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Modified Direct Torque Control for Permanent Magnet Synchronous Motor Drive Based on Fuzzy Logic Torque Ripple Reduction and Stator Resistance Estimator

A. Ameur*, B. Mokhtari*, N. Essounbouli**, F. Nollet**

* Materials Laboratory (LEDMaSD), Electrical Engineering Department, Laghouat University, BP 37G, Ghardaia Street, Laghouat (03000), ALGERIA, (e-mail: amaissa1@yahoo.fr)
** Reims University, Center of Research in Science and Technologies of Information and Communication 10026 Troyes CEDEX, FRANCE (E-mail: najib.essounbouli@univ-reims.fr.)

Abstract: The two important disadvantages of Direct Torque and Flux Control (DTC), are torque and flux ripples and stator resistance variation (which affects seriously the estimation stator flux and electromagnetic torque). This paper proposes a fuzzy-logic based DTC (FLC) using modified switching table for permanent magnet synchronous motor (PMSM) and Fuzzy-logic Resistance Estimator. The high-performance of the proposed FLC applied to PMSM drive, are investigated and compared with traditional DTC. The proposed system has proven successful in controlling the instantaneous torque so as not to depend only on the estimation flux, torque and position, but also on variable amplitude torque hysteresis bands and stator resistance ($r_s$) delivered by fuzzy-logic.

Keywords: DTC, PMSM, FLC, Switching table, Torque and flux ripples, Stator resistance estimator.

1. INTRODUCTION

Recently, the areas of industrial application of high performance AC drives are considerably expanded with the development of power electronics, Microelectronics and computer Engineering. Indeed, technological developments have permitted alternative machines, especially the synchronous machine; to acquire the control suppleness and high dynamic performance naturally obtained, (Boussak, 2005). In addition, depth research has led to the development of the new materials, such as permanent magnets based on rare earths, (Kadjoudj et al., 2007). These allow obtaining synchronous machines which are compared to other types of DC machines, synchronous with electrical excitation and asynchronous many advantages, among others, low inertia and high power density and efficiency, (Zhong et al., 1999). They are currently the best placed to meet the requirements of applications such as robotics, machine tools, space technology (actuators aviation, satellites) and general embedded systems.

DTC offer high advantages performances in terms of simplicity control scheme and a very good torque dynamic response, as well as the fact that it does not need the rotor speed or position to realize the torque and flux control. Moreover, except stator resistor, DTC is not sensitive to parameters variations, (Takahashi and Ohmori, 1989).

In the classic DTC the employment of the hysteresis controllers to regulate the stator magnetic flux and torque is natural to have high torque ripples and variable switching frequency, which is varying with speed, load torque, selected hysteresis bands and difficulty to control torque and flux at very low speed. It also results in higher acoustical noise and in harmonic losses, (Wang et al., 2008).

The variation of $r_s$ due to changes in temperature or frequency degrade the performance of DTC controller by introducing errors in the estimated flux linkage magnitude, position and the electromagnetic torque, (Haque and Rahman, 2001). So the compensation for the effect of $r_s$ variation then becomes necessary, (Ameur et al., 2010).

In this paper, two fuzzy-logic (FL) are proposed to overcome the problem of torque and flux hysteresis bands with variable amplitude based on switched table, in over hand the effect of $r_s$ variation is discussed and the $r_s$ is estimated by FL estimator using the error between the reference and actual stator flux linkage. The performance of the controller is examined by extensive simulation studies, which shows that the drive system becomes unstable if the $r_s$ value used in the controller differs at real resistance.

2. PMSM MODEL

The stator and rotor flux equation of PMSM can be written in the reference frame of Park, in the following form:

$$
\begin{bmatrix}
\dot{\phi}_d \\
\dot{\phi}_q
\end{bmatrix} = 
\begin{bmatrix}
L_d & 0 \\
0 & L_q
\end{bmatrix} 
\begin{bmatrix}
I_{sd}
I_{sq}
\end{bmatrix} + 
\begin{bmatrix}
\phi_e \\
0
\end{bmatrix}
$$

(1)

In this same reference, the stator voltages equations are written in the following form:

$$
\begin{bmatrix}
\nu_{d} \\
\nu_{q}
\end{bmatrix} = 
\begin{bmatrix}
L_d & 0 \\
0 & L_q
\end{bmatrix} 
\begin{bmatrix}
I_{sd}
I_{sq}
\end{bmatrix} + 
\begin{bmatrix}
0 \\
-pL_q
\end{bmatrix} I_{sm} + 
\begin{bmatrix}
0 \\
-pL_q
\end{bmatrix} I_{av}
$$

(2)
In addition the electromagnetic torque can be expressed by:

$$T_e = \frac{3}{2} p \left( (I_d - L_s) I_d + I_q + \omega_0 I_q + \omega_0 I_q \right)$$

(3)

The motor mechanical equation can be expressed as follows:

$$J \ddot{\Omega} = T_e - T_I - f_\Omega \Omega$$

(4)

3. CONVENTIONAL DTC

The methods of DTC as shown in figure 1 consist of directly controlling the turn OFF or turn ON of the inverter switches on calculated values of stator flux and torque from relation (6). The changes of state of the switches are linked to the changes in electromagnetic state motor. They are no longer controlled based on voltage and frequency references given to the commutation control of a pulse width voltage modulation inverter, (Mokhtari et al., 2009). The reference frame related to the stator makes it possible to estimate the stator flux (magnitude and argument) and torque. The aim of the switches control is to give the vector representing the stator flux the direction determined by the reference value.

$$\phi_{s\alpha} = \int (v_{s\alpha} - r_{s\alpha}) \, dt$$

$$\phi_{s\beta} = \int (v_{s\beta} - r_{s\beta}) \, dt$$

(5)

The DTC is deduced based on the two approximations described by the formulas (6) and (7):

$$\bar{\sigma}_s(k + 1) \approx \bar{\sigma}_s(k) + \bar{V}_s T_e \rightarrow \Delta \bar{\sigma}_s \approx \bar{V}_s T_e$$

$$T_e \approx k (\bar{\sigma}_s \times \bar{\sigma}_s) = k |\bar{\sigma}_s| \sin(\delta)$$

(6)

(7)

Moreover:

$$\dot{\phi}_s = \sqrt{\dot{\phi}_{s\alpha}^2 + \dot{\phi}_{s\beta}^2}$$

$$\angle \phi_s = \arctg \frac{\dot{\phi}_{s\beta}}{\dot{\phi}_{s\alpha}}$$

(8)

Fig. 1. Diagram of DTC control applied for PMSM supplied with a three-phase inverter with PWM.

A two levels classical voltage inverter can achieve seven separate positions in the phase corresponding to the eight sequences of the voltage inverter, (Takahashi and Ohmori, 1989).

Fig. 2. Different vectors of stator voltages provided by a two levels inverter.

Where:

$I(D)F$ : Increase (Decrease) of Flux amplitude.

$I(D)T$ : Increase (Decrease) of Torque.

Table 1. Vectors voltage localization.

<table>
<thead>
<tr>
<th>$\Delta \phi_i$</th>
<th>$\Delta T_e$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
<th>$S_5$</th>
<th>$S_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>101</td>
<td>100</td>
<td>110</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>001</td>
<td>101</td>
<td>100</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td></td>
</tr>
</tbody>
</table>

4. DTC MODIFIED

The same principle of basic DTC control of the PMSM, which is supplied by a two-level inverter, is applied for the other ST.

All sectors are shifted by an angle of 30° leading to an angle of the first sector between 0° and 60° as shown in figure 3.

Fig. 3. Different vectors of stator voltages, in case of table with sectors shifted by 30°.

The difference between a DTC with a simple switching table and that with sectors shifted is summarized in table 2.
Table 2. Comparison between the simple table and the table with sectors shifted by 30°.

<table>
<thead>
<tr>
<th>Traditional DTC</th>
<th>Modified DTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>$-30^\circ \rightarrow 30^\circ$ Torque undetermined</td>
</tr>
<tr>
<td>$V_2$</td>
<td>$30^\circ \rightarrow 90^\circ$ IT, IF</td>
</tr>
<tr>
<td>$V_3$</td>
<td>$90^\circ \rightarrow 150^\circ$ IT, DF</td>
</tr>
<tr>
<td>$V_4$</td>
<td>$150^\circ \rightarrow 210^\circ$ Torque undetermined</td>
</tr>
<tr>
<td>$V_5$</td>
<td>$210^\circ \rightarrow 270^\circ$ DT, DF</td>
</tr>
<tr>
<td>$V_6$</td>
<td>$270^\circ \rightarrow 330^\circ$ DT, IF</td>
</tr>
</tbody>
</table>

Table 3 presents the switching table when the sectors are shifted by 30°. We can see the difference from the conventional DTC in the third and the fourth lines for conventional switching table, (Mokhtari et al., 2012).

Table 3. Switching table of DTC with shifting 30°.

<table>
<thead>
<tr>
<th>$\Delta \phi$</th>
<th>$\Delta T_e$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
<th>$S_5$</th>
<th>$S_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>100</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
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<tr>
<td>0</td>
<td>0</td>
<td>011</td>
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<td>101</td>
<td>100</td>
<td>010</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>100</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td></td>
</tr>
</tbody>
</table>

5. REDUCTION OF ELECTROMAGNETIC PMSM TORQUE RIPPLES USING CONTROLLERS BASED ON FUZZY LOGIC

The basic idea is to replace bands flux and torque controllers hysteresis desired by bands issued by FLC. The value of the change in the speed error can be used for measuring or estimating the torque smoothing, (Zidani and Nait Said, 2005).

The equation of mechanical motor neglecting viscous friction is:

$$ J \frac{d\Omega}{dt} = T_e - T_i \tag{9} $$

Replacing the error speed $e = \Omega - \Omega_{ref}$ in equation (9), we find:

$$ J \frac{d(\Omega_{ref} + e)}{dt} = J \frac{d\Omega_{ref}}{dt} + J \frac{de}{dt} = T_e - T_i \tag{10} $$

For a constant reference speed and a constant load, the change of the error speed is related to motor torque by:

$$ \frac{de}{dt} = \frac{T_e - T_i}{J} \tag{11} $$

From (11), we can conclude that the change of speed error signal can indeed be a good measure and a good indicator of motor torque ripple.

We will present in the following a fuzzy approach dedicated to reducing torque ripples.

A fuzzy controller seems to be a reasonable choice to evaluate the hysteresis bands of the torque and flux amplitude, (Adam et al., 2007).

In this approach, the hysteresis bands of torque and flux are not prefixes, but they are determined by two fuzzy controllers. Figure (4) shows the two adapted controllers torque and flux hysteresis bands.

![Fig. 4. Adapted fuzzy bands torque and flux hysteresis controller.](image)

Based on the proposed analysis and the diagram above, two inputs are chosen, error rate speed and stator current, variations:

$$ e_i(k) = \Omega_s(k) - \Omega_{ref}(k - 1) \tag{12} $$

$$ e_s(k) = i_s(k) - i_{s,ref}(k - 1) \tag{13} $$

The magnitude of the stator current is deduced from the following relation: $i_s = \sqrt{i_{s,a}^2 + i_{s,b}^2}$.

The net output (with a hysteresis band appropriate) is integrated in such a way that the amplitude of the hysteresis band of the torque and flux is obtained from the following two equations:

$$ b_{\tau}(k) = b_{\tau}(k - 1) + \Delta b_{\tau}(k) \tag{14} $$

$$ b_{\phi}(k) = b_{\phi}(k - 1) + \Delta b_{\phi}(k) \tag{15} $$

The fuzzification of input variables and outputs of the two fuzzy controllers is shown in figure (5).
Fig. 5. Fuzzy controller inputs and outputs membership functions.

Table 4. Linguistic rules base for two PI-Type fuzzy-logic controllers.

<table>
<thead>
<tr>
<th>$e_1$</th>
<th>$e_2$</th>
<th>PB</th>
<th>PM</th>
<th>PS</th>
<th>ZE</th>
<th>NS</th>
<th>NM</th>
<th>NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$P$</td>
<td>$P$</td>
<td>$PS$</td>
<td>$ZE$</td>
<td>$NS$</td>
<td>$NS$</td>
<td>$N$</td>
<td></td>
</tr>
<tr>
<td>$ZE$</td>
<td>$P$</td>
<td>$P$</td>
<td>$PS$</td>
<td>$ZE$</td>
<td>$NS$</td>
<td>$N$</td>
<td>$N$</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>$P$</td>
<td>$NS$</td>
<td>$PS$</td>
<td>$ZE$</td>
<td>$NS$</td>
<td>$N$</td>
<td>$N$</td>
<td></td>
</tr>
</tbody>
</table>

For example, for $e_1$ Positive Big (PB), and a variation $e_2$ Positive (P), then $\Delta b_{Te}$ must be Positive (P) as well. In this case, the overshoot in the torque error can touch the upper band which will lead us to select a reverse voltage vector. This will cause a rapid reduction in torque but slow response torque below the hysteresis band, (Zidani and Nait Said, 2005). Thus, $\Delta b_{Te}$ should not be Positive Small (PS) but positive ($P$), to avoid this situation.

6. EFFECT OF STATOR RESISTANCE VARIATION

The unknown of $r_s$ may have several origins. They may be due to an incorrect identification of the parameters of the machine, change in the load or the temperature of the surroundings. Because an incorrect value of the $r_s$ certainly causes an error estimation of the stator flux module its position. It can cause serious problems in the choice of voltage vector to apply, (Tang et al., 2002). Several studies have been proposed for this estimate to address the problem of variation of $r_s$ (Mir et al., 1998), . In this section we will propose to illustrate the influence of this variation, and then we present a block estimate that compensates each variation of $r_s$, using a fuzzy-logic controller.

In DTC drive, the stator flux is estimated by integrating the difference between the input voltage and the voltage drop across the $r_s$, as given by equation (5).

$$\phi_s = \phi_{sa} = \hat{\phi}_s = \int_0^t (v_s - r_s I_s) dt$$

The estimated and actual electromagnetic torque are given by

$$T_e = T_{ea} = \hat{T}_e = \frac{3}{2} p (\phi_{sa} I_{sb} - \phi_{s\beta} I_{sa})$$

Any variation of $r_s$ can cause an imbalance in the equations of the stator flux PMSM components, expressed in steady state.

$$\phi_{sa} = \hat{\phi}_s + \Delta \phi_s = \int_0^t (v_s - (r_s^2 + \Delta r_s) (I_s + \Delta I_s)) dt$$

$$T_{ea} = \hat{T}_e + \Delta T_e = \frac{3}{2} p ((\phi_{sa} + \Delta \phi_{sa}) (I_{sb} + \Delta I_{sb}) - (\phi_{s\beta} + \Delta \phi_{s\beta}) (I_{sa} + \Delta I_{sa}))$$

The quantities estimated by the controller are given by:

$$\Delta \phi_s = \phi_{sa} - \hat{\phi}_s = - \int_0^t (\Delta r_s) (I_s + \Delta I_s) dt$$

$$\Delta T_e = T_{ea} - \hat{T}_e = \frac{3}{2} p ((\Delta \phi_{sa} - \Delta \hat{\phi}_s) (I_{sb} + \phi_{sa} \Delta I_{sb}) - (\Delta \phi_{s\beta} + \Delta \hat{\phi}_{s\beta}) (I_{sa} + \Delta I_{sa}))$$

Equations (22) and (24) gives the errors of the stator flux and torque are taking into account the variation of the $r_s$ during operation. Estimated quantities differ sensibly from actual magnitudes of the machine, so the resistive term can be comparable to the supply voltage $V_s$ and the error in the stator flux becomes more important, leading to a malfunction in the choice of voltage vector applied to the machine, so the DTC will lose performance and may become unstable.

7. FUZZY ESTIMATOR OF STATOR RESISTANCE VARIATION

A Fuzzy-logic corrector is developed to establish the DTC and to obtain a good estimation of flux and electromagnetic torque. This FL estimator can detects the $r_s$ variation by using the error between the reference and actual stator flux linkage

$$\phi_s = \sqrt{(\phi_{sa})^2 + (\phi_{s\beta})^2}$$
The inputs to the $r_s$ fuzzy estimator are the normalized error between the reference and estimated stator Flux, $e(k) = \phi_s^*(k) - \phi_s(k)$, and the normalized change in Flux error $\Delta e(k) = e(k) - e(k-1)$, whose block diagram are illustrated by the figure (6). The selected inputs and output memberships for the fuzzy estimator are given in the figure (5), the centroid defuzzification algorithm is used, in which the output fuzzy variable value is calculated as the centre of gravity of the membership function which is always added to the previously estimated $r_s(k-1)$. This updated stator resistance can be used directly in DTC algorithm estimation. In addition, the rule base controlling the defuzzified output according to the fuzzified input values is given in Table (5).

**Table 5. Rules base of FLC stator resistance estimator.**

<table>
<thead>
<tr>
<th>$e\phi$, $\Delta e$</th>
<th>PB</th>
<th>PS</th>
<th>ZE</th>
<th>NB</th>
<th>NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PS</td>
<td>ZE</td>
</tr>
<tr>
<td>PS</td>
<td>PB</td>
<td>PB</td>
<td>PS</td>
<td>ZE</td>
<td>NS</td>
</tr>
<tr>
<td>ZE</td>
<td>PB</td>
<td>PS</td>
<td>ZE</td>
<td>NS</td>
<td>NB</td>
</tr>
<tr>
<td>NB</td>
<td>PS</td>
<td>ZE</td>
<td>NS</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>NS</td>
<td>ZE</td>
<td>NS</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>

8. RESULTS OF SIMULATION

Table (6), summarizes the PMSM parameters used in this simulation.

**Table 6. PMSM parameters.**

<table>
<thead>
<tr>
<th>Pole pairs</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power KW (at 50 Hz)</td>
<td>1.5</td>
</tr>
<tr>
<td>Rated voltage (V)</td>
<td>220/380</td>
</tr>
<tr>
<td>Rated Flux (Wb)</td>
<td>0.30</td>
</tr>
<tr>
<td>Rated torque (Nm)</td>
<td>5</td>
</tr>
<tr>
<td>$R_s$ (Ω)</td>
<td>1.4</td>
</tr>
<tr>
<td>$L_d$ : $L_q$ (H)</td>
<td>0.0066; 0.0058</td>
</tr>
<tr>
<td>Flux magnet (Wb)</td>
<td>0.15</td>
</tr>
<tr>
<td>$J$ (Kg.m²)</td>
<td>0.00176</td>
</tr>
<tr>
<td>$f_r$ (Nm/(rad/s))</td>
<td>0.0038</td>
</tr>
</tbody>
</table>

Fig. 8. Diagram of DTC control applied for PMSM with a fuzzy $r_s$ estimator.

In this simulation study, we will carry two cases of the PMSM Control:

8.1 Control without compensation.

We simulated the system drive for a reference speed of 100 (rd / s) load at startup. At $t = 0.08$ (s), the PMSM is tracking load equal to 5 (Nm), then from $t = 0.02$ (s), we assumed a variation of $r_s$ (see Fig. 8).

Figure (9), presents the influence of such variation on the actual and estimated electromagnetic torque of PMSM. It is noticed that the couple deviated of its reference. In addition, the actual flux of the PMSM machine shown in figure (10), moves away by approx 0.04 (Wb) form its reference value.

8.2 Control without compensation.

In this part of simulation, we introduce a fuzzy-logic $r_s$ estimator in order to correct the estimate of stator flux and electromagnetic torque using modified switching table two FL controllers torque and flux hysteresis adapted band, Figure (11) illustrates the evolution of real and estimated resistances, (delivered by the proposed fuzzy compensator). The two values are practically equal in steady state. The actual and estimated electromagnetic torque, are illustrated by figure (12). It is noticed that these two curves coincide when estimated resistance reaches its value in steady state. The figure (14), shows the good compensation of the stator flux response by using the fuzzy regulator. This flux was restored correctly with its reference.

According to the figures (13), we see that the electromagnetic torque is improved by shifting the sectors by 30 ° with adapted fuzzy band torque and flux hysteresis controller. Indeed, the fluctuations are significantly reduced compared to the case of simple table and modified table. It is appreciated that the flux ripples decreases when hybrid modified DTC and fuzzy controller are in use but as shown in figure (15).

As in Figure 16, it illustrates rotor speed (rad / s) issued by PMSM, the speed response is achieved without dip and with a shorter recovery time.
Fig. 9. Evolution of motor's electromagnetic torque without compensation of $r_s$.

Fig. 10. Evolution of motor's stator flux without compensation of $r_s$.

Fig. 11. Estimated and real stator resistance.

Fig. 12. Evolution of motor's electromagnetic torque.

Fig. 13. Scale of the estimated electromagnetic torque.

Fig. 14. Evolution of motor's stator Flux.
9. CONCLUSIONS

To reduce the ripples torque and stator flux of the PMSM, controlled by conventional DTC, we proposed in this work, firstly a modified switching table which the sectors are shifted by 30° and secondly, two fuzzy-logic controllers adapted hysteresis bands.

The effects of the stator resistance variations have been studied, and to eliminate them, a Fuzzy-logic compensator has applied.

The simulation results suggests that the proposed modifications via conventional DTC of PMSM can achieve a good reduce of ripples, a precise control of the stator flux and torque and a stability to the study system.

NOMENCLATURE

\begin{align*}
\mathbf{dq} & \text{ Synchronously rotating frame.} \\
I_{dq} & \text{ dq stator current components.} \\
\phi_{dq} & \text{ dq stator flux components.} \\
\phi_e & \text{ Flux magnet.} \\
M & \text{ Mutual inductance.} \\
l_d, l_q & \text{ Stator d and q axis inductances.} \\
R_s & \text{ Stator resistance.} \\
J, f_r & \text{ Rotor inertia, friction coefficient.} \\
T_{em} & \text{ Electromagnetic torque.} \\
T_l & \text{ Load Torque} \\
p & \text{ Number of pole pairs.} \\
\Omega_r & \text{ Rotor angular velocity.} \\
T_s & \text{ Sampling Period} \\
k_i, k_p & \text{ Integral and proportional (IP) speed controller.} \\
I & \text{ Identity matrix} \\
\end{align*}

REFERENCES


