not able to keep its temperature steady. For this reason, a closed loop controller is necessary.

A controller with this purpose was developed. In this controller the error was reduced by modifying the voltage value of the power supply. This error was the difference between the current value and the set point value, and it could be changed freely. A diagram where the working principle of this controller is depicted appears in Figure 2.

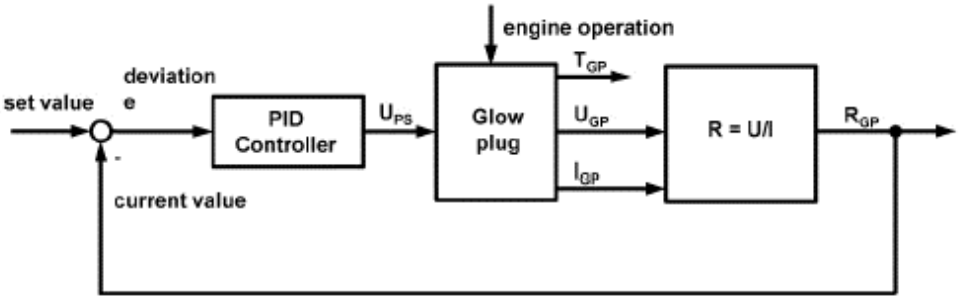


Figure 2: Previous close-loop temperature control of the hot surface ignition system [1]

Engines trials running with this controller showed some results that establish limits in the ignition system temperature. Two sections of different behaviour, which are shown in Figure 2, were discovered. On the one hand, in the section 1 the combustion centre CA50 happens earlier as long as the resistance increases. On the other hand, in the section 2 the plug temperature has no influence in the CA50, and this is kept almost steady. This strange behaviour has been studied, coming to the conclusion that it is due to partial burns and precombustion phenomena that happen much earlier than the central dead position [2].

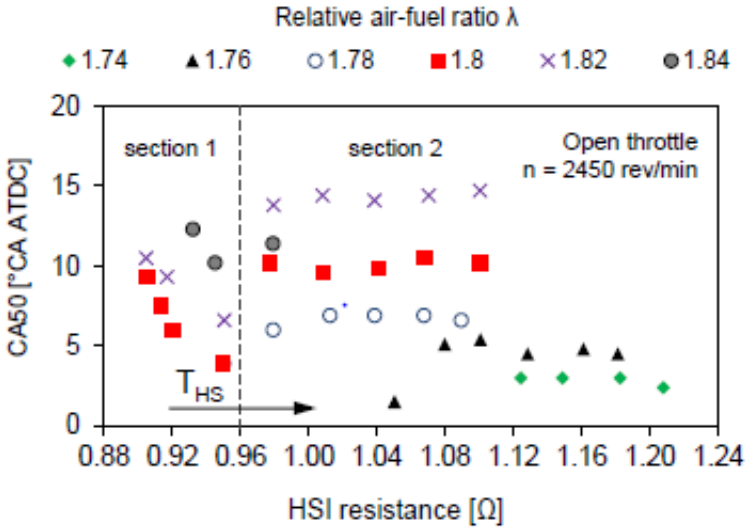


Figure 3: Combustion centre CA50 over HSI resistance for relative air-fuel ratios 1.74-1.84 [2]

This behaviour along with the minimum temperature, which the mixture can ignite, sets the limits for the temperature operation of the glow plug between 0.7 and 1 Ω.

In addition to these limits related to the mixture ignition, other restrictions associated with the controller happen. Experiments working with the previous controller showed that there are certain resistance values, where the controller works much better. The temperature control is most stable when heat released from combustion is relatively low and produces low combus-

tion temperatures. This happens when the engine works with high air-fuel ratios or advanced combustion phasing.

Considering this behaviour, it can be said that perturbations have a big influence in the stability of the controller. For this reason, the design of a new controller is necessary to open up the operation conditions that are restricted for the current controller.

1.1 Goals of the Thesis

As it was explained, the current controller restricts the operation of the engine. The aim of this thesis, is to build a controller that can keep constant temperature under any operation conditions. To attain this aim, it has been split into different goals to be achieved.

First of all, it is necessary to build a circuit that prepares both voltage and current signals, which are used for the resistance calculation. These signals are modified and turned into digital form before being sent to the microcontroller. Aspects like noise, speed reading and resolution will have a special importance.

After this, the next step will be to select a microcontroller for implementing the controller algorithm. Once the whole circuit is ready, several tests will be made in order to find the best controller condition for the system.

The last step will be to identify improvements that can be applied to the controller.

1.2 Basic concept of the controller

The first concept, which is important to know when a controller is used, is the difference between an open loop and a closed loop controller. In these two groups, the different controllers can be separated. It is a general separation but it is useful to understand how a controller works.

An open loop controller is by far the simplest kind of controller; its use is limited and only in processes where the external conditions are steady and the precision is not quite important it can be used. This kind of controller has no feedback. Different outputs can happen although the input remains the same, or in others words, it cannot correct any errors. In Figure 4 the open loop control diagram is shown.

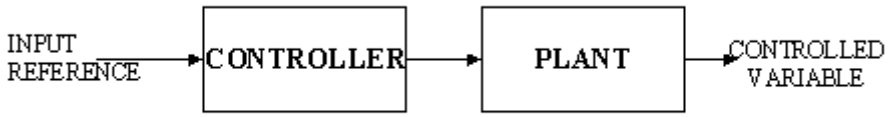


Figure 4: Diagram for a generic open-loop control

As it can be seen in the figure, the controller does not have any way to know if the value of the controlled variable is the desirable one.

On the other hand, the closed loop controller shows there is feedback. This kind of controller compares the desired output with the actual output, giving an error signal. Thanks to this, the system can correct errors and allows reaching the desirable output regardless whether the external conditions change or not. Its appearance is shown in the Figure 5.

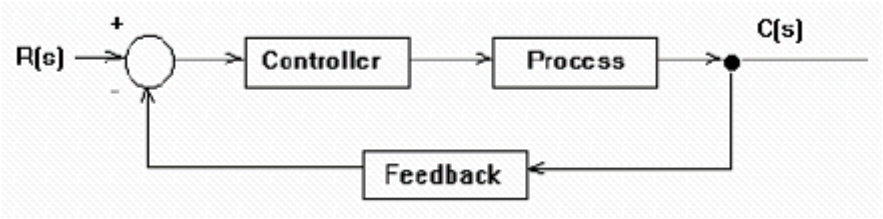


Figure 5: Diagram for a generic close-loop control

For the controller of the application, a close-loop control design was chosen. To the processing of the error signal a PID controller can be used. It is a highly extended kind of controller, which is used in most of the Industrial controlling processes because of its flexibility and good performance.

Basically, the PID is made out of three parts; a proportional part, which corrects present values of the error, an integral part, which corrects past values of the error and a differential part that corrects possible future values of the error. By adjusting the value of these three parameters, the desired loop dynamics is obtained. In the next picture a scheme for a PID controller can be seen.

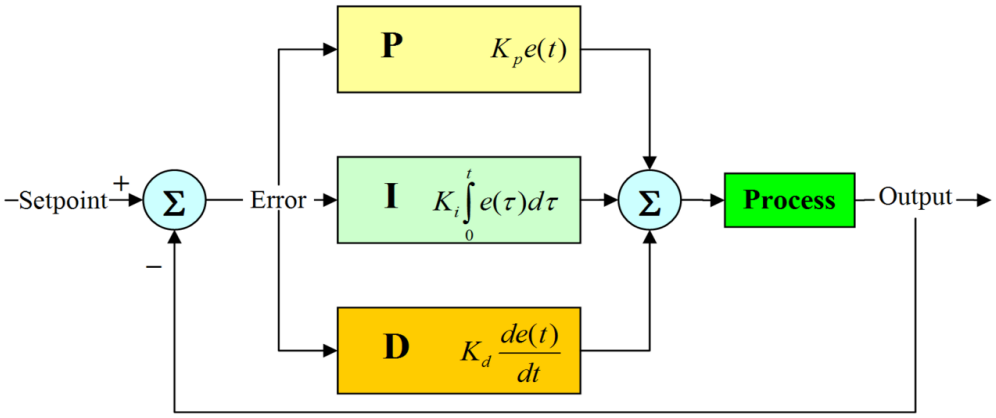


Figure 6: PID controller

A digital PID can be easily programmed by using a microcontroller. There are also mechanical PIDs but their use is limited, since they are more difficult to build and they have no flexibility. With a microcontroller, all kind of digital controllers can be programmed and the same microcontroller can be used to control a big number of processes, whereas a mechanical control can only be used for the application that was built.

One of the most important advantages of working with a PID implemented in a microcontroller is the flexibility to change its parameters. This is quite important, because it helps in the process of tuning the controller. Although there are tools that help to choose the parameters that can fit with the process, these are not really accurate and therefore in most of the cases, the final values are gotten with a process of trial-and-error. The tools are used basically to get closer to the solution.

Because a digital controller is implemented, the inputs also have to be digital. Therefore a process of transforming physical signals into a digital values is necessary; for this purpose, the signals must be processed. This requires the use of transducers, a process of signal-conditioning and the use of converters.

For the controller, there are two physical values that need to be known for the calculation of the resistance, these two values are the voltage between both sides of the glow plug, and the current that flows through it. This signal will be sent to the microcontroller after the appropriate signal processing.

The last process of converting a physical signal to a digital value is made for the ADC module, which is an analog digital converter. This ADC receives a voltage signal, which it is converted in the ADC into a series of 0s 1s.

One of the signals, which has to be read, is already a voltage signal whereas the other signal is a current value. Because the ADC can only read a voltage signal, this current has to be converted into a proportional voltage drop. For this purpose, there are different techniques that will be explained later in this document.

Once the values, which are necessary, are in the form of a voltage signal, the next step is to modify them, with the purpose of making sure that they are within the two limit values where the ADC can read, as well as with the aim of getting the best precision. This process is called signal conditioning.

Most of the time, in this process, the voltage is amplified and this can become a problem when there is noise in the signal, since this noise will be also amplified. To avoid this from happening, there are different techniques to be used, going from a correct layout of the components to a filters design.

After these two processes, the signal can be inserted into the ADC. As it was said before, inside it there is a process that converts the input voltage into a digital output. This process depends on the kind of ADC, and the election of it depends on each application. Later in this document, the election of the ADC will be justified. Important aspects of this selection will be the bits resolution and the frames per seconds.

After converting the signal, the microcontroller is ready to work with the digital values of each signal and thanks to the program, that has been pre-configured in its memory program, the appropriate control signal is given. This signal will switch on and off the circuit where the glow plug is placed.

A mechanical switch cannot be used, since it will work at really high speed and this would generate big amount of heat in the mechanical parts. Ruling out the mechanical switches, the most common solution is the use of bipolar transistors, Mosfet, relays and optocoupler.

We use a switch because our glow plug will be always connected to a fixed voltage power supply; in this way, with the switch, the power of the glow plug can be controlled.

2 MATLAB and Simulink

A Simulink model that simulates the behaviour of the engine was developed to know how the different parameters, which have some kind of influence during the engine operation, change and the influence that they have on glow plug temperature. Thanks to its graphical programming environment, these different parameters can be directly displayed while the program is running. For this reason, this program meant a quick and graphical tool to a better understanding of how the engine works and what the desirable characteristic of the new controller will be.

Furthermore, its communication with MATLAB allows to save the data after each simulation, giving the possibility to compare different simulations to find out how the different condition values affect engine performance.

With the purpose of saving this simulation to study further, a program in MATLAB was developed. This program permits to save data in a excel file after each simulation. It will be fully explained later in this document.

2.1 Brief description of the program

To explain the model, it can be split into three parts. The first part calculates the resistance value variation that the glow plug suffers during its operation, the second part is related with engine operation and its behaviour depends on which stroke the engine is and the third part is the implementation of the PID controller.

The first part, previously defined as the one which calculates the resistance value, can be divided at the same time into three processes: convective heat transfer, conductive heat transfer and electric power for resistance heating. By constantly calculating the value of these three processes, and using these results to calculate an energy balance, Simulink can obtain how the resistance differs over the time. In this calculation the radiation heat transfer has been neglected, because its influence is low compare with the influence of the other processes.

In the second part, the simulation identifies in which of the four strokes the engine is working, for each stroke a different subsystem is running. With this part, the conditions inside the combustion chamber as well as the process of combustion are recalculated each time of the simulation.

In the third part, a PID controller with omitted D value was implemented to control the temperature of the glow plug. As the real controller, it reads the value of the current and voltage that are placed in the glow plug, and from these values it calculates the current resistance value. After that, the current resistance value is compared with the set point value, getting the

error and sending it to the PID. The PID controller according to its tuning parameters, gives the new voltage value of the power supply. Figure 7 shows the set of blocks, which originally was used for the control of the resistance value.

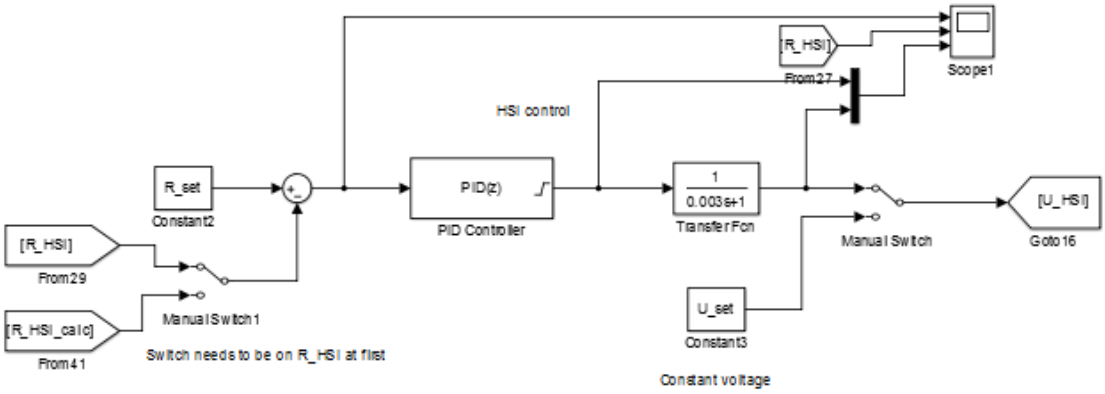


Figure 7: Blocks for PID controller of the original Simulink model

2.2 Development of the program

So as to adapt the model to the new proposal of controller, some changes were made, and later their influence in the overall engine performance was studied.

The first change was related to the reading resolution. Since the controller is digital, this always comes along with a digitization error. This error, due to the digital conversion, is an approximation to the original analogue value, the magnitude of it depends on the resolution of the ADC.

To implement this in Simulink, a set of blocks of Gain, Rounding Function and Gain, were used. They are illustrated in the Figure 8. The process is simple, and it just consists of multiplying the value by the resolution, rounding the result, and dividing it by the resolution. As it can be seen, the upper set of block simulates the process of voltage reading and the bottom block, the process of current reading.

The second variation is due to the process of power supply regulation. The new design of the controller requires the power supply to be controlled by using a switch, this means that a PWM signal to control this switch is required. The blocks that makes this transformation are shown in Figure 9.

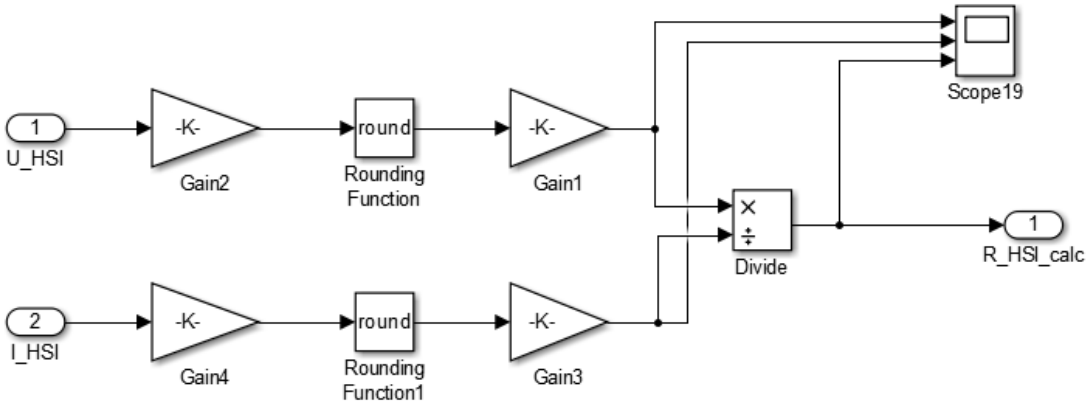


Figure 8: Blocks for selecting precision in the new Simulink model

In the figure below, inside the square the process of PWM signal creation is depicted. MATLAB provides directly a block that can create a PWM signal by inserting the duty cycle and configuring its frequency parameter. This block generates a PWM signal with an amplitude of 1, thus a product block has to be added to give the signal the desirable amplitude, and in this case, it is 11.

Although the original power supply has around 12V, in the simulation is used 11V since the hot losses in the cables are not simulated in the model. In order a better simulation of what really happens, a voltage drop in the cable of 1 V is assumed.

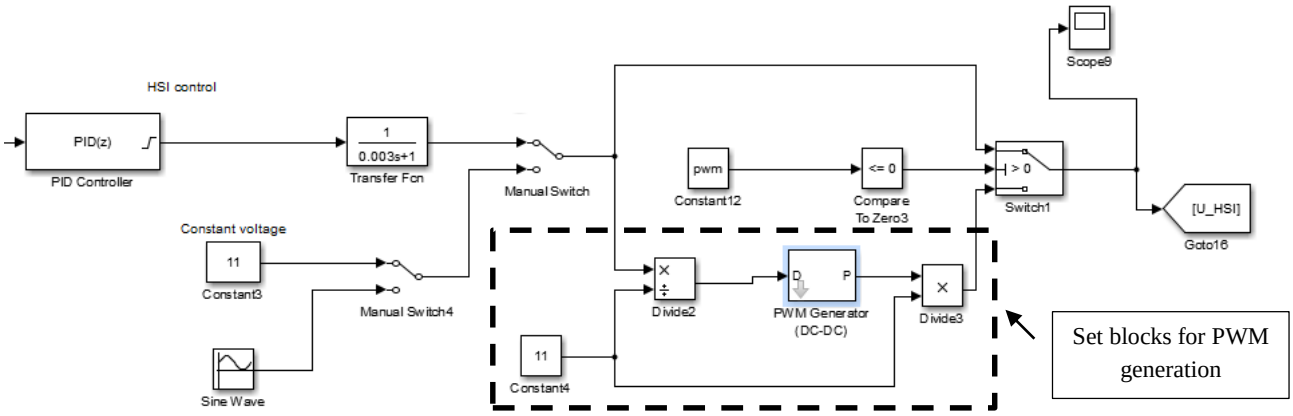


Figure 9: PWM signal transformation in the new Simulink model

As it can be seen, other changes have been made regarding to the original model, but they were not done because of the use of the new controller, but because of the possibility of

changing these parameters when the MATLAB program is executed. This MATLAB program will be explained in the following section.

2.3 Making tests with Simulink

For the process of testing with Simulink, a MATLAB program, which enables to run different tests by only introducing the different constant values for each simulation, was developed. At the same time, the data for each simulation will be stored in an excel file at the end of all the simulations.

This program was programmed in two MATLAB files; the first one, where the different values are inserted by the user and the Simulink model is executed, and the second part where the information for each simulation is stored in the excel file. How both parts work is explained in the following section.

2.3.1 Selecting values of the different parameters and running tests

In the beginning, a program, which asks for the value of the different parameters and runs the Simulink model according to this configuration, was created. All this is done from the Command Window of MATLAB. Running the Simulink model can even be done from the command window, using the following structure:

```
sim('HSI_continuous_w_PID_controller_variance_media')
```

The function is sim() and it is only required to write the name of the Simulink file between two apostrophes.

MATLAB also allows using the variables of the workspace to execute a Simulink program, by only writing the name of the variables inside the block configuration. This option gives a good number of possibilities, for example a program that asks the user for the values of the parameters, can be created. And later these parameters are used to run the Simulink model. To do this, the next function is used:

```
value= input('Introduce the different value of the variable selected: ');
```

The input() is the function, if something is written between the brackets using apostrophes, this message will be shown in the Command Window. The value that is inserted by the keyboard is stored, in this example, in the variable “value”. This command is used in the program inside a For loop to introduce the value of the different parameters.

In the program, the variables that can be changed from one simulation to the other, are included in a structure. The reason is because the number of element cannot be known directly with a command. The problem of using a structure, is that the variables must have the same length. Therefore, their names have to be adapted, using extra characters. In Figure 10 it is depicted the name of the variables inside the data structure.

```
data.precision__select=[];
data.sigma__CD__select=[];
data.sigma__SOC_select=[];
data.resistance_select=[];
data.revolution_select=[];
data.lambda_____select=[];
data.pwm_signal_select=[];
data.pwm_____frequency=[];
```

Figure 10: Parameters that can be changed when different Simulink tests are run

Now that the way to store variables and execute Simulink from MATLAB has been explained, it is time to clarify how the different values are sent from Simulink to the workspace of MATLAB. This is quite simple, since Simulink has a specific block for this purpose, the name of the block is To Workspace and is shown in Figure 11:

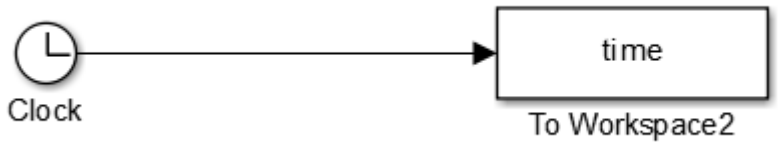


Figure 11: Block use for communication between MATLAB and Simulink to send the values of the variable

In this previous picture, the value of the time is stored in the variable time. Once the simulation has finished, the different values will be able to be used in the Workspace of MATLAB.

2.3.2 Second part, writing data in an Excel file

To store date in an Excel file, the following function is used:

```
xlswrite(filename,A,sheet,xlRange)
```

Xlswrite() is the function and the parameters are: filename; name of the excel file that creates MATLAB, A; variable where the information that wants to be written is, sheet; number of the

excel sheets where MATLAB will write and xlRange; which is the box where the data will be written. The main problem of this code was to say MATLAB where it must write, because Matlab cannot detect if one part of the excel sheet has already data. In Figure 12, it can be seen how an Excel file looks likes after having written data in it.

precision__select	time	CA50	P_HSI_avera	P_HSI_var	R_HSI	R_HSI_var
16	50,00	2,4	25,05	0,006	0,8001	0,00015
sigma__CD__select	50,03	2,4	25,05	0,006	0,8001	0,00015
0	50,05	2,4	25,05	0,004	0,7998	0,00012
sigma__SOC_select	50,08	2,4	25,06	0,014	0,8001	0,00015
0	50,10	2,4	25,06	0,017	0,8000	0,00012
resistance_select	50,13	2,4	25,07	0,014	0,8001	0,00015
0,8	50,15	2,4	25,07	0,008	0,8001	0,00015
revolution_select	50,18	2,4	25,07	0,010	0,7995	0,00014
2000	50,20	2,4	25,06	0,009	0,8001	0,00015
lambda_____select	50,23	2,4	25,06	0,006	0,7999	0,00012
1,5	50,25	2,4	25,05	0,005	0,8001	0,00015
pwm_signal_select	50,28	2,4	25,05	0,006	0,8001	0,00014
0	50,30	2,4	25,05	0,006	0,8001	0,00015
pwm_____frequency	50,33	2,4	25,05	0,007	0,8001	0,00015
500	50,35	2,4	25,05	0,004	0,7998	0,00012
	50,38	2,4	25,05	0,013	0,8001	0,00015
	50,40	2,4	25,06	0,016	0,8000	0,00012
	50,43	2,4	25,07	0,013	0,8001	0,00015

Figure 12: Appearance of Excel data for saving data from Simulink tests

In the picture above, it can be seen that before each new test, Matlab writes the constants configuration for the test, and then the different values for the variables for each moment of the simulation.

2.4 Test trials

Simulink model was used with two main purposes. The first one was to know what kind of influence the new conditions will have during engine working.

The second reason is because the glow plug is exposed to changing conditions, such as the ones that happen during the combustion or during the entry of the mixture. With this simulation, how they affect to its temperature can be known. Influence of new controller.

2.4.1 Influence of new controller

Since the controller has to read the value of the current and the voltage digitally, an error comes along with this process. As explained before, a set of blocks were used to simulate this process and by changing their parameters, different values of precision were checked. The influence of these values in the glow temperature is depicted in the Figure 13.

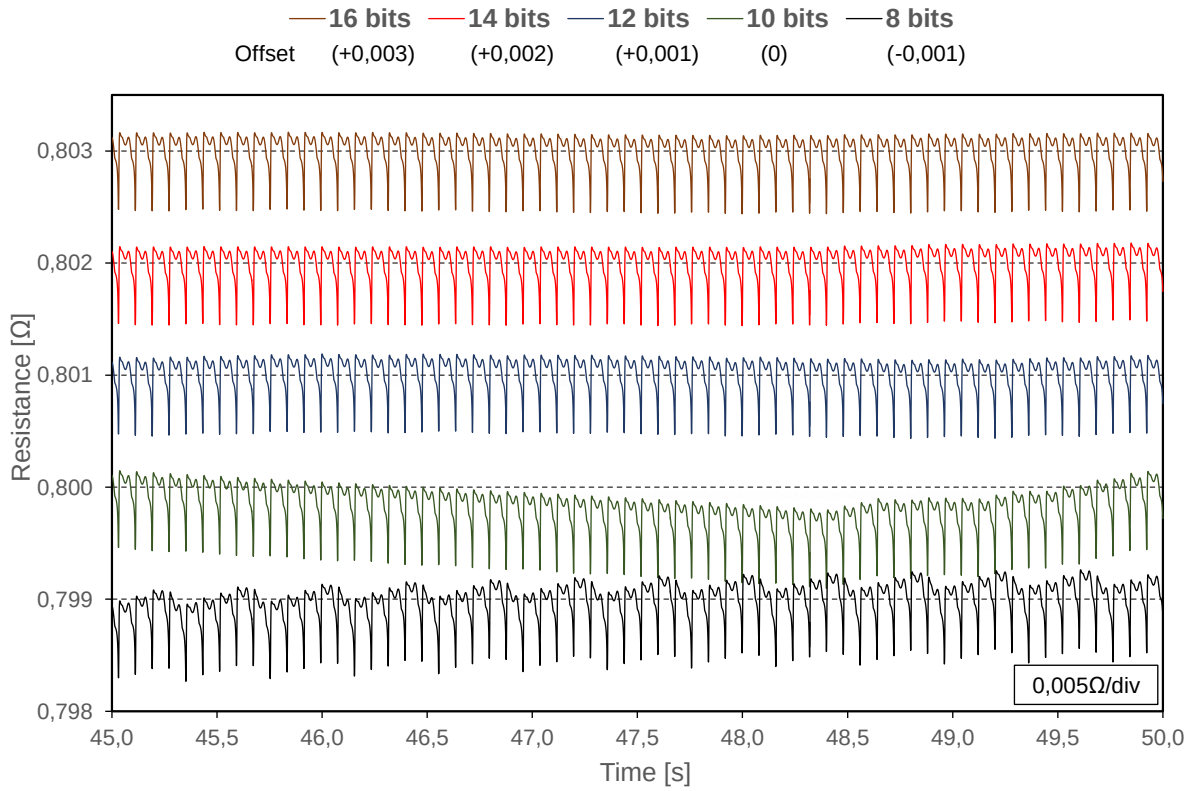


Figure 13: Influence in the resistance value due to the usage of different read resolution with Simulink model (R_set= 0.80, sigmaSOC=0 , sigmaCD=0,rpm=1500, λ=1.5)

The Figure 13, shows how the behaviour of the resistance is, whose set point is 0.8Ω, for different values of resolution. The scale is 0.005 Ω/div, and the different signals are represented with a different offset value for a better visualization.

As it can be seen in the figure, there is not a high influence of the resolution for the control of the process, for a resolution of at least 12 bits. Only with resolutions of 8 and 10 bits, a variation from cycle to cycle can be appreciated.

The power supply for different resolution values also was checked and it is depicted in Figure 14.

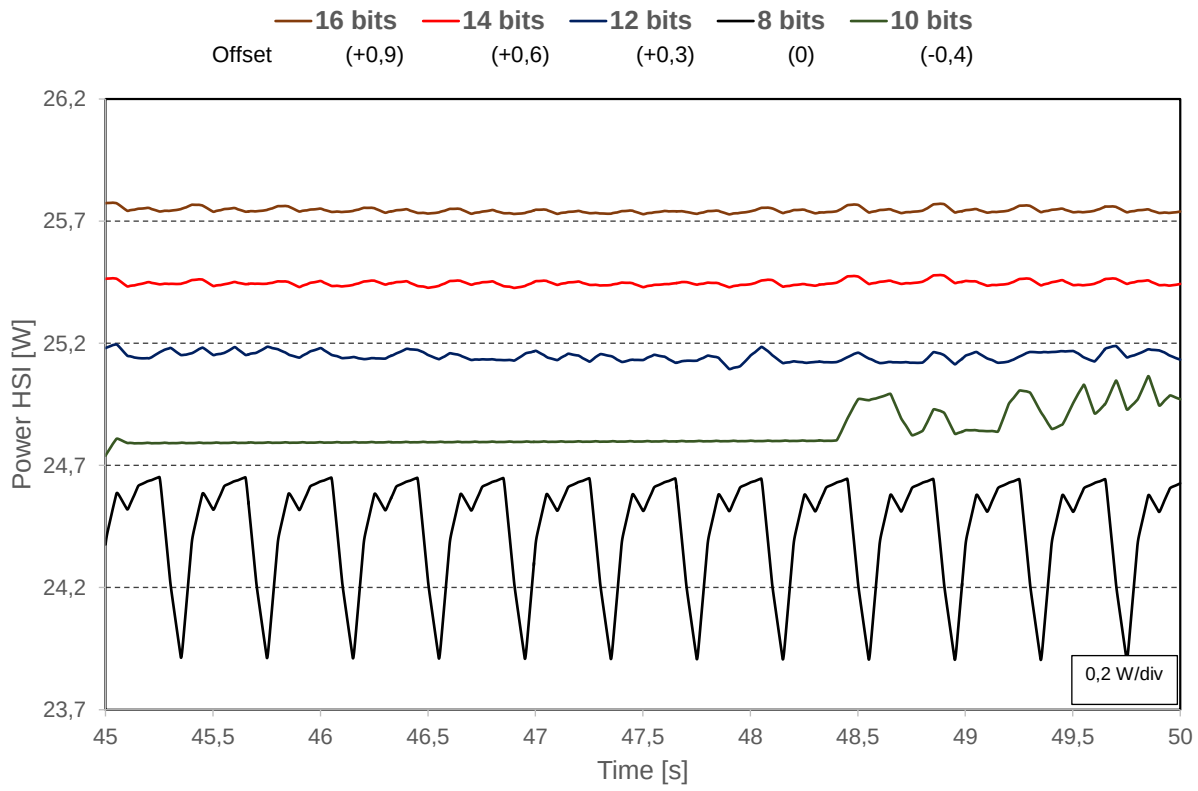


Figure 14: Influence in the power supply value due to usage of different read resolution with Simulink model (R_set= 0.80, sigmaSOC=0 , sigmaCD=0,rpm=1500, λ=1.5)

In Figure 14 the power supply for the different precision are represented with a certain offset value. The same results as in the other picture can be seen, for 12 14 and 16 bits the power supply is almost the same, only using a resolution of 8 and10 bits a difference can be easily appreciated.

Another modification that the use of the new control causes, is related with the way that the control operates. The old controller modifies the value of the voltage of the power supply, meanwhile the new one modifies the duty cycle of the signal that opens and closes the main circuit. After implementing this new condition, two tests were made, using for both of them the same parameters. The results for these two tests is depicted in Figure 15.

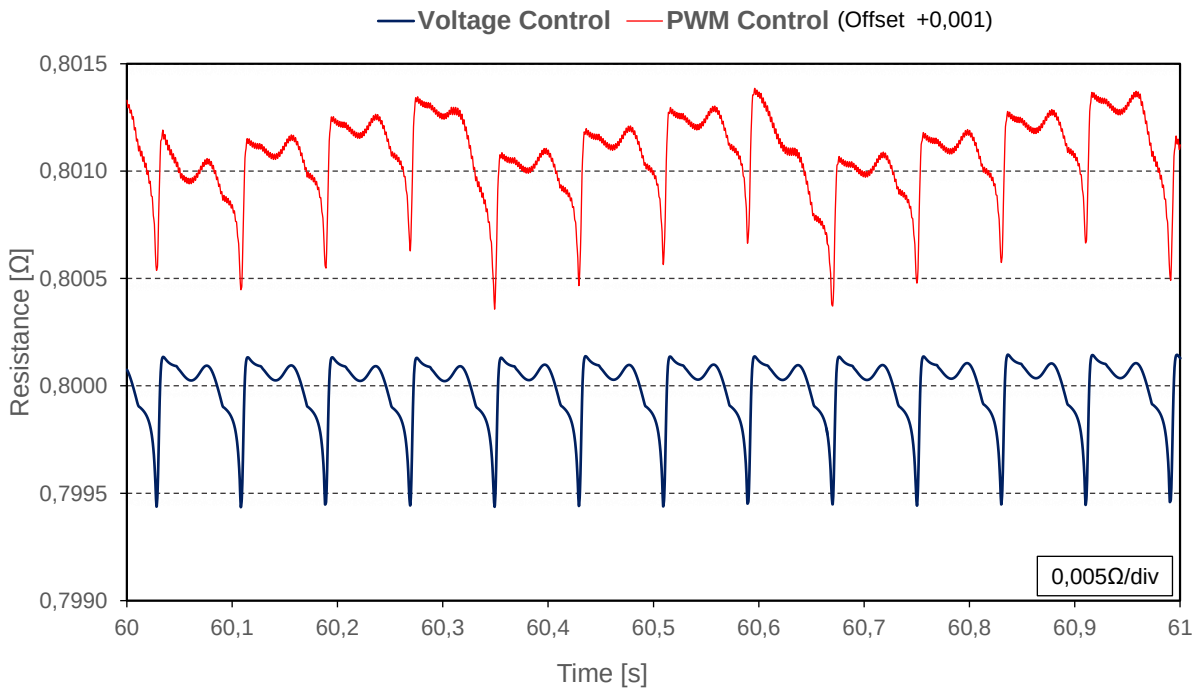


Figure 15: Comparison of Resistance control using the PWM and the voltage variable controllers with Simulink (R_set= 0.80, sigmaSOC=0, sigmaCD=0, rpm=1500, λ=1.5)

As it can be seen, the influence of using PWM signal to regulate the power supply is bigger than the influence of the resolution. According to the results, it can be said that the use of PWM control adds a variation about 0.0003Ω to the resistance value. The frequency that was used for this test has a value of 500 Hz.

2.4.2 Conditions in the combustion chamber

Since the engine is running at a speed of 2450 rpm, the condition in the combustion chamber changes in a short period of time. This will have a big influence on the temperature of the glow plug. Hence to be able to control it, what happened inside the combustion chamber must be known.

As said before, the glow temperature is calculated from the heat of the convection and conduction process and the electric power of the glow plug. In Figure 16, the heat of both processes is depicted. Because of the information explained before, the same power from these two values has to be delivered by the power supply but with the opposite sign, in order to keep the resistance value constant.

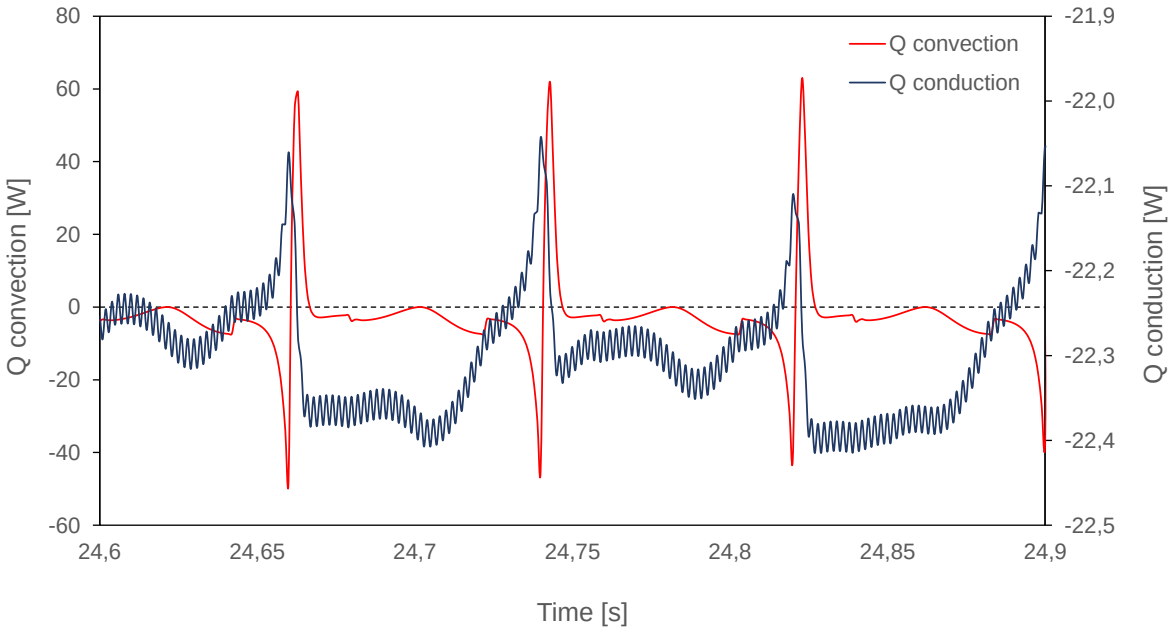


Figure 16: Heat from the conduction and convection process affecting the glow plug during engine working with Simulink model (R_set= 0.75, sigmaSOC=0, sigmaCD=0,rpm=1500, λ=1.5)

As it can be seen in the figure above, the heat from conduction will be always negative, which means the glow plug will always lose heat through this process. However the heat from convection is both negative and positive, which makes sense owing to the engine cycle. The positive value of this process is because the combustion is happening and the hot surface is exposed to hot residual gases, while for the rest of the time it has negative values.

Another important parameter that can be observed using the Simulink model is the temperature in the combustion chamber. As happened with the other two processes, the temperature changes depending on which time of the cycle it is. This temperature is shown in Figure 17 along with the heat from convection. These two variables have a direct influence between each other, since when the chamber temperature is bigger than the glow plug temperature, the convection heat will be positive, and the same when it is lower, but the opposite.

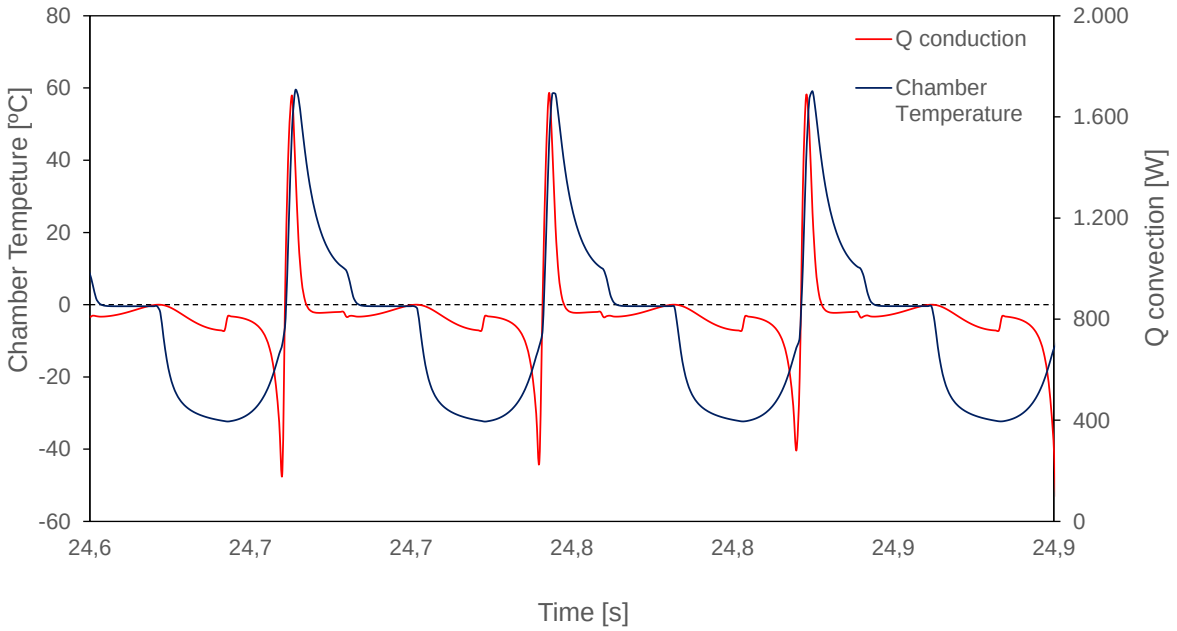


Figure 17: Chamber Temperature and convective heat transfer (1 zone Woschni model) in the glow plug with Simulink (R_set= 0.75, sigmaSOC=0 , sigmaCD=0,rpm=1500, λ=1.5)

3 Circuit design and its components

With all information that was collected from the different tests with MATLAB, the necessities for the controller were established. After that, the process of searching the right components and the best solution for the controller started. To do this, the controller was divided into 4 parts, which are listed below:

- A microcontroller.
- Circuit to measure the voltage.
- Circuit to measure the current.
- Switch circuit.

This division is justified because the performance of each part can be checked regardless of the others 3 parts.

In the next section, each part will be explained and justified. Also it is given information about the chosen components as well as considerations related with the circuit layout.

3.1 Microcontroller

The most common solution for a controller is to use a digital controller, whose main part is based on a microcontroller.

There is a large range of microcontrollers, so the selection of one of them is not an easy task, the selection of Arduino microcontroller was based on its flexibility for operation. One of the main characteristic is that it does not require an external circuit for its programming process. It can be done directly by connecting Arduino board by USB with our computer.

As a brief introduction to microcontrollers, some of their most important characteristics as well as its different parts will be clarified. These parts shared for almost all microcontrollers, are shown in Figure 18.

In the top left part of the figure is the oscillator. The oscillator is the clock that controls the operation of a microcontroller, this clock can be an internal signal or an external signal, depending on the configuration. All the microcontrollers need a clock signal for the execution of instructions with synchronism. By modifying the frequency of the oscillator, it can be changed the working speed of the microcontroller as well as its power consumption and heat generation, which are directly related with each other.

The next part is the CPU, where the instructions are executed. Depending on the microcontroller, the number of the instructions is higher or lower, microcontrollers with from 35 to 200 instructions can be found. The bigger the number of instructions, the more options to configure it, but also the greater the difficulty to work with it. The instructions are written in the program memory and are executed one by one controlled by the clock speed. All the instructions require the same amount of time to be executed. Usually this time is 4 clock cycle.

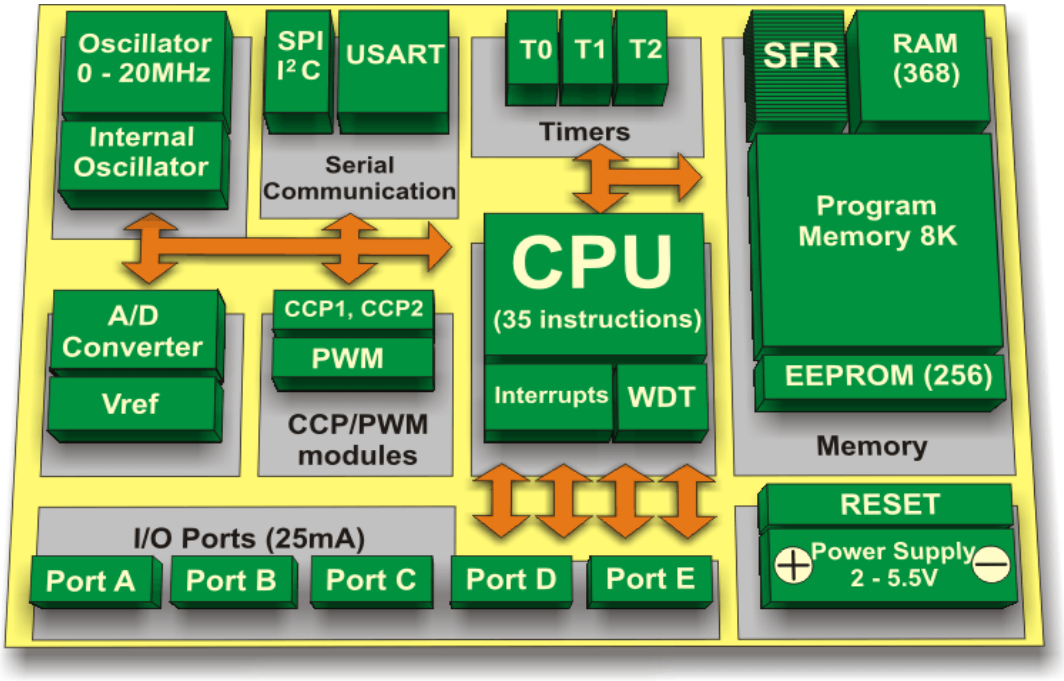


Figure 18: Structure for a generic microcontroller [3]

Besides the memory program, there are other three kinds of memories:

- ROM memory, also called memory program, because the instruction that the CPU has to execute is saved here. It is a memory that can be written and erased many times. It is a non-volatile memory.
- EEPROM memory, it is also a non-volatile memory but with the difference that its value can change during the operation. The big disadvantage of this memory is its slowly writing process.
- RAM memory, this memory is volatile and can be changed during its operation, it is much faster than the EEPROM. Therefore, it is used to save values that are used during the operation.

Usually the microcontrollers work with information coming from the outside or need to send information to other processes. For the communication with the outside the microcontrollers have serial communication modules. This microcontroller module is called I/O ports.

This information that is sent to the microcontroller does not often come in a digital form, but in a voltage signal. For this reason, most of the microcontrollers have an ADC module that enables to convert this signal into a digital one so that the CPU can work with it.

A way to exchange information with the outside has been explained, but it is not the only option, the microcontrollers also have communication modules that allow to exchange information by using different protocols based on serial communication. Some of them have been used in this project, and they will be explained later.

Another module is the timers module, which enables the microcontroller to calculates time or events and according to this information executes operations. They are also used to generate interactions. And of course a microcontroller needs a supply power, whose value is often 3.3 V or 5V and because the demanding of the current is very variable, it requires a bypass condenser close to this pin.

3.2 Circuit for voltage measurement

A conventional 12V automotive battery is used to feed the glow plug. Despite this, the voltage drop between both edges of the glow plug does not remain constant. The high value of the current flowing through the circuit, creates a voltage drop in the cables that connect the glow plug to the power supply, setting its voltage drop always lower than 12V.

Due to the continuous changes of the voltage drop in the glow plug, it is necessary to know its instantaneous value in order to make an accurate calculation of its resistance.

Since a digital control will be implemented, to be able to work with this analog signal, firstly it has to be transformed into a digital signal, using the ADC module. This ADC module, which will be explained later, can convert a voltage value within a range of 0 to 5 V into a digital value.

For this reason, the first requirement for this circuit is to convert the original value range of the voltage drop into the range where the ADC can read. For doing this, there is a simple solution based on the use a voltage divider.

A voltage divider consists of a pair of resistors connected in series. The input voltage is applied across both the resistors and the output voltage emerged from the connection between

them. This output is a fraction of the input voltage, which depends on the relation of the resistance values of the two resistors.

In Figure 19 a scheme for a general voltage divider is depicted. The voltage value for the output is calculated using the next formula:

$$V_{out} = V_{in} \cdot \frac{R_1}{R_1 + R_2}$$

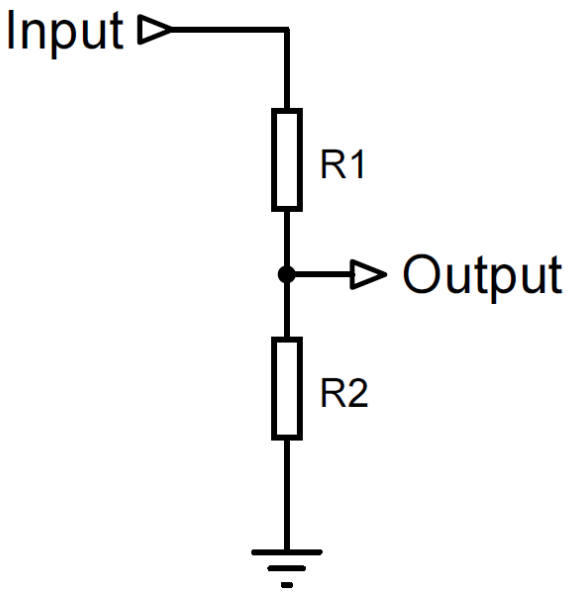


Figure 19: Scheme for a general voltage divider

This solution has a clear disadvantage, if a voltage divider is used, most of the values that are in the range of the ADC will not be reached by the system. As a consequence, the sensitivity will be much higher that if only the values that can be reached are included. The normal voltage drop values of the glow will be around 10-11.5 V, instead of the 0-12V. The Figure 20 shows the difference of sensitivity in both processes.

In order to get the biggest sensitivity, the purpose of the circuit is to transform the range of 10-11.5V into a new range of 0-5V. A solution is to use operational amplifiers along with a voltage reference. The use of operational amplifiers gives a broad range of possibilities due to the big number of configuration that can be built from them.

In order to do this, the first step is to compare the voltage between both edges of the glow plug. With this purpose, the not inverted differential amplifier is used. Since the voltage drop is bigger than the saturation limit of the amplifiers, the relation of the resistance values that made up the configuration must be lower than 1, thus the output for this configuration will be

a fraction of the voltage drop in the glow plug. The scheme for this amplifier configuration is shown in Figure 21.

Since the value of the resistor is 8.2 kΩ and 3.3 kΩ, the output of this circuit according to both inputs will be:

$$Vout = \frac{3.3}{8.2} \cdot (V_+ - V_-)$$

In this way, for a voltage difference of 12V, the output will be 4.83 V, which is lower than the saturation of the operational amplifier. This saturation is close to 5.5 V, as to a power supply of ±7.5V is used.

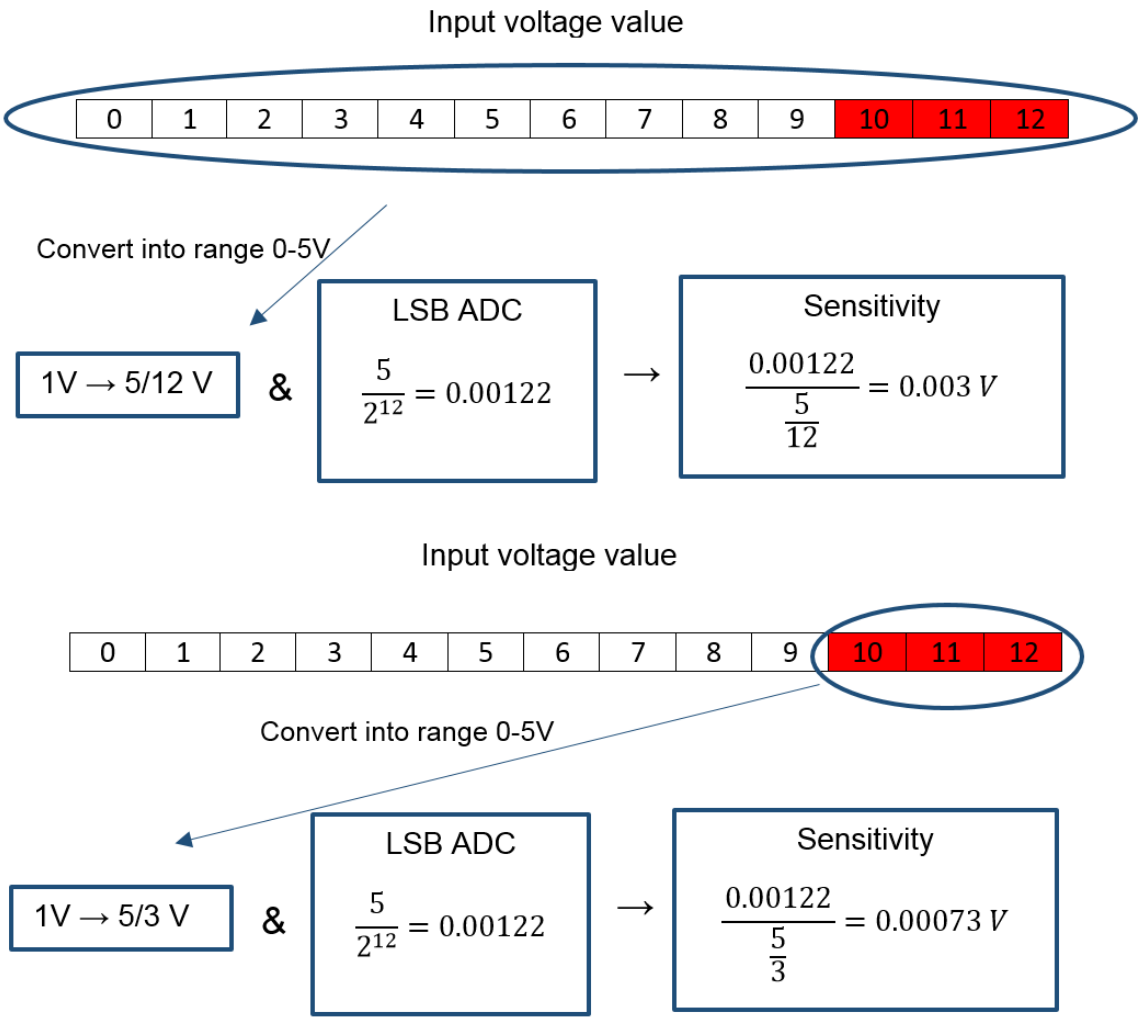


Figure 20: Sensitivity comparison between the use a voltage divider and the use of the specific circuit for voltage measurement

In the next step, the output of this first amplifier is compared with the reference voltage, but firstly this voltage has to be generated. In order to do this, a precision programmable reference along with resistor and a bipolar transistor are used. The use of the transistor is to make the value of the voltage reference steady although small changes in the voltage level of the power supply happen. Before the reference value is sent to the next differential amplifier a buffer is used. A buffer is a kind of amplifier configuration where the output is the same as the input and it is used to isolate the input circuit from the output circuit. The whole circuit that is used to generate this voltage reference along with the buffer is shown in Figure 22.

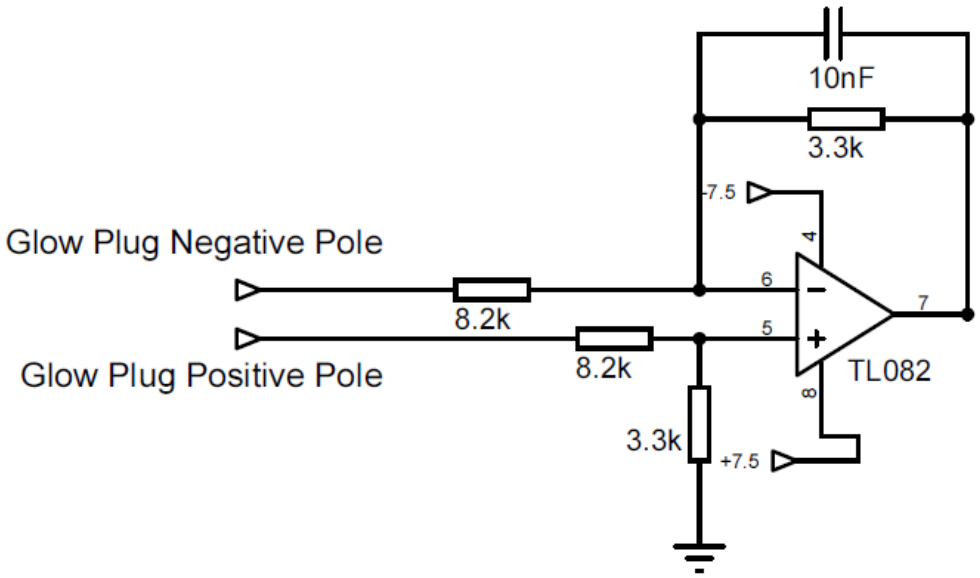


Figure 21: non inverting differential amplifier use to compare the voltage between both edges of the glow plug

As can be seen in the figure, also a potentiometer is used, this potentiometer allows to select the voltage reference, and in this way the voltage from where the ADC will start to read can be selected.

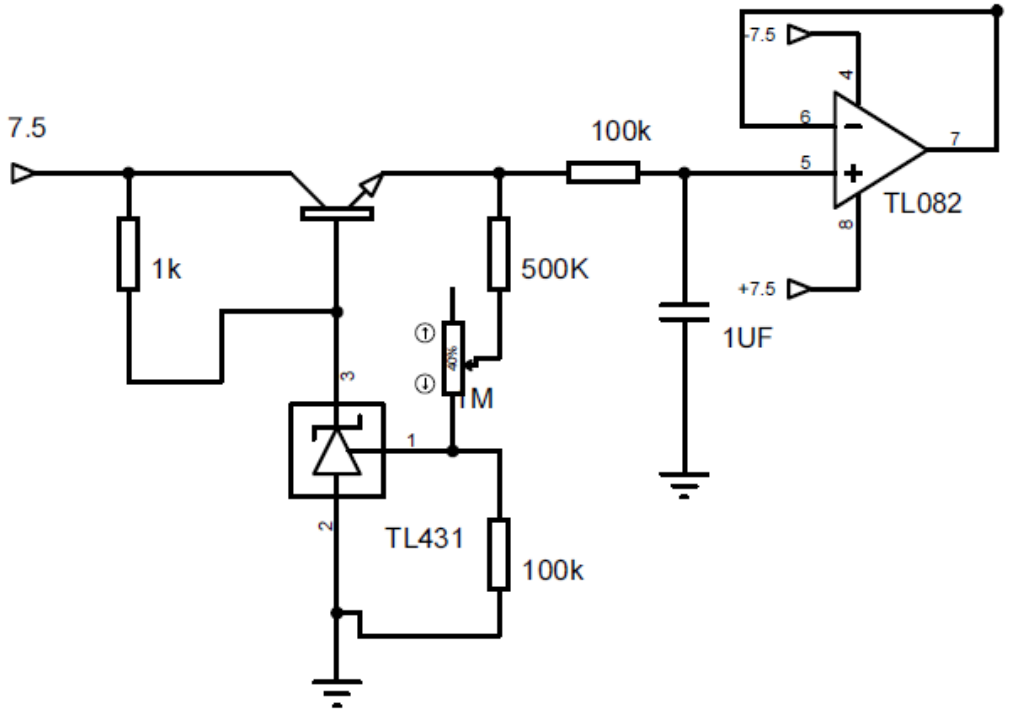


Figure 22: Circuit to generate a constant voltage reference

As it was explained before, now these two signals are compared, using also the non-inverting differential configuration. Since in the output of this new amplifier either positive or negative voltage values can appear, a rectifier has to be used in order to eliminate the negative values. If a negative voltage value is send to the ADC, it might automatically be destroyed. Both amplifier configurations are depicted in Figure 23.

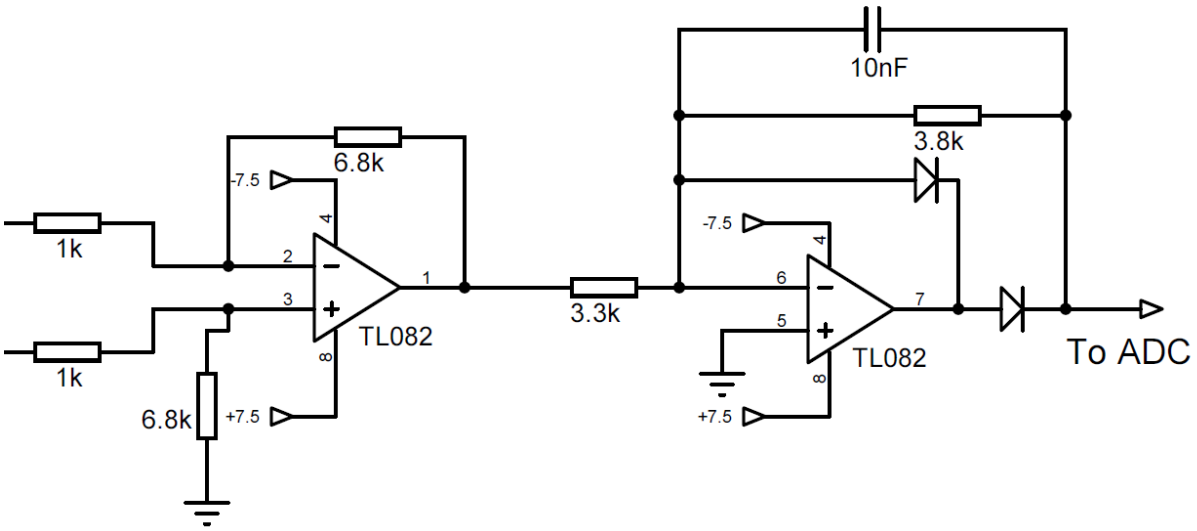


Figure 23: non-inverting amplifier configuration and rectifier configuration using operational amplifiers use to send right voltage values to the ADC

The rectifier works in this way: if a positive value is sent to its negative input, its output will have the voltage level of the ground that is used by the amplifier, whereas if a negative value is sent to the negative input, in the output there will be a positive voltage level proportional to the voltage value in the input. This proportional relation depends on the resistance value of the resistors. In this case, this relation is about 1.15 (3.8k/3.3k). In this way, this ensures that only positive values can be sent to the ADC regardless the voltage drop in the glow plug.

3.2.1 Circuit sensitivity

The sensitivity of circuit refers to how the output of the circuit changes according to the input of the circuit, in this case, the input is the voltage drop in the glow plug. Form this calculation, it can be also known what the minimum variation that the ADC can detect is.

The voltage value of the glow plug is amplified three time inside this circuit, and then it is sent to the ADC. Also, it is compared with a voltage reference, but this operation, since it is a subtraction, does not affect the process sensitivity. For this reason, this aspect in this calculation is ruled out.

For the amplification of the signal as it was seen before, it is used the configuration that is depicted in the Figure 24. The equation that describe how the V_{out} responds to variation in both inputs is:

$$V_{out} = \frac{R_2}{R_1}(V2 - V1)$$

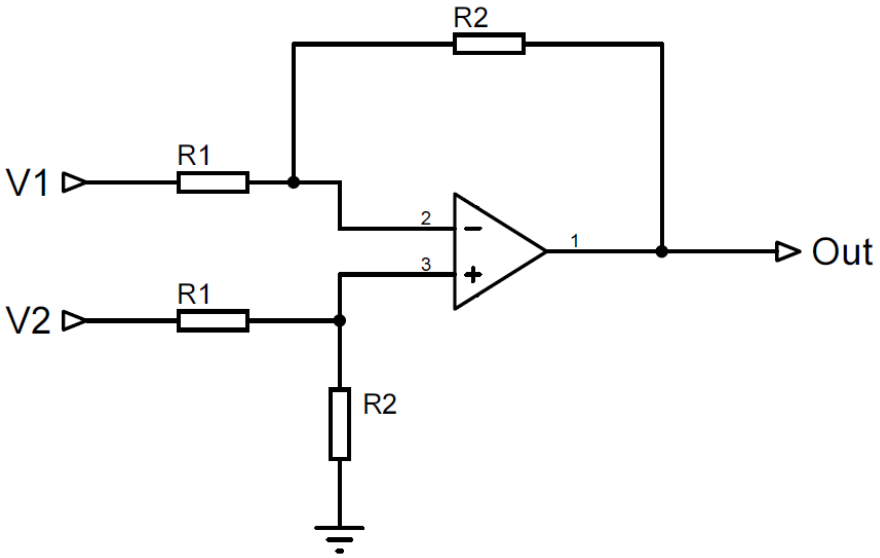


Figure 24: Scheme for a general non-inverting amplifier

In the first amplification, the values of the resistance are R_1=8.2 k Ω and R_2=3.3 k Ω, giving a constant of amplification of:

$$Sensitivity1 = \frac{R_2}{R_1} = \frac{3.3}{8.2} = 0.402\ \text{V/V}$$

In the next amplification, the values of the resistance are R_1=1 k Ω and R_2=6.8 k Ω, giving a constant of amplification of:

$$Sensitivity2 = \frac{R_2}{R_1} = \frac{6.8}{1} = 6.8\ \text{V/V}$$

And in the last amplification, the values of the resistance are R_1=3.3 k Ω and R_2=3.9 k Ω, giving a constant of amplification of:

$$Amplification3 = \frac{R_2}{R_1} = \frac{3.9}{3.3} = 1.18\ \text{V/V}$$

Adding all amplification together, the amplification for the overall circuit is obtained. This amplification is:

$$Senstitivity\_process = \text{Amplification1} \cdot \text{Amplification2} \cdot \text{Amplification3}$$

$$Sensitivity\_process = 0.40 \cdot 6.80 \cdot 1.18 = 3.21\ V/V$$

The meaning of this amplification is that if the voltage in the glow plug changes 1V, the voltage in the output of the circuit will change 3.21, therefore the sensitivity of the circuit is 3.21V/V.

Because the ADC can read values in a range of 5V and the sensitivity of our circuit is 3.21V/V, this means that it can be read a range of 1.56 V (5/3.21) regarding to the glow plug voltage.

3.3 Circuit for current measurement

The other physic variable that has to be measured is the current. The ADC cannot directly measure current, therefore firstly the current has to be converted into a proportional voltage value. For doing this, there are different techniques, which were studied with the purpose of finding the best one for the controller application. In the next section this different techniques are explained.

3.3.1 Shunts

Use the famous Ohm's Law to convert the current through a circuit in a drop voltage. The Ohm's Law says that I=V/R, so by placing a resistance with a known value, the value for the current can be found out indirectly.

By reading this voltage value and then converting this value into current thanks to the relation between voltage, intensity and resistance, the value of the resistance can be known.

Because a resistance is placed in the circuit, the working operation conditions suffer a slightly modification, thus it will be advisable that the resistance value will be as low as possible. And for this reason a shunt can only be placed in a circuit where galvanic isolation is not needed.

The advantage of this technique is that it can measure high current at high frequencies, and using along with an operational amplifier, high precision can be reached taking into account the ADC that is used.

3.3.2 Direct current current-transformer

These sensors work on the principle that when a magnetic core saturates, it loses its inductance. A typical DCCT has an excitation winding wound onto a torroidal core which has enough excitation to just drive it into saturation. A primary conductor is passed through the core. The conductors current will modulate the core saturation which, in turn, will modulate the second harmonic of the excitation current. This is then the monitored output. For mains frequency applications, they can be excited using a sinusoidal main frequency voltage. Figure shows DCCT principle.

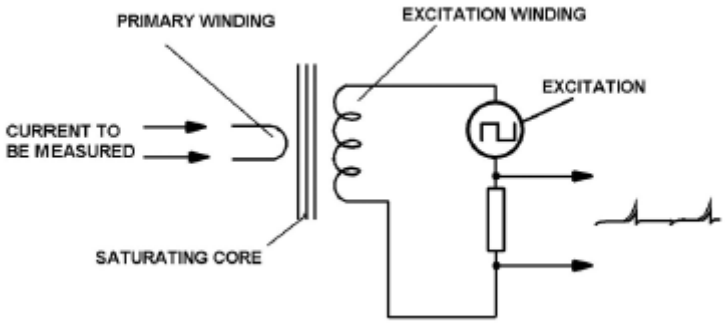


Figure 25: Direct current transformer principle [4]

As the name suggests, DCCTs can measure DC and AC currents with galvanic isolation. The strengths of these devices are simplicity and ruggedness against overload; if an appropriate core material is selected, they are sensitive to low (<20mA) currents; their offset is stable over a wide temperature range; and they offer good immunity to stray magnetic fields. But they don't have very good linearity; their frequency response is low (~500Hz) for a basic unit; they have limited dynamic range of current; and the output may carry excitation noise. A single core design injects noise into the primary circuit.

3.3.3 Open-loop Hall Effect current transducers

These fundamentally simple devices can, with the selection of appropriate components, exhibit admirable performance. There are two distinct families: - units with a magnetic circuit and units without. The latter technology simply uses a magnetic field strength sensor to measure the flux surrounding a current carrying conductor. Figure 26 shows a Hall Effect sensor without magnetic circuit.

This is very simple and generally low cost technology and it is appropriate for some applications. Strong points are simplicity and low cost, providing galvanic isolation for measuring

AC and DC currents; compact design especially when high (~150A) currents are to be measured; reasonable frequency response up to 50 kHz; and good signal to noise ratio for high current sensing.

Weak points i.e. are very sensitive to stray magnetic fields. Even the earth's magnetic field gives a 0.5A error. Stray fields could arise from nearby conductors or contactor coils. Needs to be located very close to the current carrying conductor, this can then lead to insulation and electrostatic screening issues. Controlling the drift of offset voltage with temperature can be quite a challenge. Gain changes with temperature can be an issue.

The gain calibration of the devices will be very loose, as their output is very dependent on conductor position. This means that in-process calibration probably will be required. This technology may be worth a look if it is necessary to measure reasonably high current cheaply and can tolerate imprecision.

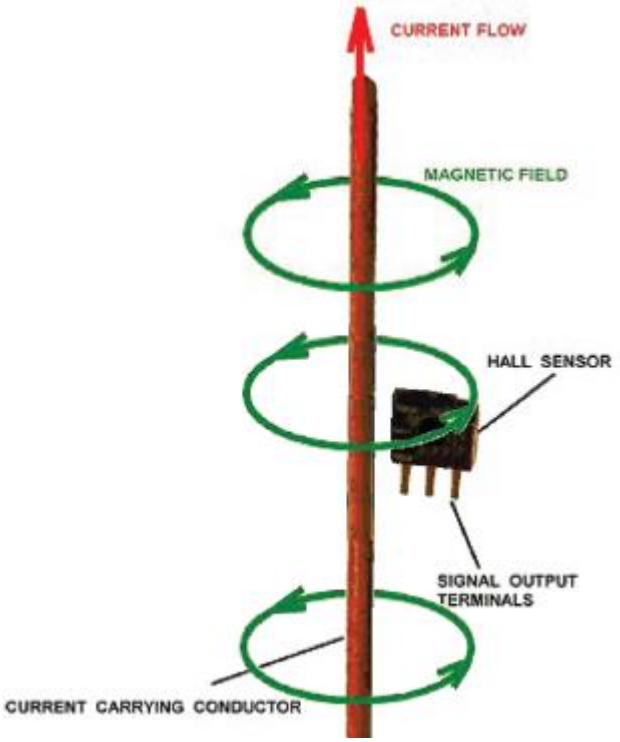


Figure 26: Hall Effect without magnetic circuit [4]

Because precision have a high importance in our measurement, this is not good solution for the circuit.

3.3.4 Closed-loop hall effect current sensors

These sensors work on a principle similar to the open-loop Hall sensors, but include a feedback winding to null the flux in the core (Figure 7). GMR sensors may be used in place of the Hall element. Because of the servo effect, excellent linearity results and gain become very independent of temperature. The feedback coil and associated amplifier does add some cost however.

The strong points i.e. are good DC and AC accuracy over a reasonable dynamic range. Low insertion loss; good frequency response (~100 kHz); reasonable cost if a commitment made to ASICs; good immunity to stray magnetic fields and electric fields with suitable screening.

Weaknesses, in turn, are dynamic range limited in practice by core hysteresis and null drift with temperature; physically larger and costlier than open loop devices. Also, high quiescent current particular when the primary current is high. This makes for self-heating which, in

turn, limits their use to lower ambient temperatures. These factors make them less attractive for automotive applications.

The performance of closed-loop sensors has stabilized, while that of open loop continues to progress with the introduction of new materials and components. There are now few instances where closed-loop sensors are needed rather than their less costly open-loop counterparts.

3.3.5 Selection

Because its simplicity and its characteristics fit perfectly with the demands for the controller circuit, the shunt resistor was chosen.

The shunt resistor that it is used in the circuit is shown in the Figure 27. Its main characteristic is that it can deal with current up to 30 A offering a drop voltage of 75 mV and therefore its resistance value is 2.5mΩ.

According to the normal resistance values of the glow plug during the working, the shunt will generate around 0.3% of the heat that is generated in the glow plug.

Figure 27: HOBUT plate shunt SHR30A75 with a resistance of 0.00025Ω [RS online]

3.3.6 Scheme for the circuit

The idea for this circuit is similar to the idea of the circuit for voltage measurement. During the normal engine working, there will be a current with a value around 10-14A, the goal for this circuit is to convert this range of current into a voltage range of 0 to 5 V. As it was explained before, this is the range where the ADC can convert analog signals into digital signals.

The first step to make this conversion requires to convert the current into a proportional voltage value. For this purpose, the shunt, which was selected before, is used. Due to its small resistance value, the voltage drop in the shunt for this levels of current will be around 25 – 35 mV.

This voltage level is rather small to be read accurately by the ADC, thus an amplification of this signal is required. For doing this an operational amplifier with a non-inverting differential configuration is used. The scheme is shown in Figure 28.

The amplification of the voltage drop in the shunt is around 122, thus in the output of this amplifiers, there will be voltage values within 3.05-4.88V. The next step is to compare this output with a voltage reference. The circuit to generate the voltage reference is almost the same as the one used for the circuit to voltage measurement. A potentiometer is also used to modify the value of the voltage reference and therefore can select the minimum current value that the ADC can read. The scheme for the voltage reference is depicted in Figure 29.

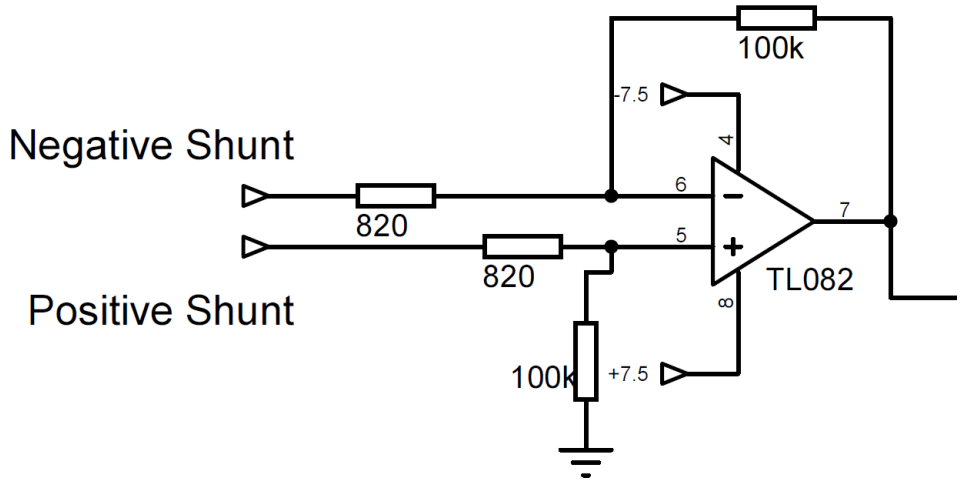


Figure 28: Non-inverted differential amplifier for the amplification of the voltage drop in the shunt

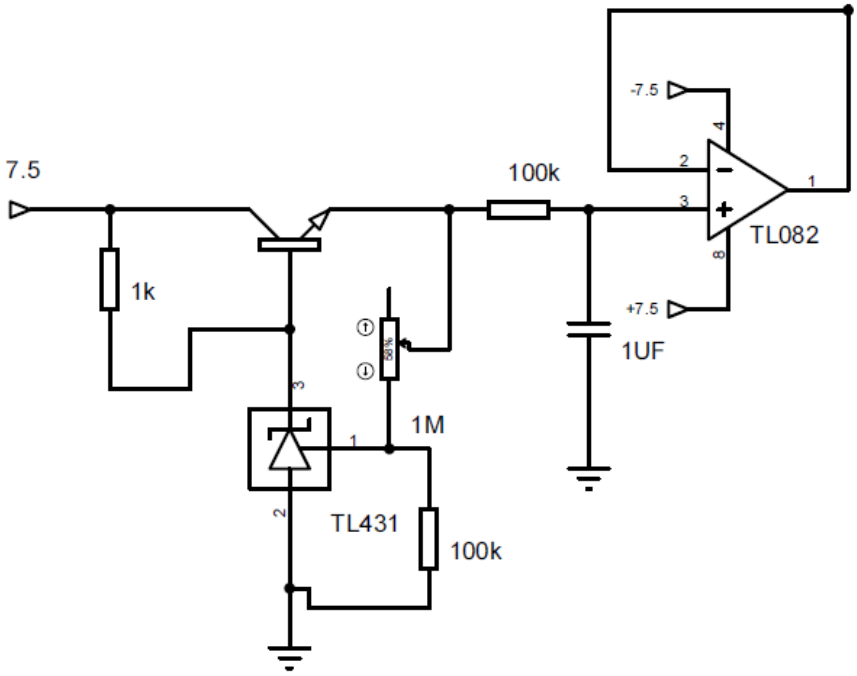


Figure 29: Circuit that generate the voltage reference uses in the circuit for current measurement

Now, these two voltage are compared using also a non-inverting differential amplifier and the output is sent to the precision rectifier. The scheme is shown in Figure 30.

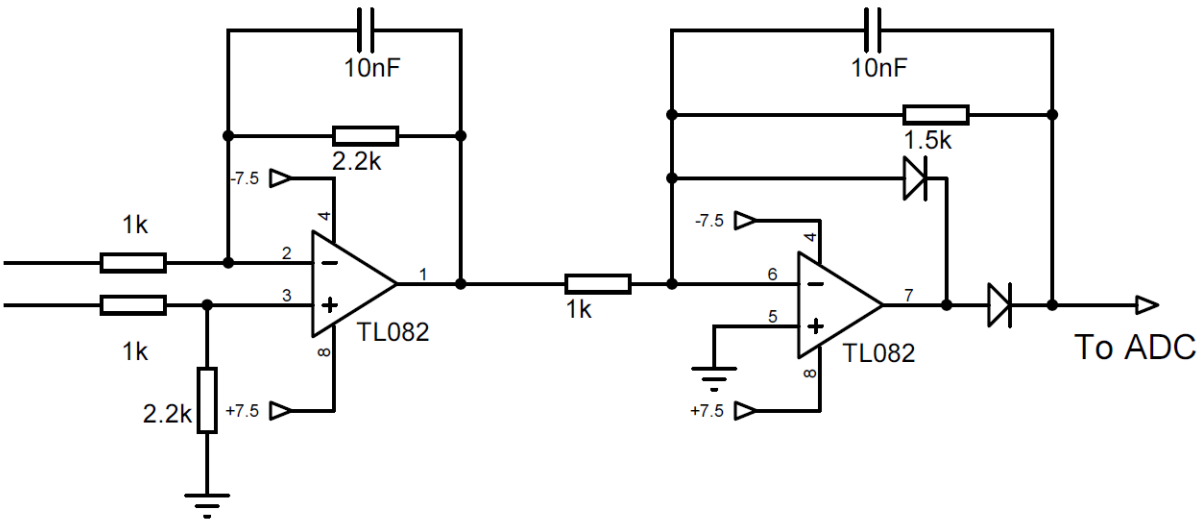


Figure 30: Non-inverter differential amplifier and precision rectifier use in the circuit for voltage measurement

3.3.7 Circuit sensitivity

As it was done in the last circuit, the sensitivity of this circuit is also calculated. In this case, its units are A/V, because it is measured how the voltage output changed compared with the current of the circuit.

For this reason, in this process in addition to the different amplification stage, it has to be taken into account the transformation that happened in the shunt.

The transformation that happened in the shunt is ruled by the value of its resistance, since it is the variable that relates voltage and current. Since the output is current, the sensitivity of the process is the resistance value of the shunt:

$$Sensitivity\_shunt = 0.0025\ V/A$$

For the amplification process, the same configuration as in the last circuit has been used, and its scheme can be seen in Figure 24.

In the first amplification, the values of the resistance are R_1=0.82kΩ and R_2=100 kΩ, giving a constant of amplification of:

$$Sensitivity1 = \frac{R_2}{R_1} = \frac{100}{0.82} = 121.95\ \mathrm{V/V}$$

In the next amplification, the values of the resistance are R_1=1 kΩ and R_2=2.2 kΩ, giving a constant of amplification of:

$$Sensitivity2 = \frac{R_2}{R_1} = \frac{2.2}{1} = 2.20\ \mathrm{V/V}$$

And in the last amplification, the values of the resistance are R_1=1 kΩ and R_2=1.5 kΩ, giving a constant of amplification of:

$$Sensitivity\ 3 = \frac{R_2}{R_1} = \frac{1.5}{1} = 1.50\ \mathrm{V/V}$$

Putting the different amplification stages together, the amplification for the overall circuit is obtained. This amplification is:

$$\boldsymbol{Senstitivity\_process} = \boldsymbol{Sensitivity\_shunt} \cdot \mathrm{Sensitivity1} \cdot \mathrm{Sensitivity2} \cdot \mathrm{Sensitivity3}$$

$$Sensitivity\_process = 0.0025 \cdot 121.95 \cdot 2.2 \cdot 1.5 = 1.01\, V/A$$

In this case, because the sensitivity of the process is 1.01V/A and the range of the ADC is 5V, the range of current that the ADC will read will be 4.95A (5/1.01).

As it can be seen the values of the resistance have been selected, to reach this range, which was the objective when the circuit started to be built

3.4 Digital Switch circuit

Since a power supply with a constant voltage is used, in order to regulate the power consumption in the glow plug, the circuit is opened and closed successively.

For doing that, a switch between the glow plug and the power supply is placed. This switch is controlled by a PWM signal that is sent by the microcontroller. A PWM signal is a signal with two different voltage levels and a typical frequency. These levels are called on and off level and the time that the signal remain in each level can be easily regulated by modifying their duty cycle. The duty cycle describes the portion of time in "on" level regarding the signal period and is expressed in percentages. An example of duty cycle is depicted in Figure 31.

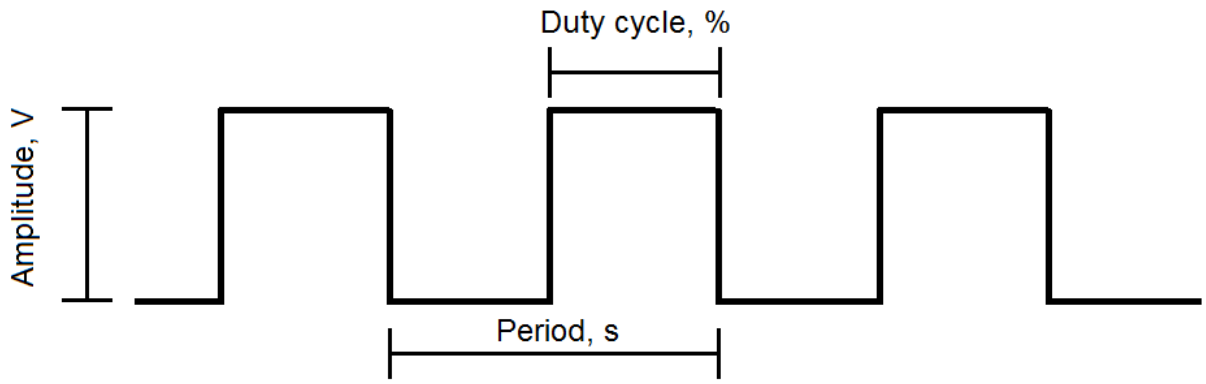


Figure 31: Example of a PWM signal with its main characteristic

For the digital switch, there are several possibilities. Because the frequency that is required for the application is more than 100 Hz, electromechanical switches were ruled out. The most reasonable choice, due to the frequency of the application, is a solid state device.

For a solid state device, there are also different possibilities, such as a bipolar transistor, Mosfet transistor and solid-state relay. Generally bipolar transistors are used for application where the current levels are lower than 1A, so this option cannot be used for this application, whereas a Mosfet, due to its low $R_{DS(on)}$, can work with high current values. A normal Mosfet

can easily deal with current of 15 Amperes. Since the current for our application will be always lower than this value, this device was selected.

A Mosfet is a transistor that has three terminal; gate (G), source (S) and drain (D). It is controlled by a voltage that is applied to the gate terminal. When the voltage, which is applied to the gate, is bigger than a certain value, the device turns on and current can flow between source and drain. This value of current is usually bigger than 8 V. In Figure 32, a scheme for an N-channel Mosfet, as the use for the application, is depicted.

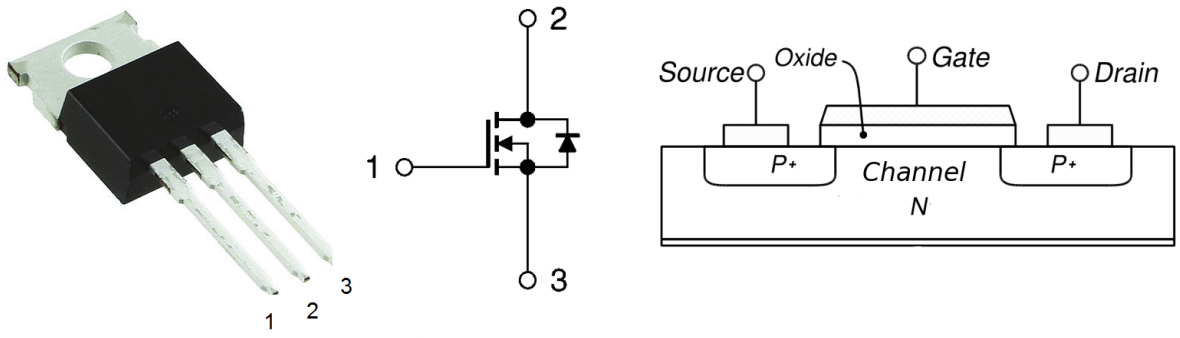


Figure 32: Scheme for an N-Chanel Mosfet

The problem for operating with the Mosfet is that Arduino PWM signal levels is 0 and 5V, therefore, it is not enough for turning on the Mosfet. For this reason, a circuit that will amplify the PWM signal is required. The objective of this circuit is to increase the voltage level of 5V to at least a value that allows the transistor to be turned on and off.

For doing that a circuit that connects Arduino PWM signal with the gate terminal of the Mosfet is used. This circuit is depicted in Figure 33.

In the circuit bipolar transistors are used. In this case, they are perfect for the application, since the current flowing through them will be relatively low. The bipolar transistors are controlled by current, and Arduino can provide enough current to control them. Furthermore, the time for the switch on and off process is quite small. For all these reasons, they are the perfect device to build up this circuit.

The circuit works in this way: the first transistor is connected to Arduino through its base terminal, when Arduino is sending a high level, there will be current flowing from the base to the emitter of the transistor and the transistor thus will be on. When there is a low level in Arduino, the output of the transistor will be off.

As it can be seen in the figure, if the first transistor is on, the base of the next stage of transistor will be connected to the ground whereas if the transistor is off, it will be connected to 12V through the resistor 220Ω. In this next stage, when the base is connected to the 12 V, the NPN transistor will be on and subsequently the gate of the Mosfet will be connected to 12V, meanwhile when the base is connected to the ground the PNP transistor will be on, connecting the gate of the Mosfet to the ground.

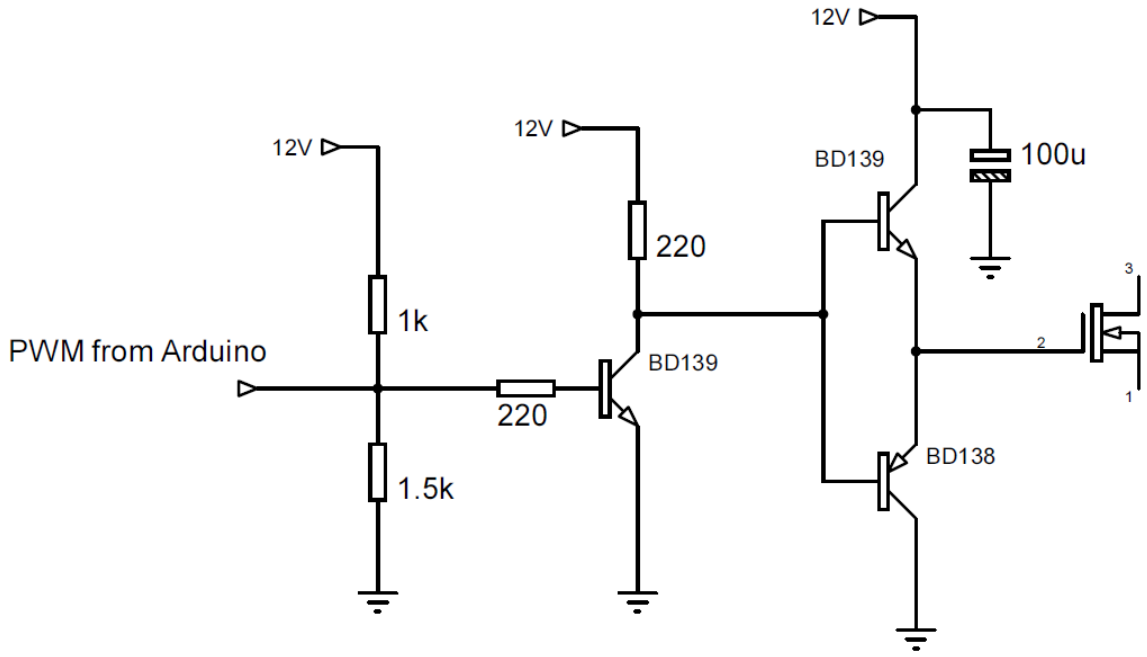


Figure 33: Circuit used to amplify the PWM signal from Arduino

Summarising how this circuit works, the gate of the Mosfet will be connected to 12V if Arduino is sending a low level, whereas the Mosfet will be connected to ground if Arduino is sending a high value. Due to that, the duty cycle that is programmed in the Arduino has an inverse effect in the Mosfet; as the duty cycle decreases the power consumption in the main circuit gets bigger.

Two stages of amplification are used due to the switch on process of the Mosfet. In this process a not intended capacitor that is formed in the gate of the Mosfet must be filled, for this reason, the bigger the current value, the lower the time that is necessary. Using two stages of amplification, it makes sure that the transistor does not limit the current than flows to the gate terminal of the Mosfet.

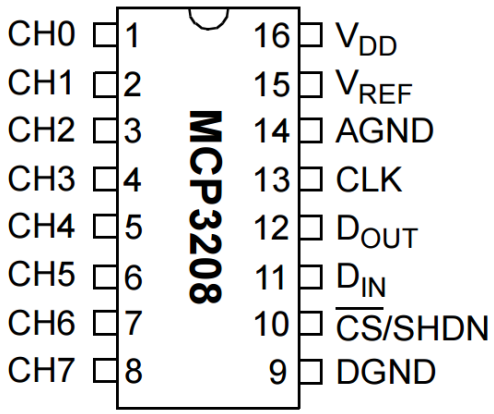
4 Components

4.1 Analog-to-digital converter (ADC)

Although, the microcontroller that is used in Arduino board has an internal ADC, an external ADC was used. Since internal ADCs are placed so close to digital signals, these signals can introduce additional noise. Therefore, the use of an internal ADC is not advisable, when a good resolution is required for the application.

For this reason, the use of the internal ADC of Arduino was ruled out. Furthermore, the results using the engine model of Simulink, showed that working with a resolution of 10 bits, has a small influence in the control process, and this influence almost disappeared when the resolution was at least 12 bits. Bearing these two aspects in mind, an external ADC with at least 12 bits resolution was desirable.

The ADC that was chosen for the controller was the MCP3208 manufactured by Microchip. It is a Successive approximation ADC with 12 bits resolution. It has 8 input channels, which allow the device to work either with a pseudo-differential or a single-ended input. The Figure 34 shows the pin configuration of the ADC.



Name	Function
V_{DD}	+2.7V to 5.5V Power Supply
DGND	Digital Ground
AGND	Analog Ground
CH0-CH7	Analog Inputs
CLK	Serial Clock
D_{IN}	Serial Data In
D_{OUT}	Serial Data Out
$\overline{CS}$/SHDN	Chip Select/Shutdown Input
V_{REF}	Reference Voltage Input

Figure 34: ADC MCP3208 pin configuration [Datasheet]

The MCP3208 can operate over a broad voltage range (2.7 to 5.5 Voltage). When this voltage is 5V, the maximum sample rate is 100 ksps whereas with a voltage of 2.7 is 50 ksps. For this reason, it will be used 5 V as power supply.

Regarding to the ADC architecture, a successive approximation (SAR) ADC use a circuit called sample-and-hold (SHA) to save and keep the signal constant during the conversion cycle. This voltage value is successively compared with the DAC using a comparator, which determines whether the SHA output is bigger or not than the DAC output and sends the results to the successive-approximation register (SAR) as 0 to 1. This process is made as many times as bits of resolution have the ADC, in a process of comparison to determine with the minimum of operation the voltage of the sample taken. In Figure 35 a scheme of the architecture of a successive approximation ADC is shown.

The process of conversion can be divided in two process, the first corresponds to the process of storing the value in the SHA circuit. The component that is used for this purpose is frequently a capacitor, thus enough time to store the value is required, and this time is called T_{sample}. The second process is the comparison process, which requires one cycle of clock for each bit of conversion. These two processes together give the conversion time that is usually given in the components datasheet in unit of clock cycle. Thus the sampling rate will depend on the frequency of the clock signal and on the times that are required to complete the reading process.

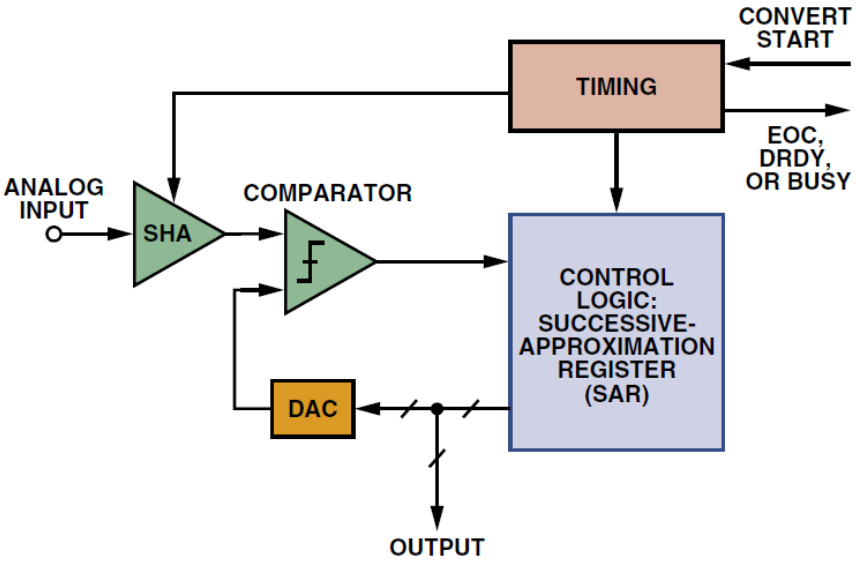


Figure 35: Architecture for successive-approximation ADC [6]

Related with the communication of the ADC with the microcontroller or with other devices, most of the SAR ADCs use a serial interface. In the case of the MCP3208, this communication is done using the Serial Peripheral Interface (SPI) bus.

The SPI bus is a synchronous serial communication interface used for short distance communication. SPI devices communicate in full duplex mode using a master-slave architecture with a single master. The master device originates the frame for reading and writing.

It is a four-wire synchronous serial communication protocol. This four logic signal are:

- SCLK, it is the clock signal and is sent from the bus master to all slaves.4
- SS, it is the slave select signal, used to select the slave the master communicates with;
- MOSI, it is the data line from the master to the slaves.
- MISO, it is the data line from the master.

A diagram for a SPI communication is depicted in Figure 36. In this case the master establishes communication with three devices. The communication can only be done between master and slave, never between slaves. And the master can only communicate at the same time with a slave.

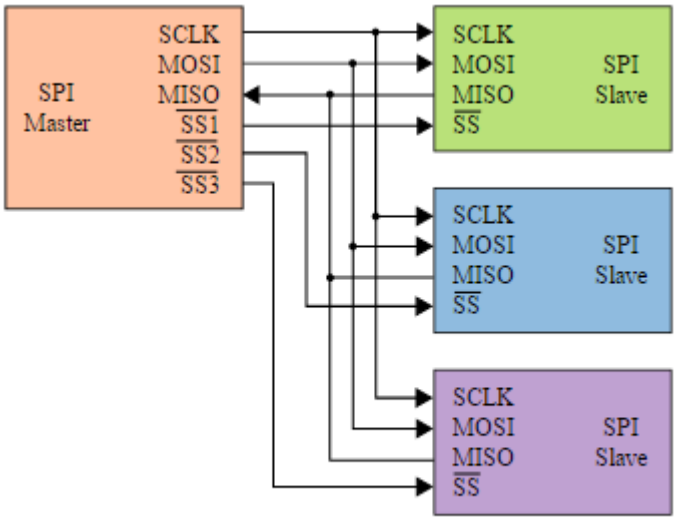


Figure 36: Diagram for a SPI communication between a single master and multiple slaves [5]

The SPI communication between MCP3208 with the microcontroller, it requires to send group of eight bits, also called byte. And the total number of bytes used to complete the communication are three. The sequence of these 3 bytes is shown in Figure 37. As it can be seen in the figure, the communication is initiated bringing the $\overline{CS}$ line low, the first and second bytes of the D_{in} line contain the Start information and the information related with the selection of the kind of reading and the input where the value will be taken form. The second and third bytes of the line D_{out}, contain the digital value of the sample voltage.

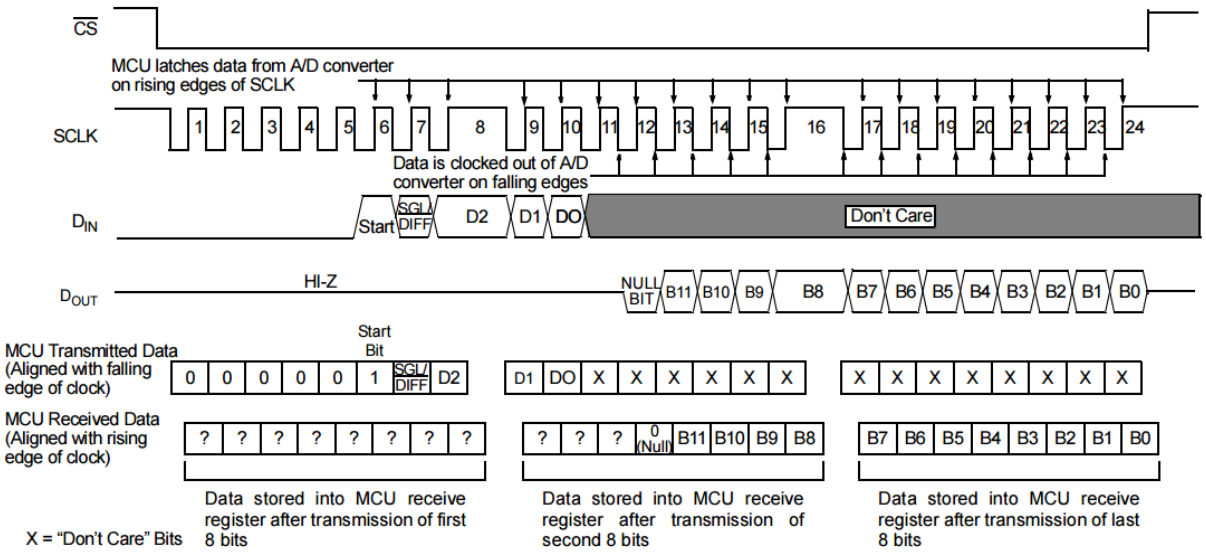


Figure 37: SPI communication between MCP3208 ADC and Microcontroller

4.2 Liquid crystal display

A LCD is an electronic visual display that uses the light-modulating properties of liquid crystals. They are prefect to display words or digits or even images with a low information content.

For the controller application, the LCD will be used to show the controller menu as well as some data information such as resistance, voltage and current values. Since the glow plug will be inside the engine, and it cannot been seen from the outside, the LCD give a quick and easy way to visualize what it is happening in the glow plug during the engine working.

For the communication with the microcontroller, the LCD comes along with an I2C module. This module allows the communication between the Arduino and the LCD display by using the inter-integrate-circuit (I2C) bus. It is a serial, half duplex bus that uses two bidirectional open-drain lines: Serial Data Line (SDA) and Serial Clock Line (SCL). The scheme for an I2C communication is shown in Figure 39.

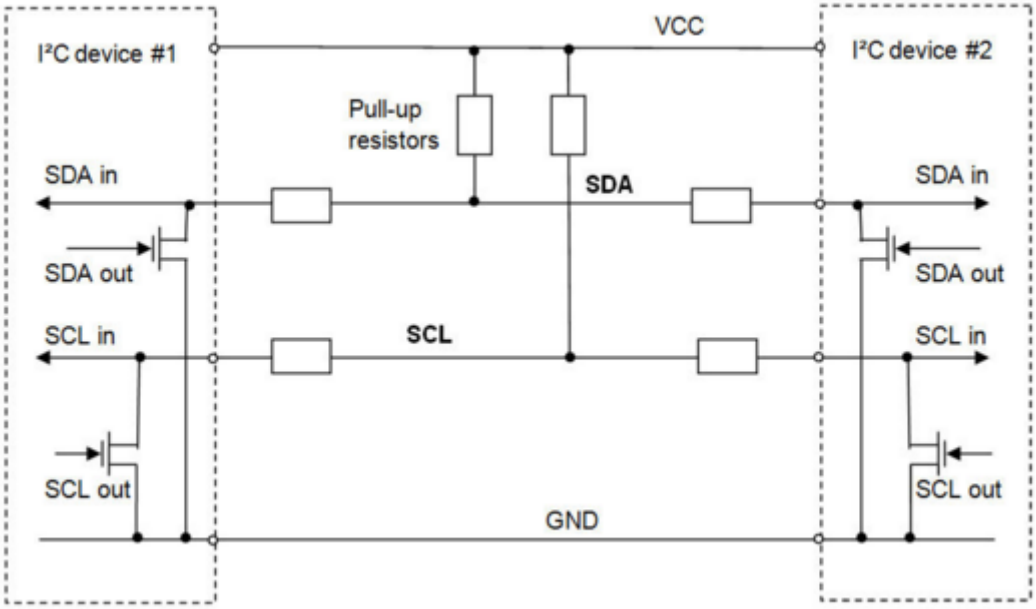


Figure 38: Scheme for a communication using I2C interface

The output is configured as an open collector; therefore, it has to be connected to Vcc using a resistor, this combination is called pull up resistor. This configuration allows all the devices to generate the same logic signal voltage level, enabling the communication between devices with CMOs technology and TTL technology.

The communication is governed by a protocol. This communication always start with a START condition that is received by all the slaves. Then the master sends the ADDRESS along with the information of what kind of communication is wanted (Read or Written communication).The address should fit one of the slaves addresses, starting the communication with it after this generates a response called ACKNOWLEDGE signal. Now one of the device send the data, depending on the kind of communication previously selected, and when it is over, the master generates the STOP condition.

4.3 Push button

In order to scrolling through the program menu, push button are used. Each button is connected in one of its terminal to one analog input of Arduino. The other terminal is connected to the 5V supply of Arduino. Also a pull down is used to make sure that the analogue input will receive a 0V signal when the button is not pushed. In Figure 39, the connection is shown.

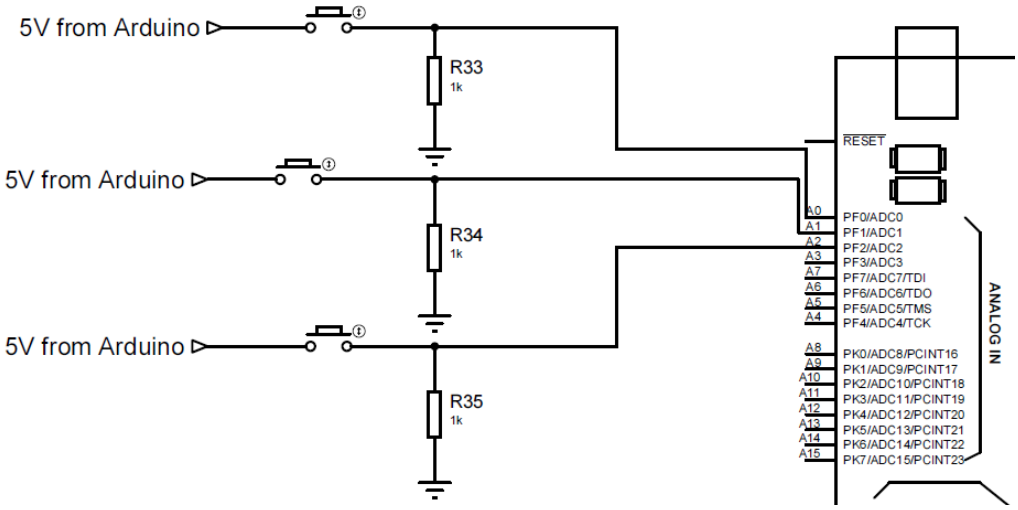


Figure 39: Diagram for the connexion of the button with the respective analog input

In this way, when the button is pushed, the input will be high and during the rest of the time the input will be low. With these buttons, it can be selected what data the display will show and changed the set point of the glow plug.

4.4 Precision programmable reference

The device that was selected to generate the voltage reference was the TL431, manufactured By Texas Instruments. It can generate a voltage reference from2.5 V to 36 V depending on the external resistor. Its basic scheme is depicted in Figure 40.

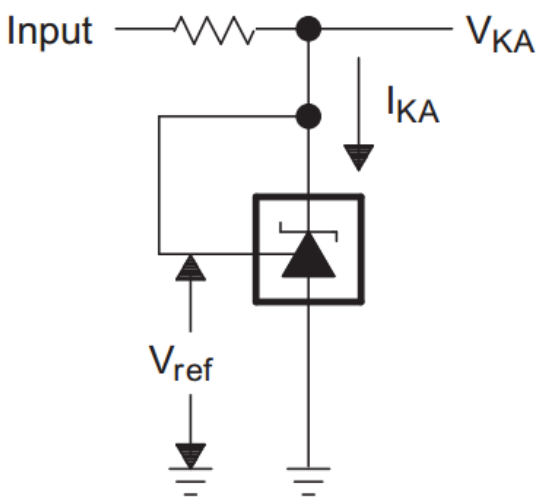


Figure 40: TL431 Precision Programmable Reference

In this scheme the voltage reference is set using two external resistors. In the application another configuration is used in order to get a better stability, as it was explained before. A remarkable characteristic is its low output drift versus temperature, which ensures good stability over the entire temperature range (-40ºC to 125ºC).

4.5 Operational amplifier

It is the main component for both circuit: current measurement and voltage measurement. The operational amplifiers that was used is TL082, manufactured by STNicroelectronics. It is a dual supply amplifier that requires a negative and positive supply for its working. The package for the transistor along with its pin configuration is depicted in Figure 41.

As it can be seen in the picture, in the same package there are two operational amplifiers. The power supply for both of them is the same. Some interesting absolute maximum ratings that must be known are; its maximum voltage supply is ±18 V, its input voltage is ±15 V. The values for our application keep much lower than these restrictive values, therefore the device is able to work in the circuit without getting damaged.

Some of its most remarkable characteristic are: low input bias and offset current, output short-circuit protection, high input impedance J-Fet input stage, internal frequency compensation and high slew rate 16 V/µs.

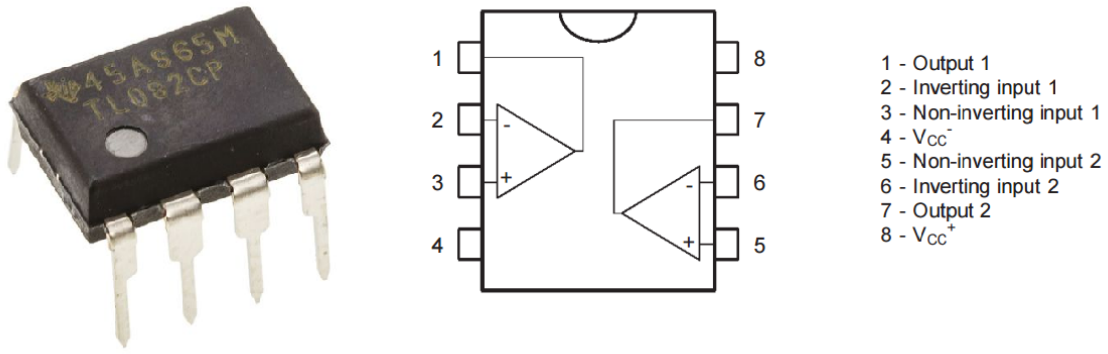


Figure 41: Package and pin configuration for the operational amplifier TL082 [Datasheet TL082]

Other different models of operation amplifier were tested, but it was the TL082, the one that showed the best result. This result will be shown in the section of practical testing.

4.6 Noise considerations for the circuit design

The quality of the reading processes might depend mostly on the level of noise in the signal that is sent to the ADC from the circuits for current and voltage measurement. For this reason, the noise level has to be reduced to the minimum possible level, before being sent to ADC. The first aspect to bear in mind, is the layout for the circuit.

In the datasheet of the ADC, some tips regarding the layout are given. When laying out circuit board to be used with analog components, care should be taken to reduce noise wherever possible. Digital and analog traces should be separated as much as possible on the board, with no traces running underneath the device or the bypass capacitor. Extra precaution should be taken to keep traces with high frequency signals as far as possible from analog traces. In Figure 42, an example of a correct layout is shown.

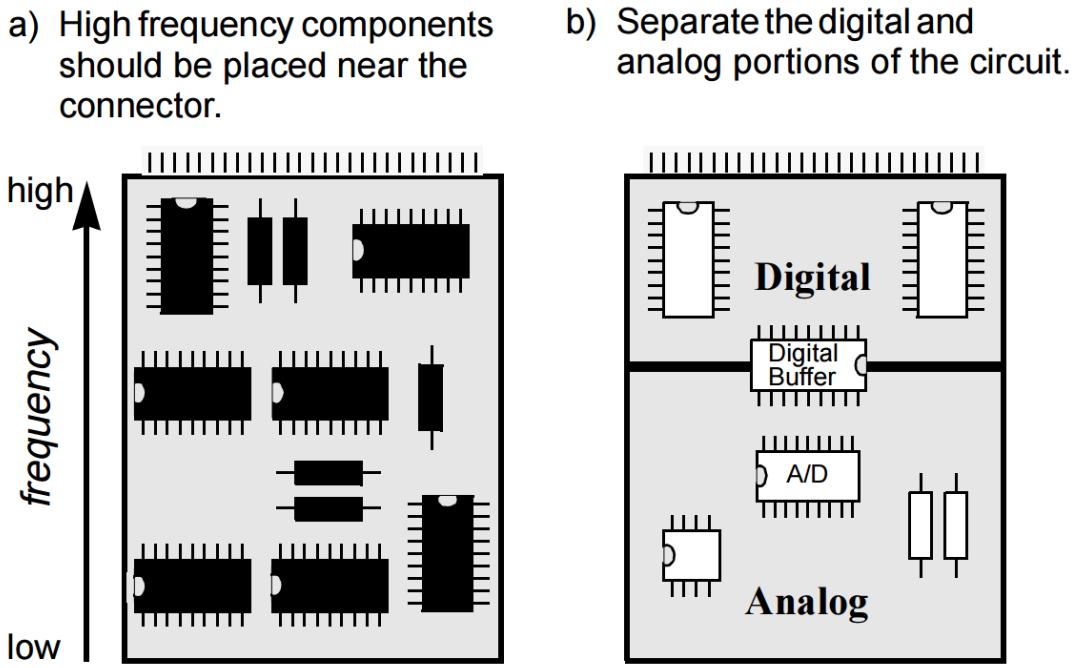


Figure 42: Example of a good layout in a board where there are digital and analog signal together [10]

Furthermore, the datasheet also recommends the use of an analog ground plane in order to keep the ground potential the same for all the devices of the board.

The next step to reduce noise is to design analogue filters. An analog filter is a device that removes from a signal some unwanted components or features. In this case, it wants eliminate these signals whose frequency is not similar to the frequency of the system.

The filters that are used for this application are Low-pass filters. A low-pass filter passes signals with a frequency lower than a certain cut-off frequency and attenuates signals with frequencies higher than the cut-off frequency. The amount of attenuation for each frequency depends on the filter design. In this project, the values for the capacitor and the resistance determine this cut-off frequency. In Figure 43, the Bode plot of a Low-pass filter is depicted, whose cut-off frequency is 1000.

As it can be seen in the figure, the attenuation happens gradually from one specific value of frequency. The cut-off frequency is defined as the value where the attenuation is -3 dB.

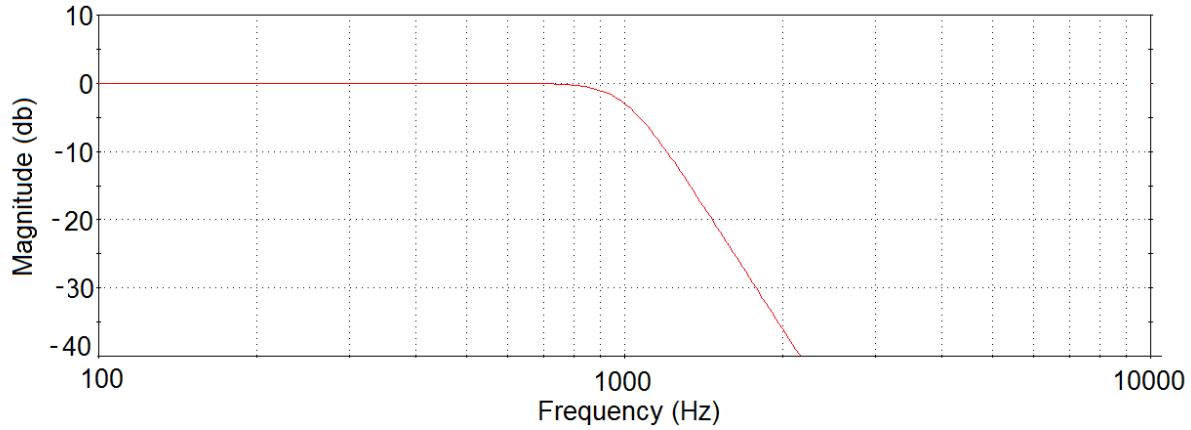


Figure 43: Low-past filter with a cut-off frequency of 1000 Hz

In the design of a filter, the signal attenuation is not the only aspect that must be taken into account. By placing filters, the response of the circuit is also modified, making its speed response slower. For this reason, the filters design requires special attention.

During the filters design, the response was checked with the help of the oscilloscope for the purpose of getting a trade-off between the speed response and the noise reduction.

5 Practical Testing

Before the construction of the final circuit, several tests and changes were made. No desirable behaviour and dangerous situations for the different devices were corrected and avoided.

All electronic circuits are designed to work in specific working conditions. Nevertheless, not desirable condition can happen. This anomalous behaviour can exceed some of the absolute maximum rating values of the components and thus, they will be destroyed. To avoid this to happen, circuit protections are used. The purpose of these circuits is not to change the normal circuit working, they will work only under these anomalous situations.

When there are reading processes of a physical variable, a common problem is the noise that can be placed in their analogue signal. This noise is caused either by components of the same circuit or by external devices. To avoid this to happen, special attention in the design of the circuit layout has to be paid. Furthermore, it can be reduced by using analog filters.

Owing to the use of electronic devices, another problem to be taken into account is their time response delay. Furthermore, the use of filters increases the time circuit response. Since the glow plug is working in a quick changed environment, the time response of the circuit has to be relatively low. This response has to be kept much lower than the system frequency.

In the next section, it will be explained further different changes and tests that were made in order to correct these working problems. Finally, it is described the improvement process of circuit response.

5.1 Digital Switch circuit

As it was explained before, for this circuit a Mosfet along with a previous circuit transistor are used.

Since this circuit only differences between high and low voltage values, the noise is not an important problem. Nevertheless, because it has to turn on and off the main circuit, its time response has a particular importance.

The time response for bipolar transistor is much faster than the Mosfet time response. Therefore, it will be the time response of the Mosfet that determines mostly the overall time response for this circuit.

To know how a Mosfet responds, the datasheet provides information. This information is generally given in 4 times that describe the Mosfet behaviour accurately. These four times are:

- T_{on_delay}; It is the time taken by the Mosfet to start turning on.
- T_{off_delay}; It is the time taken by the Mosfet to start turning off.
- T_{fall}; It is the time taken by the Mosfet to change from on to on.
- T_{rise}; It is the time taken by the Mosfet to change from off to off.

In Figure 44, these four time be visualized. In the picture it is represented the response of a Mosfet when a voltage change in its gate terminal happens. The low level can completely turn off the Mosfet, whereas the high level can turn it on.

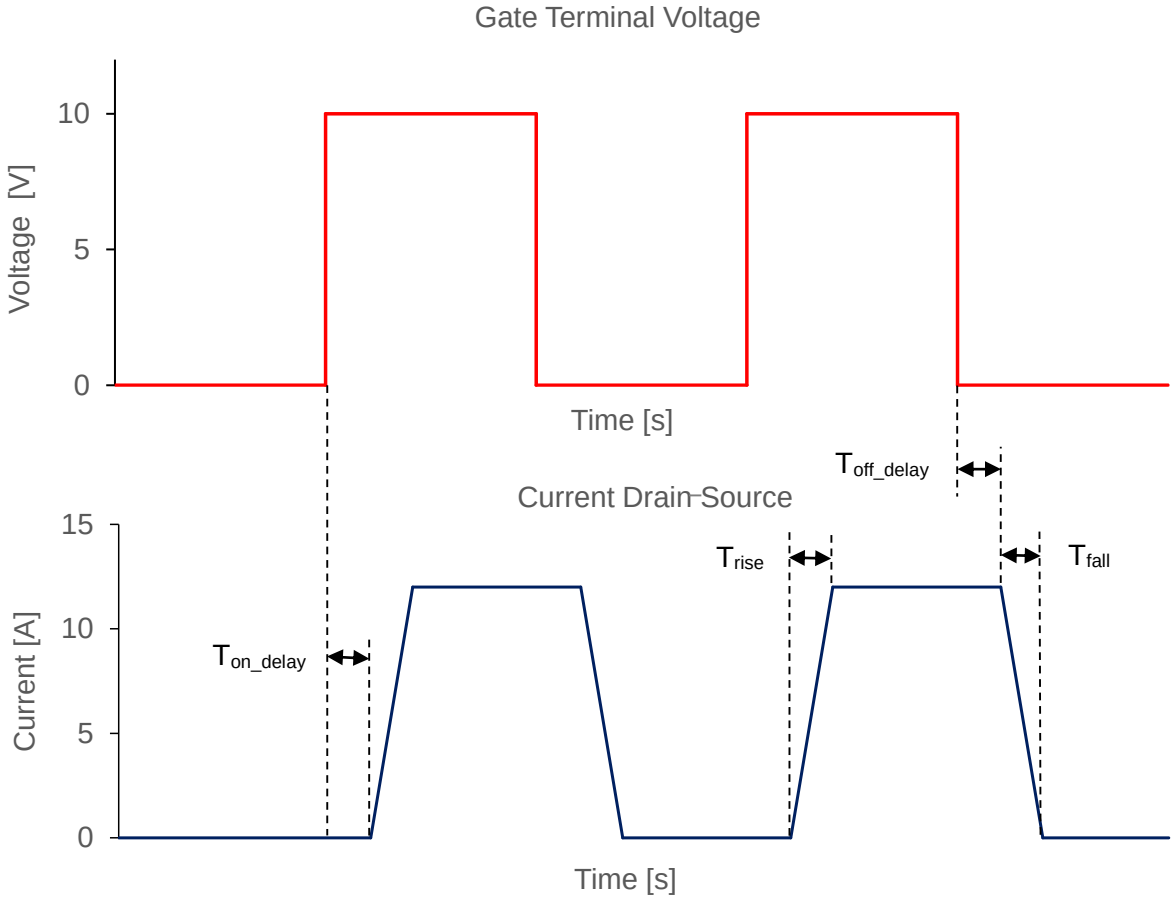


Figure 44: Typical Time response for a Mosfet transistor

In addition to checking the parameters that the datasheet includes, the real response of the transistor along with the circuit that connects it with the Arduino PWM output was checked. For the tests, two different Mosfets were used and compared. In the next photos, the responses

of the Mosfets can be seen, and the time response can be analysed. The response when the Mosfets are switching off can be seen in Figure 45 and Figure 46, while in Figure 47 and Figure 48 the response when they are switching on.

The Mosfets that were used were the IRFZ44N, manufactured by International Rectifier and the TK42E12N1 manufactured by Toshiba. Both of them can deal with current bigger than 40A, therefore they can be perfectly used for the application.

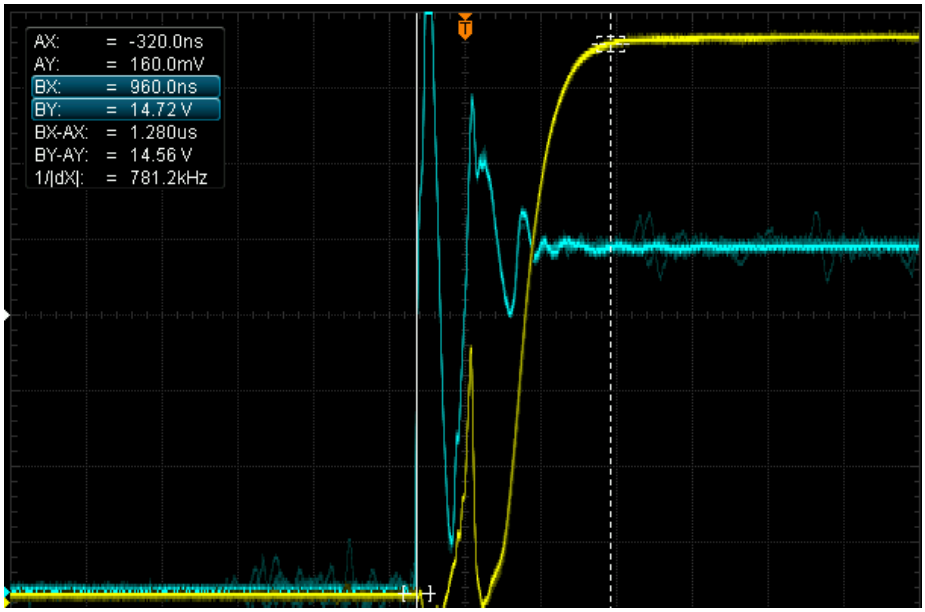


Figure 45: IRFZ Mosfet switching off

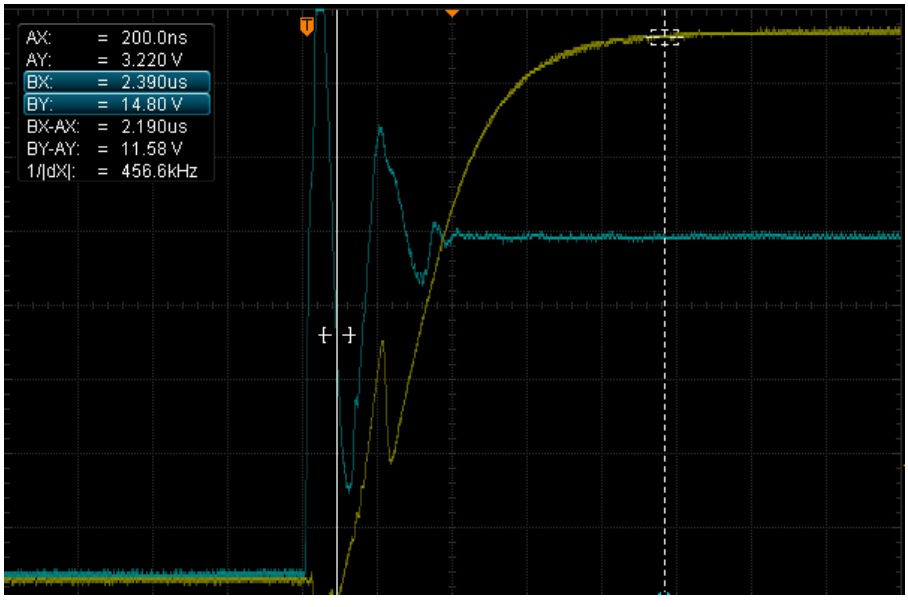


Figure 46: Toshiba Mosfet switching on

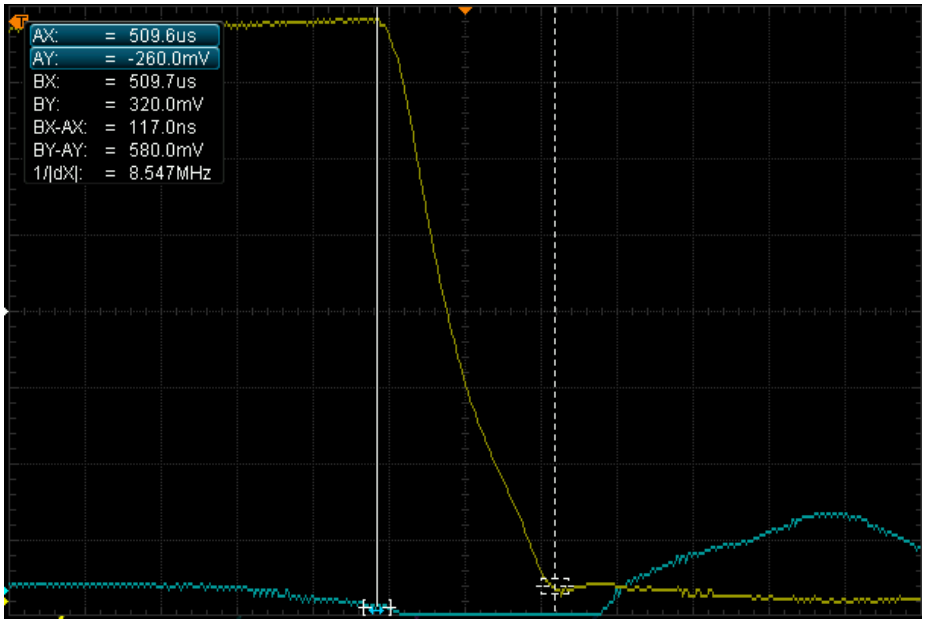


Figure 47: IRFZ Mosfet switching off

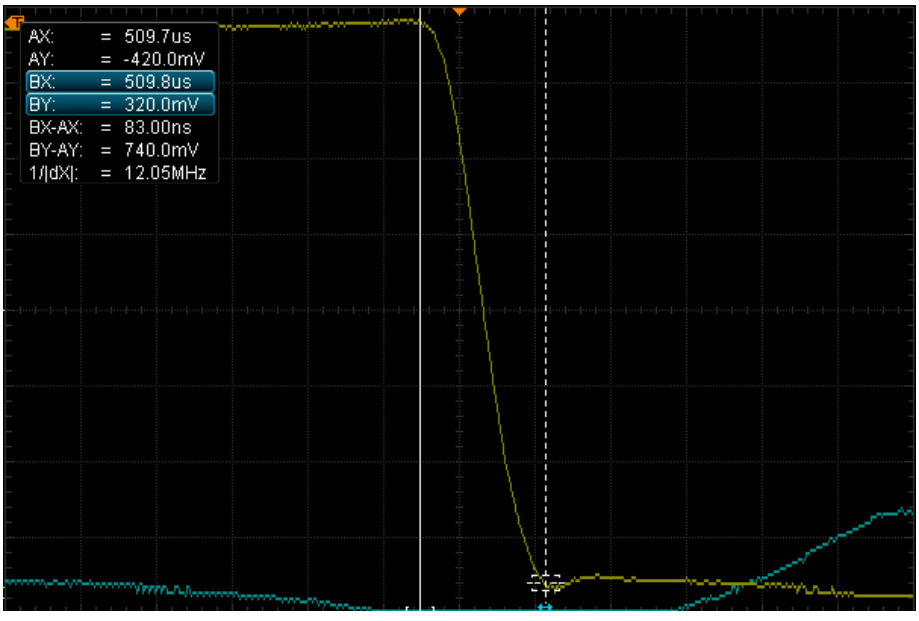


Figure 48: Toshiba Mosfet switching on

Analysing the results, the response of IRFZ Mosfet is faster than the one of Toshiba Mosfet in the switch off process, whilst in the switch on process the response of Toshiba Mosfet is faster.

Since there is not a big different between both Mosfets and the price of the Toshiba Mosfet is much lower, the Toshiba Mosfet was selected.

Initially the circuit does not have the pair of resistances that work as a pull-up resistor. Due to that, one Mosfet got damaged. When the Mosfet was connected to the power supply and glow plug through its source and drain terminal, and Arduino was not sending any PWM signals, there was current flowing through the main circuit. This unexpected behaviour happened because the voltage in the gate was bigger than the voltage in the source, and this made the Mosfet to conduct. But because this voltage difference was not big enough, the Mosfet was in the ohm region and therefore its resistance was much bigger than $R_{DS(ON)}$. As a result, a big amount of heat was generated in Mosfet, ending up in its destruction.

In Figure 49 it is shown how the Mosfet regulates the current depending on its V_{DS}. When the Mosfet has a temperature of 25 C and the voltage Gate is 4.5 V, the current that can flow through it is lower than 10 amperes, and this current becomes lower as the gate voltage decreases. For this reason, and because in the real application there will be a current bigger than 10A, this situation must be avoided.

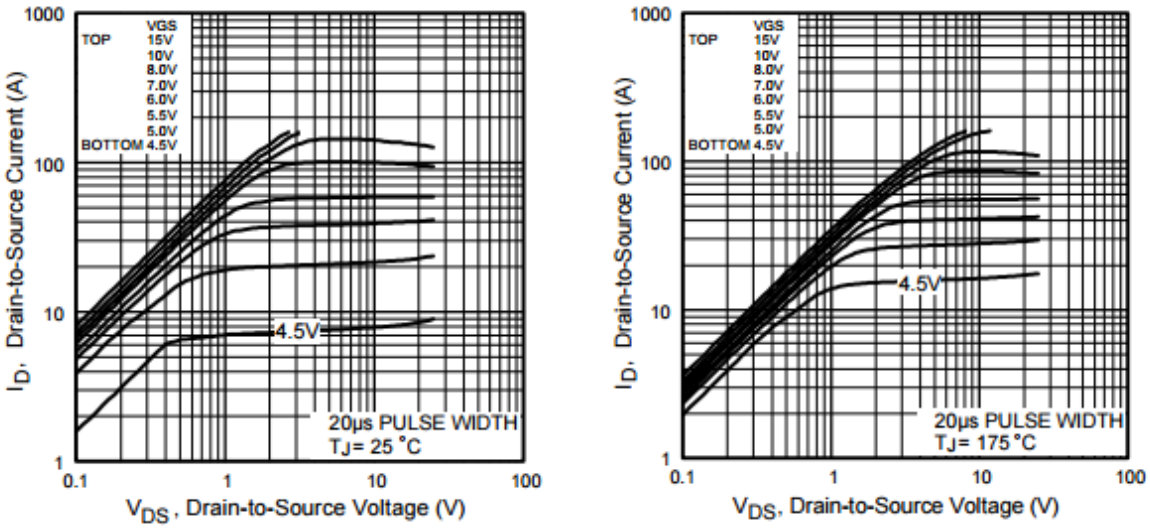


Figure 49: Drain-to-Source Voltage versus Drain-to-Source Current for the Mosfet IRF44N [Datasheet]

To avoid that to happen, a pull-up resistor was set between the signal PWM, and the positive terminal of the power supply. In this way, when there is no PWM signal, the Mosfet will be closed.

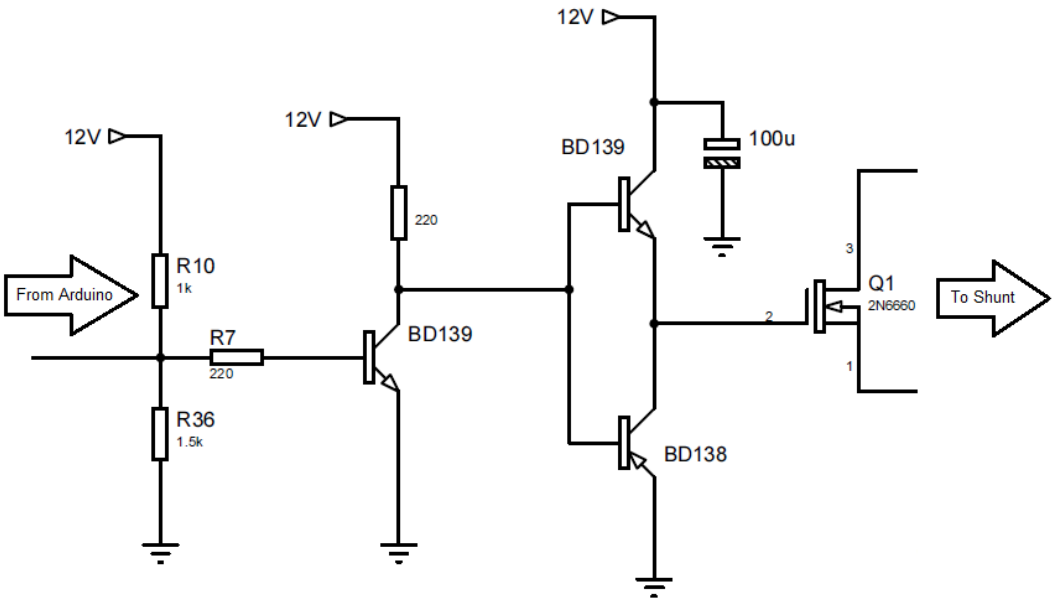


Figure 50: Final design for the PWM signal amplifier using pull up resistor

The two resistances R36 and R10 ensure that when there is no signal coming from Arduino the first transistor will be on and therefore the Mosfet will be off.

5.2 Problem with the computer adapter

This was a problem that affected the circuits for current and voltage measurement. When these circuits were firstly tested, a big level of noise with no apparent cause appeared in their outputs. All the considerations, which were explained in section of 4.6, were taken into account. Although the level of noise kept almost with the same value.

The level of noise made the control process unable, since the oscillation of the reading values gave as a result a resistance oscillation bigger than the maximum permitted. This noise can be seen in Figure 51, where the output of the circuit for the current measurement is depicted.

As it can be seen, the noise is around 200mV. Due to the sensitive of the processes, this means a noise in the voltage calculation of 0.062 V and a noise in the current calculation of 0.198 A.

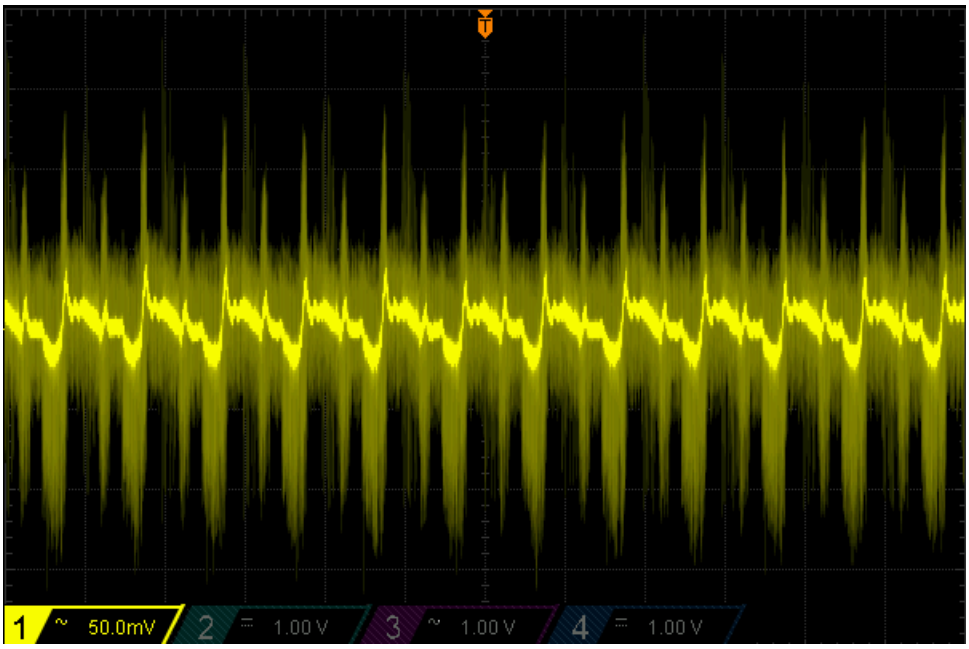


Figure 51: Noise in the circuit of current measurement when computer adapter is working

In order to reduce the noise level, besides the techniques explained before, different kinds of amplifiers were used, until the real cause of the problem was found.

In one of the countless tests, the real problem was discovered. In some way, the computer adapter was generating this amount of noise in the signal. When the computer adapter was not working, the noise was considerably reduced. In Figure 52 it is depicted the output signal of the circuit measurement when the adapter is not used.

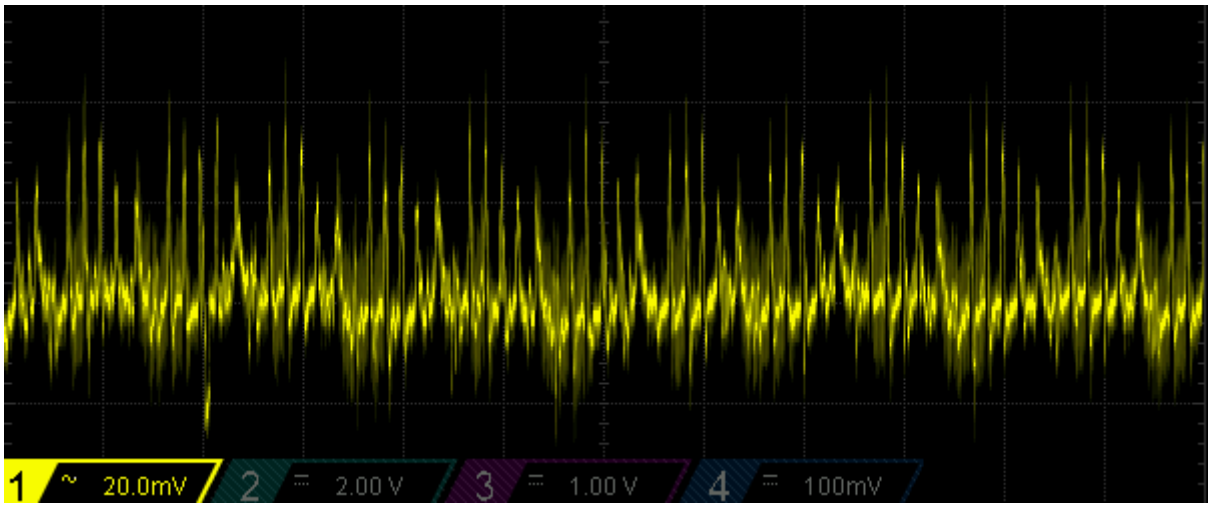


Figure 52: Noise in the output of circuit for current measurement when the computer adapter was not working

The noise level is around 50 mV when the adapter is not used. It must be noted, that all the noise is not due to the circuit as voltage supply also has an internal noise. Anyhow, when the adapter is not used the noise is reduced 4 times.

5.3 Circuits for current and voltage measurement

These two circuits are explained together since both of them shared the same problems and thus the same solutions were applied. The components that are used for both circuits are the same and their circuit schemes are highly similar.

The big problem, which was faced with these circuits, was related with the noise in their outputs. This problem was explained in the previous section, where it is clarified that it was a problem due to the computer adapter.

Trying to solve this problem, different kinds of amplifiers were tested as well as their different configurations. In this section the results for the different tests are shown, as well as it is justified the final selection.

Depending in the power supply that is used, the operational amplifiers are divided into single-supply and dual supply. The schemes for both configurations are shown in Figure 53.

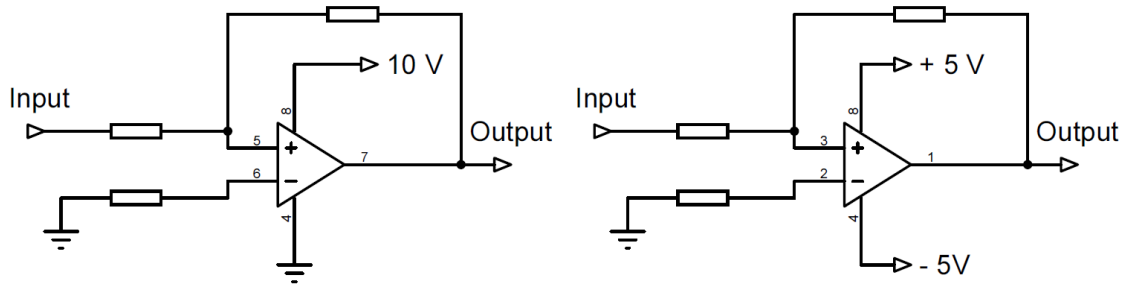


Figure 53: Comparison between single supply op amp (Left) and dual supply op amp (right)

When op amps are powered from dual supplies, see figure above, the supplies are normally equal in magnitude, opposing in polarity, and the centre tap of the supplies is connected to ground.

Meanwhile when op amps are powered from single supply, its negative terminal is connected to the ground of the circuit. It can be used one or another configuration for power supply, depending on the amplifier to be used. There are op amps that can operate for both cases.

For the circuit, both configurations were tested, selecting one of them. The TL082 op amp for working was used to work with dual supply whereas the LM 358 for single supply. This last op amp can be used with both supply configurations but it is advisable to work with single supply, since it was optimized for this working condition.

In the tests, the time response to a step input as well as the noise level were studied. In Figure 54 and Figure 55, the responses to a positive step input using both amplifiers are depicted.

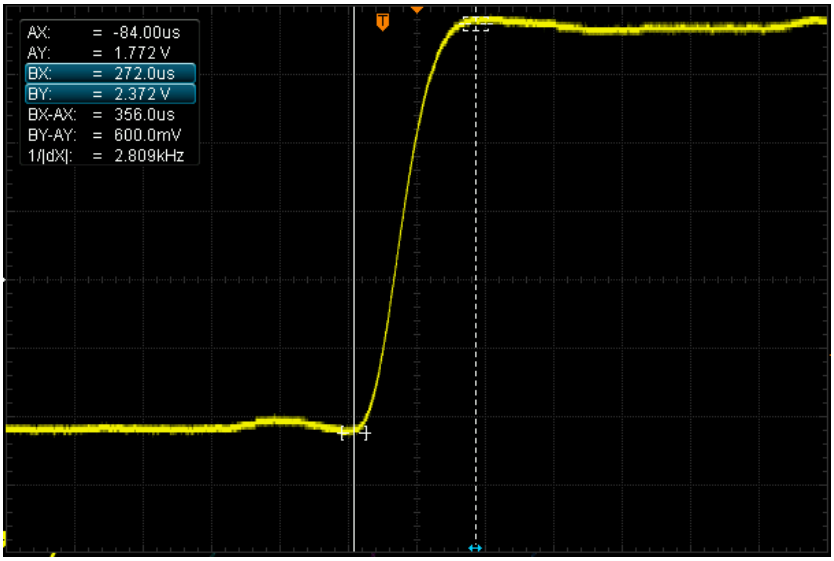


Figure 54: Response to positive step input using TL082 amplifier

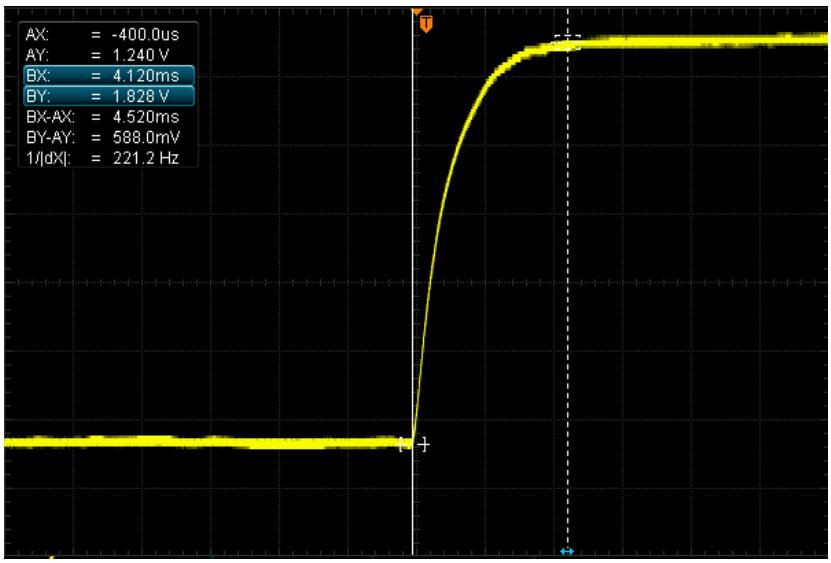


Figure 55: Response to positive step input using LM358 amplifier

In Figure 54, the response for the TL082 amplifier is represented, the time that it is necessary to reach the final value is round 360µs. This time can be seen in a variable that appears in the

picture with the name of BX-AX. While for the LM358 amplifier, the time that it is necessary for the same step input is 4.120 ms, this means the LM358 is more than 10 times slower than the TL082 responding to a positive step.

The same tests were made for a negative step input, and the results are represented in Figure 56 and Figure 57.

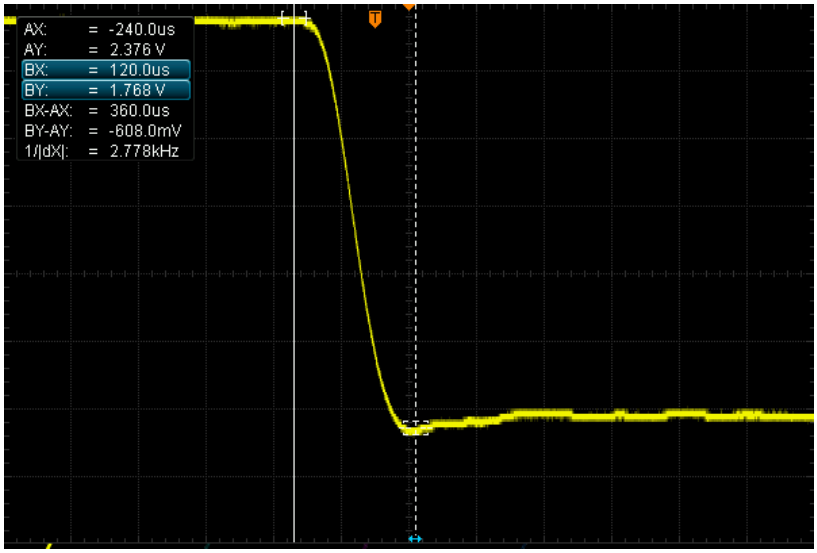


Figure 56: Response to negative step input using TL082 amplifier using the circuit for current measurement

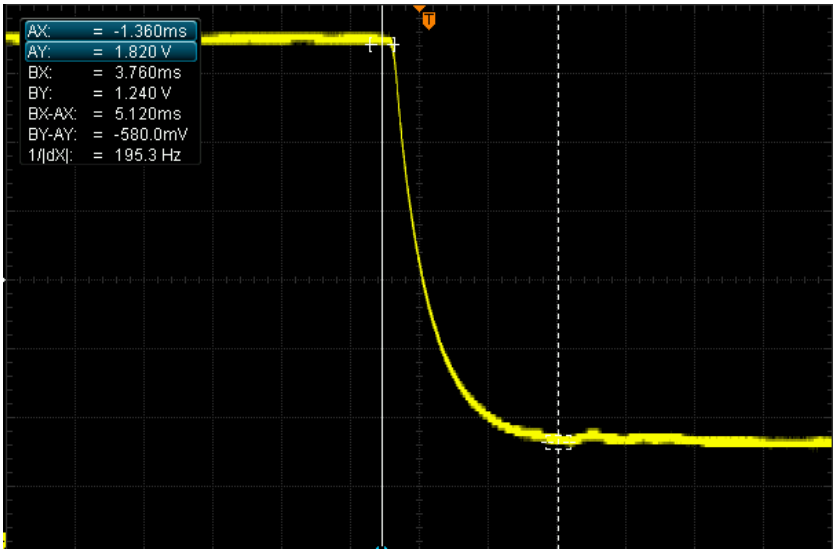


Figure 57: Response to negative step input using LM351 amplifier using the circuit for current measurement

The time that is required for the TL082 to respond to a negative step is the same as the time for the positive step, 360 µs. However, for the other amplifier this time is even higher, with a value around 5.120 ms.

These two tests were made with the circuit for current measurement. Tests were also done with the circuit for voltage measurement, and the results were similar. They showed a clear advantage working with the TL082 amplifier. Although in this circuit it was more difficult to identify the time response, since the power supply, as it is said in its manual, needs 3 ms to respond to a change of voltage. The response of the power supply as well as the response for the voltage circuit are depicted in Figure 58.

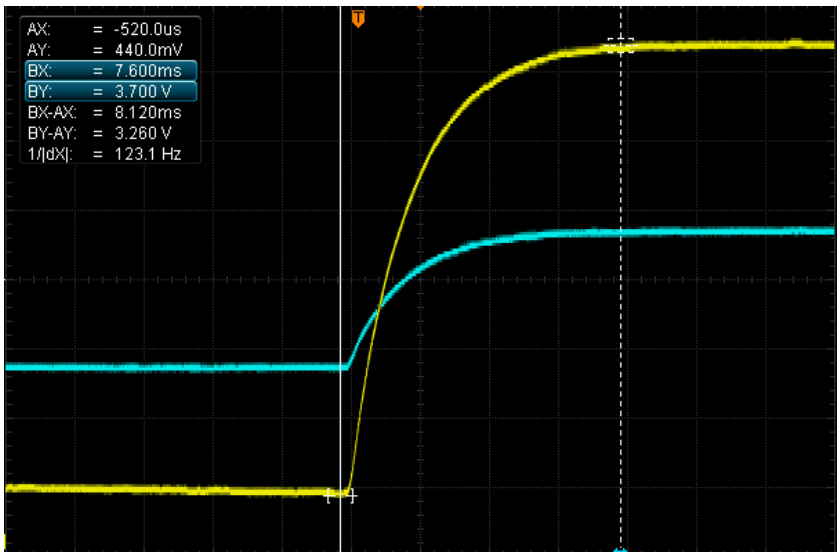


Figure 58: Response voltage measurement circuit

In the figure above, the power response is represented in blue, and it can be seen that it requires a time to reach the final value. The voltage circuit response is represented in yellow. In this case, it is not a response to a step input, so the response time cannot be identified.

After the results shown by the tests, it can be said that there is a clear advantage of the TL082 amplifier over the LM351 amplifier. For this reason, the first one was the selected amplifier and the configuration that was used was the dual supply.

In order to get the dual supply used by the op amps, two resistor of the same value are placed between the terminals of a power supply. In this way using this simple tension divider, the ground reference for the op amps will appear between the resistors. Furthermore, the positive terminal of the power supply will be used as a negative supply for the op amps and the same with the negative terminal but the opposite.

If the point between the resistors is connected directly to the different amplifiers, there will be more current flowing through one resistor, therefore the ground will be not perfectly placed in the middle voltage of the power supply. To avoid that to happen, a buffer amplifier is used. Because the amplifier has a high input impedance, the current through the line taken from the middle of both resistances will be so small that can be neglected.

The output for a buffer amplifier has the same value than its input. In this way, the ground as well as the positive and negative supply for the op amps are gotten. The scheme for this small circuit is shown in Figure 59.

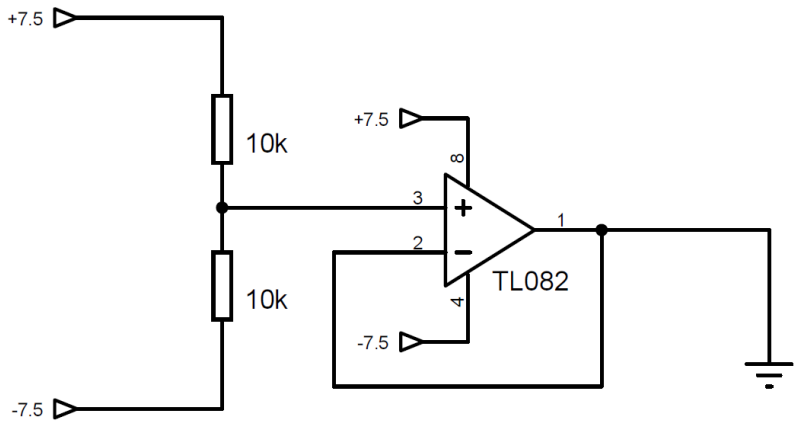


Figure 59: Circuit with buffer amplifier to generate the ground reference for the amplifiers

5.4 Calibration of the circuits for current and voltage measurement

The circuits explained before sending voltage signals to the ADC. These signals are converted into digital signals in the ADC and subsequently sent to the microcontroller. These digital values represent voltage values but initially the relationship is unknown. In order to know this relationship a calibration process is required.

Calibration is the process of finding the relationship between two quantities. In this case, between the digital value and its corresponding voltage or current value. To find this relationship the current analogue value must be known. For this purpose a power supply, which enables to know the actual value of current and voltage, is used.

This power supply is used as a standard of the calibration. And by modifying the value of the desirable variable it can be known the relationship between the two quantities for different values and whether the relationship is linear or not.

For the voltage calibration, the power supply is connected directly to the circuit and it is not necessary the current to be flowing whereas for the current calibration that is required. This

makes the calibration of the current more difficult, since the values of the current to be calibrated are quite high to be kept for a long period of time. This makes the current calibration a process much slower than the voltage calibration.

To know the value of the digital value, the monitor series of the Arduino IDE is used. This monitor series is a window, where Arduino writes what was previously configured. In this case, it is said that Arduino represents the digital value of voltage and current.

Once the simulation has finished, this data can be used to be compared with the corresponding analog value. For this purpose, an excel file was used and the relationship was represented in a graph. The current relationship is shown in Figure 60 and the voltage relationship is shown in Figure 61.

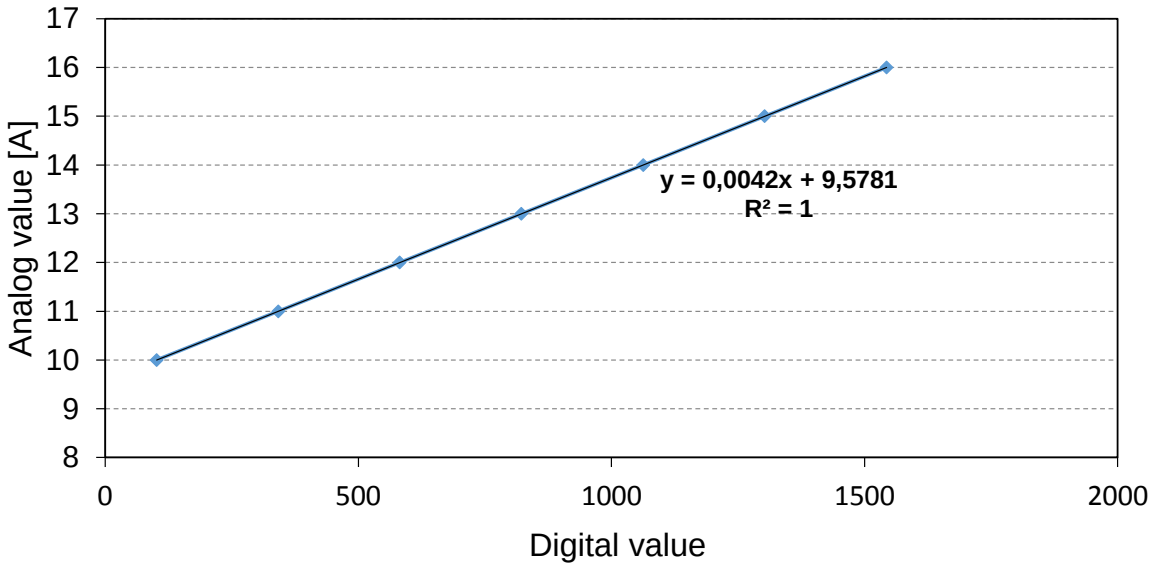


Figure 60: Relationship between the analog value and digital value for the current using Arduino and the external ADC to make the measurements

As it can be seen in both figures, the relationships, as it was expected, are linear for both cases, so the relationship can be approximated with a first degree equation. This relationship is inserted in the Arduino programme so that Arduino can transform automatically the digital value into the appropriate value.

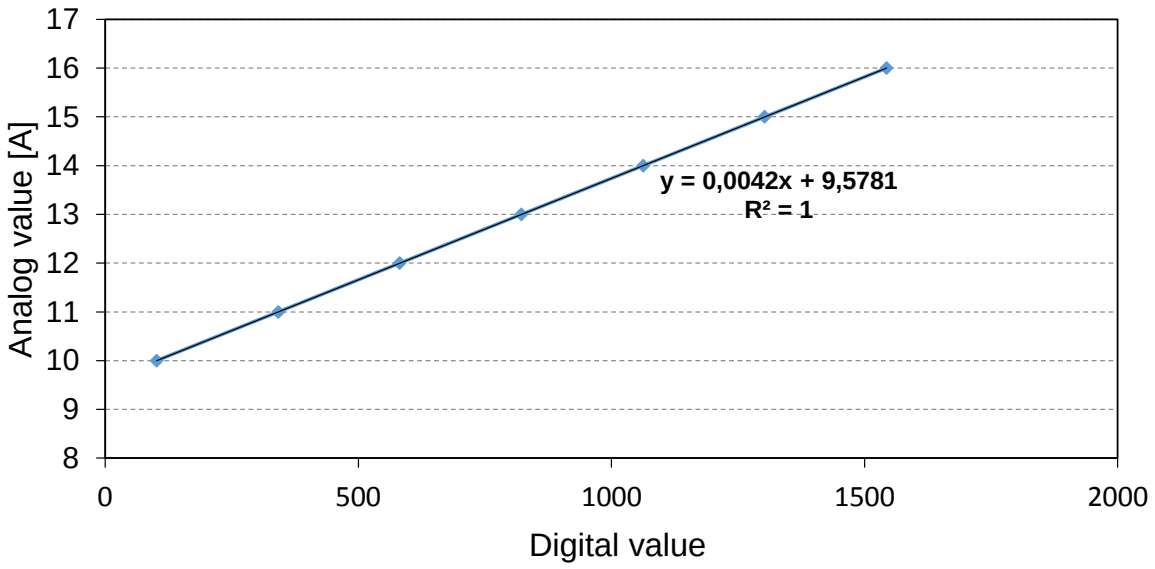


Figure 61: Relationship between the analog value and digital value for the voltage using Arduino and the external ADC to make the measurements

If a change in the circuit happens, for instance, the position of the potentiometer is modified, the calibration of the circuit has to be done again.

6 Programming Arduino

The software that is used to write the program in the Arduino board is called Arduino IDE (integrated development environment).This IDE is a cross-platform application written in the programming language Java.

The Arduino IDE supports the languages C and C++ using special rules to organize code. The Arduino IDE supplies a software library called Wiring from the Wiring project, which provides many common input and output procedures. A typical Arduino C/C++ sketch, shown in Figure 62, consists of two functions that are compiled and linked with a program stub main() into an executable cyclic executive program:

- **setup():** a function that runs once at the start of a program and that can initialize settings.
- **loop():** a function called repeatedly until the board powers off.

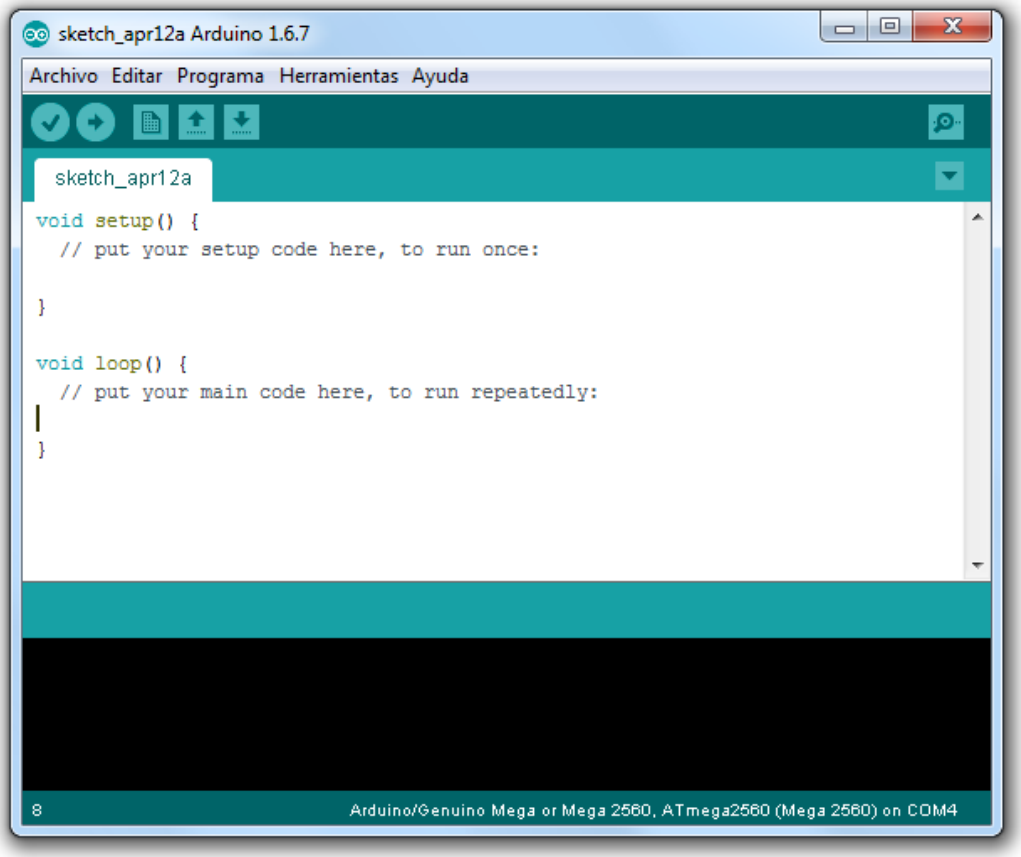


Figure 62: Structure of Arduino IDE for a new project

Both functions setup() and loop() are required for the program to work. Setup() is used to initialize pin modes, start using libraries or begin serial communications. It must be included in a program even if there are no statements to run. Loop() is the core of all Arduino programs and does the bulk of the work.

Furthermore, at the beginning of the program, before the function setup(), part of the code is written. In this part of code, it is included the necessary libraries and the global variables are declared. Some special functions need to be initiated in this part as well.

One of the greatest advantages of working with Arduino is the different libraries that can be found online. These libraries make the communication with external device easier, for instance, in this project, a library for the communication with the display is used.

After this brief introduction to the Arduino program language, the code for the program will be explained in the next section.

6.1 Programming code

To explain the code, it has been split into three part: beginning of the program, setup () and loop ().

6.1.1 Beginning of the program

In this part it is not executed any code, it is used for including the variables and declaring the global variables. Its function is to prepare the program so that the rest part of the code can be executed.

The libraries that are used in this program are shown in Figure 63. These libraries are necessary to establish connection with the ADC and the display and to run the controller.

```
#include <SPI.h>
#include <PID_v1.h>
#include <HardwareSerial.h>
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
```

Figure 63: Libraries used in the programing code of the controller

In relation with the use of the ADC and the display, a special initiate code must be programmed in this part of the program, for instance, the pins that will be used with this purpose are declared.

Finally, the different global variables are introduced. These variables are used in the whole program, for this reason, they need to be declared in this part of the code. Variables that are only used in a specific part will be declared in the specific loop.

6.1.2 Setup()

In the beginning of this part, the prescalers of the timer 0 and 3 are adjusted. These prescalers determinate the frequency of the PWM signal. Each one is assigned to a specific pin, whose PWM signal can be modified in terms of the frequency, for instance, the timer 0 is used for pins 13 and 4.

This change is totally necessary, since the default frequencies for the pins are 490 Hz or 980 Hz and the designed system cannot work at these frequencies. The frequencies that are used for the system are 60 Hz (in pin 4) and 120 Hz (in Pin 3). In Figure 64 it is shown the different frequencies in pins 13 and 4 that are available by changing timer 0.

```
prescaler = 1 ---> PWM frequency is 31000 Hz
prescaler = 2 ---> PWM frequency is 4000 Hz
prescaler = 3 ---> PWM frequency is 490 Hz (default value)
prescaler = 4 ---> PWM frequency is 120 Hz
prescaler = 5 ---> PWM frequency is 30 Hz
prescaler = 6 ---> PWM frequency is <20 Hz
```

Figure 64: Different PWM frequencies for the different prescalers of the timer 0 in Pins 13 and 4

In this part of the code, the use of the libraries for the controller, the ADC and the display requires some programming sentences. Furthermore, the serial communication of Arduino is initiated.

Finally, due to the system working, the two digital outputs (pins 3 and 4) start sending the PWM signal with a certain duty cycle. This is necessary, because the controller will become unstable if it starts working with the glow plug at room temperature. To solve this problem, during a period of time (around 10s) after the controller is initiated, current starts flowing through the main circuit controlled by the PWM signal and thus the glow plug is heated up. Meanwhile in the display can be seen a welcomed message. For its programming, the function delay and a specific function for the LCD are used, this part of the code can be seen in Figure 65.

```
//Message to show in the display when the program is initiated
lcd.setCursor(0,0);
lcd.print("Welcome to:");
delay(500);
lcd.clear();
lcd.setCursor(2,0);
lcd.print("The  fast HSI ");
lcd.setCursor(3,1);
lcd.print("controller ");
delay(200);
```

Figure 65: part of the code that generates the welcomed message and the time delay for the glow plug heating

6.1.3 Loop()

This is the core part of the program, which will be executed until the microcontroller is shut down or rebooted.

This part of the program can be split into two parts. The first part that includes the controller operation as well as the data acquisition (digital values of current and voltage). The second one, where the data to be shown in the display are programmed.

In the first part, the first thing to do is the acquisition of the digital values of current and voltage from the ADC. This process is programmed to be done only when there is current in the main circuit. During the high level of the PWM signal, Arduino asks uninterruptedly the ADC for the data, and during the low level, the mean value is calculated using these data, getting the digital value of current and voltage for the cycle.

After this, and thanks to the relationship, these digital values are converted into the appropriate analog values. Then the resistance and subsequently the error are calculated. Afterwards the code of the controller uses this error to modify the duty cycle of the signal.

The second part is programmed with different IF loops. The program will enter to one of them depending on the selection of the user through the bottom

This part is only executed each time that the first part is executed a certain number or times (in the code this number is 40 but it can be modified). The reason is because of the visualization of the information in the display; otherwise, the data will be constantly changing making it impossible to read the values.

7 Fast Adaptive Saturated (FAS) Controller

The name of the controller come from the way it operates. It has two principal characteristic; its three ranges of operation, which are explained later, and the saturation, because the change in the duty cycle is concentrated in the first cycles after the error happens and then it remains the same value.

In the beginning, A PID controller was programmed in the Arduino board in order to control the temperature of the glow plug. However, the results showed using a PID, were not as good as expected. These tests show in this section were all done with the glow plug working outside the engine.

For this reason the response of the system to different changes of the duty cycle was studied. Thanks to these tests, it could be appreciated more accurately how the glow plug works and gave an idea of what the controller should make.

The tests shown in this section were all done with the glow plug working outside the engine. When the glow plug was tested inside the engine, a problem came up. This problem will be explained in the next section.

7.1 Controller operation

The controller operation is divided into three range, whose behaviours are totally different. Each region has its own justification that will be explained later. Firstly, they are introduced:

- Range 1: |error|<0.5 mΩ. Value of the new duty cycle:

Error positive	(Previous)Duty cycle)+4	Previous Duty cycle
Error negative	Previous Duty cycle	(Previous Duty cycle)+4

- Range 2: 0.5 mΩ<|error|>4 mΩ. Value of the new duty cycle:

  Previous Duty cycle – (error · constant)

- Range 3: |error|>4mΩ. Value of the new duty cycle:

Error positive	(Previous Duty cycle) + Limit variation per cycle
Error negative	(Previous Duty cycle) – Limit variation per cycle

The first range works when the error is quite small. It was programmed with the objective of reducing the error when the temperature in the glow plug is steady. The reason for this is that the reading process has a variation of around 0.5 mΩ; therefore, when stability is reached, for the actual glow plug temperature, different values can be measured, being these values in a range of 0.5 mΩ. Using a PID creates an oscillation bigger than 2 mΩ, so a different behaviour for this range was programed.

This range works as a controller of two state. When the error is positive, it gives a certain duty cycle, when the error is negative, it makes this duty cycle increase by 4 the objective of this duty cycle is that the measurement of the temperature moves from positive to negative or negative to positive each cycle, remaining always inside this range.

With this range, the stationary error of the controller is lower than 0.5 mΩ.

The second range woks when the value of the error is moderately big. The duty cycle is governed by a constant value. In this range, the controller works like a PID with only integral part. Each cycle, a modification of the duty cycle is calculated using the formula shown before. In this way, the duty cycle can be changed each cycle when the error is in this range.

The third part works when the error is quite big. There is a maximum variation of the duty cycle, and in this range this maximum variation is reached. Therefore, when the error is in this range, this maximum variation will be added to the previous duty cycle value each cycle. This maximum variation will be positive or negative depending on whether the error is negative or positive.

For a better understanding of how this three ranges work, a graph is shown in Figure 66.

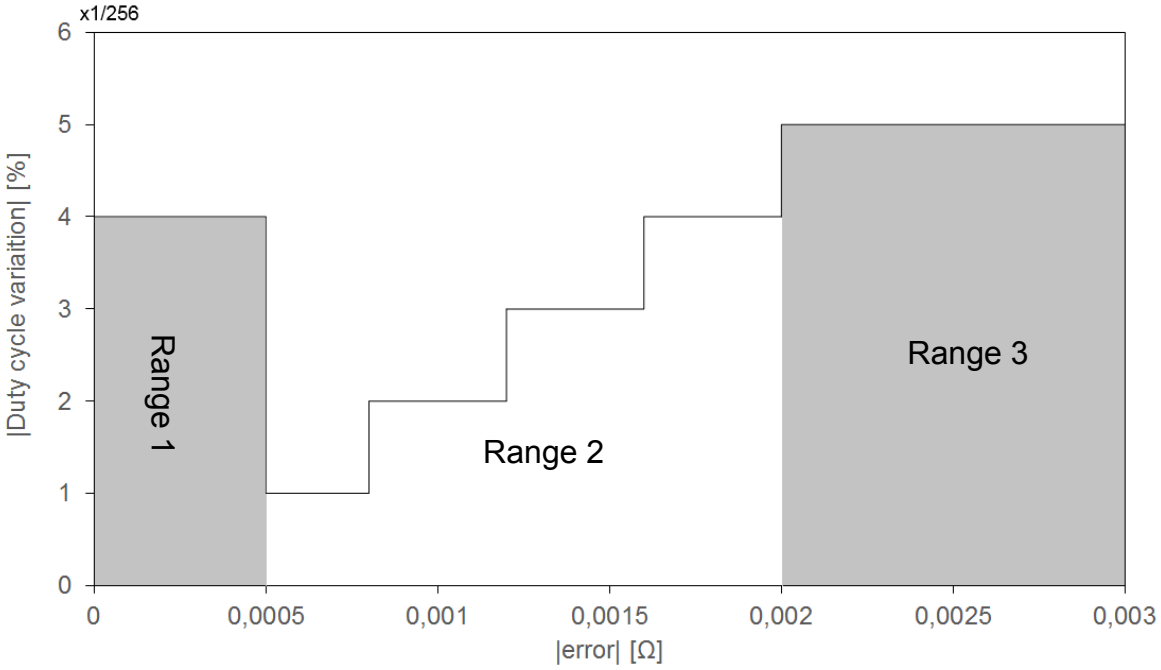


Figure 66: The variation of the duty cycle depending on the error for the three range of the controller

Besides these three ranges, there is another fact that enables this controller to respond faster and without oscillation. For the variation of the duty cycle a limit was established, where the controller enters in a saturation state. The controller can only increase or reduce its value by 30 during 0.5s. With this limit, once a big error happens, there is only variation in the duty cycle during the first cycles after the error is detected. Once this limit duty cycle time variation is reached, its value remains the same until the sign of the error changes or after 0.5 s.

7.2 Test of the controller working

With the three ranges for the controller previously defined, the search for the best parameters started. Firstly the response to a modification in the set point was studied.

The set point was increased and decreased, studying the time and the shape of the response to this variation. With the different responds, it was tried to identify what possible variations in the parameters can make the response better. One of these initial tests is shown in Figure 67.

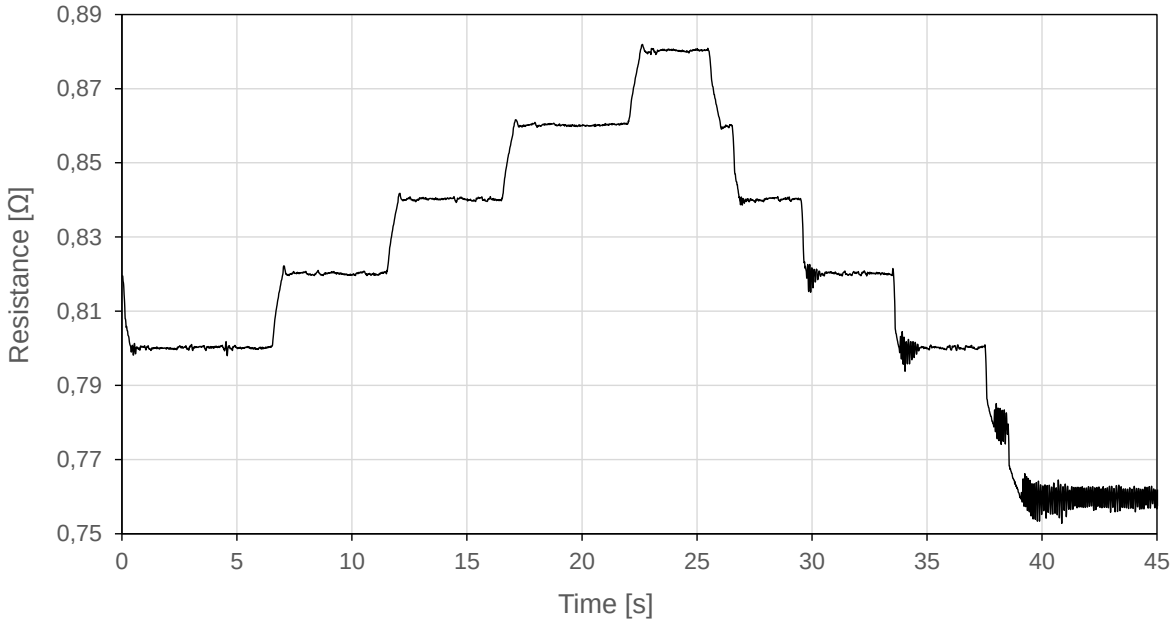


Figure 67: Initial test of the glow plug temperature working with the FAS controller

As it can be seen in the picture, the set point was increased and decreased by 0.02 and an anomalous behaviour in this test happens. When the set point is decreased, an oscillation during the first cycles after the set point is reached happens. The cause of this behaviour was due to a low value of the duty cycle. Due to this low duty cycle, the main circuit was active only during a quite short period of time, making the ADC unable to read enough values and thus the resistance calculation varied too much. For this reason a limit for the duty cycle was established. Figure 68 shows the final results once this problem was solved.

In Figure 68, it can be seen how these oscillations have been completely eliminated, and even for lower values of resistance, these oscillations do not appear. Regarding to the new response, it can be seen that the controller responsds even faster. However for low glow plug temperature, when a positive change in the set point happens, the response of the controller has a not desirable overshoot. This problem could not be solved without making the response slower. For this reason, this behaviour was considered to be good.

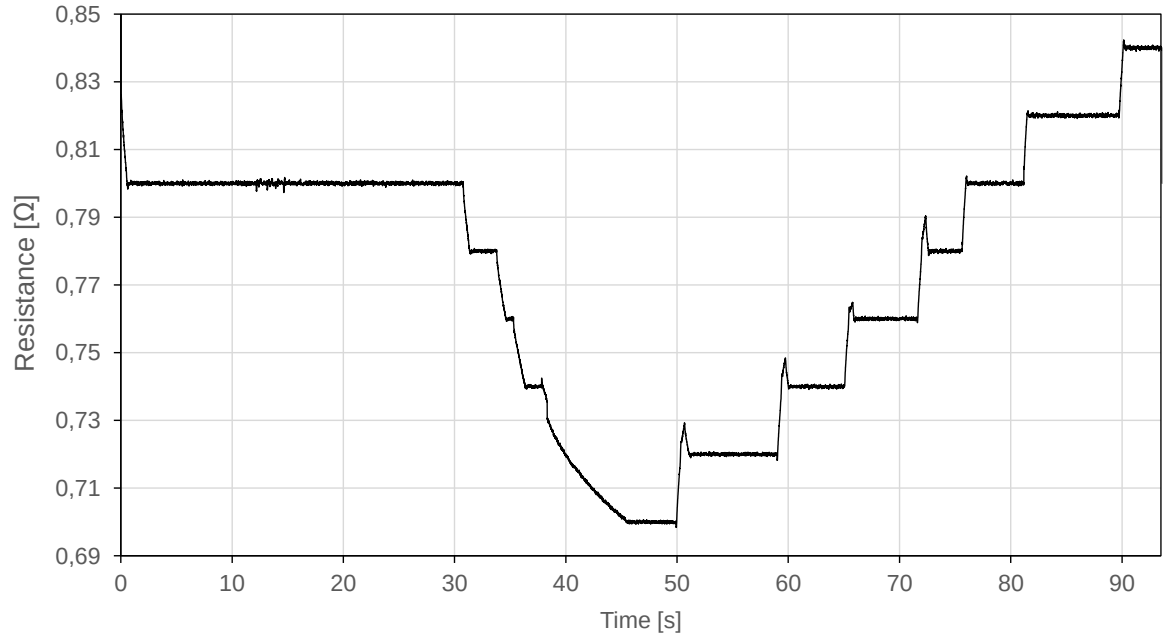


Figure 68: Final test of the glow plug temperature working with the FAS controller

Furthermore, the stationary response was also studied. Initially when the controller started to be designed, the first range of the controller was not used. It was after its stationary response was analysed, when this range was added. It was obvious that a special behaviour was necessary when the error was smaller than a certain error.

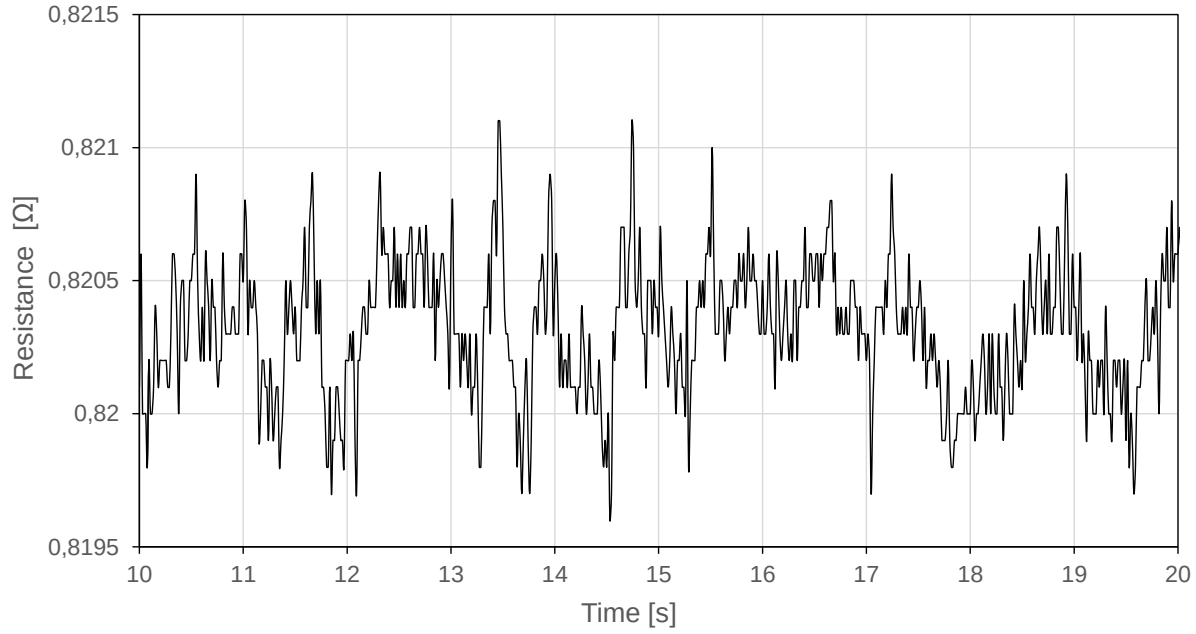


Figure 69: Stationary error of the glow plug temperature working with the FAS controller in its first stage of development

The figure above shows that the stationary error remains positive almost all the time. This is due to a different inertia in the glow plug. The inertia of the glow plug is bigger when its temperature decreases than when its temperature increases. For this reason, the glow plug heat quicker, and thus the error remains positive almost all the time.

7.3 Response of the controller

In order to show how the controller responds, the response to a negative variation in the set point was compared with the response of the system when the controller is not used. In the Figure 70, this comparison is shown.

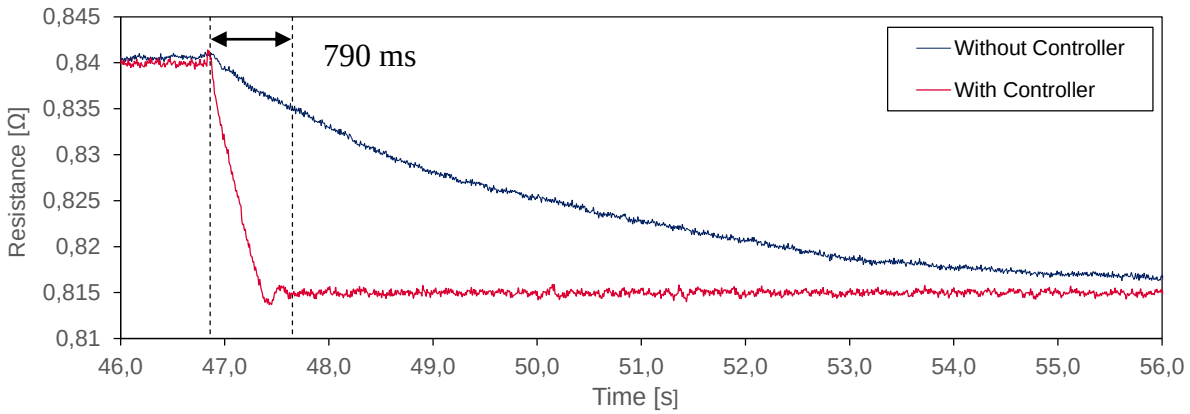


Figure 70: Response for a negative variation in the set point, using the FAS controller and without controller

For the response without a controller, it needs a lot of time to get a steady response, even in the graph this steady response cannot be observed. However, when the system is working with the FAS controller, it requires only 620 ms to reach a steady response.

The same study was done for a positive variation of the set point, and similar results were gotten. The response is depicted in Figure 71. The controller responds also much faster than when it is not used.

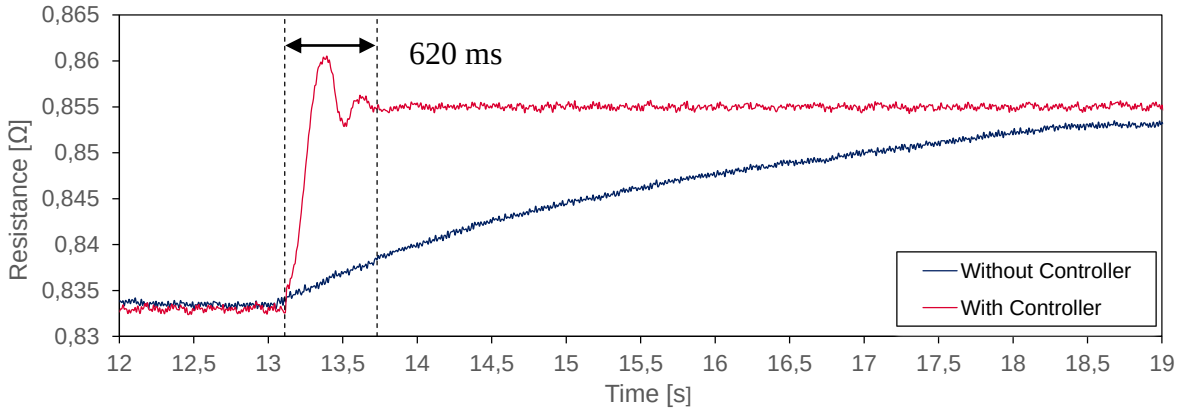


Figure 71 : Response for a positive variation in the set point, using the FAS controller and without controller

Comparing both images, it can be appreciated that the inertia of cooling and heating process is different. As it was explained before, the inertia is bigger when the glow plug is releasing heat, and this can be observed during the time that is required for both processes to reach the stationary behaviour. Due to its biggest inertia, the process of lowering the temperature requires more time.

IT can also be appreciated the overshoot in the controller response when the set point is increased. The reason of this overshoot is the inertia; in this case, the lower inertia of the process of increasing the temperature.

Furthermore, the stationary noise made by the last controller design was checked. In Figure 72, this response is depicted. As it can be seen the temperature of the glow plug remains almost all the time between the values 0.7995 and 0.8005, and the problem that was explained before was solved. The temperature of the glow plug does not remain almost all the time above the set point.

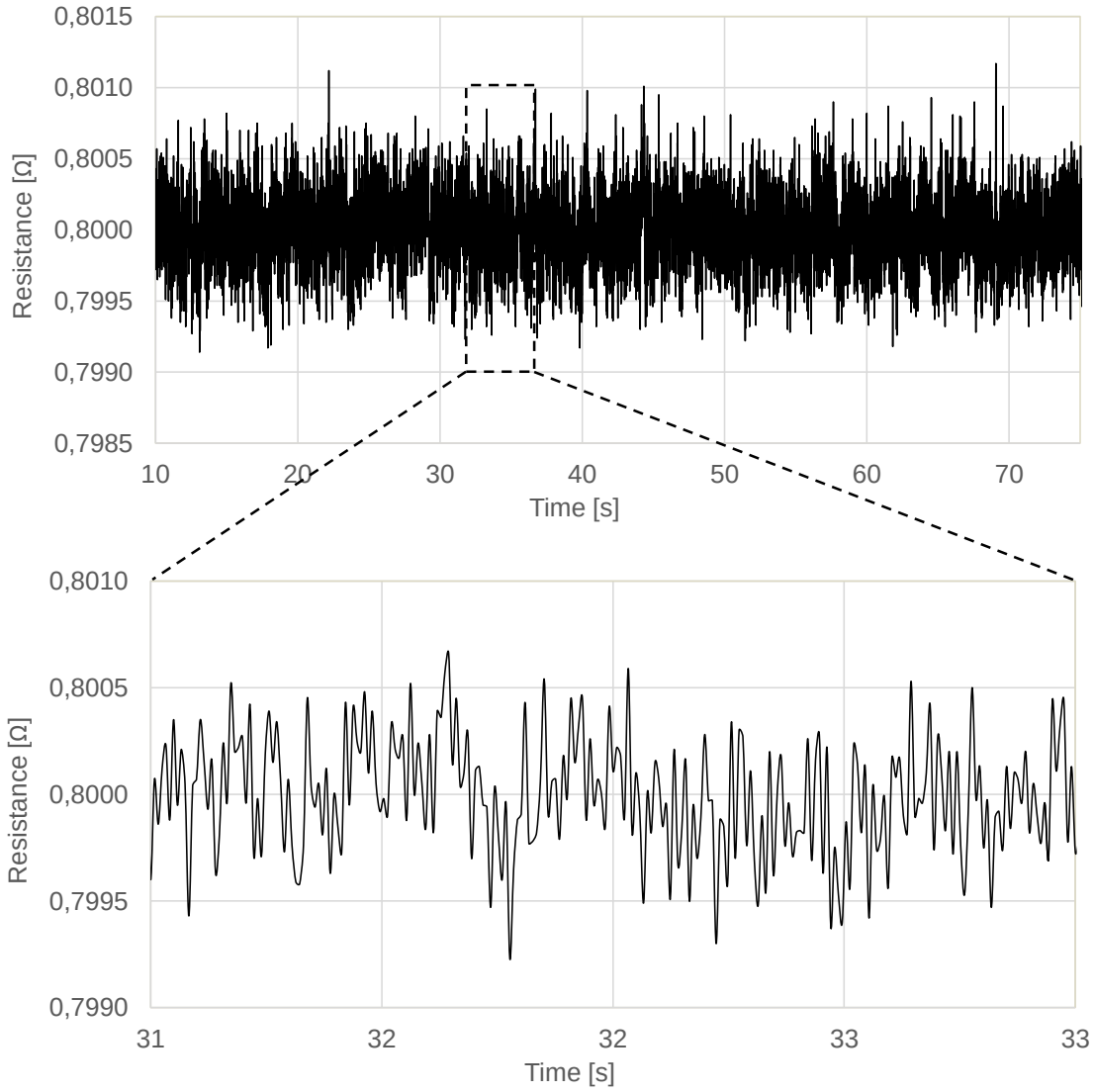


Figure 72: Stationary error of the glow plug temperature working with the FAS controller in its last stage of development

8 Problem working with the engine

As it was mentioned before, a problem happen with the controller circuit when the glow plug works inside the engine. This problem is due to the installation ground, which it is connected to one edge of the glow plug.

Due to safety reasons, the engine has to be connected to the installation ground. Since the engine is connected to one part of the glow plug, this part is also connected to the ground. Therefore this part of the glow part remains in a constant level of voltage, since the ground of the installation has a big inertia.

Because this part of the glow plug remains in constant voltage level, the ground that is used for the controller circuit is constantly changing. This change in the ground inserts noise in the measurement process of the voltage and the current, making the controller unable to keep the value of the resistance steady.

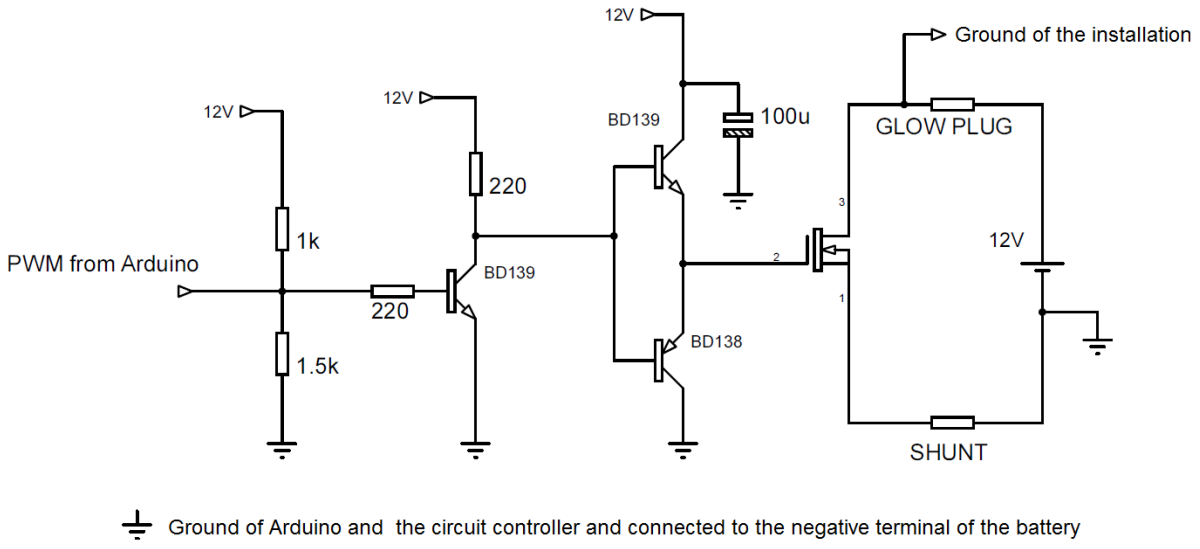


Figure 73: Switch circuit scheme to show the two different grounds

As it can be seen in the figure, in the circuit, the negative terminal of the battery is connected to the ground of the controller circuit. When the Mosfet opens the circuit, the ground of the circuit has a voltage of -12 V respect to the installation ground, since the ground of the installation is connected to the positive terminal of the battery. While when the Mosfet closes the circuit, the ground of the installation is connected to the negative terminal and due to the current, the ground of the circuit have a voltage lower than the ground of the installation. This value depends on the losses in the cables, transistor and shunt and is around 1 to 2 V.

For this problem, there is a solution. This solution is based on the insulation of both circuits; in this way, the ground of the controller circuit has not to be connected to the negative terminal of the battery. To do this, an optocoupler is used in the switch circuit. Instead of the first bipolar transistor, an optocoupler is placed. The design of this circuit can be seen in Figure 74.

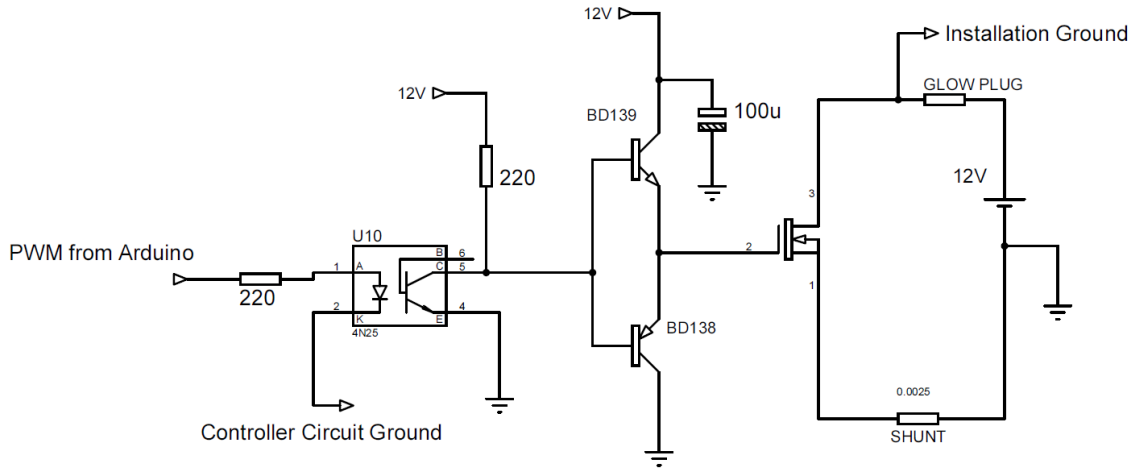


Figure 74: Switch circuit with optocoupler to solve the problem of the installation ground

Although the circuit could not work inside the engine, the controller was checked during the engine working. The FAS controller was programmed in the computer that was the responsible to control a power supply by modifying its voltage value. And later, the engine was operated using the glow plug controlled by the FAS controller.

The results showed that the new controller allowed for a significant improvement of controller performance. The resistance value kept almost steady and it allowed to modify the set point for the glow plug during the engine working without becoming unstable. In spite of the good performance of the new controller, the cycle-to–cycle variations remained high, being much bigger than the normal values during spark ignition operation.

9 Conclusion

The circuit that was built to control the glow plug was able to remain the stationary error value around 0.0005Ω and showed good response to changes in external conditions. With regard to the components that made up this circuit, the shunt resistor responded with high speed to the different changes and with an almost perfect linearity; hence it can be said that it is a right technique fort these applications. Moreover, the use of operational amplifiers along with the voltage reference allowed selecting the ranges of both measurements that wanted to be read.

The negative aspect of the performance of this circuit is the noise in the measurements. This noise depends mostly on the noise of the signals that are sent to the ADC, so the use of an ADC with more resolution will not improve its performance. In order to reduce this noise, it is necessary to narrow the range of temperature where the glow plug can operate, so that it allows further amplification of both signals, and, as a consequence, the influence of the noise over the measurements will be reduced.

Furthermore, due to the connexion of one edge of the glow plug to the ground of the installation, it requires the isolation between the battery and the power supplies that are used to feed the microcontroller and the circuit.

Concerning the performance of the controller, the use of the FAS controller has shown that it is possible to maintain the resistance value of the glow plug highly stable during engine operation. However, cycle-by-cycle variations in the start of combustion remain high, which leads to the conclusion that combustion stability would not profit from further optimisation of this type of constant-temperature controller.

Since the temperature remains steady in the surface of the ignition system, the start of the combustion is highly reliant on the local conditions that happen close to the glow plug. As a consequence, the start of the combustion fluctuates.

In order to reduce the cycle-by-cycle variation, a new behaviour of the controller is proposed. Instead of keeping the temperature steady, the controller must work with two levels of temperature. One of those levels corresponds to the temperature of the glow plug when combustion starts, whereas the other level of temperature must be reached for the glow plug during the rest of the time. The difference between those two levels will depend on the inertia of the system, that is, how fast the temperature of the glow plug can be decreased or increased.

With this controller, the start of combustion becomes also dependent of the glow plug temperature, making lower the influence of the internal conditions. And in this way, the cycle-to-cycle variation might decrease.

To conclude, this study has shown a method of implementing a controller with better stability and faster response. However, this was a proposal which leaves the door open to further research.

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Table of Figures

Appendix A: Programming code for Arduino

```
#include <SPI.h>
#include <PID_v1.h>
#include <HardwareSerial.h>
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);



// definde the pin for the serial comunication with the ADC
#define SELPIN 53  // chip-select
#define DATAOUT 51  // MOSI
#define DATAIN 50  // MISO
#define SPICLOCK 52 // Clock

//define the digital output that are used for the PWM signal
int pwm_61Hz = 4;
int pwm_122Hz=3;

//define variable used for the controller
double Setpoint;
double Output;
double consKp=2500, consKi=0, consKd=0;

//define varibles used for the read process
const int numReadings = 200;
float readingsvoltage[numReadings];
float readingscurrent[numReadings];
float totalvoltage;
float totalcurrent;
double resistance;
float temperature;

// variables use for the special cases of the controller
int cycle=200;
int limit[]={0, 0, 0, 0 ,0 ,0, 0, 0, 0, 0, 0 ,0 ,0, 0, 0, 0, 0, 0, 0 ,0 ,0, 0, 0 ,0 ,0, 0, 0, 0, 0, 0 ,0
,0, 0, 0, 0, 0, 0 ,0 ,0, 0 ,0 ,0, 0, 0, 0, 0, 0 ,0 ,0, 0,0 ,0, 0, 0, 0, 0, 0 ,0 ,0, 0};
```

```
int v=0;
int lastvalues=0;
int save=0;

// define variable that are used for the external buttom
int up = 0;
int down= 1;
int select = 2;

int datashow=0;

//the contoller is initiated
PID controller(&resistance, &Output, &Setpoint, consKp, consKi, consKd, REVERSE);

void setup(){

 //Modife the timer divider to get the desireble frequency of the PWM signal
 TCCR0B = TCCR0B & 0b000 | 0x05;
 TCCR3B = TCCR3B & 0b000 | 0x04;
 TCCR2B = TCCR2B & 0b000 | 0x05;

 //set pin modes

 pinMode(select, INPUT);
 pinMode(up, INPUT);
 pinMode(down, INPUT);
 pinMode(SELPIN, OUTPUT);

 lcd.begin(16,2);

 // disable device to start with
 digitalWrite(SELPIN, HIGH);

 SPI.setClockDivider( SPI_CLOCK_DIV8 ); // slow the SPI bus down
 SPI.setBitOrder(MSBFIRST);
 SPI.setDataMode(SPI_MODE0);  // SPI 0,0 as per MCP330x data sheet
 SPI.begin();

 Serial.begin(115200);///start the serial comunication
```

```
 analogWrite(pwm_61Hz,cycle);
 analogWrite(pwm_122Hz,cycle);
 Setpoint=0.78;



 //Message to show in the display when the program is initiated
 lcd.setCursor(0,0);
 lcd.print("Welcome to:");
 delay(500);
 lcd.clear();
 lcd.setCursor(2,0);
 lcd.print("The fast HSI ");
 lcd.setCursor(3,1);
 lcd.print("controller ");
 delay(200);

 // set the parameters for the controller
 controller.SetMode(AUTOMATIC);
 controller.SetSampleTime(1);
 controller.SetOutputLimits(-5,5);
}


void loop() {
 int i;
 // bucle for execute 40 time, afte teh data in the display is updated and agin this bucle is exe-
cuted
 for(int j=0;j<40;j++){

 analogWrite(pwm_61Hz,cycle);
 analogWrite(pwm_122Hz,cycle);

 totalcurrent=0;
 totalvoltage=0;
 start:
 readingscurrent[0]= read_adc(0);
 // wait for a digital value of the current bigger than 70
 if ( readingscurrent[0] < 70){
    goto start;}
```

```
// bucle for that read value of the ADC while the circuit is on or during 200 times
for(i=0;i<numReadings;i++){

 // code for a comunication with the ADC
 int a1=0;
 int a2=0;
 // read current
 digitalWrite (SELPIN, LOW);
 SPI.transfer(B00000010);
 a1= SPI.transfer( B00000000);
 a1 |= B11100000;
 int hi1 = a1 & B00001111;
 a2=SPI.transfer( B00000000);
 int lo1=a2;
 digitalWrite(SELPIN, HIGH); // turn off device
 readingscurrent[i] = hi1 * 256 + lo1;

 //read voltage;
 a1=0;
 a2=0;
 digitalWrite (SELPIN, LOW);
 SPI.transfer(B00000010);
 a1= SPI.transfer( B10000000);
 a1 |= B11100000;
  hi1 = a1 & B00001111;
 a2=SPI.transfer( B00000000);
 lo1=a2;
 digitalWrite(SELPIN, HIGH); // turn off device
 readingsvoltage[i] = hi1 * 256 + lo1;

 // the values of read form the adc are stored in the arrays readingscurrent[i] and readingsvolt-
age[i]


 // bucle to leave the bucle for if the current drop to certain value
 if ( readingscurrent[i] < 70){
   goto vamos;
 }
```

```
 }
 vamos:

 //eliminate the first three values and the last seven values of the measurements
 for(int t=3;t<(i-7);t++){
 totalcurrent=totalcurrent+readingscurrent[t];
 totalvoltage=totalvoltage+readingsvoltage[t];
 }




 // the resistance value is calculate
 totalcurrent=totalcurrent/(i-10);
 totalcurrent= totalcurrent*0.00408+9.945;//use relationship between digital and analog value
 totalvoltage=totalvoltage/(i-10);
 totalvoltage=totalvoltage*0.000742+10.70;//use relationship between digital and analog val-
ue
 resistance=totalvoltage/totalcurrent;

// error for the controller is calculated and stored in the variable Output
 controller.Compute();

//Code for the controller with the special cases
 if (Output>0,85){
 Output= Output+0.5;
 }
 if (Output<-0,85) {
  Output= Output-0.5;
 }
 if (abs(lastvalues+Output)!=abs(lastvalues)+abs(Output)){
 lastvalues=0;
 for (int i=0;i<41;i++){
 limit[i]=0;
 }
 }

 if(v>40){
  v=0;
 }
```

```
lastvalues=lastvalues-limit[v];
limit[v]= (int)Output;
lastvalues=lastvalues+limit[v];
if(Output>-0,85 && Output<0,85){

if (save!= 4*(Output/abs(Output))&& limit[v]<abs(10)){
limit[v]=4*(Output/abs(Output));
save=limit[v];
}
}

if(lastvalues<=30 && lastvalues>=-30){
cycle= limit[v] + cycle;
}
else{
if(lastvalues<0){

  lastvalues=lastvalues-limit[v];
  limit[v]= -30 - lastvalues;
  cycle= limit[v] + cycle;

  lastvalues=lastvalues+limit[v];

}
else{

  lastvalues=lastvalues-limit[v];
  limit[v]=30 - lastvalues;
  cycle= limit[v] + cycle;
  lastvalues=lastvalues+limit[v];
}
}

// the code of the controller finish

v++;

// security limits for the duty cycle
if ( cycle > 230){
   cycle=230;
```

```
  }
 if ( cycle < 150){
    cycle=150;
  }

 }

// the data to be shown in display is selected with the next code
//It can be selected between
 int option= analogRead(up);
 int option1= analogRead(down);

 if(option>1000 || option1>1000){
  datashow=datashow+1;
  if (datashow>1){datashow=0;}
 }
 if ( datashow=1){
 lcd.clear();
 lcd.setCursor(0,0);
 lcd.print("current:");
 lcd.setCursor(0,1);
 lcd.print("voltage:");
 lcd.setCursor(8,0);
 lcd.print(totalcurrent,2);
 lcd.setCursor(14,0);
 lcd.setCursor(8,1);
 lcd.print(totalvoltage,2);
 lcd.setCursor(14,1);
 }
 if ( datashow=0)
 {
 lcd.clear();
 lcd.setCursor(0,0);
 lcd.print("resistance:");
 lcd.setCursor(5,1);
 lcd.print(resistance,3);
 }

 // with the next part of the code the set point can be changed
```

```
 if(analogRead(select)>1000)
 {
 do{
 lcd.clear();
 lcd.setCursor(0,0);
 lcd.print("Change S.Point ");
 lcd.setCursor(0,1);
 lcd.print("S.Point:");
 lcd.setCursor(9,1);
 lcd.print(Setpoint,2);
 delay(100);
 if (analogRead(up)>1000){
  Setpoint=Setpoint+0.01;
 }
 if(analogRead(down)>1000){
  Setpoint=Setpoint-0.01;
 }
 }while(analogRead(select)<1000);
 }

}

//function use to read from the ADC

int read_adc(int channel){
 int adcvalue = 0;
 int b1 = 0, b2 = 0;
 int sign = 0;

 // command bits for MCP3304
 // 0000 = diff, ch0 = in+, ch1 = in-
 // 0010 = diff, ch2 = in+, ch3 = in-
 // 0100 = diff, ch4 = in+, ch5 = in-

 digitalWrite (SELPIN, LOW); // Select adc

 // first byte
 // first byte will always be B000010xx where xx are the D2 and D1 channel bits
 byte commandbits = B00000010;
 if (channel>=4){
```

```
 commandbits = B00000111;
 channel= channel & B011;
}
   // high bit of channel

SPI.transfer(commandbits);    // send out first byte of command bits

// second byte; Bx0000000; leftmost bit is D0 channel bit
commandbits = B00000000;
commandbits |= (channel << 6);
   // if D0 is set it will be the leftmost bit now
b1 = SPI.transfer(commandbits);    // send out second byte of command bits

// hi byte will have XX0SBBBB
// set the top 3 don't care bits so it will format nicely
b1 |= B11100000;
//Serial.print(b1, BIN); Serial.print(" ");
int hi = b1 & B00001111;

// read low byte
b2 = SPI.transfer(b2);       // don't care what we send
//Serial.print(b2, BIN); Serial.print("\r\n");
int lo = b2;
digitalWrite(SELPIN, HIGH); // turn off device

int reading = hi * 256 + lo;



return (reading);
}
```