Abstract-- this paper presents a comparison between a fuzzy gain adaptive controller and a conventional PI controller used for speed control of a Brushless DC motor (BLDCM) or electronically commutated (ECM). First, we establish a dynamic model for direct current to the input of the switch that the electromagnetic torque of BLDCM is proportional to this current. This model is intended to facilitate the procedures for setting and controlling the current, and an adaptive PI controller is proposed for the speed control of BLDCM in the presence of the variations parametric. A fuzzy-Type 1 inference system is used to adjust in real-time the controller gains. The obtained results show the efficacy of the proposed method.

Index Terms-- brushless DC motor, direct current model, Type-2 Fuzzy Logic Control, speed control.

I. INTRODUCTION

Recently, the DC motors have been gradually replaced by the BLDC motors since the industrial applications require more powerful actuators in small sizes. Elimination of brushes and commutators also solves the problem associated with contacts and gives improved reliability and enhances life. The BLDC motor has the low inertia, large power to volume ratio, and low noise as compared with the permanent magnet DC servo motor having the same output rating [1]-[3].

In general, the BLDCM is supplied through a three-phase inverter transistor that acts as the electronic switch of the phase current, the control of the torque is then up to a current control \( i_d \) [4]. The control of the phase currents required since the reconstitution of these currents which is not easy. It is easier to directly control of the current. In most cases using a voltage inverter current controlled. As the engine torque is proportional to the DC input of the switch where the interest to influence the form of the current to optimize torque and to minimize the current [5]. The control strategy based on PI gain scheduling, a number of methods have been proposed in the literature for PID gain scheduling [6] a stable gain-scheduling PID controller is developed based on grid point concept for nonlinear systems. Different gain scheduling methods were studied and compared [7, 8], a new PID scheme is proposed in which the controller gains were scheduled by a fuzzy inference scheme. Many method and research works in this domain in [9-12]. The interested readers can find a brief review of different fuzzy PID structures in [13].

The remainder of this paper is organized as follows. In section I, the model of three-phase BLDCM Section II develops the dynamic model. Section III is devoted to the PI gain adaptive control based on the type-2. The simulation results to demonstrate the effectiveness of the proposed approach is presented in Section IV, Finally in the conclusion are set out the essential findings of this work.

II. EQUATIONS OF ELECTRICAL AND MECHANICAL OF BLDCM

The model simplified of the BLDCM is shown in figure 1:

For a symmetrical winding and a balanced system (Fig. 1), the vector of voltages across the three phases of the BLDC motor is given by:

\[
\begin{bmatrix}
 v_a \\ v_b \\ v_c 
\end{bmatrix} = \begin{bmatrix}
 0 & R & 0 \\
 0 & 0 & R \\
 0 & 0 & 0 
\end{bmatrix} \begin{bmatrix}
 i_a \\ i_b \\ i_c 
\end{bmatrix} + \begin{bmatrix}
 L-M & 0 & 0 \\
 0 & L-M & 0 \\
 0 & 0 & L-M 
\end{bmatrix} \begin{bmatrix}
 \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} 
\end{bmatrix}
\]

(1)

Where \( v_a, v_b, \) and \( v_c \) are the phase voltages of the BLDCM, \( i_a, i_b, \) and \( i_c \) are the phase currents, \( R \) and \( L \) are the resistance and inductance of the machine, \( e_a, e_b, \) and \( e_c \) are the electromotive forces of the phases. The electric torque is given by:

\[
C_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_c}
\]

(2)

Where \( C_e \) is the electromagnetic torque.

III. MODELING OF THE BLDCM

Figure 2 show the schematic diagram for controlling the BLDCM:

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We will make the following assumptions:

- The six transistors $T1$, $T2$, $T3$, $T1'$, $T2'$ and $T3'$ have identical characteristics. In the state "OFF" and in the state "ON" are respectively represented by an infinite impedance and threshold voltage $v_T$ in series with a dynamic resistance $r_T$.

- Similarly, it is assumed that the diodes $D1$, $D2$, $D3$, $D1'$, $D2'$ and $D3'$ has an infinite impedance in the state OFF and in the state ON are threshold voltage $v_D$ in series with a dynamic resistance $r_D$.

- The model of the machine is generally established in a landmark three-phase $(a, b, c)$ related to the stato r due to the trapezoidal shape of the FCEM. For a symmetrical machine winding connected in star and whose permanent magnets are mounted on the surface [14].

This model can be written as follows:

$$
\begin{align*}
V_a &= R_i a + L_c \frac{d}{dt} i_a + e_a \\
V_b &= R_i b + L_c \frac{d}{dt} i_b + e_b \\
V_c &= R_i c + L_c \frac{d}{dt} i_c + e_c
\end{align*}
$$

(3) (4) (5)

Depending on the position of the inductor, the current $i_d$ is switched in phase at the time the trapezoidal FCEM in this phase has its flat part positive or negative “Fig. 3”, “Fig. 4”.

Figure 2. Block diagram for controlling the BLDC motor

Figure 3. Control pulses of transistors for the direct sense.

a. Current $i_a$ and FCEM $e_a$ and pulses $T1$ and $T1'$

b. Current $i_b$ and FCEM $e_b$ and pulses $T2$ and $T2'$

c. Current $i_c$ and FCEM $e_c$ and pulses $T3$ and $T3'$
Figure 4. Control pulses of transistors for reverse rotation

From the signals of the Hall sensors, the sequence is generated by choosing a sequence of notice pulses of transistors well defined “Fig. 3”, “Fig. 4”, there are 6 distinct intervals noted \( iT \). The opening of the 2 transistors of an arm of the electronic switch produces the conduction of a diode \( D_p \) and \( D_n \). This corresponds to setting a series of phase with the remaining 2 in parallel in these intervals are denoted \( ID \) and \( ID' \).

IV. CONTINUOUS MODEL OF BLDC MOTOR

Is characterized by two distinct modes:

A. DC1 Mode

DC1 mode corresponds to the two phases in series “Fig.5”:

In this case the voltage node checks:

\[
\begin{align*}
\mathbf{u}_d & = \mathbf{u}_1 - \mathbf{u}_2 \\
\end{align*}
\]  

Where \( \mathbf{u}_1 \) and \( \mathbf{u}_2 \) are respectively represented the voltage of the neutral point to positive terminal and the voltage of the neutral point to the negative terminal of the continuous bus.

\[
\begin{align*}
\mathbf{u}_1 &= \mathbf{V}_a + \mathbf{v}_r + \mathbf{r}_d \\
\mathbf{u}_2 &= \mathbf{V}_b - \mathbf{v}_r + \mathbf{r}_k \\
\end{align*}
\]  

By replacing \( \mathbf{v}_a \) and \( \mathbf{v}_b \) their respective expression (3) and (4), as \( i_a = i_d \) and \( i_b = -i_d \), \( \mathbf{u}_1 \) and \( \mathbf{u}_2 \) are given by:

\[
\begin{align*}
\mathbf{u}_1 &= \mathbf{R}_d + L_c \frac{di_d}{dt} + e_a + \mathbf{v}_r + \mathbf{r}_d \\
\mathbf{u}_2 &= -\mathbf{R}_d + L_c \frac{di_d}{dt} + e_b - \mathbf{v}_r - \mathbf{r}_d \\
\end{align*}
\]  

Therefore \( u_d \) is given by:

\[
\begin{align*}
\mathbf{u}_d &= 2(\mathbf{R} + \mathbf{r})i_d + 2L_c \frac{di_d}{dt} + (e_a - e_b) + 2\mathbf{v}_r \\
\end{align*}
\]  

For the two phases in series, the FCEM present their party platform in opposition, so we have:

\[
\begin{align*}
e_a &= e_b = E = k_e |\omega_r| \\
\end{align*}
\]  

With \( k_e \) the coefficient of the FCEM and \( \omega_r \) the rotation speed of the motor. Finally in this mode dynamics DC1 current \( i_d \) is expressed by:

\[
2L_c \frac{di_d}{dt} = \mathbf{u}_d - 2(\mathbf{R} + \mathbf{r})i_d - 2E - 2\mathbf{v}_r \\
\]  

B. DC2 Mode

In this mode, a phase in series with the other two phases in parallel “Fig.5”:

This mode is then \( iTj \) intervals, we assume that the dynamic resistances of the components are identical:

\[
\mathbf{r}_r = \mathbf{r}_D = \mathbf{r} \\
\]  

In this case the dynamics of the current \( i_d \) check in DC2 mode: are given by:

\[
3L_c \frac{di_d}{dt} = 2\mathbf{u}_d - 3(\mathbf{R} + \mathbf{r})i_d - 2E - 3\mathbf{v}_r + \mathbf{v}_D \\
\]  

V. FUZZY TYPE-1 GAIN-ADAPTIVE STRATEGY

Conventional PI controllers are is a generic control loop feedback mechanism (controller) widely used in industrial control systems.
They are simple and easy to use due to the fact that they do not need any mathematical model of the controlled process or complicated theories. But one of the main drawbacks of these controllers is that there is no certain way for choosing the control parameters which guarantees the good performance.

Although PI controllers are robust against structural changes and uncertainties in the system parameters, their performance may be affected by such changes or may even lead to system instability. Therefore in real world applications these gains need to be fine-tuned to keep the required performance.

To overcome this shortcoming, Fuzzy Type-1 Gain Adaptive PI Controller is used to tune PI gains online where the tracking error and the change of the tracking error are used to determine control parameters.

The control scheme for BLDCM using the Fuzzy Type-1 Gain-Adaptive controller is presented in Figure 7.

A set of linguistic rules in the form of (15) is used in the Fuzzy Type-1 Gain Adaptive PI Controller structure:

\[ \text{if } e(k) \text{ is } A_i \text{ and } \Delta e(k) \text{ is } B_i \text{ then } K_p \text{ is } C_i \text{ and } K_i \text{ is } D_i \] (15)

Where \( A_i, B_i, C_i \) and \( D_i \) are fuzzy sets corresponding to \( e(k), \Delta e(k), K_p \) and \( K_i \), respectively. The membership functions for the input are defined with the Gaussian shapes (Figure 8), and the output variables \( K_p \) and \( K_i \) with the singleton shapes (Figures 9 and 10).

All the fuzzy sets for input and output values are normalized for convenience.

Table 1 and 2 show the linguistic rules used in the Fuzzy Gain Adaptive PI Controller. In these tables, N, B, M, represent negative, big and medium for the outputs function and NB, NM, NS, ZE, PS, PM, PB represent negative, big, medium, negative medium, negative small, zero, positive small, positive medium, and positive big respectively for the inputs function.

In this work, the controller fuzzy rules are gathered in Table 1 and 2.
The generated surfaces for the Fuzzy Gain Adaptive PI Controller are shown in Figure 11 and 12.

The machine used is characterized by the following:

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>resistance of phase</td>
<td>$R$</td>
<td>4Ω</td>
</tr>
<tr>
<td>phase inductance</td>
<td>$L_c$</td>
<td>0.002H</td>
</tr>
<tr>
<td>inertia constant</td>
<td>$J$</td>
<td>4.65e-6kg.m²</td>
</tr>
<tr>
<td>Back-EMF Constant</td>
<td>$k_e$</td>
<td>26.1e-3V/rd.s-1</td>
</tr>
<tr>
<td>coefficient of friction</td>
<td>$k_f$</td>
<td>1.5e-606N.m/rd.s-1</td>
</tr>
<tr>
<td>supply voltage</td>
<td>$u_n$</td>
<td>24(V)</td>
</tr>
<tr>
<td>rated current</td>
<td>$I_n$</td>
<td>1(A)</td>
</tr>
</tbody>
</table>

The power components are modeled by conduction regime threshold voltages and resistances following dynamics: $v_T=0.8 \, (V), v_D=0.8 \, (V), r_T=0.075 \, \Omega, r_D=0.05 \, \Omega$. The motor control is based on the cascade structure of Figure 2 and 7; the output $I_c$ of the speed controller PI-add and the current setting $i_d$ is made by the regulator PI and provides the signal $u_c$. The test of control by Fuzzy Gains PI adaptive and PI controllers is performed to a level of speed value $(150 \, \text{rd/s})$ for the direct sense during the time interval $[0s, 0.02s]$ and then applying a zero reference $\omega_{ref}=0$ in the interval $[0.02s, 0.035s]$. The nominal load torque $0.5N.m$ and parametric perturbations are applied throughout the test.

![Figure 11. Surface for $K_p$](image1)

![Figure 12. Surface for $K_i$](image2)

![Figure 13. Response of the motor using PI controller](image3)
and proposed method with error of \( \text{ref} \) is saturated to the value \( I \). We note that reference negative either the current \( (t = 0.02 \text{ at } t = 0.035) \)

\[ I \text{ref} \text{ is necessary to compensate the load torque. During operation mode of the motor } I_d \text{ is positive } (t=0s \text{ to } t=0.02s), \text{ it follows strong reference } I_{\text{ref}}. \]

In braking mode where the current \( I_d \) is negative either \( (t = 0.02 \text{ at } t = 0.035) \), the current \( I_d \) does not reference \( I_{\text{ref}} \) because of the low kinetic energy of the machine.

**VII. CONCLUSION**

In this paper, the speed regulation of BLDCM with two controllers, traditional PI and Fuzzy Gain Adaptive PI controllers has been designed and simulated. To do this, we have established the dynamic model of the DC input of the switch. The comparative study shows that the Fuzzy Gain Adaptive IP controller can improve the performances of speed of the BLDCM control. The simulation results have confirmed the efficiency of the Fuzzy Gain Adaptive PI controller for different working conditions.

**REFERENCES**


