Direct Torque Control of Induction Motor Based on Particle Swarm Optimization

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Abstract: *Induction Motor (IM) is most commonly used in different industrial applications, that require fast dynamic response and accurate control over wide speed ranges. Therefore, this paper proposes high performance Direct Torque Control (DTC), which is closed loop control system to improve the dynamic performance of IM. The main objective of this work is to improve the speed response of IM during different load and speed conditions. Proportional-Integral (PI) controller based on Particle Swarm Optimization (PSO) technique is used for optimal gains tuning. The results show the improvement in the speed response of DTC using PSO technique when compared with conventional PI and the conventional DTC (without PI), in terms of reducing steady state error, settling time, overshoot and ripple reduction which make this controller more robust to variation in load and speed. The simulation* *of the overall drive system is performed using MATLAB/Simulink program version 7.10 (R2010a).*

Keywords: Induction Motor (IM), Direct torque control, PI controller and Particle Swarm Optimization (PSO).

1. Introduction

Induction motors are the most common motors used in industrial motion control systems, as well as in main powered home appliances. Simple and rugged design, low-cost, low maintenance and direct connection to an AC power source are the main advantages of AC induction motors [1].

Although Induction motors are easier to design than DC motors, the speed and the torque control in various types of induction motors require a greater understanding of the design and the characteristics of these motors [1].

There are many different methods to drive IM; these methods can be mentioned as: scalar and vector control.

Scalar control is known as V/f control. It assumes a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback. However, this controller doesn’t achieve a good accuracy in both speed and torque responses, mainly due to the fact that the stator flux and the torque are not directly controlled [2,3].

Vector Control can be classified to: Field Oriented Control (FOC) and Direct Torque Control (DTC).

FOC was introduced for the first time by Blaschke in the early 1970s. The main objective of this control method is, as in separately exited DC machines, to independently control the torque and flux; this is done by choosing a d-q rotating reference frame synchronously with the rotor flux space vector [4,5,6].

FOC is based on maintaining the amplitude and the phase of the stator current constants, avoiding electromagnetic transients. FOC involves controlling the stator currents represented by vectors. This control method is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system [7].

DTC was proposed in the middle of 1980 by Takahashi and Depenbrok [8].

DTC has emerged over the last two decades to become one possible alternative to the well-known vector control of induction machines [9,10]

2. Mathematical Model of IM

The mathematical representation of an IM can be depicted as a transformer with moving secondary winding, where the coupling coefficients between the stator and rotor phases change continuously with the change of rotor position [11, 12].

The machine model can be described by differential equation with time varying mutual inductances. Therefore, axis transformation is applied to transfer the three phase parameters (voltage, current and flux) to two–axis frame called (dq-axis stationary frame or park transformation). Park transformation is applied to refer the stator variables to a synchronously rotating reference frame fixed in the rotor, by such transformation the stator and rotor parameters rotate in synchronous speed and all simulated variables in the stationary frame appear as DC quantities in the synchronously rotating reference frame [11,12].

The per-phase equivalent circuit diagrams of an I.M. in two-axis synchronously rotating reference frame.

The two- axis synchronously rotating reference frame equations for the stator and rotor can be written as [10]:

● Stator equation:

$$V_{qs}{}^{e} = R_s i_{qs}{}^{e} + \frac{d\Psi_{qs}}{dt} + w_e \Psi_{ds} \qquad \text{………………… (1)}$$

$$V_{ds}{}^{e} = R_s i_{ds}{}^{e} + \frac{d\Psi_{ds}}{dt} - w_e \Psi_{qs} \qquad \text{………………… (2)}$$

● Rotor equation:

$$V_{qr}^{\ e} = R_r i_{qr}^{\ e} + \frac{d\Psi_{qr}}{dt} + (w_e - w_r)\Psi_{dr} \quad \text{...............(3)}$$

$$V_{dr}^{\ e} = R_r i_{dr}^{\ e} + \frac{d\Psi_{dr}}{dt} - (w_e - w_r)\Psi_{qr} \quad \text{...............(4)}$$

Where:

e : referred to the synchronously rotating reference frame quantities.

$V_{qs}^{\ e}$, $V_{ds}^{\ e}$: quadrature and direct axes stator voltages.

$V_{qr}^{\ e}$, $V_{dr}^{\ e}$: quadrature and direct axes rotor voltages.

R_s : stator resistance .

$i_{qs}^{\ e}$, $i_{ds}^{\ e}$: quadrature and direct axes stator currents .

$i_{qr}^{\ e}$, $i_{dr}^{\ e}$: quadrature and direct axes rotor currents .

Ψ_{qs} , Ψ_{ds} : quadrature and direct axes stator flux.

Ψ_{qr} , Ψ_{dr} : quadrature and direct axes rotor flux.

ω_e : electrical rotor angular velocity (rad / sec).

ω_r : rotor speed (rad/sec).

The development torque by interaction of air gap flux and rotor current can be found as:

$$T_e=(3/2)(P/2)\overrightarrow{\Psi_m} \times \overrightarrow{I_r} \quad \text{................(5)}$$

By resolving the variables into d^e-q^e components [10]:

$$T_e= (3/2)(P/2)\left(\Psi_{ds} i_{qs}^{\ e} - \Psi_{qs} i_{ds}^{\ e}\right) \quad \text{................(6)}$$

The dynamic torque equation of the rotor:

Where: ω_r = is the rotor speed; P: no. of poles; J= rotor inertia; T_L= load torque

The stator current can be found by:

$$i_{ds}{}^{e} = \frac{\Psi_{ds} - \Psi_{qm}}{L_s} \qquad \text{.............(7)}$$

$$i_{qs}{}^{e} = \frac{\Psi_{qs} - \Psi_{qm}}{L_s} \qquad \text{..........(8)}$$

$$\Psi_{qm} = \frac{L_{m1}}{L_s}\Psi_{qs} + \frac{L_{m1}}{L_r}\Psi_{qr} \qquad \text{..........(9)}$$

$$\Psi_{dm} = \frac{L_{m1}}{L_s}\Psi_{ds} + \frac{L_{m1}}{L_r}\Psi_{dr} \qquad \text{.........(10)}$$

Where,

$$L_{m1} = \frac{1}{(\frac{1}{L_m} + \frac{1}{L_s} + \frac{1}{L_r})} \qquad \text{.............(11)}$$

Ψ_{qm} , Ψ_{dm} : quadrature and direct mutual flux .

L_s, L_r, L_m : stator, rotor and mutual inductances respectively

From the previous equations the dynamic model of an induction motor is simulated as shown in figure (1).

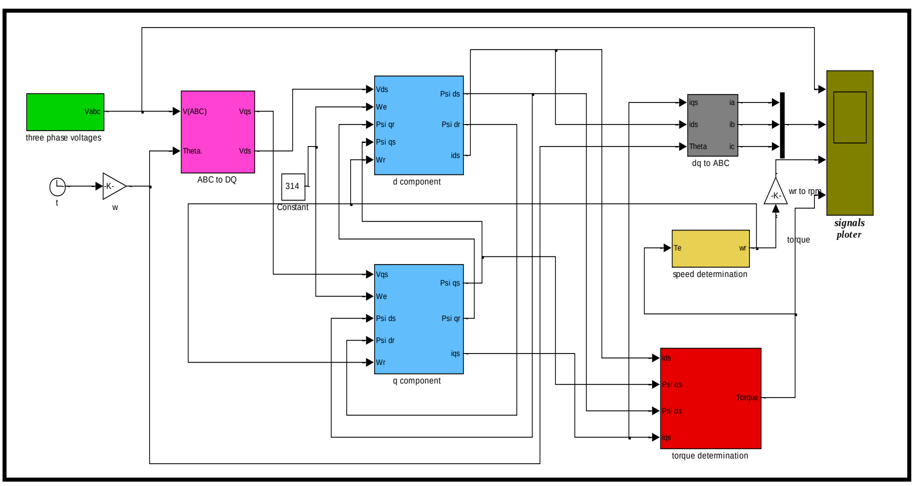


Figure (1) IM dynamic model

3. Direct Torque Control

The DTC has the advantage that it is based on estimation of instantaneous values of flux and torque from only stator variables which are easily measurable. Flux and torque errors with respect to the reference values are used to determine the optimum inverter switching state. Thus the DTC scheme is a very simple structure requiring a pair of bang-bang controllers and a look-up table to select an adequate voltage vector to supply the induction machine [11]. Figure (2) shows the block diagram of DTC

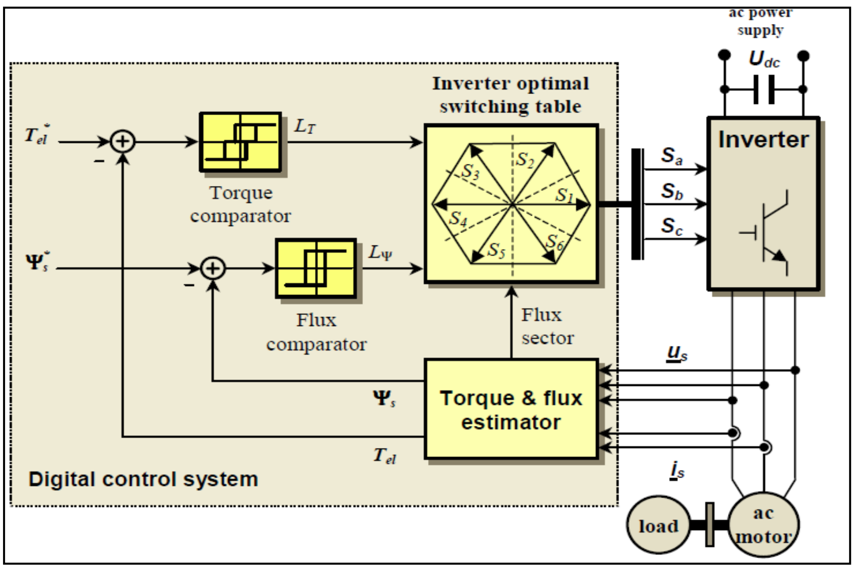


Figure (2) DTC block diagram.

Generally, in a symmetrical three phase induction motor, the instantaneous electromagnetic torque is proportional to the cross product of the stator flux linkage space vector and the rotor flux linkage space vector [13].

$$T_e = \left(\frac{3P}{2}\right) \psi_s \psi_r \sin\delta \qquad \text{.........................} (12)$$

Where ψ_s , is the stator flux linkage space vector , ψ_r is the rotor flux linkage space vector referred to stator and δ is the angle between the stator and rotor flux linkage space vectors.

The estimator equations for stator flux (ψ_s), stator flux position (θ_s) and torque are:

$$\psi_s = \sqrt{{\psi_{qs}}^2 + {\psi_{ds}}^2} \quad \text{..... .... (13)}$$

$$\theta_s = \tan^{-1}\frac{\psi_{qs}}{\psi_{ds}} \quad \text{.... .... (14)}$$

$$T_e = \left(\frac{3p}{2}\right)(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \quad \text{....... .... (15)}$$

4. PI Controller

The PI controller has been widely used in industry due to simple implementation, low cost and the ability to apply in a wide range of applications. It also improves the dynamic response of the system as well as reduces or eliminates the steady state error and the error sensibility. This is achieved by providing a proportional gain (K_p) for the error input term with an integral component correction (K_i). PI controller has the general form**:**

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau \quad \text{..................(16)}$$

Where, u(t) is the output of the PI controller and e(t) is the error signal.

5. Particle Swarm Optimization

The PSO algorithm is one of the optimization techniques developed by Eberhart and Kennedy in 1995. This method has been found to be robust in solving problems featuring non-linearity and non-differentiability, which is derived from the social-psychological [14]. It was inspired by the social behavior of bird flocking and fish schooling, and has been found to be robust in solving continuous nonlinear optimization problems. PSO becomes a focus these days due to its simplicity and ease to implement [15].

In PSO, each single solution is a “bird” in the search space; this is referred to as a “particle”. The swarm is modeled as particles in a multidimensional space, which

have positions and velocities. These particles have two essential capabilities: their memory of their own best position and knowledge of the global best position. Members of a swarm communicate good positions to each other and adjust their own position and velocity based on good positions. The particles are updated according to the following equation (17.a &b) [16].

$$v(k+1)_{i,j} = w.\,v(k)_{i,j} + c_1 r_1\big(gbest - x(k)_{i,j}\big) + c_2 r_2\big(pbest_j - x(k)_{i,j}\big) \quad \text{................(17.a)}$$

$$x(k+1)_{i,j} = X(k)_{i,j} + v(k)_{i,j} \quad \text{................(17.b)}$$

Where,

$v_{i,j}$: velocity of particle i and dimension j.

$x_{i,j}$: position of particle i and dimension j.

c_1,c_2: known as acceleration constants.

w : inertia weight factor.

r_1,r_2 : random numbers between 0 and 1.

pbest: best position of a specific particle.

gbest: best particle position of the group.

Figure (3) shows the PSO algorithm flow chart.

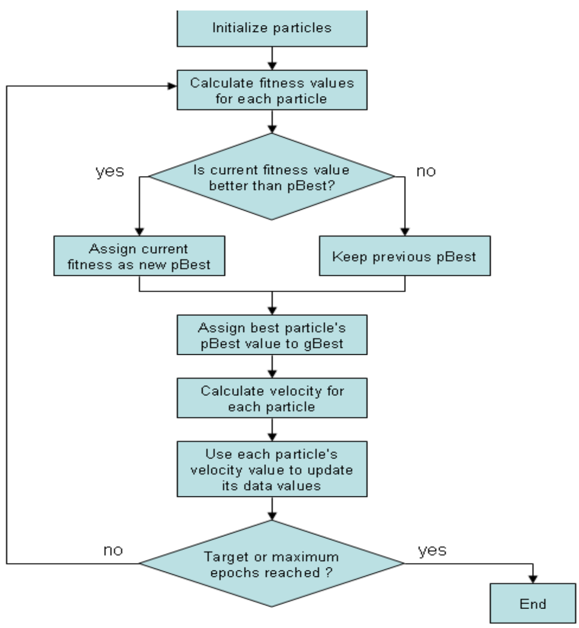


Figure (3) Flow chart PSO algorithm

6. Performance Criteria of PSO-PI Controller

In most intelligent optimization algorithms, there are commonly performance criteria such as: Integrated Absolute Error (IAE), the Integrated of Square Error (ISE), and Integrated of Time Square Error (ITSE). That can be evaluated analytically in frequency domain. These performance criteria are including the overshoot, rise time, settling time and steady-state error. In addition, it has been indicated the optimization, and robust of the drive system [14].The performance criterion formulas are as follows:

Integral Square Error (ISE) $= \int_0^\infty e^2(t).\,dt$ …………………...(18)

Integral Absolute Error (IAE) = $\int_0^\infty |e(t)|.\,dt$ …………… (19)

Integral Time Square Error (ITSE) $= \int_0^\infty t.\,e^2(t).\,dt$ ………(20)

In this work the (ITSE) time domain criterion is used as a "fitness function" for evaluating the PI controller performance. A set of good controller parameters K_p and K_i can yield a good step response that will result in performance criteria minimization [14].

7. Simulation and Results

The electrical design parameters values for 3 phase squirrel cage IM used in the simulation are shown in Table (1).

Table (1) motor design data

Item	Value
Rated power	2.2KW
Nominal frequency	50Hz
Rated voltage	400V
No. of pole pairs	2
Rated speed	1430rpm
Stator resistance	2.3 Ω
Rotor resistance	3.14 Ω
Stator inductance	0.0136 H
Rotor inductance	0.0136 H
Mutual inductance	0.3 H
Moment of inertia	$4.5*10^{-3}$ $Kg.m^2$ /sec

Table (2) Shows the used lookup table for optimum switching state

Table (2) switching table

Flux error	**Torque error**	**Flux sectors**					
		S1	**S2**	**S3**	**S4**	**S5**	**S6**
1	1	001	011	010	110	010	100
	0	000	000	111	000	111	111
	-1	010	100	001	011	101	110
0	1	011	101	110	010	100	001
	0	111	111	000	111	000	000

The conventional DTC block diagram is implemented by Simulink program as shown in figure (4)

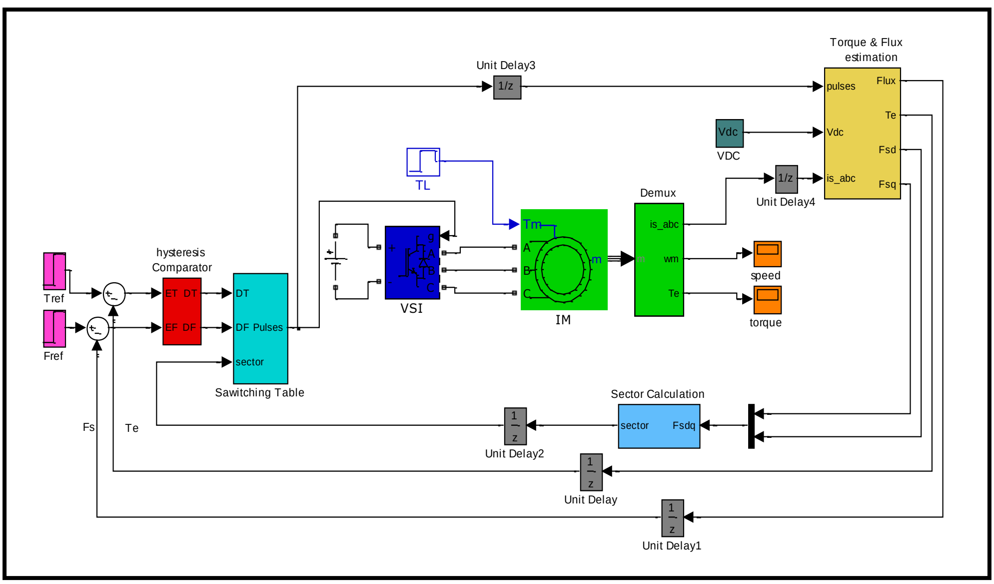


Figure (4) Conventional DTC circuit

Speed and torque responses of IM for conventional DTC for no load at (0-0.3) sec, 14 N.m.at(0.3-0.7)sec, and 7N.m. at (0.7-1)sec are shown in figures (5,6,7).

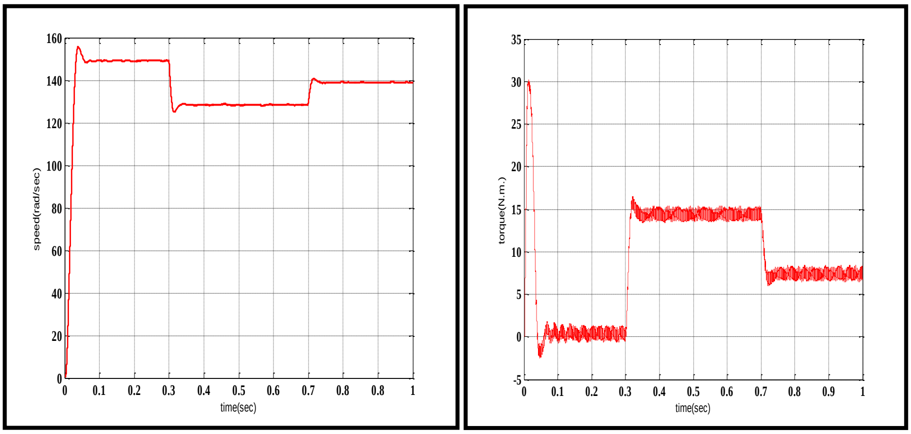


Figure (5) Speed and torque responses

at ω=149 rad/sec,TL= (0-14-7)N.m.

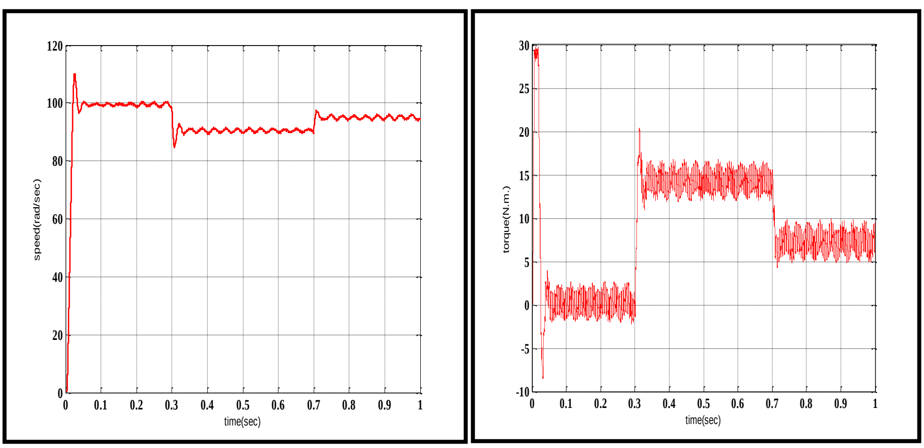
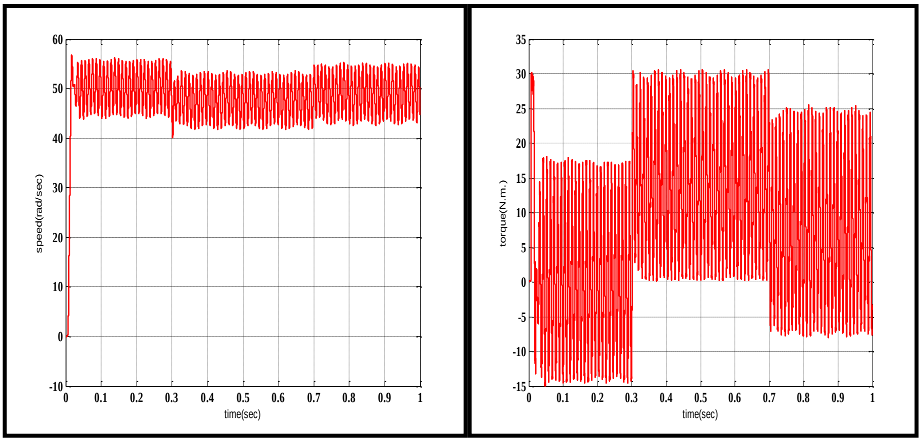


Figure (6) Speed and torque responses

at ω=100 rad/sec, TL= (0-14-7)N.m.



Figure(7) Speed and torque responses

at ω=50 rad/sec, TL= (0-14-7)N.m.

DTC with conventioanl PI controller simulink program is shown in figure (8).

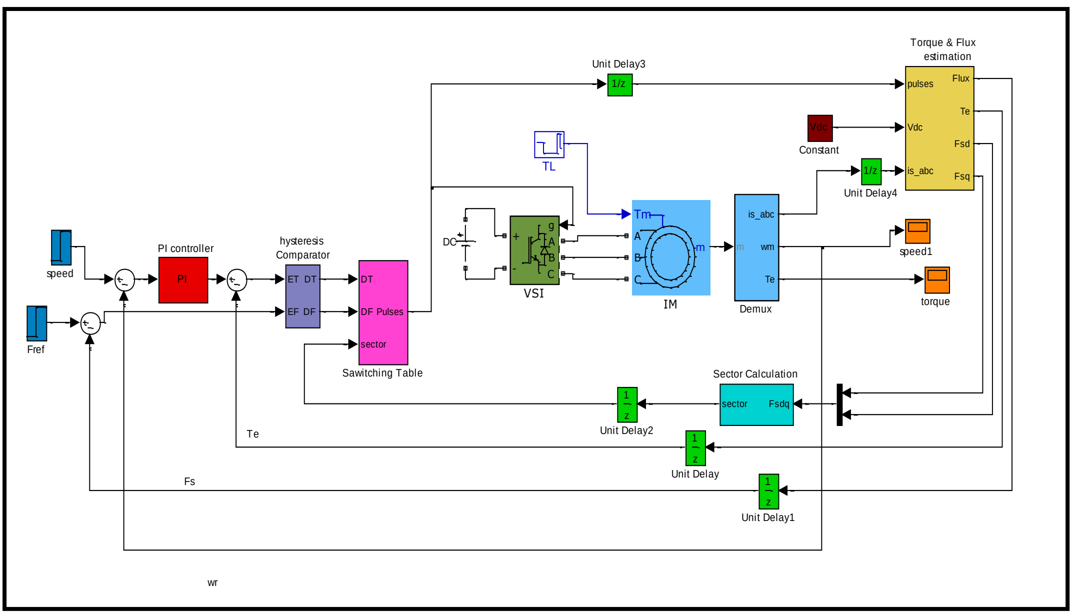


Figure (8) Simulink program of DTC with conventional

PI controller

The conventional PI controller is tuned manually by trial and error method, the obtained gains are kp= 1.7 and ki=0.25.

Speed and torque responses of IM for DTC with PI controller tuned by trial and error for no load at(0-0.3)sec, 14 N.m. at (0.3-0.7)sec, and 7N.m. at (0.7-1)sec are shown in figures (9), (10) and (11).

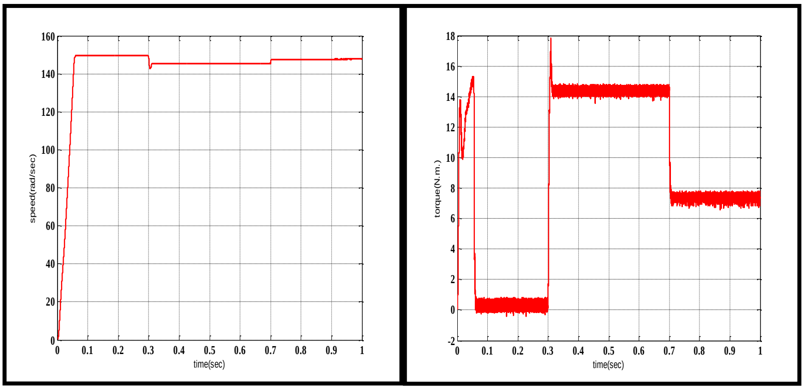
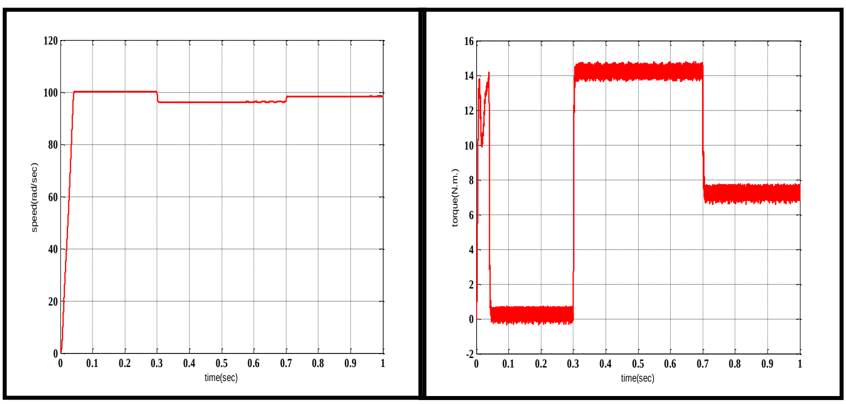


Figure (9) Speed and torque responses at ω=149 rad/sec,

TL= (0-14-7)N.m.



Figure(10) Speed and torque responses at ω=100 rad/sec,

TL= (0-14-7)N.m.

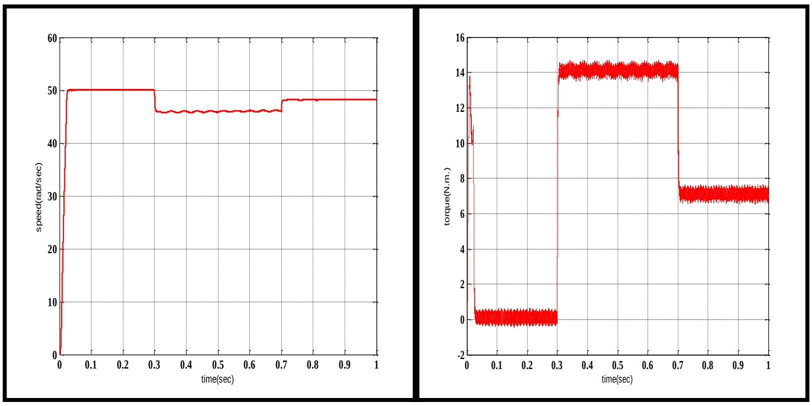


Figure (11) Speed and torque responses at ω=50 rad/sec,

TL= (0-14-7)N.m.

The PSO tuning method in this work depends on ITAE performance index. The parameters of PSO algorithm that achieve better solution are listed in Table (3).

Table (3) PSO parameters

Swarm size (Number of birds)	20
Number of iterations	20
Cognitive coefficient (C_1)	3
Social coefficient (C_2)	4
Inertia weight (w)	0.9

PI-PSO gains that taken by using this technique are kp=4.663, ki=1.957, Speed and torque responses of IM for PI-PSO controller at different loads are shown in figures (12), (13) and (14).

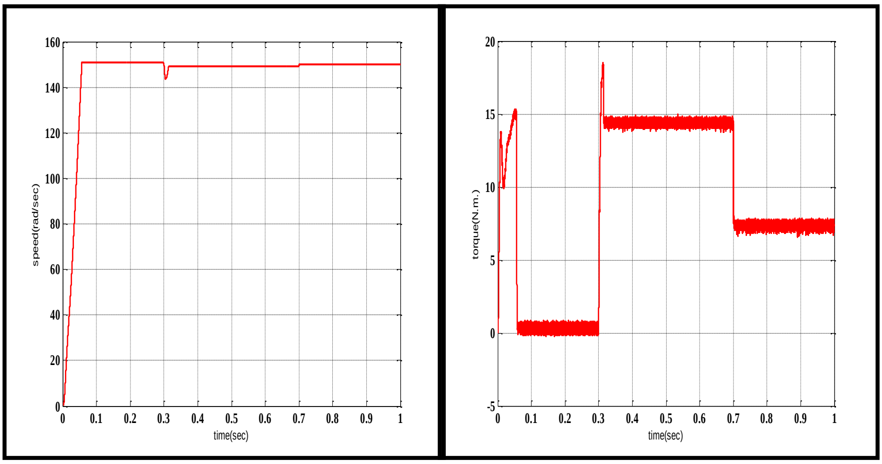


Figure (12) Speed and torque responses at ω=149 rad/sec,

TL= (0-14-7)N.m.

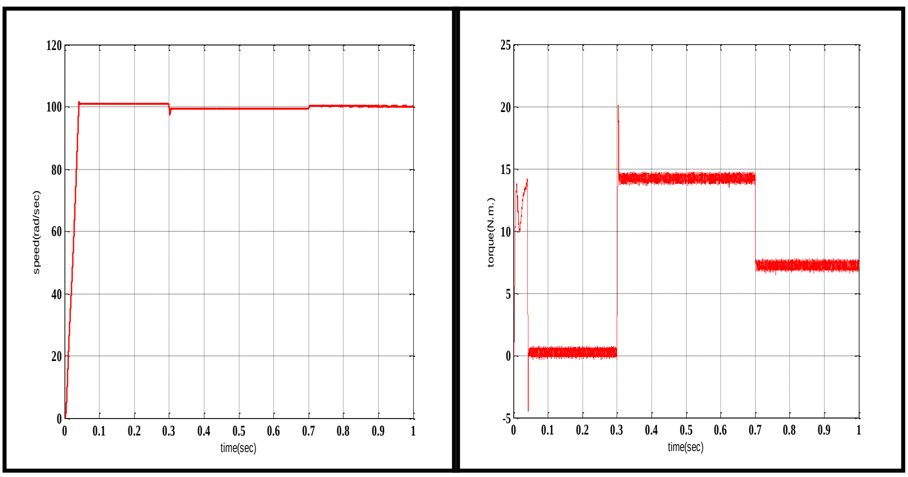


Figure (13) Speed and torque responses at ω=100rad/sec,

TL= (0-14-7)N.m.

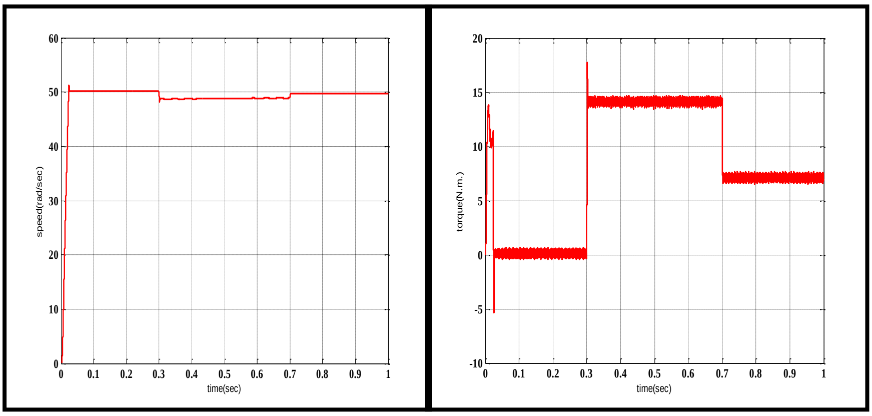


Figure (14) Speed and torque responses at ω=50rad/sec, TL= (0-14-7)N.m.

The zoomed speed responses of IM at different loads (no load,14,7)N.m, for conventional DTC,PI-trial&error and PI-PSO are shown together in figures (15), (16) and (17) .

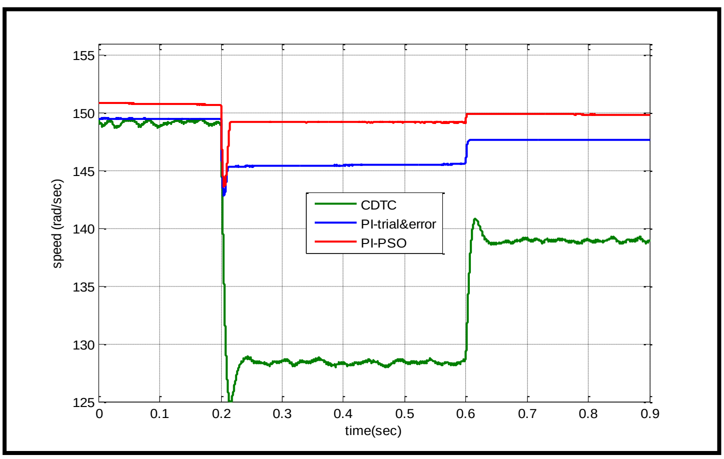


Figure (15) peed response at ω= 149rad/sec.

(CDTC: conventional DTC)

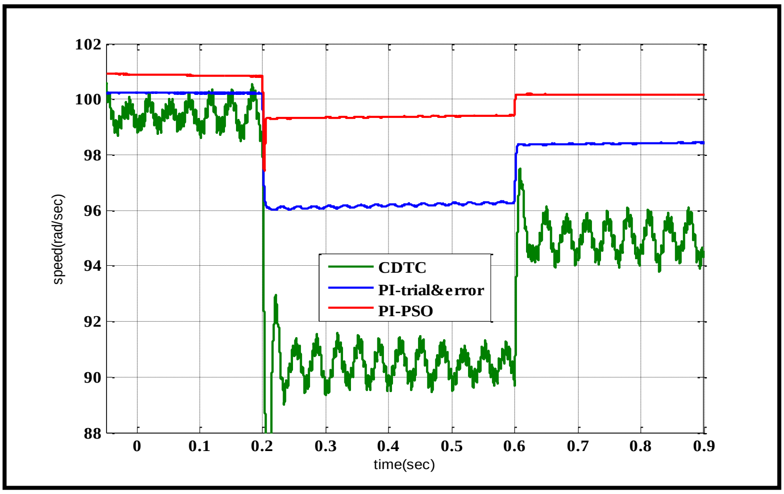


Figure (16) Speed response at ω=100rad/sec.

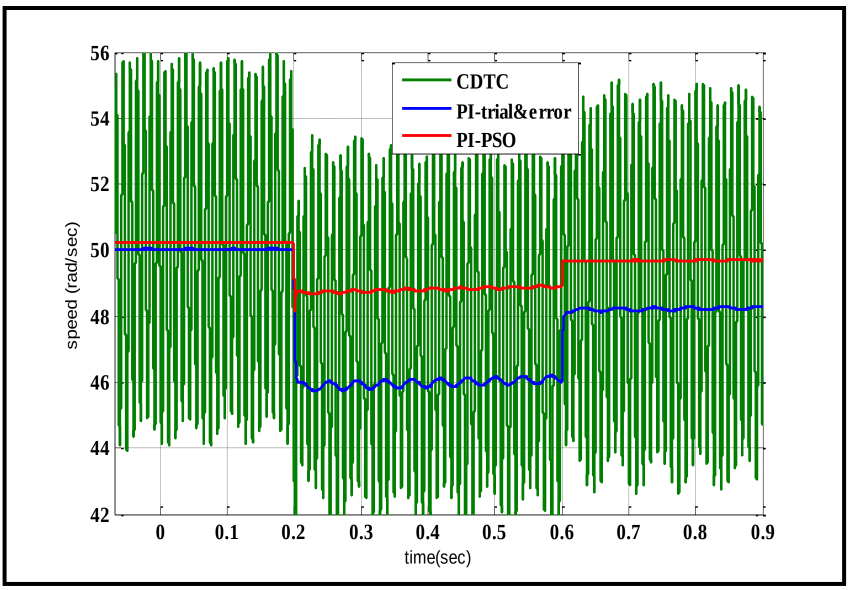


Figure (17) Speed response at ω=50rad/sec.

The speed and torque responses can be more explained in the tables (3),(4)and (5).

Table (4) Speed and torque responses at ω= 149 rad/sec

	No load			Full load			Medium load		
Controller	**CDTC**	**PI-trial and error**	**PI-PSO**	**CDTC**	**PI-trial and error**	**PI-PSO**	**CDTC**	**PI-trial and error**	**PI-PSO**
Steady state error	0.1	0.51	1.7	20.5	3.5	0.25	10.4	1.33	0.8
Settling time with error ±(1 rad/sec)	0.075	0.062	0.058	0.35	0.313	0.315	0.74	0.705	0.703
Torque ripple N.m.(peak to peak)	2.75	1.2	1	2	0.8	0.8	1.9	1.1	1.1

Table (5) Speed and torque responses at ω=100 rad/sec

	No load			Full load			Medium load		
Controller	**CDTC**	**PI-trial and error**	**PI-PSO**	**CDTC**	**PI-trial and error**	**PI-PSO**	**CDTC**	**PI-trial and error**	**PI-PSO**
Steady state error	**0.6**	**0.24**	**0.75**	**9.5**	**3.5**	**0.65**	**5**	**1.64**	**0.16**
Settling time with error ± (1rad/sec)	**0.05**	**0.048**	**0.043**	**0.327**	**0.31**	**0.305**	**0.723**	**0.706**	**0.702**
Torque ripple N.m.(peak to peak)	**4.9**	**0.85**	**0.85**	**4.75**	**1.17**	**1.17**	**4.8**	**1.2**	**1.2**

Table (6) Speed and torque responses at ω=50 rad/sec

	No load			Full load			Medium load		
Controller	**CDTC**	**PI-trial and error**	**PI-PSO**	**CDTC**	**PI-trial and error**	**PI-PSO**	**CDTC**	**PI-trial and error**	**PI-PSO**
Steady state error	**6 , - 6**	**0.025**	**0.24**	**8 , -8**	**4**	**1.5**	**6.3, -6. 3**	**1.75**	**0.3**
Settling time with error ± (1rad/sec)	**0.032**	**0.03**	**0.027**	**0.305**	**0.306**	**0.304**	**0.71**	**0.706**	**0.702**
Torque ripple N.m.(peak to peak)	33.5	1.05	1.05	31	1.2	1.2	32.5	1.3	1.3

8. Conclusion

The PI controller is normally used in the industry due to its simple structure, and its ability to be applied for a wide range of applications. The selection of the PI-controller gains by trial and error is difficult and time consumer, in order to overcome this difficulty the PSO is used to obtain the optimal gains. PSO tuning technique takes less time and has fast convergence.

PI -trial and error controller has advantages over conventional DTC in terms of less steady state error, less settling time, less torque ripple and zero over shoot at any load condition as shown in figures (15), (16) and (17).

PI-PSO controller has advantages over PI-trial and error in terms of less steady state error at different loads, less settling time, zero over shoot at rated speed and very small over shoot at the low speeds as shown in figures (15), (16) and (17).

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السيطرة المباشرة على العزم في المحرك الحثي بأستخدام تقنية أفضلية الحشد الجزيئي

أ.م.د. عبد الرحيم ذياب حمود وئام اسماعيل
الجامعة التكنولوجية – قسم الهندسة الكهربائية

المستخلص:

يعد المحرك الحثي الأكثر شيوعا في التطبيقات الصناعية المختلفة، التي تتطلب إستجابة ديناميكية سريعة ودقة في السيطرة لمديات واسعة من السرعة، لذا تم في هذه الدراسة اقتراح استخدام تقنية السيطرة المباشرة على العزم (DTC) العالية الاداء، والتي تعتبر من طرق السيطرة ذات الحلقة المغلقة لتحسين الاستجابة الديناميكية للمحرك. الهدف الاساس من هذا العمل هو تحسين أداء المحرك عند أحمال وسرع مختلفة. إستُخْدِم المسيطر التناسبي–التكاملي (PI) المستند على تقنية أفضلية الحشد الجزيئي (PSO) للأختيار الامثل لقيم المتغيرات (gains). تبين من النتائج التحسين الذي طرأ على أداء تقنية السيطرة DTC في استجابة السرعة بإستخدام PI-PSO اذا ما قورِنَ مع المسيطر PIالتقليدي وDTC التقليدي (بدون PI)، من حيث تقليل أخطاء الحالة المستقرة، زمن الوصول، التجاوز بالاضافة الى تقليل التموج (التذبذب) في موجتي السرعة والعزم، وهذا يجعل المسيطر أكثر متانةً لتغيرات الحمل والسرعة. إستُخدِم لمحاكاة هذا العمل برنامج MATLAB/Simulink الاصدار 7.10 لسنة 2010.