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Title:

Design and Implementation of an Automatic Voltage Regulator of an engine generator set using microcontroller

Prese

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Dedication

I dedicate this work to my lovely parents,
they are the light of our way and the reason of our happiness.
To my two brothers Mohamed El amine & Wassim.
To my childhood friend and cousin, Might Allah Bless her Cherine.
To my soulmates Souhier & Sarah & Aamirah
To my best friends Asma & Linda
And to all my friends and colleagues without exception.

Hanane KAOUANE !

Dedication

I dedicate this work to my family and many friends. A special feeling of gratitude to my loving parents and grandmothers whose words of encouragement and push for tenacity ring in my ears, and in the memory of my grandfathers.

I also dedicate this work to my many friends, colleagues and neighbors who have supported me throughout the process. I will always appreciate all they have done, especially **Belkham Zakaria** for providing me with resources that helped me to finish this work.

I dedicate this work and give special thanks to **Mr. Metidji**.

Bachir RAYANE !

Acknowledgement

First of all, we thank Allah, the Most Beneficent, the Most Merciful, for helping us to finish this humble work.

Throughout our work,
We have been extremely fortunate in having the support and the encouragement of many people. We would like to thank everyone who helped make this project possible.

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Special thanks go to our supervisor **Pr. H.Bentarzi** for all his guidance and support during the realization of this final project with many useful comments and suggestions that are greatly appreciated.

Abstract

AC generators commonly use a combination Exciter-Voltage Regulation system to maintain generator field current under varying electrical loads. The basic voltage regulation system is designed to automatically regulate generator output terminal voltage within close tolerances of a specified value. The generic regulation system is a 'closed loop' feedback system in which generator output voltage is automatically compared to a reference voltage. The error signal is used to change generator excitation.

The objective of this project to design and implement an Automatic Voltage Regulator for an engine generator set using Microcontroller. the output voltage of the generator will be transformed, rectified and filtered in order to be measured by the Arduino controller, which controls the excitation voltage through a high frequency switching device using PID controller program implemented inside the Arduino.

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Chapter 01 :
General Introduction

General Introduction:

Electrical energy is one of the fundamental resources of modern industrial society where the user receives electrical power instantly, at the rated voltage and frequency of the needed amount. This important performance is achieved through careful planning, design, installation and operation of a very complex network including generators, transformers, and transmission and distribution lines. One of the most important elements of electric power system is synchronous generator, which is electrical energy source in power system. Therefore, regulation of synchronous generator voltages is important that affects not only in the generator itself, but also in the entire power system.

Generator is an electrical device that converts mechanical energy into electrical energy. In synchronous generator, mechanical energy of the rotor is transformed into electrical energy in the stator winding. This energy transformation is performed by the excitation of synchronous generator where the induced voltage is regulated by the excitation system. Two major classes of these excitation systems maybe used which are: separate excitation systems and self-excitation systems. In this study, a self-excitation system is chosen due to its simplicity and widely used. The variation in the generated voltage damages the equipment of the power system and loads. With variation of a load, a generator terminal through the use of voltage will vary. It is desired to keep the terminal voltage with limits. The Automatic Voltage Regulator is used to regulate the voltage terminal, mitigate functions of voltage, and keep the magnitude of voltage constant.

The main objectives of this project is to design and implement an Automatic voltage regulator (AVR) of an engine generator set using microcontroller. A microcontroller controls the excitation current for maintaining a constant output voltage of the generator. If the output voltage of the generator is increased, the microcontroller will decrease the excitation current and hence decreases the output voltage of the synchronous generator until it reaches the preset value. If the output voltage is decreased, the microcontroller will increase the excitation current, so that the output voltage will increase until it reaches a preset value. In this project, one of the suitable digital controller is used due to its simplicity, speed and integrity, which is the Arduino Uno with its relative good performance.

This report contains seven chapters where its organization is as follows:

The first chapter deals with an introduction of our project in which an overview about power electronics in general and generators and synchronous generators in particular as well as the objectives to be achieved.

The second chapter presents a theoretical background about the synchronous generator; it introduces what is synchronous generator, its construction and characteristics. In addition, the principles of the synchronous generator operation have been presented.

The third chapter presents a theoretical background about the automatic voltage regulator, its definition and working principle and its relation with the synchronous generator.

The fourth chapter was about the microcontroller. Definition and types of the microcontroller was mentioned too. Where an Arduino Uno was presented since it is the type of the microcontroller used in this project.

The simulation is performed in chapter sex using MATLAB /Simulink. The simulation of a synchronous generator associated with an automatic voltage regulator using a PID as a controller.

Finally, is the implementation part of the project where an automatic voltage regulator was implemented using synchronous generator and Arduino Uno.

The last chapter presents the general conclusion that summarizes the tasks investigated in the project, states the achievements of work, assesses several difficulties faced and suggests further improvement for the system simulator that can be found in this chapter.

Chapter 02 :
Synchronous Generator

2.1 Introduction:

[1] Alternating generator is an electrical machine that converts mechanical energy into alternating electric energy. [2] There are two basic types of Alternating (AC) generators: synchronous and asynchronous. This chapter deals with Synchronous generators, it lock in with the fundamental line frequency and rotate at a synchronous speed related to the number of poles.

2.2 Three-phase generator:

Synchronous generators or as they also called alternators are used to supply most of alternative (AC) power used today. There are used rather than single-phase alternators to obtain the maximum output from a given weight.

The three phase of alternator are mechanically spaced at equal intervals from each other by 120° electrical degrees.

2.3 Construction of synchronous generator:

A three-phase synchronous generator consists of an inner rotating cylinder called the rotor and an outer stationary housing called the stator as shown in Figure 2.1:

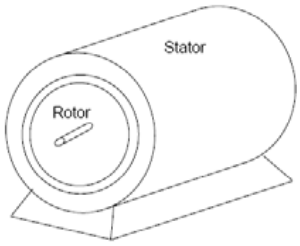

Figure 2.1: Construction of synchronous generator.

2.3.1 Stator: [3] The Stator is the stationary part of the generator and is built up of sheet steel laminations having slots on its inner periphery. The slots are laminated and are insulated from each other by a thin coating of oxide and enamel. Open slots are used, permitting easy installation of stator coils and easy removal in case of repair.

A 3- phase winding is placed in these slots and serves as the armature winding of the alternator.

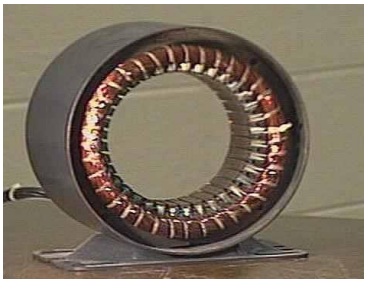

Figure 2.2: Stator of a synchronous generator.

2.3.2 Rotor: [4] The rotor carries a field winding that is supplied with direct current (DC) through two slip rings by a separate DC source.

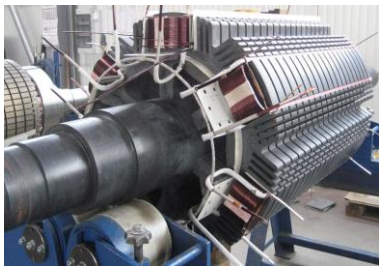

Figure 2.3: Rotor of a synchronous generator.

Depending on the construction of the rotor, the alternators are classified into two types: Salient or projecting pole type and Non-Salient or Cylindrical or Wound type.

2.3.2.1 Salient pole type: Salient pole type rotor is used in low and medium speed alternators. Construction of AC generator of salient pole type rotor is shown in the figure 2.4:

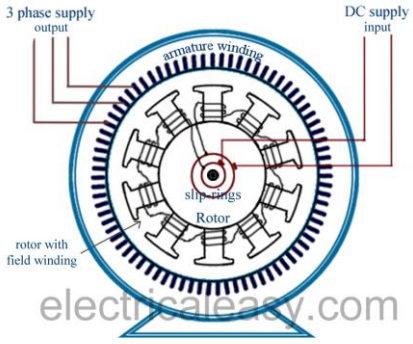

Figure 2.4 : Salient pole Synchronous generator.

[4] This type of rotor consists of large number of projected poles (called salient poles), bolted on a magnetic wheel. These poles are also laminated to minimize the eddy current losses. Alternators featuring this type of rotor are large in diameters and short in axial length.

2.3.2.2 Non-Salient type: Non-Salient or Cylindrical type rotors are used in high speed alternators, especially in turbo alternators. This type of rotor consists of a smooth and solid steel cylinder having slots along its outer periphery. Field windings are placed in these slots.

The DC supply is given to the rotor winding through the slip rings and brushes arrangement.

2.4 Synchronous generator characteristics:

2.4.1 Electrical frequency: Electrical frequency produced is locked or synchronized to the mechanical speed of rotation of a synchronous generator.

$$f = \frac{PN}{120} \quad (2.1)$$

Where f = Electrical frequency in Hz

P = Number of poles

N= Mechanical speed of the rotor, in r/min

2.4.2 The generated voltage: The generated voltage of a synchronous generator is given by:

$$Ea = K\varphi\omega \quad (2.2)$$

Where:

φ = Flux in the machine (function of I_F).

ω = Angular speed.

K = Synchronous machine constant.

2.4.3 Equivalent circuit: The internal voltage E_a produced in a machine is not usually the voltage that appears at the terminals of the generator. The only time E_a is same as the output voltage of a phase is when there is no armature current flowing in the machine.

The reasons that the armature voltage E_a is not equal to the output voltage V_f are :

–The armature reaction that is the distortion of the air-gap magnetic field by the current flowing in the stator.

–The self-inductance of the armature coils.

–The resistance of the armature coils.

–The effect of salient-pole rotor shapes.

When the rotor of a synchronous generator is spinning, a voltage E_a is induced in its stator. When a load is connected, a current starts flowing creating a magnetic field in machine's stator. This stator magnetic field Bs adds to the rotor (main) magnetic field Br affecting the total magnetic field and, therefore, the phase voltage.

The load current Ia will create a stator magnetic field Bs, which will produce the armature reaction voltage Estat. Therefore, the phase voltage will be:

$$V\emptyset = Ea + Estator \quad (2.3)$$

$$Estator = -jXIa \quad (2.4)$$

$$V\emptyset = Ea - jXIa \quad (2.5)$$

Where:

X=represents the effect of armature reaction reactance only.

In addition to the armature reaction, the stator coils have self-inductance and resistance, therefore we define:

$$Xs = X + Xa \quad (2.6)$$

$$V\emptyset = Ea - jXsIa - RaIa \quad (2.7)$$

2.4.4 Three Phase Equivalent Circuit: The voltages and current of the three phases are identical but 120 apart in angle. The three phases can be also either Y connected or connected.

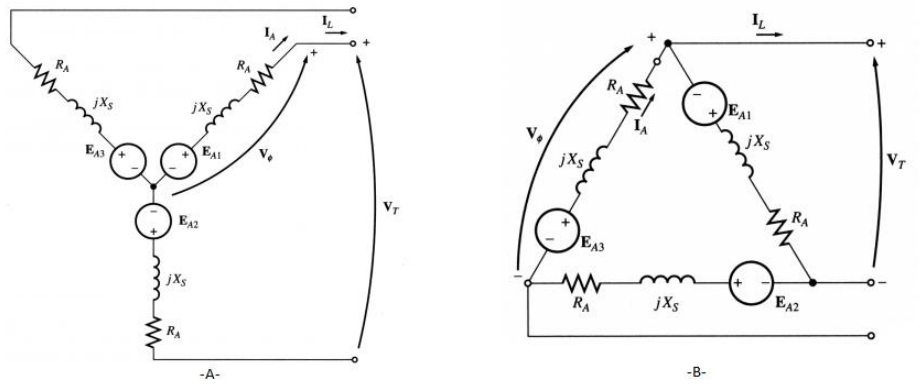

Figure 2.5: a: Y Connected 3 phase armature winding**.**

b: Δ Connected 3 phase armature winding.

2.4.5 Phasor diagram: Voltages in a synchronous generator are expressed as phasors because they are AC voltages. Since we have magnitude and angle, the relationship between voltage and current must be expressed by a two-dimensional plot.

It is noticed that, for a given phase voltage and armature current, a larger induced voltage EA is required for lagging loads than leading loads.

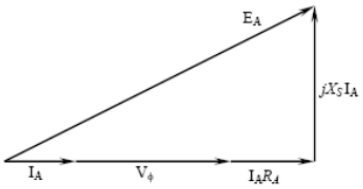

Figure 2.6: Phasor diagram of a synchronous generator at unity power factor (purely resistive Load).

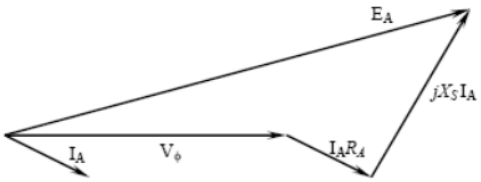

Figure 2.7: Phasor diagram of a synchronous generator at lagging factor (Inductive Load).

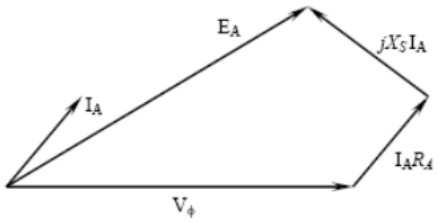

Figure 2.8: Phasor diagram of a synchronous generator at leading factor (Capacitive Load).

2.5 Principle of operation:

[5] Electricity is produced in alternators by electromagnetic induction. To generate electricity in a coil either the coil should rotate with respect to a magnetic field or a magnetic field should rotate with respect to the coil.

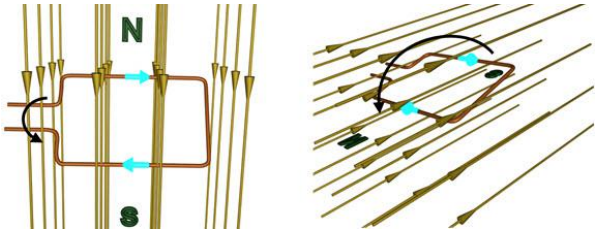

Figure 2.9: Basic working of a synchronous generator.

In our case, we are going to study the last approach, where a magnetic field should rotate with respect to the coil.

2.5.1 Main Parts and Working: Rotor and Stator are the two main parts of an alternator. Rotor produces a rotating magnetic field. Stator or Armature coils are stationary and rotating magnetic flux associated with the rotor induces electricity in the armature coils.

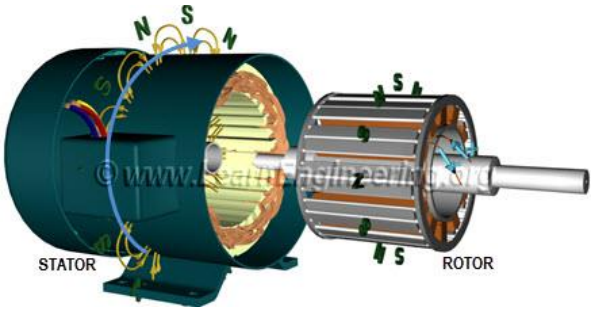

Figure 2.10: Components of synchronous generator.

The kind of rotor discussed here is known as Salient pole rotor. For gaining better insight of its working let us consider a rotor with just 4 poles. Rotor coils are excited with a DC power source. Magnetic field produced around it would be as shown in Figure 2.11.

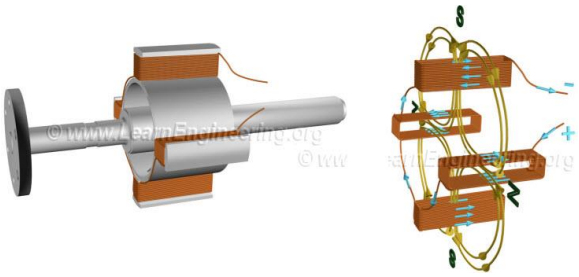

Figure 2.11: A 4-pole salient pole rotor and magnetic field produced around it when excited by a D.C power supply.

The rotor is made to rotate by a prime mover. This makes the rotor flux also rotate along with it, at the same speed. Such revolving magnetic flux now intersects the armature coils, which is fitted around the rotor. This will generate an alternating E.M.F across the winding.

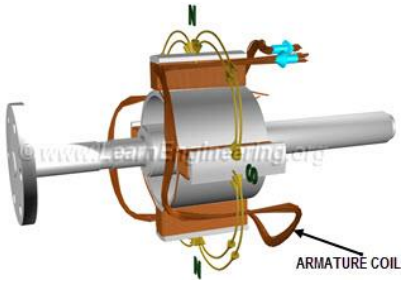

Figure 2.12: When rotor is made to rotate electricity gets induced in armature coils.

2.5.2 Frequency of Induced E.M.F: Since 4 pole rotor has got 2 pairs of N-S pole, when the rotor turns a half revolution the induced E.M.F takes one complete cycle. Therefore, it is clear that frequency of the induced E.M.F is directly proportional to the number of poles and rotor speed. It can be easily established that frequency of induced E.M.F f (Hz), rotor speed N (rpm) and number of poles P are connected through the equation (2.1):

$$f = \frac{PN}{120} \qquad (2.1)$$

It is clear from this relationship that, frequency of electricity produced is synchronized with mechanical rotational speed

2.5.3 Production of 3 Phase Electricity: For producing 3 phase A.C current, 2 more such armature coils which are in 120 degree phase difference with the first is put in the stator winding.

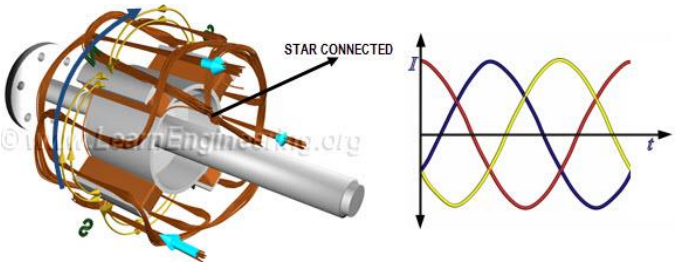

Figure 2.13: For producing 3-phase electricity 2 more armature wingdings, which are 120 degree apart from the first, which is introduced.

Generally, one end of these 3 coils are star connected and 3 phase electricity is drawn from the other ends. Neutral cable can be drawn from the star connected end.

2.5.4: Self Excited Generator: DC current is supplied to rotor via a pair of slip rings. This is the reason why rotating magnetic field approach is used in alternator. If rotating coil method were used, slip rings have to fitted along with the armature coils in order to collect electricity. However, transferring such high voltage electricity via slip ring is rather impractical. It is quite possible to transfer low voltage DC excitation current via slip rings.

This DC current is supplied either from an external source or from a small DC generator that is fitted on the same prime mover. Such alternators are called self excited.



Figure 2.14: Slip rings are used to supply DC current to the rotor coil; this DC current could come from an inbuilt DC generator.

2.6 Conclusion:

Synchronous generators are the workhorse of the power generation industry. The variation in voltage damages the equipment of the power system. With variation of load generator terminal output voltage will vary. It is desired to keep the terminal voltage in a specified limit. An automatic voltage regulator (AVR) helps in achieving this. Voltage regulation can be easily achieved by controlling the field current. If terminal voltage is below, the desired limit AVR increases the field current, thus the field strength. This will result in increase in terminal voltage. If terminal voltage is above, the specified limit the reverse is done.

Chapter 03 : Automatic Voltage Regulator

3.1 Introduction:

[6] An automatic voltage regulator is an electronic equipment that is used and designed to maintain the constant voltage level. [7] It is used to regulate the voltage where it takes the fluctuate voltage and changes them into a constant voltage. The fluctuation in the voltage mainly occurs due to the variation in load on the supply system.

The variation in voltage damages the equipment of the power system. This variation in the voltage can be controlled by installing the voltage control equipment at several places likes near the transformers, generator, feeders, etc.

3.2 Automatic voltage regulator of a generator:

[8] The AVR or Automatic Voltage Regulators function for generator is to ensure voltage generated from power generator running smooth to maintain the stable voltage in specified limits. It can stabilize the voltage value when it suddenly changes due to the load power supply demand change. If the generator running in parallel condition, the AVR can controlled the voltage that it produce to ensure of equal value for reactive load sharing.

[9] The AVR is an electronic device for automatically maintaining generator output terminal voltage at a set value under varying load and operating temperature. It controls output by sensing the voltage V_{out} at generator terminal and comparing it to a reference. The error signal is then used to adjust an average value of the field current.

3.4 Working of Automatic Voltage regulator:

3.4.1 Basic working: [10] An automatic voltage regulator is a device that is housed inside an electronic device. It is primarily used to maintain a consistent voltage level. It can regulate alternating as well as direct current.

3.4.2 How it works: It works on the principle of detection of errors. The output voltage of an AC generator obtained through a potential transformer and then it is rectified, filtered and compared with a reference. The difference between the actual voltage and the reference voltage is known as the error voltage. This error voltage is amplified by an amplifier and then supplied to the main exciter or pilot exciter.

[7] Thus, the amplified error signals control the excitation of the main or pilot exciter through a buck or a boost action (i.e. controls the fluctuation of the voltage). Exciter output control leads to the controls of the main alternator terminal voltage.

3.5 Application of the Automatic Voltage Regulator: The main functions of an AVR are as follows.

It controls the voltage of the system and has the operation of the machine nearer to the steady state stability.

It divides the reactive load between the alternators operating in parallel.

The automatic voltage regulators reduce the overvoltages, which occur because of the sudden loss of load on the system.

It increases the excitation of the system under fault conditions so that the maximum synchronizing power exists at the time of clearance of the fault.

[7] When there is a sudden change in load in the alternator, there should be a change in the excitation system to provide the same voltage under the new load condition. This can be done by the help of the automatic voltage regulator. The automatic voltage regulator equipment operates in the exciter field and changes the exciter output voltage, and the field current.

3.6 Operations of Automatic Voltage Regulators:

Automatic voltage regulator is designed for both single and three phase alternating current applications. The phase and phase regulation has been classified into two types .The single phase voltage regulation is the best method as it provides balance phase to phase voltage level .In case of three phase regulation, large difference in voltage level causes failure of electronic and electric devices due to overheating and vibration.

3.6.1 Single Phase regulation:

The single phase regulators are used in units pole that are mounted outdoors .Single phase voltage regulators are combined together and they provide voltage regulation for three phase .

3.6.2 Three Phase regulation :

Three phase regulator can regulate all three phases at once or it may regulate all the three phases independently .In three phase power, it has not been observed that one phase has very high voltage while other has low voltage.

3.7 Conclusion:

In this chapter, we have seen that the Automatic Voltage Regulator controls the voltage of the system and has the operation of the machine nearer to the steady state stability. It reduce the overvoltage, which occur because of the sudden loss of load on the system. The Automatic Voltage Regulator increases the excitation of the system under fault conditions so that the maximum synchronizing power exists at the time of clearance of the fault.

Chapter 04 : Microcontroller

4.1 Introduction:

Microcontrollers have directly or indirectly impact on our daily life; However, their presence is just unnoticed. They are used to control the functions of embedded systems in office machines, robots, home appliances, motor vehicles, security system, industrial automation and many other gadgets. This tremendous use of the microcontrollers is due to their high accuracy, performance and reliability compared to the analog controller systems that have been used before the microprocessor revolution.

4.2 Microcontroller definition:

[12] A microcontroller is known as a small computer, it is a programmable digital integrated circuit comprises components like processor, memory elements, inputs/outputs with interconnection between them known as sequential circuits like flipflops and counters.

A microcontroller contains: Central processing unit (CPU), Random access memory (RAM) , Read only memory (ROM) , Input/output ports ,Timers and counters , Analog to digital converter (ADC) , Digital to analog converter (DAC) , Interrupts, oscillators and serial ports.

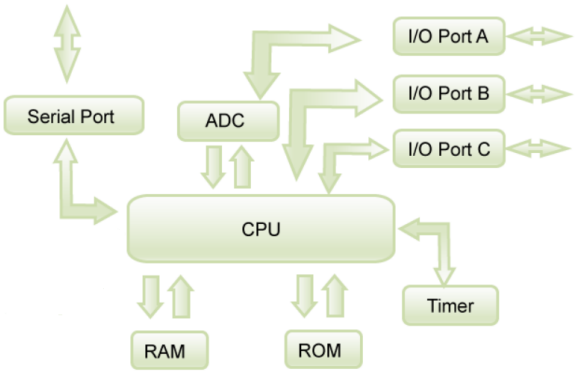

Figure 4.1: Components of Microcontroller.

4.3 Types of microcontrollers:

[13] There are a so many microcontroller families available, those are 8051, PIC, AVR, ARM …etc. they are divided into categories according to their memory and bits and instruction sets architecture.

4.3.1 Classification according to memory devices:

4.3.1.1: External memory microcontroller: it has not all the functional blocks available on the chip.

4.3.1.2: Embedded memory microcontroller: it has all the functional blocks available on the chip.

4.3.2 Classification according to number of bits:

4.3.2.1: 8 bits microcontrollers: they execute logic and arithmetic operations, they are used in position and speed control applications.

4.3.2.2: 16 bits microcontrollers: they execute with greater precision and performance compared with 8-bit, they are used in high speed applications such as Robotics.

4.3.2.3: 32 bits microcontrollers: they execute with high precision and performance, they are used in very high speed applications as intelligent control systems and medical appliances.

4.3.3 Classifications according to instruction set:

4.3.3.1: RISC architecture: it means reduced instruction set computer, it reduces the cycles per instruction at the cost of the number of instructions per program.

4.3.3.2: CISC architecture: it means complex instruction set computer, it reduces the number of instructions per program sacrificing the number of cycles per instruction.

4.3.4 Classification according to memory architecture:

4.3.4.1:Harvard Memory Architecture Microcontroller: it has a dissimilar memory address space for the program and data memory.

4.3.4.2: Princeton Memory Architecture Microcontroller: it has a common memory address for the program and data memory.

4.4 AVR Microcontrollers:

[14] AVR was developed by Atmel in 1996 where the AVR architecture was developed by Alf-Egil Bogen and Vegard Wollan that is why AVR stands for **A**lf-Egil Bogen and **V**egard Wollan's **R**ISC processor. AVR and is a Harvard embedded memory architecture 8-bit RISC microcontroller. AVR takes only one clock cycle per instruction with a speed of 12 million instructions per second which is higher than the 8051 and PIC microcontrollers and it consumes less power.

4.4.1 Comparison between the most common families of microcontroller:

Table 4.1: Comparison between the most common families of microcontroller:

Descriptions	8051	PIC	AVR
SPEED	Slow	Moderate	Fast
MEMORY	Small	Large	Large
ARCHITECTURE	CISC	RISC	RISC
ADC	Not present	Inbuilt	Inbuilt
Timers	Inbuilt	Inbuilt	Inbuilt
PWM Channels	Not Present	Inbuilt	Inbuilt

4.4.2 Types of AVR: AVR microcontrollers are divided into three main types:

- TinyAVR
- MegaAVR
- XmegaAVR

Table 4.2: Types of AVR microcontrollers:

	Pins	Flash Memory
TinyAVR	6-32	0.5-8 KB
MegaAVR	28-100	4-256KB
XmegaAVR	44-100	8-384KB

4.5 ATmega328/P :

ATmega328 is a 28-pin low power high performance megaAVR microcontroller up to 20 million instructions per second.

4.5.1 Features of ATmega328/P :

- 32KB flash memory
- 1 KB EEPROM (Electrically-Erasable Programmable Read-Only Memory)
- 2 KB SRAM (Static RAM)
- 23 general purpose I/O lines
- Two 8-bit timers
- One 16-bit timer
- A/D converter
- Six channel PWM

4.5.2 Pin Description of ATmega328 :

[14] ATmega328 is shown in the figure bellow:

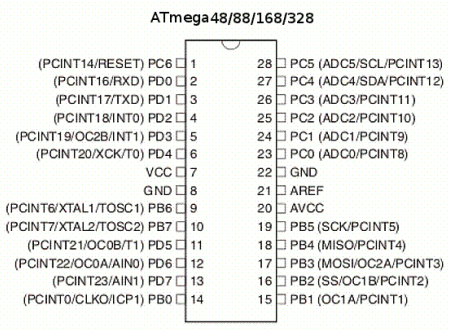

Figure 4.2:ATmega328.

Vcc: Digital supply voltage.

GND: Ground.

Port B: Port B is an 8-bit bi-directional I/O port.

Port C: Port C is a 7-bit bi-directional I/O port with internal pull-up resistors,

PC6/RESET

Port D: It is an 8-bit bi-directional I/O port with internal pull-up resistors.

AVcc: AVcc is the supply voltage pin for the ADC.

AREF: AREF is the analog reference pin for the ADC.

4.6 Arduino Uno:

4.6.1 Arduino Uno definition: [15] Arduino Uno is an open source hardware microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack and a reset button. It contains everything needed to support the microcontroller.

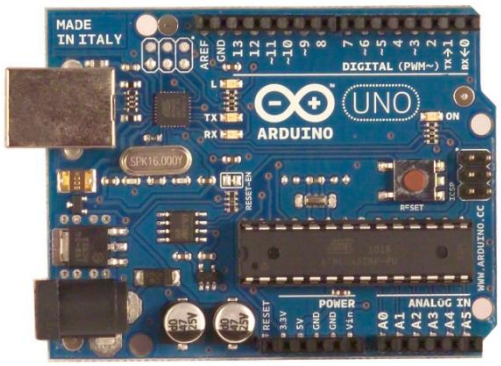

Figure 4.3: Arduino Uno.

4.6.2 Board description: Arduino Uno diagram is shown in the figure bellow

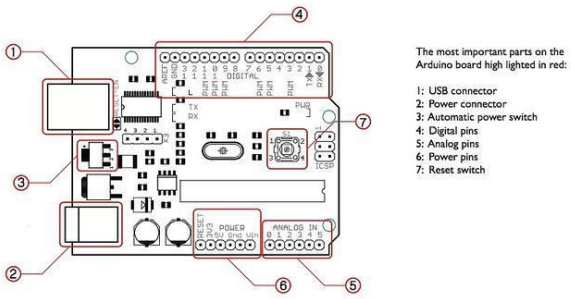

Figure 4.4: Arduino Uno diagram.

Power: Arduino can be power either from the pc through a USB or from external source through the power connector or Vin pin. It can operate on an external supply of 7 to 12V.

Digital pins: It consists of 14 digital inputs/output pins, each of which provide or take up 40mA current. pins 3,5,6,9,10,11 which provides PWM output and pin 13 where LED is connected.

Analog pins: It has 6 analog input/output pins, each providing a resolution of 10 bits.

Reset: It resets the microcontroller when low.

4.7 Conclusion:

In this chapter, one powerful digital controller has been introduced and due to its simplicity, speed and integrity which makes the Arduino Uno with its relative good performance a good choice for our project to implement an automatic voltage regulator to serve as a controller for our synchronous generator excitation system.

Chapter 05 :
Design and simulation with Simulink

5.1 Introduction:

One of the major auxiliary parts of the synchronous generator is the automatic voltage regulator (AVR). Its role is to regulate the terminal voltage of the synchronous generator whenever any drop in terminal voltage occurs due to sudden or accident change in loads or at any fault occurrence. The AVR also improves the transient stability of the power system. This chapter deals with the design and the simulation of an automatic voltage regulator of an AC synchronous generator using microcontroller. This simulation was developed using MATLAB/Simulink.

5.2 AVR Design:

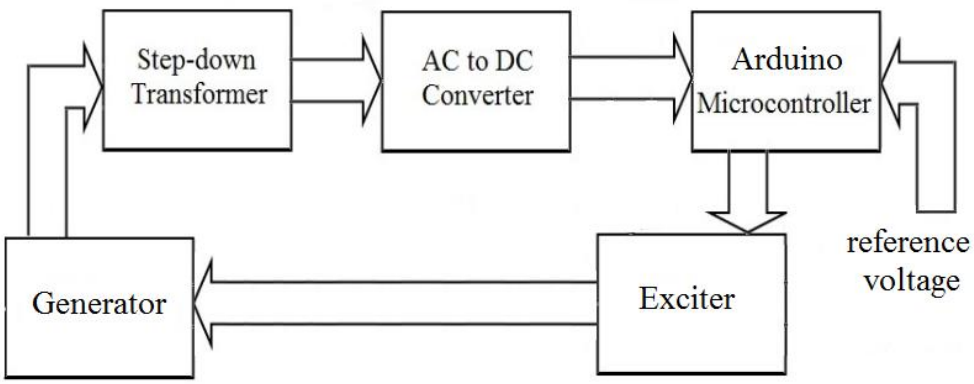

Figure 5.1: General Block Diagram of the design of the AVR of Synchronous generator using microcontroller.

The function of the AVR, where its block diagram shown in figure 5.1,is to maintain the generator terminal voltage at a constant value. Any change in the terminal voltage from the desired value is detected and is used as the actuating signal to control the excitation system. The output voltage of the synchronous generator will be transformed, converted, rectified and filtered. Then it will be supplied to the microcontroller that will be used to control the excitation current. If the output voltage of the generator is increased, the microcontroller will decrease the excitation current, which decreases the output voltage of the synchronous generator until it reaches a

constant value. If the output voltage is decreased, the microcontroller will increase the excitation current, so that the output voltage will increase until it reaches a rated value.

5.3 Results and discussion:

5.3.1 Using a Generator Simulink Model: In figure 5.2, the output voltage of the synchronous generator will be reduced using a step-down transformer. Then, this output voltage will be converted to DC through a full wave rectifier and capacitor filter. The DC voltage will be compared to a reference voltage in order to produce an error signal. The error signal enters to the PID block that will control the duty cycle of the PWM signal. The PWM signal will switch ON and OFF the IGBT with high frequency in order to control the DC voltage that may be used to excite the synchronous generator.

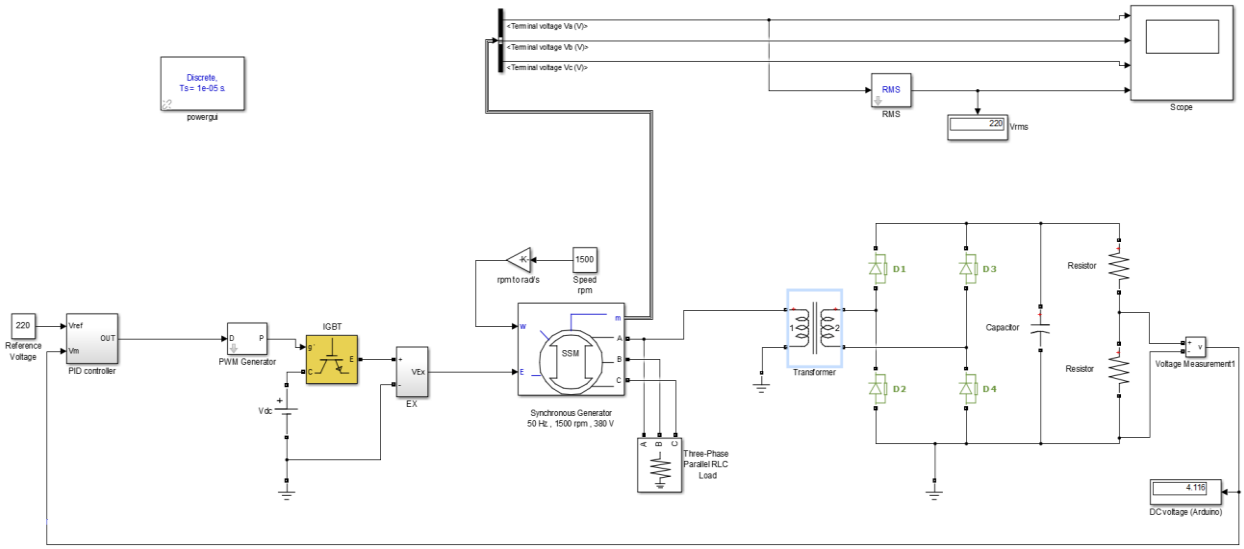

Figure 5.2: The Simulink Model of the synchronous generator associated with AVR.

After running the simulation of the circuit illustrated in figure 5.2 using MATLAB/Simulink, the three-phase voltage output generated by the synchronous generator is visualized using the scope as shown in figure 5.3.

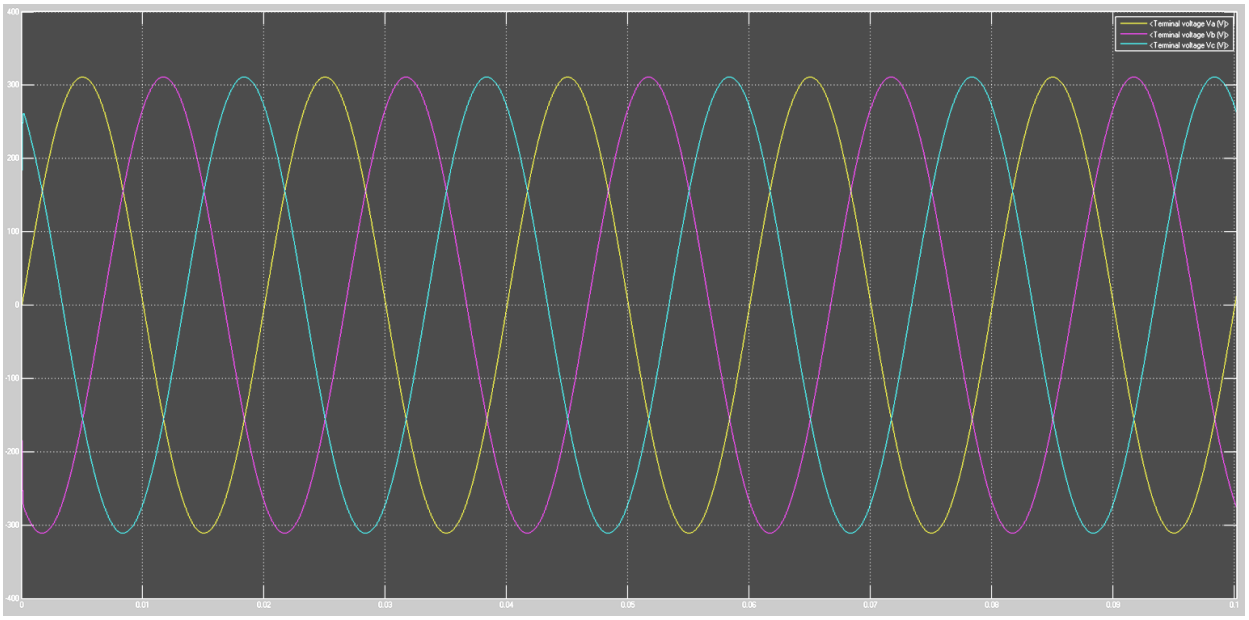

Figure 5.3: Simulation results shows voltage profile of the synchronous generator.

In order to analyze the system and design controller, the output voltage is needed to be in the RMS value. The open loop data of our system has been recorded as shown in figure 5.4.

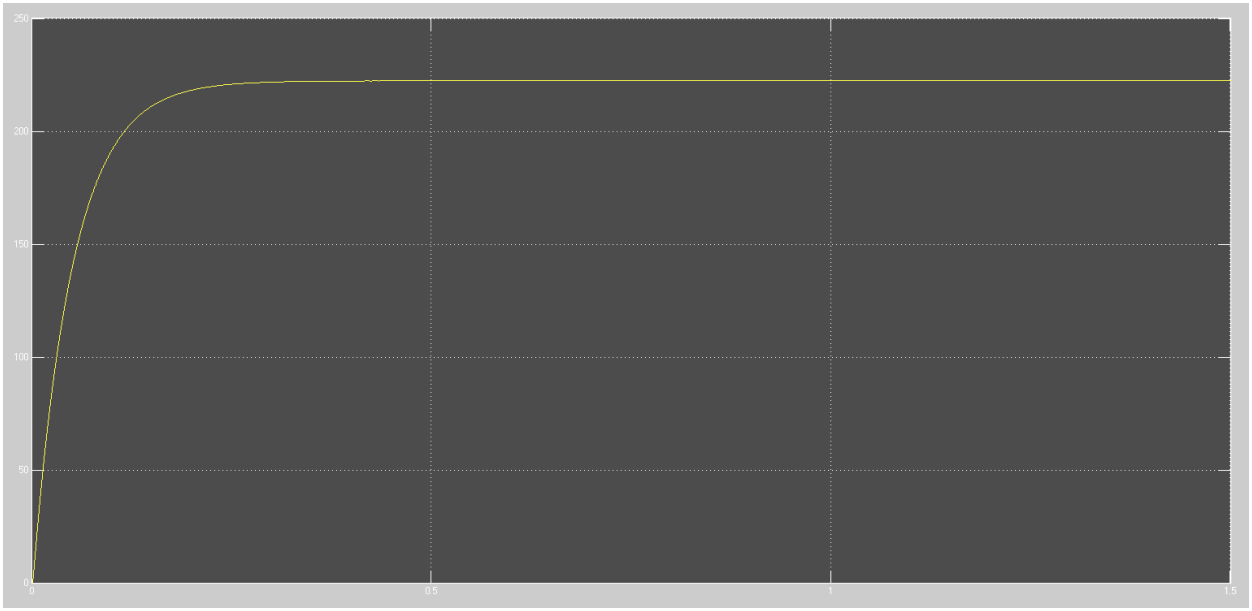

Figure 5.4: The RMS value of the output voltage.

A PID controller is used to control the system and to get a better response. For this reason, the transfer function of this system is obtained using the system identification toolbox provided by MATLAB. This process has been done several times with several estimated number of poles and zeros. The following model transfer function with two poles gives the best approximation with 99.79% of accuracy.

$$G(s) = \frac{1.132e04}{s^2+584.8\,s+1.132e04} \quad (5.1)$$

The open loop system transfer function has the following poles which define the system behavior: -569.99 + 573.83i, -569.99 – 573.83i, -20.03. This system is stable by nature because all its poles are located in the left half plane of the S domain. Using MATLAB, different time domain characteristics have been calculated to evaluate the system, which are given in table 5.1.

Table 5.1: The open loop characteristics:

Rising time	Settling time	Overshoot	Steady-state error
0.19 s	0.29 s	0%	0%

The open loop system simulation was done using the Simulink generator model, and because of that, the whole system has relatively a good time response as shown in table 5.1. However, a closed loop system is needed in case of disturbances and for better input tracking.

The closed loop system has been constructed then the model has been simulated giving an output shown in figure 5.5:

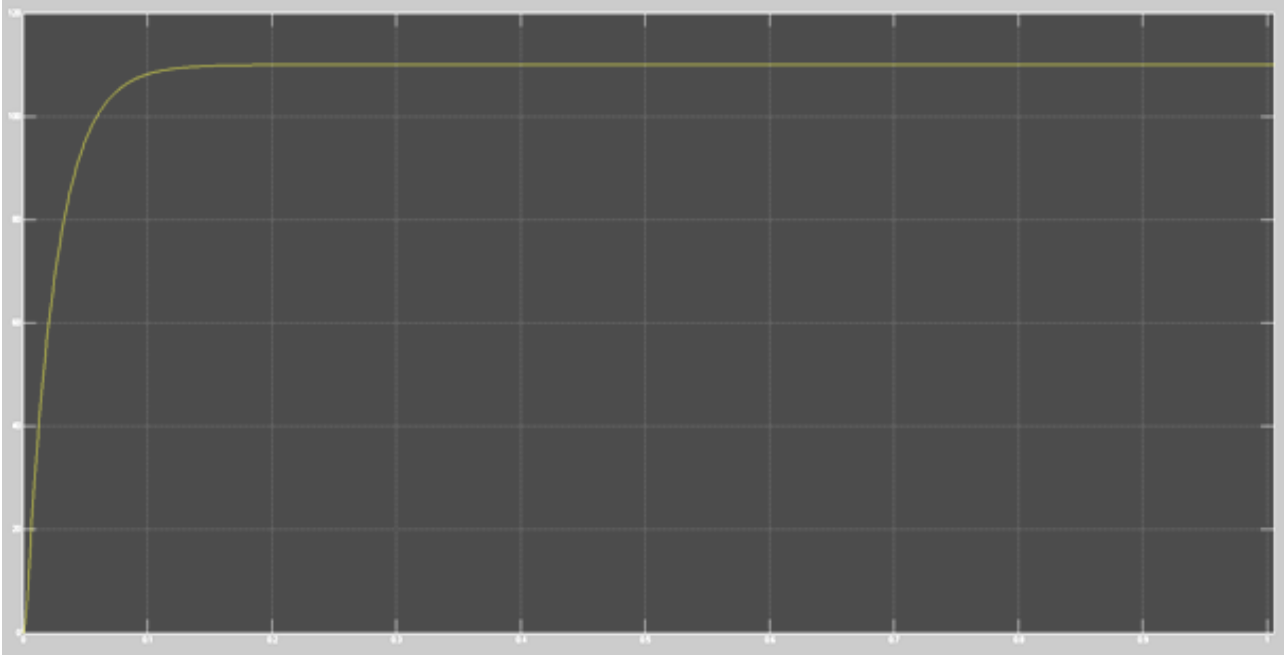

Figure 5.5: The closed loop the system response.

The closed loop system transfer function has the following poles: -559.22 + 563.73i, -559.22 + 563.73i, -41.55 , with a time domain characteristics shown in table 5. 2.

Table 5.2: Closed loop characteristics without using PID:

Rising time	Settling time	Overshoot	Steady-state error
0.07 s	0.1 s	0%	-50%

The closed loop system without any controller has a better transient response compared to the open loop system; however, the steady state error is very high. In order to decrease the error and speed up the system a PI controller is implemented with coefficients calculated using the PID auto-tune library provided with MATLAB.

PI controller coefficients can be obtained to enhance the performance of the system and each one results a different output response. Two cases results are illustrated in Figure 5.6 and Figure 5.7 with time performance measures presents in table 5.3.

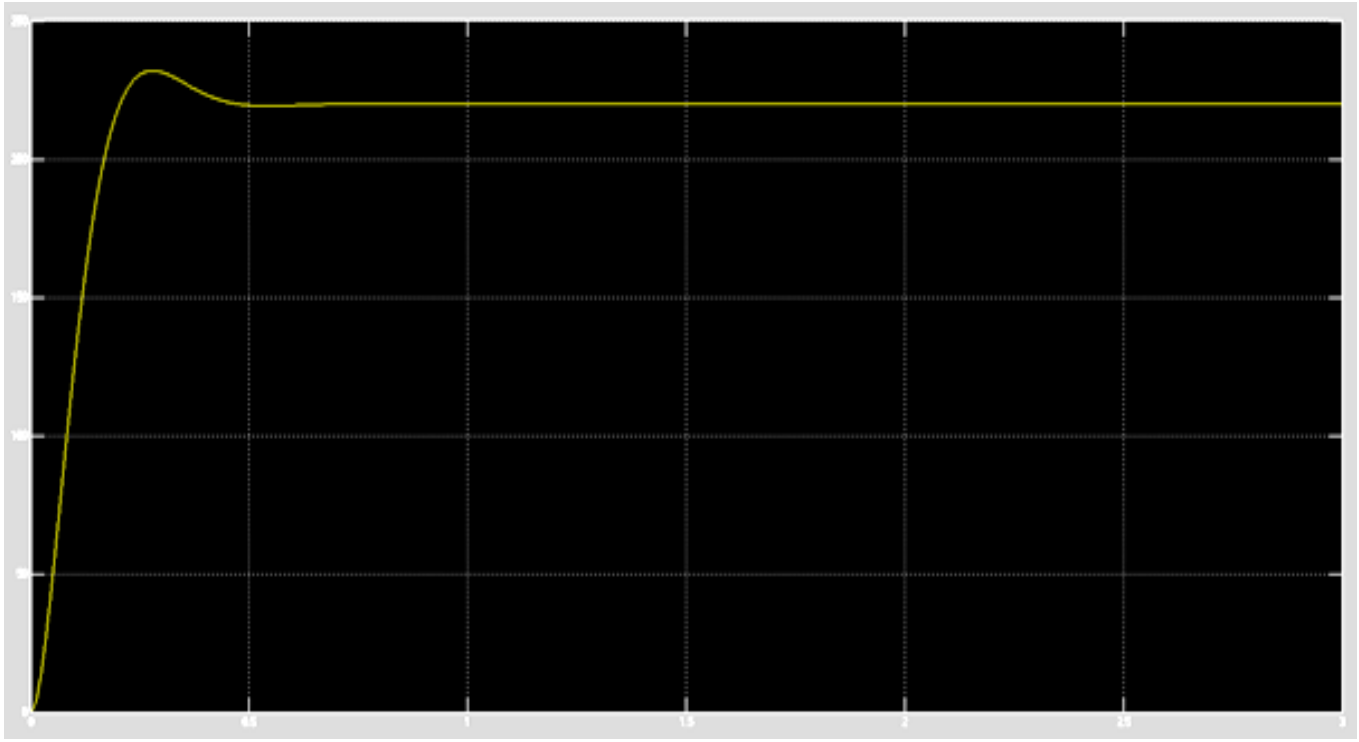

Figure 5.6: Closed loop step response with Kp = 0.1, Ki = 20.

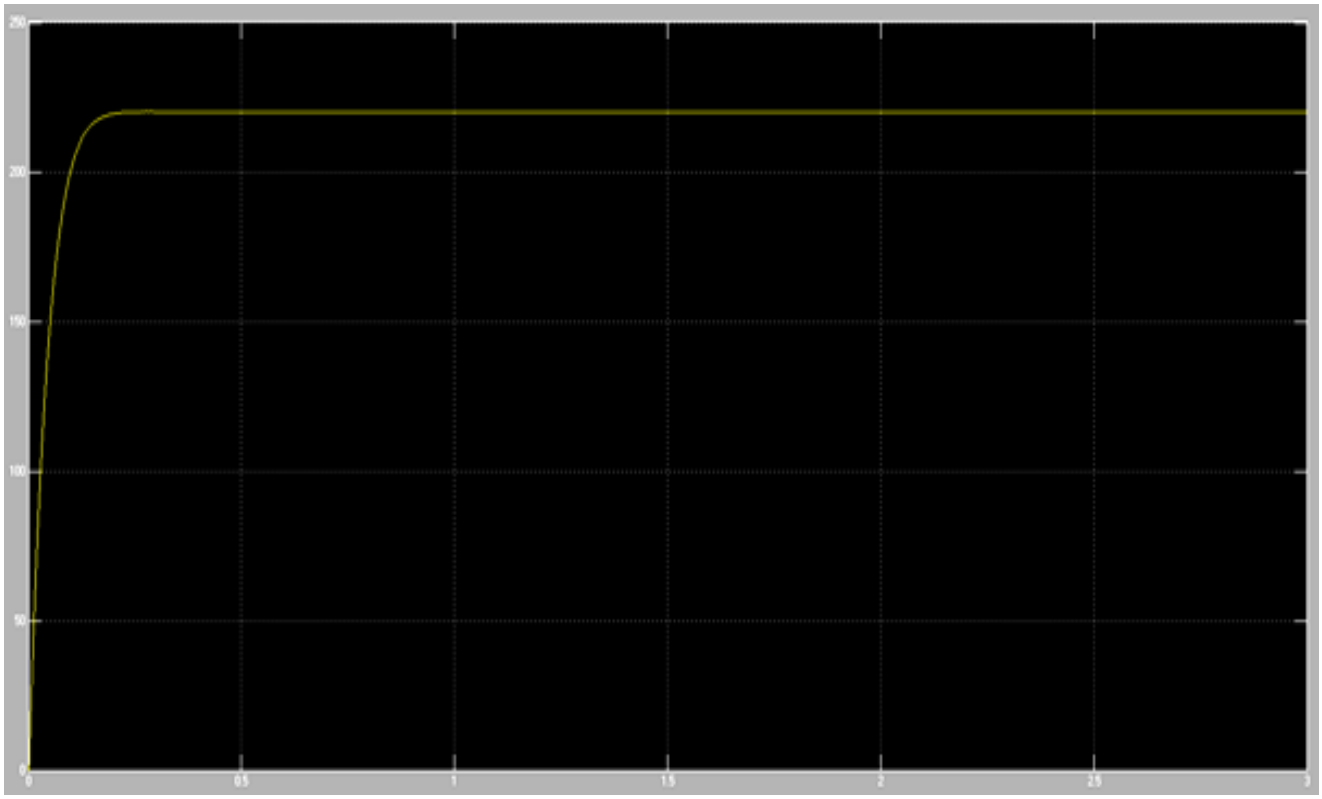

Figure 5.7: Closed loop step response with Kp = 1.8, Ki = 40.

Table 5.3: Closed loop characteristics using PI:

	PI values	Settling time	overshoot
Figure 5.6	Kp = 0.1 ,Ki = 20	0.28 s	5.45%
Figure 5.7	Kp = 1.8 ,Ki = 40	0.1 s	0.07%

The first case has a better settling time but worst overshoot than the open loop response. Whereas, the second case has a better settling time and a small overshoot which can be neglected. As a conclusion, we can conclude that the results shown in figure 5.7 and the parameters explained in table 5.3 help us to reach our objectives.

5.3.2 PID Parameters Identification: In this part, the simulation has been done with our measured data from the system in order to get the PID parameters for our implementation. Three different transfer function estimations have been obtained with different orders using the system identification toolbox in MATLAB as shown in figure 5.8.

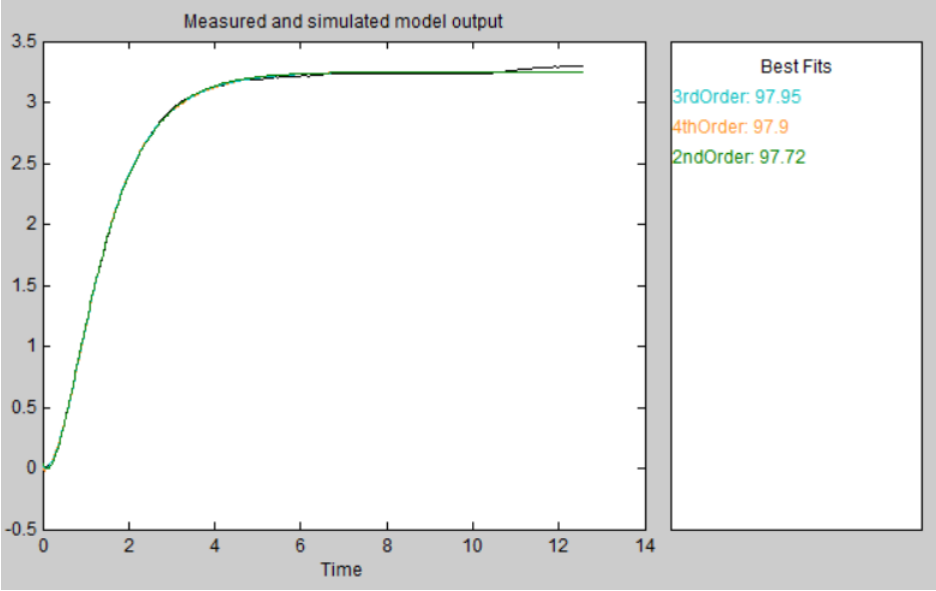

Figure 5.8: Transfer function estimations using toolbox in MATLAB.

The obtained open loop transfer functions are:

Second order estimation: $$G1(s) = \frac{2.058}{s^2+3.046\,s+2.091} \quad (5.2)$$

Third order estimation: $$G2(s) = \frac{4.51}{s^3+4.662\,s^2+8.424s+4.579} \quad (5.3)$$

Fourth order estimation: $$G3(s) = \frac{338.5}{s^4+61.95\,s^3+291.2\,s^2+592\,s+343.4} \quad (5.4)$$

The transfer functions have been simulated with Simulink in order to analyze the system. As shown in figure 5.9.

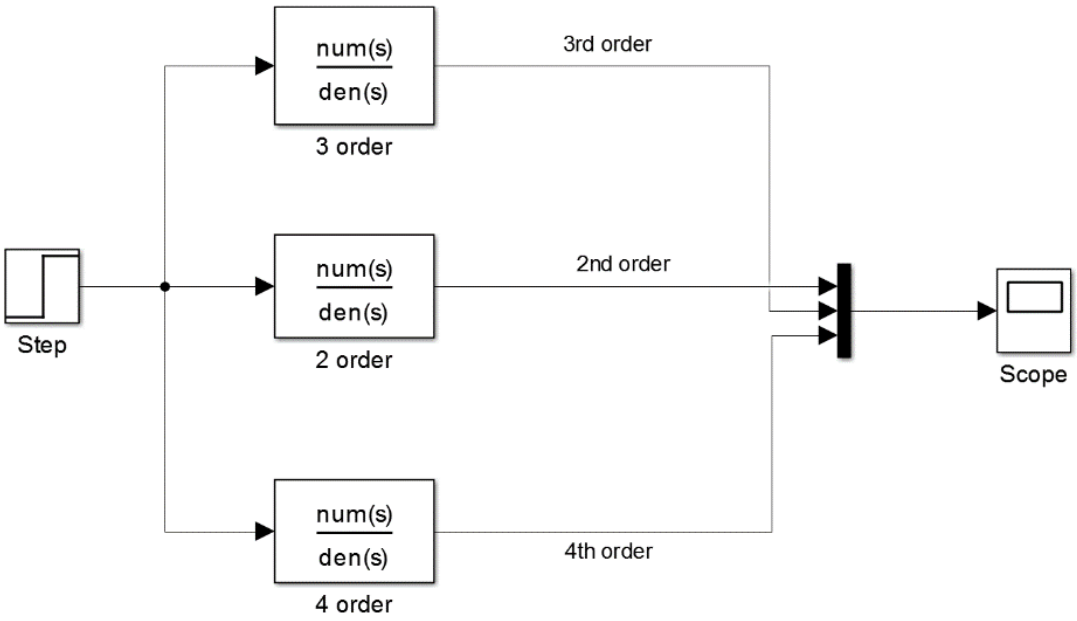

Figure 5.9: The open loop transfer functions implementation using Simulink.

Where the step response of each estimation is shown in figure 5.10.

The time response characteristics of each estimation are shown in table 5.4.

Table 5.4: The time response characteristics of each estimation:

	Rising time (s)	Settling time (s)	Overshoot (%)	SteadyState error %
2 order	3.3	4.44	0	1.5
3 order	3.57	5.05	0	1.59
4 order	3.45	4.93	0	1.6

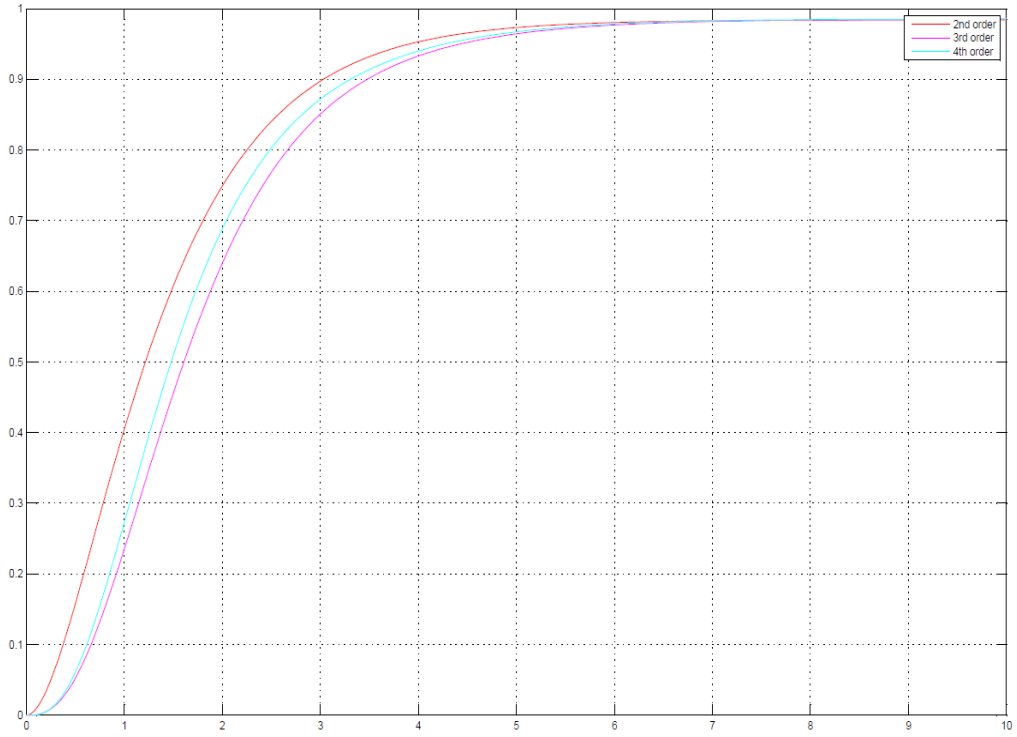

Figure 5.10: Step response of each estimation.

From the simulation results, it is clear that the open loop system is stable by nature with a negligible steady state error and no overshoot; however, the rising and settling times are not optimal which makes the system a bit slow.

After closing the loop in Simulink as shown in figure 5.11:

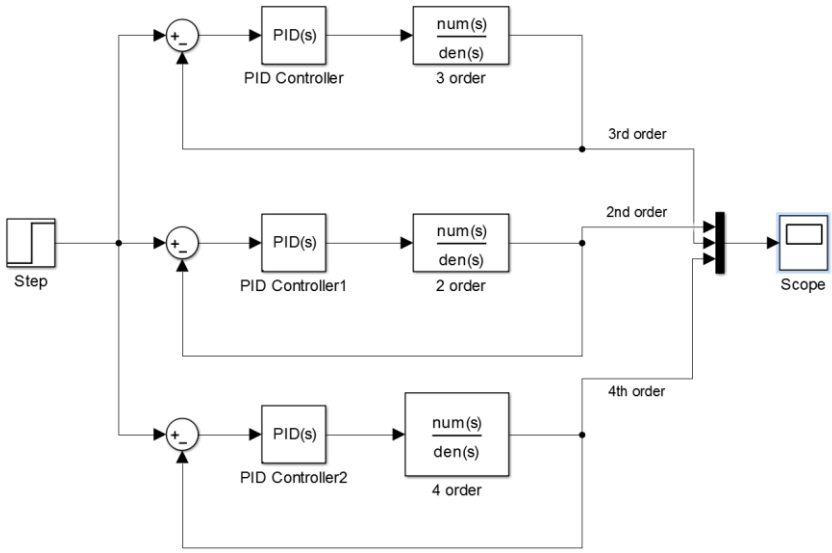

Figure 5.11: The closed loop implementation using Simulink**.**

The resulting step responses are shown in figure 5.12 with time response characteristics shown in table 5.5.

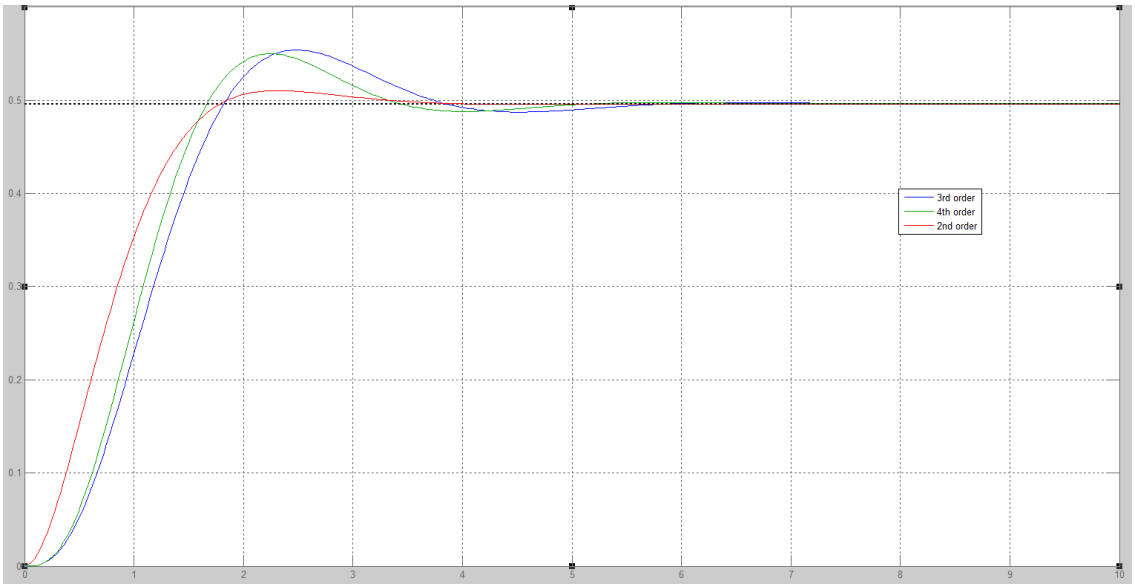

Figure 5.12: Step response of the estimated transfer functions.

Table 5.5: Time response characteristics:

	Rising time (s)	Settling time (s)	Overshoot (%)	SteadyState error %
2 order	1.36	2.83	2.91	50
3 order	1.33	3.58	11.64	50
4 order	1.2	3.18	10.81	50

The performance of the closed loop system has been enhanced using a PID controller with coefficients obtained using the auto-tune library in MATLAB. The results are shown in figure 5.13 and table 5.6.

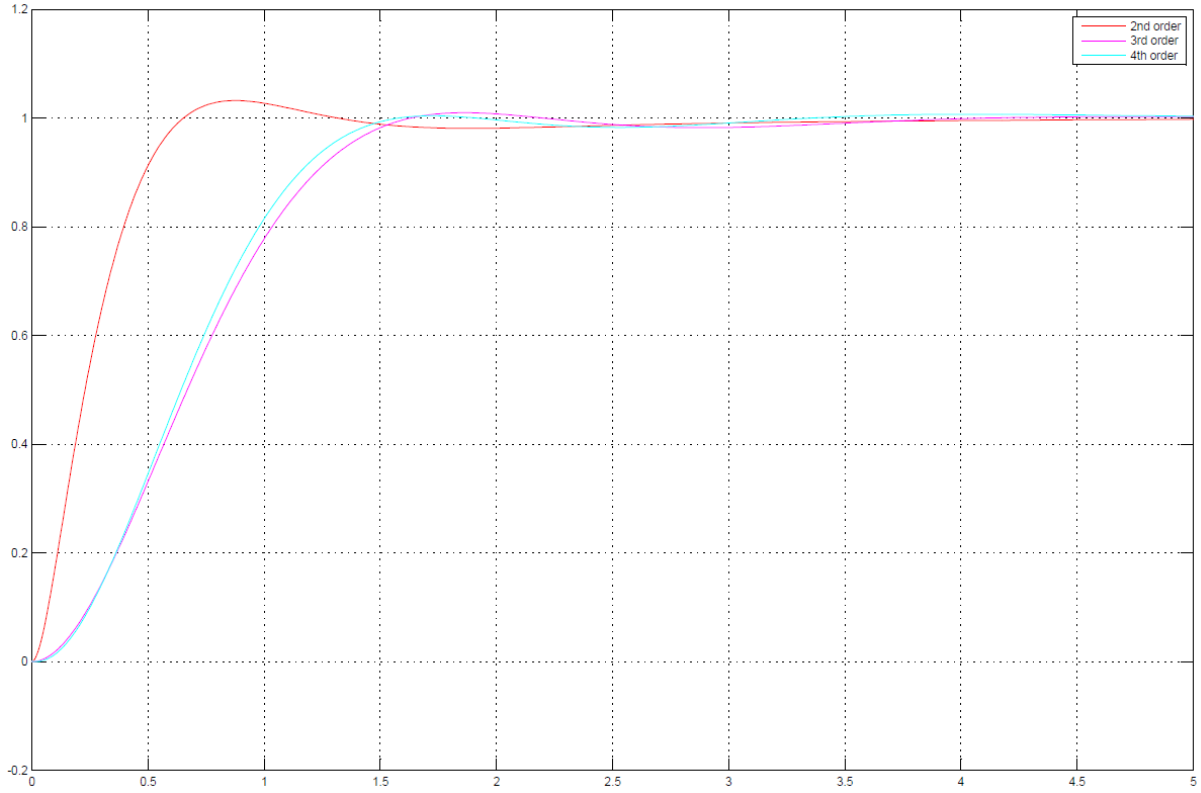

Figure 5.13: Closed loop step responses with PID.

Table 5.6: PID coefficients and time response characteristics:

	Proportional gain Kp	Integral gain Ki	Derivative gain Kd	Rising time (s)	Settling time (s)	Overshoot (%)	SteadyState error %
2 order	6.20	3.63	1.17	0.41	1.09	3.2	0
3 order	2.27	1.42	0.90	0.98	1.49	0.96	0
4 order	2.15	1.50	0.76	0.9	1.41	0.68	0

From the previous analysis, it can be noticed that the second order transfer function is less accurate than the two other models, and the third and fourth order transfer functions have approximately the same time performance measures in both open and closed loop. In addition, our system consists of generator which is a first order system, and a transformer which is a first order system too, and a low pass filter which is also a first order system, so the hole system is a third order system, this leads to restrict the next analysis to only the 3rd order transfer function model.

5.4 Conclusion:

In this chapter, the design and the simulation of an Automatic Voltage Regulator have been done using MATLAB/Simulink. Also, we have used a generator Simulink model in order to test the circuit model of the AVR. In addition, in the section 5.3.2, the PID controller parameters have been identified using MATLAB in order to implement an AVR to control the generator available in our laboratory.

Chapter 06 : Design and implementation

6.1 Introduction:

Due to the difference between the real world application of electrical systems and the software bases analysis, a design or development in a network needs a practical approach in order to show how this system works in real installations. The AVR of a synchronous generator using microcontroller have been designed and implemented in this project. It is used to regulate the output voltage of the AC generator around 132V RMS.

6.2 Instrumentation of the AVR:

This part includes the instruments needed in the implementation of the project:

6.2.1 Potential Transformer: It is a device that measures the voltage of electrical power supplied to the consumers. It uses the principle of electromagnetic induction to transform the voltage (alternating difference) from high value to low safe one.

6.2.2 Full Wave Rectifier (Bridge of diodes): A Full wave rectifier is a circuit arrangement, which converts the input alternating current (AC) to direct current (DC). In this rectifier, four diodes are used. The four diodes are connected in the form of a bridge to the transformer and the load as shown in figure 6.1.

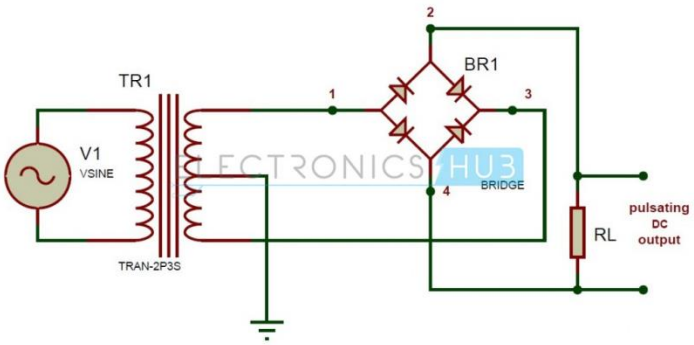

Figure 6.1: Bridge Rectifier Circuit Diagram

6.2.3 Filter: A filter consists of a capacitor, which filters out a certain frequency or range of frequencies from a circuit. The DC voltage of the rectifier output is not pure DC, in this reason a filter capacitor is placed across the output terminals. These capacitors smooth out the pulsation and give almost pure DC voltages.

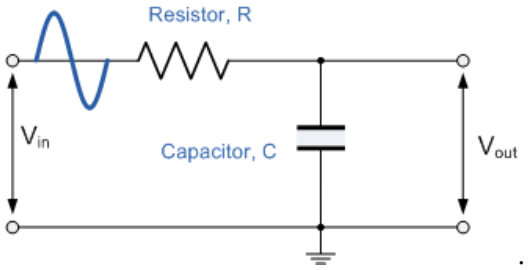

Figure 6.2: Low pass filter.

6.2.4 MOSFET: The metal–oxide–semiconductor field-effect transistor is a unipolar transistor. It has an insulated gate whose voltage determines the conductivity of the device. In this project, MOSFET is used in the cutoff and saturation region, this means it is used as switching device

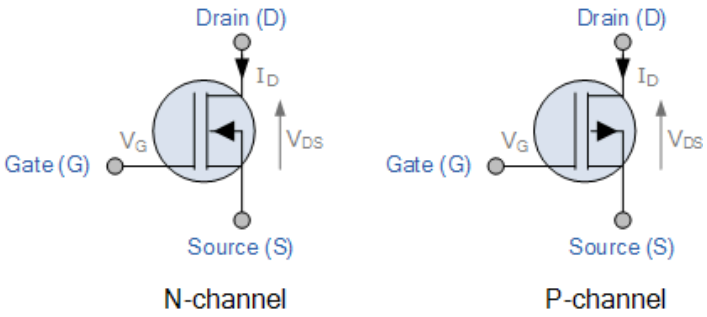

Figure 6.3: MOSFET.

6.2.5 Optocoupler: The optocoupler also known as an optical isolator is a component that transfers electrical signals between two isolated circuits by using a light emitting diode and a phototransistor.

In this project, the optocoupler is used as a gate driver for the MOSFET, and to protect the Arduino from a high current sink from the circuit.

6.2.6The Pulse width modulation: PWM technique is used in the control of the generator excitation voltage by varying its average value; this is done through varying the duty cycle of the signal over the full range.

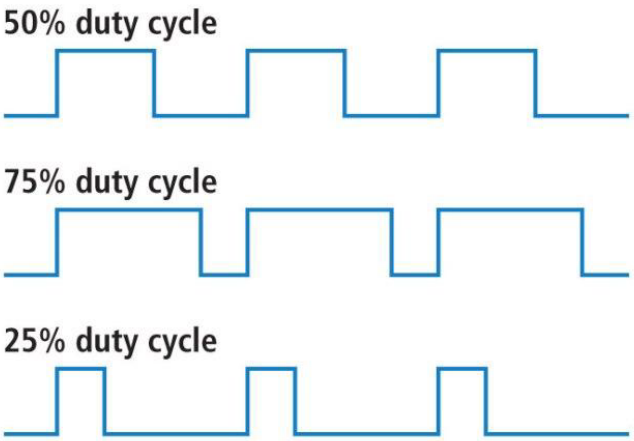

Figure 6.4: PWM signals with different Duty Cycles.

The term duty cycle describes the proportion of ON time to the period of signal. Duty cycle is expressed in percent.

$$Duty\ cycle = \frac{\text{On Time}}{\text{Period}} \times 100\% \quad (6.1)$$

6.3AVR implementation using PID:

6.3.1 PID Controller: A PID controller continuously calculates an error value e (t) as the difference between a desired set point and a measured process variable and applies a correction based on proportional, integral, and derivative terms. The controller attempts to minimize the error over time by adjusting a control variable u (t)

$$u(t) = Kp.e(t) + Ki\int_0^t e(\tau)d\tau + Kd\ \frac{de(t)}{dt} \quad (6.2)$$

Where Kp, Ki and Kd denote the coefficients for the proportional, integral, and derivative terms, respectively.

6.3.2 PID Algorithm Implementation: PID algorithm has been implemented within the Arduino software using C++ programing language.

The PID program is shown in Figure 6.5

```
float  PID_compute(float setPoint, float measured, float timeStep )
{
  // Calculate error terms
 float  error = setPoint - measured ;
 float  errorIntegral += (error + errorPrevious) / 2 * timeStep ;
 float  errorDerivative = (error - errorPrevious) / timeStep ;

 // save the current error to the next step
 float  errorPrevious = error;

  // Calculate the PID output
  float  PID_out = Kp * error + Ki * errorIntegral + Kd * errorDerivative;

return PID_out;
  }
```

Figure 6.5: The implemented PID algorithm (PID program)

6.4 Schematic diagram:

The schematic diagram consists of two parts, the generator and the microcontroller. The output voltage of the generator is reduced and converted to DC through a step-down transformer and a full wave rectifier and a capacitor, a Zener diode is added in parallel with the capacitor to protect the Arduino from a higher voltage than 5V . The obtained DC voltage will be supplied to the Arduino ADC to be converted into a 10-bit digital value, then; it will be processed by the microcontroller program in order to control the generator excitation voltage.

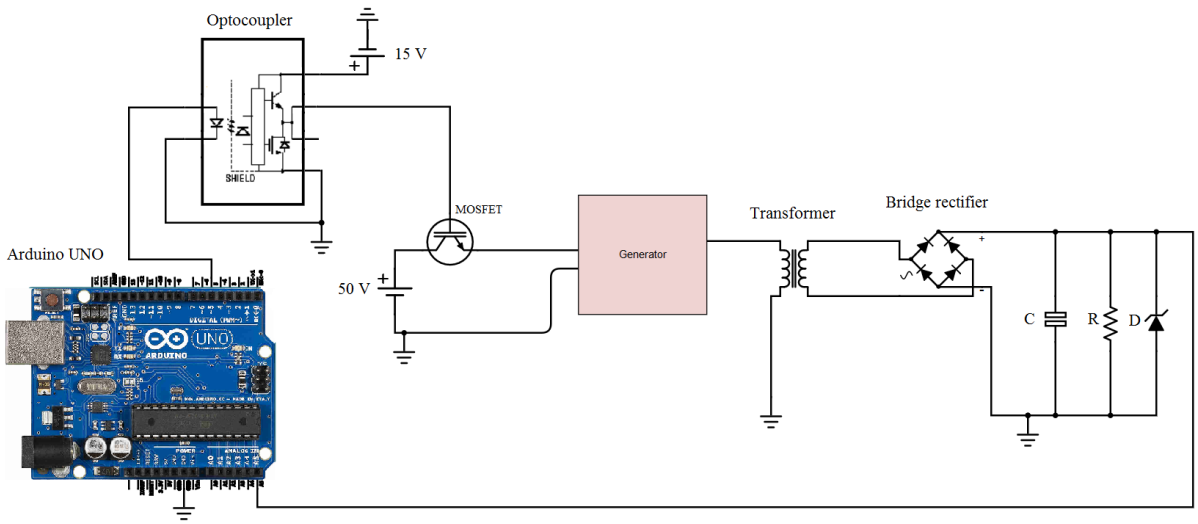

Figure 6.6: Schematic diagram

The microcontroller generates a PWM signal to the gate driver of the MOSFET which controls the excitation voltage fed from a DC power supply; by changing the PWM duty cycle, which in turn increases or decreases the output voltage of the synchronous generator.

6.5 Results and discussion:

The schematic diagram shown in figure 6.6 has been implemented successfully as shown in figures 6.7 and 6.8

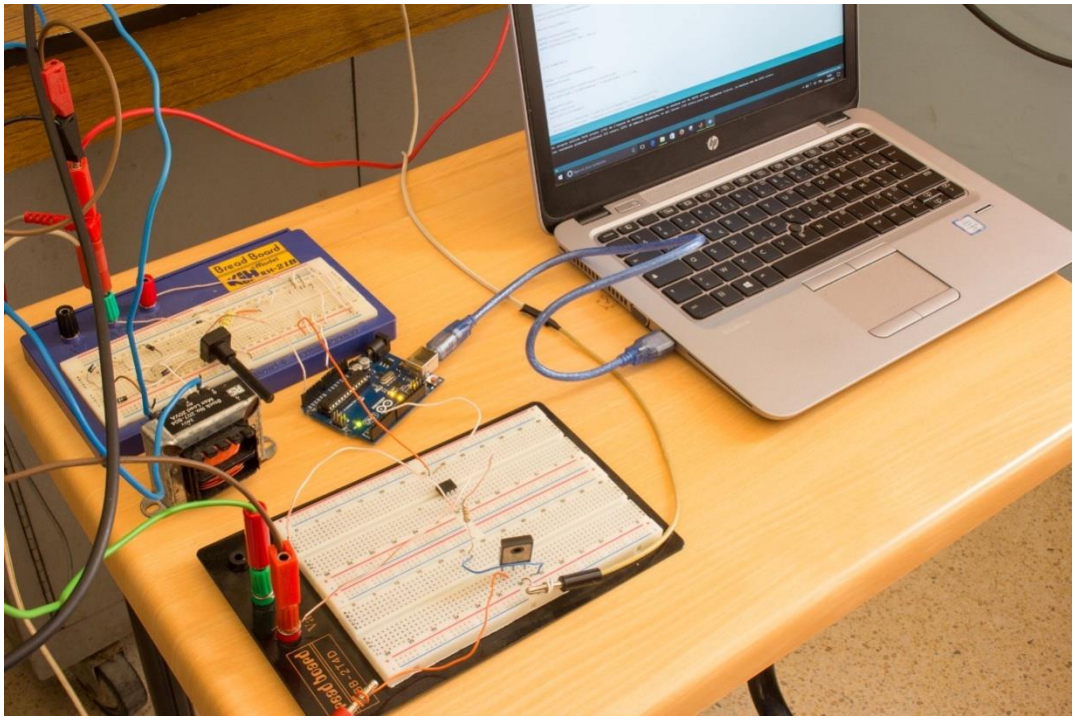

Figure 6.7: The implemented circuit

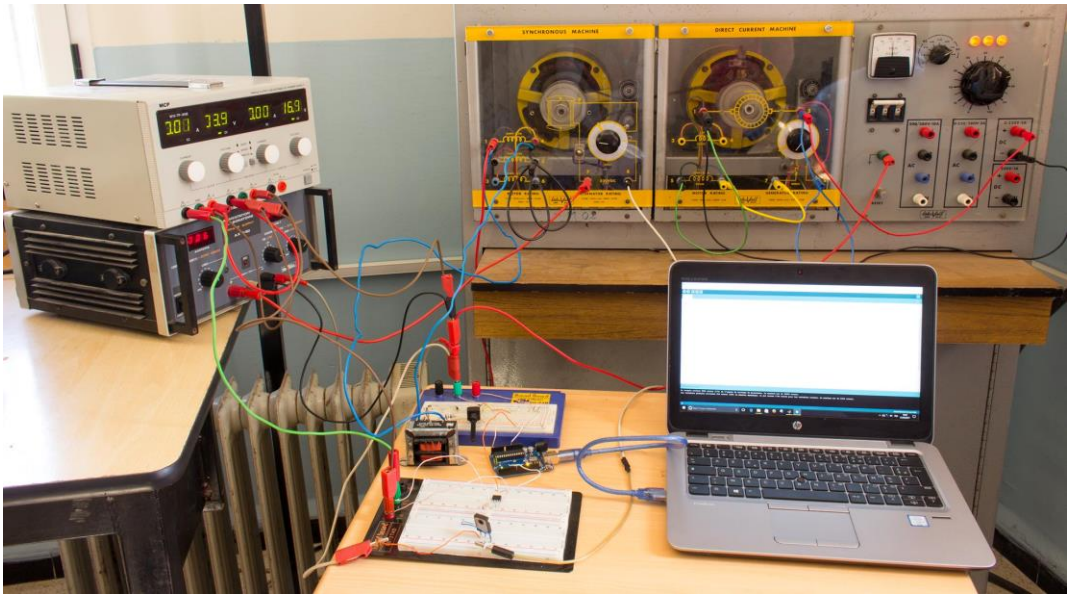

Figure 6.8: The implemented circuit with the synchronous generator

The system has been run with and without the PID controller in order to compare the obtained results, the serial plotter provided with Arduino software has been used to plot the measured data as shown in figures 6.9 and 6.10

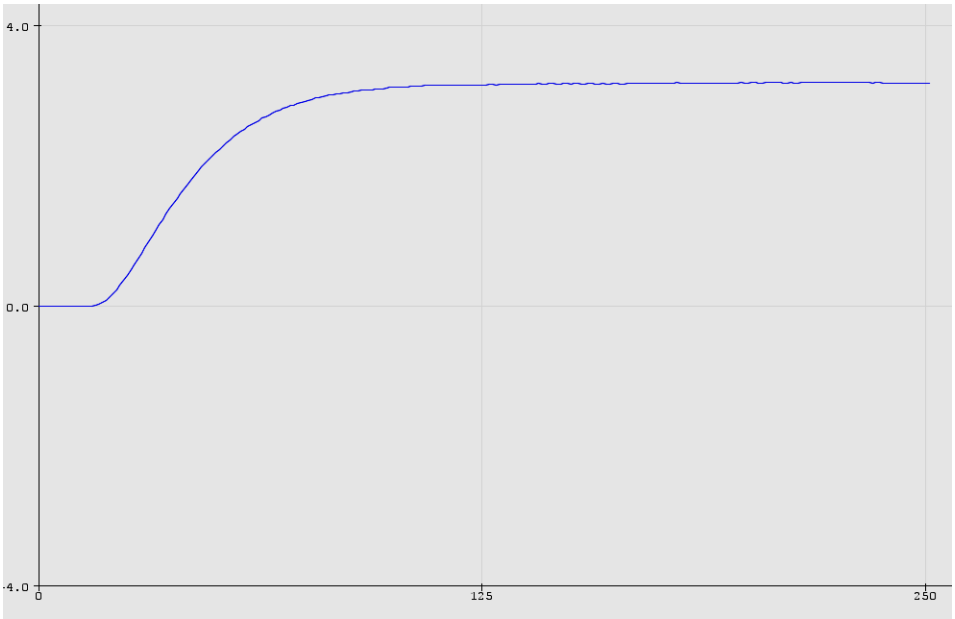

Figure 6.9: The system recorded data without PID

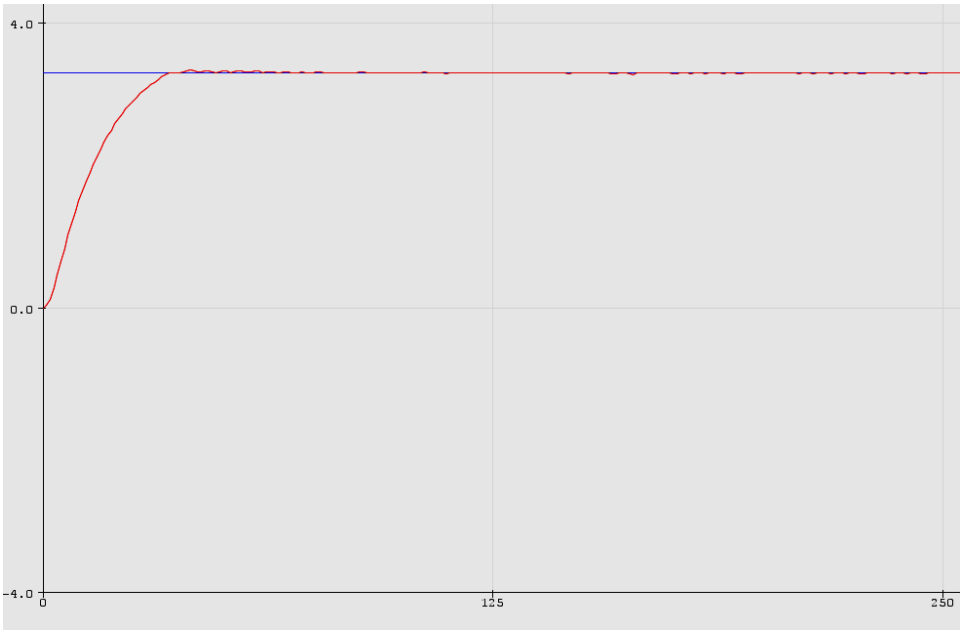

Figure 6.10: closed loop system data with PID

One can notice clearly that the two systems are stable but the one with PID controller has a better time response. In order to compare the two plots precisely and get the system time domain characteristics the data has been transferred to MATLAB, and plotted in figure 6.11

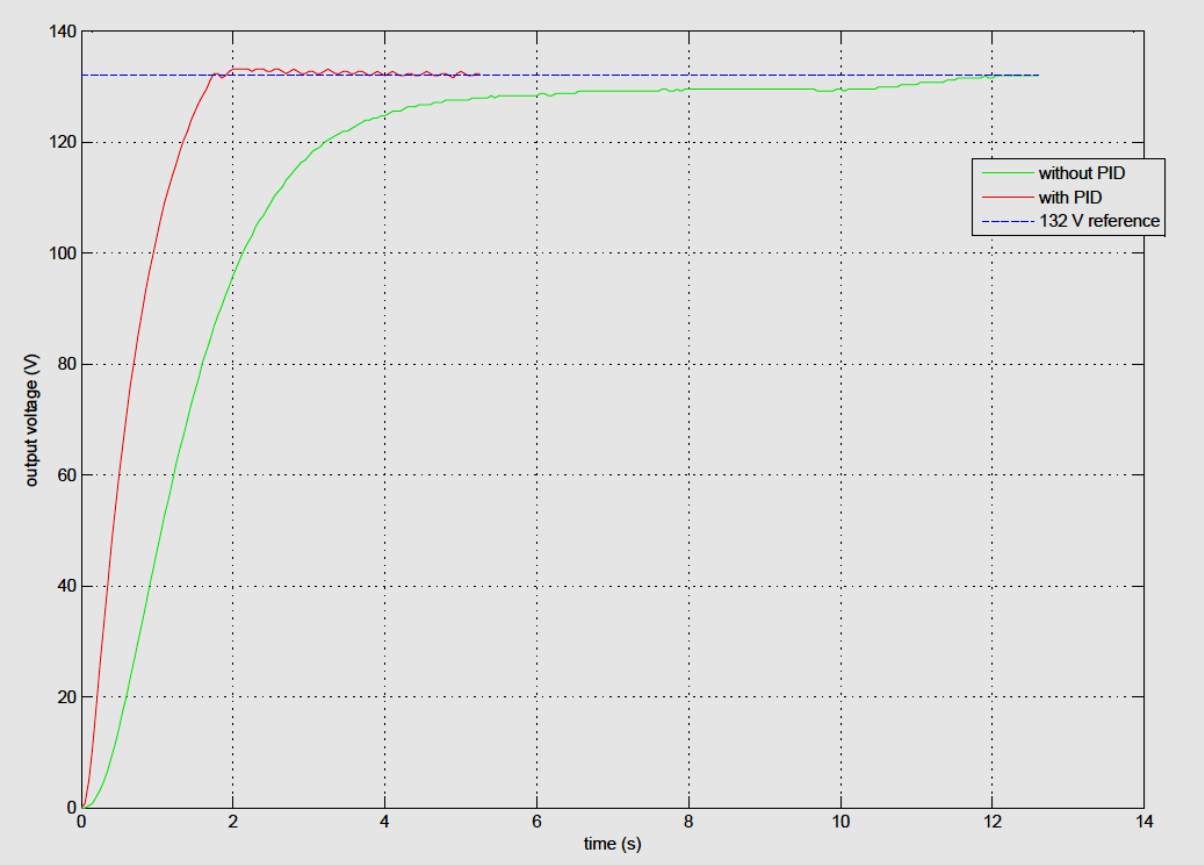

Figure 6.11: Output voltage with and without PID controller

As the open loop transfer function has been identified in the previous chapter, it is necessary to identify the controlled closed loop transfer function obtained from the implementation and compare it with the closed loop 3rdorder model obtained from the simulation in section 5.3.2.

A 3rd order model controlled with PID gives a closed loop transfer function with 2 zeros and 4 poles, so the implemented model has been estimated using the identification toolbox with 2 zeros and 4 poles given the following transfer function

$$G(s) = \frac{10.48\,s^2 + 27.93\,s + 160.2}{s^4 + 9.26\,s^3 + 49.34\,s^2 + 132.1\,s + 159.7} \tag{6.3}$$

With a step response and time domain characteristics compared to the open loop system in figure 6.12 and table 6.1

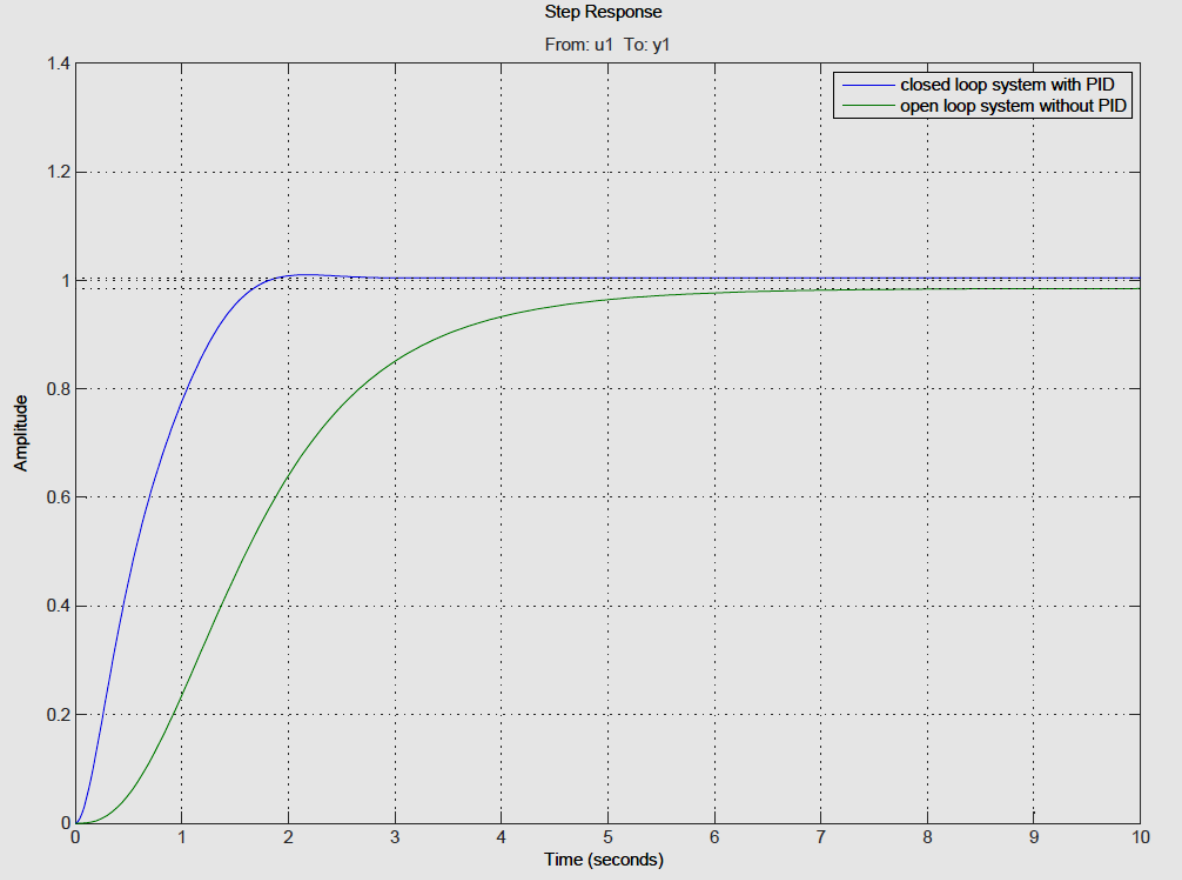

Figure 6.12: open loop vs closed loop with PID step responses

Table 6.1: The time domain characteristics of open loop vs closed loop with PID:

	Rising time (s)	Settling time (s)	Overshoot (%)	SteadyState error %
Open loop	3.57	5.06	0	1.59
Closed loop with PID	1,38	1.66	0.72	0

The results were approximately as expected, the AVR PID controller really gives a good result, and to confirm that a last step is needed which is the comparison of the simulated PID with the implemented PID as illustrated in figure 6.13and given in table 6.1.

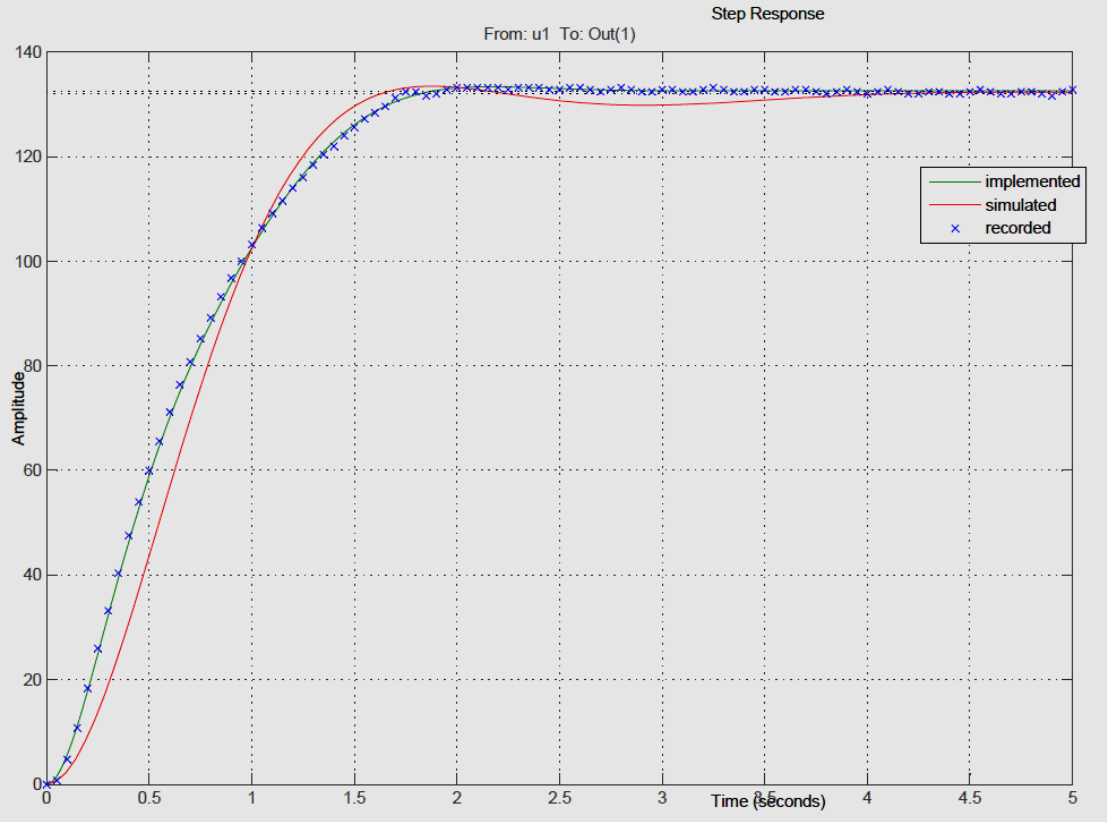

Figure 6.13: Comparison between the simulated and implemented PID systems.

Table 6.2: comparison between the simulated and implemented PID systems

	Rising time (s)	Settling time (s)	Overshoot (%)	SteadyState error %
simulated	0.98	1.49	0.96	0
implemented	1,38	1.66	0.72	0

As shown in figure 6.13 the output of the implemented system is not exactly the same as the simulated one but they are close enough, the data from table 6.2 approves it with a difference of 0.4 seconds in the rising time, and a 0.17 second in the settling time, and 0.24% in the overshoot, and that difference is because of the absence of disturbance and noise in the simulation within MATLAB.

Finally, it was impossible to plot the AC output voltage of the synchronous generator using the scope, because the scope available in the lab can display a maximum of 10 volts per division which means 50V peak value; however, using a multimeter the RMS voltage has been measured giving values between 133V and 131V which means 132V ± 0.75%

And the stepped down voltage of the transformer was plotted instead, as shown in figure 6.14

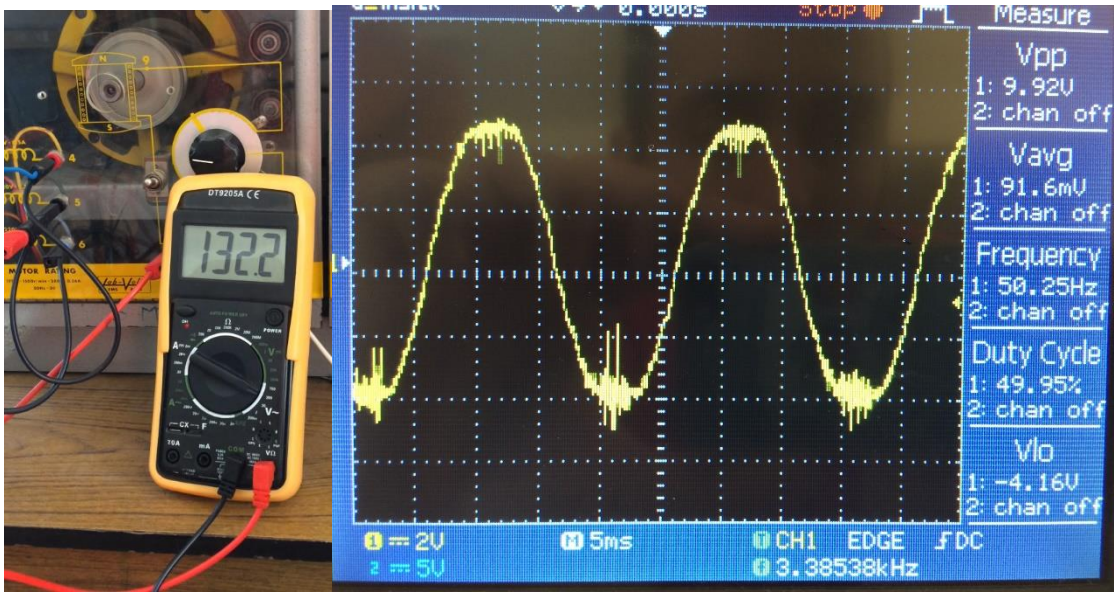

Figure 6.14: The measured RMS and the stepped down AC voltage

As expected the AC voltage frequency of the generator is approximately 50 HZ, and it is noticeable that the AC voltage was not a perfect sinusoidal but a bit noisy, that is because of the disturbance and the old materials used in the implementation

6.6 Conclusion:

The implementation of a project is the most important work that could be done. It permits to apply the theoretical materials that have been covered during the period of study. By working on this project, several problems has been faced, as the burning of H-Bridges that were used before using the MOSFET because of the current overshoot provided by the power supply. Even the later has not been sufficient to reach 220V from the generator, but this was not a big problem because the objective of this project was not to reach a 220V but regulating the output voltage to a stable value, 132V was chosen randomly within the ability of the power supply. Besides the faced problems, the implementation of the project has been done with positive results. In this project, the objective of design and implementation of an automatic voltage regulator of an engine generator using an Arduino microcontroller has been reached successfully.

Chapter 07 :
General Conclusion

General Conclusion:

There are a number of control less problems in the generation and distribution of electrical power; however, attention will be focused on the automatic voltage regulator. The automatic voltage regulator is used to regulate the voltage terminal of the generator. In this report, details about the design and the implementation of an automatic voltage regulator of synchronous generator using a microcontroller have been presented in order to investigate the regulation of the voltage in a synchronous generator using Arduino Uno as a microcontroller.

The literature review has been performed to get familiar with synchronous generator and its main working principles, in addition to the microcontroller as a new smart device and to get familiar with the problems facing a power system without regulation of the voltage.

In the simulation part, the design of an automatic voltage regulator was done using MATLAB / Simulink. Our objectives have been perfectly achieved that are having a constant voltage terminal of synchronous generator by using a PID controller.

The study of an electrical system requires the implementation besides the simulation, because reality is not like theory were unexpected problems can be faced. In this project, the output voltage of the generator have been transformed, rectified and filtered in order to be measured by the controller Arduino, which controls the excitation voltage through a high frequency switching device. At the beginning, an H-bridge was used for that purpose but it was damaged by the current overshoot, so a protective circuit was needed. This problem was solved by changing the H-bridge with a power MOSFET. Our new approach is to improve our system by developing a sensor that can measure high voltages directly without the need of a transformer and AC to DC converter. Moreover, we can develop our system by adding speed control to the excitation control in order to adjust the frequency of the AC output voltage of the generator.

Finally, we can say that from this work that we have designed and implemented an automatic voltage regulator of a synchronous generator using a controller Arduino Uno.

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