# A PROTOTYPE CO-RELATION OF PID, FUZZY LOGIC, AND ARTIFICIAL NEURAL NETWORK CONTROLLERS FOR AUTOMATIC VOLTAGE REGULATOR

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***Abstract:***

*This paper presents the design of various controllers for regulating the voltage within limits. AVR is the automatic voltage regulator device that stabilized the output voltages under the influence of variable loads. AVR regulates the voltage but there are too many fluctuations in voltage, PID controller, Fuzzy logic controller, and Artificial Neural Networks (ANN) are designed for tackling such issues. By comparing the output of these controllers better and optimal results are concluded. For constant, continuous, and stabilized output voltages, optimal tuning of PID controller, fuzzy logic, and ANN controller is necessary, and their tuning schemes are presented by computer simulations in an AVR system.*

## 1 Introduction

The AVR technology is developed by Atmel Corporation in 1996 and introduced their microchip technology in 2016 known as Automatic Voltage Regulator (AVR). The stability of AVR is improved by controlling the excitation voltage of a generator. The terminal voltage of the generator is regulated by AVR by adjusting the exciter voltage. Load variation, varying fields, and high inductance decrease the stability of the system and make the system slower. The fast response of the controller is associated with AVR under loaded conditions, responsible to keep the voltage within specified limits. The fruitful functioning of AVR relates to a well-known controller to meet the specifications such as proportional integral derivative (PID) controllers [1]. For effective output, it becomes mandatory to provide the voltage within limits without transients. Fluctuations are the major causes of heating of equipment and due to sparking inside the equipment; there is a high risk of burning of equipment. While working, the load does not remain constant because the load varies with time. To confront such issues, it is necessary to provide the constant voltage within nominal limits [2]. AVR is designed to overcome this problem by holding the terminal voltage within limits. It works in a field where fluctuations in the system are much higher and the output voltage is not stable [3]. AVR controls the generator terminal voltage by providing control through PID or fuzzy logic to the exciter of the generator [4]. Effectual techniques and methods are developed to achieve better and more effective output from the generators. PID controller is one of them. PID plays a significant role with AVR in regulating the

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voltage. PID has versatile applications and achieved by tuning of PID controller is very necessary for better results. Tuning is done by the hit and trial method [5]. Effective techniques have been designed artificially for the designing as well as tuning of PID controllers. These techniques are fuzzy logic, neural network, etc. A combination of both AVR and a suitable controller is necessary to provide output within limits [6]. Fluctuations are produced in a system due to non-linearity interactions between different control loops. These fluctuations reduce the stability of the model and produce an irregular response. AVR system is associated with different intelligent techniques for minimizing fluctuations by using PID, fuzzy logic, fuzzy PID controller, robust controlling, etc. [6].

This paper presents several novel contributions to the field of voltage regulation and control systems. It provides comparative analysis of PID, Fuzzy Logic and Artificial Neural Network (ANN) controllers on a common AVR model using MATLAB Simulink, which is not widely covered with this level of integration and simulation detail in one study. Unlike most studies that focus on one or two control methods, this proposed work provides a comprehensive analysis of three distinct controllers, highlighting their performance in AVR applications. A key innovation is the application of ANN with detailed MATLAB/Simulink implementation, demonstrating its superiority over traditional PID and Fuzzy Logic in terms of settling time, overshoot, and stability. The paper also improves PID tuning by employing MATLAB's adaptive PID Tuner Tool, reducing reliance on manual hit-and-trial methods. Additionally, the Fuzzy Logic controller is designed with custom membership functions and rule-based strategies tailored for voltage regulation, enhancing its practical applicability. This experimental approach not only validates the ANN's effectiveness but also highlights its practical advantages over conventional controllers, especially in dynamic and nonlinear environments where self-tuning and adaptability are crucial.

### *1.1 Automatic voltage regulator (AVR)*

AVR is an electronic device used for controlling generator output terminal voltage at a set value and varying load conditions. AVR regulates the voltage via excitation of the system. With time load changes, the load never remains constant. The main function of AVR is to maintain the generator voltage at a set value under all conditions of load via an excitation system [7]. AVR plays an important role in dividing the reactive power when two generators are connected in parallel to each other. Due to sudden conditions, surges have been produced that harm the system. The AVR also reduces the overvoltage in that conditions to protect the overall power system [8]. The response time of AVR is very short, it responds so quickly according to conditions [9]. The alternator consists of rotor winding, stator winding and exciter stator, and rotor winding. The voltage generated inside a stator field is fed to the connection box, that connection box is connected to an AVR as well as load via main cable [10]. The general block diagram of AVR is shown below in Figure 1.

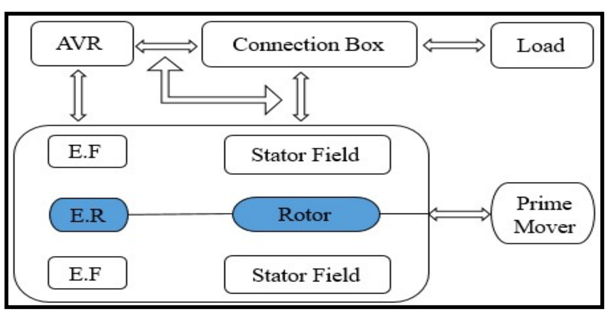


*Figure 1. General block diagram of AVR.*

***Case I***

If the generating voltage by the stator winding is quite low, then AVR will sense the incoming voltage and send the enhancement signal to the exciter winding. Meanwhile, the exciter winding produces the field; as a result, the rotor speed increases will consequently increase the voltage because the rotor is rotating inside the exciter field.

***Case II***

If the Alternator is rotating at its rated speed, meanwhile load is applied. Excessive load decreases the rotor speed and voltage. This change in voltage is sensed by AVR and it provides excitation voltage to the exciter field resulting in the increase of rotor speed.

***Case III***

If the generator is supplying load in overloaded condition and there is sudden decrement in load, will increases the alternator speed due to which the voltage increases beyond the limits [11]. In this case, the AVR immediately detects this change in voltage and decreases the amount of excitation voltage resulting in the decrease of output voltage and protecting the equipment.

## 2 Mathematical modeling of AVR

AVR model is installed on the synchronous generator to regulate its terminal voltage. AVR regulates the terminal voltage in four major units known as comparator, amplifier, exciter, generator, and sensor. The main function of AVR is to regulate the terminal voltage and control the reactive power of the generator according to varying loads [12]. The circuit diagram is shown below;

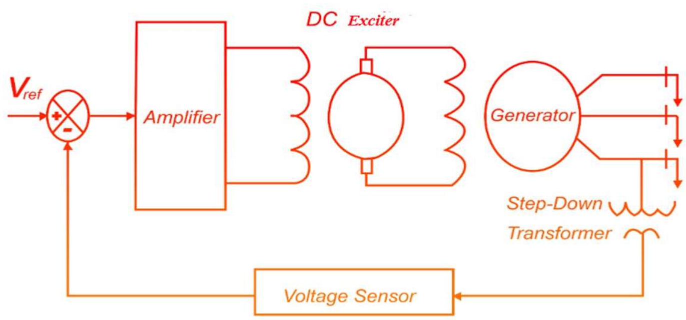


*Figure 2. Circuit diagram of AVR.*

AVR works on the basis of the comparator. The comparator senses the output voltage and compares it with a reference input voltage. If the output voltage is less than the reference voltage the positive error signal is produced. An error signal is fed into an amplifier the amplifier amplifies the signal and sends it to the exciter. A high signal increases the exciter terminal voltage due to which the generator EMF increases [8]. The effectiveness of activity increases the terminal voltage hence the reactive power of the system is restored to its equilibrium position and the error signal is improved. The close loop model diagram of AVR is portrayed below;

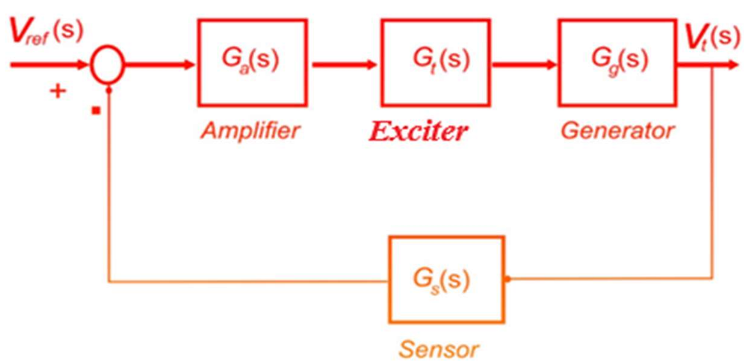


*Figure 3. Closed-loop model of AVR.*

### 2.1 Models of AVR units

Since $V_{ref}(s)$ is the input voltage and $V_t(s)$ is the output voltage of AVR. Assuming that the error occurs in the system and the output voltage decreases. The comparator sense this change and generates an error signal which is regulated through the comparator [13], [14].

#### 2.1.1 Comparator

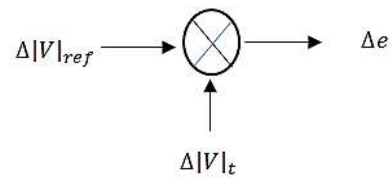


*Figure 4 . Schematic of comparator.*

$$e = |V|_{ref} - |V|_t \tag{1}$$

The error signal increases with the decrease of output voltage. Feeding this signal into AVR units results in the increment of $V_R, I_R, V_F$, and $I_F$. Where $V_R$ and $V_f$ are the output voltages of amplifier and exciter respectively. The equation of comparator is –

$$\Delta e = \Delta|V|_{ref} - \Delta|V|_t \tag{2}$$

Taking Laplace transform of the above equation-

$$\Delta e(S) = \Delta|V|_{ref}(S) - \Delta|V|_t(S) \tag{3}$$

#### 2.1.2 Amplifier

The error signal is fed into the Amplifier. The amplifier amplifies the error signal and generates output voltage $V_R$. The output voltage of $V_R$ is directly proportional to the magnitude of an error signal. Greater the error signal greater will be the $V_R$ and vice versa.

$$\Delta|V|_R \propto \Delta e \tag{4}$$

$$\Delta|V|_R = K_A \Delta e \tag{5}$$

where the $K_A$ is the amplifier gain. Taking Laplace of the equation no (..)

$$\Delta|V|_R(S) = K_A \Delta e(S) \tag{6}$$

$$K_A = \frac{\Delta|V|_R(S)}{\Delta e(S)} \tag{7}$$

The above equation gives the instantaneous response of the amplifier but the response is not that fast, it requires a time delay [15] so the amplifier transfer function is –

$$G_A = \frac{\Delta|V|_R(S)}{\Delta e(S)} = \frac{K_A}{1 + sT_A} \tag{8}$$

where $\frac{1}{1 + sT_A}$ is due to the time delay of an amplifier.

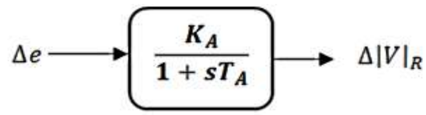


*Figure 5. Block diagram of Transfer Function.*

Typical values of the gain $K_A$ range from 10 to 400 while the time constant $T_A$ is so small which is 0.02s to 0.1s and most of the time it is negligible.

### *2.1.3 Exciter*

An exciter is used to provide the direct current to the field of the generator. The direct current that is provided depends upon the magnitude of amplifier voltage. By varying the field current speed of the rotor is regulated. The output voltages of the exciter are $V_f$ [16]. These voltages are directly fed into the generator circuit as shown below –

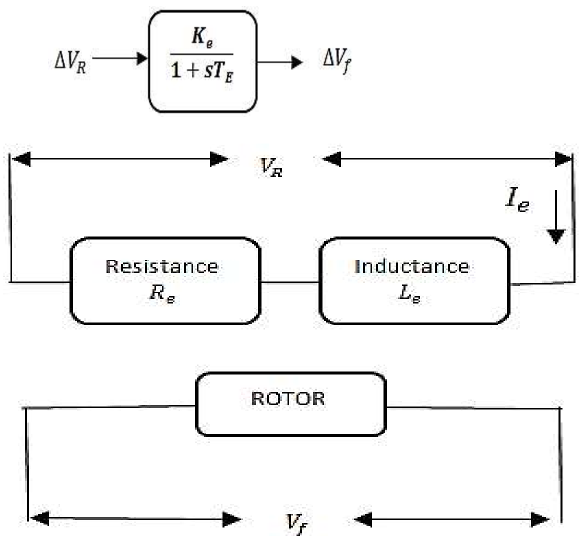


*Figure 6. Current flow diagram from the amplifier to the exciter.*

Applying KVL to the exciter circuit for developing equations for the transfer function.

$$\Delta V_R = R_e \Delta I_e + L_e \frac{d}{dt} \Delta I_e \tag{9}$$

Where, the voltage on the exciter $V_f$ is directly proportion to excitation current. Greater the excitation current greater will be the exciter output terminal voltage –

$$V_f \propto \Delta I_e \qquad \Delta V_f = K_1 \Delta I_e \tag{10}$$

Simplifying the equation 9 and 10 and the taking Laplace transform –

$$\Delta V_R(S) = R_e \Delta I_e(S) + L_e S \Delta I_e(S) \tag{11}$$

$$\Delta V_R(S) = (R_e + L_e S) \Delta I_e(S) \tag{12}$$

$$\Delta V_f(S) = K_1 \Delta I_e(S) \tag{13}$$

Hence the transfer function for the exciter model is –

$$G_e = \frac{\Delta V_f(S)}{\Delta V_R(S)} = \frac{K_1 \Delta I_e(S)}{(R_e + L_e S)\Delta I_e(S)} = \frac{K_1}{(R_e + L_e S)} = \frac{K_1}{R_e\left(1 + \frac{1}{R_e} L_e S\right)}$$
$$= \frac{K_1}{R_e(1 + \frac{1}{R_e} L_e S)} = \frac{\frac{K_1}{R_e}}{(1 + \frac{1}{R_e} L_e S)} \tag{14}$$

$$G_e = \frac{K_e}{1 + sT_E} \tag{15}$$

$$K_e = \frac{K_1}{R_e} \text{ (Gain of the exciter)} \tag{16}$$

$$T_E = \frac{1}{R_e} L_e \text{ (Time constant for exciter in second)} \tag{17}$$

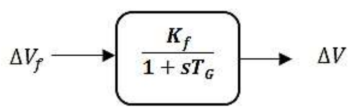


*Figure 7. Transfer function of Gain.*

Here the exciter gains range from 1 to 400 while and time constant ranges from 0.5s to 1s -

### *2.1.4 Generator model*

After the excitation of the rotor the current enters into the generator field. For developing transfer function model of generator for AVR, let us apply KVL on generator field circuit.

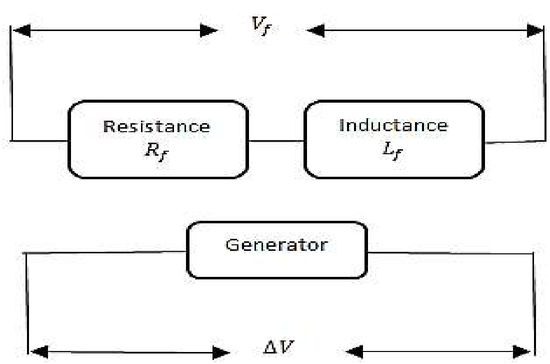


*Figure 8. Current flow diagram from the exciter to generator.*

$$\Delta V_f = R_f \Delta I_e + L_f \frac{d}{dt} \Delta I_e \tag{18}$$

Taking Laplace of equation, no 13 and we get –

$$\Delta V_f(S) = R_f \Delta I_e(S) + L_f S \Delta I_e(S) \tag{19}$$

$$\Delta V_f(S) = (R_f + L_f S)\Delta I_e(S) \tag{20}$$

Generator internal EMF is –

$$E_{max} = I_f X_L = \omega L_{fa} \quad (21)$$

where $L_{fa}$ is the mutual inductance of rotor field and the stator field of generator as shown in figure above [19]. The RMS value of internal EMF is-

$$E_{rms} = \frac{1}{\sqrt{2}} I_f X_L = \frac{1}{\sqrt{2}} I_f \omega L_{fa} \quad (22)$$

Re arranging the above equation-

$$I_f = \frac{\sqrt{2}}{\omega L_{fa}} E_{rms} \quad (23)$$

$$\Delta I_f = \frac{\sqrt{2}}{\omega L_{fa}} \Delta E_{rms} \quad (24)$$

Taking Laplace of equation, no 24 –

$$\Delta I_f S) = \frac{\sqrt{2}}{\omega L_{fa}} \Delta E(S) \quad (25)$$

Now substitute equation -

$$\Delta V_f(S) = (R_f + L_f S) \frac{\sqrt{2}}{\omega L_{fa}} \Delta E(S) \quad (26)$$

For developing the transfer function, the ratio of output over input is;

$$G_e = \frac{\Delta V(S)}{\Delta V_f(S)} = \frac{\Delta E(S)}{\Delta V_f(S)} = \frac{\Delta E(S)}{(R_f + L_f S)\frac{\sqrt{2}}{\omega L_{fa}} \Delta E(S)} = \frac{1}{(R_f + L_f S)\frac{\sqrt{2}}{\omega L_{fa}}}$$
$$= \frac{\omega L_{fa}}{\sqrt{2} R_f \left(1 + \frac{1}{R_f} L_{fa} S\right)} = \frac{\omega L_{fa}}{\sqrt{2} R_f} \frac{1}{\left(1 + \frac{1}{R_f} L_{fa} S\right)} = \frac{K_f}{1 + sT_G} \quad (27)$$

Hence the generator transfer function is –

$$G_e = \frac{K_f}{1 + sT_G} \quad (28)$$

$K_f = \frac{\omega L_{fa}}{\sqrt{2} R_f}$ (Gain for the generator)

$T_G = \frac{L_{fa}}{R_f}$ (Time constant for a generator in seconds)

The generator gain range from 0.7 to 1 and the time constant ranges from 1s to 2s respectively.

*2.1.5 Sensor Model*

Sensor model is the first order model having the output voltage ΔV that is sensed through a potential transformer and rectified it through a bridge rectifier.

$$G_s = \frac{K_f}{1 + sT_G} \tag{29}$$

Here the time constant ranges from 0.01s to 0.06s [17],

*2.1.6 Block diagram of AVR*

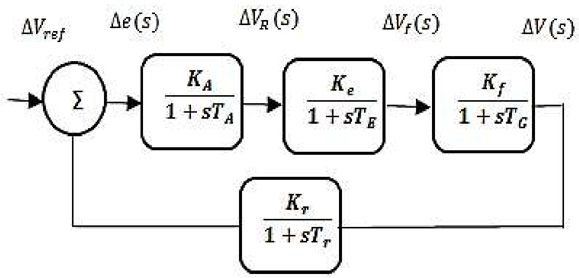


*Figure 9. Implemented block diagram of AVR.*

For the design of the AVR model, the values for the gain and time constants of the amplifier, exciter, generator, and sensor model are required [18]. The gain values and time constants for the AVR model of synchronous generator are given below;

*Table 1. Input block parameters of AVR.*

| | Gain | Time constant (s) |
|---|---|---|
| Amplifier | 10 | 0.1 |
| Exciter | 1 | 0.4 |
| Generator | 1 | 1.0 |
| Sensor | 1 | 0.05 |

For designing the AVR model of the synchronous generator, parameters in Table 1 are used -

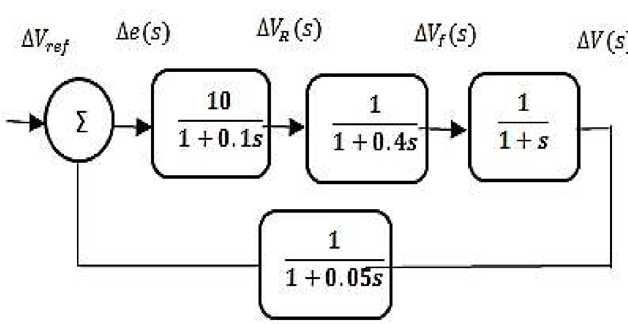


*Figure 10. Block diagram of closed-loop AVR for synchronous generator.*

## 3 Simulation results of AVR

The closed-loop control system of the AVR model is implemented in Simulink by using transfer function blocks and input as step responses. The output of the model is displayed as a graph and digital display.

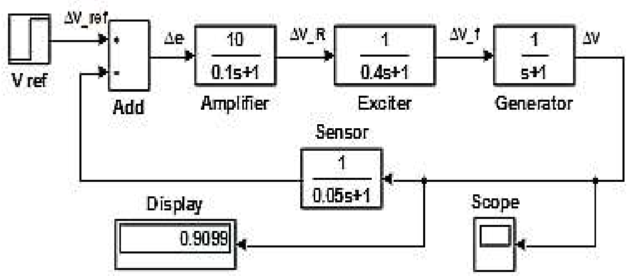


*Figure 11. Simulink block diagram of AVR.*

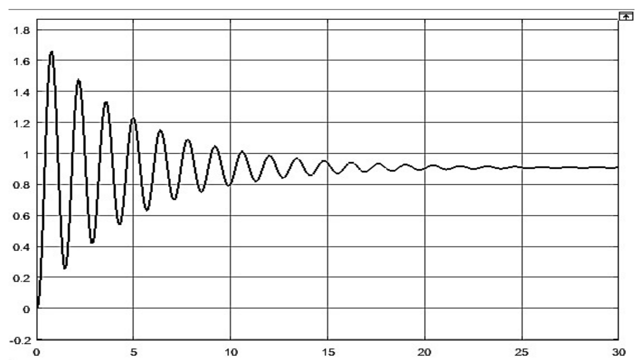


*Figure 12. Simulink model.*

## 4 Results of AVR

Here it can be seen that terminal voltage is around 0.9 per unit but the terminal voltage has to be one per unit as required. Furthermore, the output of this AVR model has oscillatory terminal voltage response with high overshoot. By setting the controller the desired value and stable terminal voltage is achieved. Commonly PID controllers are used to make our system stable.

### *4.1 PID controller*

Until now the PID controllers are considered to be best option as an industrial controller. Even though the complex industrial controllers also use the PID controllers. PID is just one form of feedback controller. It is the simplest type of controller that still uses past, present, and future errors. PID comprises proportional P, integral I, and derivative D terms in its controller [19]. In the PID controller, the proportional controller is not able to remove offset error or steady-state error due to which the integral controller is used to remove offset error. Since I controller removes the offset error, but it leads to severe oscillations which are not desirable. The derivative D controller removes this oscillatory response due to its high sensitivity and leads to a stable system.

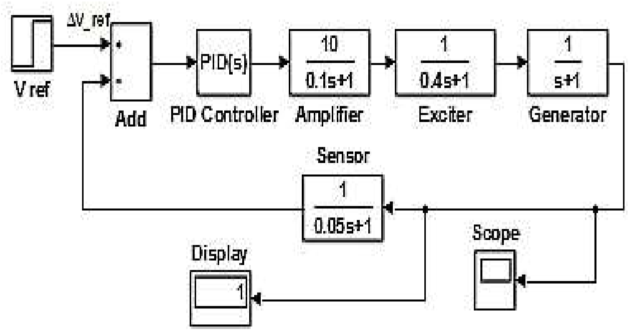


*Figure 13. Simulink block diagram of AVR with PID.*

For designing the PID controller of AVR, the PID tuning block tool is used in MATLAB. It is tuned for reducing stability errors to get better control. This control is achieved by using the "Pidtool" command in MATLAB. By using this tool, the value of PID coefficients is automatically adjusted and shows a better response. Besides this hit and trial methods are used that are time-consuming [20]. For getting better results the values of the co-efficient are changed again and again by the hit and trial method and we get better results at $K_P = 1$, $K_d = 0.28$, and $K_i = 0.25$. By adjusting these values, a suitable controller that adjusts the terminal voltage at 1 per unit as show in Figure 9. Below is the Simulink result of the AVR model using PID controller toolbox.

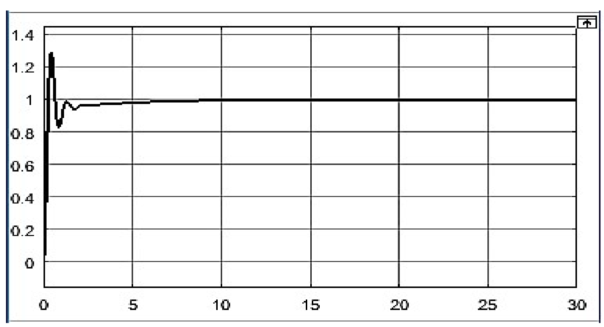


*Figure 14. Simulink results of AVR with PID controller.*

Output voltage of the grids is in volts and the transmission is carried out at 11kV. Therefore, multiply the results with a gain block to get terminal voltage in volts. To find the actual volts that are [1];

$$V_{actual} = V_{pu} \times V_{base} = 1\text{pu} \times 11\text{kV} = 11\text{kV}$$

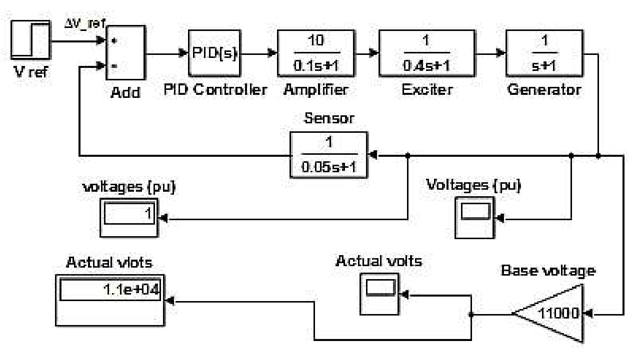


*Figure 15. Block diagram of AVR with PID at actual voltage.*

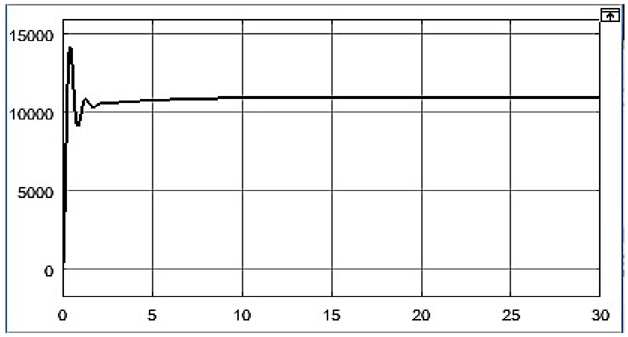


*Figure 16. Simulink results of AVR with PID controller at actual voltage.*

Figure 16 portrays output of the complete AVR model for the synchronous generator regulated by the PID controller. Keen observation shows that the output has a large overshoot and also a very long settling time. By changing the values of gain of PID controller again and again as can get an improved response.

*4.1.1 PID tool*

Designing of a controller with zero overshoot and small settling time is a crucial and time taking task, for convenience automatic regulating "Pidtool" box is used to make system more stable at required values of PID coefficients [21]. The Pidtool automatically set the controller response of voltage graph. The PID tuner automatically generates the original graph of model and compared with PID tuner model graph at the same time. Furthermore, it automatically tuned the model at small overshoot and small settling time.

$$K_P = 0.21394582359363$$
$$K_d = 0.0650447903714705$$
$$K_i = 0.173528421018465$$

There are the input values of PID controller before and after the use of PID tool module shown below;

Controller Parameters

| | Tuned | Block |
|---|---|---|
| P | 0.21395 | 1 |
| I | 0.17353 | 0.25 |
| D | 0.065045 | 0.28 |
| N | 173.2203 | 100 |

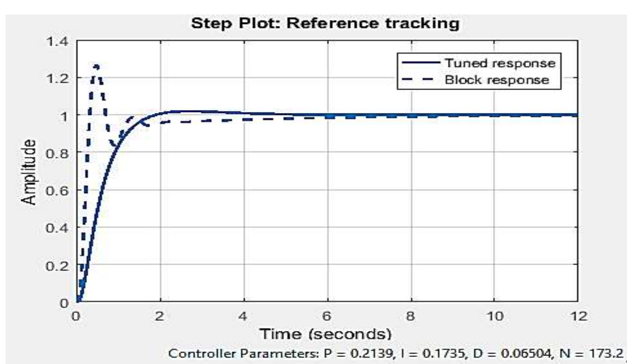


*Figure 17. Results of AVR with PID controller and PID tool.*

Performance and Robustness

| | Tuned | Block |
|---|---|---|
| Rise time | 1.02 seconds | 0.196 seconds |
| Settling time | 1.66 seconds | 5.13 seconds |
| Overshoot | 1.87 % | 26.3 % |
| Peak | 1.02 | 1.26 |
| Gain margin | 24.2 dB @ 13.3 rad/s | 10.2 dB @ 12.5 rad/s |
| Phase margin | 75 deg @ 1.52 rad/s | 39.7 deg @ 6.1 rad/s |
| Closed-loop stability | Stable | Stable |

A clear difference in parameters between the PID controller before and after the use of PID tool module is evidently seen. The controlled designed by hit and trial method is stable but its settling time and overshoot is high due to which its response is slow whilst the controller whose tuning is performed by PID tool have small rise time and also small overshoot comprises with small settling point give the fast response of controller. The comparison Table is the AVR model with PID controller and PID TOOL If we compare the tuned model and un-tuned model it is clearly seen that the tuned model has very less settling time and less overshoot time as compared to the unturned model. Furthermore, it is seen that both the systems are stable but as observing overshoot percentage and high peaks of overshoots, the tuned model has a better response as compared to the un-tuned model.

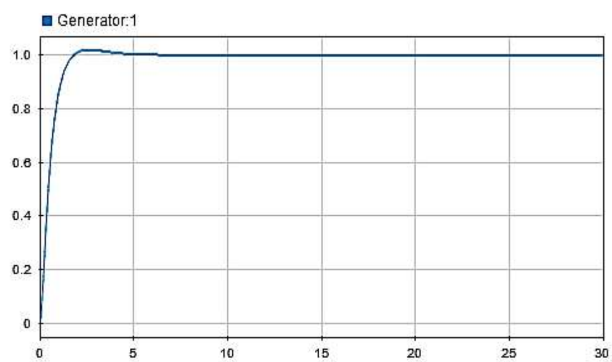


*Figure 18. Simulink results of AVR model comprises of PID Tool.*

### *4.1.2 Importance of PID*

Modifying the controller gain will result in stable gain and for getting a fast response the settling time is reduced, but this raises two major issues [22];

- Fast response gives rise to overshoot.
- Decreasing overshoot will increase the settling time and make the controller slow.

### *4.1.3 Limitation of PID*

In practice of a control system, the faster response is much more important that's why we use a faster response controller with a small settling time and moderate overshoot value. The slow controller is not used because it has zero overshoot and has less response rate [23]. PID controller have limitations in PID tuning parameters and it cannot change its perimeters simultaneously itself for different conditions [24].

### *4.1.4 Fuzzy Logic*

The fuzzy logic has a wide area of application in electrical engineering. Due to its diverse nature of fuzzy logic control, it is found applicable in every field of engineering. The meaning of Fuzzy is "not clear" or" blurred" which means that this logic control is applied to complex systems successfully whose mathematical formulation is not clear or not well defined. Initially, controlling techniques used Boolean algebra whose output is only in the form of 0 and 1 [7]. This technique does not provide wide applications due to this specific Range. Most of the practical applications are complex enough, and beyond the range of Boolean algebra. For this purpose, fuzzy Logic is designed that provides its range not only at 0 and 1 but also gives output between all the decimal points between 0 and 1 and so on. Basically the fuzzy Logic is the superset of Boolean algebra [25], [26]. Thus it is said that fuzzy Logic have the ability to provide best optimal control for all conditions as compared to PID control. Each system has inputs and outputs to control its response. Fuzzy Logic deals with these inputs and outputs. It consists of three steps fuzzification, Inference engine system and de-fuzzification [22]. The simple FLC block diagram is shown below;

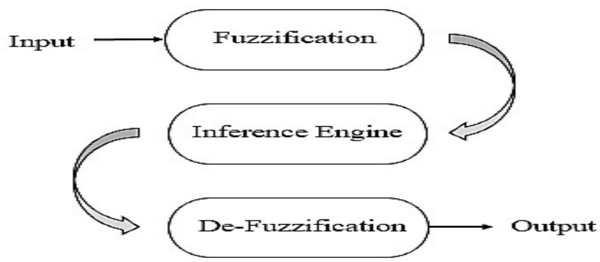


*Figure 19. Schematic flow of Fuzzifization.*

*4.1.5 Fuzzification*

It is the process of converting the numerical value into a linguistic variable (breaks into different part known as membership function). It is the measure of input variable which is going to be fed in FLC. In AVR model, when the load varies the speed of generator is effected that results in the variation of output voltage. By comparing output voltage and reference voltage, change in voltage is concluded. This change in voltage is the input of FLC and the excitation of rotor is the output of FLC [31]. As shown in Figure below, FLC model having input and output model is defined.

The input ranges between [0 1]. So, divide this input into various membership functions name as
EL =Change in voltage is extremely low = trapezoidal membership function= [0 0 0.1 0.2]
VL = Change in voltage is very low = triangular membership function= [0.1 0.2 0.3]
L = Change in voltage is low = triangular membership function= [0.2 0.3 0.4]
N= Change in voltage is normal = triangular membership function= [0.3 0.4 0.5]
H= Change in voltage is high = triangular membership function= [0.4 0.5 0.6]
VH = Change in voltage is very high = triangular membership function= [0.5 0.7 0.9]
EH = extremely high = trapezoidal membership function = [0.8 0.9 1 1]

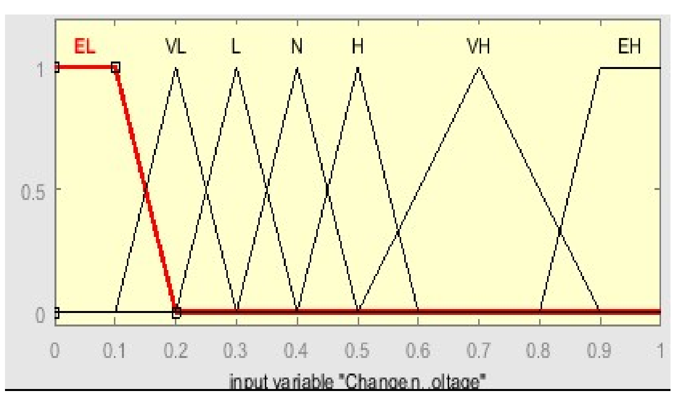


*Figure 20. Input membership function ranges.*

### *4.1.6 Fuzzy associat ive memory*

Fuzzy logic operates by using various Logic such as If then. The controller operates the input using the logics and generates the output. The membership function of the controller is trained with logics so the controller operates accordingly [3], [27]. As the truth table contains various inputs and accordingly the outputs, the memory of the controller contains the same type of mismatches. A simple voltage regulating strategy is; "When the change in voltage is low the excitation at the rotor should also be low"-

$$\Delta e = \Delta|V|_{ref} - \Delta|V|_t = 220 - 210 = 10V \tag{30}$$

In this case, the change in the voltage (Δe) is minimum, so the excitation of the rotor is low.

$$\Delta e = \Delta|V|_{ref} - \Delta|V|_t = 220 - 180 = 40V \tag{31}$$

In aforementioned case, the change in voltage is more as compared to the previous case hence the excitation at the rotor goes on increasing to make our system stable.

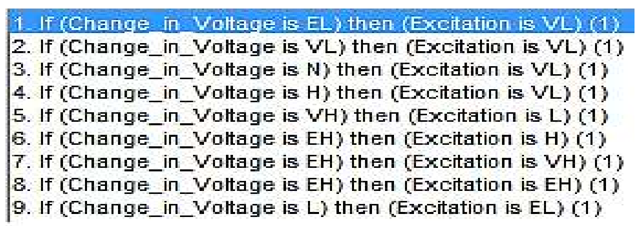


*Figure 21. Logic fed into FLC.*

### *4.1.7 De-Fuzzification*

It is the process of obtaining single crisp output from a set of linguistic values. In this part, the output is taken out in the form of excitation [7], [26]. The output of PID ranges from [0 8]. For the proper functioning, the controller has trained again by dividing our output into various membership functions.

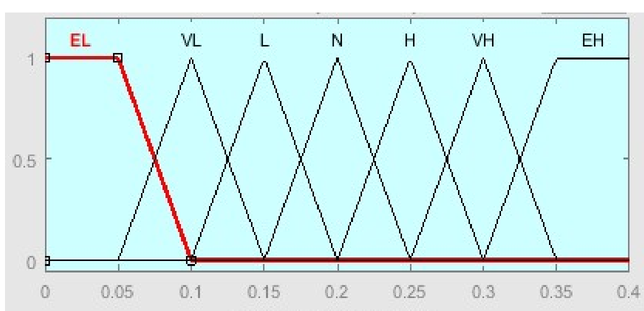


*Figure 22. Output membership function ranges for FLC.*

EL = Change in voltage is extremely low = trapezoidal membership function= [0 0 0.05 0.1]
VL = Change in voltage is very low= triangular membership function= [0.05 0.1 0.15]
L = Change in voltage is low=triangular membership function= [0.1 0.15 0.2]
N= Change in voltage is normal = triangular membership function= [0.15 0.2 0.25]
H= Change in voltage is high= triangular membership function= [0.2 0.25 0.3]
VH = Change in voltage is very high= triangular membership function= [0.25 0.3 0.35]
EH = extremely high= trapezoidal membership function= [0.3 0.35 0.4 0.4]
In De-Fuzzification different types of membership functions depend upon the nature of input and logic that is fed into the inference block of FLC.

### 4.1.8 Simulation of FLC

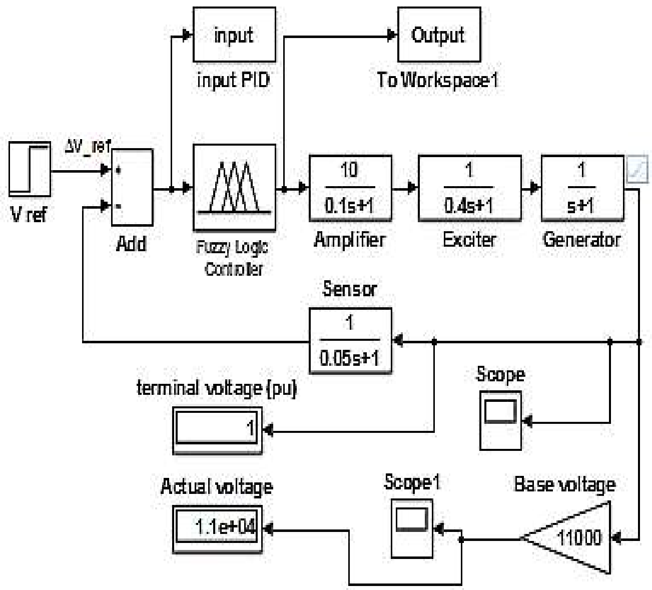


*Figure 23. Simulink model of AVR with FLC.*

The output of designed controller gives linearly stable output with zero overshoot and small rising as well as settling time. It gives purely linear output for the AVR model at 1 per unit.

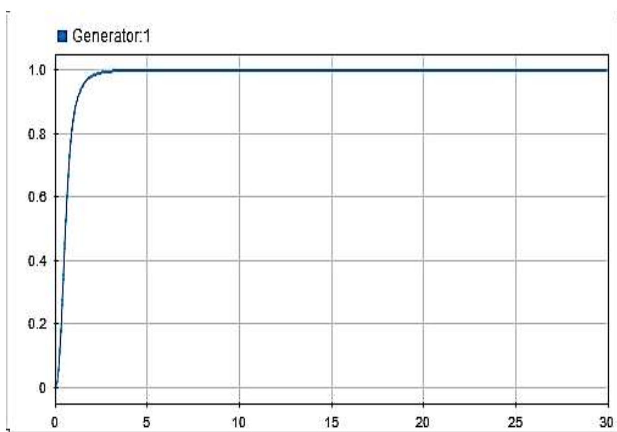


*Figure 24. Simulink results of AVR with FLC.*

## 5 Artificial Neural Network (ANN)

An artificial neural network is a computing system that is motivated by the human brain's analysis and transfer of information. Like fuzzy logic, there are various applications of artificial neural networks in emerging fields of engineering such as robotics and control systems as well as industrial automation. Due to its diverse nature, it is difficult to implement ANN [28], [29]. The aim of the ANN is to train and work like a human brain. Whereas it is not able to perform multiple tasks in a limited time like a human brain. The input is fed into ANN which passes through a number of iterations. This process continues until there is no error is left behind. The ANN system consists of three layers of neurons. These are input, hidden and output layers respectively. The number of neurons in each layer is adjusted according to the required data. The number of neurons in the input layer is set according to the number of inputs of the model. The input has a lot of samples for the better training of ANN [30]. A Block diagram of ANN is delineated below;

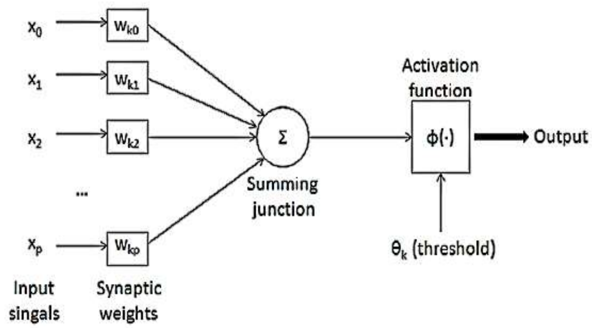


*Figure 25. Block diagram of ANN.*

*here,*
$X_j$ = Input signals to ANN
$W_{Kj}$ = synaptic weights = Strength of signals
$\theta_k$ = Threshold = Set of conditions or the activation function
$Y_k$ = Output of ANN
In the mathematical form, the above circuit diagram of ANN is written as $u_k = \sum_{j=1}^{p} W_{Kj} X_j$
This input signal is fed into the activation function block after executions of various techniques and output is generated that is –

$$Y_k = f(u_k - \theta_k) \tag{32}$$

It is the output of ANN which is the function of input minus threshold [30].

ANN does not require any mathematical equations for processing. It requires only input and output data. Based upon this data ANN goes into training process of learning and understanding the relationship between input and output data. Once the training is completed the ANN gives the output of the given input. For such purpose it is necessary to collect the input data for ANN from experimental and practical applications [31]. Collect the maximum number of samples and combined them to form a one input then initialize the ANN by the following MATLAB code [32];
Net = shows the ANN
newff = New feed forward ANN is executed
minmax(I)= min and max value of input data.
[1, 5, 1] = show no of neurons in input, hidden and output layers.
'logsig', 'tansig', 'purelin'}=activation functions of input, hidden and output layers of neurons chosen arbitrarily.
'trainlm' = It is a training algorithm (most common algorithm is Leven Berg-Marquardt propagation)
net = init(net); = initialize the ANN.
net.trainParam.show =1= The result of error is shown at each iteration.
net.trainParam.epochs = 1000= Shows no of Iterations.
net.trainParam.goal=1e-12=Thresh hold limit or conversion limits.
net=train(net, I, T)=Start training the network.

### *3.1 Simulink results of ANN*

All inputs and outputs from PID controller are fed into workspace. Then run the ANN code to initialize ANN;

```
I = Input';        T = Output';
net=newff(minmax(I), [1, 5, 1], {'logsig', 'tansig', 'purelin'}, 'trainlm');
net = init(net);   net.trainParam.show =1;
net.trainParam.epochs = 1000;   net.trainParam.goal =1e-12;
net= train(net, I, T);
```

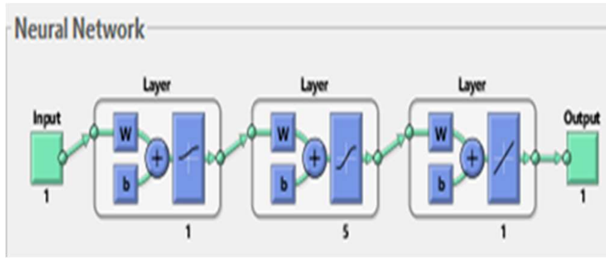


*Figure 26. Layers of ANN.*

Designing of ANN for single input and output, only single neuron in input and output layers of neuron is used. In the hidden layer, there is no such restriction for choosing the number of neurons. It depends on the output but for the starting training to trainee five neurons are the minimum used to trainee the ANN.

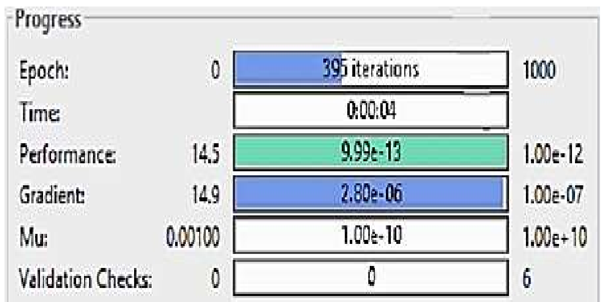


*Figure 27. Progress of ANN.*

The progress of ANN is clearly seen from Figure 16 that the ANN training is completed in the 395$^{th}$ number of iterations depending upon the input data and it took an extremely small time in training. It depends upon the complexity of the model. Stopping criteria or accuracy is set at $1.00e^{-12}$ and it was successfully achieved at the 395th iteration. The linear regression curve as shown in graph 8 is the important criterion for the successful training of ANN. ANN training is successfully completed when the regression curve is equal or nearly equal to 1. In the regression graph, the blue line is the ideal result of ANN while the scattered circles around the ideal line show the input data. Satisfactory results were achieved because since the input points are scattered around the ideal line as marked below;

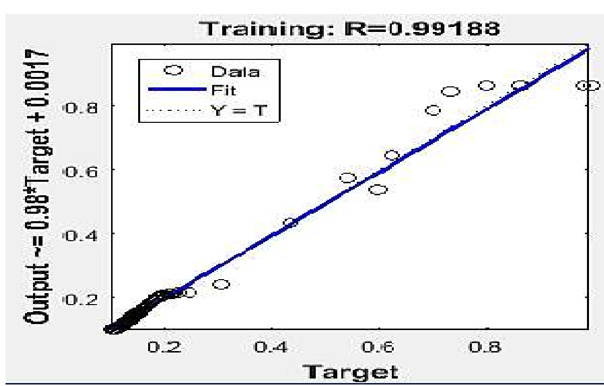


*Figure 28. Regression curve of ANN.*

For getting better results the no of neurons and number of iterations are changed arbitrarily to get satisfactory results and then import this trained ANN into the desired model by following the MATLAB command;
Genism (net, -1), Net = name of the trained ANN
-1 = sampling time for continuous-time simulations

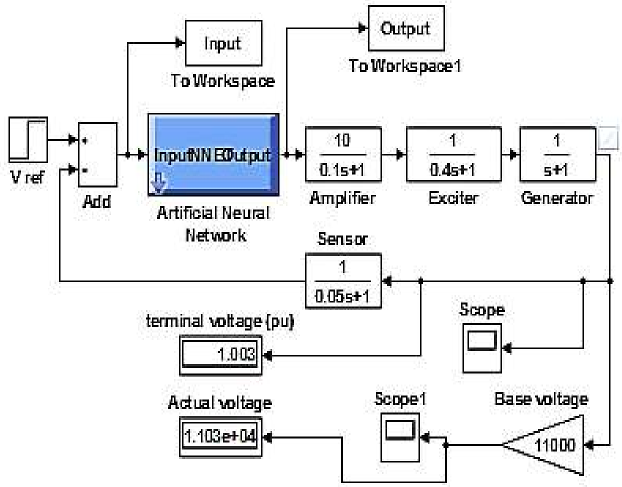


*Figure 29. Simulink model of AVR with ANN.*

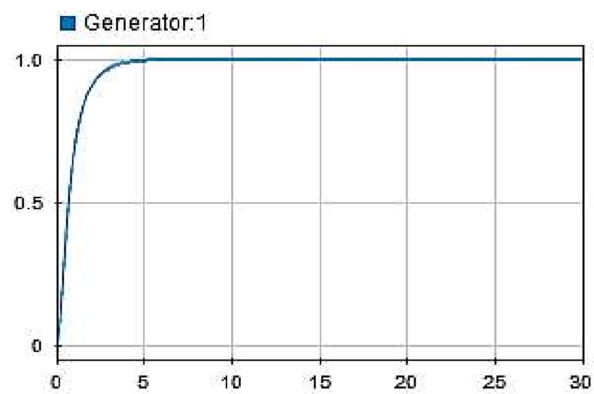


*Figure 30. Simulink results of AVR with ANN.*

The Simulink results show that the output of this model is at 1 per unit which means that the ANN controller is successfully designed. Furthermore, it is observed that the output of ANN line linearly stable and free from any oscillations and overshoot.

## 6 Comparison among PID, FLC and ANN Controller

Table 2 portrays the concise and clear comparison among the three controller techniques discussed in this paper i.e. PID, Fuzzy Logic and ANN. Table highlights the key features, advantages and limitations of these techniques [33].

*Table 2. Comparison of PID, Fuzzy Logic & ANN Controllers for AVR Systems.*

| Feature | PID Controller | Fuzzy Logic Controller (FLC) | ANN Controller |
|---|---|---|---|
| **Control Principle** | Proportional-Integral-Derivative action | Rule-based linguistic control | Data-driven, adaptive learning |
| **Tuning Method** | Manual hit-and-trial / MATLAB PID Tuner | Based on expert-defined rules | Self learned from data (training process) |
| **Design Complexity** | Simple | Moderate | High |
| **Overshoot** | High | Low | Minimal or zero |
| **Settling Time** | Long | Moderate | Shortest |
| **Adaptability to Load Changes** | Low | Medium | High |
| **Mathematical Model** | Required | Not Required | Not Required |
| **Performance Stability** | Oscillations under disturbances | Smooth but slower than ANN | Most stable |
| **Advantage** | Simplicity and reliability | Handles imprecise inputs | Self-learning, optimal performance |
| **Limitation** | Requires constant retuning for new conditions | Rule design complexity | Performance depends on training quality and data size |

The abovementioned Table summarizes the paper's core findings, demonstrating ANN is proposed superior choice for modern AVR systems as compared to its counterparts.

## 7 Conclusion

This paper comprises of brief information about AVR and performed its mathematical modeling to generate transfer functions of its units. Furthermore, to regulate the terminal voltage of AVR for synchronous generator various types of controllers have been designed in MATLAB Simulink to get desirable output voltage with minimum overshoot and settling time. After comparing results, it has been observed that ANN has better and more reliable performance due to its architecture as compared to PID and Fuzzy logic controllers. ANN performs better than PID and FLC in speed, stability and precision.

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