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IMPROVED DIRECT TORQUE CONTROL OF PERMANENT MAGNETIC SYNCHRONOUS MOTOR USING PSO-FUZZY CONTROLLER

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Abstract- The paper proposes an improved control of Permanent Magnet Synchronous Motor (PMSM) based on direct torque control (DTC) using a fuzzy logic controller (FLC) tuned by a Particle Swarm Optimization (PSO) technique. Although, the DTC control has many advantages, an excellent torque dynamic, good robustness to variations the parameters of motor, no need the rotor position angle, absence block calculations of PWM, no need to use a speed sensor to implement it. But it also has many disadvantages like, poorly controlled operation at low speed, torque and flux ripples important, the switching frequency is not controlled, to minimize torque ripple and improve performance of the control system, this paper proposes a FLC of speed tuned by PSO algorithm instead of using classical Proportional Integral (PI) controller. The effectiveness of proposed control and the advantages (decrease in response time, and the overshoot) compared with conventional PI controller tuning by traditional technique and FL controller tuning by Trial/error method, is shown by the simulation result on MATLAB/Simulink

Keywords: Permanent Magnet Synchronous Motor (PMSM), Direct Torque Controller (DTC), Fuzzy Logic Controller (FLC), Particle Swarm Optimization (PSO).

1. INTRODUCTION

Due to its ease of control, efficiency, robustness, high power-weight ratio and good dynamic performance, the PMSMs are replacing the classical Induction Machine and Asynchronous Machine in different applications. Many researchers were interested in the controlling PMSM. [1] Propose an intelligent backstepping sliding mode control of an experimental PMSM. The reference [2] presents speed control of an Electric Vehicle based on (PMSM) using the Field Oriented Control and he has studied the performance of control in case changing of motor parameters. The aim of [3] is presentation an algorithm of Sensor less control of speed using Finite Control Set Model Predictive of PMSM. [4] give a study of control strategy of electric vehicles, based on PMSM.

The [5] Presents a predictive model of torque control for PMSM using fuzzy control. The purpose of [6] is vector control study of PMSM, simulation and experimental results. The DTC were developed by Takahashi and Depenbrock for induction machines [7, 8], based on possibility to control the torque and the stator flux with decoupled way. In the last two decades, due to its simple structure, and high response of Torque control compared to other strategies, the DTC became one of the most popular controllers used to controlling the electrical machine. Moreover, DTC control is independent of the machine parameters and does not use the current controller, which allows to have a fast response of torque control with a good robustness to variation of parameter machines. But like all other control, DTC also has a drawback, essentially flux and torque ripples. In recent, many researches have been developed with the aim of improvement of electrical machine control by DTC.

The references [9, 10] present an improvement of DTC to minimize torque ripple of Induction Motor (IM) control. [11] use a new Optimized Switching Strategy, to control of IM by DTC. [12] use a multilevel inverter in DTC to minimize of torque ripple. Reference [13] give an improvement of the performance of IM by using DTC Technique. The paper [14] Use an adaptive Sliding Mode Control in DTC of IM Based on Discrete Space Vector Modulation. In order to improve DTC, this paper propose to control of PMSM with a Fuzzy controller instead of using a classical PI controller, but finding parameters of this controller (gains of scaling and parameters of membership function) is not easy. Regularly, they are determined by trial/error technique. in recent years, some optimizing methods have been used to identify these parameters [16-18].

In this paper, the rule base and the membership function parameters of the used FLC is provided by expert experience, and scaling gains will be optimally tuned by the PSO algorithm. The results of simulation show that the PMSM speed and Torque control based on Adaptive Fuzzy controller based on PSO algorithm has better performance (response time, overshoot) then the conventional PI controller or manual FL controller.

2. CONTROL STRATEGY OF DTC

The strategy of proposed DTC presented by Figure 1.

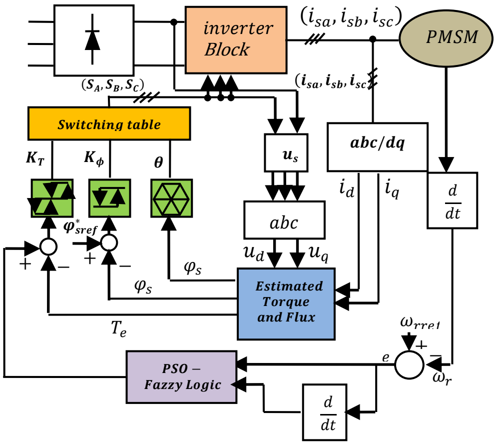


Figure 1. A Proposed direct torque control scheme

The result error (e) and its derivative (de) of comparator speed are treated by FLC to generate the torque reference. The torque references and stator flux ϕ_s are compared with their estimated values given by block estimation to feed the hysteresis controllers. The output of the hysteresis controllers and the position (θ_s) of $\vec{\phi}_S$ are transmitted to selector block to calculate S_a, S_b and S_c which are used by the inverter to deliver the supply voltage to PMSM.

2.1. Voltage Vector V_s and Electromagnetic Torque T_e Estimator

The stator flux is given by:

$$\frac{d\vec{\phi}_S}{dt} = \vec{v}_S + R\vec{i}_S \tag{1}$$

The voltage $R_s.i_s$ is considered negligible to the voltage v_s applied to the PMSM, during a sampling time, the stator flux at iteration (k+1) is given by Equation (2):

$$\vec{\phi}_s(k+1) - \vec{\phi}_s(k) \approx \vec{v}_s T_e \tag{2}$$

The voltage v_s is proportional to the stator flux $\vec{\phi}_s$. Figure 2 shows the evolution of $\vec{\phi}_S$ in plane (α, β). Therefore, to increase the stator flux, we have to apply a voltage vector collinear and the direction of the stator flux $\vec{\phi}_s$, and vice versa.

So, in order to increase $\vec{\phi}_s$, we need to apply a collinear voltage vector and in same direction of $\vec{\phi}_s$, and vice versa. The electromagnetic torque is expressed by:

$$T_e = k_e \left\|\vec{\phi}_s\right\| \cdot \left\|\vec{\phi}_m\right\| \sin(\theta) \tag{3}$$

where, the electromagnetic torque depends on the magnitude of stator flux $\left\|\vec{\phi}_s\right\|$, magnitude of rotor flux $\left\|\vec{\phi}_m\right\|$ and the position θ between $\vec{\phi}_s$ and $\vec{\phi}_m$. Then we can control the T_e and the magnitude of $\vec{\phi}_s$ in a decoupled way.

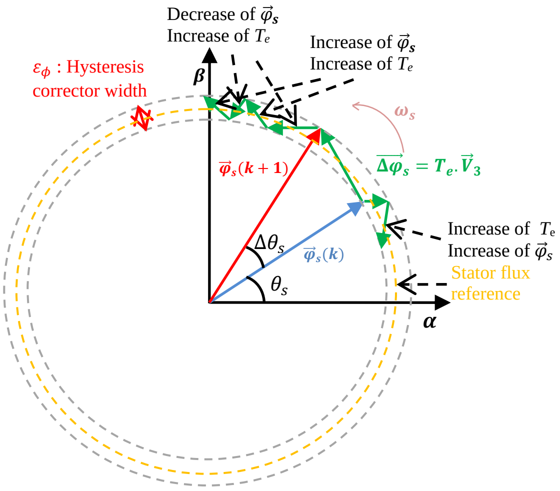


Figure 2. Evolution of $\vec{\phi}_s$ in (α, β) plane

The recommended out-put stator voltage vector of inverter is deduced from the difference between reference of electromagnetic torque and actual electromagnetic torque ($T_{ref} - T_e = k_T$), and the difference of stator flux reference to actual stator flux ($\phi_{s_{referce}} - \phi_s = k_\phi$) and the rotor position (θ) in reference (α, β). When the stator flux vector in section i on plane (α, β), the choice of stator voltage vector $\vec{v}_s$ to increase or decrease of $\vec{\phi}_s$ and/or torque is done as shown in Figure 3.

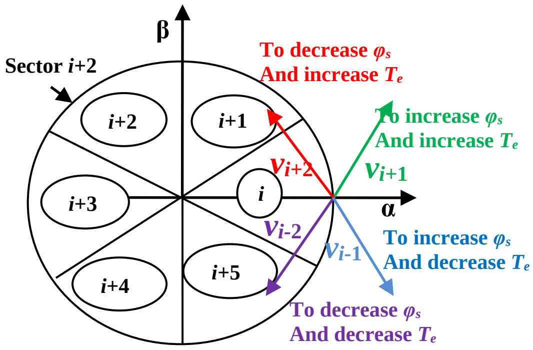


Figure 3. Choice of vector voltage

2.2. Estimators of $\phi_{s\alpha}$, $\phi_{s\beta}$ and Torque

- Stator flux and θ_s estimator

The estimates components vector of $\phi_{s\alpha}$ and $\phi_{s\beta}$ given by:

$$\hat{\phi}_{s\alpha} = \int (v_{s\alpha} - R_s i_{s\alpha})dt \tag{4}$$

$$\hat{\phi}_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta})dt \tag{5}$$

The voltages $v_{s\alpha}$ and $v_{s\beta}$ obtained from (S_a, S_b, S_c). With applying the Concordia transformation [19]:

$$\vec{v}_s = v_{s\alpha} + jv_{s\beta} \tag{6}$$

$$\begin{cases} v_{s\alpha} = \sqrt{\frac{2}{3}} U_0 (S_a - \frac{1}{2}(S_b + S_c)) \\ v_{s\beta} = \frac{1}{\sqrt{2}} U_0 (S_b - S_c) \end{cases} \tag{7}$$

With application the CONCORDIA transformation to actual currents i_{sa}, i_{sb} and i_{sc}, we obtained the components $i_{s\alpha}$ and $i_{s\beta}$.

$$i_s = i_{s_\alpha} + j i_{s_\beta}$$

$$\begin{cases} i_{s\alpha} = \sqrt{\frac{2}{3}} i_{sa} \\ i_{s\beta} = \frac{1}{\sqrt{2}} (i_{sb} - i_{sc}) \end{cases} \tag{8}$$

The stator flux magnitude is:

$$\phi_s = \sqrt{\phi_{s\alpha}^2 + \phi_{s\beta}^2} \tag{9}$$

The positioning zone of φ_s is determined by the angel θ_s defined by:

$$\theta_s = arctg \frac{\phi_{s\beta}}{\phi_{s\alpha}} \tag{10}$$

- Estimator of torque T_e:

The estimated torque is given by Equation (11) [19]:

$$\hat{T}_e = \frac{3}{2} p \left(\hat{\phi}_{s\alpha} i_{s\beta} + \hat{\phi}_{s\beta} i_{s\alpha} \right) \tag{11}$$

2.3. Control of Stator Flux Vector

- Stator flux corrector

To control the $\vec{\phi}_s$, we are using a simple two-level hysteresis corrector with Boolean value K_φ in output, which indicates, if we must increase ($K_\varphi = 1$) or decrease ($K_\varphi = 0$) the value of stator flux. (Figure 4)

$$\left| \phi_{s_{ref}} - \phi_s \right| \le \varepsilon_\phi \tag{12}$$

With:

ϕ_s : Actual stator flux

ϕ_{sref} : Reference stator flux,

ε_ϕ : Hysteresis corrector width.

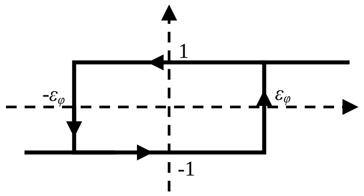


Figure 4. hysteresis corrector of stator flux

- Corrector of electromagnetic torque:

To keep the torque within limits Equation (13), a three level-hysteresis corrector is used (Figure 5), to purposes of controlling motor in two directions and minimize the switching of the switches.

$$\left| T_{ref} - T_e \right| \le \varepsilon_T \tag{13}$$

where, T_{ref} is Torque reference, and ε_T: Hysteresis corrector width.

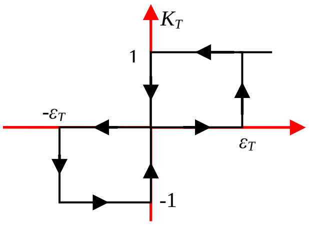


Figure 5. hysteresis correctors of torque

2.4. Voltage Table of DTC Control

The voltage table using to control the $\vec{\phi}_s$ and T_e is given by Table 1 [19, 20].

Table 1. Switching table presented by Takahashi and Noguchi

$\Delta\varphi$	ΔT	θ_1	θ_2	θ_3
1	1	v_2(1,1,0)	v_3(1,0,0)	v_4(1,0,1)
1	0	v_7(1,1,1)	v_0(0,0,0)	v_7(1,1,1)
1	-1	v_6(1,0,1)	v_1(0,0,1)	v_2(0,1,1)
0	1	v_3(0,1,0)	v_4(1,1,0)	v_5(1,0,0)
0	0	v_0(0,0,0)	v_7(1,1,1)	v_0(0,0,0)
0	-1	v_5(0,0,1)	v_6(0,1,1)	v_1(0,1,0)
		θ_4	θ_5	θ_6
		v_5(0,0,1)	v_6(0,1,1)	v_1(0,1,0)
		v_0(0,0,0)	v_7(1,1,1)	v_0(0,0,0)
		v_3(0,1,0)	v_4(1,1,0)	v_5(1,0,0)
		v_6(1,0,1)	v_1(0,0,1)	v_2(0,0,1)
		v_7(1,1,1)	v_0(0,0,0)	v_7(1,1,1)
		v_2(1,1,0)	v_3(1,0,0)	v_4(1,0,1)

3. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a computational learning algorithm, was firstly introduced by James Kennedy and Russell Eberhart in 1995 [21], and improved in 1998 [22]. The updated of particles in iteration (k+1) is according to the Equation (14) [21]:

$$\begin{aligned} & v_{ij}(k+1) = w v_{ij}(k) + c_1 r_1 (p_{ij}(k) - x_{ij}(k)) + \\ & + c_2 r_2 (g_i(k) - x_{ij}(k)) \\ & x_{ij}(k+1) = x_{ij}(k) + v_{ij}(k+1) \end{aligned} \tag{14}$$

where,

- $i = 1, 2, ..., d$ with d dimension of particles;
- $x_{ij} = (x_{i1}, x_{i2}, ..., x_{id})$: The ith particle [23] shows that the performances are similar in the case of a swarm sizes 10 to 50. In this paper we set 40 a size of used swarm;
- $p_{ij} = (p_{i1}, p_{i2}, ..., p_{id})$: Best previous position;
- g_i: Better particle in all the population;
- $v_{ij} = (v_{i1}, v_{i2}, ..., v_{id})$: The velocity of particle i;
- (c_1, c_2): adjustable cognitive acceleration constant;
- $r_{1,2}$ is constant between 0 and 1;
- w: Inertia weight. w=0.729 is a proposed value by Clerc [24] guaranteed the convergence of PSO;

The used fitness function given by Equation (15).

$$f(k_1, k_2, k_3) = 0.5 \text{ ISE} + 0.5 \text{ IAE} \tag{15}$$

where,

- IAE: Integrated-Absolute-Error.
- ISE: Integral-Square-Error.

The steps of PSO are illustrated in Figure 6.

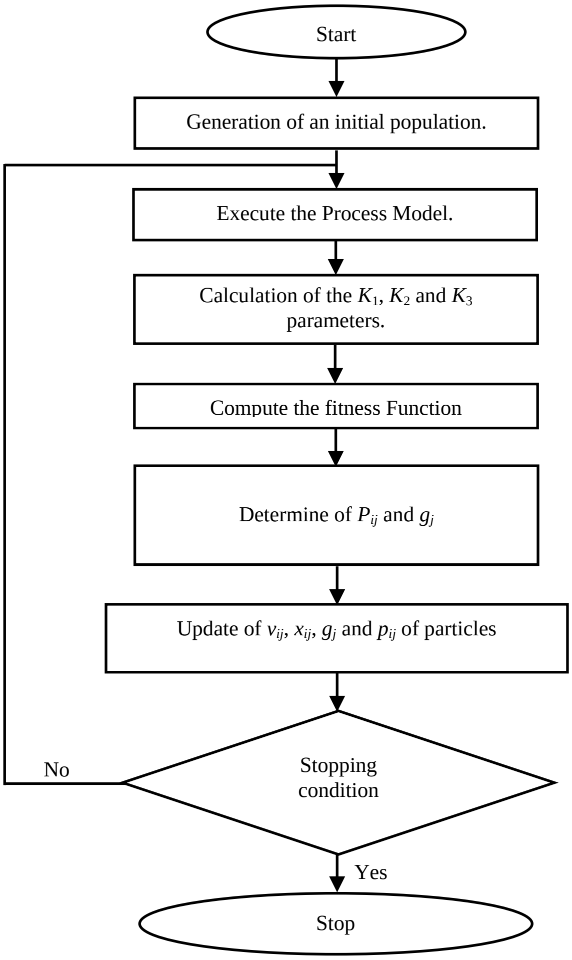


Figure 6. Diagram of PSO steps

4. THE PROPOSED ADAPTIVE FUZZY LOGIC CONTROLLER

Fuzzy logic is a technique used in artificial intelligence. It was formalized by Lotfi Zadeh [25]. The proposed PSO-FLC is equipped with two inputs and one output, as shown in Figure 7.

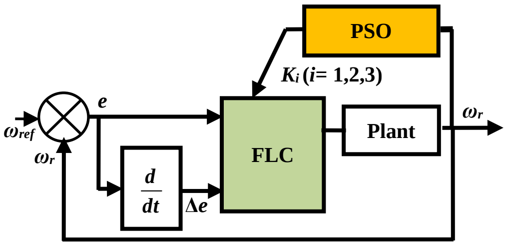


Figure 7. Diagram of proposed PSO-FLC

where,

- e is error of speed comparator, given by Equation (16):

$$e(k+1)=\omega_{r_{ref}}(k+1)-\omega(k) \quad (16)$$

Δe is the derived of the error given by:

$$\Delta e(k+1)=\frac{e(k+1)-e(k)}{T} \quad (17)$$

where, T is the sampling Time.

The regulator out-put is:

$$T_{ref}(k+1)=T_{r_{ref}}(k)+\Delta u(k+1) \quad (18)$$

The membership function of input and output signals are given by Figures 8, 9 and 10.

where, N: Negative, B: Big, M: Medium, S: Small, Z: Zero, P: Positive.

Each variable has 7 fuzzy subsets, with typical rule as "If e is NB and de is PB Then Δu is Z", we have 49 possible rules (Table 2). We use the MAMDANI'S inference method in Defuzzification blocks.

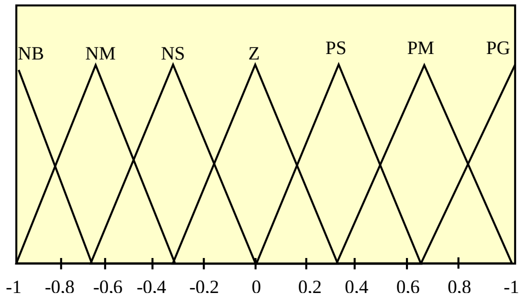


Figure 8. Membership function of error

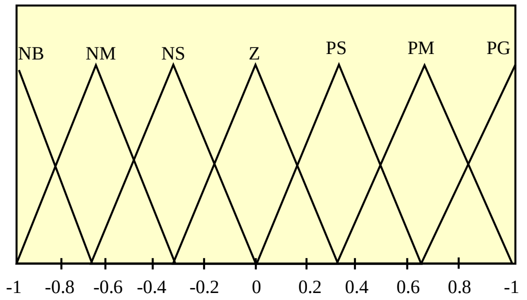


Figure 9. Membership function of differential error

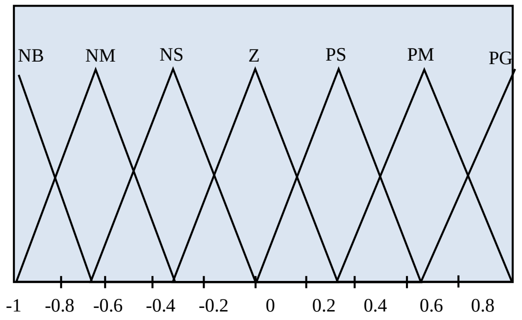


Figure 10. Membership function of control signal

Table 2. Rules base

e de	NB	NM	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PS	NM	NS	Z	PS	PM	PB	PB
Z	NB	NM	NS	Z	PS	PM	PB
NS	NB	NB	NM	NS	Z	PS	PM
NM	NB	NB	NB	NM	NS	Z	PS
NB	NB	NB	NB	NB	NM	NS	Z

5. TUNING THE FLC PARAMETERS USING PSO

For each new population resulting from the PSO swarm, the variables from the algorithm are stored and inserted in FLC Bock and, from that, the result of the fitness function Equation (15) is estimated. This is done until reaching the stopping criterion. Three parameters of the FLC need to be tuned. We use the PSO algorithm to tune of 3 gains K_1, K_2 and K_3 of block FL-controller (Figure 11).

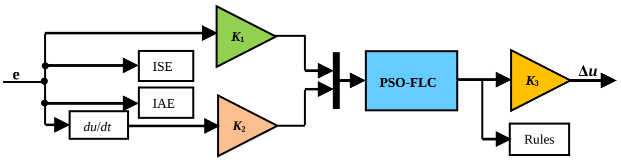


Figure 11. PSO-FLC schemes in MATLAB

The steps of the used algorithm are:

- Step 1: generating random variables parameters of PSO algorithm
- Step 2: collecting error data (*e*), differential error (*de*) and controlled signal (*du*)
- Step 3: computing the equation of objective function
- Step 4: running PSO such that minimizing
- Step 5: repeating steps 2, 3 and 4 until the convergent criterion is satisfied.

• Parameters of PSO Algorithm and the Tuned Values of K_1, K_2 and K_3

The PSO-parameters and the values K_1, K_2 and K_3 tuned by PSO algorithm are given in Table 3.

Table 3. Parameter of PSO

Variable	Value	Description
i	40	Size of the swarm
k	300	Iteration number
c_1	2	cognitive acceleration constant
c_2	2	cognitive acceleration constant
w	0.729	Inertia weight
$r_{1,2}$	0.95	random function
k_1	$1.35e^{-2}$	variables of Matrix gain of Luenberger Observer
k_2	$3.71e^{-6}$	
k_3	$9.41e^{3}$	

6. PARAMETERS OF MOTOR AND RESULTS OF SIMULATION

• Motor Parameters [19]

The parameters of Motor are given by Table 4.

Table 4. Parameters of PMSM

Parameter	Value	Unit
stator resistance	1.4	Ω
d-axis inductance	6.6	mH
q-axis inductance	5.8	mH
magnetic flux constant	0.1546	Wb
Friction coefficient	0.00038	$N.m.rad^{-1}.s^{-1}$
Motor inertia	0.00176	$kg.m^2$

To illustrate the behavior of the proposed technique, the Figures below present the results simulation using MATLAB/Simulink. The characteristics of the control are imposed by the operating conditions of the used PMSM (Table 3). Thus, we apply a load of 4 Nm at $0.05s<t<0.15s$ and -4 Nm^{-1} at $0.25s<t<0.35s$, Figure 12(a), with a speed reference 100 rad/s at $0s<t<0.2s$ and -100 rad. s^{-1} at $0.2s<t<0.4s$ Figure 13(a).

Figures 12 to 15 represent the evolution of Electromagnetic Torque, Rotational Speed, Stator Flux vector and Current Phases, in the absence and presence of load (±4 Nm) and with inversion of reference speed (±100) rad/s.

The simulation results demonstrate the good performance of proposed controller (FLC tuning by Particle Swarm Optimization algorithm PSO-FLC) in comparison with a conventional method (using classical PI controller or manual FL controller).

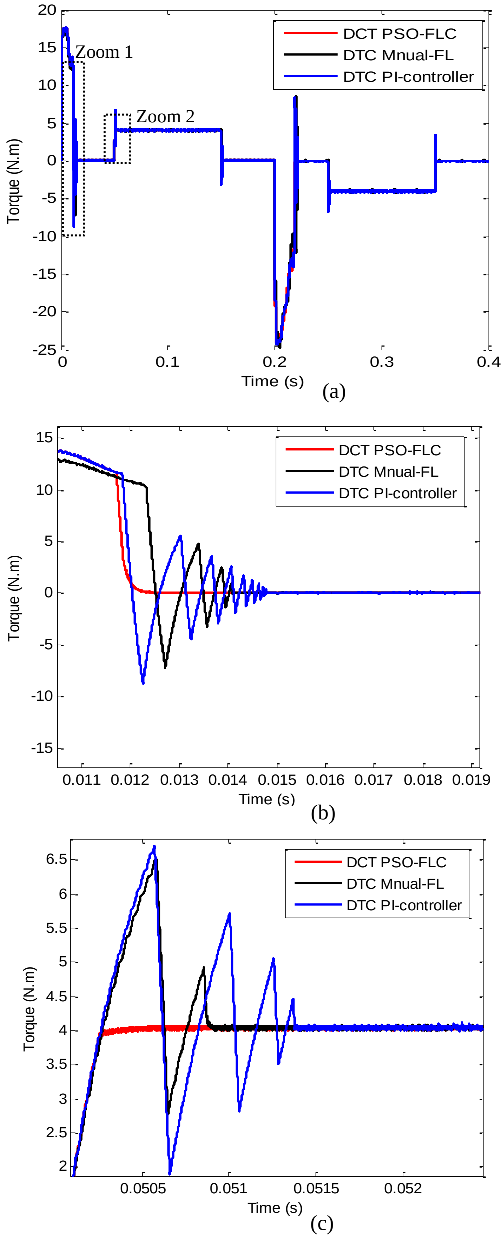
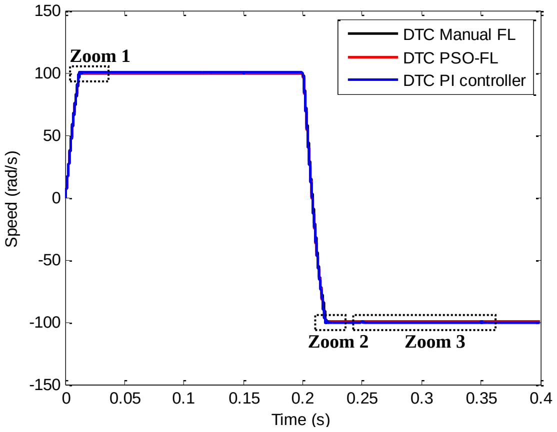
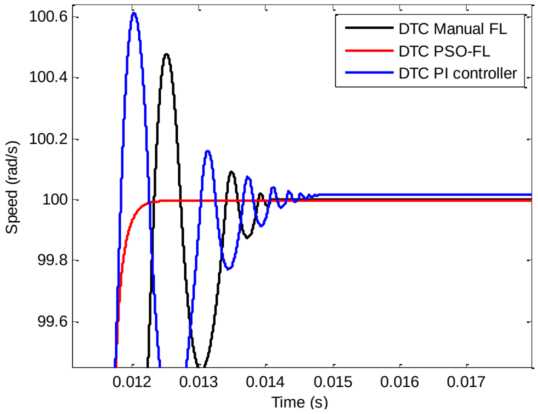


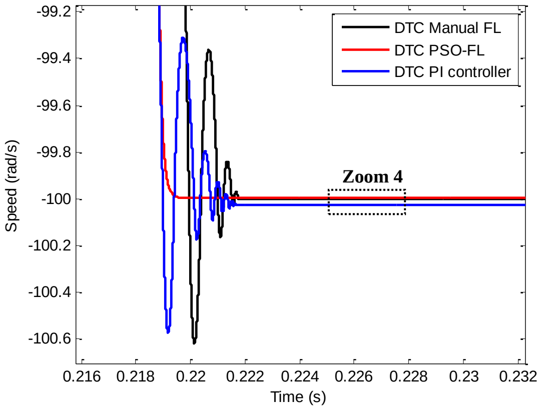
Figure 12. (a) Response of electromagnetic torque, (b) Zoom 1 in Figure 13(a), (c) Zoom 2 in Figure 13(a)



(a)



(b)



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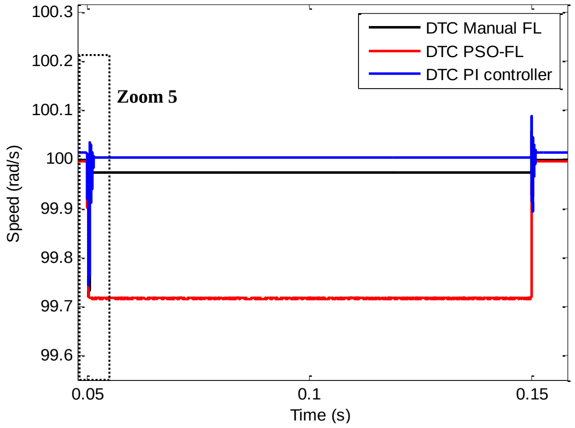
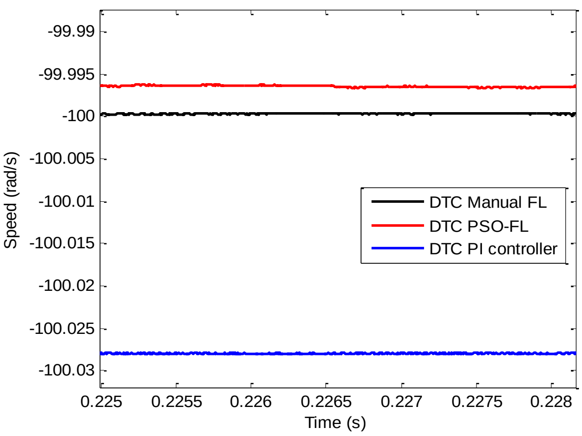


(d)



(e)

Figure 13. (a) Rotational speed of PMSM, (b) Zoom 1 in Figure 13(a), (c) Zoom 2 in Figure 13(a), (d) Zoom 3 in Figure 13(a), (e) Zoom 4 in Figure 13(c)

At 0s<*t*<0.2s the reference Speed is 100 rad/s with application a load 4Nm at *t* = 0.02s and its elimination at *t* = 0.15s. during start-up of PMSM, Figure 12(a), the torque achieves up to 17 Nm and then it stabilizes a zero value at Figure 12(b).

- *t* = 0.120s without overshoot in case the proposed control
- *t* = 0.0145s in the case of conventional PI controller, with 0.6% of overshoot.
- *t* = 0.140s in case manually FL, with 0.5% of overshoot.

with application of the load (at *t* = 0.05s), the electromagnetic Torque of PMSM responds with negligible influence in the case of the proposed control, and with an overshoot in the other cases Figure 12(a) and 12(c). At *t* = 0.2s the speed restores quickly on its reference, 100 rad/s in the case of proposed control without overshoot and with a good response time, but with overshoot on the other methods Figure 13(c).

The Table (5) gives a quantitative comparison between the three studied methods, deduced from Figures 13(b), (d) and (e).

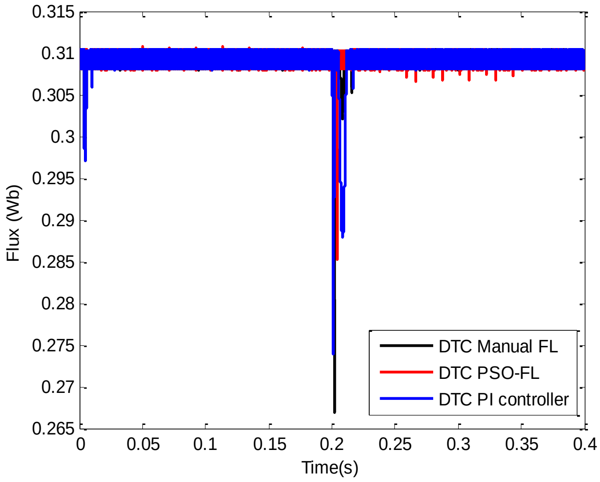
Figure 14(c) shows that the stator flux vector (Figure 14(a)) follows its reference (φ_{sref} = 0.3Wb) and the two flux components $\varphi_{s\alpha}$ and $\varphi_{s\beta}$ are in Quadrature and that and describes a quasi-circular trajectory as shown in Figure 14(d). Figure 14(b) shows that, there is no improvement of stator flux ripple by proposing control compared to other studied technique. Figure 15 shows that the stator current keeps a less noisy sinusoidal form compared to the classic CV [26] and IOL [27].

7. CONCLUSION

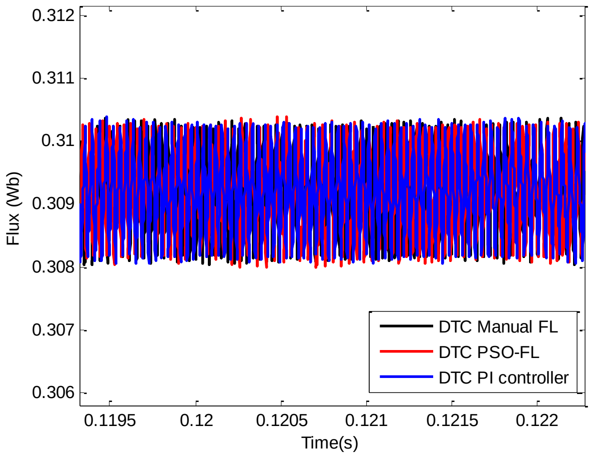
An improved direct torque control algorithm of PMSM is introduced in this paper. We used the Particle Swarm Optimization algorithm to set the three parameters of the FL controller in the DTC. The simulation results indicate that the dynamic performance (response time and overshoot) of the proposed control system is better than the conventional PI or Classical FLC system of PMSM, and he can reduce the flux and torque ripple and less current harmonic comparing to vector control or Input output linearization control.

Table 5. A quantitative comparison between the three studied methods

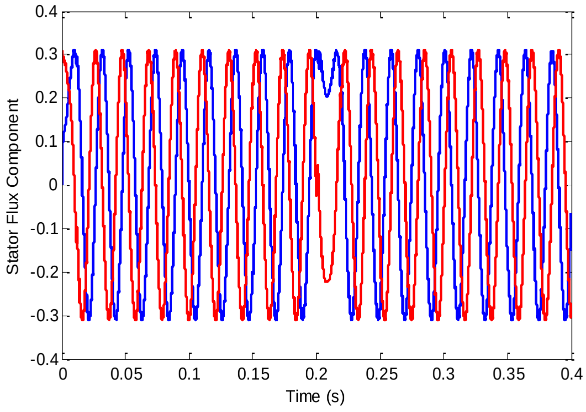
	Response time (s)	Static error		overshoot	Complexity
		(Load=0 N.m)	(Load=5 N.m)		
DTC with Classical PI	0.0128	0.014	0.0041	0.52%	high
DTC with Manual FL	0.0131	0.0004	0.027	0.50%	Very high
DTC PSO-FL	0.0117	0.0037	0.284	0.00%	Medium



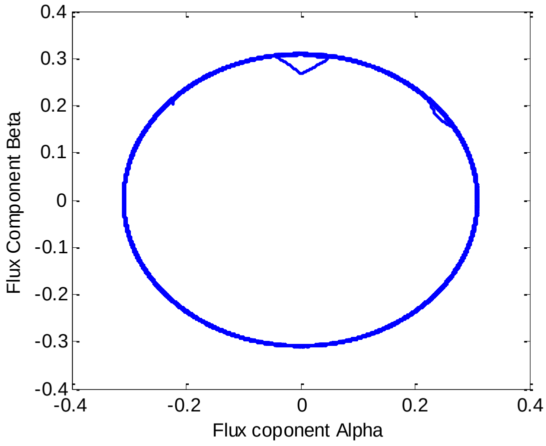
(a)



(b)



(c)



(d)

Figure 14. (a) Stator flux, (b) Zoom in Figure 14(a), (c) Stator flux components ($\phi_{s\alpha}$ and $\phi_{s\beta}$), (d) Stator flux in the plane (α, β)

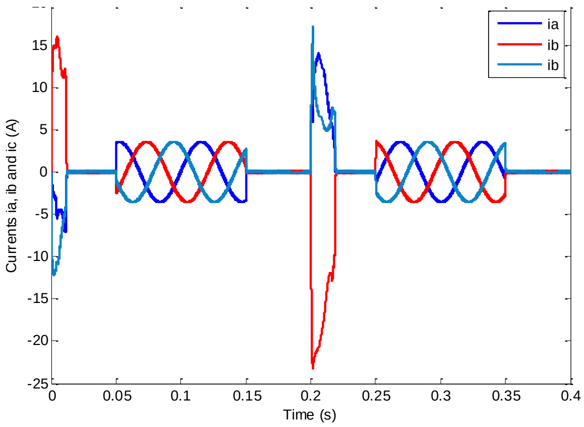


Figure 15. Currents phases (i_{sa}, i_{sb}, i_{sc})

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