International Journal of Engineering, Management, Humanities and Social Sciences Paradigms (Volume 31, Special Issue of January 2019)
ISSN (Online): 2347-601X and Website: www.ijemhs.com

Comparison of the PID and Fuzzy Regulators as They Are Used in the Operation of a Brushless DC Motor

[1*] Mr.Pradosh Ranjan Parida, [2] Mr.Ajit ku Mohapatra
[1*] *Asst. Professor, Dept. Of Electrical Engineering, NIT BBSR,*
Asst. Professor DEPT. of Electrical Engineering, NIT BBSR,
pradoshranjan@thenalanda.com, , ajit@thenalanda.com

Abstract

This paper presents the results of research on speed regulation of a brushless DC motor. This is mainly a comparative study between a PID regulator and a fuzzy regulator applied to the operation of this type of engine in order to find the best control. The BLDC engine must operate under various speed and load conditions with improved performance and robust and complex speed control. This intricacy makes it challenging for the conventional PID command to regulate a BLDC's speed. Another control method is currently being developed and is working well. This fuzzy controller manages a process based on a set point per action on the variables that describe the process, which is how process control problems are dealt with. The brushless DC machine model will be researched in order to get the desired outcomes. Both sorts of regulators will be tested using the model that was obtained. The performance of the two types of regulators powering a BLDC can be assessed by a synthesis of the observed comparison data (Brushless DC).

Keywords

Fuzzy Logic Controller, PID Controller, Brushless DC Motor, DC Motor

1. Introduction

Industrial processes require precise regulation of the speed of the drive motors. To achieve this objective, a control based on electronic semiconductor variators was used for the DC motors. This technique consisted of varying the speed in proportion to the voltage. Due to the complexity of maintaining DC motors, recent applications rarely use this system. Thanks to advances in electronics, the development of brushless motors is booming in many fields of application and for powers up to a few tens of kilowatts. These permanent magnet synchronous type motors eliminate the drawbacks associated with the collector of direct current motors, and their performance surpasses that of asynchronous motors [1].

Knowing certain physical characteristics (speed, torque, position, current, etc.) is crucial for effective speed regulation in many industrial applications of BLDCs. Hence, a fuzzy, variable speed drive with PID type control is required for this. According to the study that has already been published in the literature, PID controls are probably the most frequently employed in industrial control direct current motors [2]. The fuzzy logic control is a non-linear control with resilience features at the same time. Exploring its potential for managing the brushless DC machine is highly intriguing [3].The main objective of this work is to compare the PID control to the fuzzy control for driving the brushless DC machine and thus determine the most robust control. The work presented in thisarticle is structured as follows: the first part presents the operating principle of the BLDC, the second part presents the modelling of the machine and the last part presents the results obtained after a simulation on MATLAB Simulink andthe discussions.

2. Principle of Operation of Brushless Motors

The brushless motor works from three variable voltage sources, supplied by an inverter, and allowing to generate a rotating magnetic field. The rotor, generally equipped with a permanent magnet, tends to follow the rotating magnetic field. **Figure 1** shows the architecture of the motor and its inverter.

In the simple case of the BLDC motor, at each switching, two phases are respectively connected to the supply voltage and to the ground, and one phase is not connected. Let us take the example of **Figure 2**, phase A is not connected, phase B is connected to the supply voltage and phase C is connected to ground.

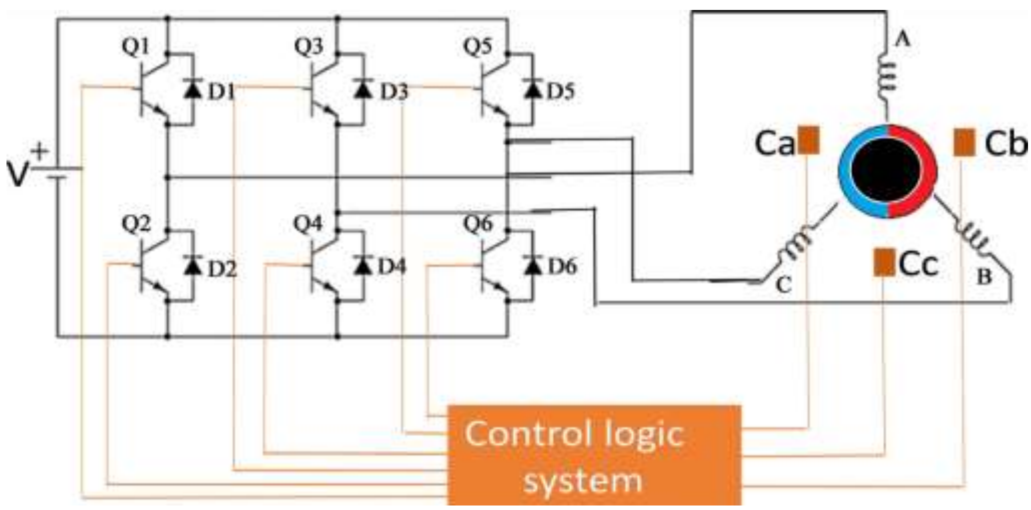

Figure 1. Operation of the inverter and brushless motor.

Figure 2. Example of switching situation.

A current flows through the coils from B to C and generates a stator magnetic fiel $\boldsymbol{B}$ in the next steered motor $\boldsymbol{y}_S$. The rotor supports a magnet whose magnetic moment $\boldsymbol{m}$, oriented from south to north, tends to align with the stator magnetic field by rotating counter clockwise.

As soon as the rotor approaches $\boldsymbol{y}_S$, the commutation will be modified to make the current flow from B to A, the stator magnetic field $\boldsymbol{B}$ rotates by π/6, so as to attract the rotor and continue the rotation in the counter clockwise direction. The angle between $\boldsymbol{m}$ and $\boldsymbol{B}$ leads to a magnetic torque $\boldsymbol{C}_m = \boldsymbol{m} \wedge \boldsymbol{B}$ [4].

3. Modelling

The modeling of a BLDC motor can be developed in the same way as a three-phase synchronous machine. As its rotor is mounted with a permanent magnet, these dynamic characteristics remain different. The flux due to its rotordepends on the magnet, which is why the saturation of the magnetic flux is typi-cal for these motors. A BLDC motor is powered by a three-phase voltage source, as shown in **Figure 1**. The source does not need to be sinusoidal. A square waveor other waveform can be applied as long as the peak voltage is less than the maximum voltage of the motor. Likewise, the armature winding scheme of the BLDC motor is represented in **Figure 3** [5] [6].

Electrical Equations

Expressions of the Voltages

By applying the mesh law to the BLDC, we obtain the following system [7]

$$V_a(t) = Ri_a(t) + L_a \frac{\mathrm{d}i_a(t)}{\mathrm{d}t} + e_a(t) \quad (1)$$

Figure 3. BLDC's motor supplied by a three-phase voltage source.

$$V_b(t) = Ri_b(t) + L_b \frac{di_b(t)}{dt} + e_b(t) \quad (2)$$

$$V_c(t) = Ri_c(t) + L_c \frac{di_c(t)}{dt} + e_c(t) \quad (3)$$

With *R*, *L* and (i_a, i_b and i_c) are respectively: the resistor, inductance and currents of stator's phase.

$$e_a = f_a(\theta) \cdot K_e \cdot \omega_r \text{, the electromotive force of phase A} \quad (4)$$

$$e_b = f_b\left(\theta - \frac{2\pi}{3}\right) \cdot K_e \cdot \omega_r \text{, the electromotive force of phase B} \quad (5)$$

$$e_c = f_c\left(\theta - \frac{4\pi}{3}\right) \cdot K_e \cdot \omega_r \text{, the electromotive force of phase C} \quad (6)$$

K_e: is the coefficient of force electromotive; $f_a(\theta)$, $f_b\left(\theta - \frac{2\pi}{3}\right)$ and $f_c\left(\theta - \frac{4\pi}{3}\right)$: are the functions whom depend only on the position of the rotor; ω_r : is the rotation speed θ : is the electrical angle which is calculated as follows $\theta = p\omega_r$ with *p* the number of pole.

The Writing voltage's matrix is written:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (7)$$

By applying the transform of Laplace we get:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R + L \cdot p & 0 & 0 \\ 0 & R + L \cdot p & 0 \\ 0 & 0 & R + L \cdot p \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (8)$$

The Equations (1)-(3) allow determining the voltage's expressions between phases:

$$V_{ab}(t) = V_a(t) - V_b(t) = R\left[i_a(t) - i_b(t)\right] + L\left[\frac{di_a(t)}{dt} - \frac{di_b(t)}{dt}\right] + e_a(t) - e_b(t) \quad (9)$$

$$V_{bc}(t) = V_b(t) - V_c(t) = R\left[i_b(t) - i_c(t)\right] + L\left[\frac{di_b(t)}{dt} - \frac{di_c(t)}{dt}\right] + e_b(t) - e_c(t) \quad (10)$$

(6) and (7) give: $V_{ca}(t) = V_{bc}(t) - V_{ab}(t)$ (11)

Expressions of the Currents

We get the expression of the currents below from Equations (9)-(11)

$$\frac{di_a(t)}{dt} = \frac{2}{3L}V_{ab}(t) + \frac{1}{3L}V_{bc}(t) - \frac{R}{L}i_a(t) - \frac{1}{3L}e_{bc}(t) - \frac{2}{3L}e_{ab}(t) \quad (12)$$

$$\frac{di_b(t)}{dt} = \frac{1}{3L}V_{bc}(t) - \frac{1}{3L}V_{ab} - \frac{R}{L}i_b(t) - \frac{1}{3L}e_{bc}(t) + \frac{1}{3L}e_{ab}(t) \quad (13)$$

$$\frac{di_c(t)}{dt} = -\left(\frac{di_a(t)}{dt} + \frac{di_b(t)}{dt}\right) \quad (14)$$

3.1.3. The Electromagnetic Torque

The electric torque generated by the BLDC is given like this:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} \quad (15)$$

By replacing the Equations (4)-(6) within (15) we have:

$$T_e = K_e\left[f_a(\theta)i_a + f_b\left(\theta - \frac{2\pi}{3}\right)i_b + f_c\left(\theta - \frac{4\pi}{3}\right)i_c\right] \quad (16)$$

Mechanical Equation

The dynamics of the rotor is defined as see:

$$\frac{d\Omega}{dt} = \frac{1}{J}\left(T_R - T_e + f\Omega\right) \quad (17)$$

Model of Hall Effect Sensors

When the rotor poles pass next to the hall effect sensors, the latter give 1 or 0

Table 1. Hall effect sensor model.

Electric Angle	Phase	Hall Effect sensors			Phase current			State of switches	
		H1	H2	H3	Ia	Ib	Ic		
0° - 60°	1	1	0	1	+	-	off	Q1	Q4
60° - 120°	2	1	0	0	+	off	-	Q1	Q6
120° - 180°	3	1	1	0	off	+	-	Q3	Q6
180° - 240°	4	0	1	0	-	+	off	Q3	Q2
240° - 300°	5	0	1	1	-	off	+	Q5	Q2
300° - 360°	6	0	0	1	off	-	+	Q5	Q4

only to indicate that the north or south pole is seen by the sensors. Based on this switching logic of the hall effect sensors, we have the switching sequence of the transistors according to **Table 1** [8].

The Inverter Model

The inverter is a static converter able to transform the electrical energy from a DC voltage source into AC, the use of inverters is very wide in industry, such as variable speed drives for three-phase motors, emergency power supplies, etc.

By the technological development of semiconductors, and the appearance of new control techniques, inverters have become more efficient. On the other hand, the output voltage form of an inverter must be closer to a sinusoid for which the harmonic rate is as low as possible, the latter largely depends on the control technique used [9]. We can see in **Figure 4** the three-phase inverter model.

The switches Q1 and Q2, Q3 and Q4, Q5 and Q6 must be complementary whatever the control law that is adopted. And whatever the currents, the switches give the voltages between the output terminals A, B, C and the (fictitious) midpoint "O" of the voltage source [10].

$$\begin{aligned} V_a - V_o &= \frac{V_s}{2} \text{; if Q1 is closed and } V_a - V_o = -\frac{V_s}{2} \text{; if Q2 is opened} \\ V_b - V_o &= \frac{V_s}{2} \text{; if Q3 is closed and } V_b - V_o = -\frac{V_s}{2} \text{; if Q4 is opened} \\ V_c - V_o &= \frac{V_s}{2} \text{; if Q5 is closed and } V_c - V_o = -\frac{V_s}{2} \text{; if Q6 is opened} \end{aligned} \quad (18)$$

The equilibrium of the system entails:

$$\begin{cases} I_a + I_b + I_c = 0 \\ V_a + V_b + V_c = 0 \end{cases} \quad (19)$$

$$\begin{cases} V_a = \frac{1}{3}(U_{ab} - U_{ca}) = \frac{1}{3}\left[(V_a - V_b) - (V_c - V_a)\right] \\ V_b = \frac{1}{3}(U_{bc} - U_{ab}) = \frac{1}{3}\left[(V_b - V_c) - (V_a - V_b)\right] \\ V_c = \frac{1}{3}(U_{ca} - U_{bc}) = \frac{1}{3}\left[(V_c - V_a) - (V_b - V_c)\right] \end{cases} \quad (20)$$

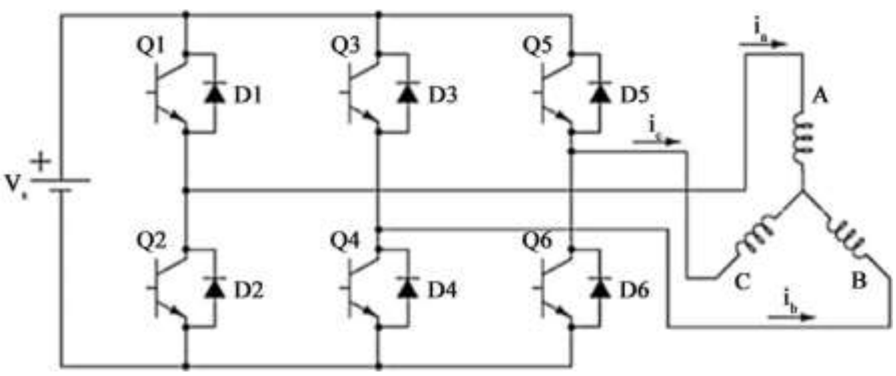

Figure 4. Inverter.

According to the circuit in the figure below, the three-phase voltages can be calculated using the following formulas

$$\begin{cases} V_a = Q_1 \dfrac{V_s}{2} - Q_2 \dfrac{V_s}{2} \\ V_b = Q_3 \dfrac{V_s}{2} - Q_4 \dfrac{V_s}{2} \\ V_c = Q_5 \dfrac{V_s}{2} - Q_6 \dfrac{V_s}{2} \end{cases} \tag{21}$$

3.5. BLDC Transfer Function

Considering a motor winding seen in **Figure 5**, we can write the following relations

$$V = Ri + L\frac{\mathrm{d}i}{\mathrm{d}t} + e \tag{22}$$

which give:

$$e = V - Ri - L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{23}$$

The transfer function is finally written:

$$G(P) = \frac{\frac{1}{K_e}}{\frac{RJ}{K_t K_e}\frac{L}{R}P^2 + \frac{RJ}{K_t K_e}P + 1} \tag{24}$$

The following constants are acquired:

- Electric constant $\tau_e = \frac{L}{R}$
- Mechanical constant $\tau_m = \frac{RJ}{K_t K_e}$

In the BLDC motor, it has 3 phases, *i.e.* the mechanical and electrical constants are written like this: $\tau_e = \frac{L}{3R}$ and $\tau_m = \frac{3RJ}{K_t K_e}$.

Therefore, the transfer function of the BLDC motor can right now be obtained as the following equations:

$$G(P) = \frac{\frac{1}{K_e}}{\tau_e \tau_m P^2 + \tau_m P + 1} \tag{25}$$

With the engine parameters we have

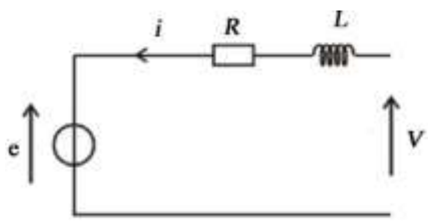

Figure 5. Model of phase.

$$G(P) = \frac{331}{0.0058P^2 + 0.250P + 1}$$

4. Comparative Study and Simulation

Simulation with the PID Regulator

Figure 6 shows the model of the closed loop PID regulator from this model the equation below is drawn

$$u = K_P e(t) + K_i \int e(t)\mathrm{d}t + K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \qquad (26)$$

Figure 7 and **Figure 8** show the results of simulation obtained with the PID

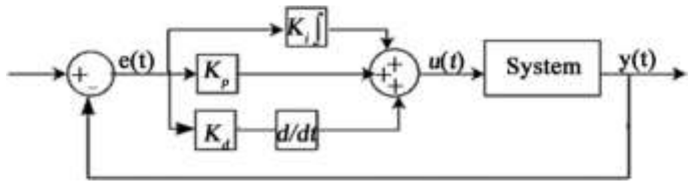

Figure 6. Closed loop PID controller.

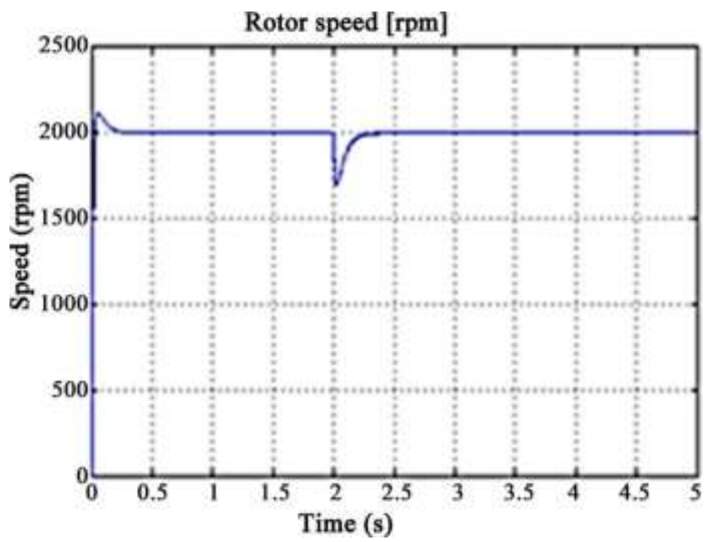

Figure 7. Rate of speed.

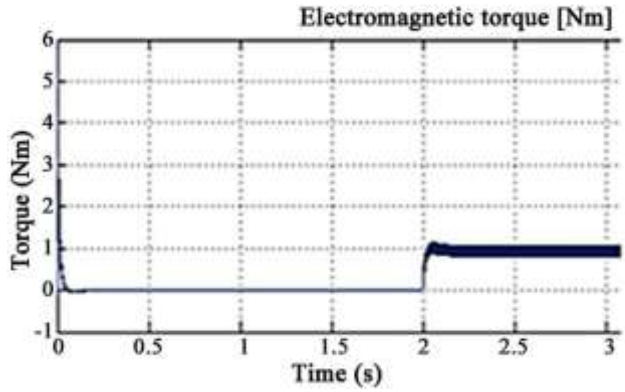

Figure 8. Rate of electromagnetic torque.

controller. When starting, the speed reaches the imposed value with a response time Trep = 0.029 seconds and an overshoot of 5.85%, at the moment 0.06 seconds, the speed decreases towards the set point (2000 rpm) that it attends to the after 0.351 seconds then it perfectly follows the imposed instruction.

The application of a torque of 1 Nm implies a disturbance of 15% at the instant 2 seconds which corresponds to a speed of 1699 rpm; then returns to the set point after 2.43 seconds.

Simulation with Fuzzy Logic

Fuzzy logic is widely used in machines for control purposes. The term fuzzy designates the logic which deals with the concept which expresses that the value is true or false. Fuzzy logic has many advantages as it gives a solution to a problem in such a way that a human operator can easily understand it and can use it to design a better controller. The design of such a controller makes the process faster and it has become easy to implement it in the system [6] [7] [9].

The internal structure of this fuzzy regulator is shown in the following functional diagram of **Figure 9**.

The rules used are:

1) IF E is GN and de is GN THEN control is GN

2) IF E is MN and de is MN THEN control is GN

The fuzzy rules are built manually in **Table 2**.

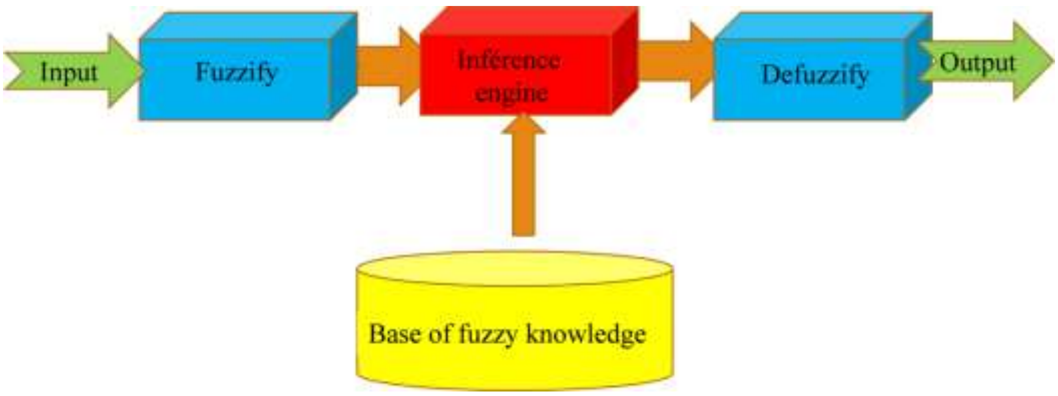

Figure 9. Synoptic overview of a fuzzy system.

Table 2. Table of fuzzy rules.

de \ E	GN	NZ	ZZ	PZ	GP
GN	GN	GN	NZ	NZ	ZZ
NZ	GN	NZ	NZ	ZZ	PZ
ZZ	NZ	ZZ	ZZ	PZ	PZ
PZ	NZ	NZ	ZZ	PZ	GP
GP	NZ	PZ	PZ	GP	GP

Z: zero, MP: positive mean and GP: large positive.

The diagram below (**Figure 10**) shows the Simulink model of BLDC motor control with fuzzy logic.

Figure 11 and **Figure 12** show the results of simulation obtained with the fuzzy logic. When starting, the speed reaches the imposed value with a response time Trep = 0.0051 seconds and an overshoot of 0%, and it perfectly follows the imposed set point (2000 rpm). The application of a torque of 1 Nm implies a disturbance of 15% at the instant 2 seconds which corresponds to a speed of 2020 R/s; then returns to the set point after 2.4 seconds.

Comparison of the two commands

Below (**Figure 13**) are the speed curves for the two types of control. By observing the results of these curves, we see that the behavior of the two regulators is identical during permanent modes, but the Flou regulator has a clear advantage:

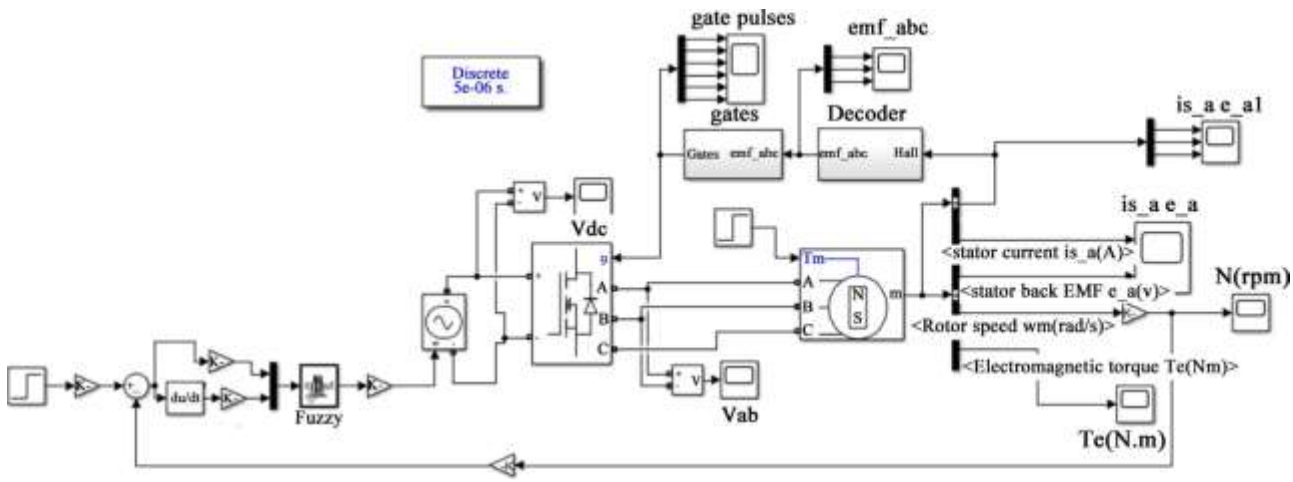

Figure 10. BLDC model with the BLUR command.

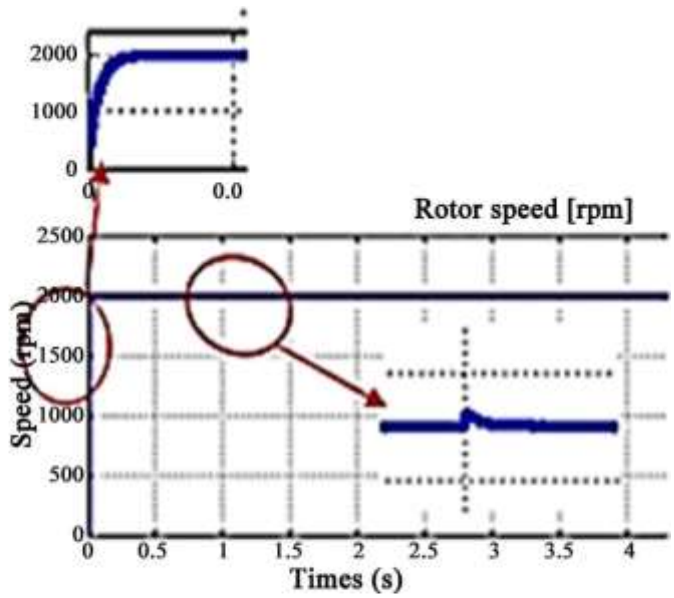

Figure 11. Pace of speed.

Figure 12. Pace of torque.

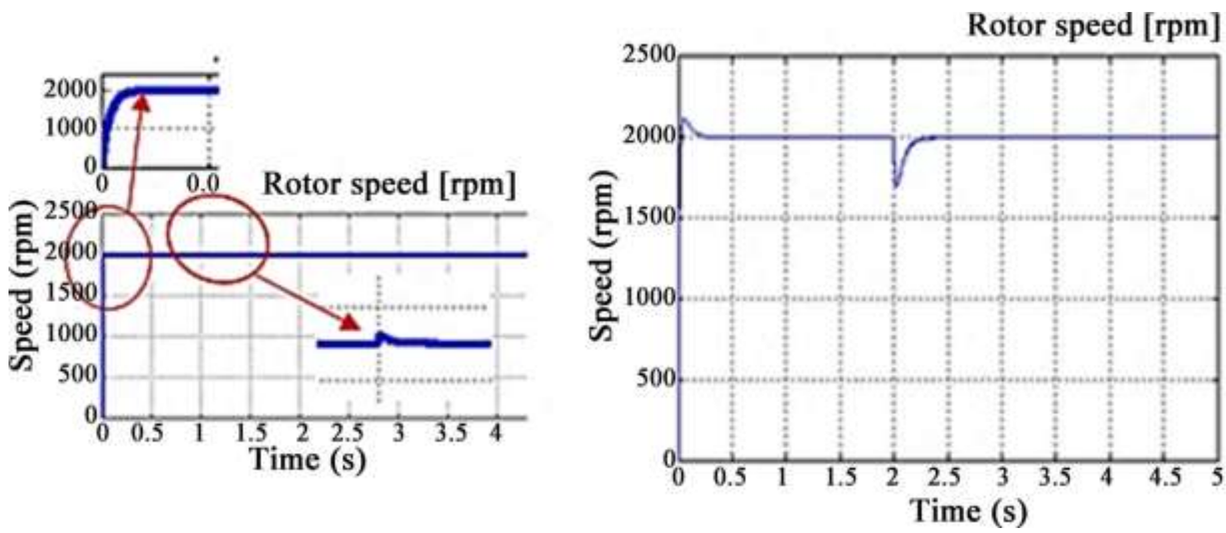

Figure 13. Speed response.

-Better climb time.

-A quick response without overspending.

-The disturbance peaks are much less important with the Flou regulator.

5. Conclusions

In this study, a brushless DC motor was subjected to the PID regulation method and the fuzzy logic regulation approach. To compare the strength of these two methods of control, this is done. After research and simulation using Matlab/Simulink, we came to extremely pleasing conclusions. They demonstrate that the fuzzy regulator, which has a shorter rise time and no over-shoot, provides superior responses than the PID regulator. Despite its effectiveness, the fuzzy regulator is still less commonly employed in industry than the PID regulator because of implementation issues.

However, it is worth highlighting the perspectives that remain open by studying the system, namely, pushing further reflection on the implementation of these two regulators on the same microcontroller or an Arduino Board.

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