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Study and Comparison The Performance of Sensorless Control of PMSM Drive System

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ABSTRACT:

Field oriented control space vector pulse width modulation (FOC- SVPWM) is one of the effective and modern methods for speed control of Permanent magnet synchronous motor (PMSM). A mathematical model and theoretical analysis of (FOC-SVPWM) driven a PMSM are presented .In this work, a control methods for PMSM using Model reference adaptive system (MRAS) are utilized to compare the performance behavior under conventional PI, Fuzzy PI, and Particle swarm optimization (PSO) control methods.

Extensive simulation results are presented using MATLAB/SIMULINK program which including (SVPWM generation, inverter, PMSM, the reference frame transformation and different PI controllers) as well as the estimation method using MRAS.

This work presents a comparative study to investigate the performance of PMSM based on MRAS when different load conditions are applied to PMSM and under three different controllers: the first controller is the Proportional-Integral (PI) based on classical trial and error method, the second controller is PI controller based on PSO technique for optimal gains tuning and thus improve the performance of the system. The obtained results show that an improvement in motor performance when using PI-PSO compared to classical PI controller. The third controller is Fuzzy-PI with scaling factor (gains) tuned by PSO technique. This method can improve the performance of the system compared with PI-PSO in terms of reducing steady state error, rising time, overshoot and smoother response to make this controller more robust to variation in load other than the rest motor controllers.

Keywords: Permanent Magnet Synchronous Motor (PMSM), Sensorless controller, PI, PSO, Fuzzy-PI controller and Model Reference Adaptive System (MRAS).

دراسة و مقارنة الأداء للسيطرة بعدم استخدام المتحسس لنظام المحرك المتزامن ذو المغناطيس الدائم

الخلاصة

طرق التحكم الأتجاهي للمتجه الفضائي لمضمن عرض النبضة هي واحدة من الطرق الفعالة و الحديثة للسيطرة على سرعة المحرك التزامني ذو المغناطيس الدائم. قدم النموذج الرياضي والتحليل النظري لطرق التحكم الاتجاهي للمتجه الفضائي لمضمن عرض النبضة لتشغيل المحرك التزامني ذو المغناطيس الدائم. في هذا العمل, تم استخدام طرق السيطرة للمحرك التزامني ذو المغناطيس الدائم بأستخدام نظام النموذج المرجعي التكيفي التي تم أستخدامه لمقارنة تصرف الأداء لمختلف طرق السيطرة.

يتم عرض نتائج المحاكاة الشاملة باستخدام برنامج MATLAB/SIMULINK و الذي يتضمن (توليد المتجه الفضائي لمضمن عرض النبضة , العاكس، المحرك التزامني ذو المغناطيس الدائم, تحويل محور الاسناد و مسيطرات مختلفة) اضافة الى تمثيل طريقة المتحسس باستخدام نظام النموذج المرجعي التكيفي.

هذا العمل قدم دراسة مقارنة لتحقيق اداء المحرك التزامني ذو المغناطيس الدائم بالأعتماد على نظام النموذج المرجعي التكيفي عندما حالات حمل مختلفة تطبق على المحرك التزامني ذو المغناطيس الدائم و تحت ثلاث مسيطرات مختلفة: المسيطر الأول هو مسيطر تناسبي-تكاملي (PI) و المعتمد على طريقة التجربة والخطأ التقليدية. المسيطر الثاني هو (PI) المعتمد على تقنية أفضلية الحشد الجزيئي (PSO) للأختيار الأمثل لقيم متغيرات (gains) وذلك لتحسين أداء المنظومة. النتائج التي وجدت تظهر تحسين في أداء المحرك عند استخدام (PI-PSO) بالمقارنة الى مسيطر (PI) التقليدي . المسيطر الثالث هو (Fuzzy-PI) مع متغيرات (gains) ضُبطت بواسطة تقنية أفضلية الحشد الجزيئي. هذه الطريقة يمكن أن تحسّن أداء المنظومة عند مقارنته مع مسيطر (PI-PSO) من حيث تقليل اخطاء الحالة المستقرة , زمن الزيادة , التجاوز و أستجابة اكثر سلاسة تجعل هذا المسيطر أكثر فعالية لتغير الحمل مقارنة مع بقية مسيطرات المحرك

INTRODUCTION

PMSMs are becoming more popular and replace classical brushed DC and induction motor (IM) drives in industrial applications, machine tools and residential applications. In a PMSM, the excitation is provided by means of using permanent magnets mounted on the rotor. PMSMs present numerous advantages over brushed DC motors, IMs and conventional synchronous motor drives. These some advantages are [1]:

- reliability;
- high efficiency;
- high power density;
- high torque to inertia ratio.

As field orientated control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model [2,3].

The idea of sensor-less is to get ride of the position transducer and try to determine the actual rotor position by measuring other variables such as voltages and currents in the PMSM. There are a lot of sensorless control strategies each of them having its own advantages, disadvantages and limitations. The term sensorless control does not mean that the PMSM is controlled without the use of any sensor.

Actually, it means that there is no position transducer or encoder used but there are sensors which measure the currents or voltages [1]

The PI-controller has been widely used in industry due to small steady-state error and low costs, but complexity of traditional PI-controller tuning and the affected by parameter variations, load disturbances, high response time and speed variation have been overcome by using artificial intelligent techniques like fuzzy logic, artificial neural networks, genetic algorithms (GA) and particle swarm optimization (PSO) which applied for vector control of ac machine [4].

The implementation of fuzzy logic control (FLC) taken a wide range in the engineering studies. because it has a number of advantages that (FLC) owned over the conventional controllers. FLC is not so sensitive to the variation of system structure, parameters and operation points and can be easily implemented in a large scale nonlinear system. Furthermore, the fuzzy logic controller is a technique that is easy to design and implement. Nevertheless, the determination of membership functions and control rules is an inevitable problem in a design. To achieve satisfactory membership functions and controlrules, designer'sexperiences are necessary[5].

Analysis and Modeling of PMSM

To analysize PMSM, the following assumption are taken into account:

- Machine core losses are negligible.
- Rotor flux is constant at a given operating point.
- Saturation and parameter changes are negligible.
- Balanced 3 phase supply voltage is considered.
- Stator windings produce sinusoidal MMF distribution.

The scalar form of the voltage equations in the rotor dq reference frame are presented in equations (1) and (2) [6]

$$\upsilon_q = r_s i_q + \frac{d}{dt}\lambda_q + \omega_e \lambda_d \qquad ...(1)$$

$$\upsilon_d = r_s i_d + \frac{d}{dt}\lambda_d - \omega_e \lambda_q \qquad ...(2)$$

The flux representation are shown in equations (3) and (4).

Where

$$\lambda_d = L_d i_d + \lambda_m \qquad ...(3)$$

and

$$\lambda_q = L_q i_q \qquad ...(4)$$

Where

- V_q and V_d are the (q , d) axis stator voltages.
- i_q and i_d are the (q , d) axis stator currents.
- L_q and L_d are the (q , d) axis inductances.
- R_s is the stator winding resistance.
- ω_e is the electrical rotor angular velocity.
- λ_m is the flux linkage due to the permanent magnets, λ_q and λ_d are the (q , d) axis stator flux linkage.

For a P-pole number machine, $\omega_e = (P/2)\omega_r$, where ω_r is the mechanical rotor speed in $\mathrm{rad/sec}$,produced electromechanical torque T_e:

$$T_e = (3/2)(P/2)\left(\lambda_d i_q - \lambda_q i_d\right) \quad \text{.. .(5)}$$

If the equation (3) and (4) is substituted in equation (5), the torque can also be expressed in the following way :

$$T_e = \left(3/2\right)(P/2)[(\lambda_m i_q + \quad \left(L_d - L_q\right) i_q i_d] \quad \text{...(6)}$$

For surface mounted PMSM, which means $L_d = L_q$ the "reluctance torque" is equal to zero ,so the torque expression for SPMSM is:

$$T_e = \frac{3}{2}(P/2)(\lambda_m i_q) \quad \text{...(7)}$$

The mechanical Torque equation is

$$T_e = T_l + B\omega_r + J\frac{d\omega_r}{d_t} \quad \text{....(8)}$$

Solving for the rotor mechanical speed from equation

$$\omega_r = \int\left(\frac{T_e - T_l - B\omega_r}{J}\right)dt \quad \text{...(9)}$$

From the previous equations the dynamic model of a PMSM was built in simulink as shown in Fig.1.

Space Vector PWM Inverter Feeding a PMSM

The SVPWM voltage-source inverters supplied PMSM are widely use in both industrial and household applications. The SVPWM inverter is used to offer 15% increase in the dc-link voltage utilization and low output harmonic distortions compared with the conventional sinusoidal PWM inverter [7]**.** While (SVPWM) is becoming a main method of the PWM realization because of the advantages including [8]:

- Lower current ripple;
- Better bus utilization;
- Less commutation losses ;
- The SVPWM also lends itself more naturally with digital control techniques and it is normally digitally implemented;
- Lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirements are minimized.

Field Oriented Control (FOC)

Field oriented control (FOC) was invented in the beginning of 1970’s [9]. To achieve fast dynamic response and smooth starting, the FOC technique is used in the design of the PMSM drive system. Like any other machine, the PMSM is inherently non-linear and possesses a multivariable coupled control system with high-order complex dynamics. Utilizing the FOC technique simplifies the dynamic model of the PMSM and the control scheme. Field Oriented Control usually refers to controllers which maintain a 90^o electrical angle between rotor and stator field components. Systems which depart from the 90^o orientation are referred to as field angle control or angle control. The electromagnetic torque is generated proportional to the product of the stator current and the PM rotor flux. The two components are orthogonal which results in high dynamic performance similar to a separately excited DC motor [10]. so that:

$$T_e = (3/2)(P/2)\,\lambda_m I_s \quad \text{...(10)}$$

Assuming that

$$K = (3/2)(P/2)\,\lambda_m \qquad \ldots(11)$$

The torque is given by

$$T_e = K.\,I_s \qquad \ldots(12)$$

Like in the dc motor, the torque is dependent on motor current [4].

Sensorless Field Oriented Control

Sensorless control is another extension to the FOC algorithm that allows synchronous motors to operate without the need for mechanical speed sensors. These sensors are notoriously prone to breakage so removing them not only reduces the cost and size of the motor but improves the drive's long term accuracy and reliability. This is particularly important if the motor is being used in a harsh, inaccessible environment such as an oil well .Instead of physically measuring certain values control engineers can calculate them from a system's state variables. This is known as the state space modeling approach and is a powerful method for analyzing and controlling complex non-linear systems with multiple inputs and outputs. Block diagram for sensorless FOC of PMSM is shown in Fig.2 [11]. During general sensorless control for high speed PMSM, the position and speed of rotor pole can be estimated by using the back EMF, and it derives several estimating methods such as [12, 13] :

- Phase locked loop;
- Neural Network method;
- Motor Basic Equation method;
- Estimators based on Kalman Filter method;
- Estimators based on the external signal injection into the motor;
- Estimators based on the state observers such as Siding Mode Observer (SMO) method;
- Estimators based on the stator flux identification such as model reference adaptive system (MRAS) method is used in this paper, which is not a computationally intensive method.

Model Reference Adaptive System (MRAS)

One type of closed loop observer that has been widely used in sensorless FOC is the MRAS. Adaptive control modifies its calculations to take into account changing parameters [11].

MRAS is based on the stator flux identification by using the motor mathematical model utilizing measured motor currents and voltages , as shown in Fig.3. First, the stator flux is calculated based on motor voltages using the voltage model which is the reference model. On the other hand, the stator flux is calculated based on motor currents and the estimated rotor flux position using the current model which is the adaptive model. If there is an estimation error in the rotor flux position, the error is directly seen in a stator flux phase angle obtained from the current model. Hence, by comparing the stator flux vector phase angle of the current model to the stator flux vector phase angle of the voltage model, one can obtain the flux error angle. This error angle is used to correct the estimated rotor speed in a way that the error angle converges towards the zero. Correction mechanism i.e. the adaptation mechanism in this case is a simple PI-controller which input is the flux error angle and the output is the estimated speed.

Estimated rotor flux angle is obtained by integrating the rotor speed. For simplicity, only a smooth air gap machine is considered i.e. it is assumed that the motor has $L_d = L_q = \mathrm{L}$, which is a reasonable assumption for most of the motors with surface mounted magnets. However, the generator saliency can be included in the current model [13]. So, two different models can used (i.e. reference and adjustable models). The equation with unknown parameters as adjustable model, and the equation without unknown parameters as reference model. Both models have outputs with the same physical significance. When two models work at same time, parameters of adjustable model can be real time regulated by using the difference value between their outputs based on the adaptive law, so as to achieve the goal of tracing reference model by controlling the output, The outputs from the reference model and adaptive model are fed into the vector cross product block to produce vector error signal

In this case, choose PMSM as reference model, and current model as adjustable model. Rotor speed can be estimated by proper adapting adjustment, on the basis of the differences between the output *d-q* current values of the two models. The rotor angle can be derived through an integration of the speed. The reference and adjustable models can be respectively expressed by [12] :

$$\frac{di_d}{dt} = -\frac{R_s}{L} i_d + \frac{1}{L} u_d + \omega_e i_q \qquad \text{...(13)}$$

$$\frac{di_q}{dt} = -\frac{R_s}{L} i_q + \frac{1}{L} u_q - \omega_e i_d - \frac{1}{L} \lambda_m \qquad \text{...(14)}$$

$$\frac{\widehat{di}_d}{dt} = -\frac{R_s}{L} \hat{\imath}_d + \frac{1}{L} u_d + \widehat{\omega}_e \hat{\imath}_q \qquad \text{...(15)}$$

$$\frac{\widehat{di}_q}{dt} = -\frac{R_s}{L} \hat{\imath}_q + \frac{1}{L} u_q - \widehat{\omega}_e \hat{\imath}_d - \frac{1}{L} \lambda_m \qquad \text{...(16)}$$

Adaptive law is:

$$\widehat{\omega}_e = \int_0^t k_i \, [i_d \, \hat{\imath}_q - i_q \, \hat{\imath}_d - \frac{\lambda_m}{L}\left(i_q - \hat{\imath}_q\right)] d\tau + K_p [i_d \, \hat{\imath}_q - i_q \, \hat{\imath}_d - \frac{\lambda_m}{L}\left(i_q - \hat{\imath}_q\right)] + \widehat{\omega}_e(0) \qquad \text{...(17)}$$

$$\theta_{\mathrm{e}} = \int_0^t \omega_e \, dt \qquad \text{...(18)}$$

The main simulink modules of MRAS method are shown as Fig.4 and 5 respectively.

PI-Sensorless Controller

PI-sensorless controllers have remarkable success in various industries. They have been applied to control almost any process one could think of, from aerospace to motion control, from slow to fast systems. Alongside this success, however the problem of tuning PI-controllers has remained an active research area [14].

The speed and current-regulation of PMSM usually adopts PI- sensorless control [15]. But it is difficult to find the proper PI parameter. Bad proportional-integral parameter (Ki), (Kp) may cause the system unstable and beyond control. Besides, for the reason that the motor is a control object of multiple variables, nonlinear and strong coupling, it must fine adjustment its PI parameter to keep working stably and precisely. But the PI controller can't adjust its parameter automatically. However, genetic algorithm , ant colony algorithm, cultural algorithm, bacterial foraging oriental, particle swarm optimization (PSO) and many other intelligent optimization algorithms can be introduced to solve these problems [15].

Particle Swarm Optimization (PSO) Technique

PSO is a population based stochastic search algorithm. It was first introduced by Kennedy and Eberhart in 1995. In PSO, this behavior of animals is imitated by particles with certain positions and velocities in a searching space, wherein the population is called a swarm, and each member of the swarm is called a particle. Starting with a randomly initialized population, each particle in PSO flies through the searching space and remembers the best position it has seen. Members of a swarm communicate good positions to each other and dynamically adjust their own position and velocity based on these good positions. The velocity adjustment is based upon the historical behaviors of the particles themselves as well as their companions'. In this way, the particles tend to fly towards better and better searching areas over the searching process [16].

To search the optimal PI controller, the PSO algorithm is applied. Here the potential solutions, called particles, these particles are randomly initialized and fly through multi-dimensional space. During the flying, these particles update its velocity and position based on the experience of its own and the whole population. The updating procedure will drive the particle swarm to move toward region with better fitness value, and finally every particle is gathered around the point with the best fitness value [17].

Fitness Function [18]

The most common performance criteria are integrated absolute error (IAE), the integrated of time weight square error (ITSE) and integrated of square error (ISE) that can be evaluated analytically in frequency domain.

These three integral performance criteria in the frequency domain have their own advantage and disadvantage. For example, disadvantage of IAE and ISE criteria is that its minimization can result in a response with relatively small overshot but a long settling time, because the ISE performance criteria weights all errors equally independent of time. Although, the ITSE performance criterion can overcome the disadvantage of ISE criterion. The performance criterion formula for, IAE, ISE, and ITSE are as follows:

$$IAE = \int_0^\infty |e| dt \qquad ...(19)$$

$$ISE = \int_0^t |e^2| dt \qquad ...(20)$$

$$\mathrm{ITSE} = \int_0^t \mathrm{t.e^2(t)dt} \qquad ...(21)$$

In this paper, the ITSE time domain criterion is used as a fitness function (FF) for evaluating the PI Controller performance, a set of good controller parameters proportional gain (KP) and integral gain (Ki) can yield a good step response that will result in performance criteria minimization the *FF* in the time domain;

FF =ITSE

These performance criteria is include the over shoot, rise time, settling time, and steady-state error.

Fuzzy Logic Control (FLC)

The Fuzzy Logic tool was introduced in 1965, by Lotfi Zadeh, and is a mathematical tool for dealing with uncertainty. It offers to a soft computing partnership the important concept of computing with words. It provides a technique to deal with imprecision and information granularity. The fuzzy theory provides a mechanism for representing linguistic constructs such as "many," "low," "medium," "often," "few." In general, the fuzzy logic (FL) provides an inference structure that enables appropriate human reasoning capabilities The fuzzy logic controller is composed of the following four elements [19]:

1) A rule-base (a set of If-Then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.
2) An inference mechanism (also called an "inference engine" or "fuzzy inference" module), which emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant.
3) A fuzzification interface, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.
4) A defuzzification interface, which converts the conclusions of the inference mechanism into actual inputs for the process [20] .

Fuzzy Tuning of PID-Controller

In FL control, proportional derivative PD-type and PI-type FL-controllers are the best-known counterparts of the proportional integral derivative PID-controller. They are used to achieve better performance with nonlinear processes. In this work PI-type used. However, the standard FL- controller, which has the error and the change in the error as inputs and the control signal or its change as an output, can't react to changes in the operating point. The FL-controller needs more information to compensate nonlinearities when the operation conditions change. When the number of the fuzzy logic inputs is increased, the dimension of the rule base increases too [21].

Simulation and Results:

In this paper, the parameters values of the PMSM used in the simulation are given in appendix A.

PI-PSO Sensorless Controller

The simulation of the complete model with PI-PSO sensorless controller is shown in Fig.6. The PI-sensorless controller gains tuned by classical trial and error method chosen as.

[Kp1 =0.5 Ki1=0.8] [Kp2=50 Ki2=2.768]
[Kp3=70 Ki3=210] [Kp4=0.4 Ki4=130]

Where:

Kp1&Ki1: gains of PI speed controller.
Kp2&Ki2: gains of PI direct current controller.
Kp3&Ki3: gains of PI quadrture current controller.
Kp4&Ki4: gains of PI MRAS controller.

The step responses of the PMSM based on FLC with conventional PI sensorless controller tuned by trial and error method and under different load conditions are shown in Fig.7 and 8 respectively. The parameters of the speed and the electromagnetic torque with conventional PI controller tuned by trial and error method are illustrated in table (1).

The PSO tuning method used in this paper depends on ITAE performance index. The parameters of PSO algorithm that achieve better solution are listed in table (2). The optimal PI sensor-less controller gains tuned by PSO method are:

[Kp1=0.2678 Ki1=0.8]
[Kp2=3 Ki2=180]
[Kp3=500 Ki3=2000]
[Kp4=0.2 Ki4=180]

Where:
Kp1&Ki1: gains of PI speed controller.
Kp2&Ki2: gains of PI direct current controller.
Kp3&Ki3: gains of PI quadrture current controller.
Kp4&Ki4: gains of PI MRAS controller.

The step responses of the PMSM based on FOC with PI sensorless controller tuned by PSO method at different load conditions are shown in Fig.9 and 10 respectively. The parameters of the speed and electromagnetic torque with PI controller tuned by PSO method are illustrated in table (3).

With the application of PSO algorithm to optimize the gains of PI sensor-less controller instead of conventional (trial and error) method have introduce an improvement in the performance of the PMSM.

Fuzzy PI-PSO Sensorless Controller

The simulation of the complete model with Fuzzy PI-PSO sensorless controller is shown in Fig.11. Fuzzy PI sensorless controller block consists of two inputs error and change of error with integral output. Fuzzy PI-speed controller block was chosen with seven membership functions MFs (triangular center MF and trapezoidal MF) for each input and output as shown in Fig.12. The optimal Fuzzy PI-sensorless controller scaling factor (gains) tuned by PSO method found as :

$K_{Ge} = 0.0007$, $K_{Go} = 1000$ and
$K_{Gce} = 0.694$

Where:
K_{Ge}: is the gain of error.
K_{Gce} : is the gain of change of error.
K_{Go} : is the gain of output.

table (4) show the used rules for fuzzy-PI sensorless controller.

Fig.13 and 14 respectively shows the step responses of the PMSM based on field oriented control with Fuzzy-PI sensor-less controller with gains tuned by PSO at different load conditions. The motor responses of the speed and electromagnetic torque of the FOC of PMSM with Fuzzy-PI sensor-less controller tuned PSO method are illustrated in table (5). A comparison in step response between the different controllers with different loads. The comparison in motor responses for the speed and electromagnetic torque with the FOC of PMSM at different controllers are illustrated in table (6).

Conclusions:

The FOC-PMSM drive based on the SVPWM inverter are investigated. The complete drive system has been modeled. The dynamic and stationary performance have been simulated. The performance and different controller parameters tuning have been studied. This work also concerned with sensorless controller design by using MRAS controller to enhance and improve the performance behavior of the drive system.

Based on the analysis and results presented in this paper, the conclusions can be summarized as:

- PI sensorless controller tuned by PSO technique is enhanced more than PI sensorless controller tuned by classical trial and error method.
- The performance of the fuzzy logic controller gain requires less computation time compared to that of the trial and error method. Therefore, it can be concluded

that the proposed optimal fuzzy logic controller gain tuned by PSO technique provides an effective method of performance improvement.

- The proposed sensorless controllers in this work can be arranged according to its performance as follows:

(a) Fuzzy PI sensorless controller with gains tuned by PSO.
(b) PI sensorless controller tuned by PSO technique.
(c) PI sensorless controller tuned by trial and error method.

So, the performance comparison can be illustrated in Fig. 15.

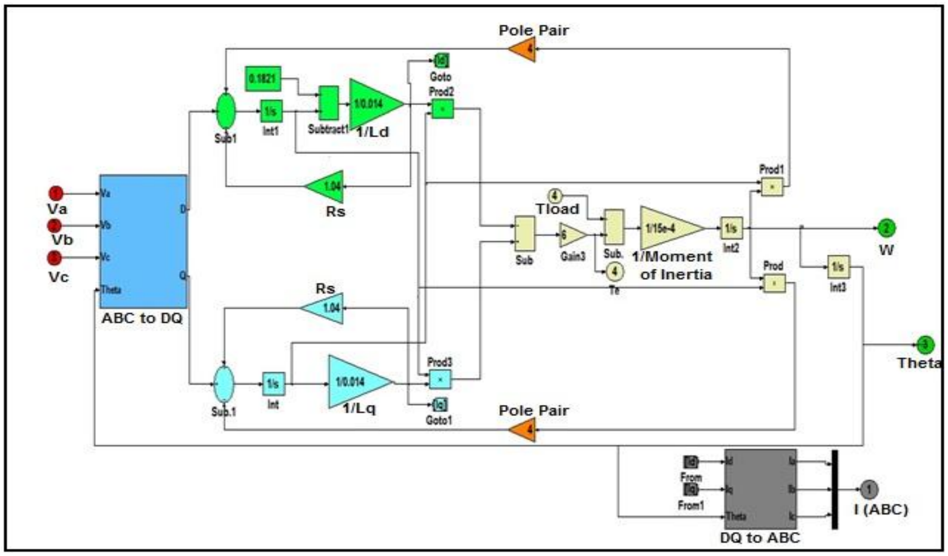


Figure.(1). Simulink model of PMSM

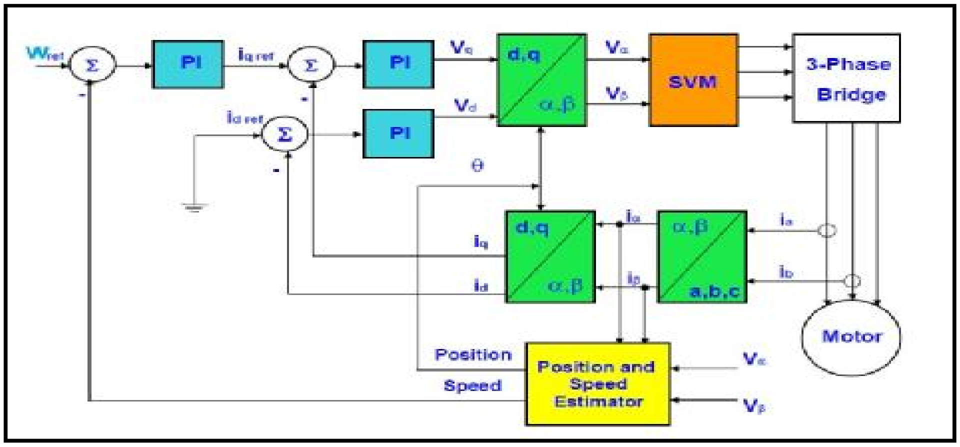


Figure.(2). Sensorless FOC for PMSM

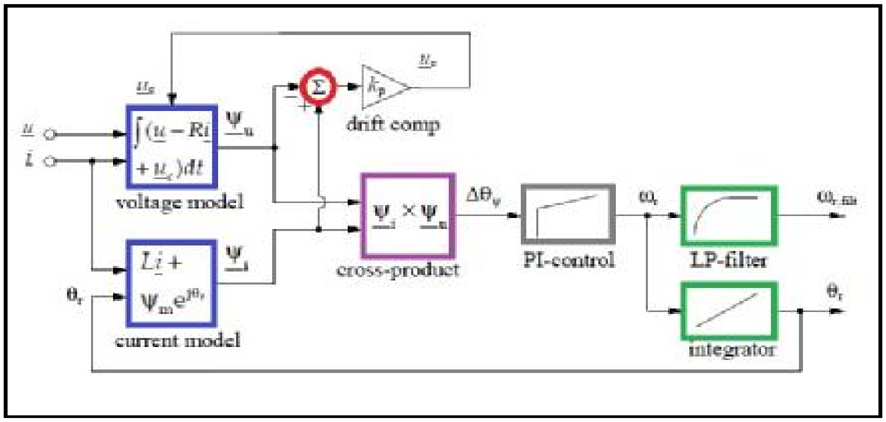


Figure (3). MRAS estimator for the rotor speed and position estimation

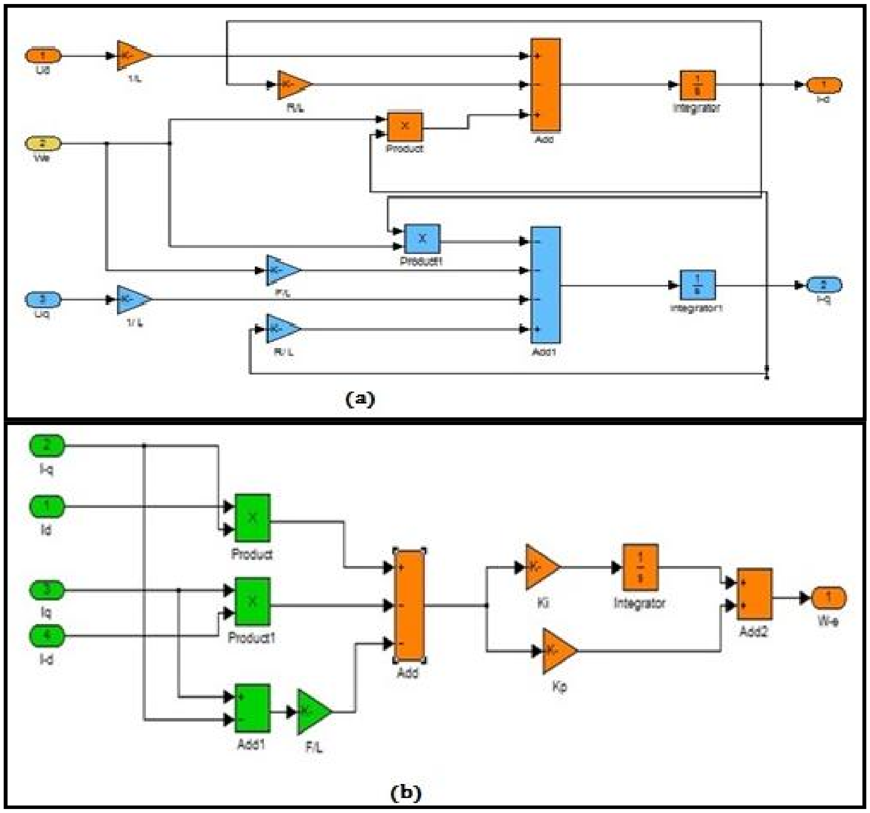


Figure (4). Simulink of (a) Reference model (b) Adjustable model

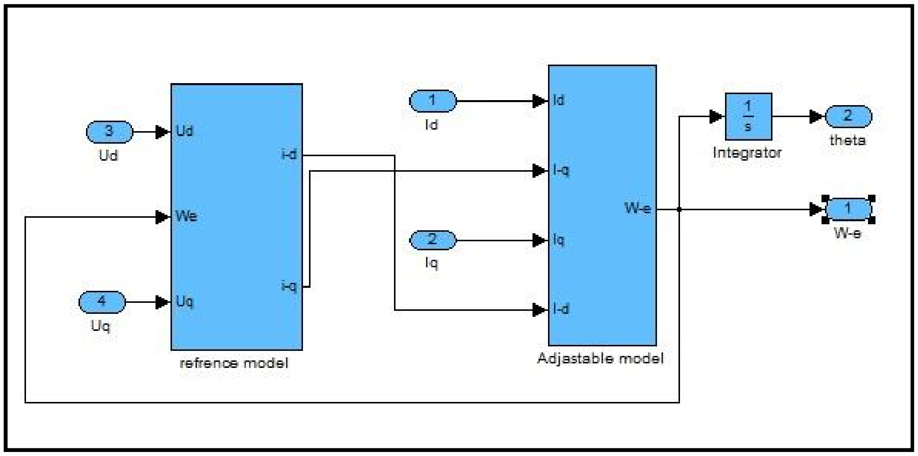


Figure.(5). Simulink of model reference adaptive system

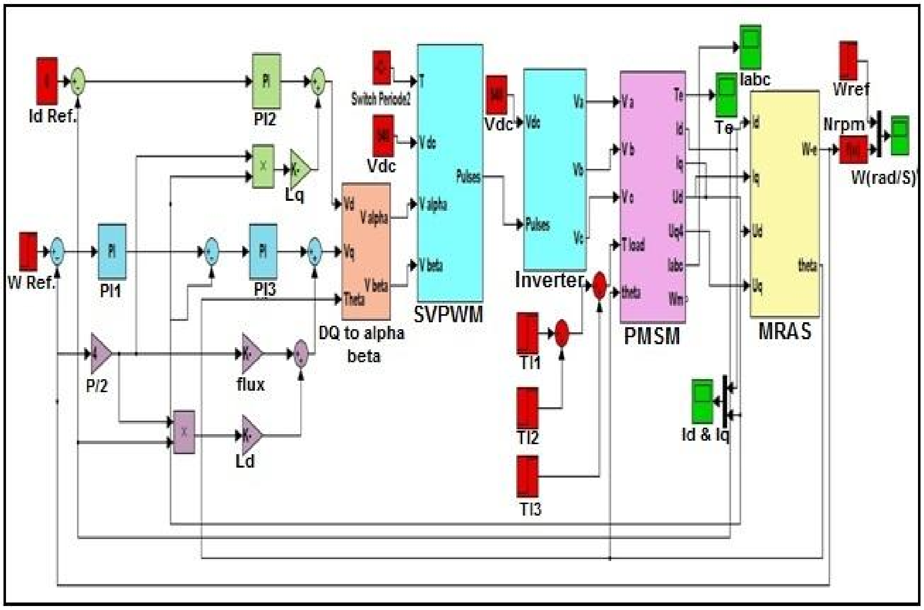


Figure (6). Simulink model of PMSM sensor-less Field-Oriented Control system

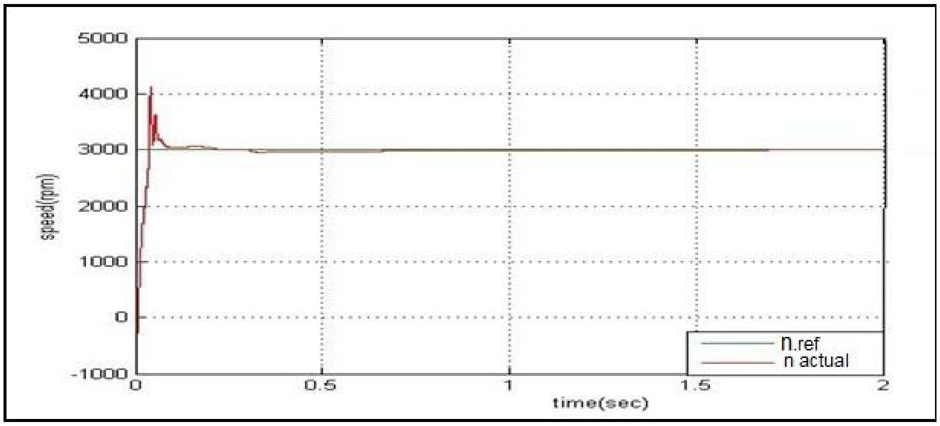


Figure.(7-a) . Speed response

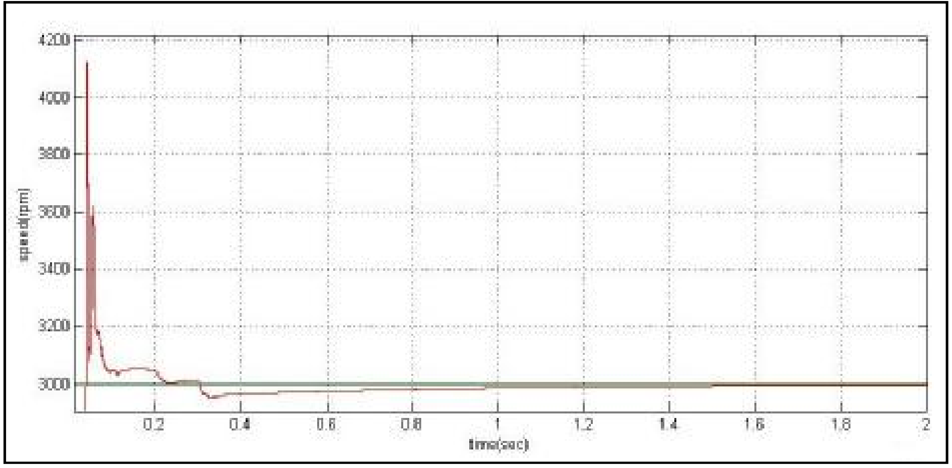


Figure.(7-b). Enlarge scale of speed response

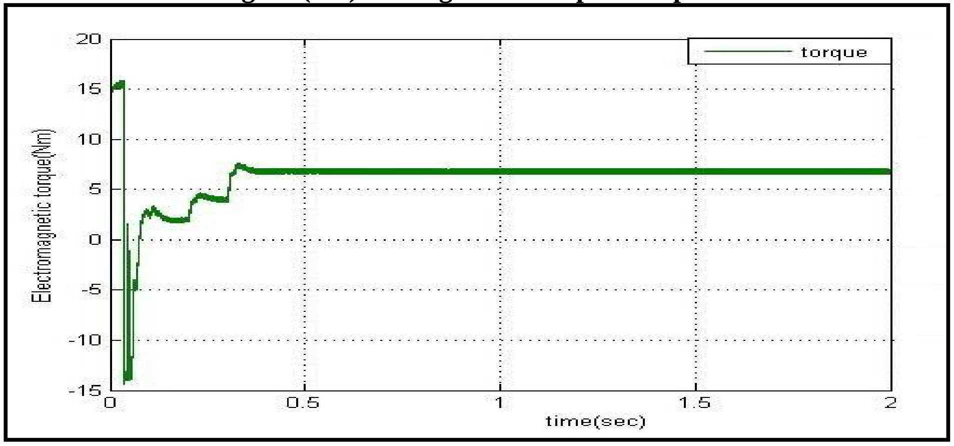


Figure.(8) . Electromagnetic torque response

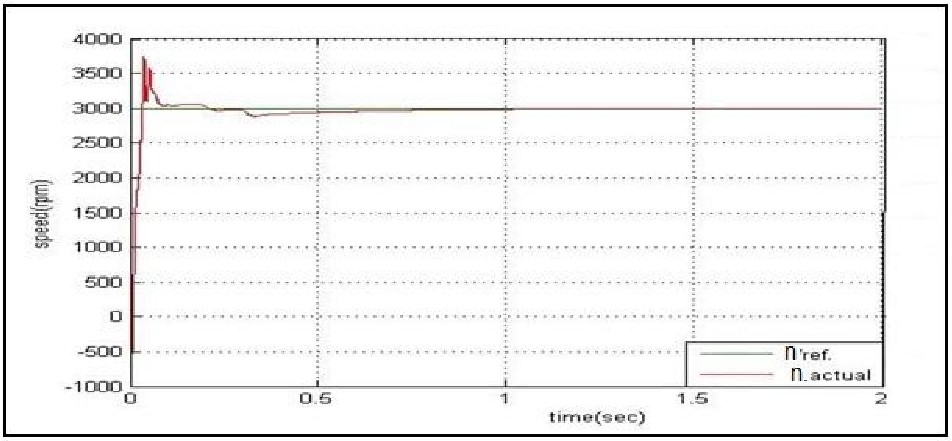


Figure.(9-a) . Speed response

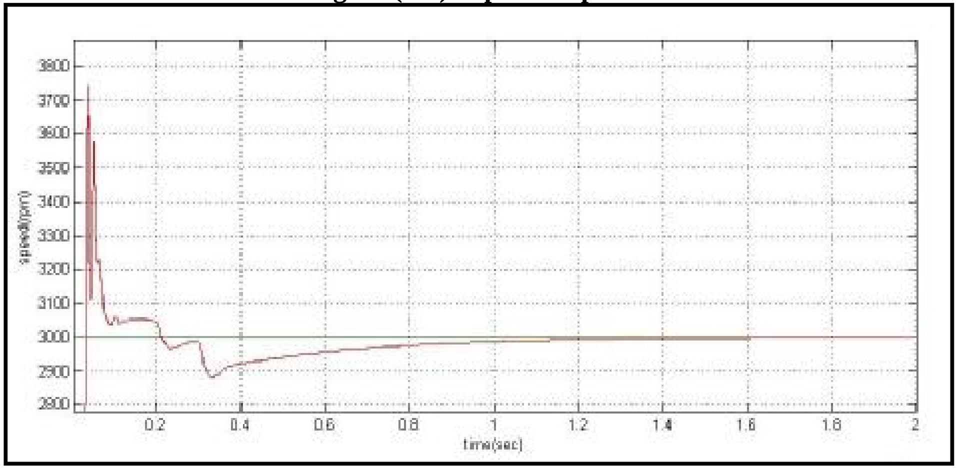


Figure.(9-b) . Enlarge scale of speed response

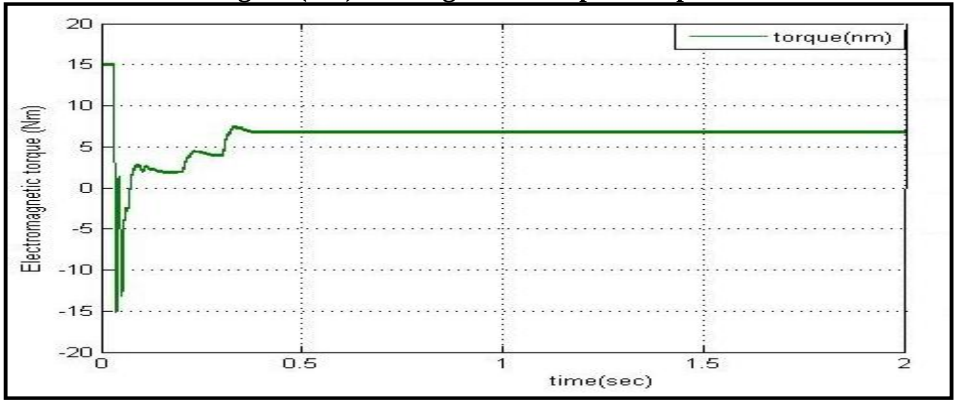


Figure.(10). Electromagnetic torque response

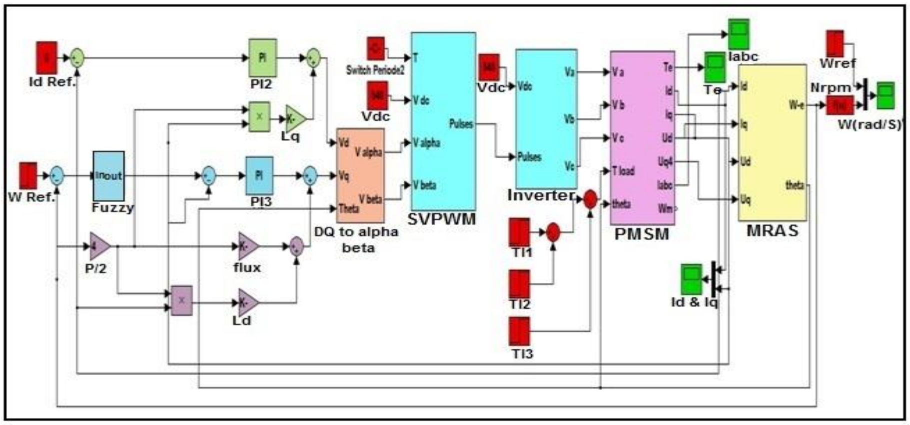
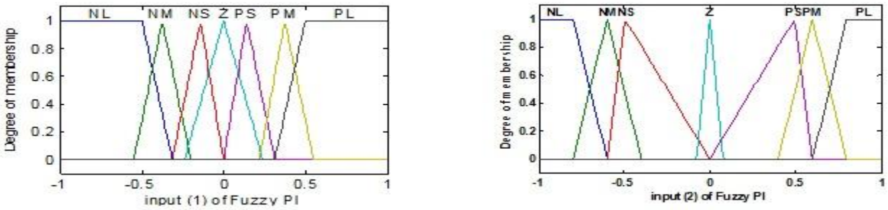
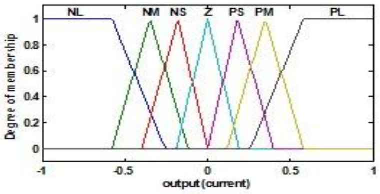


Figure (11) . Simulink of PMSM drive with Fuzzy-PI sensor-less controller



(a) Input (1) MFs of Fuzzy PI (speed error)

(b): Input (2) MFs of Fuzzy PI (change in error)



(c) output (2) MFs of Fuzzy PI (output current)

Figure (12) . Input/output tuned MFs of Fuzzy PI sensor-less controller

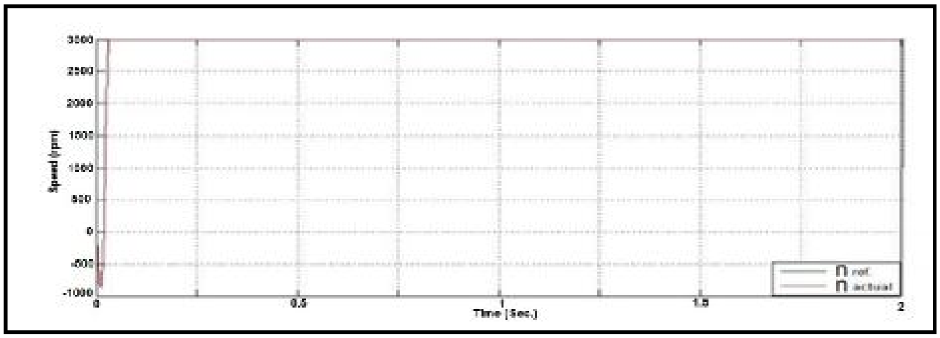


Figure (13).a. Speed response

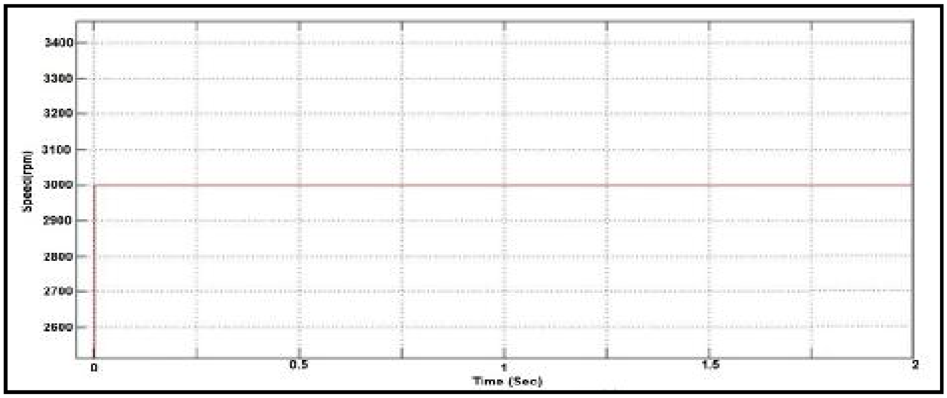


Figure (13).b. Enlarge scale of speed response

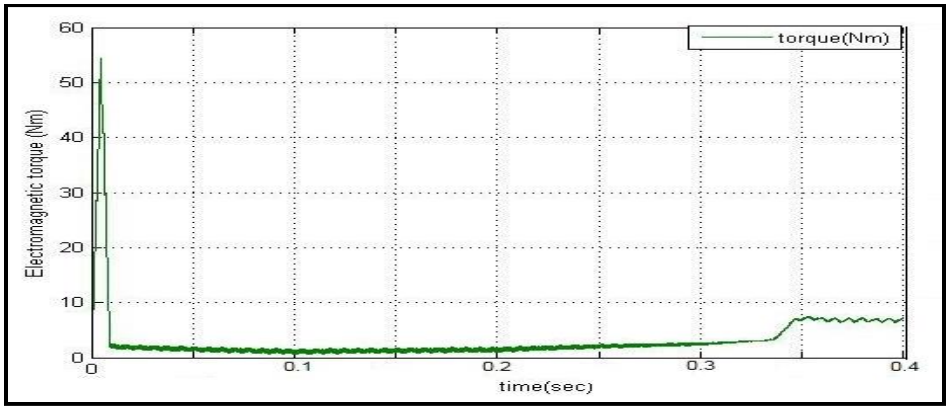


Figure (14). Electromagnetic torque response

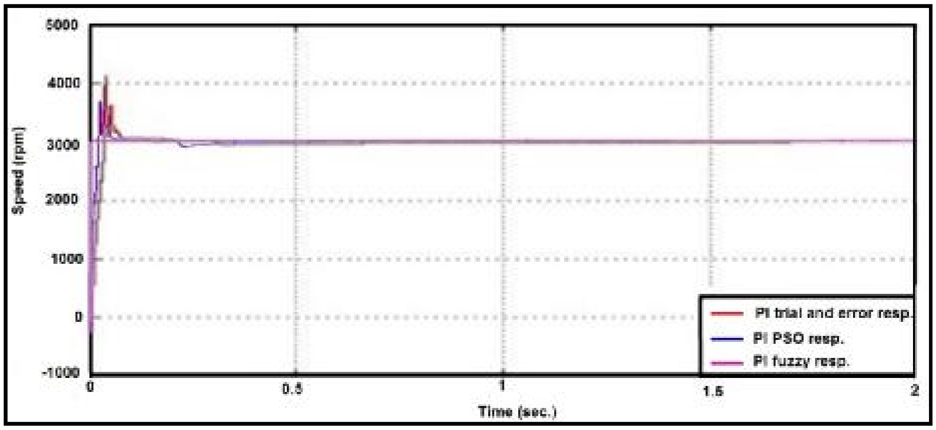


Figure (15). Comparison performance of speed response

Table (1). Motor responses

Controller Motor response			PI tuned manually
Speed response	S.S. error (rpm)	Light load=2 Nm	51.3,51
		Medium load= 4 Nm	8.8,8.7
		Full load= 6.8Nm	4.5,4
	Rising time (ms)		36.8
	Overshoot %		0.4
Electromagnetic torque	S.S. error (Nm)	Light load=2 Nm	0.2,-0.2
		Medium load= 4 Nm	0.15,-0.15
		Full load= 6.8Nm	0.15,-0.15
Three-phase currents (ripples)			High

Table (2). The parameters of PSO algorithm that achieved better solution

Swarm size (Number of birds)	30
Number of iterations	30
Cognitive coefficient (C_1)	1.2
Social coefficient (C_2)	1.2
Inertia weight (w)	0.9

Table (3). Motor responses

Controller Motor response			PI tuned by PSO
Speed response	S.S. error (rpm)	Light load=2 Nm	50,48
		Medium load= 4 Nm	13,12
		Full load= 6.8Nm	0.7
	Rising time (ms)		32.9
	Overshoot %		0.246
Electromagnetic torque	S.S. error (Nm)	Light load=2 Nm	0.08,-0.08
		Medium load= 4 Nm	0.075,-0.075
		Full load= 6.8Nm	0.09,-0.09
Three-phase currents (ripples)			Medium

Table (4). Rules for Fuzzy PI sensor-less controller

e Δe	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

Table (5). Motor response.

Controller Motor response			Fuzzy-PI tuned by PSO
Speed response	S.S. error (rpm)	Light load=2 Nm	0
		Medium load= 4 Nm	0
		Full load= 6.8Nm	0
	Rising time (ms)		6
	Overshoot %		0
Electromagnetic torque	S.S. error (Nm)	Light load=2 Nm	0.02, -0.02
		Medium load= 4 Nm	0.02, -0.02
		Full load= 6.8Nm	0.02, -0.02
Three-phase currents (ripples)			Low

Table(6). The motor responses of the speed and electromagnetic torque of the sensorless FOC of PMSM at constant speed with variable loads

Controller Motor response		PI tuned manually	PI tuned by PSO	Fuzzy-PI tuned by PSO
S.S. error of Speed Response at constant speed (3000 rpm)	Light load=2 Nm	51.3,51	50,48	0
	Medium load= 4 Nm	8.8,8.7	13,12	0
	Full load= 6.8Nm	4.5,4	0.7	0
Rising time (ms)		36.8	32.9	6
Overshoot %		0.4	0.246	0
S.S. error of Electromagnetic torque (Nm)	Light load=2 Nm	0.2,-0.2	0.08,-0.08	0.02,-0.02
	Medium load= 4Nm	0.15,-0.15	0.075,-0.075	0.02,-0.02
	Full load= 6.8Nm	0.15,-0.15	0.09,-0.09	0.02,-0.02
Three-phase currents (ripple)		High	Medium	Low

Appendix A:

PMSM parameters

Rated Power (P_{out})	2.14Kw	Number of pole pairs (P)	4
Rated Speed (N)	3000rpm	Stator resistance (R_s)	1.04Ω
Rated Current (I)	4.4A	Stator inductance (L_d and L_d)	14mH
Rated Torque (T)	6.8N.m	Permanent Magnet Flux (Ψ)	0.1821Wb
Moment of Inertia (J)	$15e^{-4}$Kg/m^2		

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