PSO-Based Optimum Design of PID Controller for Switching Reluctance Motor

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ABSTRACT

This paper presents simulation results for three phase, 6/4 poles switched reluctance motor (SRM) by using particle swarm optimization (PSO) method for formative the optimal proportional-integral-derivative (PID) controller tuning parameters.The proposed approach has superior feature, including easy implementation, stable convergence characteristics and very good computational performances efficiency. The main focus of this paper is to investigate the dynamic performance of switched reluctance (SR) motors. This investigation is achieved through simulation using MATLAB/SIMULINK. Digital simulation results show that the designed (PSO) have a good dynamic behaviour of the motor, a perfect speed tracking with no overshoot and a good rejection of impact loads disturbance. The results of applying the (PSO) mode controller to a SRM give best performances and high robustness than those obtained by the application of others controller. The obtained results of the closed loop PSO-PID response shows excellent performance with respect to the PID controller.

Keywords: Switched Reluctance Motor; Particle Swarm Optimization Strategy; Scheduling PID-PSO Controller; Speed Control.

التصميم المثالي المستند الى حشد الجزيئات للمسيطر التناسبي – التكاملي – التفاضلي(PID) لمحرك المعاوقة التبادلي

الخلاصة

يقدّم هذه البحث نتائج محاكاة لمحرك المعاوقة التبادلي (SRM)**ثلاثي الطور** 4/6اقطاب باستخدام الطريقة المثلى لحشد الجزيئات (PSO) لمشكلت وليف بارامتراتا لمسيطر المثالي التناسبي – التكاملي – التفاضلي (PID).ان النظرة المقترحة لها ميزّة متفوّقة، يضمن ذلك سهولة التطبيق، خصائص تقارب مستقرّة وكفاءة أداء حسابية جيدة جدا. إنّ الهدف الرئيسي لهذاالبحث هو ألتحرّى في الأداء الديناميكي لمحرّكات المعاوقة التبادلي . هذا التحقق ينجز من خلال استخدام المحاكاة \ماتلاب. ان نتائج المحاكاة

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الرقمية تبين بان مسيطر السرعة المصمم (PSO) يعطي سلوك دينامي جيد للمحرك وسرعة تعقّب مثالية بدون الخروج عن المدى (overshoot) و تجاوز جيد لاضطرابات الحمل. نتائج تطبيق مسيطر (PSO) على ال (SRM) تعطي أفضل اداء ومستوى عالي مقارنة بالنتائج التي نحصل عليها باستخدام مسيطر PID.

INTRODUCTION

Switched Reluctance Motors (SRMs) can be applied in many industrial applications due to their cost advantages and ruggedness. The switched reluctance motor is simple to construct. It is not only features a salient pole stator with concentrated coils, which allows earlier winding and shorter end turns than other types of motors, but also features a salient pole rotor, which has no conductors or magnets and is thus the simplest of all electric machine rotors.

Simplicity makes the SRM inexpensive and reliable, and together with its high speed capacity and high torque to inertia ratio, makes it a superior choice in different applications. However, the motor is highly nonlinear and operates in saturation to maximize the output torque. Moreover, the motor torque is a nonlinear function of current and rotor position. This highly coupled nonlinear and complex structure of the SRM make the design of the controller difficult [1].

The speed of SR motor can be adjusted to a great extent as to provide controllability easy and high performance [2- 3]. The controllers of the speed that are conceived for goal to control the speed of SR motor to execute one variety of tasks, is of several conventional and numeric controller types, the controllers can be: PID Controller, Fuzzy Logic Controller; or the combination between them: Fuzzy-Neural Networks, Fuzzy-Genetic Algorithm, Fuzzy- Ants Colony, Fuzzy-Swarm.

The application of PSO mode in switched reluctance motor speed control is described in this paper.Many electrical machine researchers are investigating the dynamic behaviour of switched reluctance motor (SRM) by monitoring the dynamic response (torque and speed), minimising the torque ripples, building different types of controllers to reduce the cost, to increase the general performance of SRM and reliability. In the present study, the switched reluctance motor is simulated to study the dynamic performance usingMatlab / Simulink environment. It is very useful and powerful simulation tool and provides greater flexibility to simulate various features of SR motors's performance[4-7].

SRM MODEL

The physical appearance of a Switched Reluctance motor (SRM) is similar to that of other rotating motors (AC and DC) Induction Motor, DC motor etc. the advantages of this motor is a very reliable machine since each phase is largely independent physically, magnetically, and electrically from the other machine phases. It can achieve very high speeds (20000 - 50000 r.p.m.) because of the lack of conductors or magnets on the rotor.

The construction of 6/4 (6 stator poles, 4 rotor poles) poles SRM is shown in figure1. It has doubly salient construction. Usually the number of stator and rotor poles is even. The windings of Switched Reluctance Motor are simpler than those of other types of motor. There is winding only on stator poles, simply wound on it and no winding on rotor poles.

MACHINE EQUATION

The switched reluctance motor has a simple construction, but the solution of its mathematical models is relatively difficult due to its dominant non-linear behavior. The flux linkage is a function of two variables, the current I and the rotor position (angle θ). The mathematical model from the equivalent circuit is [8];

$$V_j = RI_j + \frac{d\Psi_j(\mathrm{i},\theta)}{\mathrm{dt}} \quad \text{... (1)}$$

with j=1,2,…4

Then we can write:

$$V_j = RI_j + \frac{d\Psi_j(\mathrm{i},\theta)\mathrm{di}}{\mathrm{di} \quad \mathrm{dt}} + \frac{d\Psi_j(\mathrm{i},\theta)}{\mathrm{d}\theta}\omega \quad \text{...(2)}$$

j=1, 2…4

In which: $\omega = \mathrm{d}\theta/\mathrm{dt}$

The motion equation is:

$$\mathrm{J}\frac{\mathrm{d}\omega}{\mathrm{dt}} = T_0 - T_1 - f_\omega \quad \text{... (3)}$$

It is a set four non-linear partial differential equations, its solution neglecting the nonlinearity of magnetic saturation.

$$\Psi(i,\theta) = \mathrm{i}\ \mathrm{L}(\theta) \quad \text{... (4)}$$

It can be written as:

$$V_j = RI_j + \mathrm{L}(\theta)\frac{\mathrm{di}}{\mathrm{dt}} + i\frac{\mathrm{dL}(\theta)}{\mathrm{d}\theta}\omega \quad \text{... (5)}$$

j=1, 2,..4

$$T_0 = \frac{1}{2}\frac{\mathrm{dL}(\theta)}{\mathrm{d}\theta}i^2 \quad \text{... (6)}$$

The average torque can be written as the superposition of the torque of the individual motor phases:

$$T_0 = \sum_{phase=1}^{n} T_{phase} \quad \text{...(7)}$$

From the state equations (1), (2), (3) previous, can construct the model with the environment matlab simulink version 7.10.0.499(R2010a).The model of the SR motor in Simulink is shown in Figure(2).

The SRM is fed by a three-phase asymmetrical power converter having three legs, each of which consists of two IGBTs and two free-wheeling diodes. During conduction periods, the active IGBTs apply positive source voltage to the stator windings to drive positive currents into the phase windings. During free-wheeling periods, negative voltage is applied to the windings and the stored energy is returned to the power DC source through the diodes. The fall time of the currents in motor windings can be thus reduced. By using a position sensor attached to the rotor, the turn-on and turn-off angles of the motor phases can be accurately imposed. These switching angle can be used to control the developed torque waveforms. The phase currents are independently controlled by three hysteresis controllers which generate the IGBTs drive signals by comparing the measured currents with the references. The IGBTs switching frequency is mainly determined by the hysteresis band.

SIMULATION OF THE SRM DRIVE

The converter turn-on and turn-off angles are kept constant at 45 deg and 70 deg, respectively, over the speed ranges. The current is 200 A and the hysteresis band is chosen as +-10 A. The SRM is started by applying the step to the regulator input. The SRM drive waveforms (magnetic flux, windings currents, motor torque, and motor speed) are displayed on the scope as can be noted in figure 3, the SRM torque has a very high torque ripple component which is due to the transitions of the currents from one phase to the following one. This torque ripple is a particular characteristic of the SRM and it depends mainly on the converter s turn-on and turn-off angles. In observing the drive's waveforms, we can remark that the SRM operation speed range can be divided into two regions according to the converter operating mode: current-controlled and voltage-fed.

A. Current-controlled mode

From stand still up to about 3000 rpm, the motor's emf is low and the current can be regulated to the reference value. In this operation mode, the average value of the developed torque is approximately proportional to the current reference. In addition to the torque ripple due to phase transitions, we note also the torque ripple created by the switching of the hysteresis regulator. This operation mode is also called constant torque operation.

B.Voltage-fed mode

For speeds above 3000 rpm, the motor's emf is high and the phase currents cannot attain the value imposed by the current regulators. In voltage-fed mode, the SRM develops its 'natural' characteristic in which the average value of the developed torque is inversely proportional to the motor speed.

Particle Swarm Optimization (PSO)

PSO is a population-based optimization method first proposed by Eberhart and Colleagues [9], [10]. Some of the attractive features of PSO include the ease of implementation and the fact that no gradient information is required. It can be used to solve a wide array of different optimization problems. Like evolutionary algorithms, PSO technique conducts search using a population of particles, corresponding to

individuals. PSO is one of the modern heuristic algorithms; it was inspired by the social behavior of bird and fish schooling, and has been found to be robust in solving continuous non-linear optimization problems [5, 11]. PSO simulates the behaviors of the bird flocking. Suppose the food group of birds is randomly searching food in an area, all the birds do not know where the food is. But they know how each iteration. PSO learned from the scenario and used it to solve the optimization problems; solution is "bird" in the search space. We call it "particle" all of particles which are evaluated by the fitness function to be optimized, and have velocities flying of the particles [15].
In the PSO algorithm, instead of using evolutionary operators such as mutation and crossover, to manipulate algorithms, for a d-variable optimization problem, a flock of particles are put into the d-dimensional search space with randomly chosen velocities and positions knowing their best values so far (Pbest) and the position in the d-dimensional space. The velocity of each particle, adjustedaccording to its own flying experience and the other particle'sflying experience. For example, the i th particle is represented as:
$x_i = (x_{i,1}, x_{2,i}, \ldots\ldots x_{i,d})$ in the d-dimensional space. The best previous position of the ith particle is recorded and represented as:

$$\text{Pbest}_i=(\text{Pbest}_{i,1},\text{Pbest}_{i,2},\ldots,\text{Pbest}_{i,d}) \quad \ldots(8)$$

The index of best particle among all of the particles in the group is gbest. The velocity for particle i is represented as:
$\text{v}_i = (\text{v}_{i,1}, \text{v}_{i,2}, \ldots \text{v}_{i,d})$. The modified velocity and position of each particle can be calculated using the current velocity and the distance from Pbesti,d to gbestd

$$\text{v}_{\text{i,m}}^{(\text{t+1})} = \omega.\text{v}_{\text{i,m}}^{(\text{t})} + \text{c}_1 * \text{rand}(\quad) \quad * \left(\text{pbest}_{i,m} - \text{x}_{\text{i,m}}^{(\text{t})}\right) + \text{c}_2 * \text{Rand} * (\quad) \left(\text{gbest}_m - \text{x}_{\text{i,m}}^{(\text{t})}\right) \quad \ldots(9)$$

$$\text{X}_{\text{i,m}}^{(\text{t+1})} \text{x}_{\text{i,m}}^{(\text{t})} + \text{v}_{\text{i,m}}^{(\text{t+1})} \quad \ldots(10)$$

i=1,2,..,n
m=1,2,..,d
where
n - number of particles in the group
d -dimension
t - pointer of iterations(generations)
$\text{v}_{\text{i,m}}^{(\text{t})}$ - velocity of particle I at iteration t
$\text{V}_{\text{d}}^{(\text{min})} \leq \text{v}_{\text{i,d}}^{(\text{t})} \leq \text{V}_{\text{d}}^{(\text{max})}$

- Inertia weight factor

c_1,c_2 - Acceleration constant
rand()- Random number between 0and1.
Rand ()
$X_{i,d}^{(t)}$- current position of particle I atiterations.
$Pbest_i$ - Best previous position of the ith particle .
gbest - Best particle among all the particles in the population as shown in the figure 4[11].

A. Fitness Function

In PID controller design methods, the most common performance criteria are integrated absolute error (IAE), the integration of time weight square error (ITSE) and integration of squared error (ISE) that can be evaluated analytically in the frequency domain [12], [13]. These three integral performances criteria in the frequency domain have their own advantage and disadvantages. For example, disadvantage of the IAE and ISE criteria is that its minimization can result in a response with relatively small overshoot but a long settling time because the ISE performance criterion weights all errors equally independent of time. Although the ITSE performance criterion can overcome the disadvantage of the ISE criterion, the derivation processes of the analytical formula are complex and time-consuming [14]. The IAE, ISE, and ITSE performance criterion formulas are as follows:

$$IAE = \int_0^\infty |r(t) - y(t)|\, dt = \int_0^\infty |e(t)|\, dt \quad \dots (11)$$

$$ISE = \int_0^\infty e^2(t)\, dt \quad \dots (12)$$

$$ISTE = \int_0^\infty te^2(t)\, dt \quad \dots (13)$$

In this paper a time domain criterion is used for evaluating the PID controller [13]. A set of good control parameters P,I and D can yield a good step response that will result in performance criteria minimization in the time domain. These performance criteria in the time domain include the overshoot, rise time, settling time, and steady-state error. Therefore, the performance criterion is defined as follows [11]:

$$min_{kstabilizing}\, W(K) = (1 - e^{-\beta}).\left(M_p + E_{ss}\right) + e^{-\beta}.\left(t_s - t_r\right) \quad \dots (14)$$

Where K is [P, I, D], and β is the weightening factor. The performance criterion W(K) can satisfy the designer requirement using the weightening factor β value. β can set to be larger than 0.7 to reduce the overshoot and steady states error, also can set smaller than 0.7 to reduce the rise time and settling time [11]. The optimum selection of β depends on the designer's requirement and the characteristics of the plant under control. In SR motor speed control system the lower β would lead to more optimum responses. In this paper, due to trials, β is set to 0.5 to optimize the step response of speed control system.

The fitness function is reciprocal of the performance criterion, in the other words:

$$f = \frac{1}{W(K)} \quad \dots (15)$$

B. Proposed PSO-PID Controller.

In this paper a PSO-PID controller used to find the optimal parameters of SRM speed control system. Figure(5) shows the block diagram of optimal PID control for the SR motor.

In the proposed PSO method each particle contains three members I, P and D. It means that the search space has three dimension and particles must 'fly' in a three dimensional space. The flow chart of PSO-PID controller is shown in Figure(6).

Simulation Results

To control the speed of the SR motor at 3000r.p.m, according to the trials, the following PSO parameters in Table (1) were used to verify the performance of the PSO-PID controller parameters. Figure (7) shows the design system of SRM with PSO-PID controller by using the SIMULINK software in MATLAB environment. Table(2) show the performance of PSO-PID Controller and PID Controller at no-load and full- load .

The simulation results are obtained for 0.01 second range time. The best population may be plotted to give an insight into how the PSO Algorithm converged to its final values as illustrated in Figure (8). The speed responses of PID Controllertuning parameters (at half rated speed) and with using particle swarm optimization strategy are shown in Figure (9) and Figure (10), respectively. In Figure (9) we noted the over shooting for the speed between (+28, -3) but in Figure (10) is not over shooting at no-load and (-3.5) at full-load as shown in Table(2).Figure(11) shows the speed response using PSO strategy(at rated speed),Figure.(12) show the comparing performance of PSO-PID controller and PID controller, so the PID-PSO controller is the best which presented satisfactory performances and possesses good robustness (no overshoot, minimal rise time, Steady state error=0). The performance of PID-PSO controller (ParticleSwarm Optimization) Algorithm values: Kp = 4.6535; Ki = 5.4380; Kd = 0.0384.

Figure (11) show the speed response using PSO strategy (at rated speed).

Table.1Parameters of PSO algorithms.

Population Size	20
Number of Iterations	15
*w*max	0.6
*w*min	0.3
$c1 = c2$	2

Table(2) Performance of PSO-PID Controller and PID Controller at no-load and full- load.

Results	*NO-LOAD*		*FULL-LOAD*	
	PID-Con.	*PSO-PID*	*PID-Con.*	*PSO-PID*
Maximum overshot	*+28 -3*	*0*	*+1.8 -24*	*-3.5*
Rising time (sec.)	*0.5*	*0.03*	*0.2*	*0.01*
Settling time(sec.)	*1.85*	*0.04*	*1.1*	*0.1*
Steady state error (%)	*0 %*	*0 %*	*0 %*	*0 %*

CONCLUSIONS

The results show that the proposed controller can perform an efficient search for the optimal PID controller. The PID-PSO controller is the best which presented satisfactory performances and possesses good robustness (no overshoot, minimal rise time, Steady state error = 0).The advantage of using PSO Tuning PID is minimized the error when we calculate the step response of the system because the iterations are continuously run till the error minimizes.

Finally, the proposed controller provides drive robustness improvement and gives very good results and possesses good robustness.

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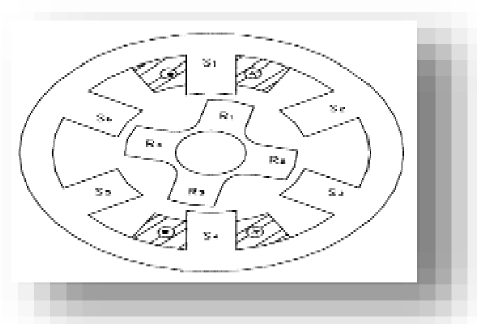
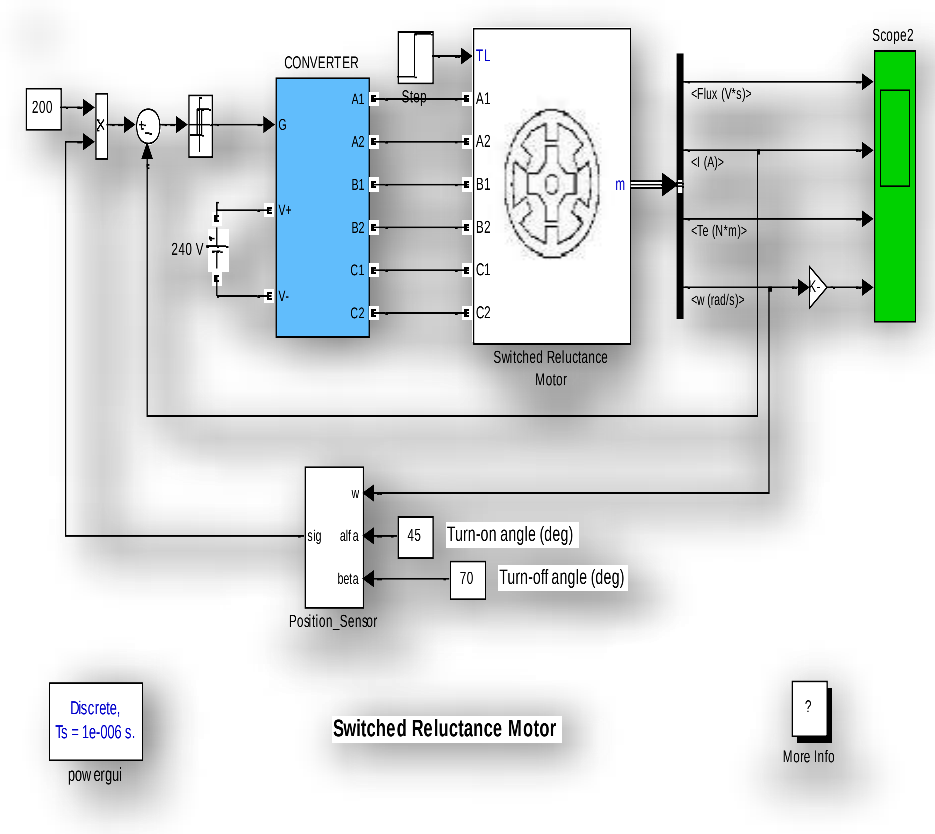
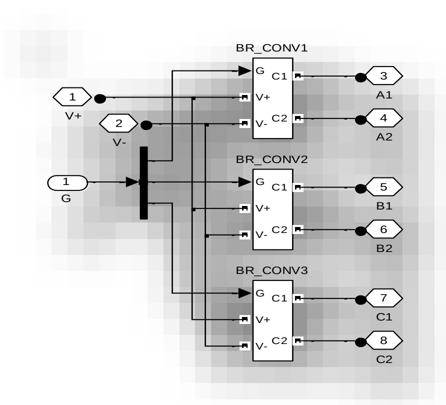
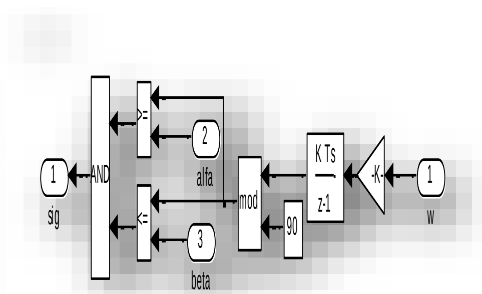


Figure.1 A cross-sectional for SRM motor.



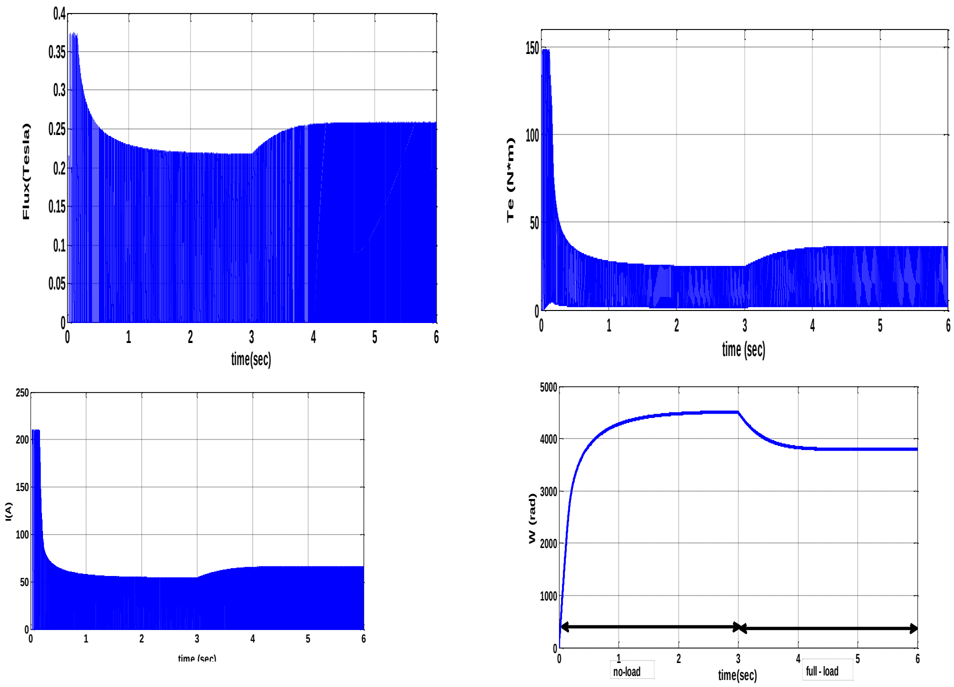


Converter

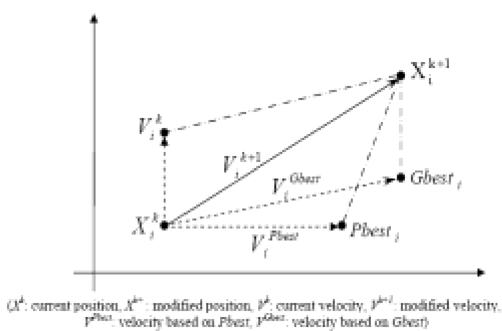


Position-Sensor

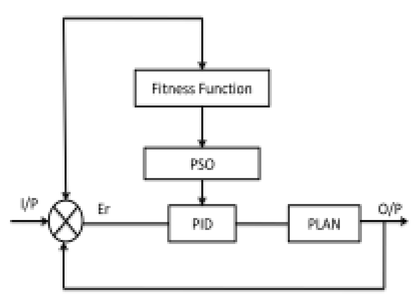
Figure(2) Block diagram of Switch Reluctance Motor



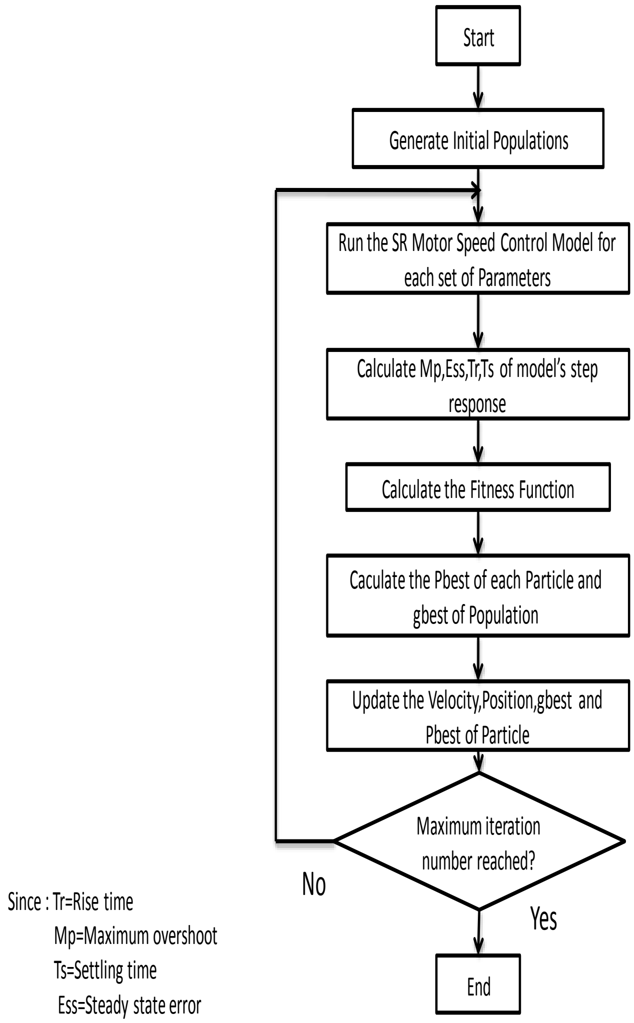
Figure(3)Open Loop response of Switched Reluctance Motor without controller (SRM) without control at no-load and full load



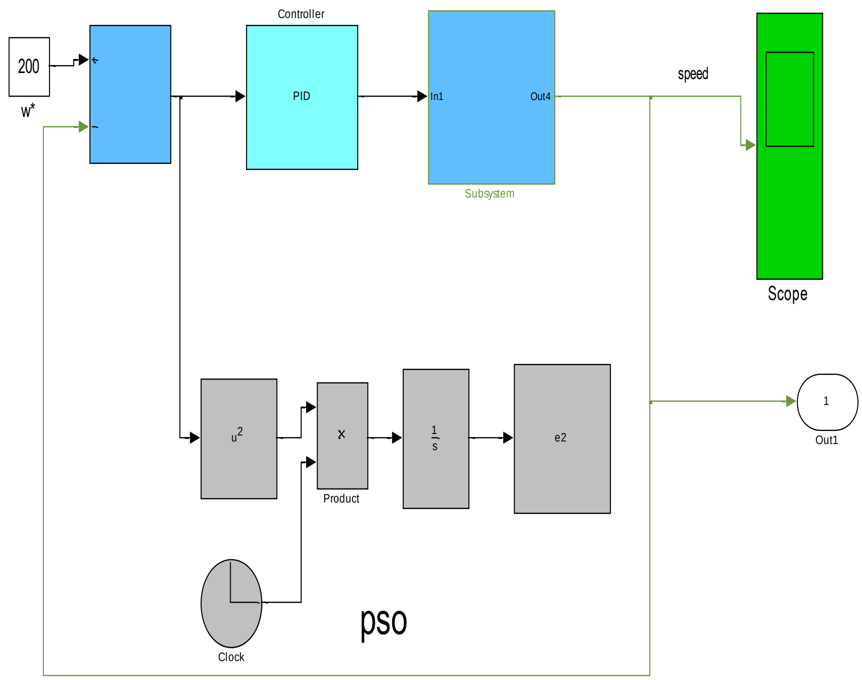
Figure(4) Concept of modification of a searching point by PSO



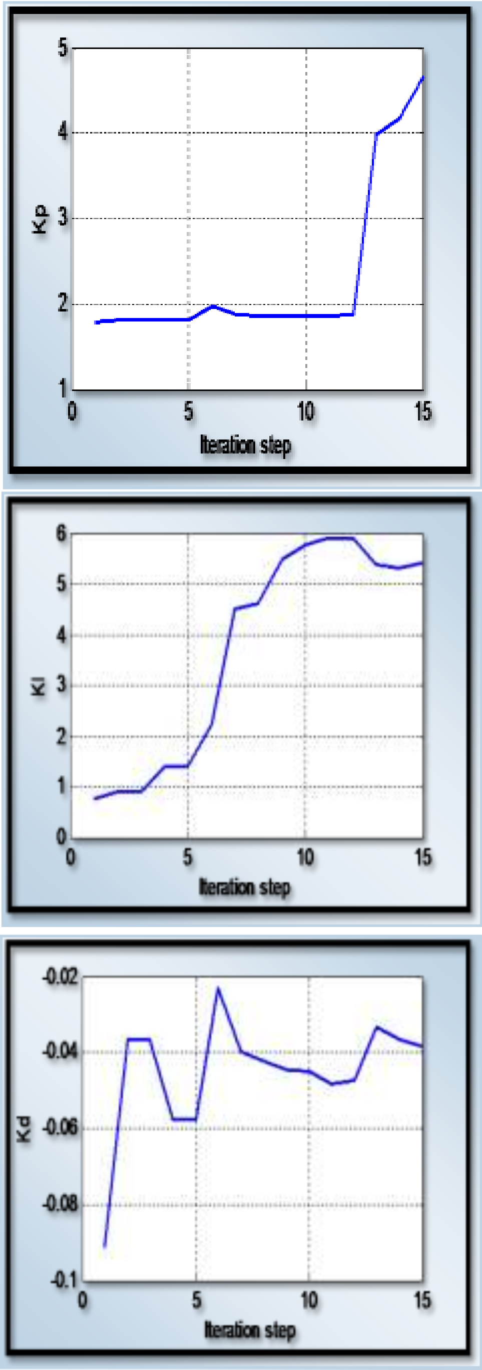
Figure(5) The block diagram of optimal PID control for the SR motor.



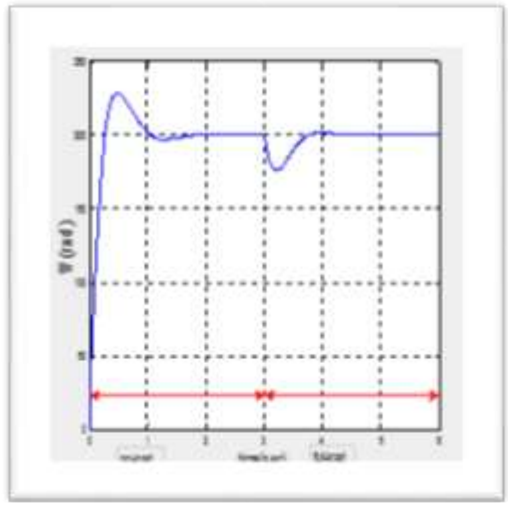
Figure(6) Flowchart of the PSO-PID control system



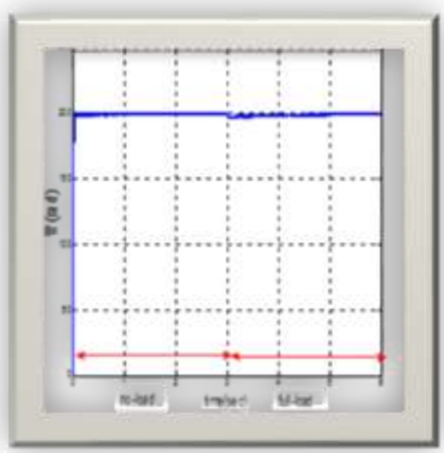
Figure(7) PID controller by using PSO-PID controller



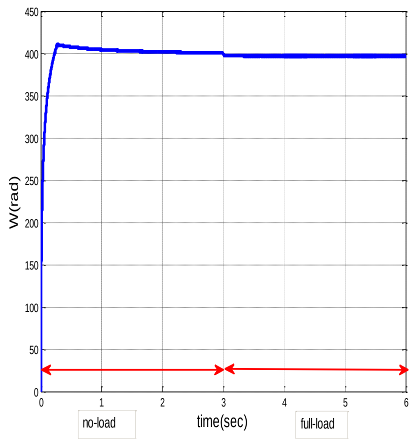
Figure(8) Illustration of PSO Algorithms converging through Kp, Ki and Kd.



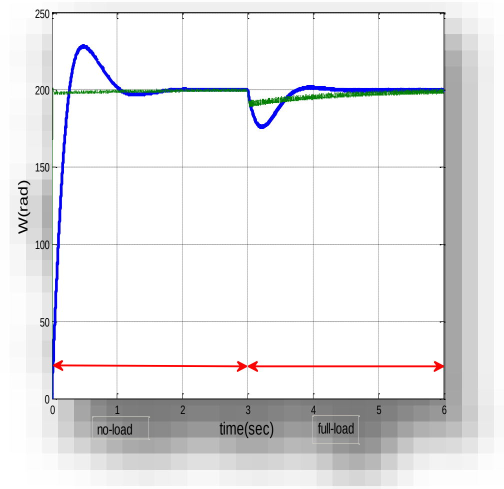
Figure(9) The speed response using PID controller



Figure(10) The speed response using PSO strategy(at half rated speed)



Figure(11) The speed response using PSO strategy(at rated speed)



Figure(12) Comparing Perfor mance of PSO- PID Controller and PID Controlle (at half rated speed)

Appendix:

The specifications of the SRM motor are detailed as follows:

This model presents a current-controlled 60*KW*, 6/4 SRM drive using the SRM specific model based on measured magnetization curves.

Stator resistance (ohm) =0.01

Inertia (*Kg.m2*) =0.0082

Friction (*N.m.s*) =0.02

Stator inductance Lq(mH)=0.67

Stator inductance Ld(mH)=23.6

Maximum current(A)=450

Rated current(A)=275

Rated speed(rad)=400

Maximum flux linkage(Tesla)=0.48

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