Modeling of Structural Human Dynamic

# Simulation of Speed Control for Synchronous Reluctance Motor Based on Tuning Cascaded PID Controller with PSO Algorithm

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## ABSTRACT

This paper presents simulation and control of synchronous reluctance motor (SynRM). The motor speed is controlled by using Traditional PID controller that have been used in cascaded form. The Particle Swarm Optimization (PSO) is used to find the optimal parameters of the PID controller. Lead-Lag controller introduce in the cascaded controller as a second stage of control. Space vector pulse width modulation (SVPWM) scheme proposed to control the motor by using variable input voltage. A comparison between the manually tuned and PSO tuned cascade controller shows that the PSO give amazing control characteristics for the motor speed and have advantage over the manually tuning controller.

**Key Words: Synchronous Reluctance Motor, PID, Cascade Controller, PSO, SVPWM**

## المحاكاة والسيطرة على سرعة المحرك *التردد المتزامن* بالاعتماد على ضبط ثوابت المتحكم المتعاقب PID و بأستخدام خوارزمية PSO

## الخلاصة

هذا البحث يمثل محاكاة وسيطرة على محرك التردد المتزامن (SynRM). يتم التحكم في سرعة المحرك باستخدام وحدة التحكم التقليدية (PID) التي تم استخدامها في شكل متعاقب. أستخدمت خوارزمية أسراب الطيور (PSO) للحصول على القيم المثلى لثوابت وحدة تحكم PID. تم أستخدام وحدة تحكم المعوض المتقدم- المتأخر كمرحلة ثانية من السيطرة. تم إقتراح إستعمال تقنية العاكس ثلاثي الاطوار (VS-SVPWM) للسيطرة على المحرك عن طريق تغيير فولتية الادخال للمحرك. تمت المقارنة بين وحدة تحكم التي تم ضبطها يدويا والتي تم ضبطها باستخدام PSO وتبين أن PSO يعطي قيم الثوابت المثلى والتي تعطي خصائص سيطرة مدهشة لسرعة المحرك ولها ميزة على وحدة التحكم التي تم ضبطها يدويا.

## 1. INTRODUCTION

Syn RM is one of synchronous machine type with no magnetic material and winding in the rotor structure. As compared to other synchronous machine SynRM is very rugged and simple in structure. In the beginning the SynRM was inferior as compared to other type of motors such as induction motor (IM), brushless DC (BLDC) motor, switch reluctance motor

(SRM) and DC motor because of low average torque, larger torque pulsation and poor power factor. The stator winding of SynRM is same as IM but the rotor structure is differ from that. In recent years a major development have been made in the rotor structure to overcome these disadvantages to enable the SynRM to give a very stable performance. SynRM is a three phase motor with rotor made of steel axially laminated barriers to overcome the low torque and poor power factor characteristics. Optimization technique is used in rotor structure design to have high quadrature axis reluctance and low direct axis reluctance. Fig. 1 shows the rotor flux barrier of SynRM. Since SynRM does not need any winding or magnetic material on the rotor structure which make the motor rugged, simple in structure , lowest cost of manufacturing requirement, high torque per unit volume possibility and operating at very high speeds capability. The SynRM has neglected rotor windings loses there for result a simple control methods and the losses minimization make SynRM an attractive and famous choice for numerous industrial and automotive applications [1,2,3,4]. The SynRM have marvelous features make this motor perfect choice for many industrial application such as elevators, fans and lightly road electric vehicles ( EVs). The speed control is very important factor and play an important role in these application[3] .

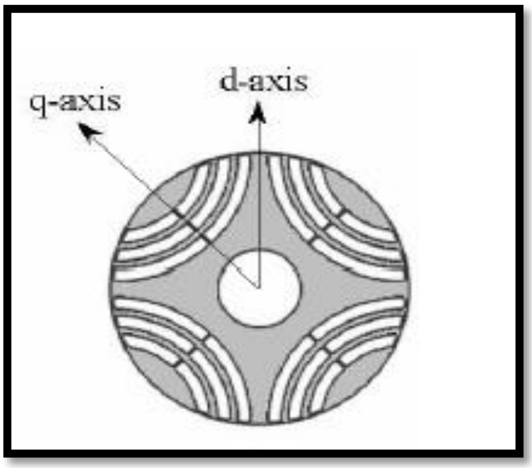


**Fig. 1 SynRM rotor flux barrier[4]**

The SynRMs does not have a starting torque so by using the new types of inverters, field orientation control (FOC) technology and the using of pulse width modulation (PWM) technique provide a very suitable technique for motor starting [5]. In recent years, the variable speed motor drive is casted over a fixed speed motor drive due to energy conservation, velocity or position control and improvement of transient response characteristics. These controllers are used to control the speed of the SynRM based on three phase VS-SVI technique and the stationary frame transformation. SynRm can be shown from it is d-q stationary axis equivalent circuits as in fig. 2. Depending on the closed loop speed control systems a fast response can be obtained. In this paper the traditional PID in cascaded form with the lead-lag controller are proposed. PSO technique are used to find the optimal parameters of the controller parameters. A comparison been made between the manually tuning and the PSO tuning and the results are discussed briefly next.

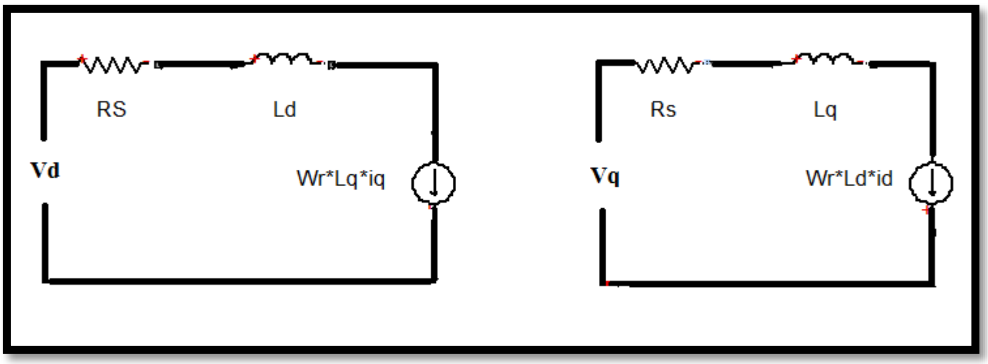


**Fig. 2 SynRM d-q axis equivalent circuit**

## 2. SynRM Mathematical Model

Three phase SynRM model is good for analyzing motor under different operation conditions, but for appropriate control action three phase analysis are rarely used. So the two axis SynRM model are mainly used for the control synthesis.

$$V_d = \mathrm{R}_s \mathrm{I_d} + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \tag{1}$$

$$V_q = \mathrm{R}_s \mathrm{I_q} + \frac{d\lambda_q}{dt} + \omega_r \lambda_d \tag{2}$$

$$\lambda_\mathrm{d} = L_d \mathrm{I_d} \tag{3}$$

$$\lambda_\mathrm{q} = L_q \mathrm{I_q} \tag{4}$$

Where $L_d$ and $L_q$ are the direct and quadratic axis winding self-inductance and measured in henri (H), $\mathrm{R}_s$ represent the stator winding resistance in ohm ($\Omega$ ) and $\omega_r$ is the rotor angular speed in radian per second (rad/sec), the flux rate of change can be obtained as will be shown in equation (5) and (6) as follow.

$$\frac{d\lambda_\mathrm{d}}{\mathrm{dt}} = \mathrm{V_d} - \mathrm{R_s I_d} + \omega_\mathrm{r} \lambda_q \tag{5}$$

$$\frac{d\lambda_\mathrm{q}}{\mathrm{dt}} = \mathrm{V_q} - \mathrm{R_s I_q} - \omega_\mathrm{r} \lambda_d \tag{6}$$

and from equation (5) the rate of change of direct axis current can obtained in equation (7)

$$\frac{\mathrm{dI_d}}{\mathrm{dt}} = \frac{1}{L_d} (\mathrm{V_d} - \mathrm{R_s I_d} + \omega_\mathrm{r} \mathrm{L}_q\, I_q) \tag{7}$$

and from equation (6) the rate of change of quadratic axis current can obtained in equation (8).

$$\frac{dI_q}{dt} = \frac{1}{L_q}(V_q - R_s I_q + \omega_r L_d I_d) \tag{8}$$

The electromagnetic torque equation for SynRM can be obtained as follow in equation (9).

$$T_e = \frac{3}{4}\frac{P}{2}\left(L_d - L_q\right)I_d I_q \tag{9}$$

where $T_e$ represent the electromagnetic torque of the SynRM in Newton meter (N.m).The total torque equation is given in equation (10).

$$T = \frac{3}{2}P\left(L_d - L_q\right)i_d i_q - \left(B\omega_r + J\frac{d\omega r}{dt}\right) - T_L \tag{10}$$

where P the number of poles is pairs of the motor and load, J represent the moment of inertia coefficient of motor in kilogram square meter ($K_g M^2$), and $T_L$ is the load torque to the motor in newton meter(N.M) and B is the viscous friction coefficient of the motor N.m.s [1, 4]. All the motor parameters are shown in Table (A) in the appendix. The motor performance at nominal speed taken from ABB motors company manual data is shown in the appendix Table (B).

## 3. Mathematical Model of Voltage Source Space Vector Inverter (VS-SVI)

Inverters are a power electronic devices used to convert the DC voltage taken from a battery or any DC source into AC voltage. According to the inverter type the transformed voltage may be single phase, two-phase and three-phase, etc. An inverter that feeding synchronous motors are primarily used in variable voltage variable frequency for high-performance variable speed application. The most popular PWM technique is SVPWM technique which is used due to the larger DC bus voltage and less harmonic distortion. Three-phase voltage-source converter circuit consist of six switches and power supply as shown in Fig. 3. this scheme confines space vectors to be applied according to region where the output voltage vector is located. Fig. 4 shows the six sectors of the space vector and the space vector phase voltages. The mathematical modelling of space vector pulse width modulation (SVPWM) inverter are shown as follows [6,7].

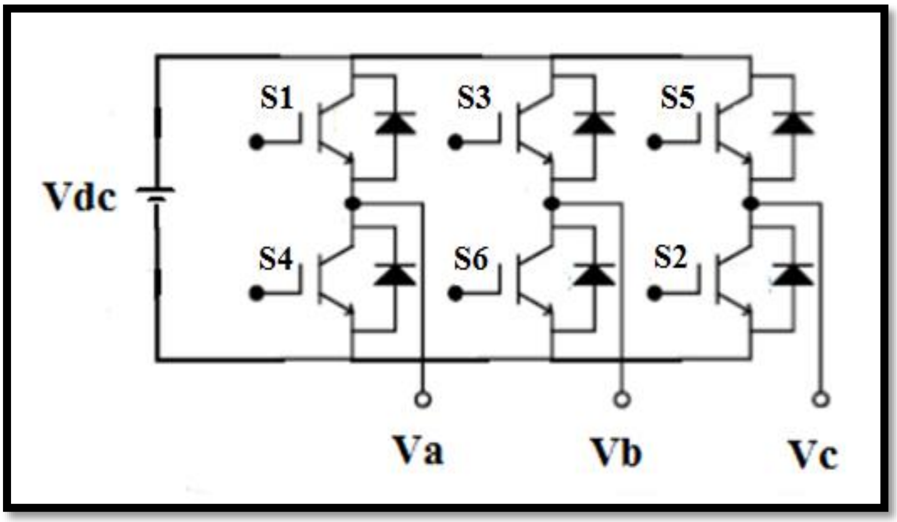


**Fig. 3 Three-Phase VSI circuit connected to power supply [6]**

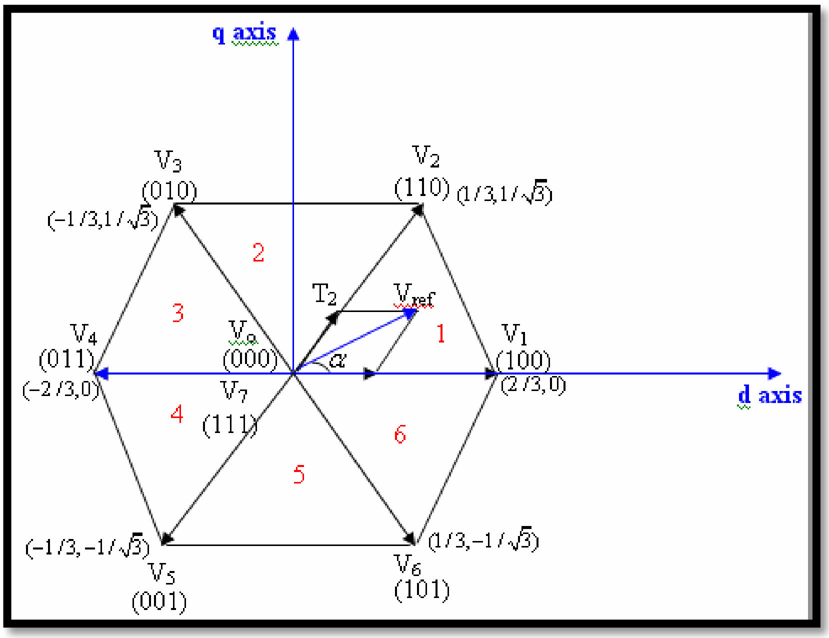


**Fig. 4 Six sectors of SVPWM [7]**

$$V_{ref} = \sqrt{V_d^2 + V_q^2} \quad (11)$$

$$\alpha = \tan^{-1}\left(\frac{V_d}{V_q}\right) = \omega_s t = 2\pi f_s t \quad (12)$$

$$V_{ref} T_s = \left(V_1 T_a + V_2 T_b + V_{0,7} T_o\right) \quad (13)$$

$$T_z = (T_a + T_b + T_o) \quad (14)$$

$$V_{ref} = V_{ref} e^{j\alpha} \quad (15)$$

$$V_1 = \frac{2}{3} V_d \, , V_{0,7} = 0 \, , V_2 = \frac{2}{3} V_d e^{j\frac{\pi}{3}} \tag{16}$$

Where $T_s$ represent the sampling period and calculated from (2*$T_z$) where $T_z$ is the switching ferquancy and $T_a$, $T_b$and $T_o$ represents the switching period that specified for $V_1$, $V_2$ and $V_{0,7}$ respectively.The reference space vector have been assumed to be constant during one switching cycle to get high switching frequency. The zero vectors represent the switching start of each switching period $T_z$ or full null per vectors per $T_s$, each null have duration width of ($T_o/2$), so the space vector equations can be writen as follow.

**Re:** $V_{ref} \cos\alpha \, T_z = \frac{2}{3} V_{dc} T_a + \frac{1}{3} V_{dc} T_b$ (17)

**IM:** $V_{ref} \sin\alpha \, T_z = \frac{1}{\sqrt{3}} V_{dc} T_b$ (18)

$$T_a = \frac{\sqrt{3}\, T_z V_{ref}}{V_{dc}} \sin(\frac{\pi}{3} - \alpha) = T_z * m_a * \sin(\frac{\pi}{3} - \alpha) \tag{19}$$

$$T_b = \frac{\sqrt{3}\, T_z V_{ref}}{V_{dc}} \sin(\alpha) = T_z * m_a * \sin(\alpha) \tag{20}$$

$$T_o = (T_z - T_a - T_b) \tag{21}$$

$$m_a = \frac{\sqrt{3}\, V_{ref}}{V_{dc}} \tag{22}$$

$$T_a = \frac{\sqrt{3}\, T_z V_{ref}}{V_{dc}} (\sin(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi)) \quad = \frac{\sqrt{3}\, T_z V_{ref}}{V_{dc}} * (\sin(\frac{n\pi}{3} - \alpha)) \tag{23}$$

$$T_b = \frac{\sqrt{3}\, T_z V_{ref}}{V_{dc}} (\sin(\alpha - \frac{n-1}{3}\pi)) \tag{24}$$

Where $\alpha$ is the voltage phase angle, $m_a$ represent the modulation index of the SVPWM inverter and $V_{dc}$ is the DC source voltage in volt[6,7].

## 4. Simulink Model of SynRM Motor

The SynRM are represented by the direct and quadrtic axis voltages. The motor voltages equations (1) and (2 ) are implemed in Matlab/Simulink enviromentin in Fig.5. where the inputs of this block are direct and quadretic axis voltages and the output are the motor speed and torque.

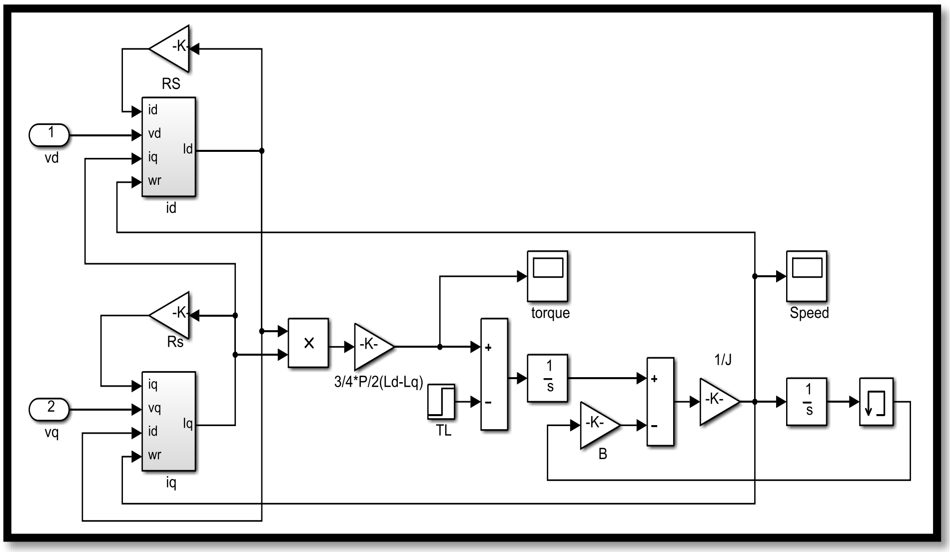


**Fig. 5. SynRM model block**

## 5. Speed Control of SynRM

Two tuning methods are applied to the cascade controller which are manually tuning with trial and error parameter estimation and PSO tuned cascade controller, each topology will be described as next.

### 5.1 Cascade Control System

The processes that have more than one variable at the output that should be controlled are well-known as multi-input, multi-output (MIMO) or multivariable processes. Interactions usually exist or sometimes not exist between the control loops of multivariable processes, which is famed by difficulties in control when compare it with the control of single-input, single output (SISO) processes. Lead-lag compensators are used to give a combines performance between both the lead and lag compensator and used as a second stage after PI and PID controllers which make the system have stabilized performance. PI controller have been used to control the direct axis current. This type of control process are shown in Fig. 6. The disadvantages of this type of control an exiguity of flexibility for interaction adjustation and when compare it with general multivariable control it have a few powerful tools for its design. SISO PID controller are tuned by control engineers , there is one simple way to tune a multi-loop PID controller by first tuning each individual loop one by one, and totally discarding the loop interactions and that is done by tune the (i) loop of cascade controller for the plant transfer. Then re-tuning all the loops together so that the overall system have stable performance and gives an acceptable load disturbance responses [8].

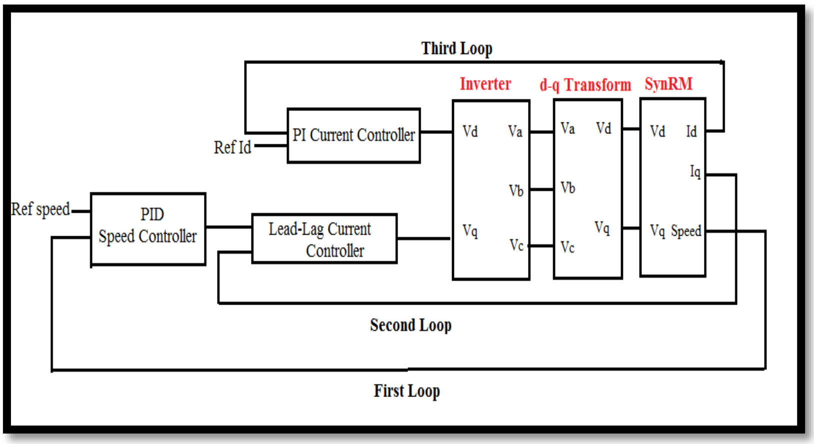


**Fig. 6. Cascade controller**

## 5.2 Particle Swarm Optimization Tuning PID Controller Parameter

Particle swarm optimization (PSO) is a population depend on computational schemes that the main concept came from the simulation of social behavior (social-psychological methods) fish schooling, bird flocking and swarm theory. PSO was firstly designed and evolved by Eberhart and Kennedy [9, 10]. This theory has been made to be powerful in solving problems exhibiting the non-linearity and the non-differentiability. The scheme is obtained from research on swarm such as bird flocking and fish schooling. Accommodation to the results of research for a flock of birds, find that birds food by flocking (not by each individual). The fitness function is casted to maximize the constrains domain or to minimize the preference constrains. The most commonly performance criteria that depend on the error criterion are Integrated Absolute Error (IAE), Integrated of Time weight Square Error (ITSE) and Integrated of Square Error (ISE) that can be calculated analytically in frequency domain. The criteria selection is depend on the system and the controller[11, 12]. In this paper the fitness functions are used depend on the Integral of Squared Error (ISE) criterion and overshoot $(M_p)$ criterion as follow:

$$\text{Fitness function} = \min(\text{ISE}) + \min(M_p) \tag{25}$$

Where

$$\text{ISE} = \int e^2(t)dt \tag{26}$$

$$M_p = \max(n) - (n_{ref}) \tag{27}$$

$$e(i) = D(i) - y(i) \tag{28}$$

where y(i) is the model output, and D(i) is the wanted output. While n is the actual speed, and $n_{ref}$ is the reference speed. The velocity $v_i(t)$ and the current position $x_i(t)$ updating for each particle in the swarm are done in equations (30, 31). The velocity of each agent can be updated by the following equation.

$$v_i^{k+1} = w * v_i^k + c_1 * R_1 * \left(lbest_i - x_i^k\right) + c_2 * R_2 * \left(gbest_i - x_i^k\right) \tag{29}$$

and, the current position can be updated by the following equation:

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (30)$$

where $x_i^k$ is the current position of particle i at iteration k, $v_i^k$ is the velocity of particle i at iteration k, $w$ is the inertia weight which can be shown in Eq. (36), $c_1$, $c_2$ represent positive acceleration constants and $R_1$, $R_2$ are random variables distributed uniformly in the range [0; 1].

$$w = w_{max} - \frac{(w_{max} - w_{min})}{iter_{max}} \quad (31)$$

where, $w_{min}$ is the inital weight, $w_{max}$ is the final weight $iter_{max}$ is the maximum iteration number. Fig.7 shows a general flowchart form for PSO algorithm.

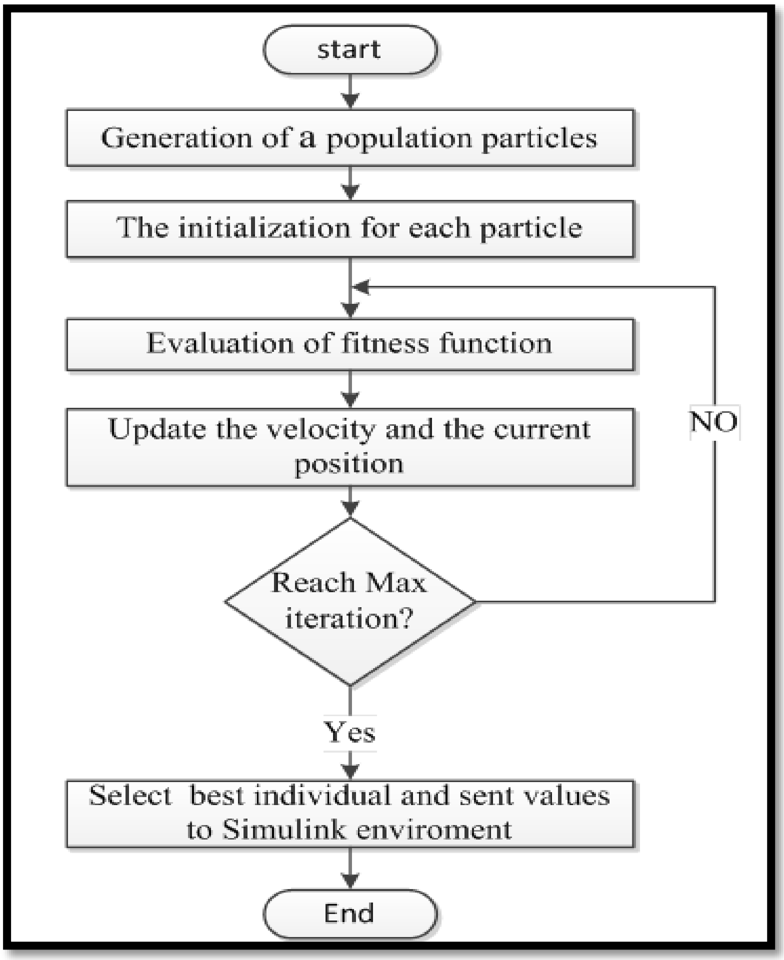


**Fig. 7: Flow chart of PSO algorithm [11]**

## 6. System Simulation and Results

This section presents simulation and results for the SynRM drive. The motor drive system with vector control method has been simulated using Matlab/Simulink environment packages. The drive system and the controller system are shown in Fig.8. The cascaded controller is shown in Fig.9. The cascade controller have a parameters shown in Table (1) which are found by trial and error. Table (2) shows the PSO algorithm parameters. Table (3) the parameters of cascade controller that been found depending on PSO algorithm. Figures (10, 11 and 12) represent the speed and torque response due to step load change at 0.8 sec time to and value of 25 N.m load applied to the motor with traditional and optimized parameters. Figures (13, 14 and 15) show the speed and torque response due to step reference speed due a step speed respond torque response. The results shows that the traditional controller with manually tuning parameters need more time to back to reference speed value when applying load to the motor in the other hand the PSO tuning parameters controller shows a major enhancement in the speed response and almost the load effect has not effect on the speed response which clarified in Table (4) . When applying step speed reference the speed is much better when using the PSO parameters and that shown in Fig.13. As a result the PSO algorithm gives a major improvement in the speed and torque response of the motor when operated at different operation conditions.

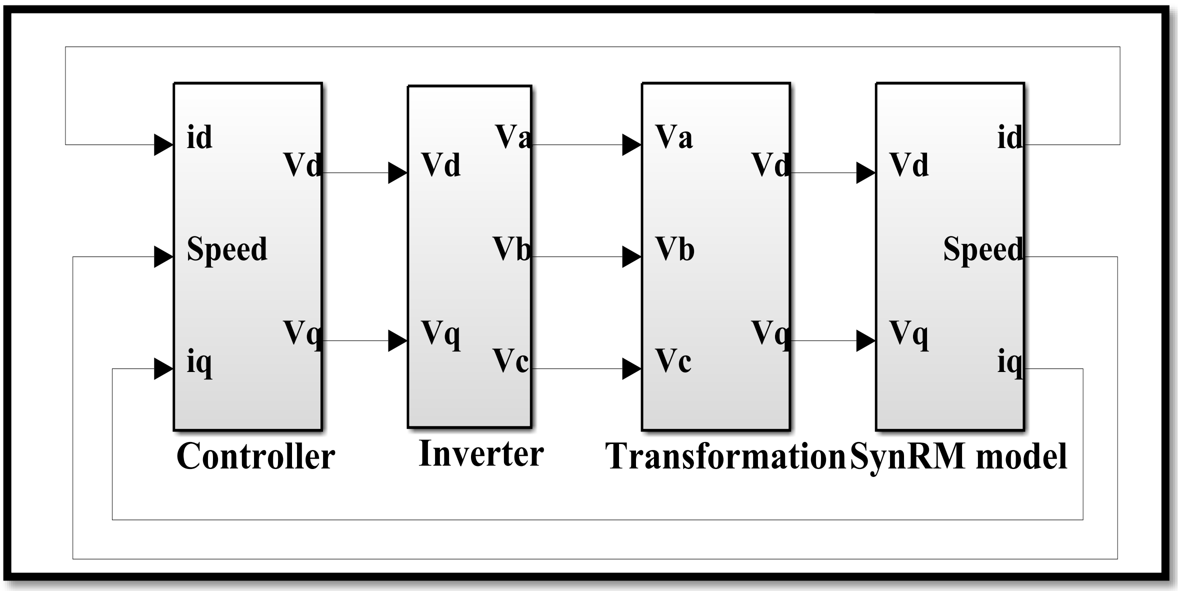


**Fig.8 Motor drive system and controller**

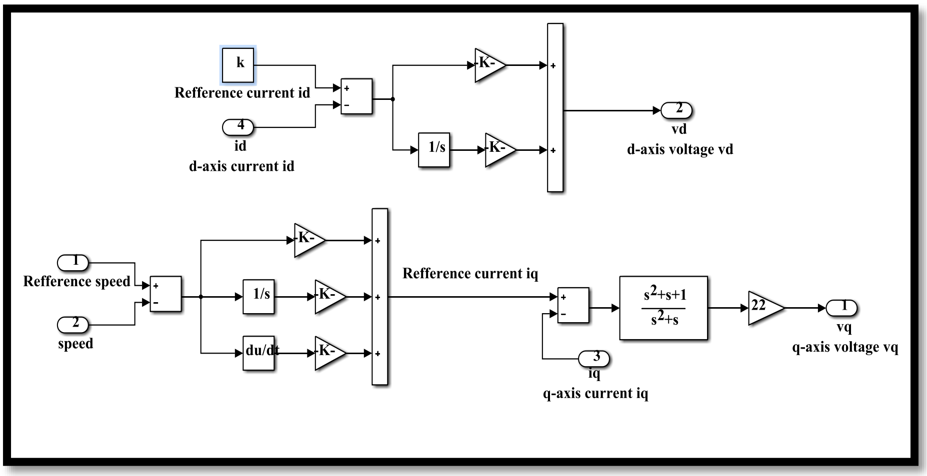


**Fig. 9 Cascade controller block**

**TABLE 1: PID PARAMETERS**

| Controller type | Speed Controller Parameters | | | q-axis Current Controller Parameters | d axis Current Controller Parameters | |
|---|---|---|---|---|---|---|
| **Parametrs** | $K_P$ | $K_I$ | $K_d$ | $K_3$ | $K_P$ | $K_I$ |
| **Values** | 40 | 10 | 1 | 22 | 1200 | 10 |

**TABLE 2: THE VALUES OF PSO ALGORITHIM PARAMETERS**

| PSO_ Parameters | Value |
|---|---|
| Maximum iteration number | 50 |
| Size of the swarm " no of birds " | 50 |
| Dimension | 20 |
| PSO parameter $c_1$ | 1.2 |
| PSO parameter $c_2$ | 1.2 |
| Wmax | 0.9 |
| Wmin | 0.2 |

**TABLE 3: PID PARAMETERS TUNED USING PSO**

| Controller type | Speed Controller Parameters | | | q-axis Current Controller Parameter | d- axis Current Controller Parameter | |
|---|---|---|---|---|---|---|
| **Parametrs** | $K_P$ | $K_I$ | $K_d$ | $K_3$ | $K_P$ | $K_I$ |
| **Values** | 200 | 8.8 | 0.749 | 20.879 | 2130 | 9.8 |

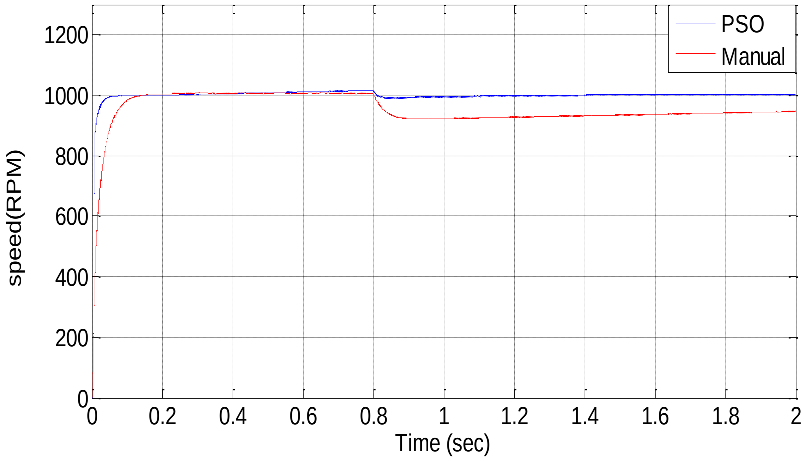


**Fig. 10 Motor torque due 1000 RPM reffrence and 25 N load at 0.8sec applied to PSO and PID controllers**

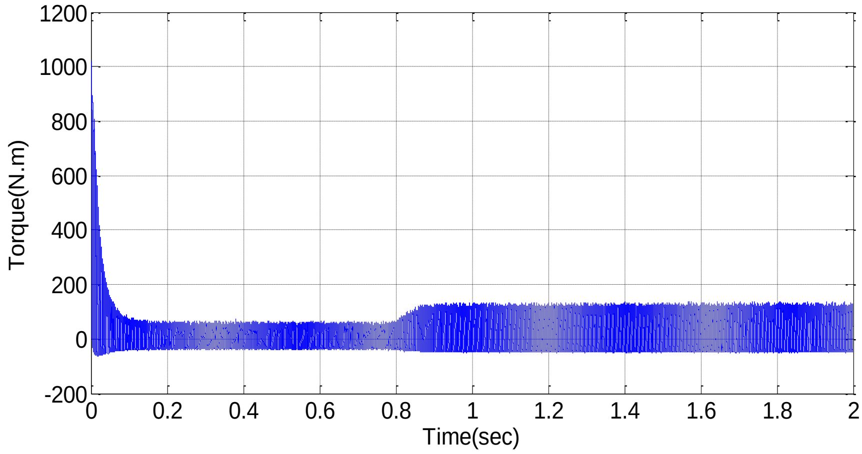


**Fig. 11 Motor torque due 1000 RPM reffrence and 25 N load at 0.8 sec applied to traditional controllers**

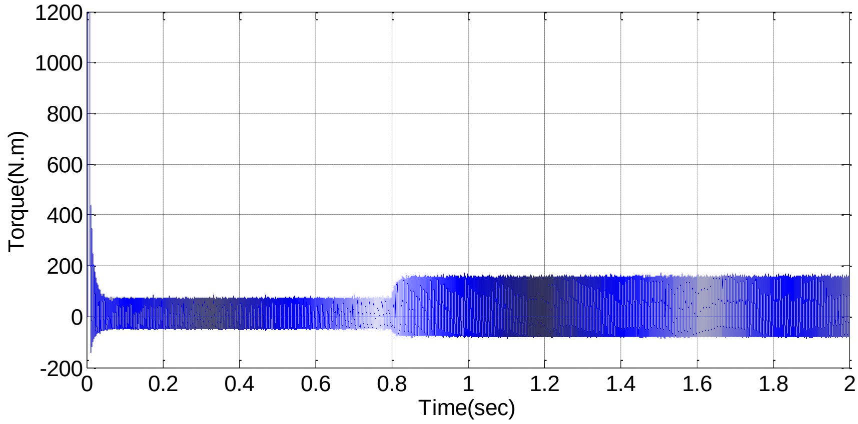


**Fig. 12 Motor torque due 1000 RPM reffrence and 25 N load at 0.8 sec applied to PSO tuned controllers**

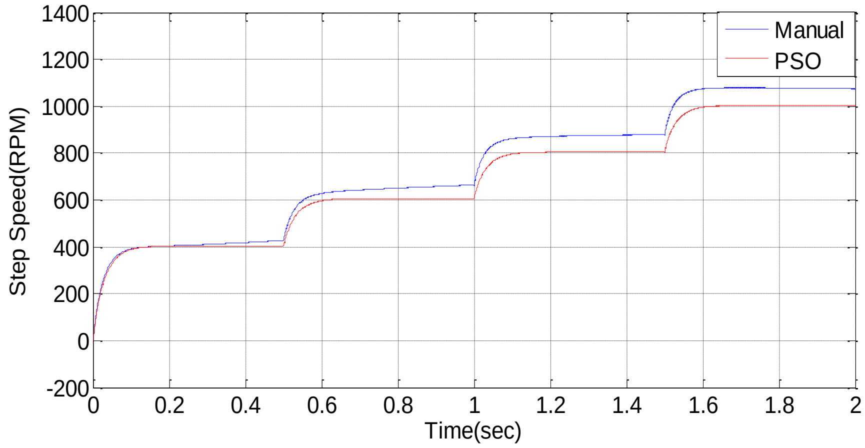


**Fig. 13 Motor speed due step reffrence speed applied to PSO and traditional controllers**

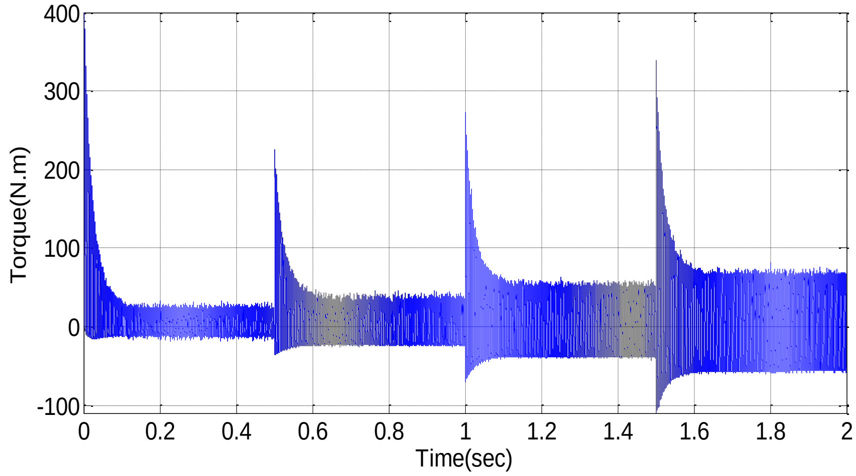


**Fig. 14 Motor torque due step reffrence speed applied to traditional controllers**

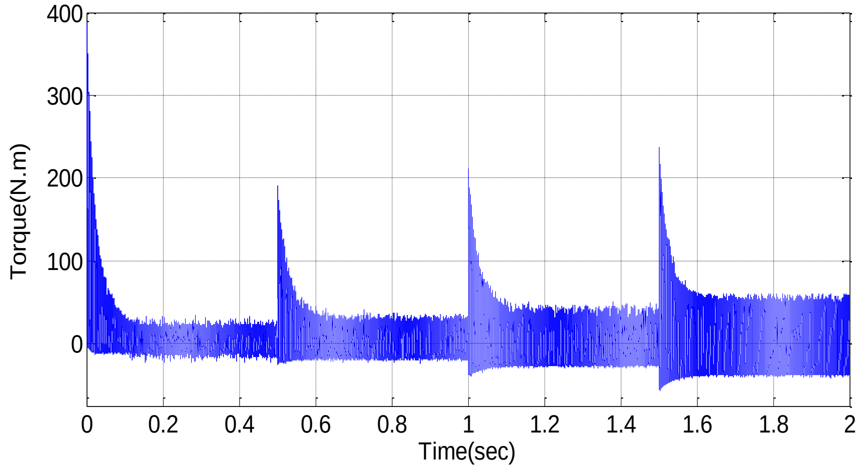


**Fig. 15 Motor torque due step reffrence speed applied to PSO tuned controllers**

**TABLE 4: COMPARISON BETWEEN THE MANUALLY AND PSO TUNED CONTROLLER PERFORMENCE**

| System Performance | Manually Tuned Controller | PSO Tuned Controller |
|---|---|---|
| Over Shoot | 1.3979 % | Approximately 0% |
| Steady State Error | $3*10^{-3}\%$ | $2*10^{-3}\%$ |
| Settling Time | 1.2589 | 0.0350 |
| Rise Time | 0.0407 | 0.0079 |

## 7. CONCLUSION

This paper has concerned the simulation and control of the synchronous reluctance machine drive systems using Matlab/Simulink environment. The main motivation was due to the large number of SynRM advantages. In this paper the vector control by depending on space vector pulse width modulation is used to control motor speed. The inverter stage represent the open loop control to the motor. The cascade controller is very difficult to tune manually so the trail and error may parameters give a good control performance but not the optimal performance so the loop intersection is the main cause of that difficulty of the tuning process. Particle swarm optimization is very suitable algorithm to tune this controller parameters. According to the PSO parameters the system performance is improved. Both the motor speed and torque response of motor are improved and any desired speed in the range of the motor characteristics the controller make the motor run at that speed.

## 8. APPENDEX

**Table (A): SynRM parameters**

| **Parameter** | **Parameter Value** | **Units** |
|---|---|---|
| **Ld** | **6.0641** | **mH** |
| **Lq** | **0.9099** | **mH** |
| **Rs** | **0.0265** | **Ohm** |
| **J** | **0.245** | $\boldsymbol{Kgm^2}$ |
| **B** | **0.0000009** | **N.m.s** |
| **P** | **2** | **poles** |

**Table (B): Performance at nominal speed From ABB motors company manual data**

| | | |
|---|---|---|
| Output power | 45 | Kw |
| Speed | 3000 | RPM |
| Operation frequency | 100 | Hz |
| Efficiency at full load | 94.6% | - |
| Current | 103 | A |
| Torque | 143 | N.m |
| Torque Ratio | 1.5 | - |

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