People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University M'Hamed BOUGARA- Boumerdes

Institute of Electrical and Electronic Engineering

Department of Power and Control Engineering

Project Report Presented in Partial Fulfilment of

the Requirements of the Degree of

'MASTER'

In Electrical and Electronic engineering

Option: Power Engineering

Title:

Design and Implementation of Automatic Voltage Regulator

Presented By:

- **MANSOUR Mohamed**
- **MEZALI Mohamed Amine**

Supervisor:

Pr. BENTARZI. H

Registration Number:……/2023

Abstract

This project presents the design of an automatic voltage regulator (AVR) implemented on ATmega microcontroller. Voltage regulation is a critical aspect of electronic systems, ensuring stable and reliable operation. Thus, it overcomes both undervoltage and overvoltage issues. The objective of this work is to develop a cost-effective and efficient AVR solution based on open-source hardware and software. The methodology involves the integration of the ATmega kit with voltage sensing and control circuits to achieve automatic regulation. The implemented AVR system successfully monitored and adjusted the output voltage within predefined limits. Experimental results demonstrate the effectiveness of the design in maintaining voltage stability under varying load conditions. The AVR exhibited an average voltage deviation of less than 5% from the desired setpoint. Moreover, the project discusses the limitations faced during the implementation and proposes potential enhancements for future cycles, such as incorporating advanced control algorithms for improved performance. This project serves as a foundation for further research and practical applications in the field of voltage regulation using Arduino-based platforms.

Acknowledgements

First of all, we would like to give thanks to God for making it possible for us to experience this great opportunity.

We would like to express our sincere appreciation to Professor H. Bentarzi for his technical support and availability as our supervisor. We are also grateful to Mr. W. Touzout for his assistance throughout the project. Special thanks go to the IEEE staff members for creating a conducive work environment and helping us achieve our project goals.

Finally, this acknowledgment would be incomplete without extending our sincerest thanks to our parents and family members for their unwavering support, encouragement, and patience throughout these years.

Contents

List of Figures

Introduction

In power system studies, power demand is never constant and this affects the output voltage and frequency levels of the generators.
The voltage regulator is a very crucial and critical part of a power source. Without proper voltage regulators, most electronic devices or projects would not be able to operate accurately. Voltages must be kept within the approved range by the electrical equipment, or else it may burn out and stop working.

The purpose of this project is to design and implement an Automatic Voltage Regulator (AVR) using an Arduino board for the sensing and implementation of a Proportional-Integral-Derivative (PID) controller. Voltage regulation plays a critical role in power generation systems, where fluctuations in generator output voltage due to load changes can occur. The AVR ensures a stable and constant output voltage, safeguarding sensitive equipment and enabling proper functioning.

The AVR design comprises three key components: the sensing module, the control module, and the power module. The sensing module incorporates a power transformer, an Arduino board, and a voltage divider circuitry. The Arduino board's analog input pins are connected to voltage sensors, allowing the board to sense the generator's output voltage. The voltage divider circuitry is employed to adjust the voltage level within the Arduino's input range.

The control module encompasses the implementation of a PID controller using the Arduino board. The PID controller utilizes predetermined proportional, integral, and derivative gains. By comparing the sensed voltage with the desired voltage level, the PID controller calculates the error signal. This error signal is then fed into the PID algorithm, which combines the proportional, integral, and derivative components to determine the output signal. The resulting output signal is used to control the excitation current to the generator's rotor, maintaining the desired voltage level.

The power module includes a power circuit responsible for providing excitation current to the generator's rotor. This circuit consists of a gate drive optocoupler and a MOSFET. The MOSFET is controlled by the output signal from the PID controller, regulating the current flowing through the field winding.

To evaluate its performance, the AVR design will be tested under various load conditions. These tests will include steady-state and transient response evaluations, aiming to assess the AVR's stability, accuracy, and response time. The outcome of this research will be a cost-effective AVR design suitable for small-scale applications, including homes and small businesses.

Chapter 1

Background

Introduction

Voltage regulation is crucial for ensuring stable power supply in electronic systems. Fluctuations in voltage levels can lead to malfunctions, damage to equipment, and even safety hazards. To address these challenges, the implementation of an automatic voltage regulator using an Arduino Mega board offers an efficient and cost-effective solution. The Arduino Mega board, known for its versatility and extensive capabilities, provides an ideal platform for developing voltage regulation systems due to its programmability, wide range of input and output pins, and compatibility with various sensors and actuators.

1.1 Fundamentals of Voltage Regulation

Voltage regulation is the process of maintaining a stable voltage output within predefined limits despite variations in the input voltage or changes in the load. The objective is to provide a consistent and reliable power supply to electronic devices, ensuring their optimal performance. Various voltage regulation techniques have been developed, ranging from traditional methods such as tap-changing transformers and mechanical regulators to modern solid-state and microcontroller-based systems. These techniques employ different control strategies and components to regulate voltage and mitigate fluctuations, offering improved efficiency, accuracy, and response time compared to conventional approaches.

Numerous automatic voltage regulation techniques have been explored in the literature. Traditional methods, such as tap-changing transformers, rely on physical adjustments to change the transformer turns ratio and regulate voltage. Mechanical regulators utilize rotating mechanisms to adjust voltage levels. However, these approaches often suffer from slow response times, mechanical wear, and maintenance issues. In recent years, solid-state voltage regulators and microcontroller-based systems have gained prominence. Solid-state voltage regulators employ power electronics components such as thyristors, transistors, and integrated circuits to achieve accurate and fast voltage regulation. [1]

1.2 Synchronous generator

The electrical machine can be defined as a device that converts electrical energy into mechanical energy or mechanical energy into electrical energy. An electrical generator can be defined as an electrical machine that converts mechanical energy into electrical energy. An electrical generator typically consists of two parts: stator and rotor.

A synchronous machine is an electro-mechanical transducer that facilitates the conversion of mechanical energy into electrical energy, or the reverse process. These conversions are made possible by two fundamental phenomena: the law of electromagnetic induction and the law of interaction.

Three phase generators is the most commonly used for supplying the majority of AC power today. It is preferred over single-phase generators due to its ability to achieve higher output with the same weight.

In a three-phase generator, the three phases are mechanically spaced at equal intervals of 120° electrical degrees from each other. [2]

1.3 Principle of voltage generation in a generator

Generators produce electrical voltage by harnessing the principle of electromagnetic induction. This phenomenon occurs when the armature conductors of the generator cut across the magnetic field. As a result, an electromotive force (EMF) is induced in the armature conductors. When the circuit is closed, the current flows through the armature conductors, generating another magnetic field. The interaction between this magnetic field and the main field exerts a force on the conductor, which opposes its rotation. To maintain the relative motion of the conductors against this force, mechanical power

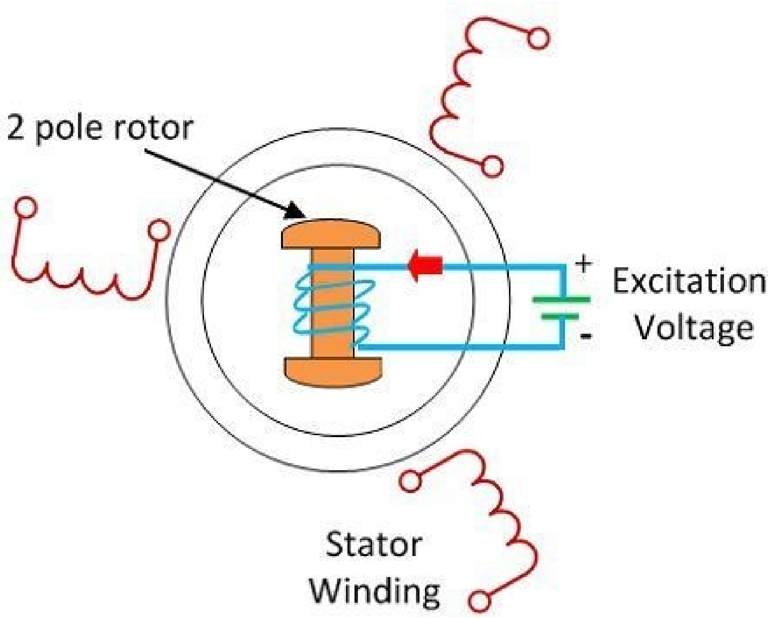

Figure 1.1: Synchronous generator

from the prime mover is supplied. Consequently, the mechanical power is effectively converted into electrical power. This process forms the foundation of voltage generation in generators. [3]

1.3.1 Construction of Synchronous Generator

In general, synchronous generator consists of two parts rotor and stator. The rotor part consists of field poles and stator part consists of armature conductors. The rotation of field poles in the presence of armature conductors induces an alternating voltage which results in electrical power generation.[4]

1.3.1.1 Stator Construction

The stator is the stationary part of the alternator. It carries the armature winding in which the voltage is generated. The output of the alternator is taken form the stator.

The stator of an alternator encompasses various components, including the frame, stator core, stator windings (also known as armature windings), and cooling system.

The stator has the following characteristics:

- The stator frame may be made up of cast iron for small-size machines and of welded steel for large-size machines.

- The stator core is assembled with high-grade silicon content steel laminations. These silicon steel laminations reduce the hysteresis and eddy-current losses in the stator core.
- The slots are cut on the inner periphery of the stator core. A 3-phase armature winding is put in these slots.
- The armature winding of the alternator is star connected. The winding of each phase is distributed over several slots. When current flows through the distributed armature winding, it produces an essential sinusoidal space distribution of EMF.[5]

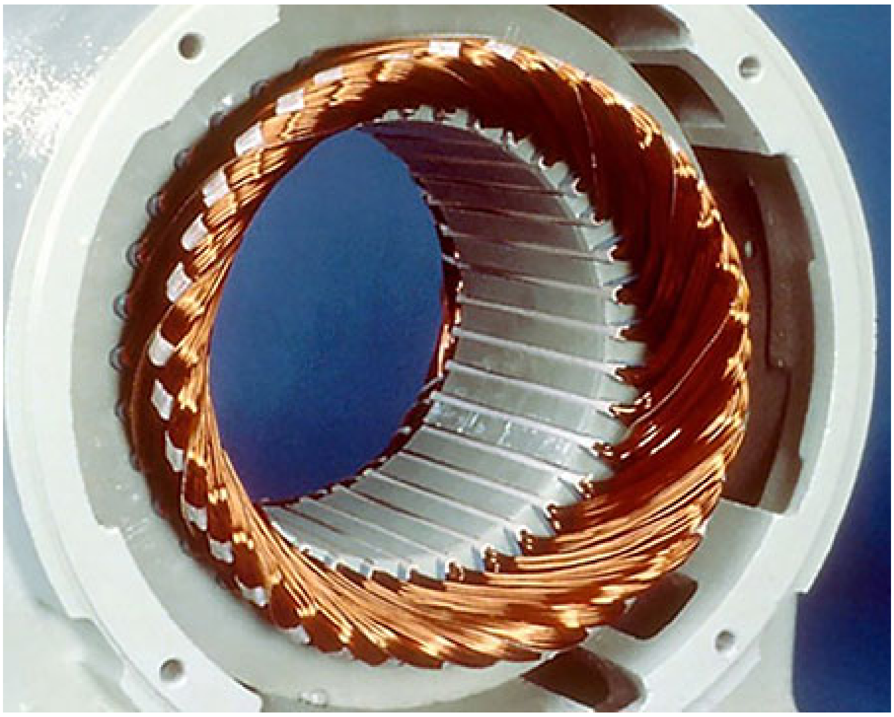

FIGURE 1.2: Stator of alternator

1.3.1.2 Rotor Construction

The rotor is the rotating part of the alternator and produces the main field flux, it houses the field winding, which is energized with direct current supplied through two slip rings from a separate DC source, known as the exciter. Typically, the exciter is a small DC shunt generator mounted on the alternator's shaft.

Two types of rotor constructions are commonly employed in alternators: the salient-pole type and the cylindrical rotor type.

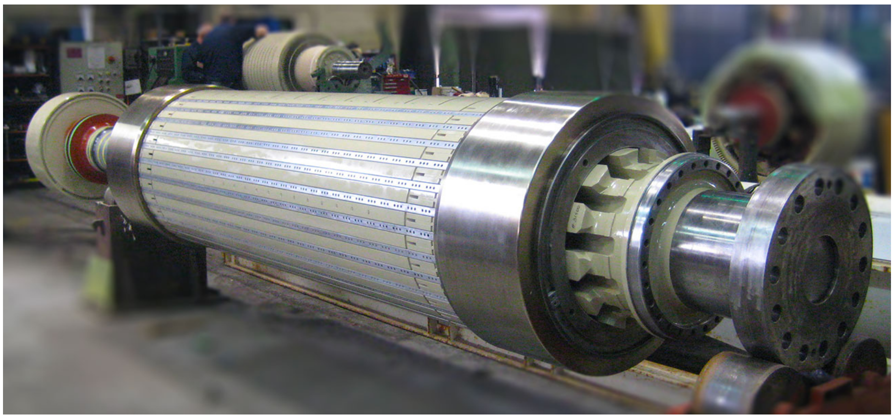

FIGURE 1.3: Rotor of alternator

- Salient-pole Rotor

The term salient means projecting. Hence, a salient pole rotor consists of poles projecting out from the surface of the rotor core. This whole arrangement is fixed to the shaft of the alternator as shown in the figure. The individual field pole windings are connected in series such that when the field winding is energised by the DC exciter, the adjacent poles have opposite polarities. [6]

The salient pole type rotor is used in the low and medium speed (from 120 to 400 RPM) alternators such as those driven by the diesel engines or water turbines because of the following reasons:

- The construction of salient pole type rotor cannot be made strong enough to withstand the mechanical stresses to which they may be subjected at higher speed.
- If the salient field pole type rotor is driven at high speed, then it would cause windage loss and would tend to produce noise.

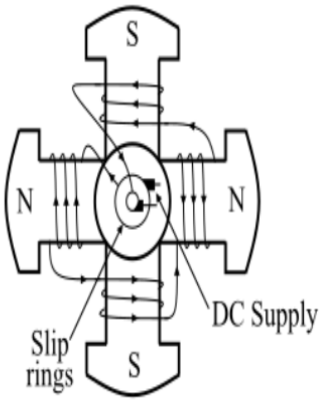

FIGURE 1.4: Salient-pole rotor

Low speed rotors of the alternators possess a large diameter to provide the necessary space for the poles. As a result, the salient pole type rotors have large diameter and short axial length.

- Cylindrical Rotor

The cylindrical rotors are made from solid forgings of high-grade nickel-chrome-molybdenum steel. [7]

- The construction of the cylindrical rotor is such that there are no-physical poles to be seen as in the salient pole rotor.
- In about two-third of the outer periphery of the cylindrical rotor, slots are cut at regular intervals and parallel to the rotor shaft.
- The field windings are placed in these slots and is excited by DC supply. The field winding is of distributed type.
- The unslotted portion of the rotor forms the pole faces.
- It is clear from the figure of the cylindrical rotor that the poles formed are non-salient, i.e., they do not project out from the rotor surface.

The cylindrical type rotor construction is used in the high-speed (1500 to 3000 RPM) alternators such as those driven by steam turbines because of the following reasons:

- The cylindrical type rotor construction provides a greater mechanical strength and permits more accurate dynamic balancing.

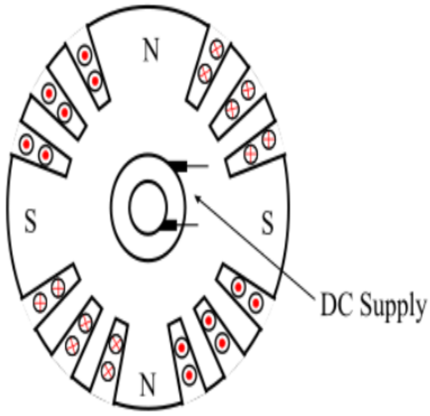

Figure 1.5: Cylindrical rotor

- It gives noiseless operation at high speeds because of the uniform air gap.
- The flux distribution around the periphery of the rotor is nearly a sine wave and hence a better EMF waveform is obtained.

A cylindrical rotor alternator has a comparatively small diameter and long axial length. The cylindrical rotor alternators are called turbo-alternators or turbo-generators. The alternator with cylindrical rotor have always horizontal configuration installation. [8]

1.3.1.3 Working Principle and Operation of Alternator

An alternator, also known as a synchronous generator, operates based on the principle of electromagnetic induction. This principle states that when the magnetic flux linking a conductor changes, it induces an electromotive force (EMF) in the conductor. In the case of an alternator, the armature winding is exposed to a rotating magnetic field, resulting in the generation of voltage in the armature winding.

To create the rotating magnetic field, the rotor field winding of the alternator is energized from a DC exciter. This energization leads to the development of alternating North (N) and South (S) poles on the rotor. As the rotor rotates in the counterclockwise direction due to a prime mover, the magnetic field of the rotor poles cuts across the armature conductors located on the stator. Consequently, electromagnetic induction takes place, inducing an EMF in the armature conductors.

The induced EMF in the armature conductors is alternating in nature since the N and S poles of the rotor pass the armature conductors alternatively. The direction of the generated EMF can be determined using Fleming's right-hand rule, which states that if you point your thumb in the direction of the motion of the conductor or the magnetic field and extend your fingers, the direction of the EMF will be perpendicular to both your thumb and fingers.

The frequency of the generated EMF depends on various factors such as the rotational speed of the alternator, the number of poles on the rotor, and the configuration of the electrical system. The frequency can be calculated using the formula:[1]

$$f = \frac{P * N}{120}. \tag{1.1}$$

Where:

- N is the synchronous speed in RPM.
- P is the number of rotor poles.

[9]

1.3.1.4 Mathematical Formulation and Dq-Model of the Synchronous Generator

By applying Maxwell's equation to the configuration shown in Figure 1.1, the generator phase voltage equations, in natural-reference frame are simply:[10] [11]

$$v_d = R_s i_d + \frac{d\lambda}{dt} + j\omega\lambda - X_s i_q \tag{1.2}$$

$$v_q = R_s i_q - \omega\lambda + jX_s i_d \tag{1.3}$$

$$T_e = \frac{3}{2} p_p \operatorname{Re}\{i_d^* i_q\} \tag{1.4}$$

$$\frac{d\lambda}{dt} = \frac{1}{T_r}\left(-\lambda + K_{pss}(v_{ref} - v_f)\right) \tag{1.5}$$

Where:

v_d, v_q : Stator d- and q-axis voltages

i_d, i_q : Stator d- and q-axis currents

λ : Flux linkage

X_s : Synchronous reactance

R_s : Stator resistance

ω : Rotor angular velocity

T_e : Electromagnetic torque

p_p : Number of pole pairs

v_{ref} : Voltage reference

v_f : Field voltage

K_{pss} : Power system stabilizer gain

T_r : Rotor time constant

The flux linkage to current relationship in phase (a) winding at any instant is given by:

$$\lambda_a = L_{aa} i_a + M_{af} i_f \tag{1.6}$$

Where:

λ_a : the flux linkage in the phase (a) winding.

L_{aa} : is the self-inductance of the phase (a) winding.

i_a : is the current flowing through the phase (a) winding.

M_{af} : represents the mutual inductance between the phase (a) winding and the field winding.

i_f : denotes the current flowing through the field winding.

Similarly, one can write the flux linkage to current relationships in phases (b) and (c). The flux linking the three-phases of the stator winding is a function of θ, i.e., the angular displacement of the d-axis from phase (a).[10] Equations (1.1) completely describe the electrical behavior of a SG. However, these equations contain inductance terms which vary with angle θ – rotor position – which in turn varies with time. For that, the machine model was further developed by Park who mathematically transformed the three-phase time-varying stator quantities (voltages, currents, and flux linkages) into time-invariant d- and q-axes quantities under steady-state conditions.[12]

1.3.1.5 Excitation Systems

Excitation circuit is an important part in any generator and the basic function of it is to provide power to the synchronous machine and that by injecting current to the field winding. Based on their excitation power gain there are two types of excitation systems:[3]

- Independent: The exciter is not connected to the grid, meaning that the excitation parameters are independent of the grid parameters. In this setup, the turbine's mechanical power is employed for excitation purposes.
- Dependent: The exciter can be categorized based on its power source or its connection to the grid. In terms of the excitation source, there are two further classifications of excitation systems: DC excitation systems and AC Static excitation systems. DC excitation systems rely on the generator's power or an independent power supply, while AC Static excitation systems are connected to the grid. These classifications provide distinctions for different types of excitation systems based on their power sources and connections to the electrical grid.

1.3.1.6 Types of excitation systems

In large machines, different schemes are utilized to provide DC excitation to the field winding. These excitation systems play a crucial role in ensuring proper operation. Some of the most important excitation systems are given below:

- DC Exciters: This is a conventional method of exciting the field windings of synchronous generators. In this method, three machines namely pilot exciter, main exciter and the main 3-phase alternator are mechanically coupled and are therefore, driven by the same shaft. The pilot exciter is a DC shunt generator feeding the field winding of a main exciter. The main exciter is a separately-excited DC generator which provides the necessary current to the field winding of the main alternator through brushes and slip rings.[13]

  This conventional method of excitation suffers from cooling and maintenance problems associated with slip rings, brushes and commutator with the higher rating alternators. The modern excitation systems have been developed by eliminating the sliding contacts and brushes.

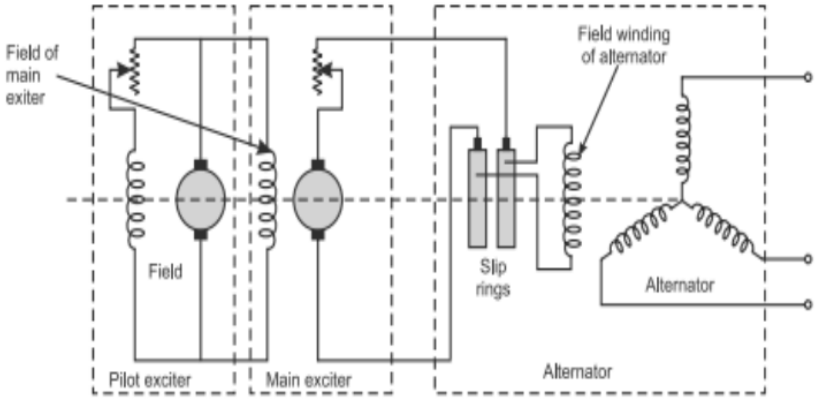

FIGURE 1.6: DC excitation system

- Static Excitation System: In this method, the excitation power for the main alternator field is drawn from output terminals of the main 3-phase alternator itself. For this purpose, a three-phase transformer T1 steps down the alternator voltage to the desired value. This three-phase voltage is fed to a three-phase full wave bridge rectifier using thyristors. The firing angle of these thyristors is controlled by means of a regulator which picks up the signal from alternator terminals through potential transformer PT and current transformer CT. [13] The controlled DC power output from thyristor unit is delivered to the field winding of main alternator through brushes and slip rings as shown in Fig bellow :

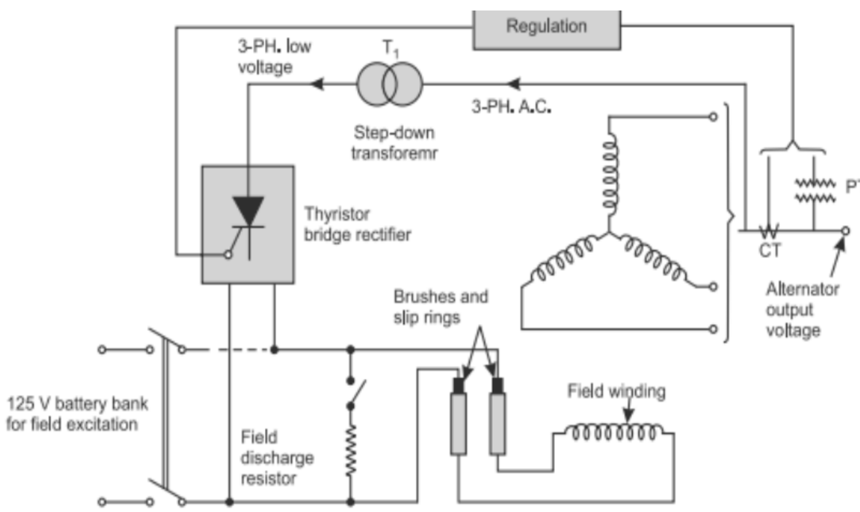

FIGURE 1.7: Static excitation system

The advantages of this excitation system are its response time, which considerably small, it also eliminates the exciter windage loss and commutator, bearing and winding maintenance. Finally, as the excitation energy is derived directly from the alternator terminals, the excitation voltage exhibits a direct proportionality to the speed of the alternator. This characteristic plays a crucial role in optimizing the overall system performance.

1.4 Automatic Voltage Regulator

An automatic voltage regulator (AVR) is a system that is commonly used in generators to regulate voltage automatically by converting fluctuating voltage levels to a constant voltage. AVRs are designed to handle a wide range of input voltages and ensure a stable output voltage. The primary function of the AVR system is to regulate generator voltage automatically and maintain the output within the required range of voltage levels, regardless of the existing load.

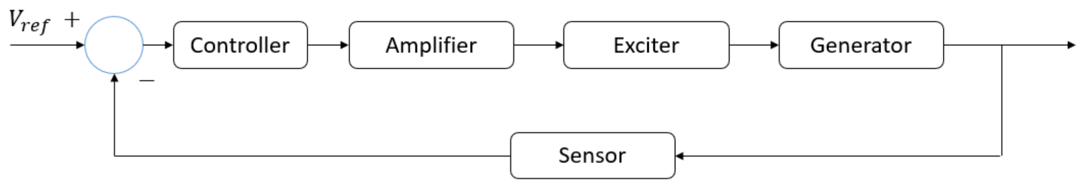

FIGURE 1.8: AVR Block Diagram

AVRs provide protection against electrical surges and generator overloads and help generators resist overloads to avoid shorting. They do this by controlling the field current applied to the generator's rotor windings. If the output voltage is too low, the AVR increases the field current to increase the voltage, and if the voltage is too high, the AVR reduces the field current to decrease the voltage. This feedback control mechanism ensures that the output voltage remains within the desired range.[4]

1.5 Working Principle of the Automatic Voltage Regulator

The primary role of the AVR is to maintain the voltage magnitude of the generator terminals at the desired level. The AVR operates based on three main steps: measurement, control, and excitation.

In the measurement step, the output voltage of the synchronous generator is sensed by a measuring circuit. This circuit includes a potential transformer to step down the generator voltage, after which the signal is rectified and filtered using bridge diodes and a smoothing capacitor.

In the control step, the control system compares the value or status of the process variable being controlled with the desired value or set-point. The control system then applies the difference or error as a control signal to bring the process variable outputs of the plant to the set-points. The control system uses feedback control to maintain the voltage level at the desired value.

In the final step, the excitation system provides the necessary field current to the rotor winding of the synchronous machine. The amount of excitation required depends on the control system signal. If the difference between the measured value and the set-point is large, then the system produces more field current, and vice versa.

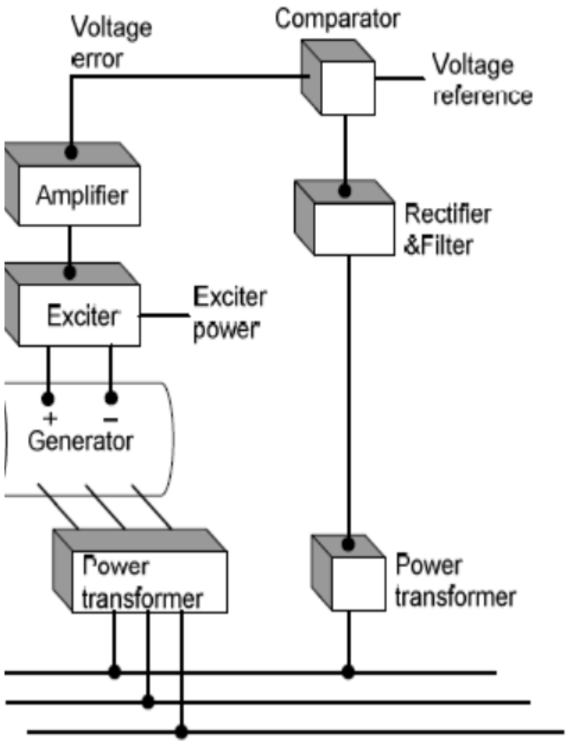

Figure 1.9: AVR model

It can be seen from the figure that a simpler AVR system contains five basic components such as amplifier, exciter, generator, sensor and controller. A unit step response of this system without control has some oscillations which reduce the performance of the regulation. Hence, a control technique must be applied to the AVR system.[5]

Conclusion

In conclusion, this chapter has provided a comprehensive overview of the fundamentals of voltage regulation, synchronous generators, its excitation systems, and the working principle of the automatic voltage regulator (AVR). The understanding of these concepts is crucial for the successful implementation of an automatic voltage regulator in a power system. In the next chapter, we will delve into the methods and equipments used in the implementation of an automatic voltage regulator using an Arduino Mega board.

Chapter 2

Methods & Materials

Introduction

To fulfill the project objectives, a combination of hardware and software materials will be utilized. This section provides an overview of the materials that will be employed in the design and implementation of the project.

2.1 Software

2.1.1 Arduino IDE

Arduino IDE (Integrated Development Environment) is a software application used for programming and developing applications for Arduino boards. Arduino is an open-source electronics platform based on easy-to-use hardware and software. The Arduino IDE provides a user-friendly interface for writing, compiling, and uploading code to Arduino boards.
Key features of the Arduino IDE include:

- Code Editor: The IDE includes a code editor where you can write Arduino sketches using the Arduino programming language. It provides syntax highlighting, auto-completion, and other useful features to aid in code development.
- Code Library: Arduino IDE comes with a library of pre-written code called "sketches" that you can use as a starting point for your own projects.

- Board Manager: The IDE supports a wide range of Arduino boards. The Board Manager feature allows you to select and install the appropriate board package for the specific Arduino board you are using.
- Serial Monitor: Arduino boards often communicate with the computer through a serial connection. The IDE includes a Serial Monitor tool that allows you to send and receive data between the Arduino board and your computer, which is useful for debugging and monitoring the behavior of your program.

FIGURE 2.1: Arduino IDE sketch

2.1.2 PID Controller

The PID control method is widely used in industries due to its simple implementation in both hardware and software. The controller continuously measures the error between the desired setpoint and the process variable and applies a corrective action based on this error. Its adaptability to different processes and systems makes it a flexible control method for industrial applications. In this system, PID controller has been used in order to achieve the control signal u(s) which is given by equation (1):

$$U(s) = \Delta V(s) \cdot \left(K_p + \frac{K_i}{s} + K_d \cdot s \right) \tag{2.1}$$

Where:

K_p : is the proportional gain

K_i : is the integral gain

K_d : is the derivarite gain

V_e : is the difference between process voltage and reference voltage

Before implementing a PID control, it is important to understand the individual components of P (proportional), I (integral), and D (derivative) control. These three controllers are then combined to create a PID controller. By understanding the characteristics of each controller, we can tune the PID controller to provide the desired response for the system being controlled.

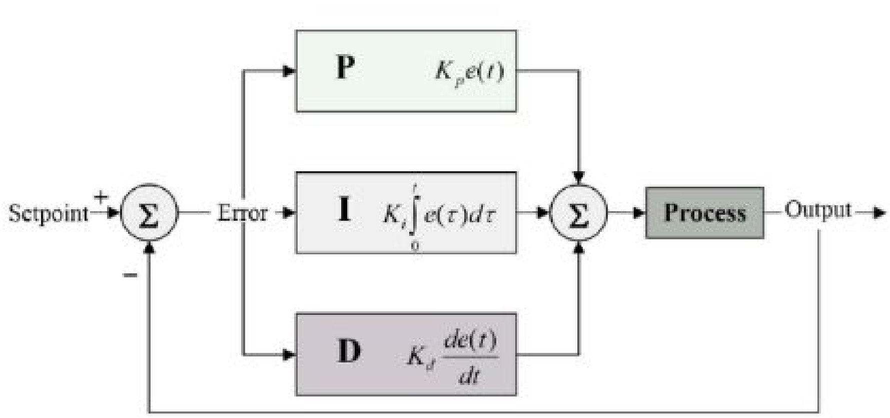

FIGURE 2.2: PID controller in feedback loop

2.1.2.1 Proportional Response

The proportional component of a PID controller responds to the difference between the setpoint and the process variable, which is known as the error term. The proportional gain, denoted as K_p, determines the output response to the error signal. For example, if the error term has a magnitude of 10 and the proportional gain is 5, the proportional response will be 50. Increasing the proportional gain generally leads to a faster control system response. However, if the gain is too high, the process variable will begin to oscillate. Further increasing K_p will cause the oscillations to grow larger, and the system may become unstable and oscillate out of control.

2.1.2.2 Integral Response

The integral component of a PID controller accumulates the error term over time. This means that even a small error term will cause the integral component to increase gradually. The integral response will continue to grow over time unless the error is zero, which helps to reduce steady-state error to zero. Steady-state error is the final difference between the process variable and setpoint. However, a phenomenon called integral windup can occur when the integral action saturates a controller without driving the error signal towards zero.

2.1.2.3 Derivative Response

The derivative component is highly sensitive to changes in the process variable and reacts to it in a proportionate manner. In other words, if the process variable is changing rapidly, the derivative component causes the output to decrease accordingly. This allows for a quick response to sudden changes in the process variable, resulting in a faster overall control system response.

However, a high derivative gain or a large derivative time constant (Td) can result in instability or overshoot in the control system. The derivative component is also highly sensitive to noise in the feedback signal, which can make the control system unstable or oscillate uncontrollably. Therefore, the derivative time constant is often kept small in most practical control systems to reduce the effects of noise and maintain stability.

2.2 Hardware

2.2.1 LabVolt Synchronous Generator 1.5kVA

The Synchronous Motor/Generator consists of a 4-pole machine rated at 1.5kVA. Each phase of the stator winding is accessible via the connection module to allow wye or delta connections. The rotor winding is connected to two slip rings for external connection to a DC power source. A squirrel cage damper winding is inserted in the salient-pole rotor to produce induction-motor action, making the synchronous motor self-starting.

FIGURE 2.3: LabVolt Synchronous Generator

2.2.2 Step down Potential Transformer(240V/6V)

A step-down potential transformer(240V/6V) is a specific type of transformer used for measuring or monitoring voltage levels. It is designed to reduce the high voltage of the primary circuit(220V) to a lower, more manageable voltage on the secondary side(6V).

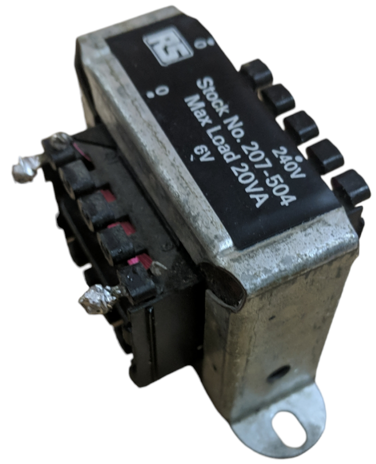

FIGURE 2.4: Step down Potential Transformer (240/6V)

2.2.3 Arduino Mega 2056 board

The Arduino Mega 2560 is a microcontroller board based on the ATmega2560 (datasheet). It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.[8]

Operating Voltage	5V
Input Voltage (recommended)	7V to 12V
Input Voltage (limits)	6V to 20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40mA
DC Current for 3.3V Pin	50mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8kb
EEPROM	4kb
Clock Speed	16MHz

TABLE 2.1: Arduino Mega 2056 data

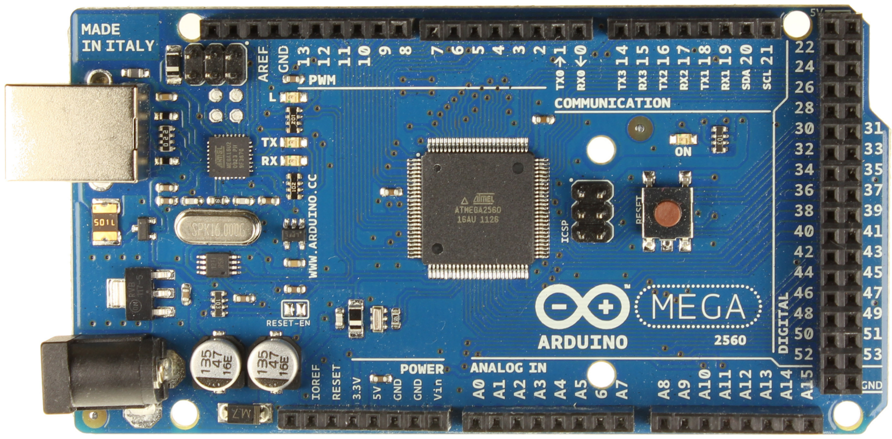

FIGURE 2.5: Arduino Mega 2056 board

2.2.4 HCPL3120 Optocoupler

An optocoupler, or optical isolator, is a component that utilizes a light-emitting diode (LED) and a phototransistor to transmit electrical signals between two isolated circuits. the aim of optoisolater in this project is to protect the low voltage circuit including arduino board and the high voltage power circuit including power mosfet and also used as a gate driver of the mosfet .

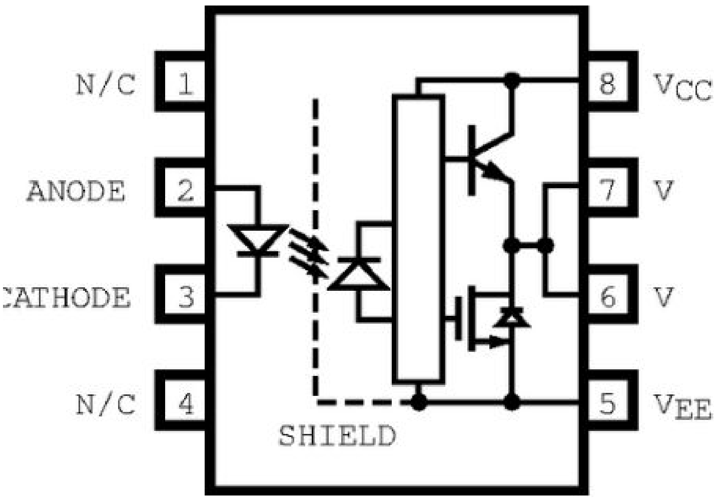

FIGURE 2.6: HCPL3120 OPTOISOLATOR

2.2.5 IRFP260N MOSFET

The IRFP260N is a specific type of MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor). It is a high-power N-channel MOSFET designed for applications that require high voltage and current handling capabilities. In this project, the power MOSFET serves as a switch, driven by a PWM signal from an ATmega2560 microcontroller through an optocoupler (HCPL3120).

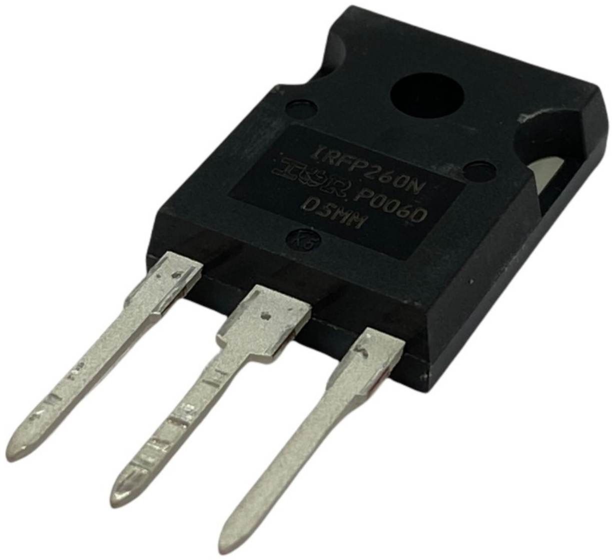

FIGURE 2.7: IRFP260N Power Mosfet

2.3 PID Parameters Tuning using Ziegler-Nichols Method

Ziegler–Nichols (ZN) rules are widely used to tune PID controllers for which the plant dynamics are precisely not known, it can also be applied to plants of known dynamics. Ziegler and Nichols proposed rules for determining values of proportional gain K_p, integral gain K_i , and derivative gain K_d based on the transient response characteristic of a given plant [9]. The Zeigler-Nichols method involves the following steps:

- Increase the proportional gain until the output oscillates continuously. This is called the ultimate gain, K_u=1.212.

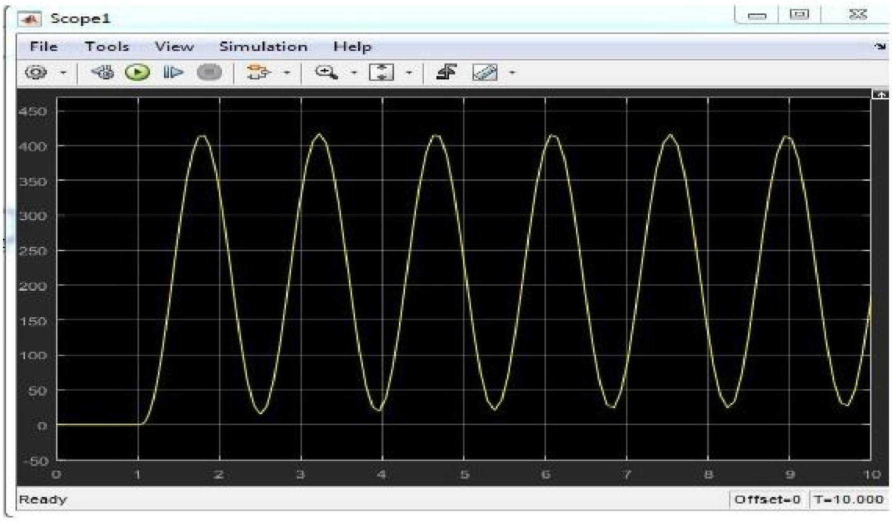

FIGURE 2.8: AVR System responce with same amplitude

- Measure the period of the oscillation T_u using cursors of matlab scope and finding that T_u= 1.284s .

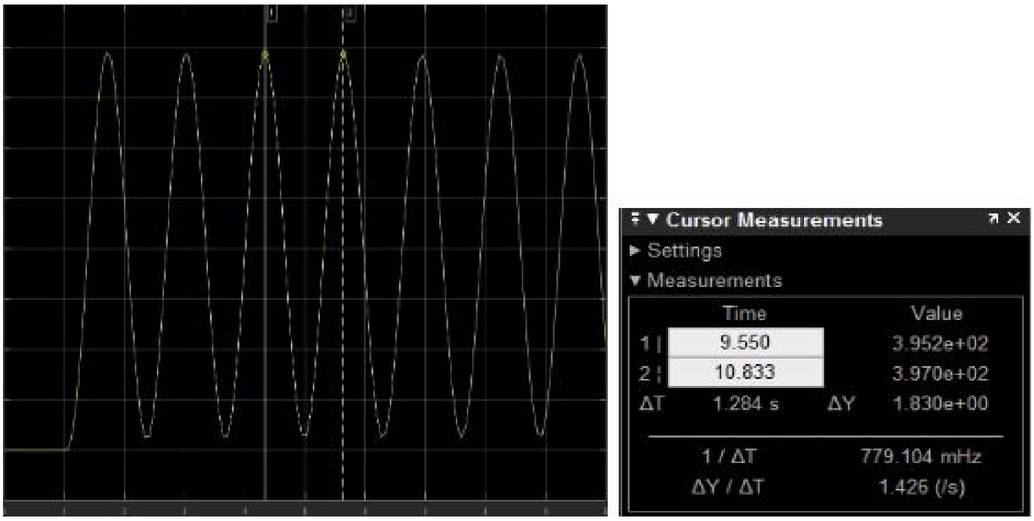

FIGURE 2.9: Period determination for Ziegler-Nichols Tuning

- Use the obtained values of K_u and T_u to calculate the parameters of the PID controller using one of the following tuning rules:

Controller	K_p	K_i	K_d
P	$0.5K_u$	–	–
PI	$0.45K_u$	$0.85T_u$	–
PID	$0.6K_u$	$0.5T_u$	$0.12T_u$

TABLE 2.2: PID parameters obtained using the Ziegler-Nichols method.

After calculating pid parameters using table of zeigler-nichols, the found gains are shown bellow in the table:

Gain	Value
K_p	0.7272
K_i	0.642
K_d	0.15408

TABLE 2.3: Final PID parameters

Chapter 3

Modelling & Simulation

Introduction

Simulation is a crucial step in the development process of any system as it helps to evaluate the system's performance before implementing it in the real world. The simulation allows for the testing of different scenarios, configurations, and parameters in a safe and controlled environment. By using software tools such as Matlab Simulink or LabVIEW, engineers can model and simulate complex systems to understand their behavior and optimize their performance. Simulations can also be used to validate the accuracy of mathematical models used in the design process and to identify potential problems that may arise during implementation. In addition, simulations can be used to generate data for testing algorithms, control strategies, and decision-making processes. Therefore, simulation is an essential tool for engineers to ensure the success of their designs and minimize risks associated with system implementation.

3.1 Modelling of the AVR system

The first step in analyzing and designing a control system is to create a mathematical model of the system, which is typically done using the transfer function method. However, before using transfer functions and linear state equations, the system needs to be linearized through appropriate assumptions and approximations of the mathematical equations describing the system. Once linearized, transfer function models can be obtained for the system components. These models can be used to simulate the system and analyze its behavior in both transient and steady-state conditions.

Synchronous generator parameters are essential for accurately modeling and simulating its behavior. They are showcased in the table below:

Nominal rms line-to-neutral voltage	U_n	220V
Frequency	f	50 Hz
Stator Resistance	R_s	2.2 Ω
Rotor Resistance	R_f	127 Ω
Direct-axis synchronous reactance (unsaturated)	X_d	75.443 Ω
Quadrature-axis synchronous reactance (unsaturated)	X_q	0.75 Ω
Direct-axis open-circuit time constant	$T_{do'}$	0.235 s
Direct-axis transient reactance	X'_d	10.309 Ω
Direct-axis transient time constant	T'_d	0.0776 s
Direct-axis sub-transient reactance	X''_d	8.5298 Ω
Quadrature-axis sub-transient reactance	X''_q	5.2637 Ω
Direct-axis sub-transient time	T''_d	0.0147 s

TABLE 3.1: 1.5 kVA salient-pole Lab-Volt SG parameters[6]

3.1.1 Generator Model

The synchronous machine generated emf is a function of the magnetization curve, and its terminal voltage is dependent on the generator load. K_G may vary between 0.7 to 1 and T_G between 1 to 2 seconds from full load to no load. The output of the exciter is fed to the generator field winding whose transfer function ($T.F_G$) is given by:

$$T.F_G = \frac{K_G}{1 + sT_G} \tag{3.1}$$

In our study, we employed a value of $K_G = 1$ and $T_G = 1$ specifically for the full load condition.

3.1.2 Exciter Model

The excitation system model is derived from the relationship between the amplification, excitation and compensation functions. So, the transfer function is:

$$T.F_E = \frac{K_E}{1 + sT_E} \tag{3.2}$$

3.1.3 Sensing Circuit Model

The sensing circuit measures the voltage through a potential transformer, with the time constant of the transformer assumed to range from 0.01 to 0.06, its transfer function is:

$$T.F_R = \frac{K_R}{1 + sT_R} \tag{3.3}$$

3.1.4 Amplifier Model

The comparator performs a continuous comparison between the reference voltage, denoted as Vref, and the actual output voltage, Vt. This process results in the generation of a voltage error signal, which is then fed to the amplifier. The amplifier can be of different types, including magnetic, rotational, or electronic. Considering the delay in the amplifier's response, its transfer function ($T.F_A$) is defined as follows:

$$T.F_A = \frac{K_A}{1 + sT_A} \tag{3.4}$$

3.2 Complete AVR block diagram

The automatic voltage regulator (AVR) incorporates key components, including an amplifier, exciter, generator, and sensor, to maintain a stable output voltage. The block diagram of the AVR showcases their interconnectedness. The sensor continuously measures the output voltage and provides feedback. This information is then processed by the amplifier, which amplifies the error signal. The exciter, controlled by the amplified signal, adjusts the generator's excitation level. By modulating the excitation, the AVR ensures the output voltage remains at the desired setpoint. The block diagram highlights the essential role of the amplifier, exciter, generator, and sensor in achieving precise voltage regulation within an AVR system.

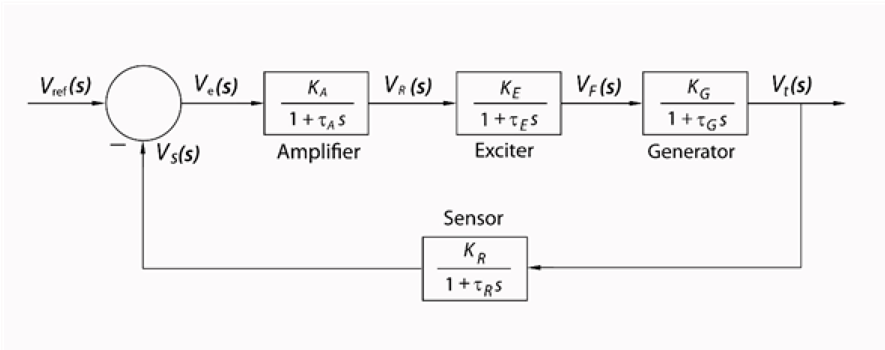

Figure 3.1: AVR model

3.2.1 AVR Model Simulation in MATLAB Simulink

To validate the performance of the AVR system, a simulation was carried out using MATLAB Simulink software. Transfer functions of all stages of the system, including transducer, exciter, amplifier, and generator, were used to develop the model. Two cases were considered during the simulation: with and without a PID controller. This simulation allowed for the study of the system's behavior, including its transient and steady states, and allowed for the evaluation of the performance of the system with and without the PID controller.

3.2.1.1 AVR Model without PID Controller

The Simulink library, specifically the Simscape library, allows for the simulation of an Automatic Voltage Regulator (AVR) block model using transfer functions for each component without a PID controller. The model is presented below, along with the time response of the simulated system:

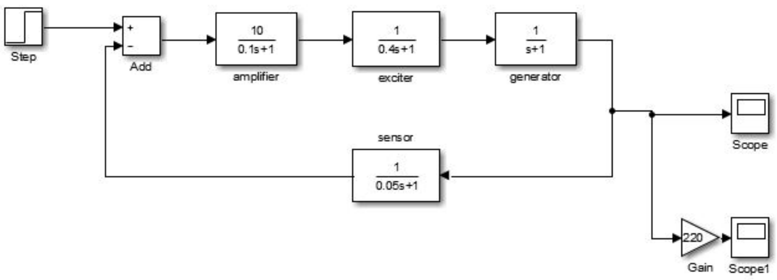

Figure 3.2: AVR MODEL IN SIMULINK WITHOUT PID CONTROLLER.

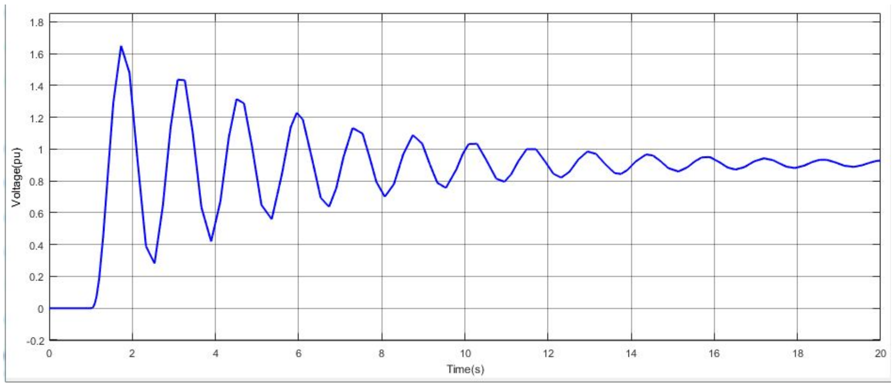

FIGURE 3.3: TIME RESPONCE OF AVR MODEL WITHOUT PID CONTROLLER.

3.2.1.2 AVR Model with PID Controller

Now, let us simulate the AVR model with the inclusion of a PID controller. The PID controller parameters have been determined beforehand using the Zeigler-Nichols tuning method.
The updated AVR model is presented bellow:

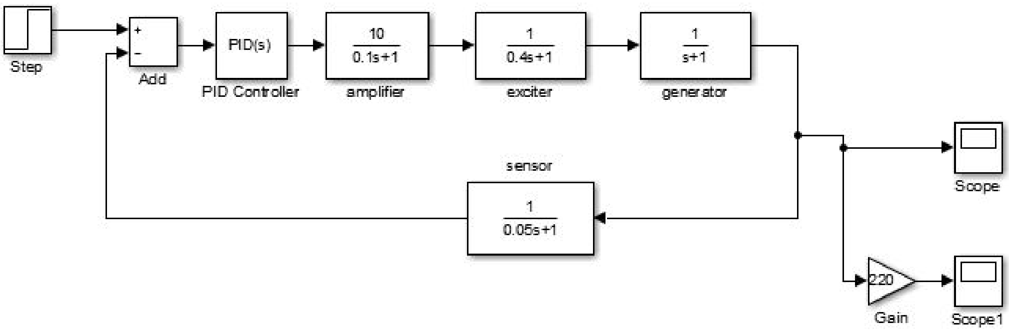

FIGURE 3.4: SIMULINK MODEL FOR AVR WITH PID CONTROLLER.

The system response, obtained using a scope, is displayed below:

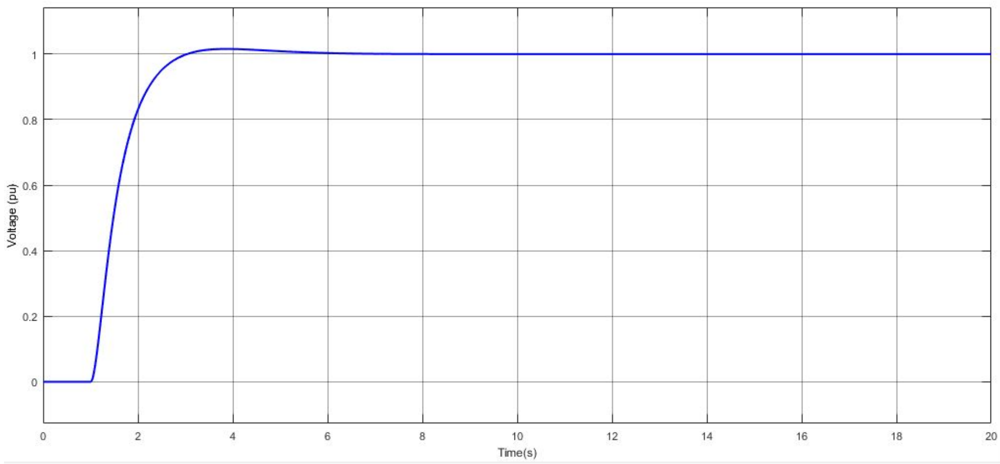

FIGURE 3.5: TIME RESPONCE OF AVR MODEL WITH PID CONTROLLER

3.2.2 SIMULATION RESULTS AND DISCUSSION

The Simulink model block of the AVR system was simulated, and a step response plot was generated in the figure for the generator AVR system. The simulation was carried out for two cases: with and without a PID controller. It was observed that the AVR system without a PID controller exhibited high overshoot and oscillations, while the model with a PID controller displayed low overshoot, minimal oscillation, and shorter settling time to reach the steady state compared to the former.

3.3 AVR Simulation

The AVR circuit in SIMULINK is divided into two main blocks. The first block is the rectifier block, which converts AC energy into DC energy required by the generator during excitation. The second block is the voltage regulator block, which functions as the control for the injected DC voltage to the generator field.

3.3.1 Rectifier Block

In this modeling, the focus is primarily on the control signal used to turn on the transistor in the rectifier block. The rectifier circuit itself utilizes the existing components available in the SIMULINK library.

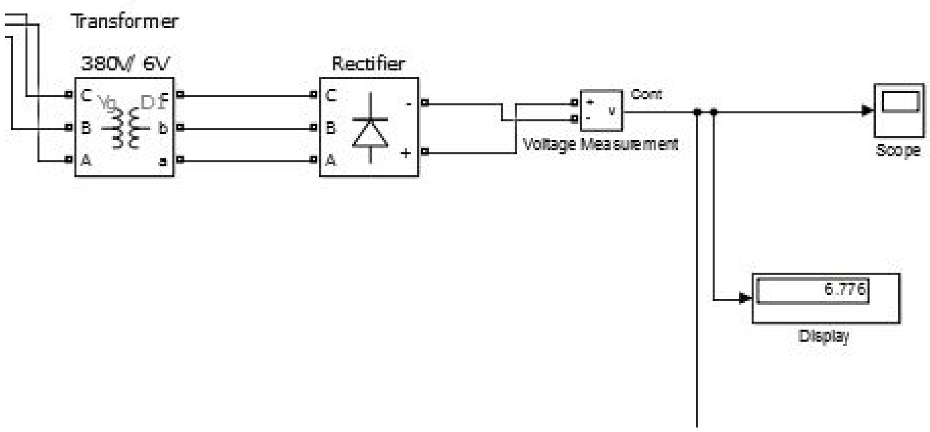

FIGURE 3.6: Rectification system in AVR model

3.3.2 Voltage Regulator Block

The voltage regulator is the most crucial component in the excitation process of a synchronous generator. In this block, there is a PID controller that functions to regulate the DC voltage to be injected into the generator field. The inputs to the voltage regulator are the DC voltage from the rectifier and the desired reference voltage. By using the PID control process, the output obtained is the excitation voltage, which serves as the input to the synchronous generator, as shown bellow in the figure :

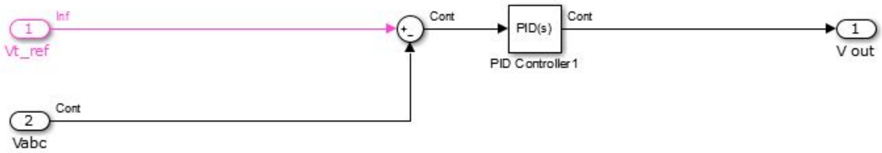

FIGURE 3.7: Block of Voltage Regulator

3.3.3 The Controlled Generator

The controlled object is a synchronous generator with 4 poles and a nominal power capacity of 1.5 kVA. It has a nominal voltage of 400V line to line, a nominal frequency of 50 Hz, and a nominal power factor of 0.8.

The simulation diagram of a synchronous generator including an automatic voltage regulator is shown bellow:

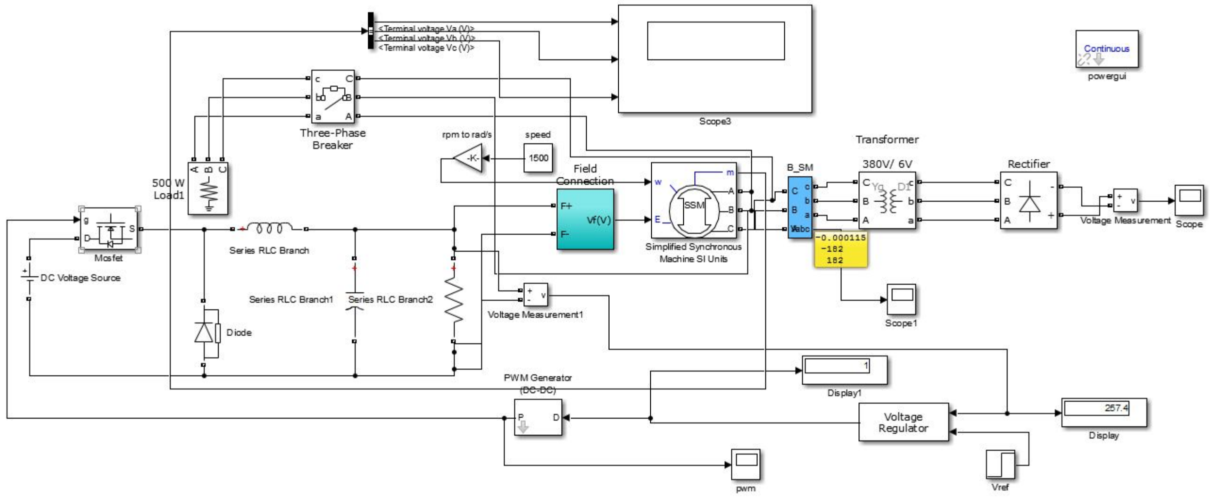

FIGURE 3.8: AVR model in simulink

3.4 Results

3.4.1 Synchronous Generator without Load

Firstly, the model was simulated without a load using fixed excitation, and the steady state was achieved. The resulting output voltage at the terminals of the generator is shown below:

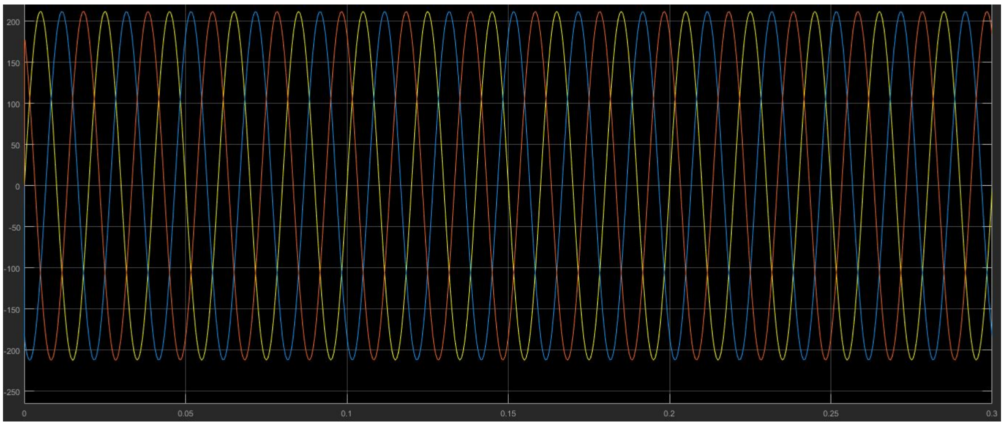

FIGURE 3.9: Terminal voltage of generator without load

3.4.2 Synchronous Generator with Fault Applied

A fault was applied in phase B using a fault block in SimScape, which implements a short-circuit between phase B and the ground. In this case, the fault was applied in phase B at t=9s. The three-phase terminal voltages are shown below:

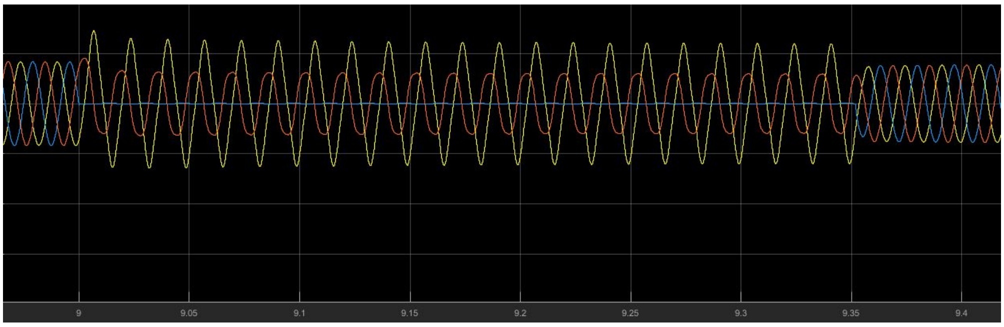

FIGURE 3.10: Terminal voltage of generator when a fault is applied to phase B at t=9s

.

When the fault occurred in phase B at t=9s, V_b became zero, while V_a and V_c increased beyond the desired voltage. As a result, the voltage regulator detected this deviation and decreased the pulse width modulation (PWM) to reduce the field voltage of the generator. After approximately 0.35 seconds, the system response reached a steady state, and the output voltage was maintained at the desired value.

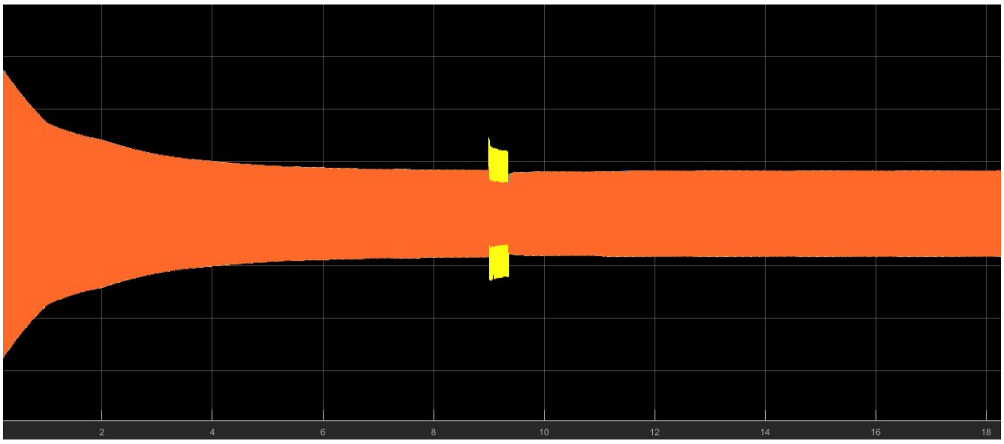

FIGURE 3.11: Terminal voltage of generator when a fault is applied to phase B at t=9s
.

3.4.3 Synchronous Generator with load

The objective of this simulation is to connect loads to the stator terminals of the generator and observe the voltage decrease. Furthermore, it aims to demonstrate the functionality of the voltage regulator in regulating and maintaining the voltage at the desired value. In this scenario, two resistive loads are connected: one with a power rating of 1000 W and the other with a power rating of approximately 500 W. The resulting output voltage is depicted below:

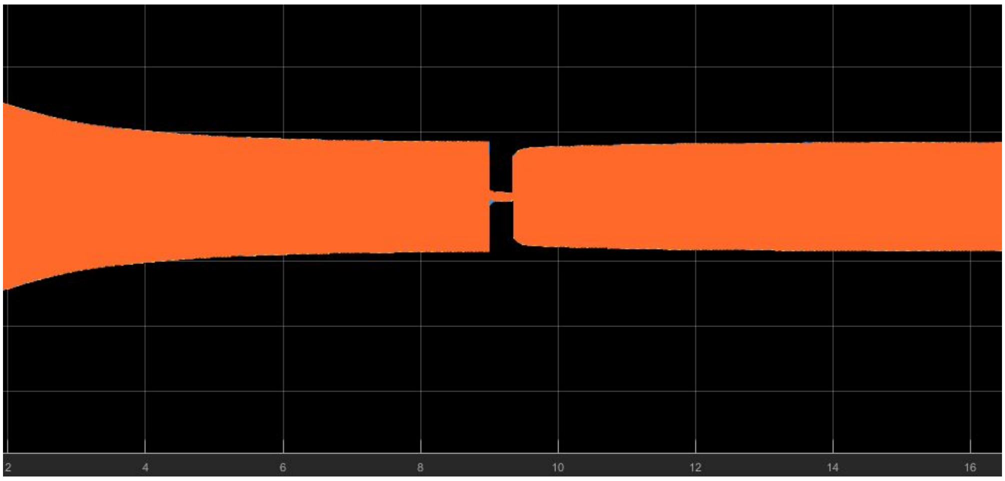

FIGURE 3.12: Terminal voltage of generator when a load is applied at t=9s .

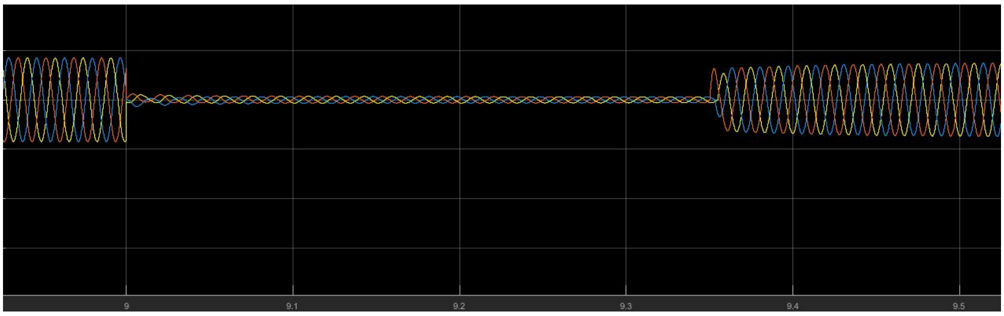

Figure 3.13: Terminal voltage of generator when a load is applied at t=9s .

To observe the decline in the output voltage of a synchronous generator, various parameters can be adjusted, including the speed of the prime mover, excitation current, and the loads connected to the generator's stator terminals. In this specific case, resistive loads were connected to the generator. During the loaded conditions, there is a momentary voltage drop approximately to 20 V followed by a return to the nominal voltage. This voltage increase is due to the function of excitation that supplies DC current to the field winding of the synchronous generator.

To regulate and maintain the output voltage at the desired value, a voltage regulator is employed. The voltage regulator compares the sensed voltage with the desired voltage and generates an error signal. This error signal serves as the input for the PWM generator, which drives the MOSFET block in the model.

By increasing the field voltage through the MOSFET, the terminal voltage of the generator is augmented to reach the desired value of around 220 volts. It reaches a steady state under load conditions in approximately 0.4 seconds.
In both of the previously studied cases, simulations were conducted to observe the operation and response of the model in Simulink under overvoltage and under-voltage conditions. The purpose of these simulations was to demonstrate how the model reacts and the time it takes to maintain the desired voltage, thus preventing any potential damage to the equipment connected to the generator.

By using the PID controller, the generator effectively compensated for voltage variations and maintained stable output voltage within the desired range.

Chapter 4

Design & Implementation of AVR

Introduction

In order to explore the distinctions between practical applications of electrical systems and software analysis, an investigation was undertaken involving the design and implementation of an Automatic Voltage Regulator. This project aimed to examine the circuit design of the regulator, highlighting the contrast between real-world electrical systems and the analytical aspects of software.

The design of AVR is divided into three main parts: sensing the generator voltage, generating corrective signals, and varying the field current according to the corrective signals. The sensing part is accomplished by a measuring circuit. The corrective signals part consists of an Arduino Mega microcontroller, which acts as a PWM controller to generate the necessary corrective signals. The field control circuit includes a MOSFET which acts as a switching element, along with an optocoupler and a resistor for some circuitry protection.

4.1 AVR Design & Construction

4.1.1 Measuring Circuit

In the context of an Automatic Voltage Regulator (AVR), measuring the sensing circuit is an essential stage of the implementation process. The sensing circuit is responsible for reading or sensing the output voltage terminal of the synchronous generator, which is a critical input for calculating the field current required to restore the output voltage to its desired value.

The sensing circuit, therefore, plays a vital role in ensuring that the generator's output voltage is maintained within acceptable limits by continuously monitoring it and making any necessary adjustments to the field current. To measure the voltage of the synchronous generator, a step-down transformer with a ratio of (240/6V) will be used to reduce the voltage. The resulting signal will then pass through a signal conditioning circuit where it will be rectified and converted into a pure DC signal using a bridge rectifier constructed from four IN 4008 diodes. A smoothing capacitor and resistor will be added in parallel to the circuit to smooth the output voltage from the bridge. Specifically, a capacitor of 4.7µF and a resistor of 4.4kΩ will be used. To obtain an output voltage within the acceptable range or limits of the Arduino board (0 to 5V), a voltage divider will be added. This will result in an output of around 3.6V, which is within the range of the Arduino board's input voltage.

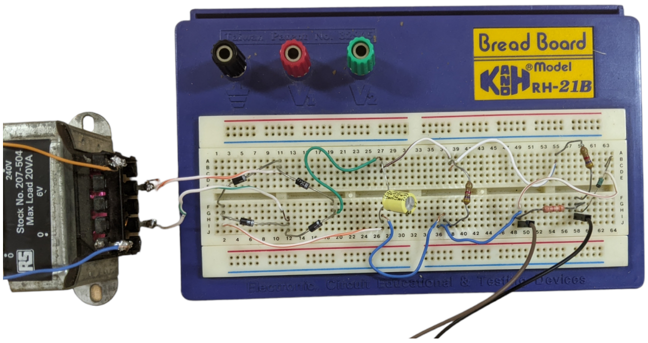

FIGURE 4.1: Measuring Circuit

Overall, this signal conditioning circuit is an essential part of the AVR system as it ensures that the voltage signal from the synchronous generator is properly conditioned and scaled to be within the acceptable range for the AVR control unit. The use of a step-down transformer and bridge rectifier, in combination with the smoothing capacitor and resistor, allows for the creation of a stable and reliable DC voltage output that can be accurately measured and controlled by the AVR system.
In summary, the sensing circuit is a crucial component of the AVR system, and proper measurement and calibration of this circuit are necessary to ensure accurate and reliable voltage regulation of the synchronous generator.

4.1.1.1 Full Wave Rectifier (Bridge of diodes)

A full-wave rectifier is a circuit that converts alternating current (AC) into direct current (DC). This rectifier utilizes a bridge configuration consisting of four diodes (IN 1004 diodes.)

4.1.1.2 Filter

The DC voltage from the rectifier output is not pure DC, so a filter capacitor is placed between the output terminals. These capacitor smooth out pulsation and provide near-pure DC voltages.

4.1.1.3 Voltage divider

The voltage divider is used to reduce the DC output voltage coming from the rectifying circuit to be within range for the Arduino board to process it without risks of damagement.
It simply consists of two resistors connected in series (R_1=4.4kΩ and R_2=3.7kΩ). The analog input to the Arduino board is the voltage accross R_2.

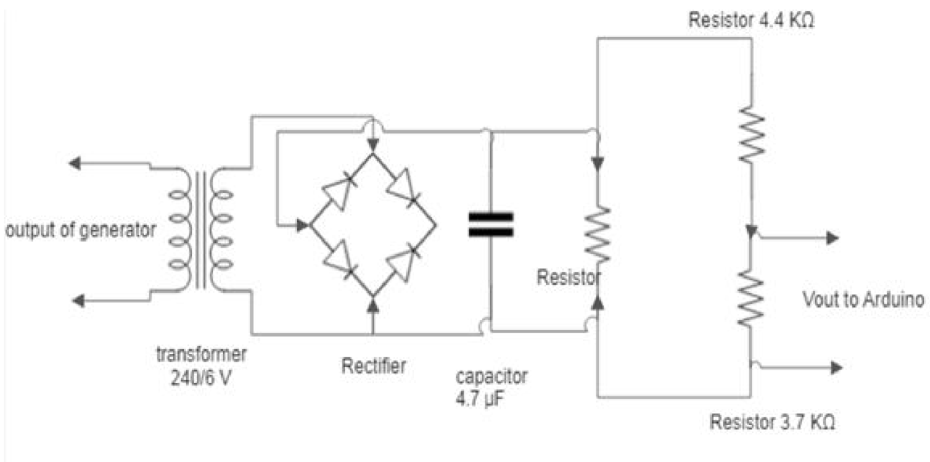

FIGURE 4.2: Schematic Diagram of Measuring Circuit

4.1.2 Control circuit

The control circuit of AVR primarily comprises an Arduino Mega 2560 microcontroller, on which the PID controllers have been implemented using the PID library.

The microcontroller reads the analog signal from the sensing circuit and converts it into a digital signal. Subsequently, the microcontroller generates a PWM signal based on the error signal from the output of the PID controller, which represents the duty cycle of the PWM signal. This process is accomplished using suitable code that facilitates the generation of the PWM signal.

4.1.2.1 Arduino Code for AVR:

The microcontroller is programmed to decrease the PWM duty cycle if the measured voltage is higher than the reference voltage, and increase the duty cycle if the measured voltage is lower than the reference voltage. Consequently, the PWM duty cycle varies in response to the voltage sensed by the measuring circuit. The field controller circuit is designed to increase the field current if the PWM duty cycle decreases, and decrease the field current if the PWM duty cycle increases.

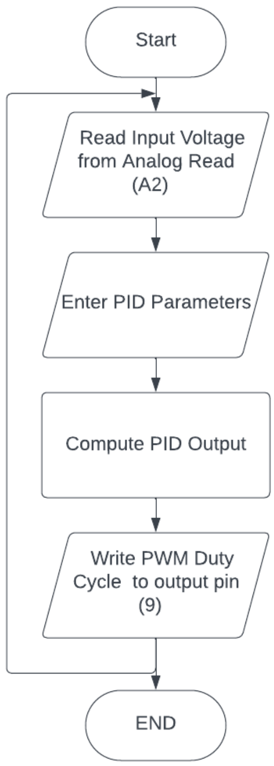

FIGURE 4.3: Flowchart of control Unit

4.1.2.2 Description of the code

The "PID_v1.h" library is a commonly used software library within the Arduino IDE. It offers a range of functions, data structures, and algorithms that greatly simplify the implementation and tuning of Proportional-Integral-Derivative (PID) controllers. This library provides essential functionalities such as initializing the controller, setting the PID gains (proportional, integral, and derivative constants), computing the control output by evaluating the error between the desired setpoint and the current process variable, and handling integral windup and other important aspects of PID control.
First, we need to insert the parameters of the PID controller, namely K_p (proportional gain), K_i (integral gain), and K_d (derivative gain), which are obtained from the Ziegler-Nichols tuning method. The Ziegler-Nichols method helps determine suitable initial values for the PID gains based on the system's response characteristics.

Next, we need to sense the terminal voltage of the synchronous generator using a measuring circuit and read it using the analog read port on your Arduino (A2). The Arduino's analog read function allows you to capture the voltage level at that specific analog input pin.

Once we have obtained the voltage reading, we can set the PID controller to run continuously by using the "automatic" mode. This ensures that the PID controller continuously calculates and updates the control signal based on the error between the measured value (terminal voltage) and the desired setpoint.

The error signal, which represents the output of the PID controller, can then be used to generate a PWM (Pulse Width Modulation) signal. we can achieve this by configuring one of the digital ports on your Arduino, such as port 3, to output a PWM signal. The PWM signal will have a duty cycle proportional to the error signal, indicating the required correction for the system.

4.1.2.3 Pulse Width Modulation (PWM)

PWM is a technique used in electronics to control the amount of power delivered to a device by rapidly switching the power on and off. The average power delivered is determined by the width of the on and off periods, known as the duty cycle. By adjusting the duty cycle, the effective power output can be controlled, allowing for precise control of devices such as motors, LEDs, and audio amplifiers. [14]

In the case of automatic voltage regulator,the PWM is generated from the arduino mega 2560 by using the IDE code shown before, the PWM signal with different width corresponding to increase or decrease or no change in terminal voltage. When the terminal voltage remains unchanged, the PWM signal will have a constant duty cycle or width. However, when there is a change in the input data associated with the measured terminal voltage or the occurrence of any disturbance, the duty cycle needs to be adjusted in order to reject the disturbance and to maintain the terminal voltage to the reference one.

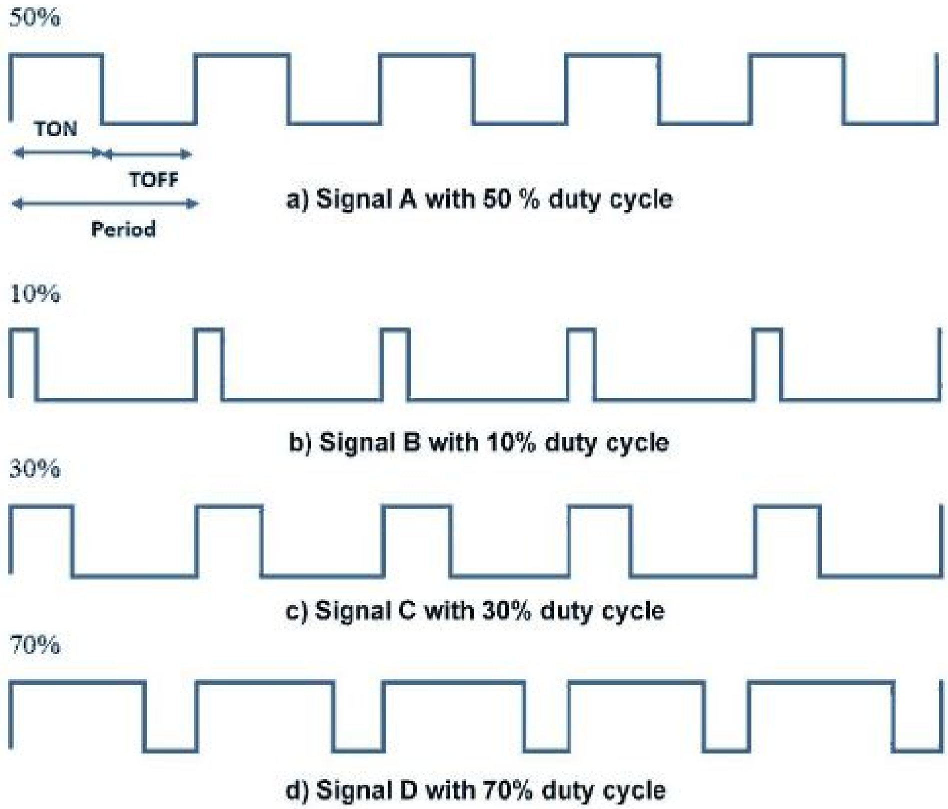

FIGURE 4.4: PWM signals with different Duty Cycles.

4.1.3 Power Circuit

The PWM (Pulse Width Modulation) signal generated by an Arduino is typically not capable of directly controlling the field voltage of a generator without amplification using power components. Therefore, a power circuit is employed to regulate and control the field voltage of the generator.

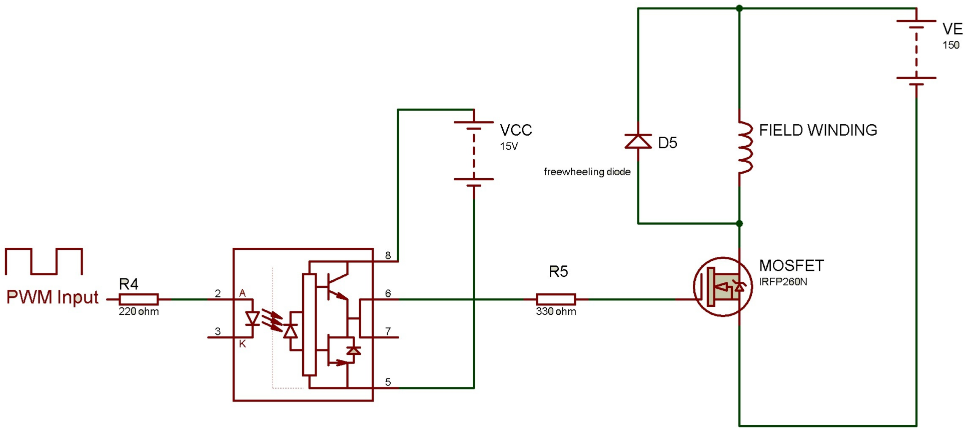

FIGURE 4.5: Schematic diagram for the Power Circuit.

The generator field is controlled by the PWM duty cycle. However, the PWM pulses from the microcontroller cannot be directly fed to the MOSFET for switching due to two reasons. Firstly, the low voltage from the microcontroller is insufficient for switching the MOSFET. Secondly, voltage spikes generated from the fast switching of MOSFET can potentially damage the microcontroller. To solve these two problems, an opto-isolator is used, which isolates the MOSFET from the microcontroller, thus preventing voltage spikes from reaching the microcontroller.

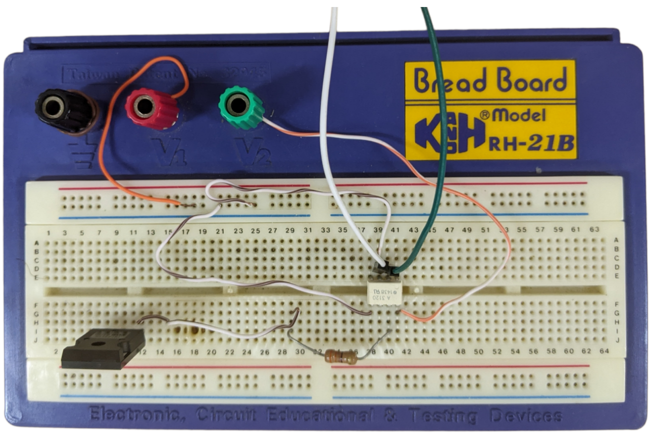

FIGURE 4.6: Power Circuit

The signal from the opto-isolator is fed to the gate terminal of the MOSFET. When the PWM duty cycle from the microcontroller increases, the MOSFET gate voltage also increases, resulting in an increase in the field current. Conversely, when the PWM duty cycle from the microcontroller decreases, the MOSFET gate voltage decreases, leading to a decrease in the field current. to protect the MOSFET during fast switching as inductor reverse its polarity to keep the current passing when MOSFET is off, a freewheeling diode is used in parallel to the field winding.

4.2 Final AVR Design

By combining the measuring circuit, Arduino Mega board, and power circuit, this AVR design provides a comprehensive solution for automatic voltage regulation. The measuring circuit ensures accurate data acquisition, while the Arduino Mega board processes the data and generates control signals. The power circuit effectively adjusts the field excitation to maintain the desired voltage. Together, these components form a robust and efficient AVR system suitable for various applications.

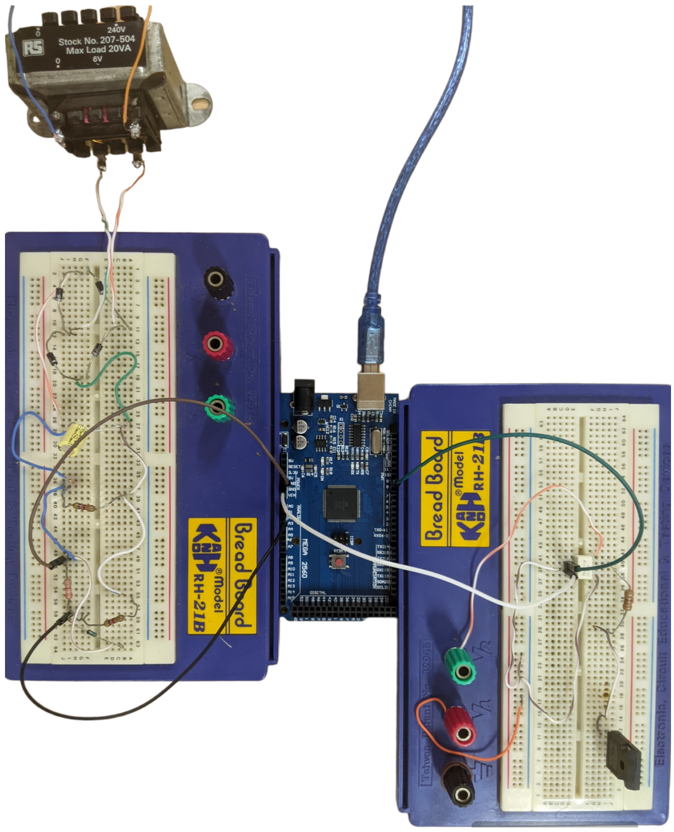

FIGURE 4.7: AVR design

4.3 Experimental determination of the SG field current:

In order to perform both simulation as well as experimental test using the laboratory 1.5kVA salient-pole Lab-Volt SG, field current of the machine need to be accurately identified.For this purpose, identification test was done as shown in figure bellow:

In this experiment, an asynchronous machine was used as prime mover of the synchronous generator supplied directly from 3 phase system which has speed of 1455 rpm to keep the speed of the generator in fixed state ,because the two parameters that can affect to the terminal of the genartor are: the speed and loads. so ,when the speed is fixed ,the focus goes to the loads for the variation of terminal voltage . by injecting different values of current to the rotor field winding of the generator,different values of terminal voltage are measured and recorded in table bellow

Field current (I_f)	Field voltage (V_f)	Terminal voltage (V_t)
0.08	10	23
0.18	20	56
0.25	30	93
0.32	40	127
0.41	50	156
0.49	60	182
0.57	70	206
0.63	79	220

Table 4.1: Electric field current and voltage effect on terminal voltage.

As known, excitation voltage is the voltage required to pass sufficient current through the field winding to produce the expected generated voltage.
Based on the data obtained from the experiment, a graph was plotted showing a proportional relationship between field current I_f and terminal voltage V_t. The graph clearly demonstrates that even a small increase in the field current results in a significant increase in the terminal voltage. Conversely, a decrease in the field current leads to a reduction in the terminal voltage.

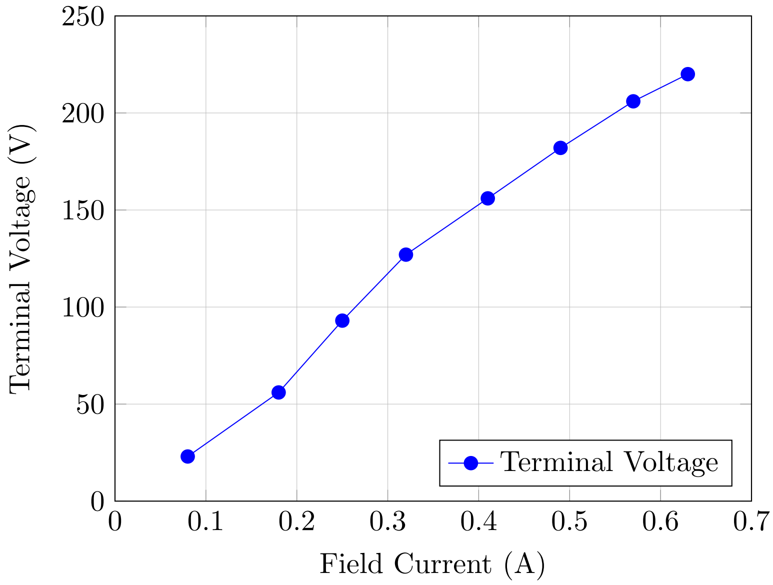

FIGURE 4.8: Field Current vs Terminal Voltage

4.4 Experimental Setup:

Automatic voltage regulator (AVR) function is to process the error signal generated from the compares of reference signal with a measured and conditioned terminal voltage. After processing the error signal the output of the regulator must activate the exciter to feed a voltage or current to the winding of the generator. This voltage affects on the induced flux and so on the terminal voltage.[15]

The AVR (Automatic Voltage Regulator) designed is tested to control the terminal voltage of the LAB-Volt synchronous generator rated at 1.5 KVA. In this setup, an asynchronous machine is employed as the prime mover to maintain a constant speed for the generator.

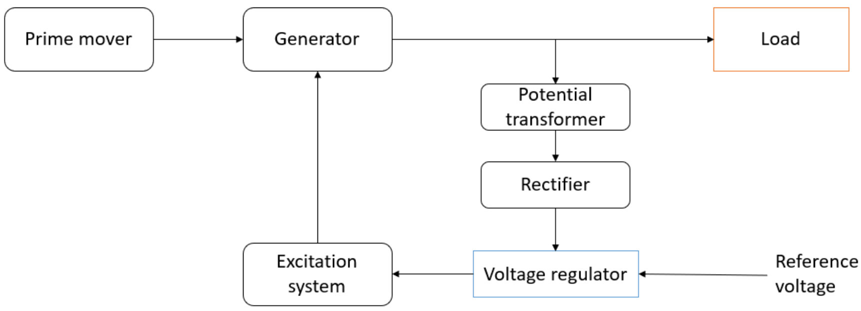

FIGURE 4.9: Implemented Laboratory Structure.

Refer to the figure below for a visual representation of the setup:

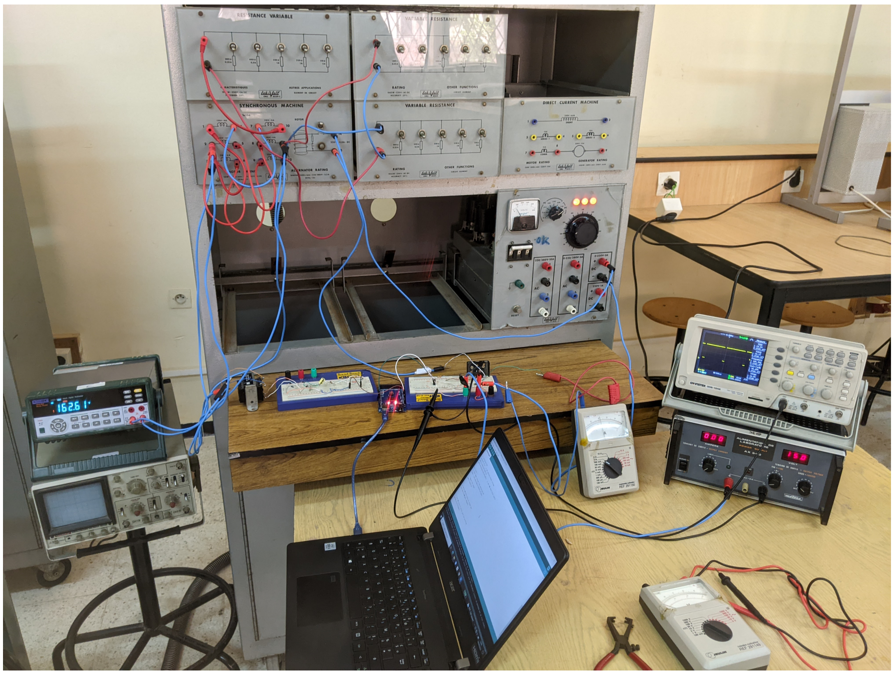

FIGURE 4.10: Experimental test of the AVR

As mentioned previously, the terminal voltage of the generator can be influenced by various factors such as speed, load, power factor, and temperature rise [16]. In our setup, where the prime mover's speed is kept constant, a sudden application of a three-phase resistive load to the generator causes a drop in the terminal voltage. To restore the voltage to the desired level of 163V, the designed Automatic Voltage Regulator (AVR) responds by increasing the Pulse Width Modulation (PWM) signal.

The specific duty cycles of the PWM signal vary based on the magnitude of the applied load. As the terminal voltage of the LAB-Volt synchronous generator decreases, the duty cycles of the PWM signal progressively increase. This adjustment continues until the terminal voltage reaches the desired value and remains stable.

To gather data on the changes in loads, terminal voltage, and PWM signal, an experiment was conducted, and the results were recorded in the table provided below:

Load (A)	Terminal voltage (V_t)	Field current (I_f)	Field voltage (V_f)	PWM
no load	220	0.61	130.2	91.33
0.5	220	0.63	134.4	92.60
1	219	0.67	143	94.16
1.5	218	0.72	153.67	96.49
1.75	219	0.75	160.08	98.05
2	220	0.78	166.48	98.83
2.25	219	0.81	172.88	99.60

TABLE 4.2: Test Results for AVR System

As you can see in the figures below, the oscilloscope displays the PWM signal with different duty cycles. These variations are caused by changes in the loads applied to the output terminals of the generator. The 15V PWM shown in channel 1 corresponds to the output signal from the optoisolator, which is utilized to drive the MOSFET.

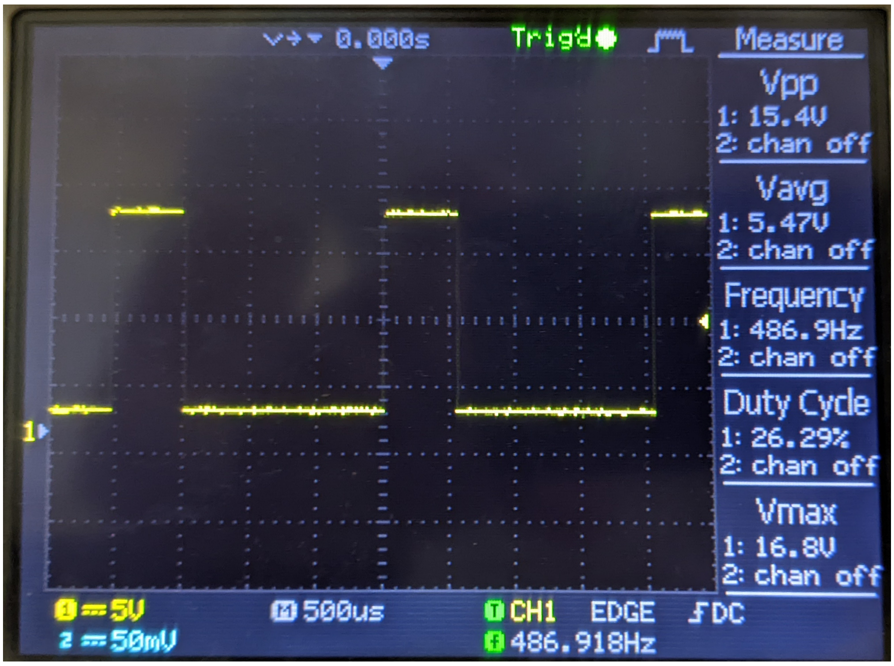

FIGURE 4.11: Generated PWM signal 26% duty cycle

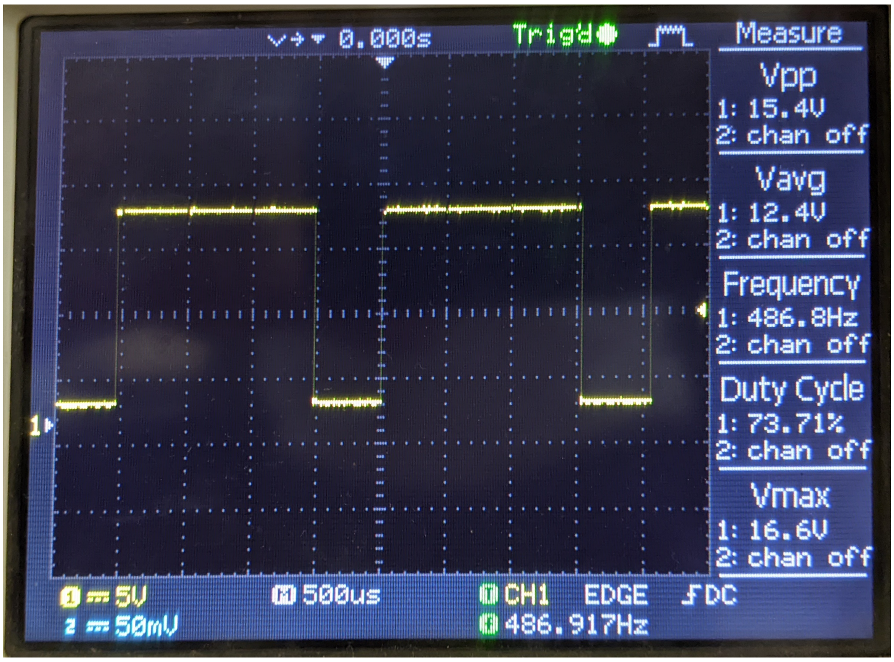

FIGURE 4.12: Generated PWM signal 73% duty cycle

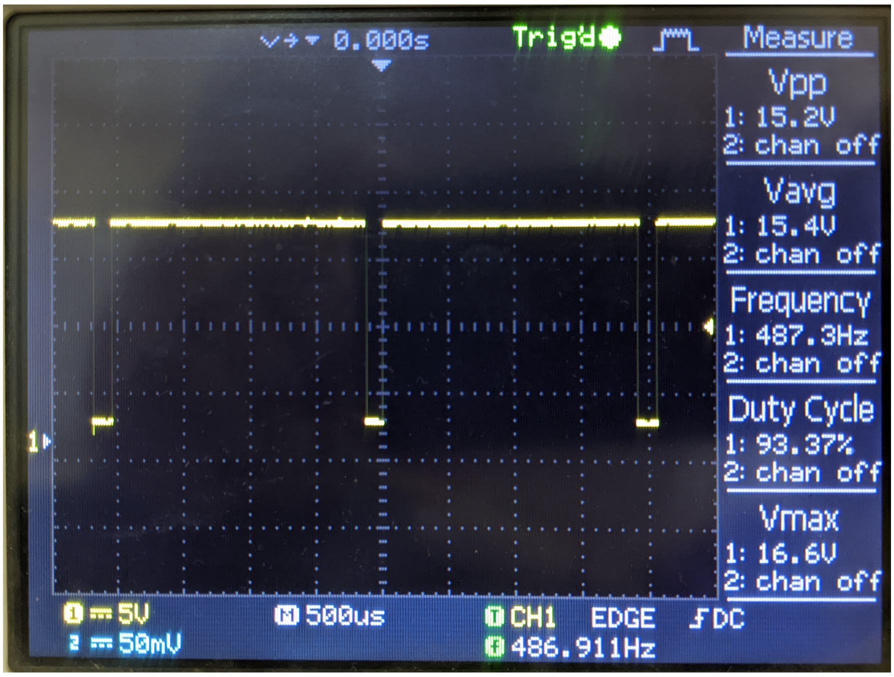

FIGURE 4.13: Generated PWM signal 93% duty cycle

4.5 Tracking of the terminal voltage using LabVIEW

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a powerful and widely used system design and development platform created by National Instruments. It is a visual programming language used in various engineering and scientific fields for data acquisition, instrument control, and industrial automation. We utilized LabVIEW to effectively track the terminal voltage to get a clear visual of the voltage drop and to observe our system's response when the load is applied. We were able to easily interface with the voltage sensor and acquire accurate voltage readings in real-time. The figure below shows the block diagram which implements the program's functionality.

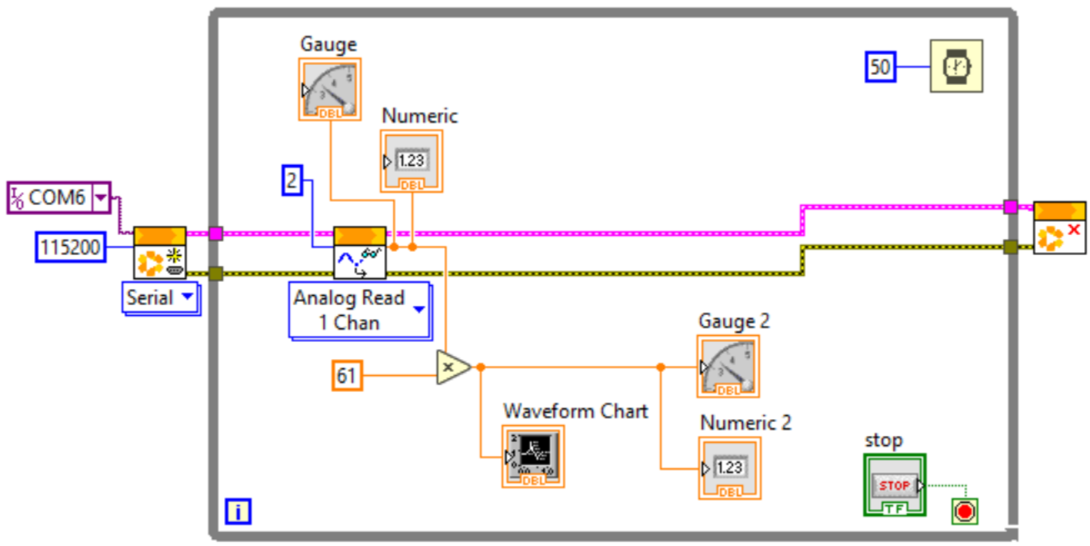

FIGURE 4.14: LabVIEW block diagram

As for the voltage drop, the figure below illustrates the progressive decrease in voltage as a load of 2A is introduced to the circuit.

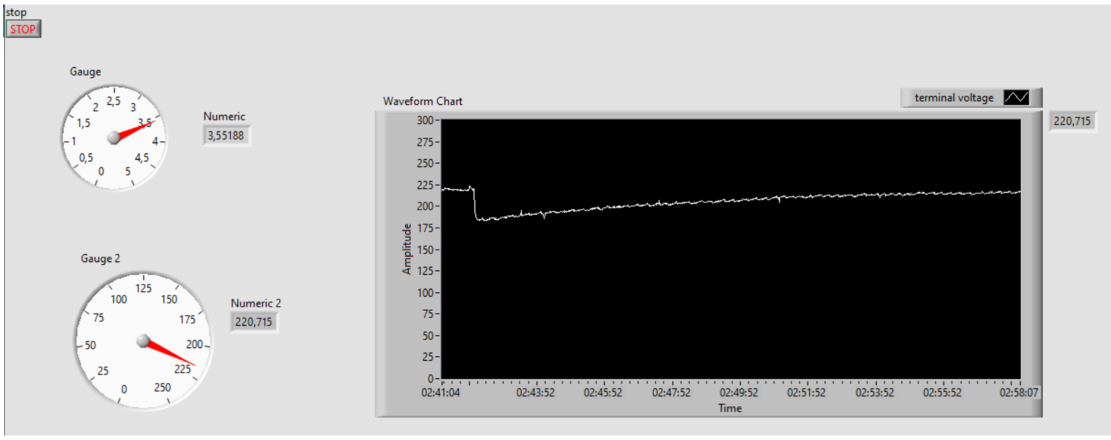

FIGURE 4.15: LabVIEW front panel load applied

The graph effectively illustrates the system's response, showcasing the implementation of voltage regulation to ensure a consistent terminal voltage even under varying load conditions. This visual representation highlights the system's ability to maintain stable voltage levels.

When the load is removed from the circuit, the terminal voltage typically rises. This is due to the fact that the load was consuming power. As it can be seen from the figure below, our system intervenes to maintain the stability of the voltage.

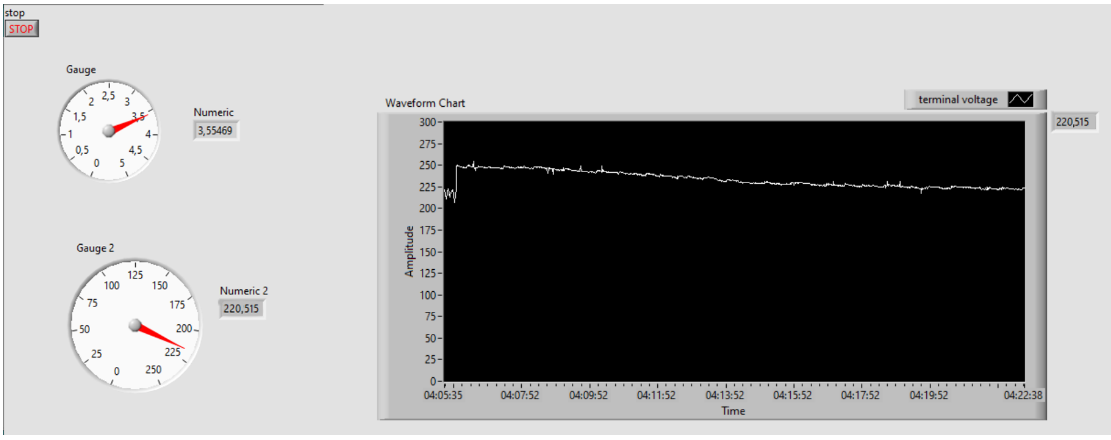

FIGURE 4.16: LabVIEW front panel load disconnected

After previously testing the AVR system with various loads, we decided to challenge it by adjusting the desired setpoint to a lower value. This test aims to evaluate the response and performance of the automatic voltage regulator under different operating conditions.

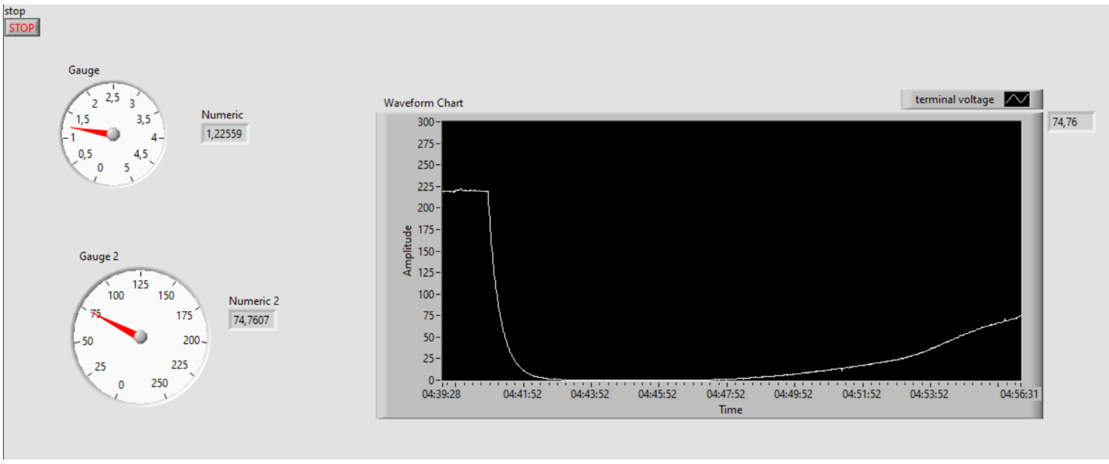

FIGURE 4.17: LabVIEW front panel new setpoint

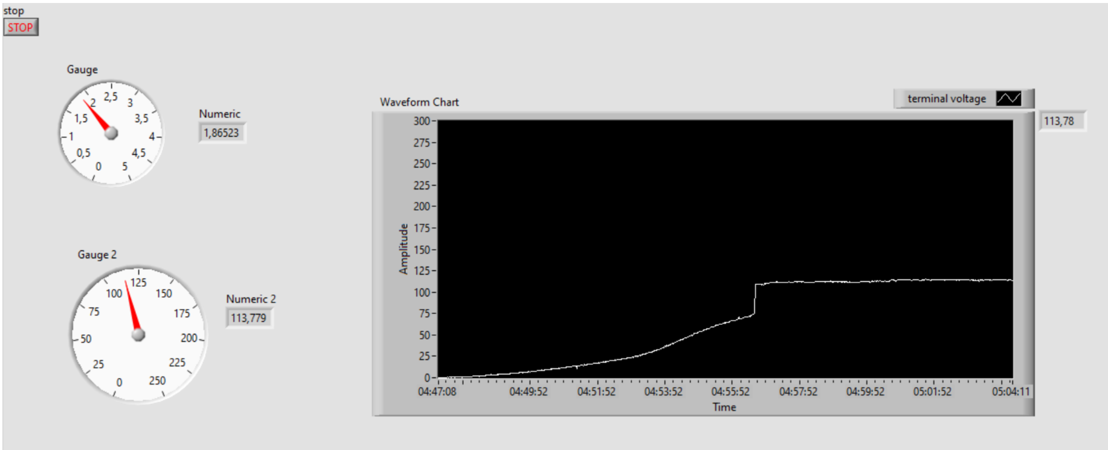

FIGURE 4.18: LabVIEW front panel new setpoint

After adjusting the desired setpoint to a lower value, We observed a sudden change in the terminal voltage. As the setpoint decreased, there was an immediate drop in the terminal voltage due to the altered reference level. The AVR system then initiated its response to rectify the voltage fluctuation. It took approximately 16 seconds for the system to stabilize and reach the new setpoint.

Conclusion

This project aimed to design and implement an automatic voltage regulator using an Arduino Mega board. The objective was to develop a reliable and efficient system that could regulate the output voltage within acceptable limits, ensuring a stable power supply for various electrical applications.

Throughout the project, significant progress was made in achieving the desired goals. The design phase involved understanding the principles of voltage regulation, selecting appropriate components, and creating a circuit schematic. The Arduino Mega board served as the central control unit, enabling precise monitoring and adjustment of the output voltage.

The implementation phase involved assembling the hardware components, programming the Arduino Mega board, and conducting extensive testing and calibration. The use of the Arduino platform provided a flexible and user-friendly interface for configuring the regulator's parameters and monitoring its performance.

The experimental results demonstrated the effectiveness of the automatic voltage regulator. The system successfully maintained the output voltage within the desired range, even in the presence of varying input voltages and load conditions. The feedback loop implemented in the control algorithm allowed for real-time adjustments, ensuring accurate response to fluctuations in the input voltage.

However, it is important to note the sensing limitations of the Arduino board. The built-in analog-to-digital converter (ADC) on the Arduino Mega has a limited resolution, which can impact the accuracy of voltage measurements. Additionally, the Arduino board may have a limited input voltage range, and exceeding this range could lead to inaccurate readings or potential damage to the board.

To address these sensing limitations, future work should focus on implementing external high-resolution ADCs to improve the accuracy of voltage measurements. By utilizing dedicated ADC modules with higher resolution and wider input voltage ranges, the system can achieve more precise monitoring and regulation of the output voltage.

Furthermore, integrating advanced filtering techniques and signal conditioning circuits can help reduce noise and improve the overall performance of the voltage sensing system. This would enhance the system's ability to accurately detect and respond to voltage fluctuations, ensuring stable and reliable operation.

In conclusion, the design and implementation of an automatic voltage regulator using an Arduino Mega board proved to be a valuable learning experience. It showcased the practical application of microcontroller-based systems in power electronics and highlighted the importance of stable voltage regulation in various electrical applications.

Moving forward, addressing the sensing limitations by incorporating external high-resolution ADCs and implementing advanced filtering techniques will contribute to the continued improvement and refinement of the voltage regulation system. These enhancements will enable more accurate voltage measurements, enhancing the system's overall performance and reliability.

Overall, this project successfully demonstrated the feasibility and effectiveness of the designed automatic voltage regulator. It contributes to the body of knowledge in the field of power electronics and serves as a foundation for further advancements in voltage regulation technologies.

Bibliography

[1] M.Saidy, F M Huges, "A predictive integrated voltage regulator and power system stabilizer," Elsevier proceedings on Electrical Power Energy Systems, voU7, No.2, pp.l0l-11l, 1995.

[2] Moundas Abdenour,"micro controller based automatic voltage regulator of generator set "IGEE,2003.

[3] Bose, B.K. Modern Power Electronics and AC Drivers. Prentice Hall PTR, ISBN 0- 13-016743-6, Upper Saddle River, New Jersey, USA. 2012.

[4] A. M. Mosaad, M. A. Attia, and A. Y. Abdelaziz, "Whale optimization algorithm to tune PID and PIDA controllers on AVR system", Ain Shams Engineering Journal, vol. 10, no. 4, pp. 755–767, 2019.

[5] Z-L. Gaing, "A Particle Swarm Optimization Approach for Optimum Design of PID Controller in AVR System", IEEE Transactions on Energy Conversion, vol.19, No.2, pp.348-391, 2004.

[6] Ahcene,F.; Bentarzi, H. Automatic voltage regulator design using particle swarm optimization. International conference on electrical engineering (2020).

[7] F. Ahcene, H. Bentarzi, A. Ouadi, Automatic Voltage Regulator Design Enhancement Taking Into Account Different Operating Conditions and Environment Disturbances. Algerian Journal of Environmental Science and Technology June edition Vol9 No2 (2023).

[8] ECAI 2014 - International Conference – 6th Edition Electronics, Computers and Artificial Intelligence 23 October -25 October, 2014, Bucharest, ROMÂNIA.

[9] Web: https://www.halvorsen.blog, April 2023.

[10] Ogata, Discrete–Time Control Systems, University of Minnesota, Prentice Hall, 1987.

[11] P. Kundur. "Power System Stability and Control", New York: McGraw-Hill Inc, 1994.

[12] Ion Boldea. "Synchronous Genrators" -Second edition- Timisoara: CRC Press, 2016.

[13] Mohamed Labib Awad. "Modeling of Synchronous Machines for System Studies", University Of Toronto, Toronto, Canada, 1999.

[14] Wetzer, P. Machines synchrones - excitation. Techniques de l'ingénieur, D3545, 1997.

[15] Quercioli, Valter , 1993. Pulse width modulated (PWM) power supplies. 1st ed. Netherland: Elsevier Science publication.

[16] Owen, B. (2011). Beginner's guide to electronics. 4th Ed. New York. A Newness Technical Book, McGraw – Hill Companies Inc. 198 – 200.

[17] Angelo J. J. rezck , Carlos Alberto D-Coelho, "The Modulus Optimum (MO) Method Applied to Voltage Regulation Systems: Modeling, Tuning and Implementation", EFEI-ESCOLa Federal de Engenhana de Itajuba, AV. BPS, 1303 Itajuba-MG-Brazil 37500-903.