ISSN 2347 - 3983
Volume 8. No. 7, July 2020
International Journal of Emerging Trends in Engineering Research
Available Online at http://www.warse.org/IJETER/static/pdf/file/ijeter31872020.pdf
https://doi.org/10.30534/ijeter/2020/31872020

Design of an Automatic Voltage Regulator Using MATLAB for Real-Time ECG Signal Transmission Monitoring applications

Aaron Don M. Africa, Jamie Lynn T. Chua, Pierre Randell S. Yao
Department of Electronics and Communications Engineering
De La Salle University, Manila
2401 Taft Ave., Malate, Manila 1004,
Philippines, aaron.africa@dlsu.edu.ph

ABSTRACT
This study tackles the issue of improving the design of the automatic voltage regulator system (AVR) based on the resulting transient response and steady-state error observed through the use of MATLAB. Focusing on the application of the AVR on the synchronous generator, three simplified designs were constructed and simulated as follows: an AVR without the controller, an AVR with a proportional- integral-derivative (PID) controller, and an AVR with a PID controller and an additional voltage sensor. Upon evaluating the systems on parameters such as the response and rise time, the percent overshoot, settling time, the steady-state error, the peak time, and the step response, the results strongly indicate that the automatic voltage regulator with a PID controller and additional voltage sensor had the best stability and the most ideal steady-state error with a proportional gain of 1. The integral and derivative having gains of 0 shows that it has no role in shaping the response of the chosen system. The system created here can be used in the biomedical field like EVG Signal Transmission monitoring.

Key words: voltage regulator, synchronous generator, proportional-integral-derivative controller, transient response.

1. INTRODUCTION

Since power supplies tend to produce a current that can more often than not damage the various components in electronics, the solution was to develop a buffer which serves to maintain the voltage at the desired level or one relatively close to it in most cases. For the most part, active voltage regulators can be classified into two different categories: the linear voltage regulator and the switching voltage regulator. The linear voltage regulator uses a field-effect transistor (FET) which allows it to serve as a voltage divider while having the resistance vary depending on the load, to thereby produce a constant output. Some drawbacks of this kind of voltage regulator, however, include the low efficiency and the need for a heat sink. On the other hand, the switching voltage regulator is one that transforms the input voltage through the rapid switching element into an output smoothened by rectifiers and/ or low pass filters, all while dissipating little to no power whatsoever. The common disadvantages of this type of voltage regulator though are the increase in the number of components necessary for the design, as well as the resulting switching noise that has to be removed [1].

A type of voltage regulator found in machines such as power generators is the automatic voltage regulators or AVRs which are used to stabilize the changing voltage produced by the system. Using solid-state devices, the automatic voltage regulator serves as a feedback and control system where it identifies whether the output signal is within a certain range using sensors, otherwise, an error signal is sent to the controller which adjusts the plant and the cycle repeats until the desired value is obtained. In this project, three automatic voltage regulator system of a synchronous generator is to be constructed, simulated, and compared using MATLAB.

2. BACKGROUND OF THE STUDY

Due to the nature and effectivity of voltage regulators, these have become a necessary component for most electronic devices to prevent an overwhelming and unregulated amount of power to course through the system, particularly for large machines which can lead to potentially dangerous outcomes. One of the large machines that will be the main focus of this study is the wind turbine. The basic principle that wind turbines operate on is that the power harnessed from the wind causing the three large propeller-like blades to rotate – otherwise called torque – is lead through the rotor and down the main shaft to a generator. This generator is called the synchronous generator, otherwise known as the synchronous alternator, which is a kind of device that takes in mechanical power and transforms it into AC electrical power [2]. One of the attributes the synchronous generator has is the constant rate at which the motor works, dubbed as the synchronous speed, regardless of the speed from the variable wind turbine. As a result, the voltage being produced is at grid frequency. The application of the automatic voltage regulator in this set-up is that it serves as a power electronic system that stabilizes the voltage to control the output voltage. Also, the AVR suppresses the noise being produced, all while protecting the system from surges of power.

Research presented by [3] describes how through modifying the standard automatic voltage regulator in the synchronous generator, they were able to produce a voltage regulation of two percent at constant maximum power capacity. Another substitute would be the self- exciting synchronous generator; however, this works with low and high-power generation via combustion as compared to the AVR which can handle constant and varying high values of power.

3. STATEMENT OF THE PROBLEM

For automatic voltage regulators, the need for suppressors and power or current surge protection increases due to the irregular amount of power being brought to the synchronous generator. Consequently, this affects the complexity in the design of the system given that there is an increase in components such as capacitors and inductors to compensate and be able to steady the output voltage with little to no noise. As previously mentioned, the purpose of this study is to design, compare, analyze, and simulate an automatic voltage regulator system of a synchronous generator through the use of MATLAB. One point of focus is the improvement of the automatic voltage regulator system through bettering the overall transient response and steady-state error [4]. Three designs will be tested: AVR without a controller, AVR with a proportional-integral-derivative (PID) controller, and AVR with a PID controller and additional voltage sensor. Besides, the main points for comparison will be the rise time, percent overshoot, settling time, steady-state error, peak time, and step response.

4. SIGNIFICANCE OF THE STUDY

Generally speaking, voltage regulators play a large part in converting and maintaining raw voltage and/ or current at the desired or relatively close level to prevent damage to the system. Known for being a low cost and efficient mechanism, these are reliable devices that are simple yet essential when dealing with modern electronics – useful especially for engineers. Automatic voltage regulators work the same way but automatically as feedback and control systems for, more often than not, devices that are sensitive to surges of power [5]. This study aims to find the automatic voltage regulator with the best transient response and a minimal steady-state error through the use of MATLAB to improve on the current systems available. Through this, developers of massive sources of mechanical energy such as wind turbines can utilize the findings of the research to understand and further identify the best design for the automatic voltage regulator in synchronous generators to maximize the electrical energy produced from the conversion of torque [6]. Furthermore, through bettering the design of the automatic voltage regulator, the control of the generator itself will be enhanced since the output can be stabilized without the threat of the system failing or causing major errors [7].

5. DESCRIPTION OF THE SYSTEM

In the automatic voltage regulator (AVR) system, the system simplify maintains the fluctuating voltage to a preset reference voltage. Additionally, the AVR system has four important parts: amplifier, exciter, generator, and sensor seen in Figure 1.

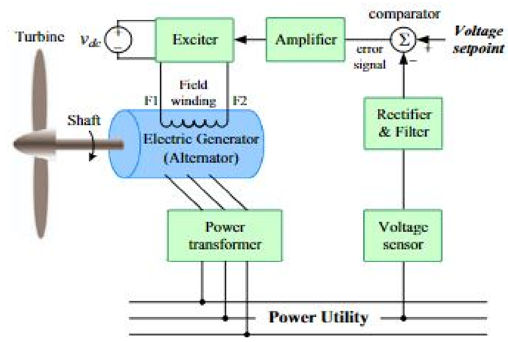

Figure 1: Diagram of the power facility

In this system, the electric generator generates the voltage which is slightly fluctuating to the power transformer [8]. After that, the power transformer transfers the voltage from the generator to the power utility. In the power utility, the voltage sensor compares the voltage level in the power utility to the preset reference voltage. If the voltage level is lower than the reference voltage, the system will increase the excitement current in the exciter which will increase the DC voltage produced by the generator. On the other hand, if the voltage level is greater than the reference voltage, the system will increase the excitement current in the exciter which will increase the DC voltage produced by the generator [9].

6. METHODOLOGY

In this project, three automatic voltage regulator design of a synchronous generator will be constructed and simulated using MATLAB [10]. Those three automatic voltage regulator designs are the following: AVR without the controller. AVR with PID controller, and AVR with PID controller and additional voltage sensor [11]. Figure 2 shows the general flow chart of the system.

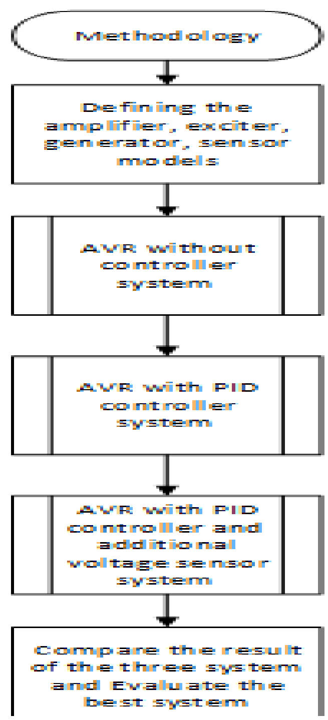

Figure 2: General Flow Chart of the system

Figures 3,4 and 5 shows the flowchart of the AVR system using various scenarios.

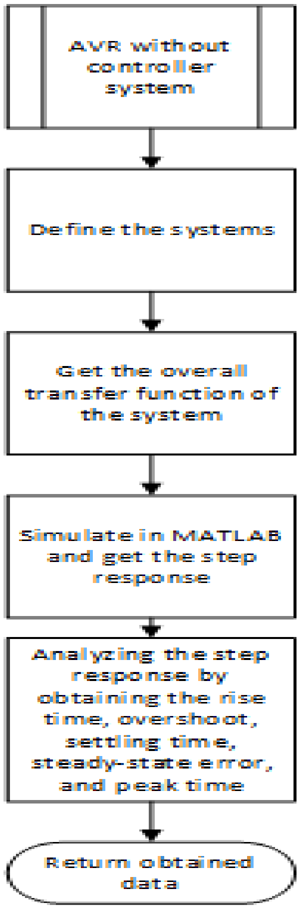

Figure 3: Flowchart of the AVR system without the controller

In the data collection of the AVR system with the PID controller, the three parameters of the PID controller will be tested which are the following proportional gain, integral gain, and derivative gain. In each of those parameters, five different values will be tested and observed [12].

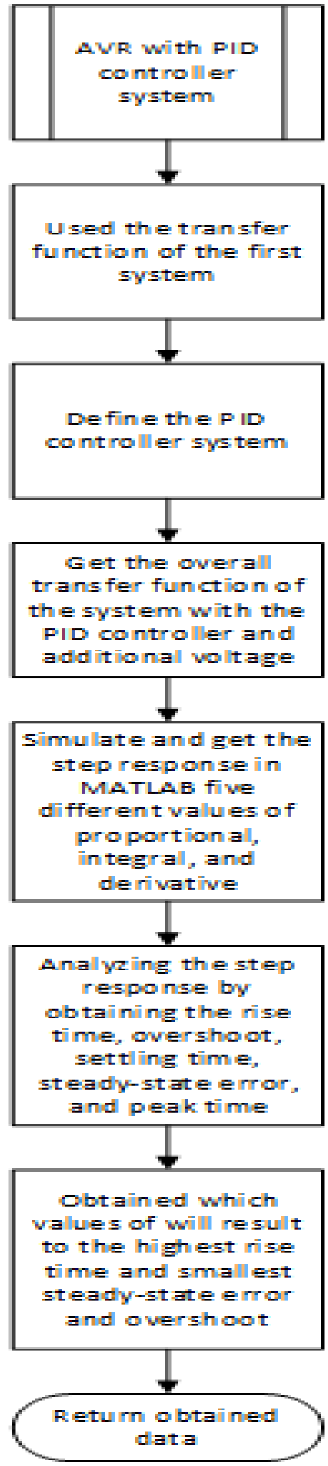

Figure 4: Flowchart of the AVR system with PID controller system

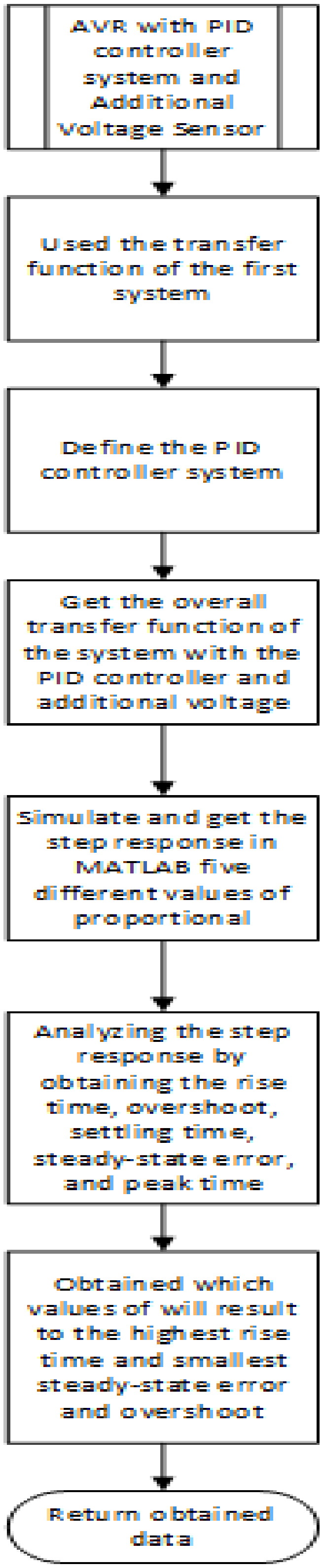

Figure 5: Flowchart of the AVR system with PID controller system and additional voltage sensor

7. THEORETICAL CONSIDERATIONS

In this project, the following models of a simple AVR: amplifier, exciter, generator, and the sensor will be used where it will be simulated in MATLAB. Furthermore, the classical PID controller will be used, for it is the most popular and simplest way of improving the AVR system's response to fluctuating voltage. Additionally, there are three parameters to control which are the proportional gain, integral gain, and derivative gain [20].

In the amplifier model, the transfer function is seen below where it has K_A as the gain and τ_A as the time constant. Typically, the amplifier depends on the designer's specifications. However, in this project, Çelik and Durgut's model will be used where K_A must range from 10 to 40, and τ_A must range from 0.02 to 0.04 seconds.

Amplifier model:

$$G_{Amplifier}(s) = \frac{K_A}{1+\tau_{AS}}$$

In the exciter model, the transfer function is seen below where it has K_E as the gain and τ_E as the time constant. Like the other model, the exciter model is a first-order transfer function but has a different range in its parameter. In its time constant, τ_E, it must range from 0.40 to 1.00 seconds. As for its gain, it must range from 1 to 10.

Exciter model:

$$G_{Exciter}(s) = \frac{K_E}{1+\tau_{ES}}$$

In the generator model, the transfer function is seen below where it has K_G as the gain and τ_G as the time constant. Like the other model, the generator model is a first-order transfer function but has a different range in its parameter. In its time constant, τ_G, it must range from 1.00 to 2.00 seconds. As for its gain, it must range from 0.7 to 1.0 seconds.

Generator model:

$$G_{Generator}(s) = \frac{K_G}{1+\tau_{SG}}$$

In the sensor model, the transfer function is seen below where it has K_S as the gain and τ_S as the time constant. Like the other model, the sensor model is a first-order transfer function but has a different range in its parameter. Additionally, the sensor is the component that measures rectifies and smoothens the voltage of the system. In its time constant, τ_S, it must range from 0.001 to 0.006 seconds, for it must be very fast of noticing the slightest variation in voltage. As for its gain, it must be 1.0, for the voltage reading must be as accurate as possible.

Sensor model:

$$G_{Sensor}(s) = \frac{K_S}{1+\tau_{SS}}$$

To have a just comparison, this project adopts the same parameter values with Çelik and Durgut's research: K_A=10,K_E=K_G=K_S=1.0,τ_A=0.1s,τ_E=0.4*s*,τ_G= 1.0*s*,and τ_S=0.01*s* [4]. Figure 6 shows the block diagram of the PID Controller. Figures 6,7 and 8 shows the block diagram of the PID Controller in several scenarios.

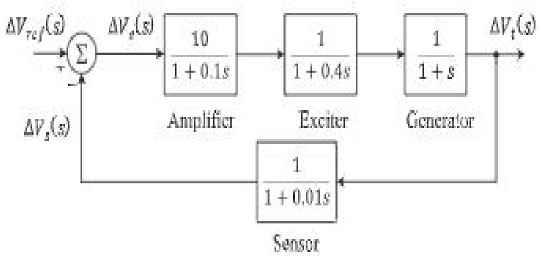

Figure 6: The Block Diagram of System without PID controller

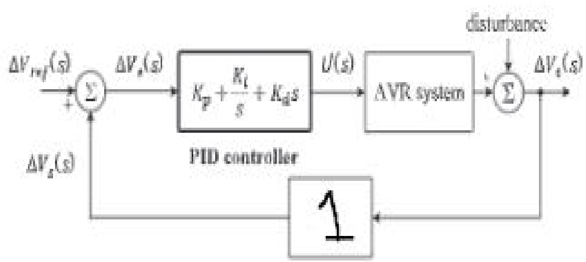

Figure 7: The Block Diagram of System with PID controller

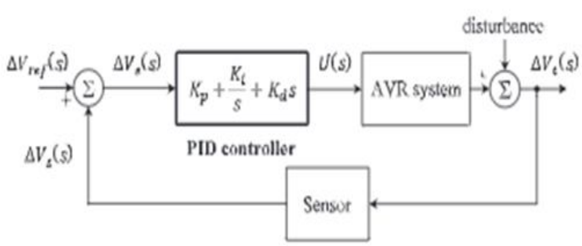

Figure 8: The Block Diagram of System with PID controller and Additional Sensor

8. DATA AND RESULTS

Figure 9 shows the overall Transfer Function.

```
AVR =

                    0.1 s + 10
  -----------------------------------------------
  0.0004 s^4 + 0.0454 s^3 + 0.555 s^2 + 1.51 s + 11

Continuous-time transfer function.
```

Figure 9: Transfer function

Step information of AVR without PID

Rise time: 0.2607s
Overshoot: 65.7226
Settling Time: 6.9865s
Steady-State Error: 0.909
Peak Time: 0.7522

Figures 10 to 13 shows the step response of the system in various conditions.

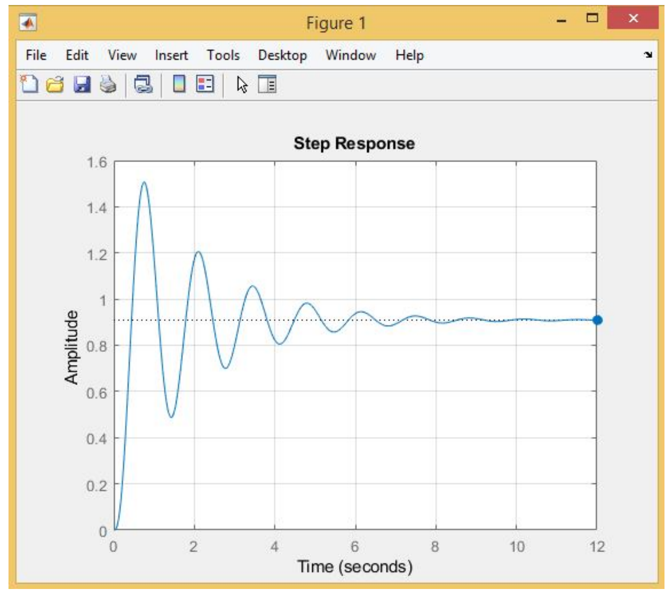

Figure 10: Step Response of AVR without PID

In the AVR with the PID controller, the following: rise time, overshoot, settling time, steady-state error, and the peak time of different proportional ranging from -2 to 10 of PID controller is obtained. In this collection of data, the derivative and integral are zero.

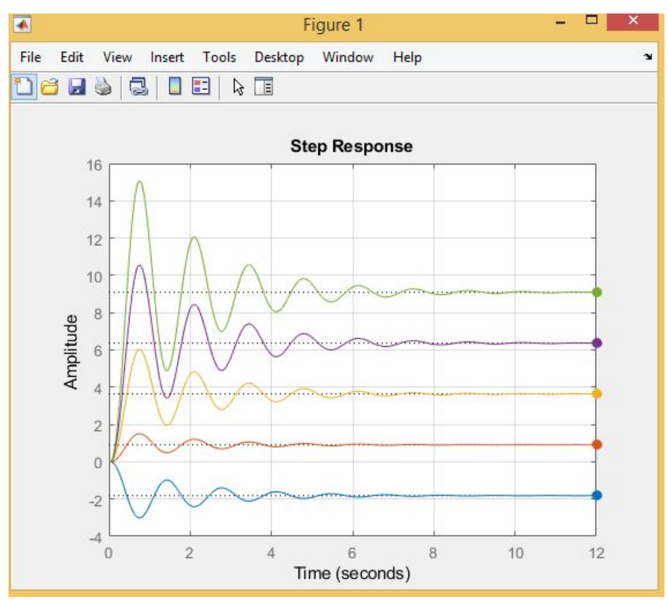

Figure 11: Step Response of Different Proportional Gain

In the different integral, the following: rise time, overshoot, settling time, steady-state error, and the peak time of different proportional ranging from -0.2 to 0.6 of PID controller is obtained. In this collection of data, the derivative gain is considered to be zero, and the proportional gain is 10.

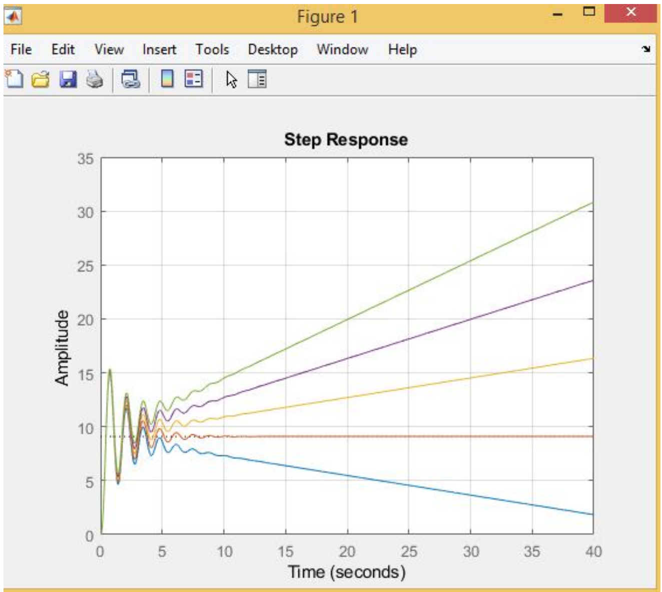

Figure 12: Step Response of Different Integral Gain

In the different derivatives, the following: rise time, overshoot, settling time, steady-state error, and the peak time of different proportional gain ranging from 0 to 8 of PID controller are obtained. In this collection of data, the integral gain is considered to be zero, and the proportional gain is 10.

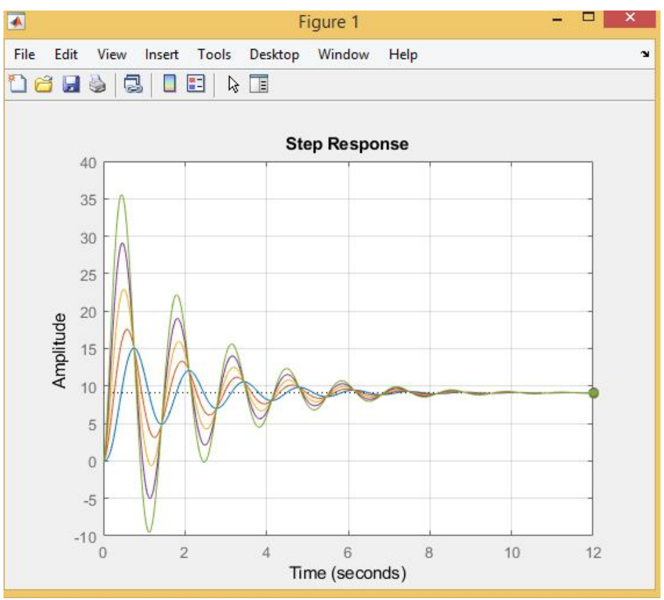

Figure 13: Step Response of Different Derivative Gain

Figure 14 shows the overall Transfer Function as outputted by Matlab.

```
con =

                          s + 100
  -------------------------------------------------
  0.0004 s^4 + 0.0454 s^3 + 0.555 s^2 + 1.51 s + 11

Continuous-time transfer function.
```

Figure 14: Overall Transfer Function

Figures 15 and 16 shows the step response when the system was inputted various differential gains.

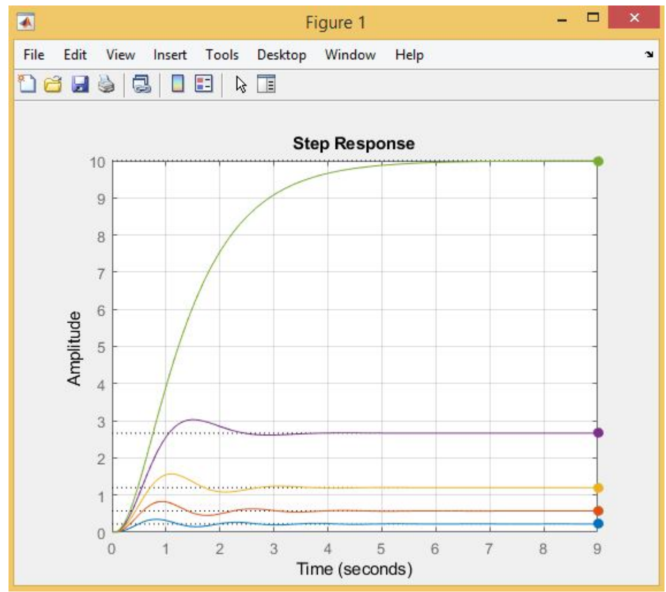

Figure 15: Step Response of Different Proportional Gain

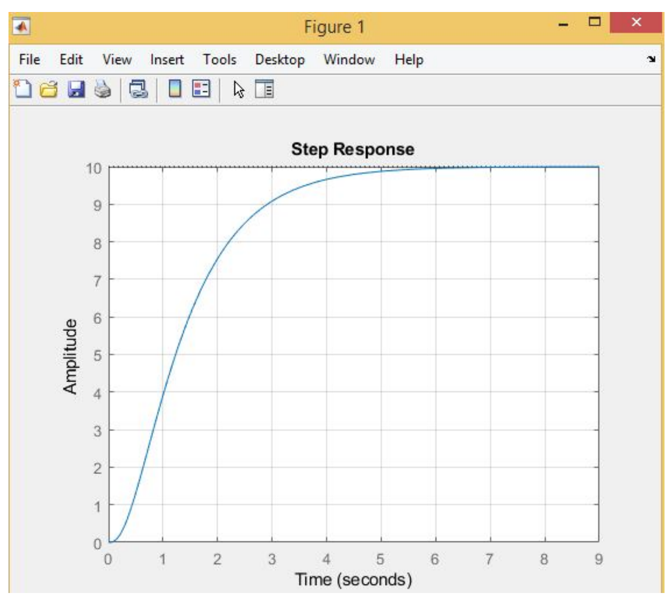

Figure 16: Step Response of AVR with PID and Additional Voltage Sensor

9. ECG SIGNAL TRANSMISSION MONITORING

In the automatic voltage regulator simulation, it is used as a power source and tested in an ECG signal transmission system. The modulated signal is shown in Figure 17.

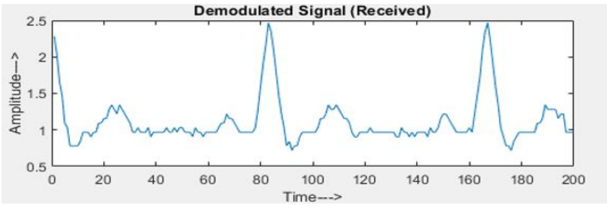

Figure 17: Step Response of the demodulated signal

10. ANALYSIS OF DATA

In the automatic voltage regulator without the controller, the step response is obtained using MATLAB where it is shown to be an underdamped response. Looking at the generated figure, the steady-state error is found to be 0.909 which is far from the targeted value of 10. Using the step info command of MATLAB, the rise time, overshoot, settling time, peak time are determined. Seen with the rise time of 0.2607s, the system has a very good transient response. However, since the system is underdamped and has a very high overshoot of 65.7% and a very long settling time of 7s, the system is found to be not suited as an automatic voltage regulator by itself.

As for the AVR system with the PID controller, in data of different proportional gain ranging from -2 to 10 of PID controller considering the derivative and integral gains are considered to be zero, Table 1 has shown that the proportional gain does not affect the following: rise time, overshoot, settling time, steady-state error, and peak time. However, looking at the step response of the different proportion, the steady-state error has improved drastically where a proportional gain of 10 has shown to be the best response, for its value of 9.09 is closer to the targeted value of 10.

As for the different values of integral gain, the standard proportional gain is 10, for it has shown to be the best responses. Like different proportion gain, the derivative gain is considered to be zero. Seen in Table 2, the system becomes unstable and very much unsuited for the AVR system. Additionally, the data has also shown that there is no way of further decreasing the overshoot for this type of system. Among the various integral gain, the zero integral gain has shown the best result.

As for the different values of derivative gain, the standard proportional gain is 10, and the integral gain is zero. As seen in Table 3, the system has shown to respond faster as the derivative gain increase. Additionally, the systems improve rise time and peak time. Seen in the graph, the derivative gain of 8 has shown the best result. However, the drawback of the increasing derivative gain is the increase of overshoot where the derivative gain of 8 has the highest overshoot. This issue is normally addressed by the integral gain but seen in the previous data, the integral gain in values other than zero will make the system unstable. For the best parameters of the PID controller, the proportional gain is 10, and the integral and derivative gains are 0.

As for the AVR system with the PID controller and additional voltage sensor, the proportional gain is the only that will be varied, for the previous system has shown that the best value for the integral and derivative gain is zero. In Table 4, the proportional gain will be ranging from 0.2 to 1, for the gain more than 1 will be unstable. In the table, the overshoot and steady-state error have improved as the gain comes closer to one unlike the system without the additional voltage sensor. Moreover, looking at the step response of the different proportions, the steady-state error has improved as it approaches one where its proportional gain is exactly 10. However, the system has shown to respond slower approaching one, for its rise time, settling time, and peak time increase. Despite its slower response, the third system with the proportional gain of 1 and the integral and derivative gains of 0 is found to be best suited for the AVR system. Additionally, the systems have shown to be very stable and closest to the targeted steady-state error.

11. CONCLUSION

In determining which system is most suited for the automatic voltage system, the response time, stability, and consistency of the system is addressed to be the efficiency and effectiveness of the voltage regulator [13]. Additionally, voltage regulators maintaining raw voltage and/ or current at the desired or relatively close level to prevent damage to the system. Upon evaluating those important parameters, the step response of the system is obtained and analyzed were the following: rise time, overshoot, settling time, steady-state error, and peak time are determined [14]. In checking the response time of the system, the rise time, settling time, peak time must be as low as possible for the AVR system to regulate the fluctuating voltage [15]. Ideally, the system must be over-damped for the system to have the output voltage as consistent as possible. This is achieved by addressing the stability and consistency of the system [16,17]. The stability and consistency of the system are observed through the overshoot, steady-state error, and the characteristics of the system. In addressing the overshoot of the system, the overshoot should be reduced or removed for the system to not experiencing any sudden surge. As for the steady-state error, the system must reach the target value which is 10 in this project. Looking at the step response, the system must be a very clean steady-state response where it has slight or no variation in its output. Furthermore, the transient response of the system must relatively be quick. Of all the system tested, the system with the PID controller and additional voltage sensor is found to be most suited to be used for an AVR system. Despite its slower response, this system with the proportional gain of 1 and the integral and derivative gains of 0 has the best stability and the ideally steady-state error. Seen in the data, the integral and the derivative gain of the PID controller has no role in shaping the response of the system.

11. RECOMMENDATIONS

In this project, the design and analysis of the automatic voltage system are extremely simplified due to the short amount of time given. Moreover, the different algorithms used in Çelik and Durgut's research could be used such as artificial bee colony (ABC) algorithm, particle swarm optimization (PSO), and differential evolution (DE) test the AVR system further. Additionally, Bode plots and the root locus of the systems could have also been analyzed. With the Bode plot, the stability of a control system can truly be determined where the gain and the harmonic of the system can be observed and analyzed. However, this will only work with the LTI AVR systems where gain and phase response of a given LTI system for different frequencies. As for the root locus of the systems, the behavior of the AVR system can be observed where the effect of the change with the variation of the parameter to the roots can be determined. As a recommendation, the more of the process of the voltage regulator may be further explained and discussed. The synchronous generator of the system could have also been examined and designed. Additionally, the cost of the AVR system could be considered to have a realistic result. Moreover, in using MATLAB, Simulink could be used to have a better simulation test. Using Simulink, the effect of external noise and disturbance to the system can be determined. Furthermore, the different and more complex AVR systems can be tested where the system is a MIMO system. With the system being a MIMO system, the system could be state space rather than transfer function to adapt to other systems. Moreover, using the other AVR system, a system with a better transient response than the AVR system could have been obtained. Overall, this project managed to obtain the best system for a simple AVR system.

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