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**Design and implementation of Automatic
voltage regulator for synchronous generator**

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Dedication

To my lovely family and to my kind friends
Saad Aymane

To my parents
To my friends and family
Abderrezak Lairedj

Acknowledgement

First, gratefulness and praise be to Allah, the most gracious, most merciful, for guiding us through all these years, and for granting us the opportunity to be surrounded by great people at IGEE Institute.

We would like to express our deepest gratitude to all the family and friends who helped us during this work. A special gratitude and respect to our supervisor Pr. H.Bentarzi , Mr. Ouadi and Mr. Zitouni for helping us through realization of this project.

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List of abbreviation:

SG: Synchronous Generator.
AVR: Automatic Voltage Regulator.
IC: Internal Combustion
WEC: The World Energy Council
PM: Permanent Magnets
DC: Direct Current
AC: Alternating Current
PWM: Pulse Width Modulation
DFIG: Double Fed Induction Generator
CRIG: Cage Rotor Induction Generator
TFG: Transverse Flux Generator
FRG: Flux Reversal Generator
ME: Main Exciter
AE: Auxiliary Exciter
VT: Voltage Transformer
CT: Current Transformer
NI: National Instrument
DAQ: Data Acquisition
EMF : ElectroMotive Force
PSO : Particle Swarm Optimization

Abstract

Automatic Voltage Regulator (AVR) is necessary for all power generation plant producing electricity using synchronous generators (SGs) to ensure constant voltage in the grid connection. This final year project aims to design and implement an AVR using Labview program for the laboratory 1.5kVA salient pole Lab-volt SG.

First, an experimental test is carried out using test bench in order to identify the relationship between the terminal voltage of the SG and current injected to the field winding, the second experiment is done to identify the PWM signals needed for different loads connected to the terminal of the generator. Then, AVR model is simulated using Simulink/ Matlab.

Finally, a model of the AVR will be constructed and tested under five different loads condition.

1.1 Generalities

In power systems, voltage stability is highly correlated with the change in reactive power. The voltage collapse phenomenon is strongly influenced by the system operation conditions, where reactive power cannot be compensated by control devices and hence the power system fails. However, such failure in a power may cause many problems in a power grid like power equipment malfunctioning that will affect negatively on the economy (cost and time). In a power plant, engineers usually rely on synchronous generators (SG) to feed the grid with power. The SG must be able to maintain a constant level of terminal voltage despite of the disturbances that may cause the deviation of the terminal voltage from its desired value. An automatic voltage regulator (AVR) may be needed to maintain the terminal voltage of a generator just by adjusting the current injected in the excitation system. When the load changes, the voltage at the generator terminal will change accordingly. However, by controlling the exciting current, the generator terminal voltage can be kept within a predetermined value limits.

1.2 Motivation

The deviation of voltage in power plant or in any generation station can damage many equipment, these damages will add extra costs and downtime. Then, the automatic voltage regulator is needed to satisfy many objectives, such as:

- Keeping the voltage levels within a safety range,
- Avoiding malfunction operations of electrical equipment,
- To maintain the system's voltage within the operating range and keep the operation of the machines near to the steady state stability limit.
- To adjust and regulate sharing of the reactive load between machines operating in parallel.
- To keep voltage under system fault conditions that ensure rapid operation of protective devices (as: relays, switches...).
- Provide close control of field circuits, in order to keep machine in synchronization with the system when it is operating at unity or leading power factor

1.3 Objective

Since an Automatic Voltage Regulator (AVR) is necessary for all generation power plants producing electricity using synchronous generator (SG). This AVR may be used to maintain a voltage level constant at the terminals of the synchronous generator. This final year project aims to design and implement an AVR using Programmable device such as Arduino or PC associated with DAQ for the laboratory salient pole synchronous generator of 1.5 kVA.

1.4 Outlines

This report is structured into five main chapters. After general introduction presented in chapter one, chapter two deals with electric generator description and its different types, then synchronous generator characteristic and its operation principle. Besides, different types of excitation system, power system control and the relationship between voltage and reactive power in a power system are also explained. Moreover, this chapter talks about the AVR principle of operation and why it is need. In chapter three, as well as the hardware setup the construction of AVR model will be introduced starting with the graphical instrumentation program (LabVIEW) used to minimize physical components. The LabVIEW as software tool will take part in measurement and control part in AVR system, the control part will be done using PID controller programmed and tuned using hit and trial method in LabVIEW. In chapter four, the complete system implementation using Matlab/Simulink for test purpose by simulation is presented. The implementation of the measurement and the excitation circuit as well as the LabVIEW program are explained. Finally, the report ends up by a conclusion as chapter five.

2.1 Introduction:

Electric energy (power) is produced by coupling a prime mover that provides the mechanical energy to an electrical generator, which converts the mechanical energy into electrical energy. An intermediate form of energy may be produced in the electrical generator, which is called magnetic energy, stored mainly between the stator (primary) and rotor (secondary). The main types of “turbines” or prime movers are Steam turbines, Gas turbines, Hydraulic turbines, Wind turbines, Diesel engines and Internal Combustion (IC) engines.

The most used technologies to produce electrical energy are electric generators coupled to prime movers, but there are also direct electric energy production methods that avoid the mechanical energy stage, such as photovoltaic, thermoelectric, and electrochemical (fuel cells) technologies. The later technologies without the use of electric generators till represent only a tiny part of all electric energy production in the earth.

The World Energy Council (WEC) estimated that a total electric energy demand of 12,000 TWh, about 18.5% was contributed by hydro in 1990. However, the world electric energy demand was estimated to be 23,000 TWh in 2020, then if only 50% of all economically feasible hydro resources were put to work, hydro would contribute 28% of total electric energy demands. According to these numbers, a new era of dynamic hydroelectric power development and the use of synchronous generators comes soon, if the world population desires more energy (prosperity for more people) with a small impact on the environment (constant or less greenhouse emission effects).

In this chapter, both synchronous generator and motor and their working principle along with their characteristics were presented. The functionality of each part of the excitation system are discussed

2.2 Types of electric generator:

Electric generators may be classified in many ways, but the following are deemed fully representative:

- by principle
- by applications domain

The applications domain implies the power level. The classifications by principle unfolded here include commercial (widely used) types together with new configurations, which are still in the laboratory (although advanced) stages.

According to principle, there are three main types of electric generators:

- Synchronous (Figure 2.1)
- Induction (Figure 2.2)
- Parametric (with magnetic anisotropy and permanent magnets)—Figure 2.3

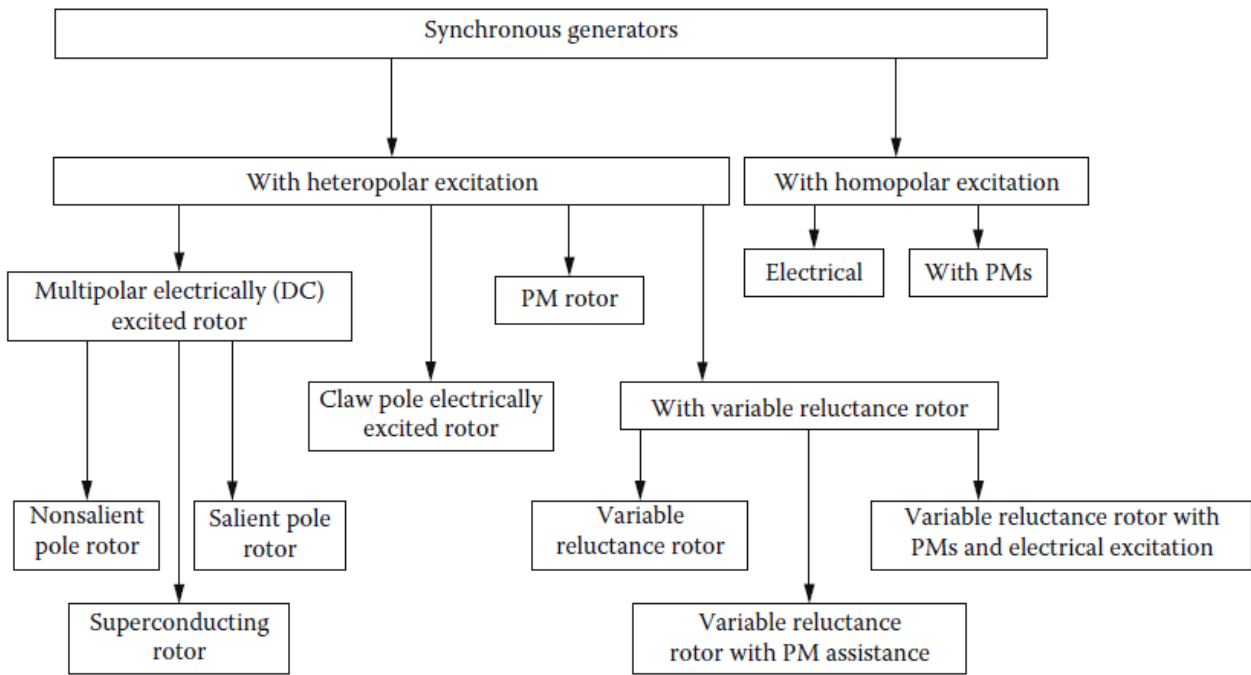


Figure 2.1 a) synchronous generator

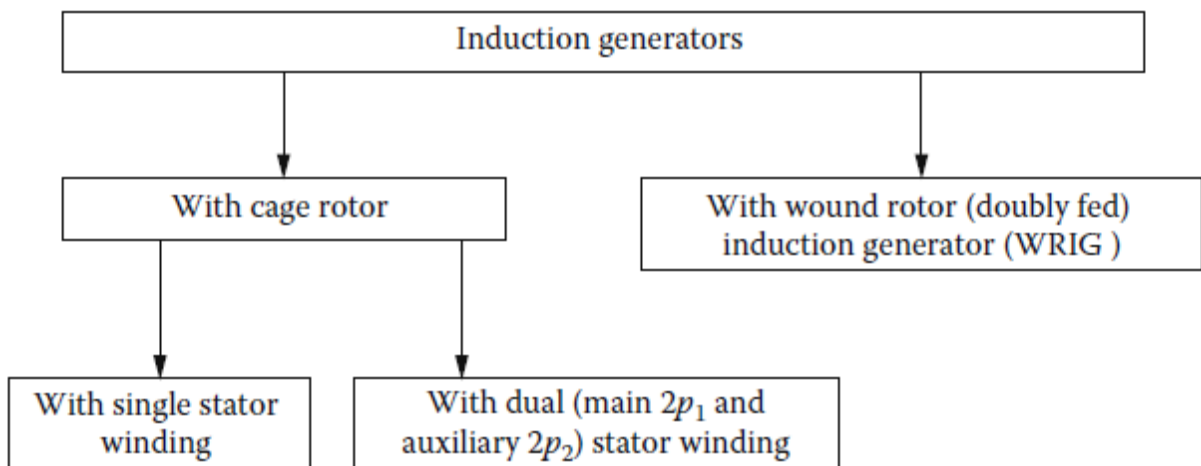


Figure 2.1 b) Induction generator

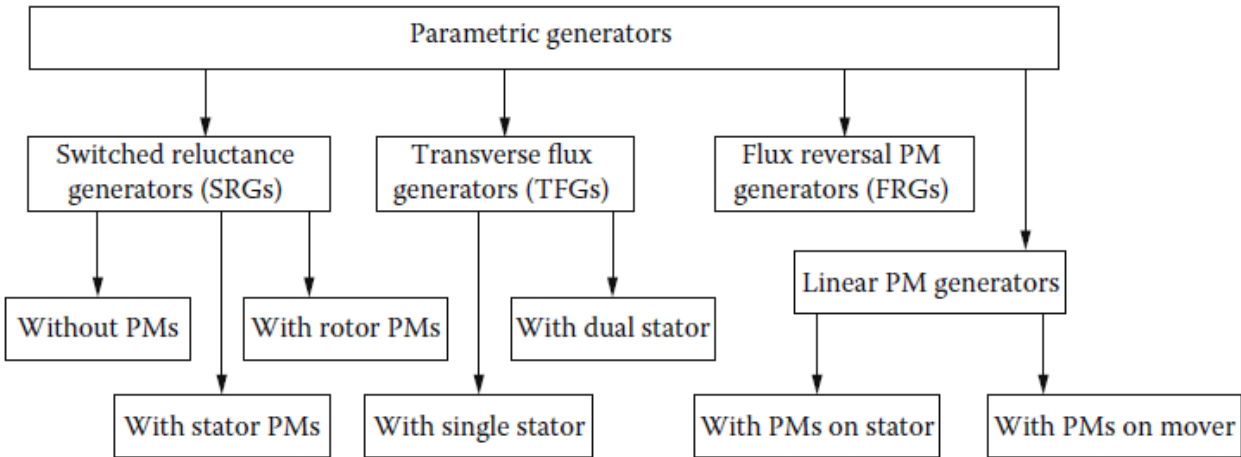


Figure 2.2 Parametric generator

Parametric generators have in most configurations doubly salient magnetic circuit structures; therefore, they may also be called “doubly salient electric generators.”

Synchronous generators (SGs) [4–7] have, in general, a stator magnetic circuit made of laminations provided with uniform slots that house a three-phase (sometimes single- or two-phase) winding and a rotor. It is the rotor design that leads to a cluster of SG configurations as can be seen in Figure 2.1. They are all characterized by the rigid relationship among speed n , frequency f_1 , and the number of poles $2p$:

$$n = \frac{f}{p} \quad (2.1)$$

Those are DC excited require power electronics excitation control, while those with permanent magnets (PMs) or (and) variable reluctance rotors have to use full power electronics in the stator to operate at adjustable speed. Finally, even electrically excited, SGs may be provided with full power electronics in the stator when they work alone or in power grids with DC high-voltage cable transmission lines [8].

For powers in the MW/unit range and less induction generators have also been introduced. They are (Figure 2.2) as follows:

- with cage rotor and single stator winding,
- with cage rotor and dual (main and additional) stator winding with different number of poles in general,
- with wound rotor.

PWM converters are connected to the stator (for the single stator winding and, respectively, to the auxiliary stator winding for the case of dual stator winding). The principle of the induction generator with single stator winding relies on the equation:

$$f_1 = p_1 n + f_2 \quad (2.2)$$

where, f_1 is the stator frequency, f_2 is the slip (rotor) frequency and n is the rotor speed (rps).

f_2 may be either positive or negative in Equation 2.2, even zero, provided the PWM converter in the wound rotor is capable of supporting bidirectional power flow for speeds n above f_1/p_1 and below f_1/p_1 . Note that for $f_2 = 0$ (DC rotor excitation), the SG operation mode is reobtained with the DFIG (double fed induction generator). The slip S definition is as follows:

$$S = \frac{f_2}{f_1} \langle \rangle 0 \quad (2.3)$$

The slip is zero as $f_2 = 0$ (DC) for the SG mode.

For the dual stator winding, the frequency–speed relationship is applied twice:

$$\begin{aligned} f_1 &= p_1 n + f_2; \quad p_2 > p_1 \\ f_1' &= p_2 n + f_2'; \end{aligned} \quad (2.4)$$

Therefore, the rotor bars experience, in principle, currents of two distinct (rather low) frequencies f_2 and f_2' . In general, $p_2 > p_1$ to cover lower speeds.

The PWM converter feeds the auxiliary winding. Consequently, its rating is notably lower than the full power of the main winding and is proportional to speed variation range. As it may work in the pure synchronous mode too, the DFIG may be used up to highest levels of powers for SGs (400 MW units have been already in use for some years in Japan) and 2. 300 MW pump storage plant is being now commissioned in Germany.

On the contrary, the cage rotor induction generator (CRIG) is more suitable for powers in the megawatt and lower power range. Parametric generators rely on the variable reluctance principle but may also use permanent magnets to enhance the power per volume and reduce generator losses. There are quite a few configurations that suit this category such as the switched reluctance generator (SRG), the transverse flux PM generator (TFG), the flux reversal generator (FRG). In general, their principle relies on co-energy variation due to magnetic anisotropy (without or with PMs on rotor or

on stator), in the absence of a pure traveling field with constant speed (f_1/p), so characteristic for synchronous and induction generators (machines).

2.3 Synchronous generator:

Synchronous generators are characterized by a uniformly slotted stator laminated core that hosts a three-, two-, or one-phase alternating current (AC) winding and a DC current excited, or PM-excited or variable saliency, rotor [4–9]. Only two traveling fields — of the stator and rotor — at relative standstill interact to produce a torque with no ripple, the speed n is rigidly tied to stator frequency f_1 , because the rotor-produced magnetic field is DC, typically hetero-polar in synchronous generators. They are built with non-salient pole, distributed-excitation rotors (Figure 2.4) for $2p_1 = 2, 4$ (that is, high speed or turbo-generators) or with salient-pole concentrated-excitation rotors (Figure 2.5) for $2p_1 > 4$ (in general, for low-speed or hydro-generators).

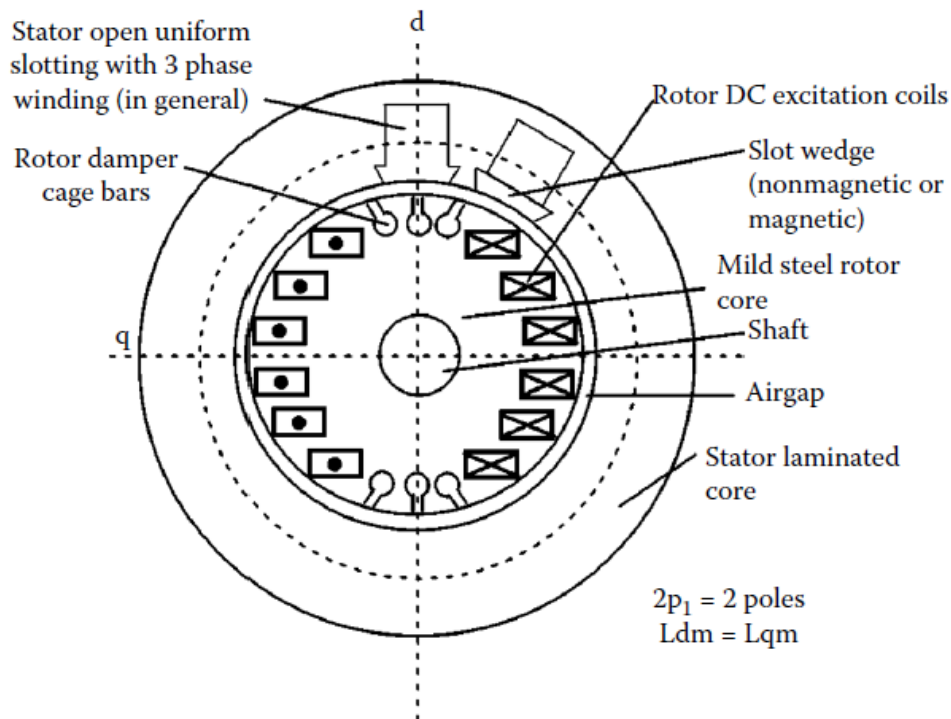


Figure 2.3 Synchronous generator with non-salient pole hetero-polar DC distributed excitation.[6]

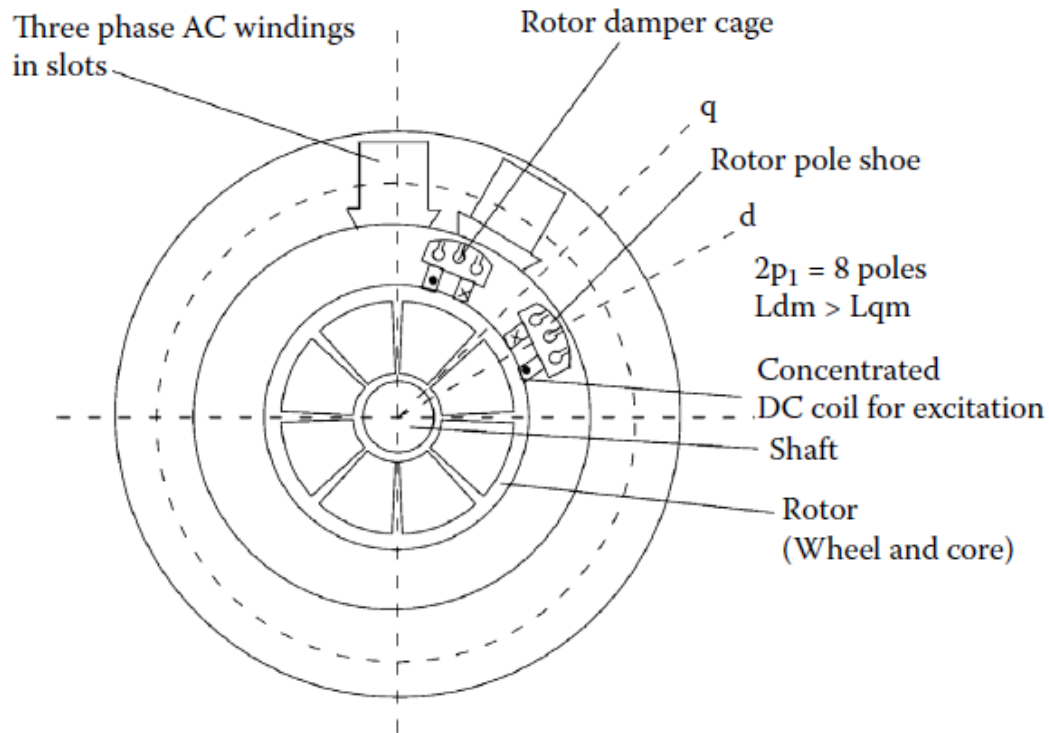


Figure 2.4 Synchronous generator with salient pole hetero-polar DC concentrated excitation.[6]

As power increases, the rotor peripheral speed also increases. In large turbo-generators, it may reach more than 150 m/sec (in a 200 MVA machine $D_r = 1.2$ m diameter rotor at $n = 3600$ rpm, $2p_1 = 2$, $U = \pi D_r n = \pi \times 1.2 \times 3600/60 > 216$ m/sec). The DC excitation placement in slots, with DC coil end connections protected against centrifugal forces by rings of highly resilient resin materials, thus becomes necessary. Also, the DC rotor current air gap field distribution is closer to a sinusoid. Consequently, the harmonics content of the stator-motion-induced voltage (electromagnetic force or no-load voltage) is smaller, thus complying with the strict rules (standards) of large commercial power grids. The rotor body is made of solid iron for better mechanical rigidity and heat transmission.

The stator slots in large synchronous generators are open, and they are provided, sometimes, with magnetic wedges to further reduce the field space harmonics and thus reduce the electromagnetic force harmonics content and additional losses in the rotor damper cage. When $n = f_1/p_1$ and for steady state (sinusoidal symmetric stator currents of constant amplitude), the rotor damper cage currents are zero. However, should any load or mechanical transient occur, eddy currents show up in

the damper cage to attenuate the rotor oscillations when the stator is connected to a constant frequency and voltage (high-power) grid.

The rationale neglects the stator magneto-motive force space harmonics due to the placement of windings in slots and due to slot openings. These space harmonics induce voltages and thus produce eddy currents in the rotor damper cage, even during steady state.

Also, even during steady state, if the stator phase currents are not symmetric, their inverse components produce currents of $2f_1$ frequency in the damper cage. Consequently, to limit the rotor temperature, the degree of current (load) unbalance permitted is limited by standards. Non-salient pole DC excited rotor synchronous generators are manufactured for $2p_1 = 2, 4$ poles high-speed turbo-generators that are driven by gas or steam turbines.

For lower-speed synchronous generators with a large number of poles ($2p_1 > 4$), the rotors are made of salient rotor poles provided with concentrated DC excitation coils. The peripheral speeds are lower than those for turbo-generators, even for high-power hydro-generators (for 200 MW 14 m rotor diameter at 75 rpm, and $2p_1 = 80$, $f_1 = 50$ Hz, the peripheral speed $U = \pi \times D_r \times n = \pi \times 14 \times 75/60 > 50$ m/sec). About 80 m/sec is the limit, in general, for salient pole rotors. Still, the excitation coils have to be protected against centrifugal forces.

The rotor pole shoes may be made of laminations, in order to reduce additional rotor losses, but the rotor pole bodies and core are made of mild magnetic solid steel.

The rotor pole shoes are provided with slots that house copper bars short-circuited by copper rings to form a rather complete squirrel cage. A stronger damper cage was thus obtained.

DC excitation power on the rotor is transmitted by either:

- Copper slip-rings and brushes (Figure 2.6)
- Brushless excitation systems (Figure 2.7)

The controlled rectifier, with power around 3% of generator rated power, and with a sizable voltage reserve to force the current into the rotor quickly, controls the DC excitation currents according to the needs of generator voltage and frequency stability [8].

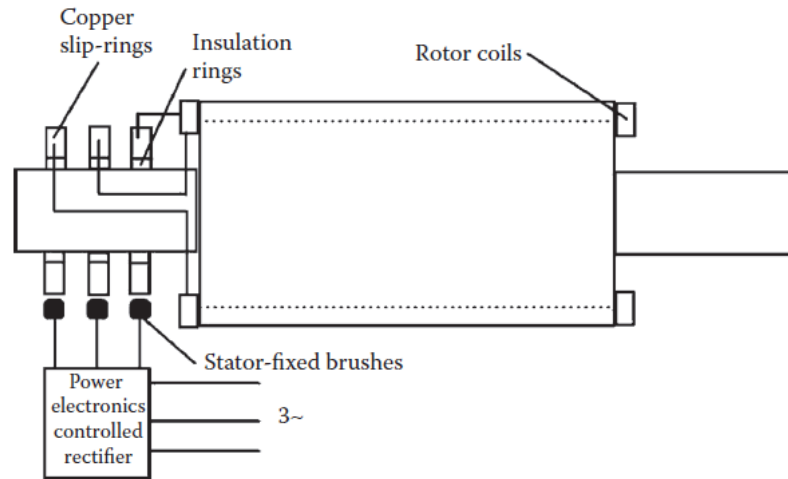


Figure 2.5 -Slip-ring-brush power electronics rectifier DC excitation system.[8]

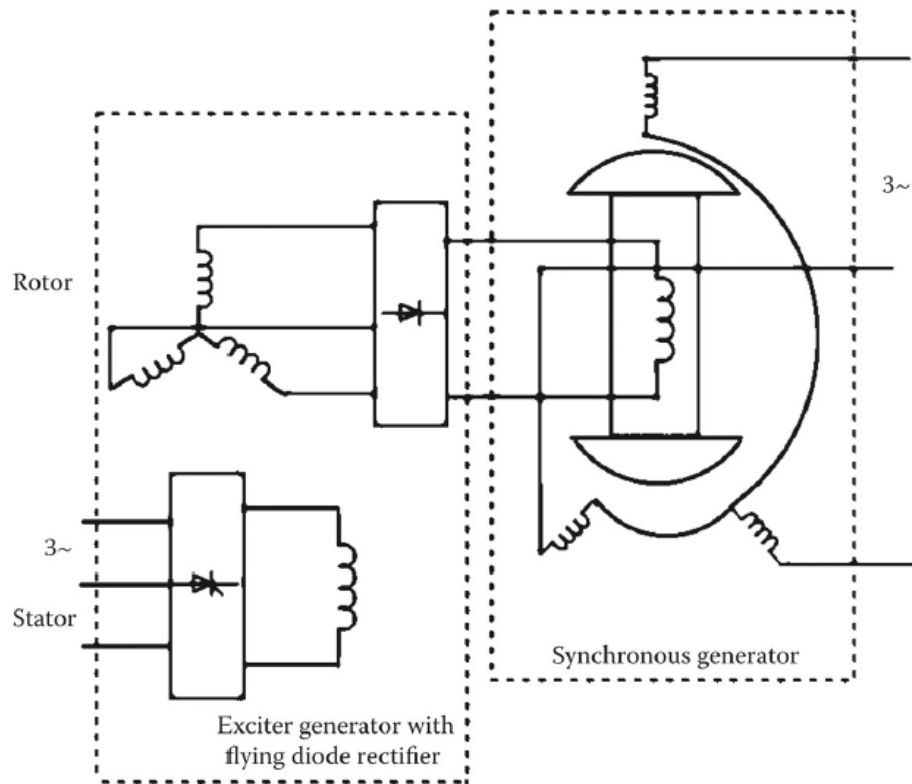


Figure 2.6 -Brushless exciter with "flying diode" rectifier for synchronous generators.[8]

2.4 Excitation systems:

The basic function of an excitation system is to provide power to the synchronous machine and that by injecting current to the field winding. Exciters are of three types, each with numerous embodiments in industry, which are AC, DC and static exciters. From power system viewpoint, the excitation system should contribute to effective control of voltage and enhancement of system stability. It should be capable of responding rapidly to a disturbance to enhance transient stability.

2.4.1 DC excitation systems:

The DC exciter (Figure 2.8), still in existence for many SGs below 100 MVA per unit, consists of two DC commutator electric generators: the main one (main exciter or ME) and the auxiliary one (auxiliary exciter or AE). Both are placed on the SG main shaft. The ME supplies the SG field winding (V_f), while the AE supplies the ME field winding.

The field winding of the AE is supplied with the voltage V_{con} controlled by the AVR. The power electronics source required to supply the AE field winding is of very low power ratings as the two DC commutator generators provide a total power amplification ratio around 600/1 in general.

The advantage of low-power electronics external supply required for the scope is paid for by:

- Rather slow time response due to the large field winding time constants of the two excitation circuits plus the moderate time constants of the two armature windings,
- Problems with brush wearing in the ME and AE,
- Still all excitation power (the peak value may be 4%–5% of rated SG power) of the SG has to be transmitted through the slip ring brush mechanism,
- The flexibility of the exciter shafts and mechanical couplings adds at least one additional shaft torsional frequency to the turbine-generator shaft.

Though still present in industry DC exciters are gradually replaced now with AC exciters or (and static exciters).

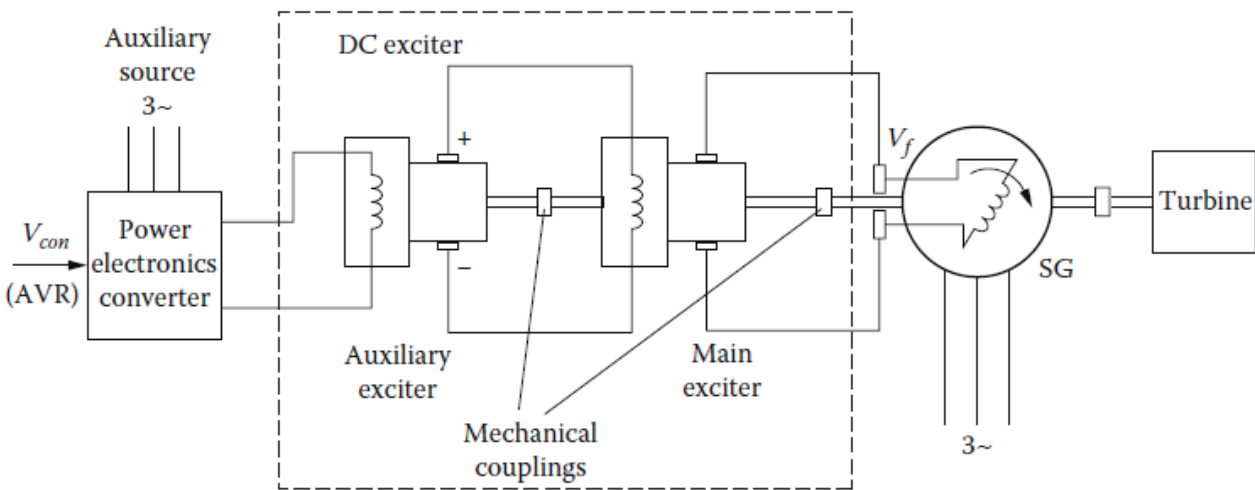


Figure 2.7 – Typical DC excitation system [8]

2.4.2 AC excitation system:

AC exciters are basically making use of inside-out SGs with diode rectifiers on their rotor. As both the AC exciter and the SG use the same shaft, the full excitation power diode rectifier is connected directly to the field winding of SG (Figure 2.9). The stator-based field winding of the AC exciter is controlled from the AVR.

The static power converter has now a rating that is about 1/20(30) of the SG excitation winding power ratings as only one step of power amplification is performed through the AC exciter. It is characterized by:

- The absence of electric brushes in the exciter and in the SG,
- A single machine addition on the main SG-turbine shaft,
- Moderate time response in V_f (SG field-winding voltage),
- Addition of one torsional shaft frequency due to the flexibility of the AC exciter machine shaft and mechanical coupling,
- Small controlled power in the static power converter: (1/20 [30] of the field-winding power rating).

The brushless AC exciter is used frequently in industry, even for new SGs because it does not need an additional sizeable power source to supply the exciter's field winding.

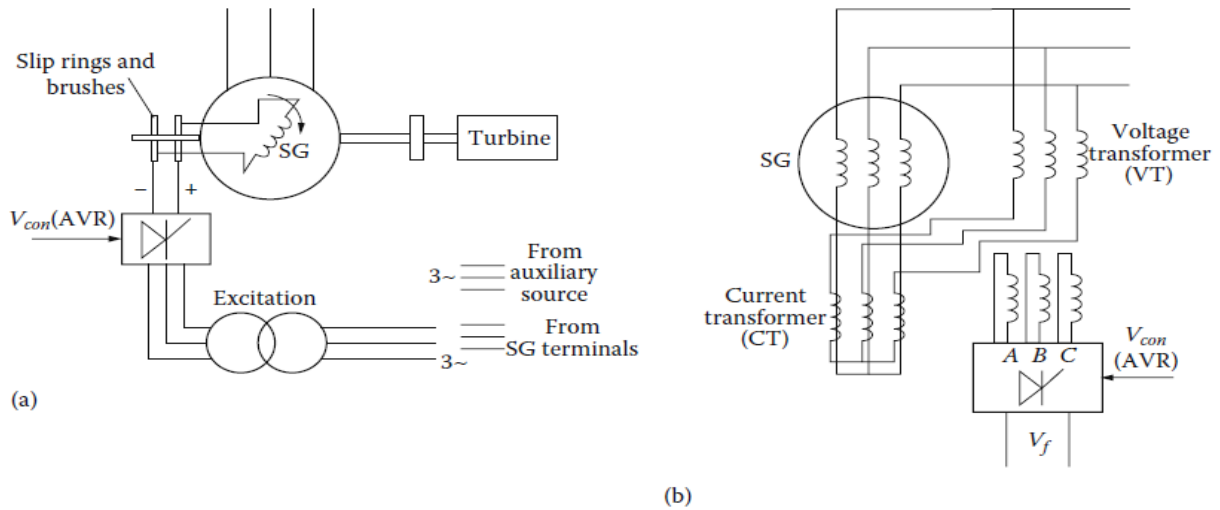


Figure 2.9 -static exciter: a) voltage fed, b) voltage and current fed.[8]

2.5 Automatic Voltage Regulation

Automatic control has played a very important role in the development of science and technology. This can be found in many industries such as factories and modern industries. The progress in the theory and practice of automatic control provides convenience for obtaining a good performance of dynamic systems, enhances quality, lowers production costs, enhances the rate of production, and eliminates routine and tedious work that must be carried out by humans.

In power systems, especially the large-scale power system normally in the control area can be expressed in groups from the existing generator. Changes in load and abnormal conditions cause changes in frequency and power scheduling in each area. These changes result in changes in voltage magnitude. This can be fatal in a system if there is an increase in the reactive power load because the generator terminal voltage will decrease. To overcome this, a control in generator excitation is needed using the AVR (Automatic Voltage Regulator). AVR is able to maintain the magnitude of voltage in a switching action or a change in load in the system [1].

In fact, when the Generator is operating (at a frequency of 50Hz with a fixed voltage output quantity), the Generator rotates at a relatively constant speed. However, the generator rotation speed is affected by the load. When the load increases, the speed will decrease, and vice versa. This has been an obstacle for AVR in maintaining voltage. Therefore, if it is expected that the generator to be operated at a constant speed when the load changes, a controller is needed to adjust the excitation field winding to keep the terminal voltage stable.

2.5.1 Relationship between reactive power and voltage in power system:

The generator excitation system maintains generator voltage and control the reactive power flow. The generator excitation of older system may be provided through slip rings and brushes by means of DC generators mounted on the same shaft as the rotor of synchronous machine. Any change in real power affects essentially the frequency, whereas a change in the reactive power affects mainly the voltage magnitude. The interaction between voltage and frequency controls is generally weak enough to justify their analysis separately.

The sources of reactive power are generators, capacitors. The generator reactive power is controlled by field excitation. Other supplementary methods of improving the voltage profile on electric transmission systems are transformer load-tap changers, switched, step-voltage regulators, and var control equipment. The primary means of generator reactive power control is the generator excitation control using automatic voltage regulator (AVR). The role of AVR is to hold terminal voltage magnitude of synchronous generator at a specified level [2].

2.5.2 Principle of operation of the automatic voltage regulator:

The main role of the AVR is to maintain the voltage magnitude of generator terminals at the desired level. The operating principle of an AVR consists of three main steps, namely measurement, control system, and the excitation.

The measurement is done by a device which detects physical quantity which is in this case the terminal voltage that is fed into control system. A control system manages, commands, directs, or regulates the behavior of other devices or systems using control loops. For continuously modulated control, a feedback controller is used to automatically control a process or operation. The control system compares the value or status of the process variable being controlled with the desired value or set-point, and applies the difference as a control signal to bring the process variable outputs of the plant to the set-points [3].

The excitation system is used for providing the necessary field current to the rotor winding of the synchronous machine. It is defined as the system which is used for the production of the flux by passing current in the field winding. The amount of excitation depends on the control system signal, which means if the difference between the measured value and the set-point is large then the system has to produce more field current and vice versa.

3.1 Introduction:

The basic function of the AVR is to maintain constant voltage whatever the load applied to the SG terminal voltage. There are different techniques and hence different structures of the AVR.

In this chapter, that will cover the description of both the hardware and the software used in implementing our AVR. LabVIEW software as well as the microcontroller (Arduino uno) along with the data acquisition board (NI-USB6009) and last but not least the PID control system as well as measurement system will be presented in details.

3.2 Software Part

3.2.1 LabVIEW Graphical Instrumentation Program:

LabVIEW is a program development application, much like various commercial development systems such as C or BASIC. However, LabVIEW is different from those applications in one important respect. Other programming systems use text-based languages to create lines of code, while LabVIEW uses a graphical programming language, G, to create programs in block diagram form. The implication is that once designed, a LabVIEW program will offer a simple method for acquiring and processing data obtained from the terminal of the synchronous generator.

LabVIEW relies on graphical symbols rather than textual language to describe programming actions. There are extensive libraries of functions and subroutines included with the software package for many programming tasks. LabVIEW© contains application specific libraries for data acquisition, instrument control and analysis. Also included in the software are many conventional program development tools to set breakpoints, animate program execution to see how data passes through the program, and single-step through the program to make debugging and program development easier.

LabVIEW programs are called virtual instruments (Vis) because their appearance and operation imitate actual instruments. Vis have both an interactive user interface and a source code equivalent, and accept parameters from higher-level Vis.

LabVIEW was used to create the program that controls the voltage/current the enter winding of the synchronous generator. LabVIEW is software created by National Instruments (NI) that provides a graphical programming system using G-code [1]. The use of graphics allows the user to better visualize the code for its application in comparison with traditional lines of text code that may be more difficult to interpret. Different visual cues help to distinguish between functions and their purpose as well as the sequencing of operations performed by the code.

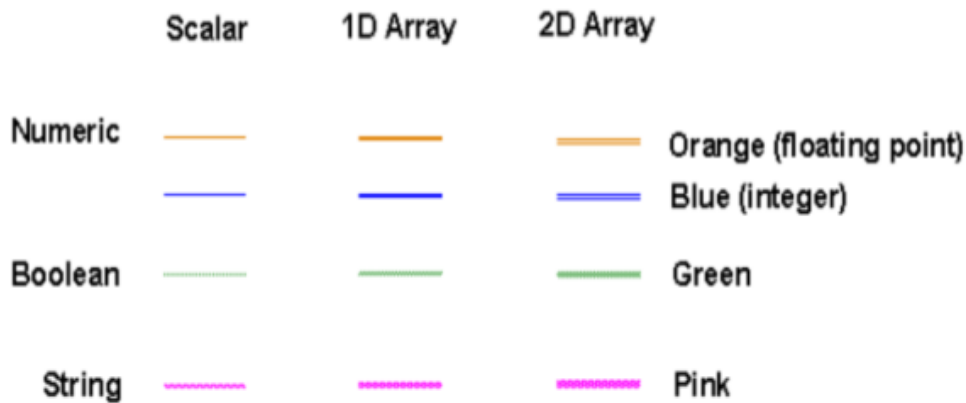


Figure 3.1: Example of LabView Wires Types

One of the foundational concepts of LabVIEW is data flow. This allows functions to execute only when the necessary input variables are available to feed into the function. Dataflow also allows independent functions to execute in parallel. Wires are used to establish dataflow from inputs to functions to outputs. Different colored wires contain different types of data, as shown in FIGURE 1, created by National Instruments [1]. Blue wires are used for integers, pink wires contain strings, and green wires are for Boolean data. The thickness also represents the data contained within the wire. A thin wire indicates a scalar value, a thicker wire is for a one-dimensional array of data, and an even thicker wire represents a two-dimensional array of data. The use of wires as well as the difference in color and thickness assist in the visualization of the way specific types of data are transferred throughout the code.

A LabVIEW program is called a virtual instrument, or VI [2]. There are two primary components of the VI interface, the front panel and the block diagram. The front panel is the screen which the application user interacts with while the program is running. This is where data collected is presented to the user and where the user can control various parameters and adjust inputs based on the collected data. LabVIEW has various visual elements built into the application such as knobs, switches, charts, and buttons that enhance the user experience and can allow for a more efficient and meaningful interaction between the user and the front panel. These visuals can be arranged freely to fit the specifications necessary for the application and draw attention to the primary components the user is concerned with.

The block diagram is where the G-code is implemented, and the programmer is able to manipulate inputs to produce desired outputs. One type of input used on the block diagram is a control. This is where the user can set a specific value, whether it is an integer, string, or Boolean, that can be used for various functions on the block diagram.

For each controller used in the block diagram, a corresponding visual element appears on the front panel for the user to interact with while the program is running. The control element on the front panel and block diagram are linked so that as the controller is manipulated on the front panel, the appropriate controller node on the block diagram receives the correct information from the user's input. The same feature also happens with outputs called indicators. Indicators display output information on the front panel in the form of single values, arrays, charts, graphs, tank levels, and more. A corresponding indicator node exists on the block diagram for the programmer to wire data to in order to display the desired output on the front panel. Similar to other coding languages, G-code utilizes structures such as for loops and while loops to build functionality in the coding. The for and while loops operate in the same manner in G-code as in other programming languages however there is a visual aspect that can assist users in understanding what code is performed within a specific loop and how data is carried to and from loops. In LabVIEW, the loops are drawn graphically in large boxes. Inside the box is the code that is performed during each loop iteration. Data can be wired into and out of loops and they can be operated in parallel, nested, or in series as desired. Another type of loop structure used in LabVIEW is the case structure (often called a case statement in traditional programming languages). In a case structure, there are specified cases that can occur either sequentially or as desired based on certain criteria being met. A case structure enclosed within a while loop becomes a powerful programming architecture called a state machine. The while loop allows the code inside to continue to run until a terminal condition has been met which allows the program to move between different cases as desired by the user or as programmed into the code. A diagram of a state machine is represented in figure 2.

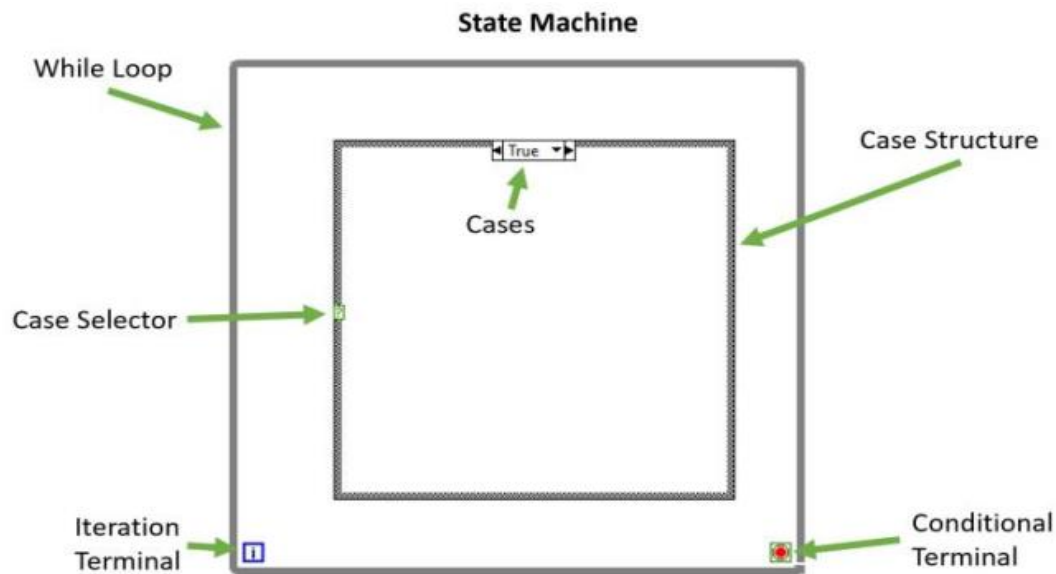


FIGURE 3.2: Example of LabVIEW State Machine Structure

This specific example only has two states, either true or false. However, an integer or enumerated list (simply called an enum) can also be wired into the case selector to create multiple states based on the integer or the string values of the enumerated list. Associating string values with the numerical list make the cases human readable, while retaining ease of mathematical manipulation and transitioning of the cases. A second and key type of input used in LabVIEW is via data acquisition, also referred to as DAQ. Using NI DAQ hardware devices, various types of data can be collected from systems and used within the VI. For example, temperature can be measured through a thermocouple and the signal can be sent through an NI DAQ device to be used as input data in a VI. Running averages, standard deviations, or charts can be developed from that data which could also be used for various calculations or setpoints elsewhere within the code. LabVIEW also has functionality to allow users to control instruments. For instance, valves can be opened and closed through user input or through a programmed PID controller and pumps can be turned on and off as needed. Often, DAQ is used in conjunction with controlling instruments in order to initiate or maintain a particular process at desired specifications.

The LabVIEW software platform was designed for the primary purpose of data acquisition, analysis and process control, especially within a laboratory setting [1]. While some programs can be designed to run without much user interaction, LabVIEW specializes in providing the functionality for an interdependence between the VI and the user to successfully control a system. The user interaction is an essential function and must be built into the program and incorporated in the front panel and block diagram. For instance, the same data can be represented with various types of indicators.

Consequentially, it is important for the programmer to select the most appropriate indicator for the data being presented. Not all data may be necessary for the user either. Therefore, the purpose of the application and how it will be used are important factors to consider when deciding what information to display and how to display it so that the user is not distracted by meaningless data. The same concept is applied to controllers as well. Some functions will require tighter control than others so the selection of the type of visual controller, whether it is a dial, sliding scale, or typed out integer, is important so that the user is able to efficiently control the program. Figure 5 displays three of the numerous types of controllers. While the sliding scale and dial may be more visually appealing to the user, they may not allow the user to have the same level of control as the numeric and thus hinder a user's ability to effectively control a system.

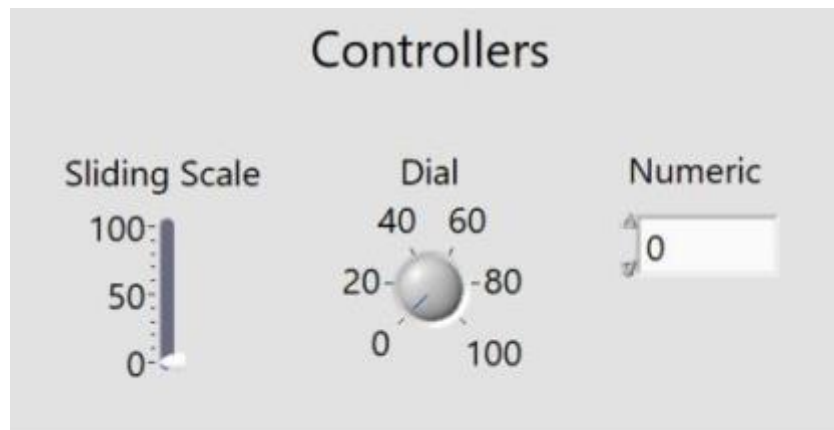


Figure 3.3: Example of Three LabVIEW Numeric Controllers

Overall, the key features of LabVIEW will be utilized to improve the existing software used to operate the distillation column. Dataflow and state machines will be incorporated to improve the code architecture. Controller and indicator selection will be used in conjunction with other techniques identified as “best practice”, such as using subVIs and minimizing wiring clutter, in order to create a more functional and maintainable program to operate the Unit Ops distillation column. Knowledge of the distillation process, process control, and the importance of hands-on experience will influence the code upgrades to create a better tool for learning. The LabVIEW interface encourages interaction between the operator and distillation column. Improving the code used to run the process will allow for students to become the operators in both manual and automatic modes. This will facilitate opportunity for more active involvement between students and the distillation experiment, thus increasing their conceptual understanding of distillation.

3.2.2 LabVIEW Control Design and Simulation Module:

With LabVIEW Control Design and Simulation Module you can construct plant and control models using transfer function, state-space, or zero-pole-gain. Analyze system performance with tools such as step response, pole-zero maps, and Bode plots. Simulate linear, nonlinear, and discrete systems with a wide option of solvers. With the NI LabVIEW Control Design and Simulation Module, you can analyze open-loop model behavior, design closed-loop controllers, simulate online and offline systems, and conduct physical implementations.

The main features in the Simulation palette are:

- **Control and Simulation Loop** - You must place all Simulation functions within a Control & Simulation Loop or in a simulation subsystem.
- **Continuous Linear Systems Functions** - Use the Continuous Linear Systems functions to represent continuous linear systems of differential equations on the simulation diagram.
- **Signal Arithmetic Functions** - Use the Signal Arithmetic functions to perform basic arithmetic operations on signals in a simulation system.

3.3 PID Control:

A successful operations of automatic control system requires anti-jamming capability, stability and ability to meet the given performance index. Since the physical structure and the working process of the controlled object are constant, the output value of a given signal could not meet the needs of system. Therefore, a controller needs to be included. The controller and the controlled object will form a closed-loop system which helps the output of the system meet the given performance index. In addition, the controller always utilizes various kinds of control rules [3].

PID (Proportional Integral Derivative) control is a widely used control method. It has huge advantage in the fields of control engineering. After a long period of engineering practiced, it has developed a complete program of control methods and a typical structure [4]. PID controller has simple structure, excellent stability, reliable performance and convenient adjustability. When the structure and the parameters of the controlled object cannot be completely acquired or cannot manifest a clear mathematic model, PID control technology becomes more useful. Because it was designed for the situation where

users cannot thoroughly learn about a system with a controlled object, or cannot obtain the system parameters by using the effective measuring methods.

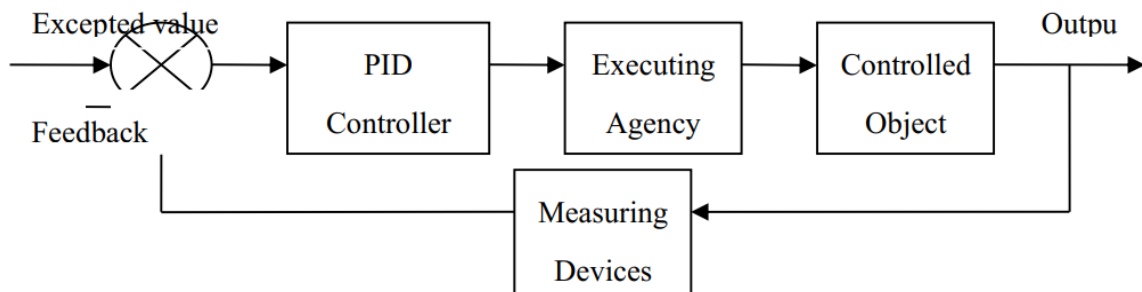


Figure 3.4 The PID Control System

PID, as its name implies, utilizes the proportion, the derivative and the integral to work out controlled quantity based on the system errors. These three elements are mutually independent and have respective functions. Users can choose any of the three based on the practical situation.

The transfer function of a standard PID controller is generally written in the way:

$$\begin{aligned} G(s) &= K_p + K_i \frac{1}{s} + K_d s \\ &= K_p \left(1 + \frac{1}{T_i s} + T_d s \right) \end{aligned} \quad (3.1)$$

Where, K_p is the proportional gain, K_i is the integral gain,

K_d is the derivative gain, T_i is the integral time constant, and T_d is the derivative time constant.

As a linear controller, it according to a given value $r(t)$ and the actual output value $y(t)$ to control deviation $e(t)$, the deviation in proportion, integral, and differential through linear combination constitute control $u(t)$, to control the controlled object. For the output of the controller input relations is shown as:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \right] \quad (3.2)$$

Where $u(t)$ is the output of PID controller, $e(t)$ is the input. Shown as Figure 3.4.

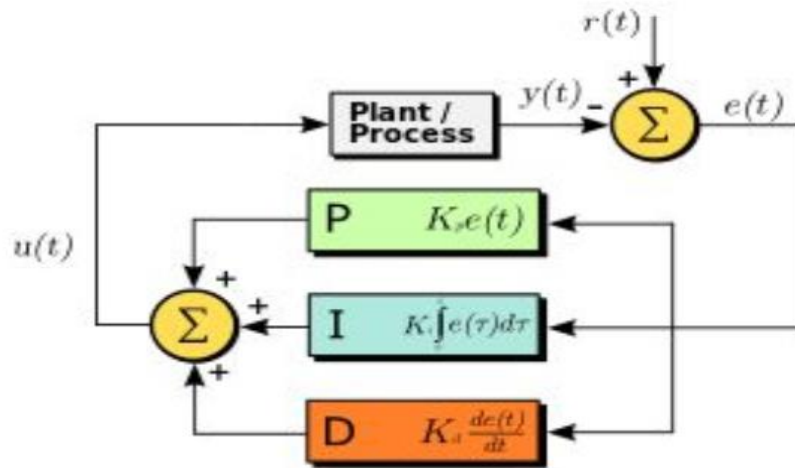


Figure 3.5: Theory of a PID Controller in a Feedback Loop

To get a PID control, we have to learn about P control, I control and D control first. Then we will combine these three controllers into PID controller.

3.3.1 P-Control (Proportional Control):

If the output of controller is only proportional to the error, that is, $u(t)=K_p e(t)$, then a proportional controller will be formed. It is thus obvious that a proportional controller is actually a variable gain amplifier (VGA). By changing the proportional action factor (K_p), the proportional controller can adjust the output. The P control is shown in Figure 3.6.

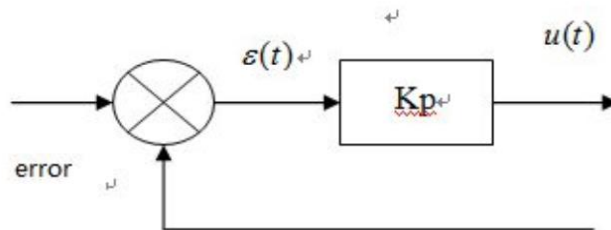


Figure 3.6 The Proportional Control

From the Figure 3.6 we can know that the P control is:

$$u(t)=K_p e(t) \tag{3.3}$$

Although the proportional controller is sensitively responsive to the error, there is always a steady-state error between the output and the value of expectation. The steady-state error can only be eliminated by manual reset, which causes huge inconvenience in practical application. Increasing K_p can increase the open-loop gain of the system, reducing the steady-state error and increasing the rapidity of the system. Nevertheless, it is likely to cause not only the stability of the system to deteriorate but also the oscillation of the system becoming more frequently. In the other hand, decreasing the value of K_p will make the system action become slowly, thus the corrective the problem which the system seldom uses P control alone [5].

3.3.2 I-Control (Integral Control):

Because the steady-state error needs resetting manually, people find that the steady-state error can be eliminated by introducing an integral term. The output of the proportional controller is in direct proportion to the error signal, and the output of PI controller is:

$$\begin{aligned} u(t) &= K_p (\varepsilon(t) + \frac{1}{T_i} \int_0^t \varepsilon(t) dt) \\ &= K_p \varepsilon(t) + \frac{K_p}{T_i} \int_0^t \varepsilon(t) dt = K_p \varepsilon(t) + K_i \int_0^t \varepsilon(t) dt \end{aligned} \quad (3.4)$$

The integral term will integrate the error and increases over time. Thus, as long as there is an error, the output will continue working. In this way, even if the error is very small, the integral term will keep increasing over time. Then, by increasing the output of the controller to make the steady-state error reduced to zero if the further all the time, the way to eliminate the steady-state error can be achieved. But the integral of time will inevitably affect the fast dynamic performance of system. Sometimes, when a system adjusted overshoot, there will be some situations, among which the worst even can cause a system breakdown [6].

3.3.3 D-Control (Differential Control):

Integral Control's dynamic property is poor. However, a differential term can just make up for this. The output of differential controller is in direct proportion to the differential of error signal, and then the output of PD Controller is:

$$\begin{aligned} u(t) &= K_p \left(\varepsilon(t) + T_d \frac{d}{dt} \varepsilon(t) \right) = K_p \varepsilon(t) + K_p T_d \frac{d}{dt} \varepsilon(t) \\ &= K_p \varepsilon(t) + K_d \frac{d}{dt} \varepsilon(t) \end{aligned} \quad (3.5)$$

D-action (Differential action) reflects the change rate of error signal, so it is predictive to the system control and can predict the change trend of error. Thus it can produce advanced control function. Even before the formation, the errors may have been eliminated by differential action regulation. If the appropriate D-action time is selected, the overshoot and the setting time of the system will be reduced, greatly improving the dynamic performance of the system.

Differential control in practice is often used to offset the unstable trend produced by integral control. Because its reaction is to change the rate of the error so that the differential control is not often used alone but only plays a part in the dynamic process. What's more,

differential control has amplification effect on noise jamming, so the differential term can become a disadvantage to the anti-interference ability of the system [7].

3.3.4 The PID Control:

PID control is namely the combination of proportional control, integral control and differential control, thus integrating the advantages of such three kinds of controllers. In practical application, there is no need to use all these three parts, but only proportional control unit is indispensable. For the PID controller, the output is:

$$\begin{aligned} u(t) &= K_p \left(\varepsilon(t) + \frac{1}{T_i} \int_0^t \varepsilon(t) dt + T_d \frac{d}{dt} \varepsilon(t) \right) = K_p \varepsilon(t) + \frac{K_p}{T_i} \int_0^t \varepsilon(t) dt + K_p T_d \frac{d}{dt} \varepsilon(t) \\ &= K_p \varepsilon(t) + K_i \int_0^t \varepsilon(t) dt + K_d \frac{d}{dt} \varepsilon(t) \end{aligned} \quad (3.6)$$

Where K_p = Proportional gain, K_i = Integral gain, K_d = Derivative gain. Finally we can get a complete PID control.

PID control actually means setting these three parameters, namely, K_p , T_i and T_d , in order to get applicable output value to control the system. The specific details on how to set them are different based on different situations. Currently, PID is not only widely applied but also rapidly developed. The intelligent controllers which can self-tune these three parameters have been massively invented [8]. After the combination between PID and digital controllers such as computer, the design method of digital PID has also emerged, whose specific principle still follows the traditional ones.

3.4 Hardware Part

3.4.1 Data acquisition board (NI USB-6009):

NI USB – 6009 has a basic data acquisition function, its applications include simple data record, a portable measurement and laboratory experiment of academic institutions. NI USB-6009 provides the basic data acquisition function for simple data recording, portable measurement and college laboratory experiments and so on. The price of this product is suitable for students, but its powerful functions are more than enough to deal with the complex measurement applications. Using NI USB - 6009 and its ready-to-use data recorder software which is included, the basic measurement can be completed within a few minutes. Or in other way, using LabVIEW or C language and included measurement service software programming can customize measurement system.

3.4.2 Pulse Width Modulation (PWM):

PWM is a technique to get an average analog output signal from a digital input. The concept of PWM can be understood by the following example of an LED. If an LED is turning on and off at a moderate rate, then the turning on and off phenomenon of the LED can be observed. However, if the rate of switching is fast enough, one can observe a dimmer LED instead of the turning on and off phenomenon. A PWM signal is represented by a square wave of a given duty cycle and frequency. A duty cycle expressed in percentage specifies the time of an input signal being “on” over a given period of time. For example, 50 % duty cycle means that the signal is on for half of the time period as shown in Figure 3.7.

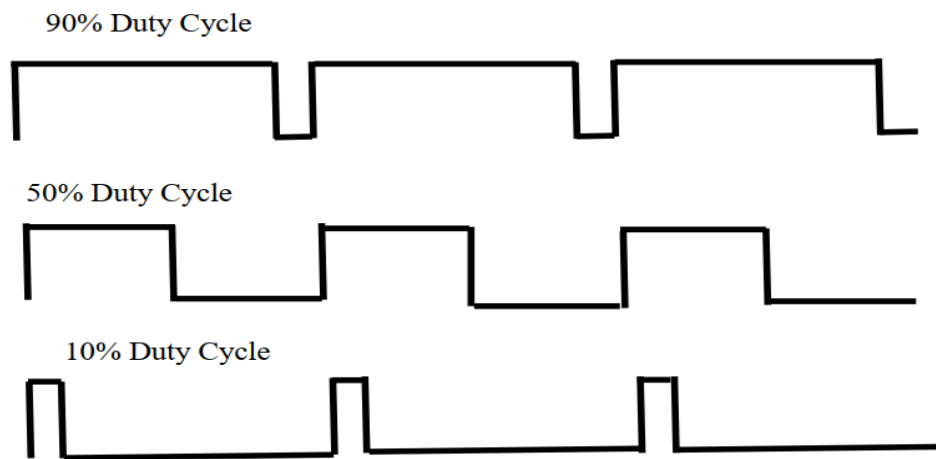
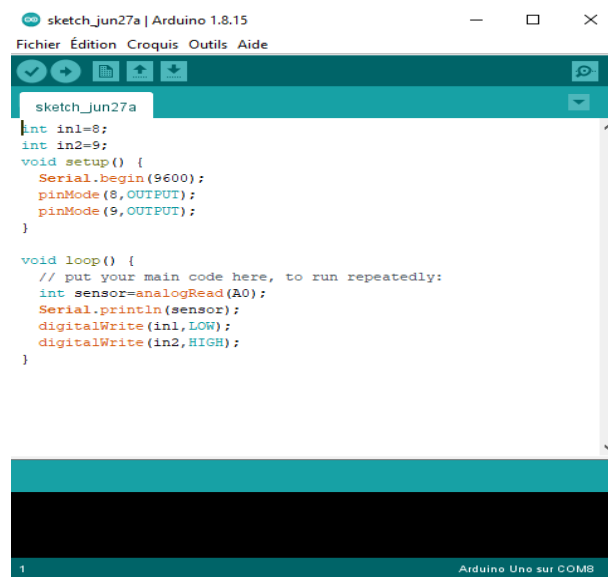


Figure 3.7 : Duty Cycles: 90%, 50%, and 10% duty cycle represent that the signal is turned on for nine tenths, half, and one tenth of the whole time period respectively.

3.4.3 Arduino IDE:

Arduino hardware are programmed using Arduino integrated development environment (IDE), which is a cross-platform application written in Java language [10]. It is designed for newcomers unfamiliar with software development and includes a code editor with features such as syntax highlighting, brace matching and automatic indentations. A simple one-click mechanism is provided for compiling and uploading a program (sketch) to any Arduino board. The Arduino IDE supports the languages C and C++ and also supplies a software library called Wiring, providing common input/output procedures. Figure 3.8 shows a typical Arduino C/C++ sketch consisting of the two functions “setup ()” and “loop ()”. When the code is compiled, it is converted into a text file in hexadecimal uploaded to the board’s firmware.



```

sketch_jun27a
int in1=8;
int in2=9;
void setup() {
  Serial.begin(9600);
  pinMode(8,OUTPUT);
  pinMode(9,OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
  int sensor=analogRead(A0);
  Serial.println(sensor);
  digitalWrite(in1,LOW);
  digitalWrite(in2,HIGH);
}

```

Figure 3.8 Arduino IDE sketch

The Arduino IDE is a free to use software for Arduinos open-source hardware, withtheadvantages and disadvantages:

- Easy to use software with all Arduino boards supported
- Huge community (lots of examples online)
- Large assortment of included libraries (for different components)
- Easy debugging environment
- Libraries are optimized for easy usage, not efficiency
- Not fully suitable for industrial use
- Arduino IDE is very limited for skilled programmers

An Arduino UNO is a microcontroller which operates by reading the sensorvalues, making logical decisions, and sending the necessary signals to the actuators [9]. A brief description of Arduino UNO shown in Fig 3.5 is as follows:

- i.) It has a USB power plug and a separate power plug. The separate power plug takes thepower supply through the external voltage source.
- ii.) It has five analog input pins that measure the signals from the sensors.
- iii.) It has a USB power plug and a separate power plug. The separate power plugtakes thepower supply through the external voltage source.
- iv.) It has twelve digital pins for digital input/output (2-13), among them five pins (3, 6, 9, 10 and 11) are PWM pins.

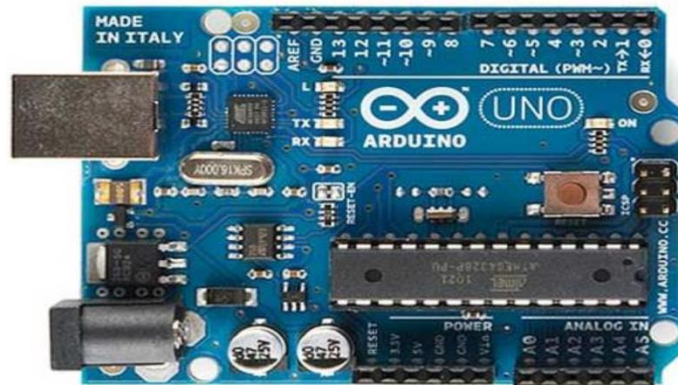


Figure 3.9 Arduino UNO Board: Arduino UNO board showing 16 digital pins, 6 analog pins, and other various parts.

- v.) Digital pins 0 and 1 are labeled RX and TX respectively, which are serial in and serialout pins.
- vi.) There are three ground pins, one input voltage pin, one 5 V pin, one 3.3 V pin, one resetpush-button, and one Analog Reference (AREF) pin.
- vii.) Atmega328 is a microprocessor used with an In Circuit Serial Programmer (ICSP).

In our project, Arduino UNO is basically performing the following task:

Reading the analog signals (voltage) from the terminals of the generator and enter it in the LabVIEW.

3.4.4 Step down Potential Transformer (PT): (220/5)

The step down potential transformer converts high-voltage to low safe voltage. The larger-gauge wire used in the secondary windings is necessary due to the increase in current. The primary winding, which doesn't have to conduct as much current, may be made of smaller-gauge wire. And in our case, we used this transformer to step down the terminal voltage from 240 to 6 as maximum.

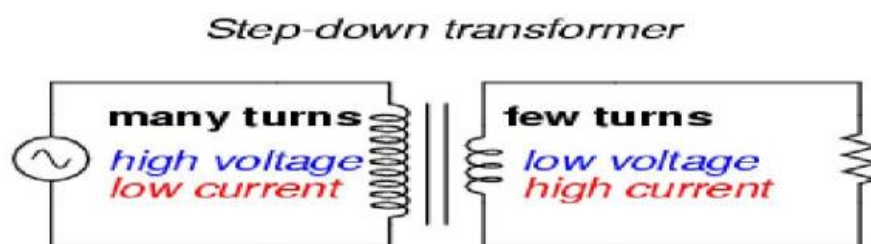


Figure 3.10: Step Down potential Transformer

3.4.5 L298N Dual H-Bridge Motor Driver:

This dual bidirectional motor driver, is based on the very popular L298 Dual H-Bridge Motor Driver Integrated Circuit shown in the figure (3.12). The circuit will allow you to easily and independently control two motors of up to 2A each in both directions. It is ideal for robotic applications and well suited for connection to a microcontroller like (Arduino) requiring just a couple of control lines per motor. It can also be interfaced with simple manual switches, TTL logic gates, relays, etc. This board equipped with power LED indicators, on-board +5V regulator and protection diodes.

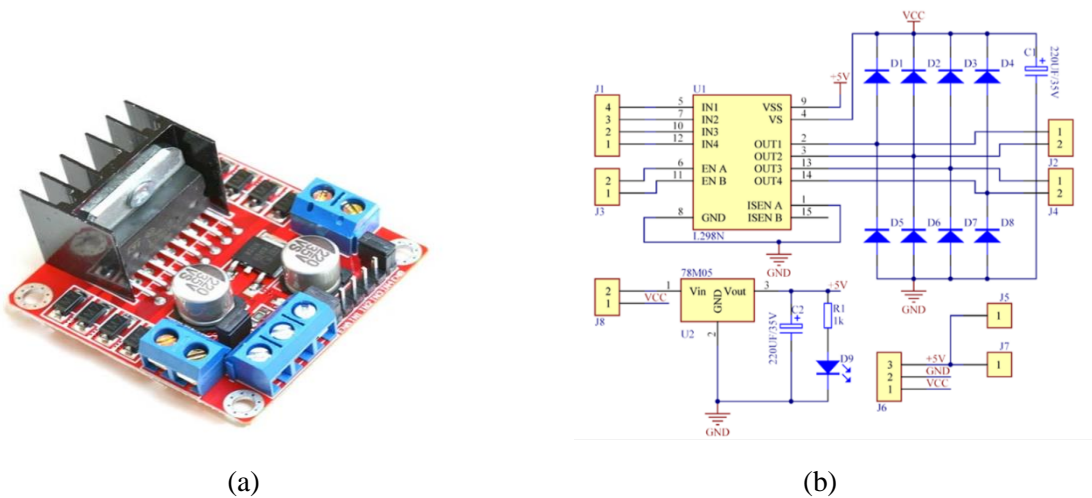


Figure 3.11: (a)L298 module (b) L298 schematic diagram

4.1 Introduction:

In the previous chapter, we have discussed the design of the AVR and we have presented the different components that may be needed for building of our design. This chapter will provide test of our AVR by simulation as well as by experiment.

4.2 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 tests are performed in power-lab. Figure 4.1 shows the test bench of the experiment.

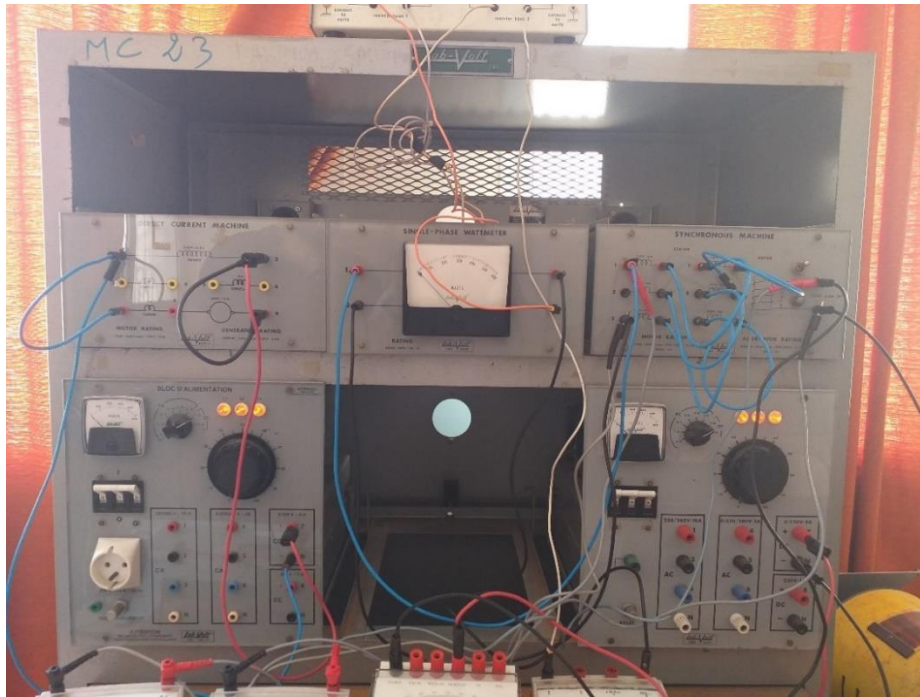


Figure 4.1: experimental test bench

In this experiment, we applied 220V to the DC Motor which acts as the prime mover. This last runs at 1100 rpm measured by the tachometer turning the rotor of the SG at a synchronous speed. After that, different values of current were injected to the field winding resulting in different values at the terminal voltage which are given in table 4.1.

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

If (field current A)	Vf (field voltage V)	Vt (terminal voltage V)
0	0	13
0.05	8	40
0.10	16.5	77
0.15	21	96
0.20	26	123
0.25	31	150
0.30	38	180
0.35	44	210
0.40	62	240

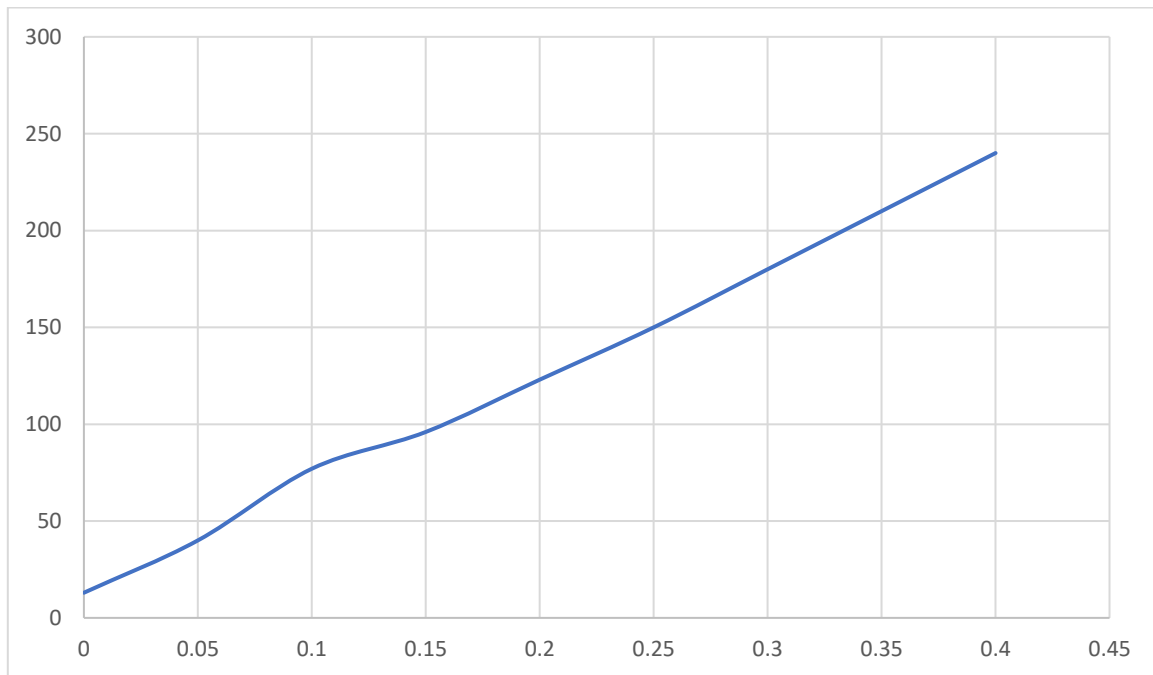


Figure 4.2: Graph of field current versus terminal voltage.

Using the obtained data of Table 4.1, a graph of field current versus the terminal voltage can be drawn as shown in Fig.4.2. It can be noted that from the graph a slight increase in the field current will lead to great increase in terminal voltage, the relationship between the two is directly proportional and so a decrease in field current will result in reduction of terminal voltage. This is due to the air gap magnetic field produced by the direct current field excitation coils which produces air gap flux density that represents a forward-traveling wave at rotor turning at rated speed. This traveling electromagnetic wave moves in front of the stator coils at the tangential velocity induces a three symmetric EMFs at the stator windings.

4.3 Experimental determination of the PWM signal:

To determine the appropriate duty cycle needed by the H-bridge we had first to apply a PWM signal that maintains the terminal voltage at 50V and then subject the terminals to different loads, results in different values as given in Table 4.2. Figure 4.3 shows the duty cycle of the PWM signal change that takes through different loads in order to keep the terminal voltage of the SG at the level of 50V. It can be noted that the curve can be divided into two portions, when the load is too small the change of the duty cycle is slow, however, when the load increases, the duty cycle change speed will be reduced.

Table 4.2 PWM needed for each load

Loads (W)	Vt(V)	If (A)	Vf(V)	IL(A)	PWM
No load	50	0.095	13	0	118(46,27%)
200	50	0.105	14	0.34	139(54,5%)
300	50	0.13	17	0.59	165(64,7%)
350	50	0.15	19	0.60	186(72,94%)
400	50	0.16	20	0.62	195(76,47%)

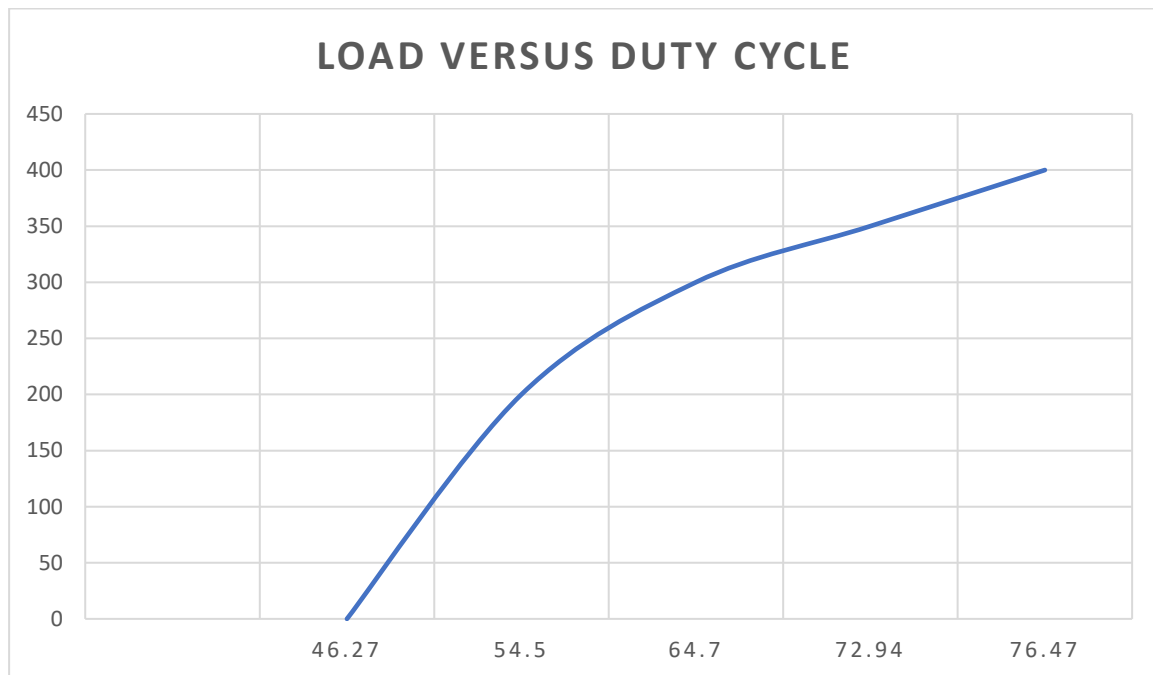


Figure 4.3 load versus duty cycle

4.4 Simulation test:

In order to validate the designed and developed any system, a simulation may be implemented first using any software tool such as Simulink in our case. For simulation, model of such system to be tested may be required.

4.4. 1 Mathematical Models [25]

For high quality mathematical modelling of a system, all the transfer functions of its main elements should be linearized, by taking into account the major time constants and ignoring the saturation and other non-linearity. The transfer functions of the main elements of the studied system will be represented as follows.

A- Excitation System Model [25]

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

So, the transfer function is:

$$G_E(s) = \frac{K_f}{1+sT_f} \quad (4.1)$$

B- Sensing Circuit Model [25]

The role of the sensing circuit is to rectify, filter and reduce the terminal voltage; its model can be obtained from the first order transfer function:

$$H(s) = \frac{K_r}{1+sT_r} \quad (4.2)$$

Where, T_r range is between 0.001 and 0.06 s.

C-Generator Model [25]

The simplified transfer function describing the Synchronous Generator is given by:

$$G(s) = \frac{K_G}{1+sT_G} \quad (4.3)$$

Equation (4.3) can be derived from Eq. (4.4) by neglecting T_{kd} and T''_{d0} ,

$$G(s) = \frac{K_G(1+sT_{kd})}{(1+sT'_{d0})(1+sT''_{d0})} \quad (4.4)$$

Where, $K_G = \frac{x_{md}}{r_f}$,

$$T'_{d0} = \frac{x_{md}+x_f}{r_f},$$

$$x_{md} = x_f \text{ and}$$

$$T_G = T'_{d0} = \frac{2x_f}{r_f} = 2K_G.$$

All these parameters can be obtained from experimental tests such as open circuit test, sustained short circuit test, slip test and sudden three phase short circuit test.

D- Automatic Voltage Regulator [25]

An automatic voltage regulator (AVR) ensures the internal stability of the closed loop system as well as the attenuation of the influence of disturbances on the output of the controlled system as shown in Fig. 4.4. The PID controller synthesis may be used to improve the dynamic response as well as to reduce or eliminate the steady state error.

The transfer function of a PID-controller is:

$$G_{PID}(s) = K_p \left(1 + \frac{1}{sT_I} + sT_D \right) = K_p \left(\frac{1 + sT_I + s^2T_I T_D}{sT_I} \right) \quad (4.5)$$

With: K_p – proportional gain, T_I – integral constant time, T_D – derivative constant time.

These parameters can be identified from experimental determined parameters of the laboratory synchronous generator and according to IEEE mathematical relations between leakage inductances.

It can be noted that, even with well-defined systems, tuning the parameters of the controller is not always easy especially in complex systems.

The model of any system does not always represent the behavior of the system very well during its operation; due to transient phenomena such as non-linearity and / or saturation. Anyway, we will always have a more or less precise idea of the mathematical model that describes the synchronous machine. In order to facilitate the tuning of the controllers, identification methods have been adopted for determining approximately the parameters of the used controller such as Particle Swarm Optimization .

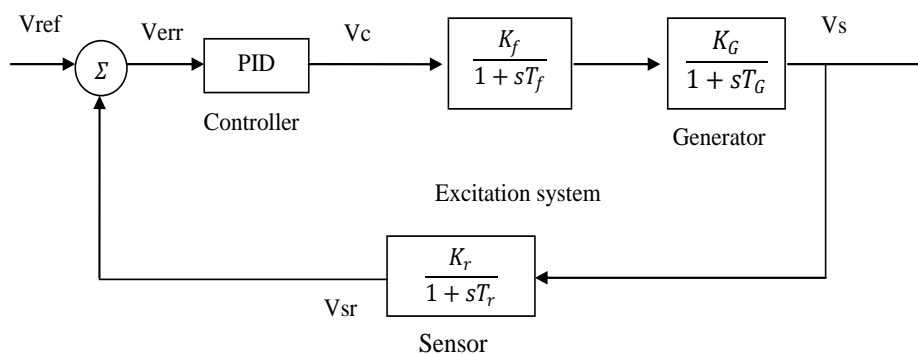


Figure 4.4 Simplified model of the complete system with voltage regulator circuit.

4.4.2 AVR Based PI Simulation [26-27]

The role of AVR is to maintain a constant voltage at the terminals of the synchronous generator (SG) during external disturbances (loads variation, load shedding, and faults.... etc.). To test the developed AVR, Simulink model of the complete system has been developed and simulated as shown in Fig. 4.5.

The controller PI parameters (K_p and K_i) are obtained using PSO technique, which are given in Table 4.3. Parameters of 1.5kVA salient-pole Lab-Volt SG that has been used in this simulation are given in Table 4.4.

The obtained results, which are the voltage profiles at the terminals of the SG, are shown in figure 4.6.

The test has been conducted under two operating conditions (see Fig.4.6). In the first case, when the simulation starts, a 0.5 kW load has been applied and after 60 seconds after the steady state another load of 1 kW has been added which is the second condition. It can be noted that after 8 seconds in the first case, the steady state can be obtained. However, in second condition, the steady state can be obtained after 10 seconds and hence the voltage level returns to its rated value thanks to the AVR.

Table 4.3:PI parameters identified by PSO

PI parameter	Value
K_p	277.12
K_i	0.015

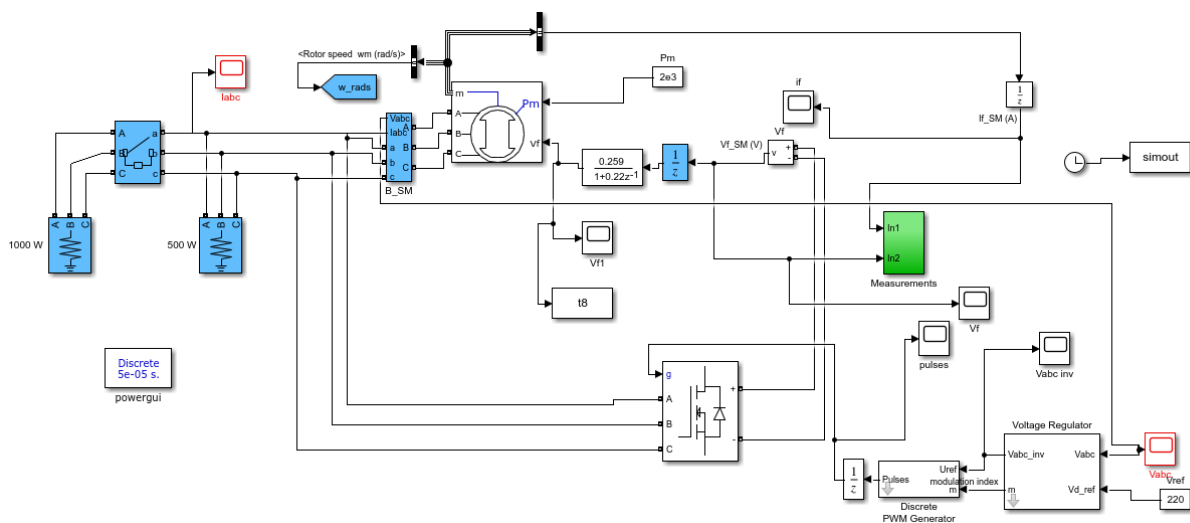


Figure. 4.5 Simulink model of the complete system (SG with AVR).

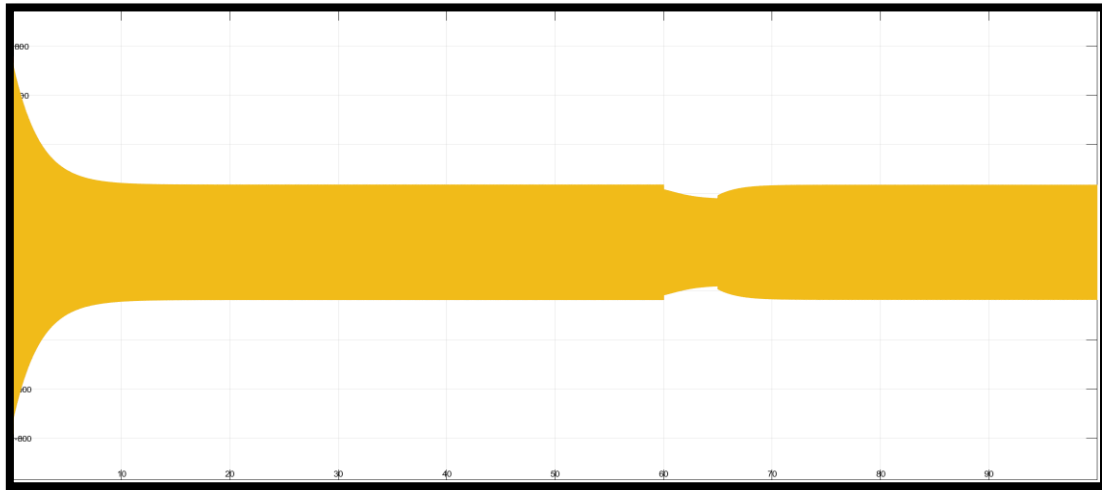


Figure 4.6 the voltage profiles at the terminals of the SG.

Table 4.4 1.5kVA salient-pole Lab-Volt SG parameters [2].

Nominal rms line-to-neutral voltage	U_n	220 V
Frequency	f_n	50 Hz
Stator resistance	R_s	2.2 Ω
Rotor resistance	R_f	127 Ω
Direct-axis synchronous inductance (unsaturated)	L_d	0.024 H
Quadrature-axis synchronous inductance (unsaturated)	L_q	0.015 H
Direct-axis open-circuit time constant	T_{do}'	0.235 s
Direct-axis transient inductance	L_d'	0.0033 H
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 constant	T_d''	0.0147 s

4.5 Experimental test

4.5.1 Measurement system:

Measurement is an essential stage for determining Terminal voltage magnitude which is required in calculating the corresponding the field current needed to be injected to the field winding in order to restore the voltage magnitude to its desired value.

In this project we are going to use LabVIEW software in order to reduce physical components to build a digital voltmeter interfacing with the data acquisition card (DAQ NI-6009), the general block diagram is shown in Fig.4.7.

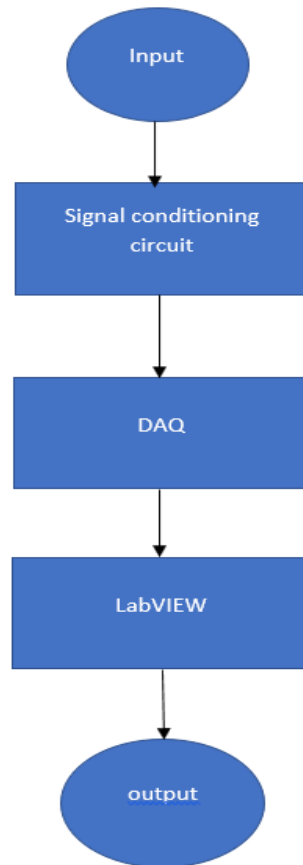


Figure 4.7 Block diagram of the measurement system

The input represented in the first block diagram consists of the image of the SG terminal voltage, which steps down the voltage through transformer with ratio of $(240/6)$. Then, the signal goes to the signal conditioning circuit that consists of a bridge connected to capacitor of $100\ \mu\text{F}$ parallel with a resistor of $4,9\text{k}\Omega$, where it will be rectified and converted into pure DC signal. The data acquisition card acquires this signal through its analog input port and converts into digital information which in turn collected in the PC using LabVIEW program. The circuit diagram of the measurement system is shown in Figure 4.8.

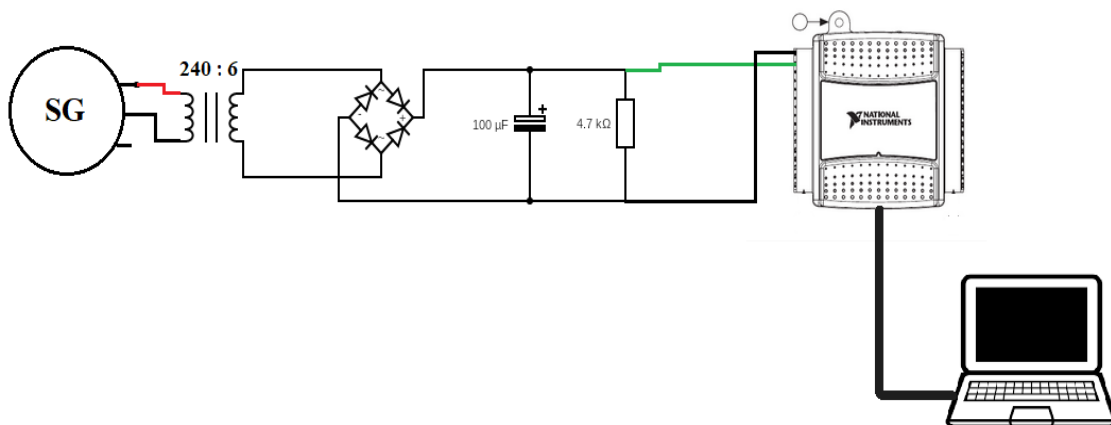


Figure 4.8 Measurement circuit diagram.

The LabVIEW program consists of the block called DAQ assistant that is configured to detect the analog signal as voltage ranging from 0V to 5V at a specific rate shown in Figure 4.9. The DAQ assistant block is connected to an indicator which is in this case a gauge to display voltage as well as it is connected also to a block PID that is designed to control and simulate a loop for the second part of the AVR that will be explained in the following step.

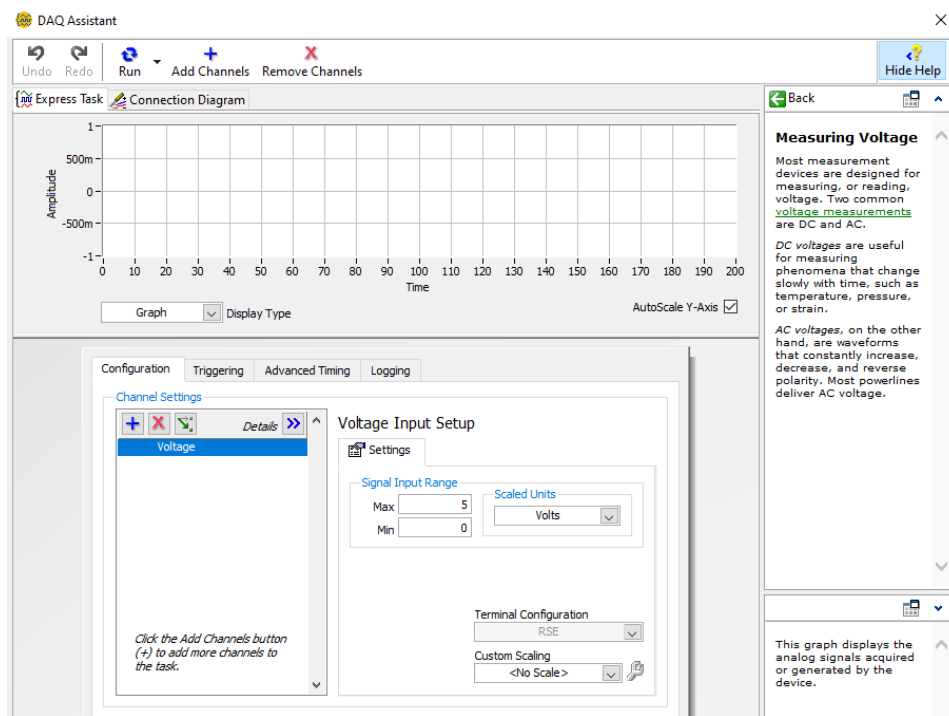


Figure 4.9 DAQ assistant configuration

We have created a ‘while loop’ in order to continuously see the updates on our program. This feature is used to prevent the user from hitting run every time as shown Figure 4.10.

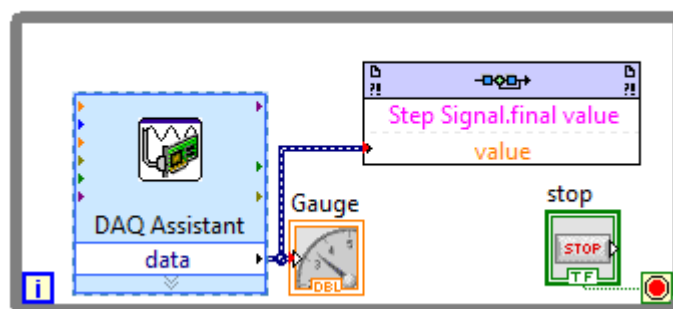


Figure 4.10: LabVIEW measurement program

The LabVIEW program was built to process the information gathered and display the terminal voltage on its front panel on the shape of both analog and digital voltmeter like it is shown in Figure 4.11.

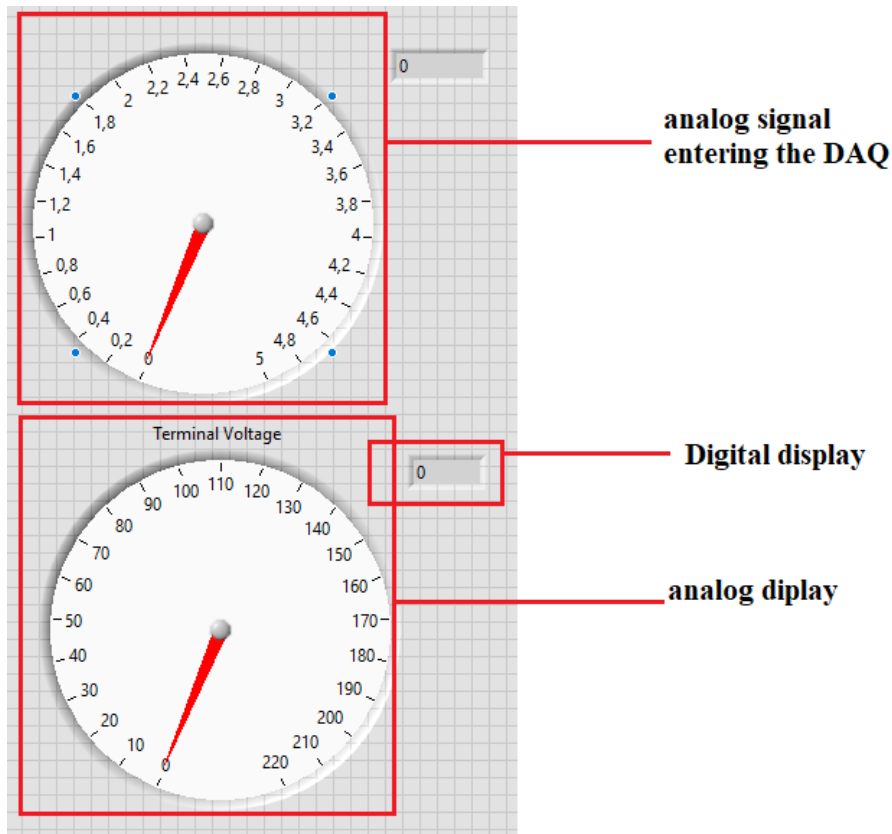


Figure 4.11: front panel display of terminal voltage

4.5.2 Control system

A control system manages, commands, directs, and regulates the output of the system using control loops designed in the control and simulation loop provided by the LabVIEW software. In the control and simulation loop (see Figure 4.12), we have designed a PID controller. The basic idea behind a PID controller is to read the value being sensed, then generates the desired system output from summation of three components obtained by proportional, integral, and derivative responses taking into consideration the set-point. The set-point that presents the desired terminal voltage is used to maintain the magnitude 50V (AC) which is meant to be at the same level during perturbation.

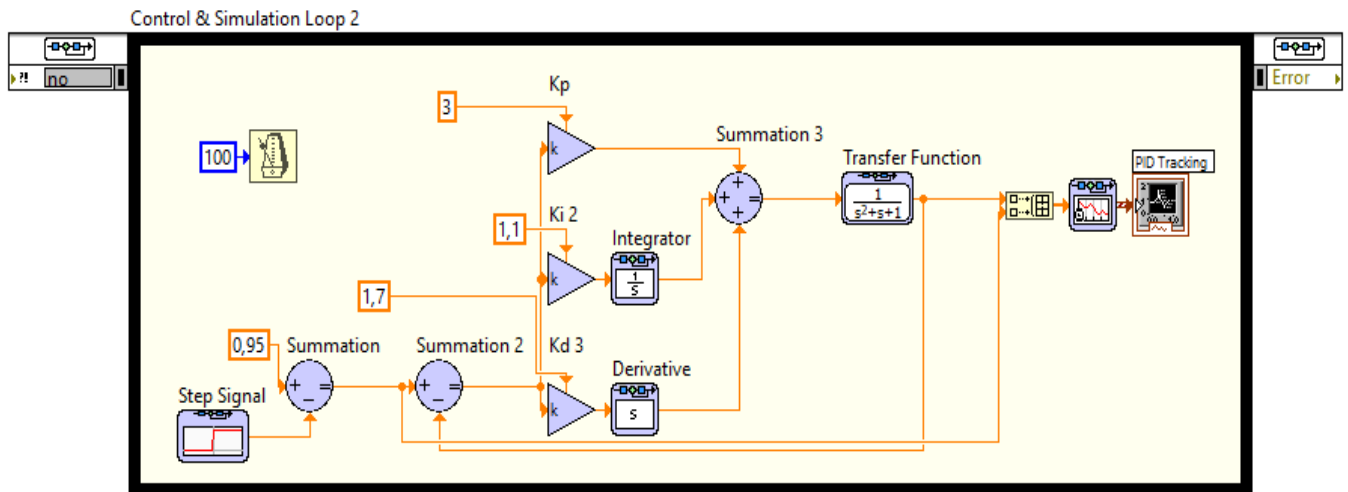


Figure 4.12 PID controller

For obtaining the PID coefficients (K_p , K_i , K_d) the program is running continuously and the system response is displayed on the front panel. We started to manipulate the three coefficients in order to get the best response, we started to increase K_p gradually to decrease the rise time, then K_i and K_d were increased also gradually to reduce the settling time and the percentage overshoot, figure 4.7 shows a graphical response of the tuned PID controller. The values of (K_p , K_i , K_d) are shown in control and simulation loop Figure 4.13.

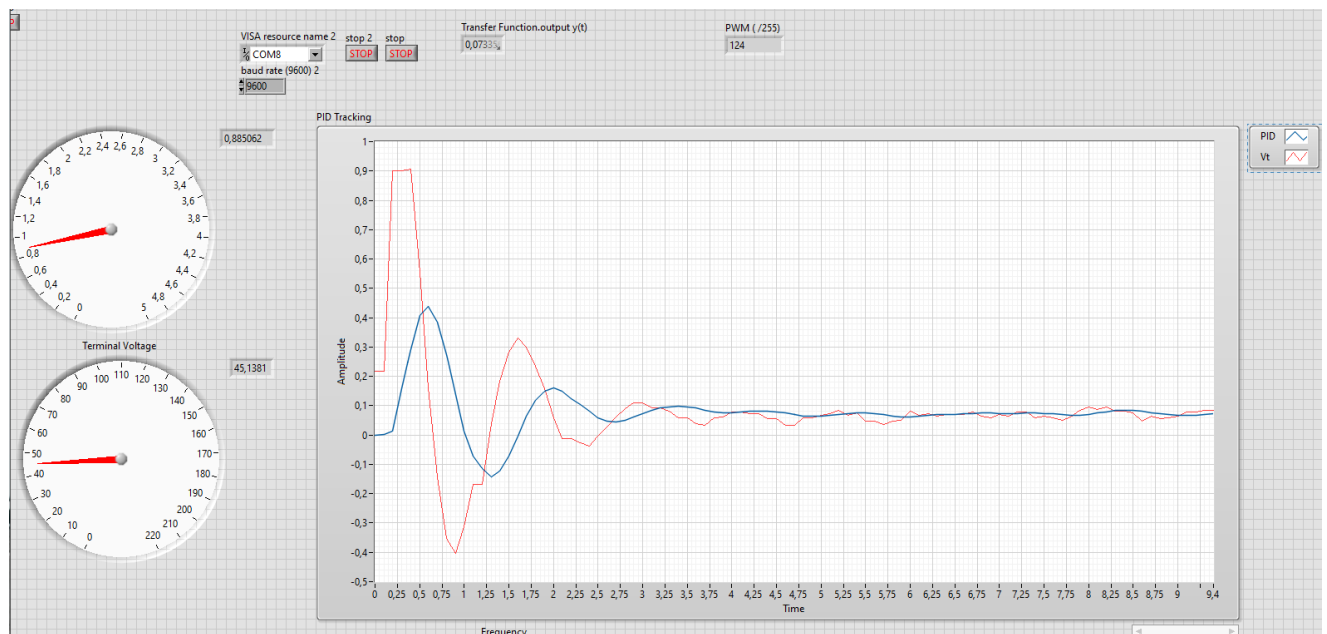


Figure 4.13 PID tracking of the terminal voltage

The control value output of the PID will be sent to the excitation system loop that will be explained in the next section.

4.5.3 Excitation system:

The excitation system of this AVR is based on H-bridge, which takes its control signal from the LabVIEW software via a microcontroller (Arduino) that works as an interface between the software and the physical circuit. PWM pulses will be sent to the H-bridge that converts DC-to-DC (chopper). It will output a voltage according to the percentage given by the duty cycle of the PWM signal. The H-bridge component which has an input DC voltage of 30V, gives an output as a percentage of the input value according to the duty cycle of the PWM (0% to 100%) that will be connected to its Enable pin. The H-bridge component needs a voltage of 5V to operate, high state connected to int1 pin and low state connected to int2 pin to control the direction of current flow. Figure 4.14 shows circuit diagram of the developed excitation system.

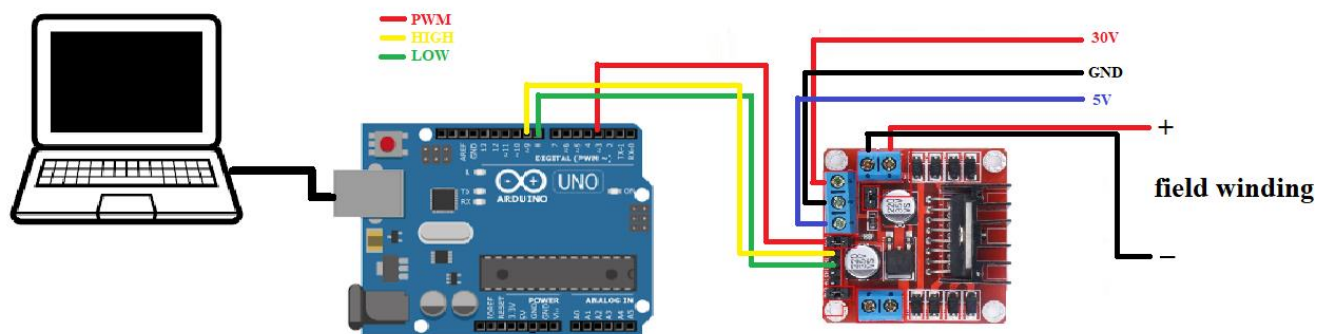


Figure 4.14 excitation system of the SG

The output signal from the PID controller will be sent to a block that is designed to generate PWM signal. A variation of (0-255) as shown in figure (4.15) leads to to the duty cycle of the PWM signal change according to the voltage needed and the loads connected to the terminal of the SG. The Arduino code that has been used to extract the PWM signal from pin 3(digital pin) is shown in figure (4.16).

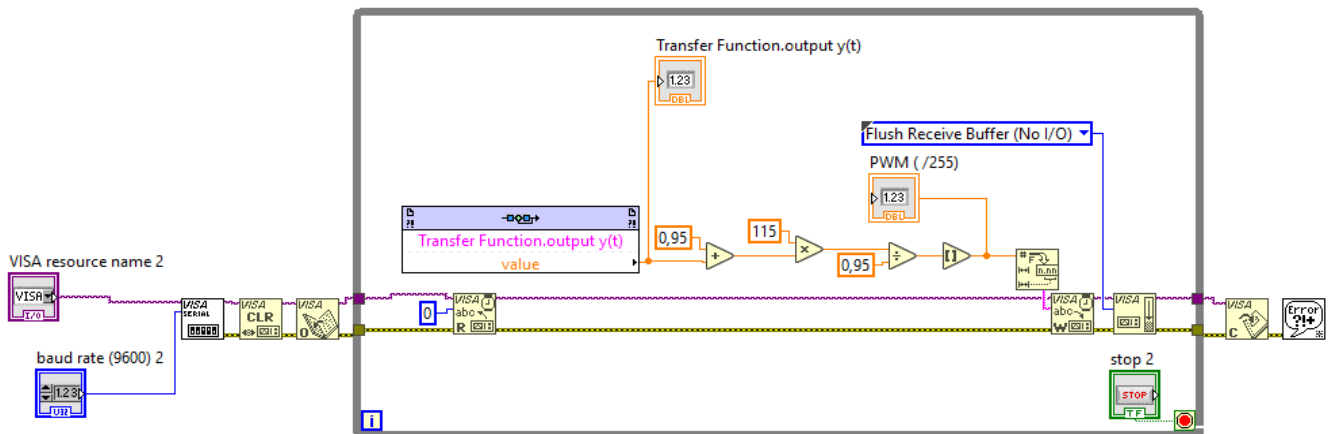


Figure 4.15 block diagram of LabVIEW software for PWM variation

```

sketch_jun27a | Arduino 1.8.15
Fichier Édition Croquis Outils Aide

sketch_jun27a $
int in1=8;
int in2=9;
int Pwm=3;
void setup() {
  Serial.begin(9600);
  pinMode (Pwm, OUTPUT);
  pinMode (8, OUTPUT);
  pinMode (9, OUTPUT);
}

void loop() {
  // TCCR0B=TCCR0B & B00111000 |B00000001;

  if (Serial.available ()>2){
  int c=Serial.parseInt();
  analogWrite (Pwm, c);
  }

  digitalWrite (in1, LOW);
  digitalWrite (in2, HIGH);
}
    
```

Figure 4.16 Arduino code

Different loads were applied to the terminal voltage of the SG and the corresponding PWM signal were displayed on the oscilloscope in the figure below where we can see all information about duty cycle changing.



Figure 4.17 PWM signals generated and injected to the field winding

The channel 1 of the oscilloscope is indicating the PWM generated by the Arduino with peak-to-peak voltage of approximately 5V and with frequency of 489.7 Hz and channel 2 indicates the signal produced by the DC-to-DC converter with input of 30V. We can notice the change in duty cycle going from 48,63 % to 56,47% until 58,18% and that is due to the change in load applied at the terminal voltage.

Conclusion

Experimental test on laboratory 1,5KVA salient pole synchronous generator to determine the relationship between field current and terminal voltage were performed, the resulting graph were presented and discussed in this work. By taking into account major time constants and ignoring the saturation and other non-linearities transfer function of the elements of the AVR system were obtained, simulation was made by means of Matlab/Simulink software and the result of the voltage profile at the terminals of the SG is presented.

The AVR system is implemented using LabVIEW program in three steps. The first step is to implement a measurement tool to read the voltage at the terminal of the SG by using step down transformer and signal conditioning circuit connected to the DAQ that reads the analog signal that will be shown on the LabVIEW front panel. The PID control system was build using the control and simulation block in the LabVIEW program, the excitation was done using H-bridge connected to Arduino uno controlled by the LabVIEW program. However, the H-bridge module used in this experiment fail to provide sufficient current to the exciter as we start to increase number of loads that are connected in parallel with the terminal voltage. Instead of using the H-bridge as a dc-dc converter it is preferable to use buck converter for the excitation and we can also dispense the use of the microcontroller and use DAQ to generate the PWM signal for the DC-DC converter

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