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Closed Loop Control of BLDC Motor Using Fuzzy Logic Controller

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Abstract: The growth of human civilization in the twenty-first century is hampered by two key challenges: energy and the environment. In recent years, energy costs have continued to rise, volatility has become more severe, public opinion on environmental protection has risen, applicable rules and regulations are more stringent, and "energy conservation" and "emission reduction" has become an urgent practical concern. As a result, utilizing new technology to reduce energy consumption and emission has become an important direction of automobile technology development, with pure EVs achieving zero emissions and low energy consumption, there is no doubt that they have become one of the most appealing solutions for energy savings and emission reduction. Hence EVs have been identified as the automobile industry's key trend in recent years. Small size, easier speed control, noiseless operation, high specific power and reduced thermal losses of Brush Less DC(BLDC) motor compared to the induction motor makes it more feasible in automotive industries. Most industrial applications employ conventional controllers to regulate the speed of BLDC motors, although it produces poor results in non-linear situations. To cater for nonlinear situations, that arise in real time, modern control techniques including Artificial Intelligence (AI) and Fuzzy Logic (FL) are gaining importance and lot of research is being conducted. A rule- based FL controller seems to be a better approach for the control of BLDC motors for EV applications as it increases the performance of drive system by using linguistic variables. In this paper, the FLC, PI and PID controllers for BLDC motors are simulated using MATLAB/Simulink and the results obtained from them are being presented in a tabular format.

***Index Terms* - Electric Vehicles, Fuzzy Logic Controller, Closed Loop Control, Classical controller, Rule base, Fuzzification, Defuzzification.**

I. INTRODUCTION

The two key issues in recent years are energy and the environment. The reserves of fossil fuels are rapidly depleting, while usage of fossil fuels is rapidly growing. This has resulted in the depletion of fossil fuels as well as an adverse impact on the ecosystem. The growing number of internal-combustion vehicles that utilize exhaustible conventional fuels has resulted in both energy and environmental problems. As a result, several nations have adopted EVs as alternatives to traditional vehicles in order to reduce dependency on oil and air pollution created by conventional automobiles. The selection of the appropriate electric motor is critical for electric vehicles. Various types of electric motors, such as DC motors, permanent magnet motors, induction motors, switched reluctance motors, and so on, have been used in electric vehicles.

Permanent Magnet Synchronous Motors (PMSM) and Permanent Magnet Brushless Direct Current Motors or also called as Brushless Direct Current Motors (BLDCM) are the two types of the Permanent Magnet motors. PMSM are the type of Permanent Magnet Motors with sinusoidal back EMF and the BLDCM are with the trapezoidal back EMF. The rotor of BLDM is made up of Permanent Magnet and the stator comprises of windings. Each phase of this motor is powered by the AC supply from the inverter which is fed from the DC supply. As the name stipulates the BLDC motors neither have brushes nor the commutators. The functionality of the brushes used in DC motors are replaced by the electronic control or a drive circuit to rotate the motor. These motors have various advantages like noiseless operation, longer life, better speed torque characteristics, higher speed range and hence used in many applications like automobile industries, home appliances, Aircraft, computers, robots and many more.

Despite many advantages the development of electronic control algorithm is convoluted as the commutation of the motor is depended on the rotor position. The two ways used to measure the rotor position are sensored and sensor less methods. Position sensors are used in the sensored method and usually the hall effect sensors are used to measure the position of rotors in many applications. In sensor less methods back EMF measurement, high frequency signal injection etc are used to sense the rotor position of the BLDC motor. Despite many advantages of sensor less technique it has many disadvantages like it is more complicated, consumes more computational time and requires processors with large amount of memory. Hence the sensor-based techniques are more preferable in the low speed and variable load conditions.

The closed loop control techniques are broadly classified into conventional control techniques and advance control techniques. The classical controllers include the Proportional, Proportional Integral, Proportional Integral Derivative Controllers. Fuzzy Logic based Controllers (FLC), Artificial Neural Network based controllers (ANN), Fuzzy-ANN based controllers are few of the examples of advanced control techniques. This paper deals with the comparative study of the classical control techniques (PI, PID) with the advanced fuzzy logic-based control.

II. CLOSED LOOP SPEED CONTROL TECHNIQUES

In general terms control action of the system is depended on the output is known as closed loop control system. In closed loop speed control, the control action is depended on the output speed. In sensor based closed loop speed control, a sensor measures the speed of the motor persistently and is used as the feedback for control action. There are many advantages of closed loop control over the open loop control like robustness, reduces the sensitivity for the disturbances, stable, more accurate.

There are various types of closed loop control techniques available to generate the PWM pulses for inverter circuit to control the speed of the motor. They are broadly classified as Classical Control techniques and advanced control techniques.

2.1 Classical Control Techniques

Classical control techniques are the most fundamental methodology which uses Proportional(P), Proportional Integral (PI), Proportional Integral Derivative (PID) type of controllers. These are considered as the base of the control techniques. These controllers are considered as the industry's most basic controllers for controlling linear systems and are the foundation of control theory.

2.2 Advanced Control Techniques

The advance Control techniques include the category of controllers like intelligent controllers, predictive control, Fuzzy Logic Controllers (FLC) etc. To cater for nonlinear situations, that arise in real time, modern control techniques including Artificial Intelligence (AI) and Fuzzy Logic (FL) are gaining importance and lot of research is being conducted. A rule- based FL controller seems to be a better approach for the control of BLDC motors for EV applications as it increases the performance of drive system by using linguistic variables.

III. FUZZY LOGIC CONTROLLER

Fuzzy logic controller is a control system, suitable for implementation on systems operated with varying values. The advantage of the controller is in the use of linguistic variables so that in design it does not require complicated mathematical equations. Several other reasons are it is easy to use, ready to model nonlinear conditions. Fig.1 shows the structure of Fuzzy Logic Controller, and it consists of fuzzification, inference engine, rule base, and defuzzification processes

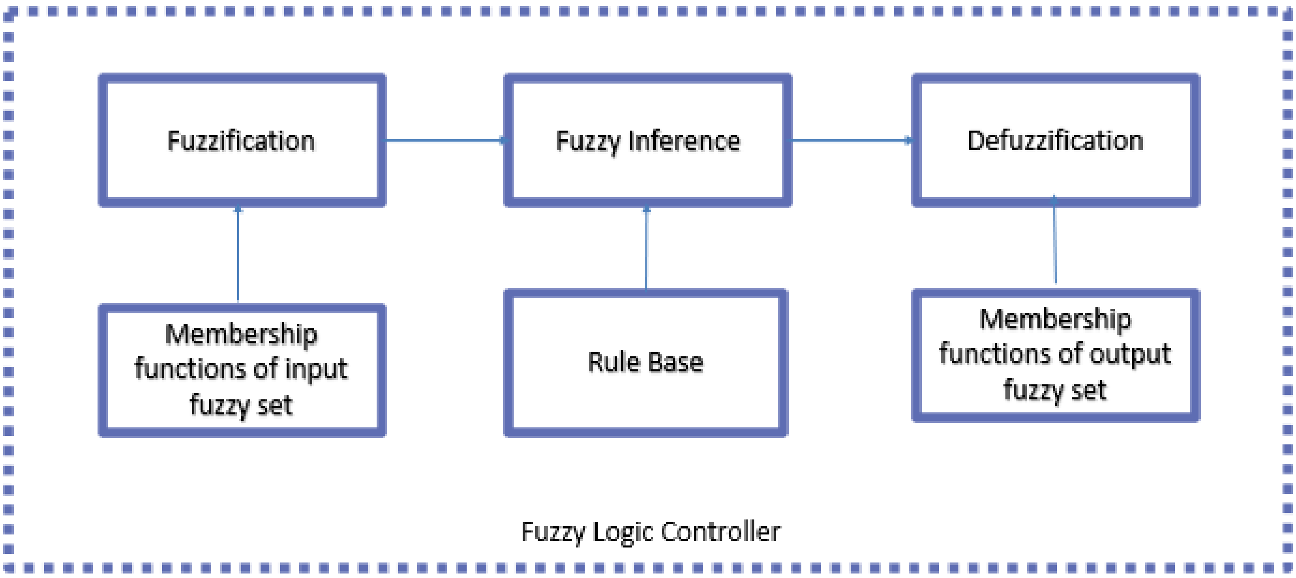

FIGURE1. BLOCK DIAGRAM OF FLC

3.1 Fuzzification

The fuzzification is the process of converting the crisp input values given to the controller into the fuzzy or the linguistic variables based on the membership functions. There are several types of membership functions like triangular, trapezoidal, gaussian etc.

3.2 Rule base

The rule base consists of the set of the rules required for the fuzzification process. The rule base is usually in the IF-THEN format. The rule evaluation is done based on the rule base and it is connected with the AND or OR operator.

3.3 Inference Engine

The inference engine responsible of generating the fuzzy output by applying the inference rules to the fuzzy input. The inference rules, in particular, are used to evaluate linguistic values and map them to a fuzzy set, which requires defuzzification to be transformed into a crisp value. There are two types namely Mamdani method and Sugeno method. These rules can be based on prior experiences, observations, and expert knowledge. Each fuzzy inference rule is made up of two concepts: if-then statements and linguistic variables. The if-then rules include the antecedents and the consequence, where the antecedent is the verbal input and the consequence is the linguistic output depending on the input.

3.4 Defuzzification

The output of the inference system is in the form of fuzzy variables. To convert the fuzzy output into the defuzzified or the crisp output the defuzzification is required. Some of the types of defuzzification methods are Centroid method, weighted average method, height method etc.

IV. Methodology of Proposed Work

The methodology and flow of the proposed work is as shown in the Figure 2.

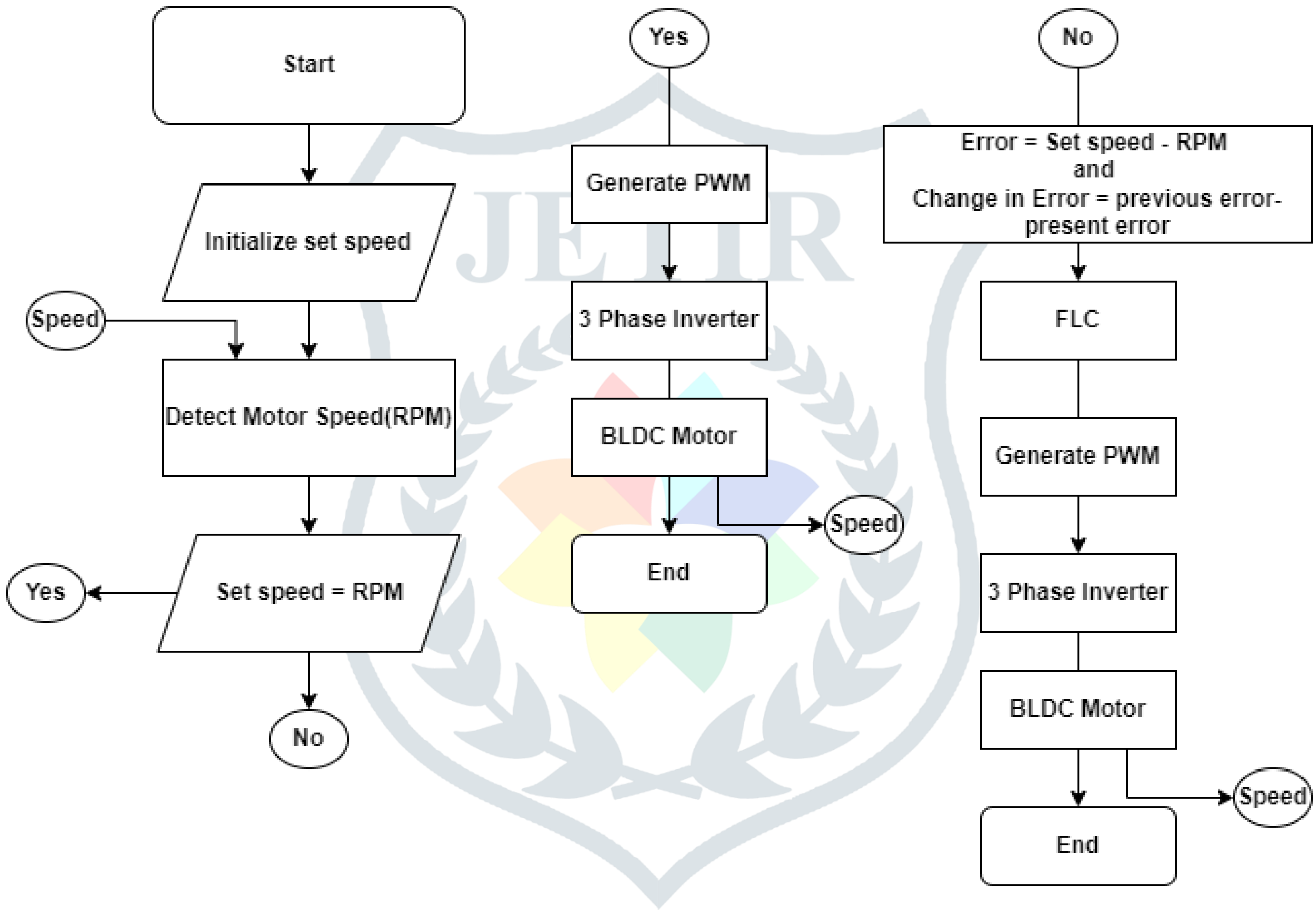

FIGURE 2. FLOW OF THE PROPOSED WORK

The project involves implementing a Fuzzy Logic Controller to regulate the speed of a BLDC motor. The BLDC motor's speed will be regulated by regulating the PWM pulses, which will control the power supplied to the motor. To begin, the required speed will be set. The sensor will determine the actual speed of the BLDC motor. For closed loop speed control, an intelligent fuzzy logic controller is used. If the actual and set speeds of the motor are the same, PWM pulses are generated and supplied to the 3-phase inverter for speed control.

If the actual speed and the motor's set speed differ, the error and change in error of the speed are computed and used as input to the FLC. The two inputs, error input and change in error, are considered to be triangle membership functions, each with seven membership values. In the fuzzification stage, these input values will be converted into linguistic variables or fuzzified values and sent into the inference engine. The values of error and change in error is calculated using the equation (1) and (2) respectively.

$$\text{Error (E)} = \text{Set Speed} - \text{Actual Speed} \quad (1)$$

$$\text{Change in error (CE)} = \text{Current error} - \text{Previous error} \quad (2)$$

Here the Mamdani fuzzy inference system is used where the rule evaluation is done using AND operator. The rules are fired according to the IF-THEN rules combined with the AND operator. The rule base consisting of 49 rules are as shown in the Table 1.

TABLE 1. RULE BASE

Error/change in error	DNB	DNM	DNS	Z	DPS	DPM	DPB
NB	ONB	ONB	ONB	ONB	ONM	ONS	OZ
NM	ONB	ONB	ONB	ONM	ONS	OZ	OPS
NS	ONB	ONB	ONM	ONS	OZ	OPS	OPM
Z	ONB	ONM	ONS	OZ	OPS	OPM	OPB
PS	ONM	ONS	OZ	OPS	OPM	OPB	OPB
PM	ONS	OZ	OPS	OPM	OPB	OPB	OPB
PB	OZ	OPS	OPM	OPB	OPB	OPB	OPB

Next step after the Inference is Defuzzification. Here the obtained fuzzified value is converted back into the crisp value by using the weighted average method. The weighted average method is formulated using the equation (3).

$$z = \frac{\sum_{i=1}^{n}(\mu i * ai)}{\sum_{i=1}^{n}\mu i} \tag{3}$$

From all these processes the controlled output will be obtained from the fuzzy logic controller. This controlled and defuzzied output will be used for the PWM generation. This PWM will be given to the Inverter in order to obtain the supply voltage required to control the speed of the BLDC Motor.

V. SIMULATION AND RESULTS

Figure 3 shows the simulation model of the speed control of BLDC motor using the Fuzzy Logic Controller. To validate the effectiveness of the controller and to compare its performance with the conventional controllers, the speed control of BLDC motor with PI, PID and FLC controller is simulated using MATLAB SIMULINK. Table.2 shows the components values considered for BLDC motor model.

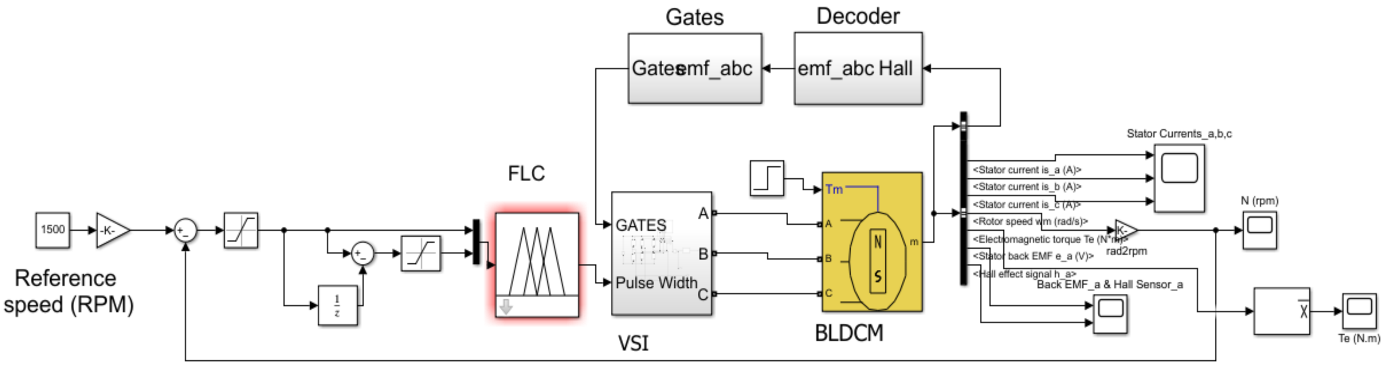

FIGURE 3. SIMULATION MODEL OF FLC

TABLE 2. PARAMETERS OF BLDC MOTOR MODEL

Parameter	Value
Stator Phase Resistance Rs	10.91
Stator Phase Inductance Ls	30.01e-3
Back EMF flat area in degrees	120
Inertia in kgm2	2 e-4
Viscous Damping	1e-3 N-m-s
Pole Pairs	4

As illustrated in Figure 4, the fuzzy system has two input variables: error, change in error and one output variable with triangle membership function was chosen. Each universe of discourse is divided into seven fuzzy sets such as Negative big (NB), Negative medium (NM), Negative small (NS), Zero (Z), Positive small (PS), Positive medium (PM), Positive big (PB).

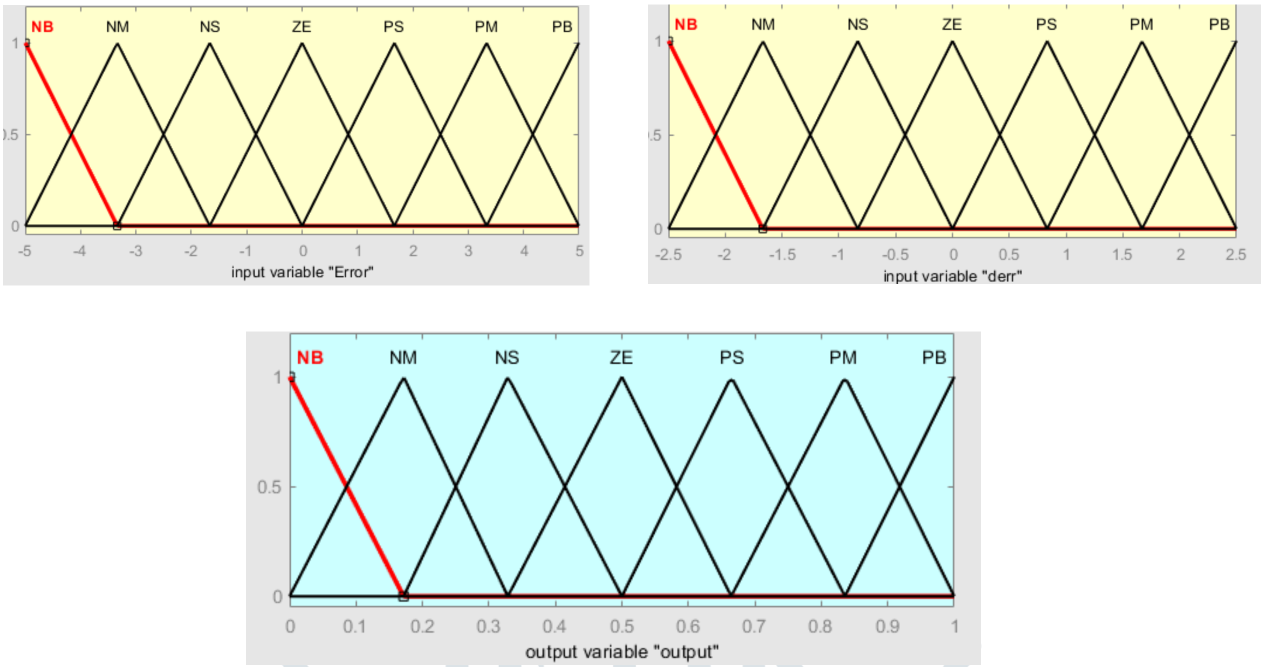

FIGURE 4. INPUT AND OUTPUT TRIANGULAR MEMBERSHIP FUNCTIONS

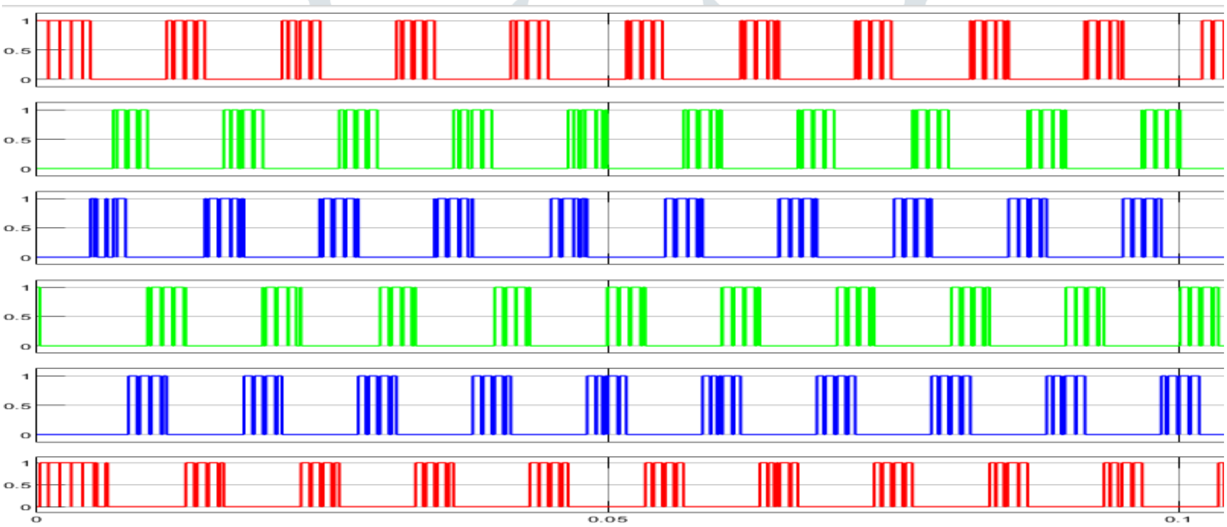

FIGURE 5. GATE SIGNALS

The Fig 7 and Figure 8 shows the stator currents and back emf of the motor. It is observed that the stator currents are quasi sinusoidal in shape and displaced by 120◦. The back EMF waveform depicts that it is displaced by 120◦ and of trapezoidal shape.

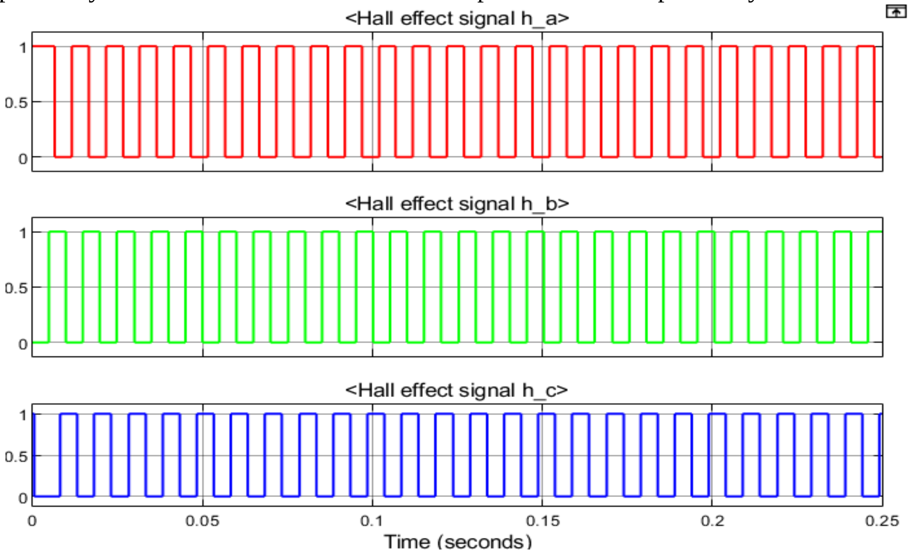

FIGURE 6. HALL EFFECT SENSOR OUTPUT

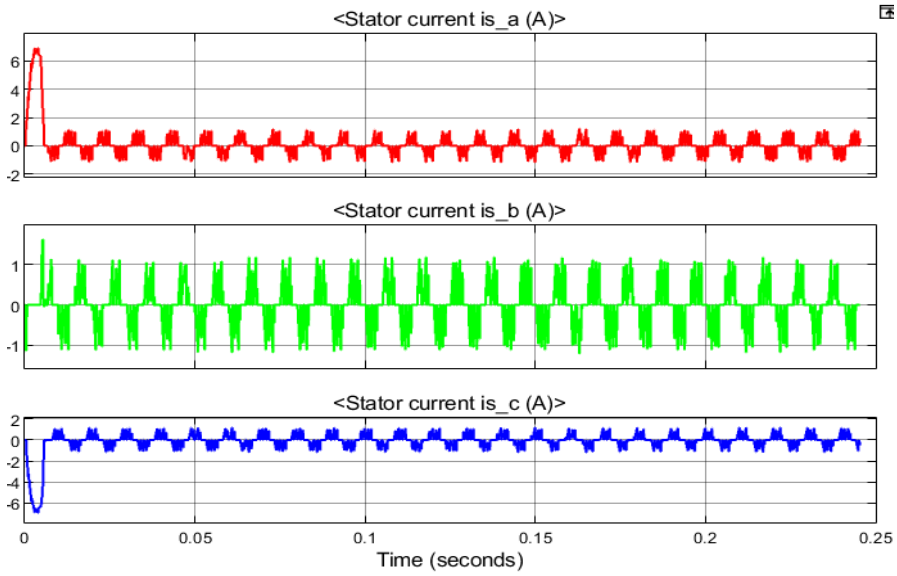

FIGURE 7. STATOR CURRENT OF DIFFERENT PHASES

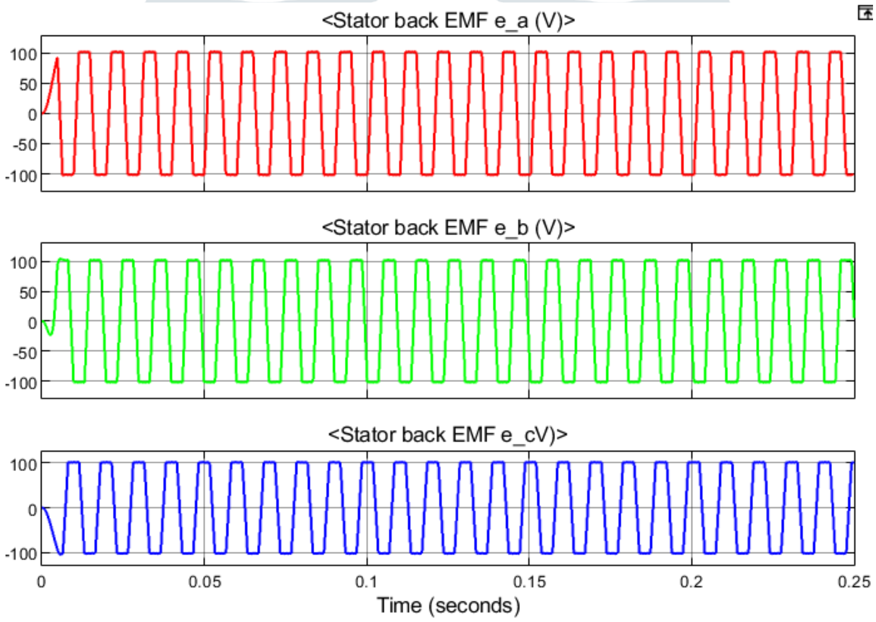

FIGURE 8. BACK EMF

The speed BLDC motor with a PI, PID, and FLC controller is shown in Figure 8. The PI controller is tuned with K_P =0.8, K_I= 0.02. PI controller gain values are K_P=0.0101, K_I =0.082, K_D =0.00026. In all circumstances, the motor achieves a speed of 1500 rpm, although with varying rising times, settling times, and stability.

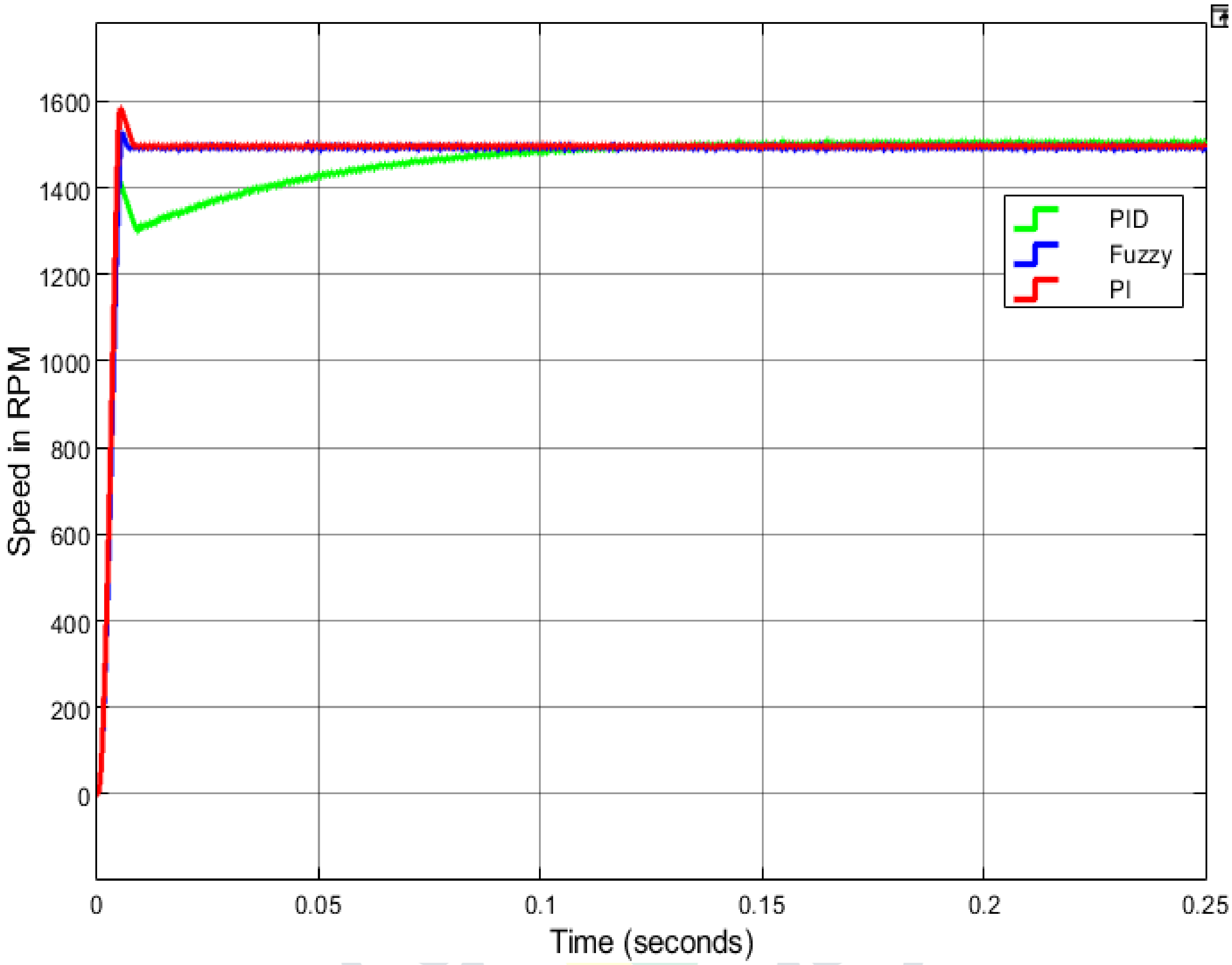

FIGURE 8. SPEED RESPONSE OF DIFFERENT CONTROLLERS

Table 3 shows the comparison of various operating conditions such as rise time, settling time, and overshoot percentage.

TABLE 3. COMPARISON OF VARIOUS OPERATING CONDITIONS OF THE CONTROLLERS

Controller	Preshoot In %	Overshoot in %	Undershoot in %	Settling Time in ms	Rise Time in ms
PI	0.532	5.851	1.998	4.228	3.010
FLC	0.515	2.577	1.997	2.801	3.309
PID	0.505	-1.516	2.595	95.549	3.061

VI. Conclusion

A Fuzzy Logic Controller based speed control of BLDC motor is presented in this paper. The results are compared with the conventional PI, PID controller. From the simulation results the BLDC motor reaches its reference speed with the settling time and rise time of 2.801ms, 3.309ms and a overshoot of 2.577% which is 4.228, 3.010 and 5.851% respectively in PI controller.
Hence the fuzzy logic controller is better than the PI Controller in terms of Overshoot and settling time but the PI controller seems to be better in terms of the rise time. The performance in terms of overshoot and the settling time can be further increased by using hybrid PI-Fuzzy Controller.

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