DTC Enhancement with Fuzzy Logic Controller Applied to Electric Traction

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Abstract - To ensure good performance, enable fast and stable torque response and solve problems caused by torque ripples, fuzzy logic-based methods have been developed, including direct fuzzy torque control based on vector PWM (DTFC-SVM).

Keywords - DTFC, SVM, electric traction, PMSM.

I. INTRODUCTION

Due to the wide range of applications, motor cycles, operating environments and price constraints, choosing the right electric traction machine can be difficult. However, torque-speed characteristics, maximum power requirements, temperature, volume and efficiency constraints all have an impact on the electric machine design process, from the determination of the number of phases, poles and winding configuration to the selection of lamination material, coil shape and permanent magnet use and material, and so on [1].

Permanent magnet synchronous motors (PMSM) are the most serious competitors to induction motors in traction applications. Many automakers, including Toyota, Honda and Nissan, have already used these motors in their vehicles. Because magnets, rather than windings, are used to magnetize the rotor, the phase inductance of the PMSM is lower than that of an induction motor, their power density and efficiency are high compared with other types of motor, they operate with a unity power factor, and they are more efficient than induction motors [2] [3] [4] [5].

Direct torque control uses only the stator resistance to estimate the stator flux and is therefore less affected by variations in motor parameters. However, it has some disadvantages, including high ripple in torque, flux and current, as well as variable switching frequency of the inverter. This ripple is caused by the pair of hysteresis controllers used for independent control of machine flux and torque, which varies with speed, load torque, selected hysteresis bands, and the difficulty of controlling torque and flux at extremely low speeds. This also results in increased acoustic noise and harmonic losses [6] [7] [8] [9] [10] [11].

Several methods have been proposed in the literature to overcome the above limitations, including a new control method called Direct Torque Fuzzy Control (DTFC), which is based on the Space Vector Modulation (SVM) technique [8] [12].

SVM-based direct torque control offers various advantages, including fast torque response, minimized torque and flux ripples, and a fixed switching frequency. In addition, it retains its transient and static properties while providing good stable operating performance over a wide range. The SVM technique is used to determine the reference of the optimal voltage vector at each cycle period to accurately adjust the errors caused by flux and torque angle [8] [13] [14] [15].

This article presents "direct torque fuzzy control", a new control approach created in this study to replace traditional DTC control. One of its most important features is the elimination of hysteresis controllers, as well as the vector selection table. In this control approach, modulation of the control output vector is performed by a vector PWM.

II. PRESENTATION OF DIRECT FUZZY TORQUE CONTROL

The proposed direct torque fuzzy control scheme uses two fuzzy logic controllers (FLC1 and FLC2) to generate a voltage space vector V_s, which is then used by space vector modulation to provide switching states for the inverter, acting on both stator flux magnitude and angle and electromagnetic torque errors. The increment angle is the output of FLC2, and the reference voltage amplitude is the output of FLC1. The inputs for the stator flux amplitude and torque errors are shown in Fig. 1. The increment angle is multiplied by the stator flux vector angle, which is used by vector modulation to generate the inverter switching states. In FLC1 and FLC2, the Mamdani and Sugeno approaches were used for the fuzzy reasoning algorithms [12] [16] [17] [18].

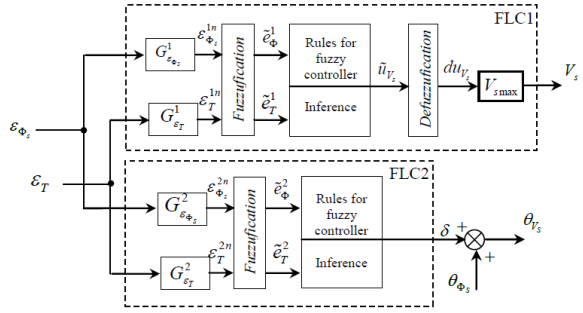


Fig. 1. Structure of fuzzy controllers.

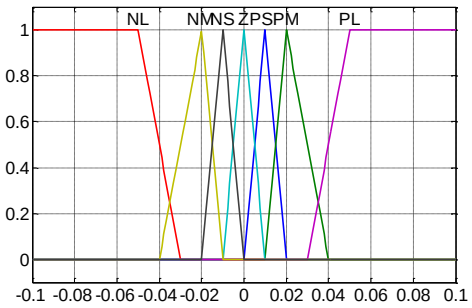
A) Generation of the reference voltage vector

Figure 2 gives the membership functions for the input and output variables of the fuzzy controller. Trapezoidal and triangular membership functions were chosen. The speech universes used are [-1, 1] for the torque errors, [-0.1, 0.1] for the normalized flow errors and [0, 1] for the fuzzy output [19].

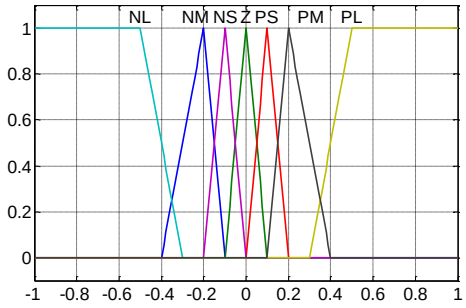
For the determination of the rules of the fuzzy controller, we considered the objectives that we had to reach [19]:

- ✓ First objective: If the torque is very far from its error band then, whatever the value of the flux, a maximum voltage module must be chosen. This objective gives us fourteen rules as shown in Table I.
- ✓ Second objective: If the torque is at an average distance from its error band then, regardless of the flux value, an average voltage modulus should be chosen. This objective gives us fourteen more rules as shown in Table I.
- ✓ Third objective: If the torque is within a small distance of its error band then, whatever the value of the flux, a small voltage modulus should be chosen. This objective gives us fourteen more rules as shown in Table I.
- ✓ Fourth objective: If the torque is within its error band, then the choice of module depends on the value of the flux. If the flux is within or at a small distance from its error band, then a voltage modulus around zero should be chosen. If the flux is at a medium or large distance from its error band, a small voltage modulus should be chosen. This objective gives us seven additional rules, as shown in Table I.

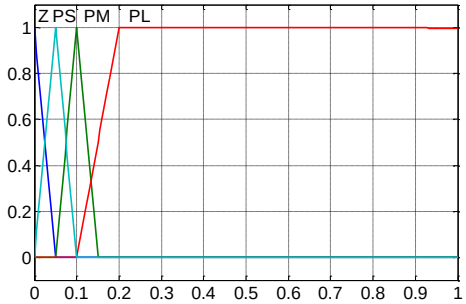
In the proposed fuzzy controller, the inference method used is max-min and for defuzzification the center of gravity method was used.



(a) $\mu_{\tilde{e}_\Phi}$



(b) $\mu_{\tilde{e}_T}$



(c) $\mu_{u_{V_s}}$

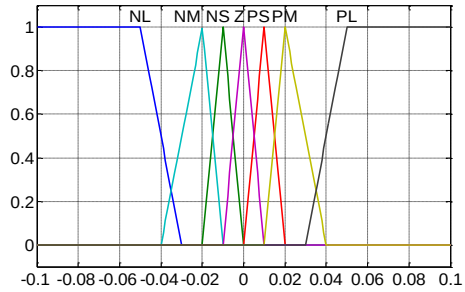
Fig. 2. Membership functions for the input and output variables of the fuzzy controller.

TABLE 1. FUZZY DECISION RULES TABLE

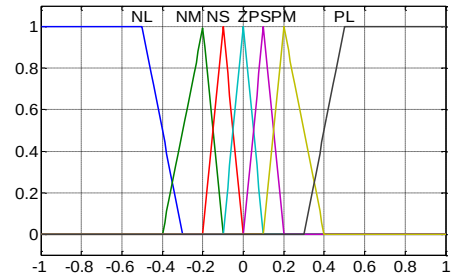
$\tilde{e}_T$ \ $\tilde{e}_\Phi$	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	PL	PM	PS	PS	PS	PM	PL
NM	PL	PM	PS	PS	PS	PM	PL
NS	PL	PM	PS	Z	PS	PM	PL
Z	PL	PM	PS	Z	PS	PM	PL
PS	PL	PM	PS	Z	PS	PM	PL
PM	PL	PM	PS	PS	PS	PM	PL
PL	PL	PM	PS	PS	PS	PM	PL

B) Selection of the position of the voltage vector

The errors of the ε_T torque and ε_{Φ_s} flux are multiplied by "scaling factors" to obtain the normalized quantities ε_T^n and $\varepsilon_{\Phi_s}^n$ using the trapezoidal and triangular membership functions, Figure 3. These quantities are used by the fuzzification block to be transformed into $\tilde{e}_T$ and $\tilde{e}_{\Phi_s}$ fuzzy values. These are used by the Sugeno type fuzzy control rules block to directly obtain the δ value that must be added to the stator flux angle.



(a) $\mu_{\varepsilon_{\Phi_s}^n}$



(b) $\mu_{\varepsilon_T^n}$

Fig. 3. Membership functions for the input variables of the fuzzy controller.

Table II shows the table for δ angle selection by direct fuzzy torque control.

TABLE 2. INCREMENT ANGLE OF THE REFERENCE VOLTAGE VECTOR.

ε_T^n \ $\varepsilon_{\Phi_s}^n$	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	$-\frac{5\pi}{6}$	$-\frac{5\pi}{6}$	$-\frac{3\pi}{4}$	π	$\frac{4\pi}{3}$	$\frac{4\pi}{3}$	$\frac{3\pi}{4}$
NM	$-\frac{5\pi}{6}$	$-\frac{3\pi}{4}$	$-\frac{4\pi}{3}$	π	$\frac{4\pi}{3}$	$\frac{3\pi}{4}$	$\frac{5\pi}{6}$
NS	$-\frac{3\pi}{4}$	$-\frac{4\pi}{3}$	$-\frac{4\pi}{3}$	π	$\frac{3\pi}{4}$	$\frac{5\pi}{6}$	$\frac{5\pi}{6}$
Z	$-\frac{\pi}{2}$	$-\frac{\pi}{2}$	$-\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$
PS	$-\frac{\pi}{3}$	$-\frac{\pi}{3}$	$-\frac{\pi}{4}$	0	$\frac{\pi}{6}$	$\frac{\pi}{6}$	$\frac{\pi}{4}$
PM	$-\frac{\pi}{3}$	$-\frac{\pi}{4}$	$-\frac{\pi}{6}$	0	$\frac{\pi}{6}$	$\frac{\pi}{4}$	$\frac{\pi}{3}$
PL	$-\frac{\pi}{4}$	$-\frac{\pi}{6}$	$-\frac{\pi}{6}$	0	$\frac{\pi}{4}$	$\frac{\pi}{3}$	$\frac{\pi}{3}$

III. VECTOR PWM CONTROL TECHNIQUE

"Der Broek et al, 2988" propose the vector modulation approach. It consists in generating a predefined sequence of inverter states. Vector modulation is a real-time modulation. The vector PWM algorithm is composed of five fundamental steps [20]:

- determination of the reference voltage vector ;
- sector calculation ;
- region calculation;
- calculation of switching times ;
- calculation of switching sequences ;
- generation of PWM signals.

A) Calculation of the reference voltage vector and vector diagram

The 27 vectors constitute the space vector diagram of the three-phase inverter with three levels as shown in Figure 4. There are 24 active vectors of which 12 are short vectors, 6 are medium vectors and 6 are long vectors, and the remaining three are null vectors (PPP, OOO, NNN). They all converge at the center of the hexagon [20].

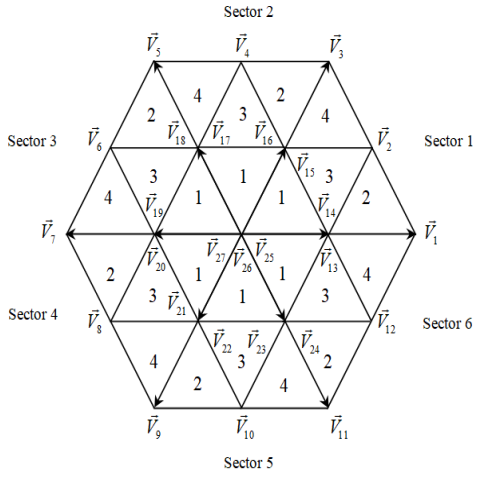


Fig. 4. Vector diagram of a three-phase, three-level inverter.

B) Calculation of the sector and region

The hexagon of the space vector diagram of a three-level inverter can be subdivided into 6 sectors, each with 4 regions, Figure 4. This gives a total of 24 regions. The sectors can be determined as follows [20]:

- If $0^\circ \prec \theta \leq 60^\circ : \vec{V}_{ref}$ is in sector 1
- If $60^\circ \prec \theta \leq 120^\circ : \vec{V}_{ref}$ is in sector 2
- If $120^\circ \prec \theta \leq 180^\circ : \vec{V}_{ref}$ is in sector 3
- If $180^\circ \prec \theta \leq 240^\circ : \vec{V}_{ref}$ is in sector 4
- If $240^\circ \prec \theta \leq 300^\circ : \vec{V}_{ref}$ is in sector 5
- If $300^\circ \prec \theta \leq 360^\circ : \vec{V}_{ref}$ is in sector 6

From Figure 5 the membership regions of the reference voltage vector can be detected by the following algorithm [20]:

- If $V_a \prec \frac{V_{dc}}{3}$, $V_b \prec \frac{V_{dc}}{3}$ and $V_a + V_b \prec \frac{V_{dc}}{3}$, then $\vec{V}_{ref}$ is in region 1
- If $V_a \succ \frac{V_{dc}}{3}$, $V_b \prec \frac{V_{dc}}{3}$ and $V_a + V_b \succ \frac{V_{dc}}{3}$, then $\vec{V}_{ref}$ is in region 3
- If $V_a \succ \frac{V_{dc}}{3}$, then $\vec{V}_{ref}$ is in region 2
- If $V_b \succ \frac{V_{dc}}{3}$, then $\vec{V}_{ref}$ is in region 4

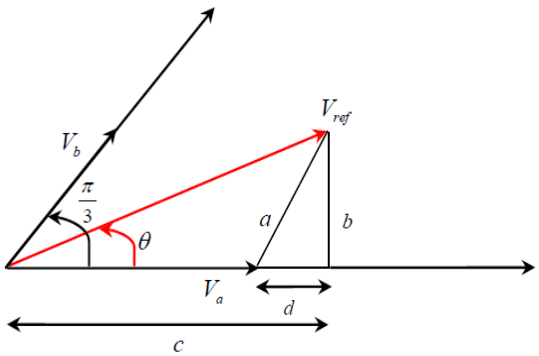
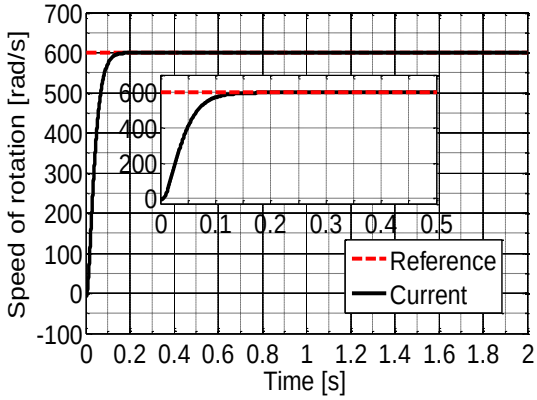


Fig. 5. Diagram for the calculation of V_a and V_b.

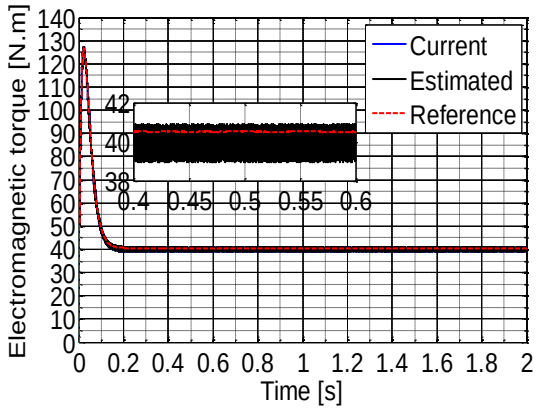
IV. SIMULATION RESULTS

The aim is to improve the DTC control approach using the direct torque fuzzy control

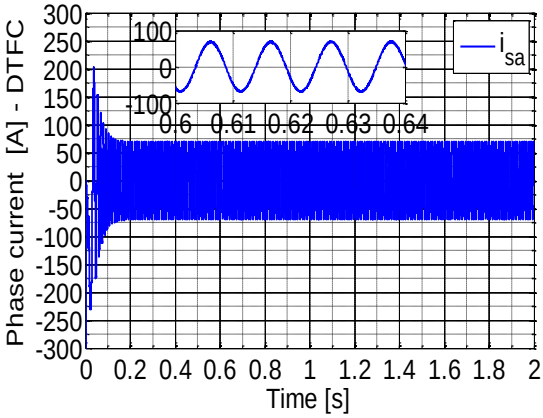
method. Figure 6 shows the best result. We see a considerable reduction in torque ripples, as well as a current that appears sinusoidal with almost no steady-state ripple.



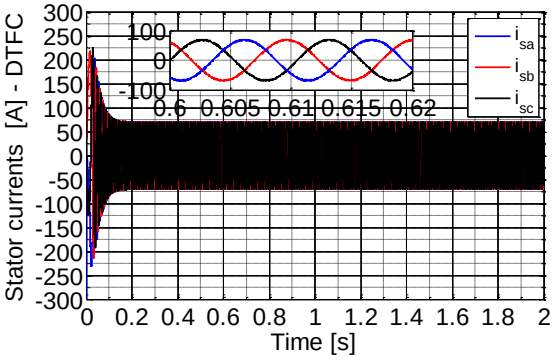
(a) Speed of motor



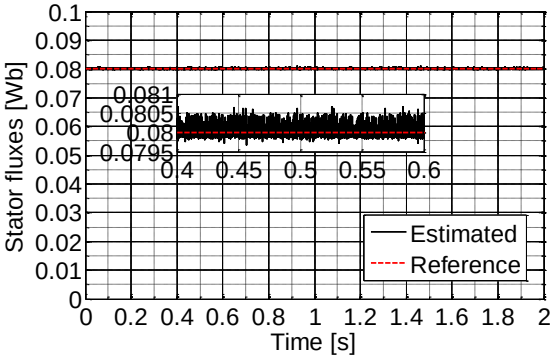
(b) Electromagnetic torque.



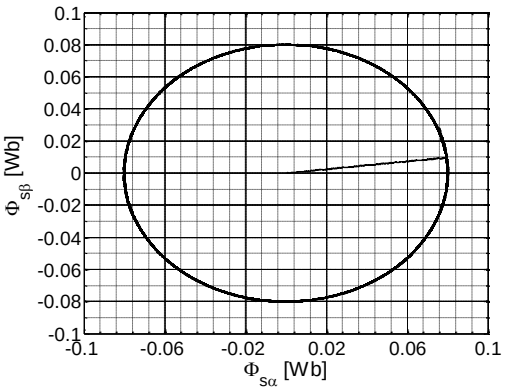
(c) Phase current.



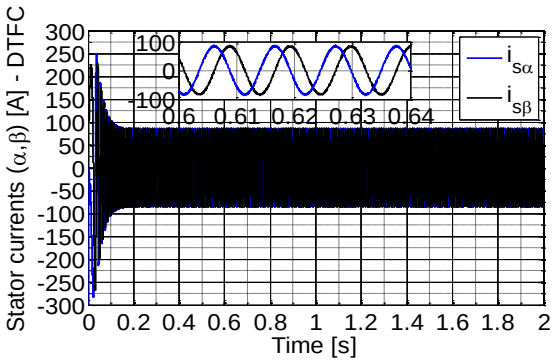
(d) Stator currents



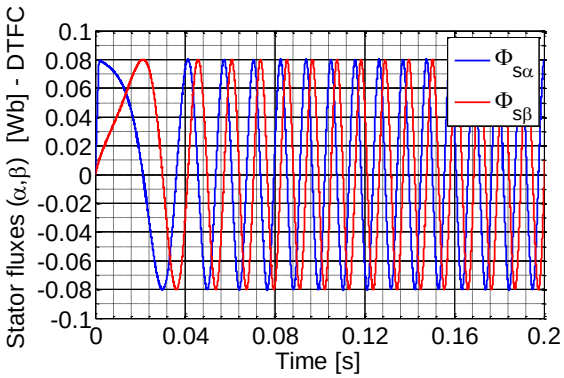
(e) Stator flux



(f) Circular trajectory of the stator flux in the (α,β) plane.



(g) Stator currents in the (α,β) plane.



(h) Stator fluxes in the (α, β) plane

Fig. 6. Simulation results.

TABLE 3. MOTOR PARAMETERS

Symbol	Parameter	Value
R_s	Stator resistor	$0,03\,\Omega$
L_d	Cyclic inductance in the d axis	$0,2$ mH
L_q	Cyclic inductance in q axis	$0,2$ mH
Φ_f	Flux due to permanent magnets	$0,08$ Wb
p	Number of pole pairs	4

V. CONCLUSION

To achieve fast torque response, as well as low torque and flux ripple, we developed a direct torque fuzzy control associated with vectorial PWM (DTFC-SVM). The fuzzy controllers replace the hysteresis controllers and the commutation table to generate the modulus and the angle of the voltage vector in order to bring the stator flux and the electromagnetic torque to their references in an optimal way. Vector modulation is used to acquire the switching states of the inverter from the generated output variables.

The advantages of direct torque fuzzy control in terms of dynamic performance, robustness and perfect decoupling between torque and flux. In addition, we discovered that, thanks to its fuzzy sets and inference rules, it enables precise selection of the voltage vector.

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