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Analysis of performance for the various types of controllers used in the Automatic Voltage Regulator System (AVR)

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ABSTRACT

The paper will present a performance analysis of various types of controllers used in the Automatic Voltage Regulator (AVR) system. The AVR is a crucial component of power systems, responsible for regulating the voltage levels of generators to ensure a stable and reliable power supply. Different types of controllers, such as proportional integral derivative (PID), Z-N tuning, and LQR controllers, are evaluated and compared based on their performance metrics, including setting time, overshoot, and steady state error. Simulation findings show that each controller has its own strengths and weaknesses in terms of regulating voltage. Moreover, the selection of a controller is contingent upon the particular needs as well as the features of the power system. This analysis can provide valuable insights for engineers and researchers in selecting and designing appropriate controllers for AVR systems.

KEYWORDS: System of AVR, PID, Control of Lead Compensator, Auto-Tune Algorithm (ATA).

1 INTRODUCTION

The power system network's voltage stability affects its dependability, security, and electric component safety; thus, the voltage output must be managed at a specified rate to keep it running smoothly [1]. When another load is introduced to the grid, the voltage immediately reduces because of the change in reactive power loading. This load will draw a high current from the grid because of this reduction in the voltage, resulting in the grid's different losses. As a result, the voltage reduction causes needless losses and undesirable oscillations in the grid. In order to prevent this from happening, a definite arrangement must be in place so that the voltage can be stabilized to a constant value in an extremely short amount of time. Because the amount of reactive power flowing through a system is proportional to its voltage terminal, it is necessary to achieve a reactive power balance between load and supply in order to regulate the system voltage. The synchronous generator can generate and absorb reactive power by changing the voltage used for the voltage excitation; increases in field excitation lead to an increase in reactive, power [2]. As a result, the voltage terminal regulation to the rated value necessitates the use of automatic voltage control to modify the DC- excitation voltage of the generator. The (AVR) unit employs a controller to modify the voltage terminal [3]. In power plants, automatic voltage regulators (AVRs) are employed to keep the voltage steady. It operates by stabilizing the excitation voltage value first, then controlling the value of the excitation voltage to control the voltage output; this gives a reliable voltage system [4]. Some problems with the AVR's output response include overshoot and steady-state value inaccuracy. In order to implement and increase the dynamic responsiveness of an AVR system, it has been investigated in the literature, how various control systems rely on robust control, adaptive control, and optimal control. There are many ways to enhance the voltage terminal of an AVR, like using PID conventional, which is widely popular because of its stable performance regardless of changes in the parameters of the system and its structural simplicity.

or used controller based on the PID [5]. In conventional PID, only three control system parameters are required to be adjusted, namely the proportional gain, integral gain and derivative gain [6], [7]. In recent years, the authors have tuned the parameter gain of the PID controller using various algorithms. The aim of the authors is to propose an algorithm with the traditional PID controller to tune the parameter gain and its superiority over other algorithms [5], like the gravitational search algorithm GSA. It is clear from the results that using (GSA) is best than the results from using genetic algorithm GA and particle swarm optimization PSO [8], ant lion optimizer algorithm (ALO) in[9], Local Unimodal Sampling Algorithm (LUS) [10], and used hybrid Algorithm Particle Swarm Optimization and the Gravitational Search Algorithm (PSOGSA) to solve problem optimization [11] , Symbiotic Organisms Search algorithm (SOS) [12] , Water Cycle Algorithm (WCA) [13], water wave optimization algorithm (WWO) , Stochastic Fractal Search (SFS) [14], Tree Seed Algorithm (TSA) algorithm[15], Equilibrium Optimizer algorithm (EOA) [16], Future Search Algorithm (FSA)[17] , Enhanced Crow Search Algorithm (ECSA) [18], and used new way to tune PID of nonlinear system Artificial Immune Algorithm (AIA) [19] . In addition, the researchers propose another controller based on PID with algorithm to tune parameter gain of this controller, Fractional Order PID (FOPID), and to tune control parameters by using the Invasive Weed Optimization algorithm (IWO) [20] , Degree of Freedom (2DOF) State Feedback PID with PSO algorithm [21], Another proposed controller to solve the problem of the AVR system is fuzzy logic based on PID (Fuzzy P+ Fuzzy I+ Fuzzy D) with hybrid genetic algorithm and particle swarm optimization (HGAPSO) [22]. It can be noted that each algorithm has its own superiority over another algorithm, as there are no proposed algorithms to solve all the optimization problems of this system. Controllers of the contemporary variety, like the (linear quadratic regulator) (LQR) and (linear quadratic gaussian) (LQG), Substituting (LQR) or (LQG) controllers for (PID) controllers might strengthen the system's responsiveness in terms of robustness [23], [24].

Voltage regulation is a critical component of power systems, and the Automatic Voltage Regulator system is accountable for ensuring stable and reliable power supply by regulating the voltage levels of generators. The present work used different types of controllers, such as proportional integral derivative (PID), Ziegler-Nichols (Z-N) to get parameter PID control (K_P, K_I, K_D), lead compensator, and linear quadratic regulator (LQR), have been implemented in order to improve the overall functionality of the AVR system. However, there is a lack of comparative studies that evaluate and compare the performance of these controllers based on their specific metrics, including settling time, overshoot, and steady state error. In this paper, we present a comprehensive performance analysis of various types of controllers used in the AVR system. specifically, we compare the traditional (Z-N) method and the Auto Tune Algorithm (ATA) in MATLAB Simulink, design a lead compensator to achieve a desired performance, and use LQR to optimize the controller parameters. Our study aims to provide valuable insights for engineers and researchers in selecting and designing appropriate controllers for the AVR system.

The paper follows this structure: It begins with an introduction section and moves on to a study of the AVR system model in part 2, control system design in part 3, and the result in part 4 and discussion in part 5.

2 THE AUTOMATIC VOLTAGE REGULATOR SYSTEM MODELING

The magnitude of the voltage terminal of a synchronous generator can be maintained at a constant value when using the automatic voltage regulator, also known as an AVR. The power stability and power quality of the system may be enhanced via generator exciter control. In Fig. 1, we see a common configuration for a basic (AVR) system. As can be seen in Fig. 1, an AVR system is made up of the following four components: amplifier, exciter, generator, and sensor [1]. The (AVR) unit's transfer function can be described using the linearized transfer functions of the various components individually, as shown below:

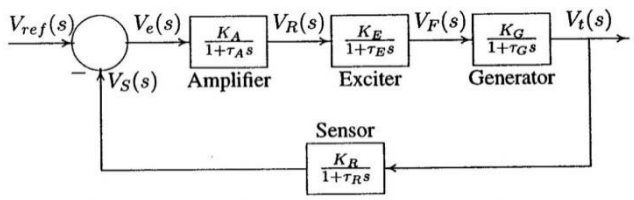

Figure 1: A common layout for a basic AVR.

Amplifier model:
The amplifier model's transfer function is:

$$\frac{V_R(s)}{V_e(s)} = \frac{K_A}{1+\tau_A s} \qquad (1)$$

The amplifier gain is indicated by the symbol (K_A), while the time constant is represented by (τ_A), the range of (K_A) is between (10 to 40) and the (τ_A) between (0.02 to 0.1 second [1].
In this research we set (K_A=10 and τ_A=0.1 second).

Exciter model:
The exciter model's transfer function is:

$$\frac{V_F(s)}{V_R(s).} = \frac{K_E}{1+\tau_E s} \qquad (2)$$

Where the gain of the exciter is denoted by the symbol K_E, the time constant is denoted by(τ_E),The values of(K_E) between (1to 10) and τ_E between (0.4 to 0.1second) [1].
in this research we set (K_E =1 and τ_E = 0.4 second).

Generator model:
The generator model's transfer function is:

$$\frac{V_t(s)}{V_F(s)} = \frac{K_G}{1+\tau_G s} \qquad (3)$$

The symbol of (K_G) is indicated to the generator gain and the symbol (τ_G) is the time constant the range values of K_G between (0.7 to 1) and the range of (τ_G) between (1 to 2sec [1]
in this research we set (K_G =1 and τ_G = 1 second).

Sensor model:
The transfer- function for the sensor model is:

$$\frac{V_t(s)}{V_F(s)} = \frac{K_R}{1+\tau_R s} \qquad (4)$$

The gain of the sensor is denoted by the symbol(K_R) and the time constant is indicated by the symbol (τ_R).
The range values of(τ_R) between (0.01 to 0.06 sec [1]
We set the K_R =1 and τ_R = 0.05 second. In this research.

Here is a depiction in equation (5) of the linearized transfer function of an (AVR) unit with out of a controller [25]

$$\frac{V_t(s)}{V_{ref}(s)} = \frac{K_A K_E K_G (1+\tau_R)}{(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)(1+\tau_R s)+K_A K_E K_G K_R} \qquad (5)$$

$$= \frac{10(1+0.05s)}{(1+0.1.s).(1+0.4.s).(1+s),(1+0.05.s)+10}$$

So, the closed loop transfer function is as follows:

$$= \frac{250(s+20)}{(10+s)(2.5+s)(1+s)(20+s)+500} \qquad (6)$$

$$= \frac{250(s+20)}{s^4+33.5s^3+307s^2+775s+5500} \qquad (7)$$

Given the aforementioned, values for the system parameters the step voltage response of (AVR) with no using a controller in Fig 2.

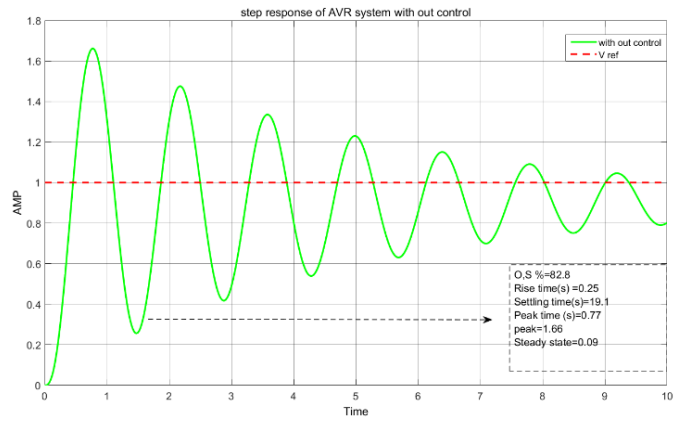

Figure 2: Step response of an AVR system's output voltage when no controller is present.

Form the figure we can see the terminal voltage despite stability because the system has four poles in left side (s=-1, s=-2.5, s=10, s=20) but it has high oscillation and error steady state. The overshoot of the system is 82.8% and rise time is 0.31 sec, settling time 19.1 steady state 0.09, peak time 0.77 and has damping ratio is 0.81. As shown, it is necessary to have an efficient additional controller arrangement in order to make the AVR unit more robust and stable in order to sustain the system voltage under a variety of system conditions.

3 CONTROL SYSTEM DESIGN

In this section, (PID) controller and design lead compensator control and LQR are employed to enhance the (AVR) unit.

3.1 The (PID) controller

The proportional integral derivative (PID) controller is often used due to its ease of usage design, which makes it easy to implement and maintain, and its ability to produce stable results. (PID) controller transfer function is [26], [27]

$$\frac{U(S)}{E(S)} = K_P + \frac{K_I}{S} + K_D S \qquad (8)$$

Where E(S) is equal to the different between reference signal $V_{ref}(s)$ and terminal voltage $V_t(s)$,U(S) is a control signal coming after parameter of PID (K_P, K_I, K_D) is applied to reduce the signal error. The parameters of PID controller are (K_P , K_D , K_I) (Proportional Gain, Derivative Gain and Integral Gain) respectively.

In Fig .3 shows the block schematic of the (AVR) unit with add the (PID) controller

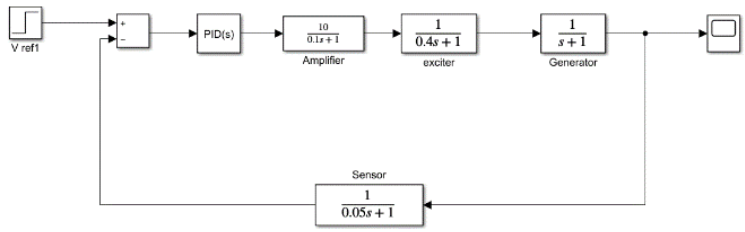

Figure 3: (AVR) with PID controller

Tuning a (PID) controller may be done in the conventional method Ziegler-Nichols (Z-N) tuning to obtain parameter gain and this method is classical and difficult way. The PID parameter gain obtain by (Z-N) is $K_P = 0.6729$, $K_I = 1.0302$, $K_D = 0.10987$.

The voltage terminal of the (AVR) unit $V_t(s)$ show in Fig.4 and unit step is applied to input $V_{ref}(s)$. In the Fig 4, we can see that the AVR system repone with PID tuning using (Z-N) way, have more oscillation the over shoot (O. S=48.19%) and settling time (s.t = 2.93 sec) and rise time (r.t = 0.28 sec). from the Fig 4 and the result can see the PID controller tuning by Z-N way and this way not improve the response of the (AVR), system.

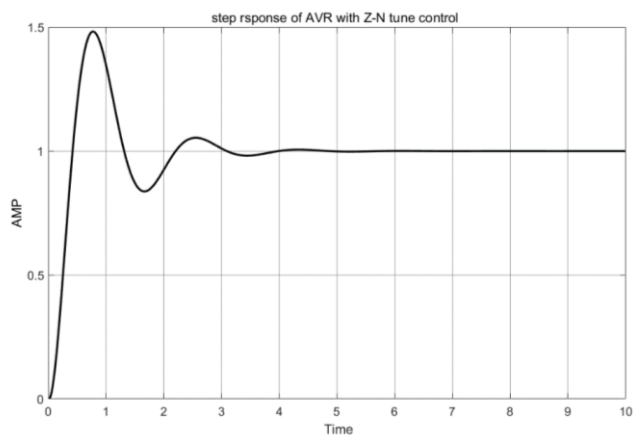

Figure 4: The voltage terminal of the (AVR) with (PID) tuning by (Z-N).

To improve this result and get better response for (AVR) system with controller (PID) we used auto tuning algorithm (ATA) in MATLAB to get parameter gain of PID. This method allows to user change in transient response and the system speed and decrease the overshoot by using the tool that in this method. The parameter gains of PID controller that tuning in (ATA) is, $K_p = 0.211212995519781$, $K_I = 0.188505105169364$, $K_D = 0.0567956349640869$ the terminal voltage of the (AVR) is shown in Fig .5 with a better response for the system, where the overshoot is reduced to (O. S=4.4282%), and settling time (s.t =3.2802), and rise time (r.t =0.9197).

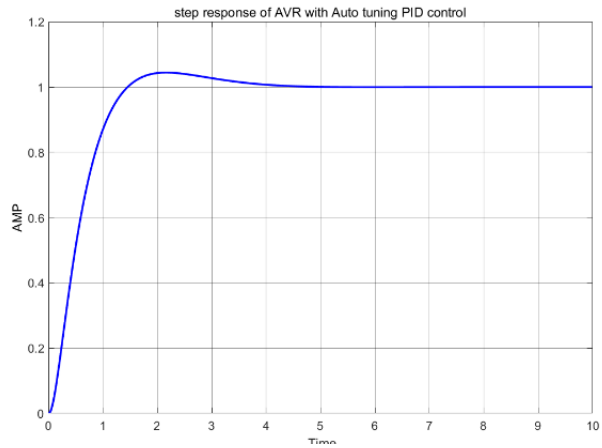

Figure 5: The voltage terminal of (AVR) with control (PID) tuning by (ATA).

3.2 Design Lead Compensator Control

The transient response and stability of a dynamic system can be enhanced by using a lead compensator, a form of control system. It is done by, adding a pole and zero to the closed loop system, which makes the gain go up at higher frequencies. This shortens the time required for the system to stabilize and reduces the overshoot in the step response [28], [29].
The transfer function of a lead compensator is given bellow [[27]:

$$G_C = K_C \frac{s+Z}{s+P} \qquad (9)$$

Where K_C is gain and Z zero and P is pole, P>>Z.

To design lead compensator control we used SISO tool in MATLAB. This way let to user choose any performance required for a system to get best response for system. Here, we choose the required performance for the (AVR) system is 10% overshoot and 0.8 settling time, Fig 6 show the dominant poles of the system, that should be moved to the position of the desired pole to meet the performance requirement.

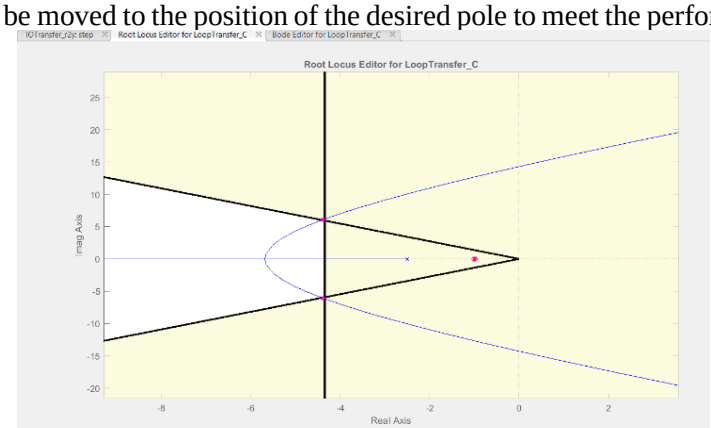

Figure 6: The Root locus of (AVR) system show the pole of closed loop and desired pole ($s_{d1,2}$=4.44±6.08 J).

When the pole of closed loop moves to the desired pole position ($s_{d1,2}$=-4.44±6.08 J), we can get the controller that will give us the requirement performance for the (AVR) system, equation (10) explain the transfer function of lead compensator control.

$$C = \frac{14.612(S+1)}{(S+87)} \qquad (10)$$

Where $K_C = 14.612$ and Z= -1, P= -87, that main we add zero in s-plain at position (-1) and pole at position (-87).

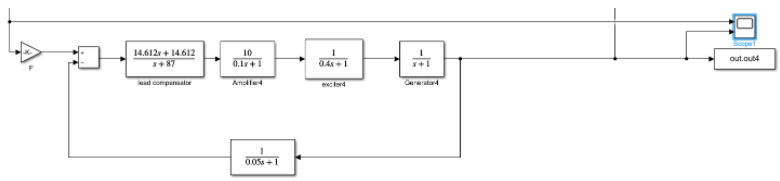

Figure 7: Block schematic of (AVR) system with lead compensator control

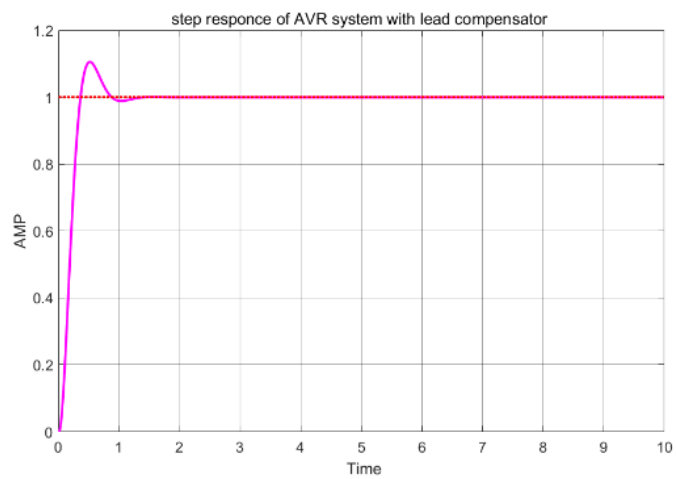

Figure 8: The voltage terminal of the (AVR). With lead compensator control

Fig 7. shows the block schematic of (AVR) system after add that the controller design by lead compensator, and we get the result as show in Fig 8 with the, performance requirement for the (AVR) system.

3.3 Design LQR control

LQR is one of the approaches that can be used for control (Linear-Quadratic-Regulator). A robust optimum control with regulator property, this control generates a minimum error in the steady state. This method can also be used to swiftly resolve any faults that may have occurred in the system. Therefore, the system is able to keep its equilibrium despite disturbances from the environment [30], [31].
In LQR, to get the best control signal, the cost function is made as small as possible. The equation for a cost function is:

$$J=\int_0^{\infty}(X^T + QX + U^T RU)dt \qquad (11)$$

The Q and R is, very important matrices and should be symmetric and nonnegative because affect to the control performance, and this matrices measures determine LQR control. These matrices are made based

on the experience of engineers who know the controlled system well. Fig 9 shows simulated block diagrams of a state feedback controller [30].

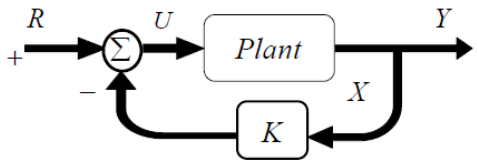

Figure 9: Block schematic of (LQR) control.

The plant represented as the steady space model

$$X^{\circ} = AX(t) + BU(t) \qquad \text{state equation} \qquad (12)$$

$$Y(t) = CX(t) \qquad \text{out put equation} \qquad (13)$$

Where the state vector is represented by the symbol (X°) and the control vector is U(t) and the output vector $Y(t)$, the size of a state matrix (A) is [n × n], and input matrix (B) is [n × 1] and the Output Matrix (C) is [1×n]. K is the gain vector and the aim of control design for control vector U(t) as equation (14).

$$U(t) = -KX(t) \qquad (14)$$

The state equation will be as the following:

$$X^{\circ} = (A - BK)\ \mathrm{X} \qquad (15)$$

Here, we chose Q and R in trial-and-error method and using MATLAB commend K=lqr (A, B, Q, R) to obtain gain vector K that employed to determine the best position cost function (J).

Fig 10 explains Steady Space model of AVR with add the gain vector K to enhancement the voltage terminal of system as show in Fig 11.

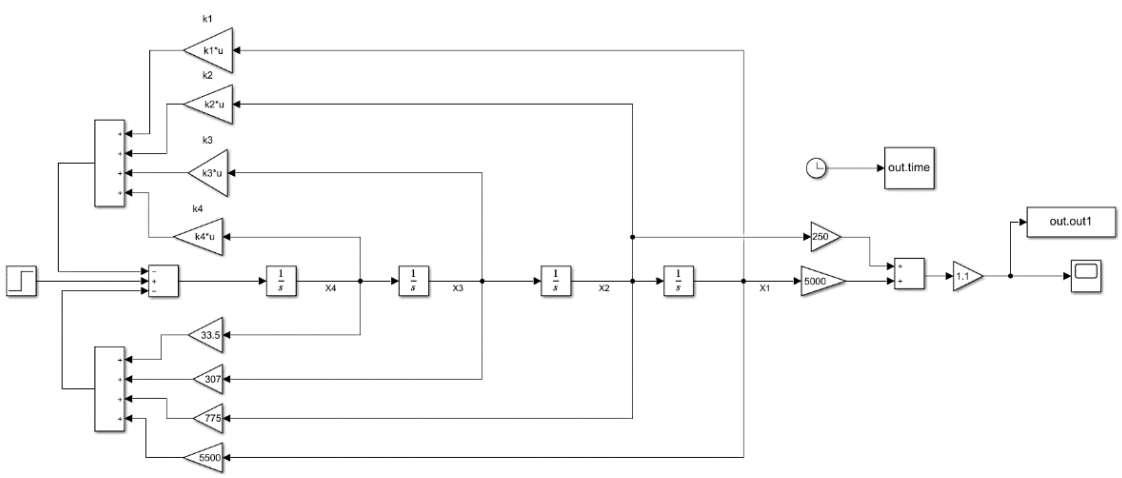

Figure 10: The (AVR) system with adding gain vector K.

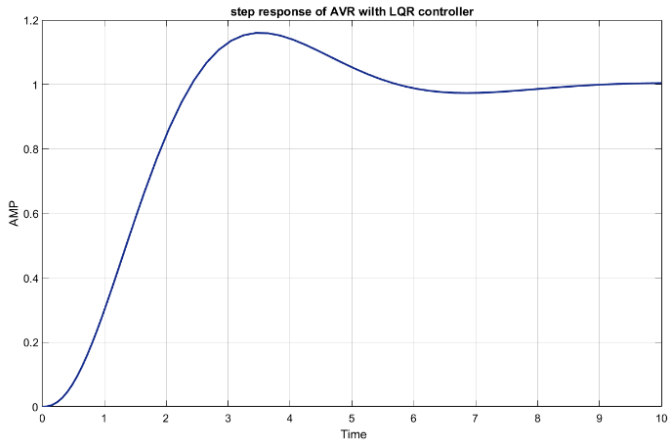

Figure 11: Output voltage of AVR with LQR control.

4 RESULTS

This research provides important information on the effectiveness of various (AVR) system controllers. Based on the findings that are reported in Table 1, it's obvious the system works better with a controller than without. The overshoot is reduced, and the rise and settling times are improved.

Table 1: Comparing and analyzing the results of various controllers

AVR system	Overshoot %	Rising-time(s)	Settling-time(s)	Peak-time (s)	Peak	Steady-state Error
Without controller	82.8	0.31	19.1	0.77	1.66	0.09
Z-N PID tune	48.197	0.28	2.93	0.74	1.48	0
Auto tune PID	4.428	0.9197	3.2802	2.163	1.03	0
Lead compensator	10.1	0.27	0.8	0.61	1.10	0
LQR control	8.86	1.31	3.87	2.82	0.898	0

The Ziegler-Nichols tuning method is a well-known method to determine the gain parameters of a PID controller. However, it can be a challenging task and time-consuming to obtain the gain parameters, as detailed in Fig 4. In this study, we utilized the (Auto-Tune-Algorithm) (ATA) method to overcome this challenge, which significantly reduced the time required to obtain the gain parameters for the PID controller (K_P , K_D , K_I), and to improve the voltage terminal of (AVR) as shown in Fig 5.
The lead compensator control method was used to design a controller with a specific performance requirement while taking the cost into consideration. This method provides the user with the flexibility to design a controller that meets the desired performance requirement, as shown in Fig 8.
We also investigated the LQR control method and found that it is not suitable for nonlinear systems. The results showed some overshoot and longer settling time, as shown in Fig 11, indicating that this method may not be appropriate for the AVR system.

The PID auto-tuning method showed good results, according to Fig 12. This may be used in the creation of a PID controller for the AVR system. This method is easy, acceptable, and low-cost, making it a practical choice for real-world applications. Overall, this research is helpful since it compares the results of many AVR controllers, which could be applied to improve the stability and performance of power systems in real-world applications.

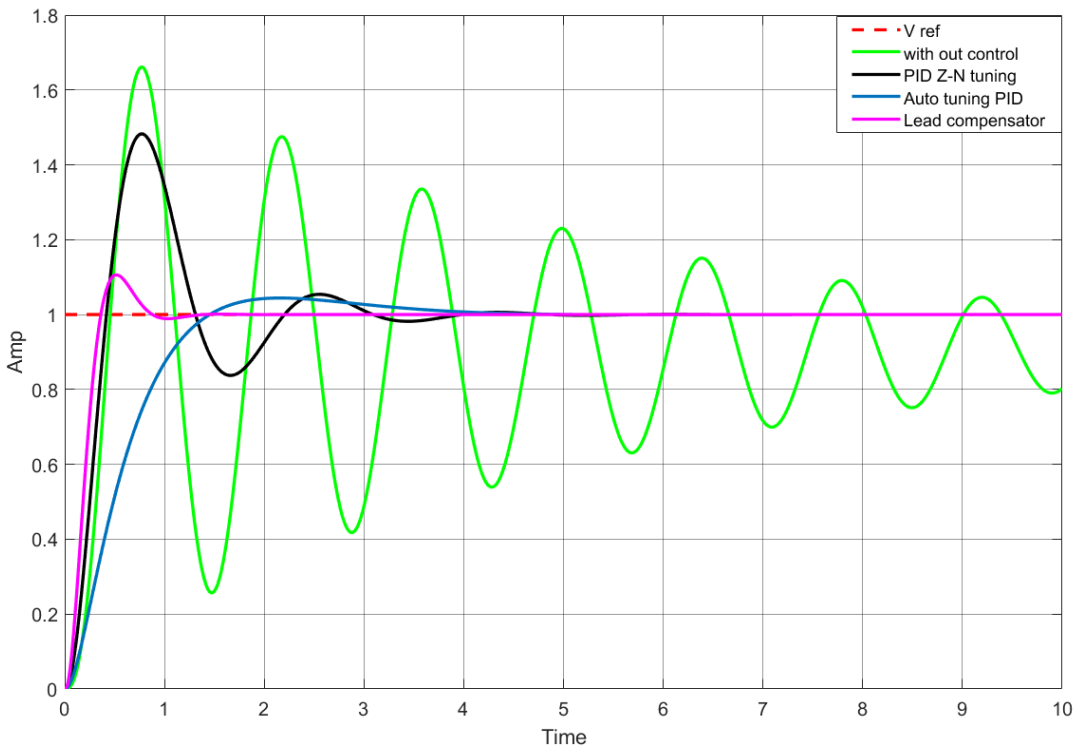

Figure 12: The voltage terminal of (AVR) explain the different. method of controller.

5 CONCLUSION

In this study, we have investigated different controllers to enhance the performance of the AVR system, and our findings demonstrate that the choice of controller has a significant impact on the system's stability and response. Specifically, we have shown that the AVR system's oscillations and transient response can be significantly reduced by implementing a PID controller with the ATA algorithm. However, the suitability of PID controllers for nonlinear systems is limited, and we have proposed the use of lead compensator control to address this issue. Moreover, our analysis of the LQR system has shown that it is not suitable for nonlinear systems, which highlights the importance of selecting the appropriate controller for the specific system being controlled .Overall, our study has significant implications for the design and optimization of power systems. By selecting the appropriate controller for the AVR system, we can improve its performance, enhance its stability, and ensure its reliability .Explain the practical aspects of the AVR system's controller and sliding mode control (SMC) in future work. Moreover, the findings of this study could be extended to other power systems to optimize their stability and reliability. In summary, our study has shown that the selection of the appropriate controller is critical to achieving the desired performance and stability of the AVR system. Our investigation of different controllers has provided insights into their strengths and limitations, and we have proposed solutions that address the limitations of existing controllers. By incorporating our findings into the design and optimization of power systems, we can ensure that they operate efficiently and reliably, even under adverse conditions.

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