TORQUE RIPPLE MINIMIZATION, SUPPRESS HARMONICS, AND NOISE OF BRUSHLESS PM SYNCHRONOUS MOTORS DERIVED BY FIELD ORIENTED CONTROL

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ABSTRACT

Conventional field oriented control for brushless PM synchronous motor depends upon mathematical model so the parameters variations, noise, electromagnetic interface, non-sinusoidal flux and harmonics in the motor or in power converter will cause performance deteriorating of the drive system. They are causing speed oscillations, ripples in torque, ripples in current and an increase the total harmonics distortion (THD). This paper is addressed these problems and suggested novel two PI controller for solving these problems. One for the torque and the other for the flux. The first PI controller is feeding from the torque error between the reference and estimated torques to get new q-axis current component representing modifier current arises from uncertain things such as earliest problems. This current will add to reference q-axis current to get robust new q-axis current to satisfy the drive requirement and solve the torque problem. With robust current, the total harmonic distortion is a decrease but doesn't reach the best value so the other PI controller is used to adjust the THD. In this PI controller, the d-axis flux is compared to rotor permanent magnet flux to solve this problem arises from non-sinusoidal of the magnetic flux. The output of the PI controller is introduced to the reference d-axis current. The new d-axis current will reach the best value of THD. The simulation of the proposed controller is compared to the simulation of conventional controller to show the advantages of the proposed controller. To display the effectiveness of the second PI controller (flux controller), the result of the new controller is displayed with new PI torque controller only and with new two proposed controller. MATLAB SIMULINK is used to simulate the drive system.

Keywords: *PMSM– FOC –Hysteresis Current Controller – PI Controller – Torque ripple– Current ripple– THD.*

1. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are widely used in high-performance drives such as industrial robots, electric vehicles, aircraft and machine tools. These motors have many advantages as: high efficiency, high power density and high-torque/inertia ratio [1].The performance of these motors in drive systems depend up on the motor control and method of control in power converter. From the most important methods to control the power converter are current and voltage controls. The current control is preferable. This is because it is simple. The quality control of this method depends upon the quality of the waveform is generated by current controlled of converter [2-3]. To get good power waveform this depends upon the following factors:-

- Switching frequency of the PWM which has low harmonics if it is high but it has drawback such as: high losses.
- Modulation method which control the magnitude of the output waveform but it has drawback such as: high order of voltage harmonics and ripple current.
- Types of current waveform. This is because each motor required own current waveform such as: induction motor and PMSM required sine wave but brushless DC motor required quasi square wave form.

The method of motor control is very important in the drive system. This is because the operation of the PMSM under effect of scalar control is suffered from complicated coupling nonlinear dynamic performance. This problem can be solved by field oriented control (FOC). PMSM with FOC emulates the separately excited DC motor. In this method of control, the stator current can be decupled into flux and torque current components. They can be controlled separately. In four quadrant with keeping magnetic circuit linear and applying the principles operation of the FOC, the linear relation can be described the motor torque.

The performance of the motor suffers from uncertainties, parameters variation, harmonics in both motor and inverter. These problems affect motor performance. These problems shape difficult in getting robust control. They lead to problems in torque and oscillation in the speed as the secondary problem comes from torque problem. To solve this problem, the torque must be studied. The motor torque is a sum of mutual torque, reluctance torque and cogging torque. These torques contain harmonics which lead to torque ripples. The mutual torque and reluctance torque have harmonics if the stator flux or rotor magnet are non- sinusoidal. The reluctance torque is exists only if the inductance is a function in the rotor position. So the torque ripples appear as a six harmonics. The cogging torque arises due to geometry and slots in the PMSM [4]. Other reasons of harmonics, the switching power of inverter causes electromagnetic interface which causes noise and increase the torque pulsations.

The machine design and control technique are used to reduce the torque ripple. The first method is complicated and high cost so the other method is preferable. Many control techniques are used to minimize the torque ripple such as: programs to cancelation the harmonics but these methods require full knowledge about the machine parameters. These methods become undesirable if the operating point changes [5-6]. The current control scheme with an adaptive internal model is proposed in many researches as [7]. Passive filter is used to reducing the torque ripples in [8] but higher circulating current arises between filter and inverter. Active filter is used to reducing the torque ripples but this method is higher cost [9]. Proportional integrator controller (PI), it is the most common controllers used in a wide range in the industrial applications. The popularity of PI control can be attributed to its simplicity. The integral controller has drawback such as saturation. This phenomenon can be avoided by introducing a limiter to the integral part of the controller before adding its output to the output of the proportional controller. The output of the PI is used as the input of controlled voltage source inverter which is fed to the motor for controlling its speed [10]. Many researches used PI controller to improve the position and speed controllers this is because it affects the performance of the drive system especially torque and speed oscillations. The PI controller is sensitive to uncertainties variation such as motor parameters, disturbance and temperature variations. So In this study two new proportional integrator corrector controller are used to optimize conventional PI controller. The first PI controller is used to reduce the noise, distortion and ripple torque. The second PI controller is used to reduce the noise, distortion and ripple in the stator currents this can be done by reducing the distortion in the stator flux. Hysteresis with current control are made. This system is simulated by MATLAB Simulink. The simulated model with proposed new PI controllers is compared with conventional PI controller in order to investigate the advantages of the new proposed control. This paper is organized as follows. Section one introduction. Section two FOC drive system of PMSM. Section three Mathematical model of PMSM. In section four Traditional control loop of the field oriented control. Section five described Hysteresis current controller. Section six Design of PI controller. Section seven Proposed control loop of the field oriented control Section eight shows the simulation results. The conclusion is in section nine.

2. FOC DRIVE SYSTEM OF PMSM

The FOC aims to control both torque and flux to force the motor to accurately track the desired values. This control is performed by regulation of the motor current. This control suffers from undefined things such as: parameters variation, harmonics and external load disturbance. To track these problems another field oriented controller drive system is proposed as shown in Figure 1. The details of the new controller system are discussed later.

3. THE MATHEMATICAL MODEL OF PMSM

The mathematical model of a PMSM is similar to that of wound rotor synchronous motor. The rotor winding of synchronous motor is replaced with high resistivity permanent magnet material, hence, induced current in the rotor are negligible. The rotor types of PMSM are shown in Figure2. The permanent magnets on the rotor are shaped in such a way as to produce sinusoidal back EMF in stator windings

The following equations represent the model of PMSM

$$v_d = r i_d + L_d \frac{d i_d}{dt} - \omega_e L_q i_q \tag{1}$$

$$v_q = r i_q + L_q \frac{d i_q}{dt} -+ \omega_e L_d i_d + \omega_e \psi_m \tag{2}$$

$$J \frac{d\omega_m}{dt} = \mathrm{T}_m - \mathrm{T}_L - \beta \omega_m \tag{3}$$

$$\mathrm{T}_m = 3\frac{\mathrm{P}}{4}[\Psi_m i_q + (L_d - L_q) i_q i_d] \tag{4}$$

$$\theta_e = \frac{\mathrm{P}}{2}\int \omega_m dt \tag{5}$$

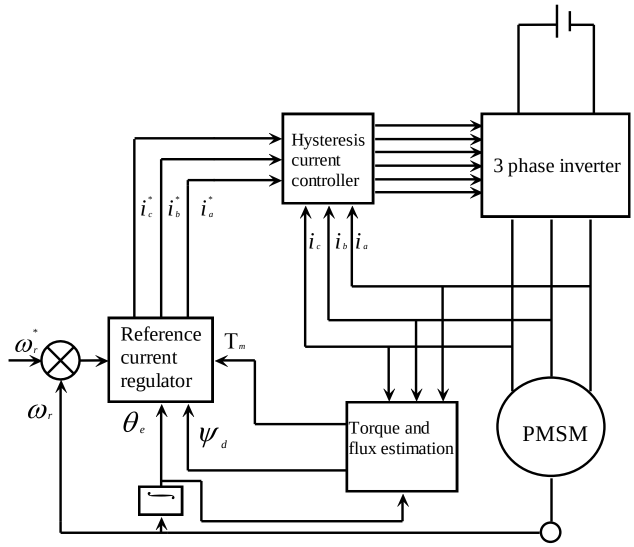
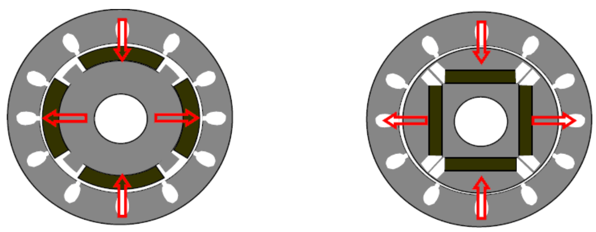


Figure 1. Block diagram of new controller FOC drive system



(a) (b)

Figure 2. The types of the rotor in PMSM: (a) PM surface inset, (b) PM surface interior (buried)

Due to the control variables are measured in synchronous reference frame and the actual values are measured in stationery reference frame, the park and Clark must be performed and vise versa. The following matrix can be applied to transform from abc to dq

$$\begin{pmatrix} S_d \\ S_q \end{pmatrix} = \frac{2}{3}\begin{pmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e - \frac{4\pi}{3}) \\ -\sin\theta_e & -\sin(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e - \frac{4\pi}{3}) \end{pmatrix}\begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} \tag{6}$$

And transformation matrix from dq to abc is

$$\begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} = \begin{pmatrix} \cos\theta_e & -\sin\theta_e \\ \cos(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e - \frac{2\pi}{3}) \\ \cos(\theta_e - \frac{4\pi}{3}) & -\sin(\theta_e - \frac{4\pi}{3}) \end{pmatrix}\begin{pmatrix} S_d \\ S_q \end{pmatrix} \tag{7}$$

Under base speed the d-axis current is forced to zero then the torque can be controlled through the q-axis current component only and the electromagnetic torque can be calculated as

$$T_e = 3\frac{P}{4}[\Psi_m i_q] \tag{8}$$

4. TRADITIONAL CONTROL LOOP OF THE FIELD ORIENTED CONTROL

Conventional field oriented control can be applied as shown in Figure 3. One PI controller is used. It is used to regulate the speed. The input of PI controller is the speed error which comes from comparing the reference and measured speeds. The output of this PI controller is a reference torque. With aid of constant torque and the output of PI controller the torque current component (i_q) can be deduced. The d-axis current component (i_d) is set to zero this is because the operation of the PMSM in a constant flux region. With aid of rotor position and two reference current components ($i_q - i_d$), the three phase reference current can be deduced. They comparing to the actual three phase current through hysteresis current controller to get pulse signals of inverter.

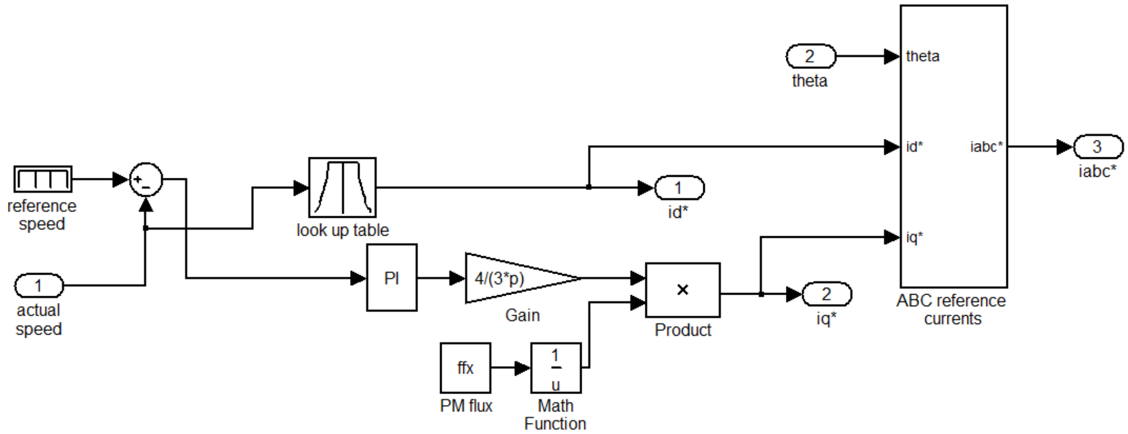


Figure 3. Conventional field oriented control

5. HYSTERESIS CURRENT CONTROLLER

In this work, the current control of converter is a hysteresis current controller. It is used due to simple, fast dynamic response and insensitive to load parameters. Figure4. represents the hysteresis current controller. In this method each phase consists of comparator and hysteresis band. The switching signals are generated due to error in the current. The error comes from comparing between the reference current and actual current. The main task of this method of control is to force the input current to follow the reference current in each phase. The deviation of these currents (error current) represents the current distortion which can be calculated as

$$\text{distortion} = \frac{100}{I_{rms}} \sqrt{\frac{1}{T} \int (i_{act} - i_{ref})^2 dt} \ \% \qquad (9)$$

In this method of control, the deviation of the current between the upper and lower in the hysteresis band is limited. In any phase, if the actual current becomes more than the upper limit of hysteresis band ($i_{ref} + HB$) the upper switch of the inverter arm is turned off, the lower switch is turned on and the current starts to decay. In contrast if the actual current reaches lower limit or less than of hysteresis band ($i_{ref} - HB$) the lower switch of the inverter arm is turned off, the upper switch is turned on and the current comes back into the hysteresis band. The band width calculates the switching frequency and current ripple. The band width is directly to current ripple and inversely proportional to switching frequency so the selection of the band width means performance of inverter. This is because the increasing in the band width will increase the current ripple in contrast; a decrease in the band width will increase the switching losses.

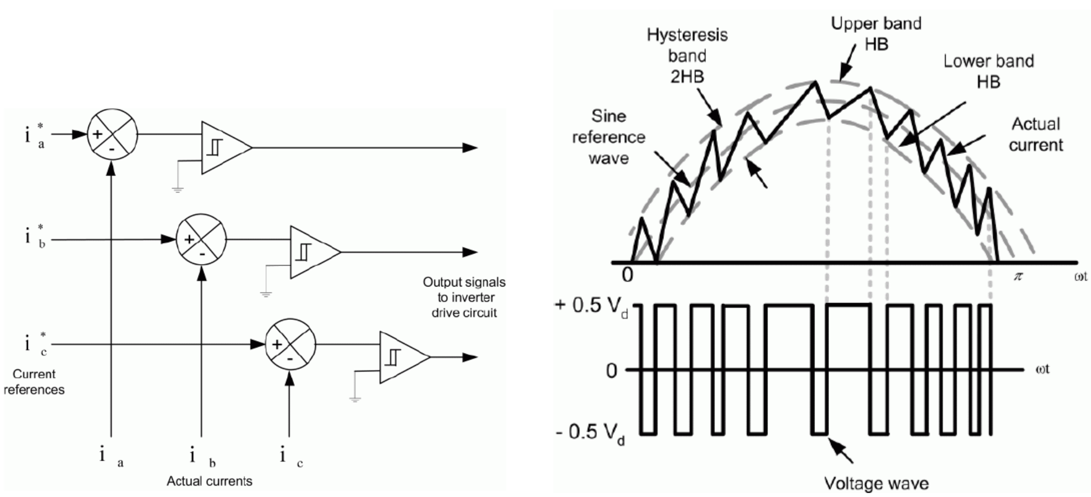


Figure 4. Hysteresis current controller basic structure and concept

6. DESIGN OF PI CONTROLLER

PI controller is a type of feedback controller which has output depending upon the error. This error is used to adjust the input of the other process. Two parameters are used to design this controller. These parameters are proportional gain (k_p) and integral gain (k_i). This controller can represent as

$$G(S) = k_p + \frac{k_i}{S} \tag{10}$$

Proportional gain is used to improve the rise time and integral gain is used to eliminate the steady state error. These parameters can be deduced by many methods such as: trial and error, Ziegler-Nichols method and internal model of control. The parameters of the PI controller are determined depending upon [11-12].

7. PROPOSED CONTROL LOOP OF THE FIELD ORIENTED CONTROL

In traditional control (FOC), the drive is influenced by uncertainties, electromagnetic interface, non-sinusoidal of stator current and permanent magnet rotor flux or all of them. They reflect on the torque and current causing unwanted problems such as ripple and noise. The ideal case of electromagnetic torque is (8) but when takes into account the effect of harmonics, it becomes

$$\begin{aligned} \mathrm{T}_m = \frac{3P}{4}[&\psi_m i_q + (L_d - L_q) i_d i_q + (\psi_{d6}\sin(6\theta) + \psi_{d12}\sin(12\theta)) i_d \\ &+ (\psi_{q6}\cos(6\theta) + \psi_{q12}\cos(12\theta)) i_q] \end{aligned} \tag{12}$$

The first term is the mutual torque, the second it is reluctance torque and the other terms represent the harmonic torques. Due to i_d^* is forced to zero so the terms which contain this current aren't most energy effective. So the torque equation can be represented as

$$\mathrm{T}_m = \frac{3P}{4} i_q [\psi_m + \psi_{q6}\cos(6\theta) + \psi_{q12}\cos(12\theta)] \tag{13}$$

This torque can be considered as

$$\mathrm{T}_m = \mathrm{T}_{em} + \mathrm{T}_{e6h} + \mathrm{T}_{e12h} \tag{14}$$

Also q-axis current component is

$$i_q = \frac{4\mathrm{T}_m}{3P} \frac{1}{[\psi_m + \psi_{q6}\cos(6\theta) + \psi_{q12}\cos(12\theta)]} \tag{15}$$

So the PI speed controller which is used to generate the q-axis current isn't sufficient to overcome the noise and ripples in torque and current. To minimize the ripple and noise in the torque another PI controller is used; the input of the new PI controller is the error in the torque. This error comes from the output of comparator which comparing the reference torque to estimated torque. The output of the new PI controller is a new q-axis current (i_{qsol}). This current is add to the reference of q-axes current to get robust current ($i_{qrobust}$) representing the solution for noise, ripple and uncertainties inside the machine.

$$i_{qrobust} = i_{qref} + i_{qsol} \tag{10}$$

With this enhanced in the q-axis current component, the distortion of the current doesn't reach the best value this can be seen in table 1 and in later figures. To reach the best value another PI controller is used. The input of this PI controller arises from comparing the estimated d-axis flux with permanent magnet flux. The output of this PI controller is added to the reference d-axis current which is forced to zero at constant flux region. The new d-axis current is reduced the distortion as shown in table 1 and as in later figures. the new dq-axes current with rotor position are used to generate the new reference current. The new proposed controller is shown in Figure 5.

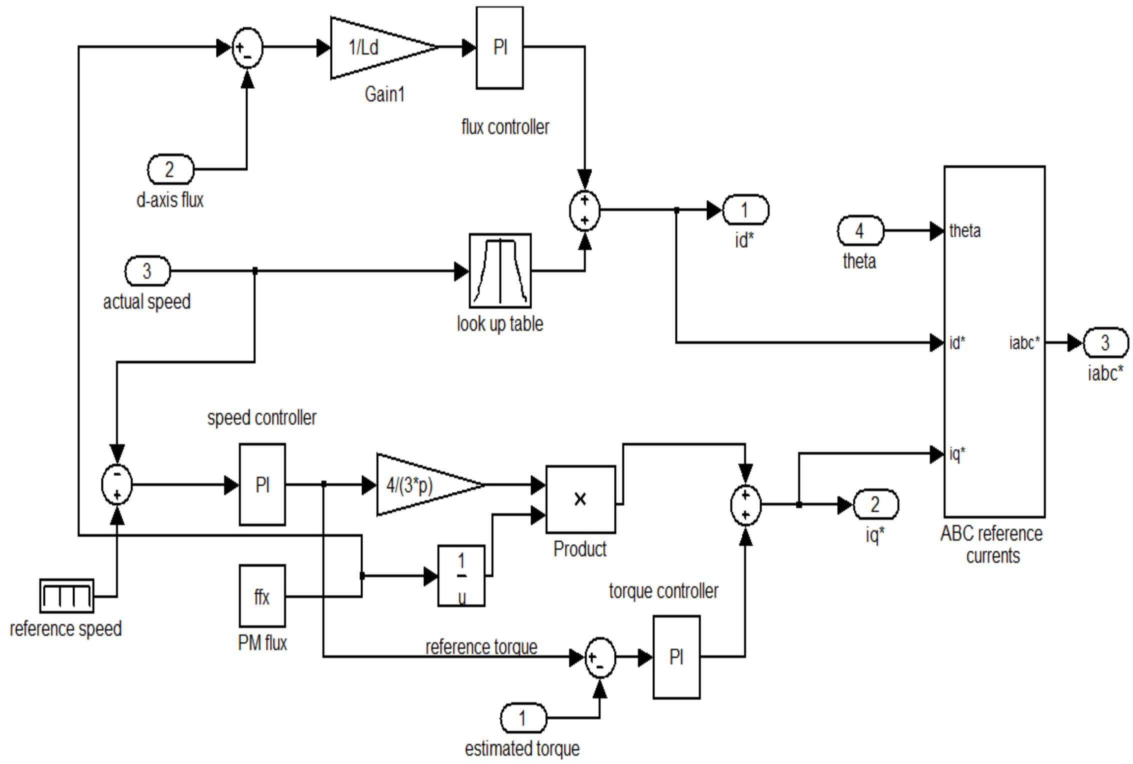


Figure 5. Proposed controller

8. SIMULATION STUDY

Here the three models are compared. These models are conventional model, modified model with PI torque controller and modified model with two PI controllers and one for the torque and the other for flux controller. These comparisons are used to show the effectiveness of each model and to show which of them is robust model. Table 2 shows the motor parameters. During the simulations, the torque set value is limited to 2 N.m. In all figures the time axis is in seconds. Here the simulation studies two cases

1. Motor starting with loading.
2. Sudden applied load.

Where it is found that,

8.1. The first case

In figure 6, dq axes currents are simulated. In conventional model figure 6. (a), the dq axes currents is highly distorted. In modified model with PI torque current controller figure 6. (b), the q-axis current is modified and closest to the best value while the d-axis current is improved but isn't reached the best value. In modified model with two PI controllers (PI controllers for torque and flux) figure 6. (c), both q-axis current component and d-axis current component are closest to the best value.

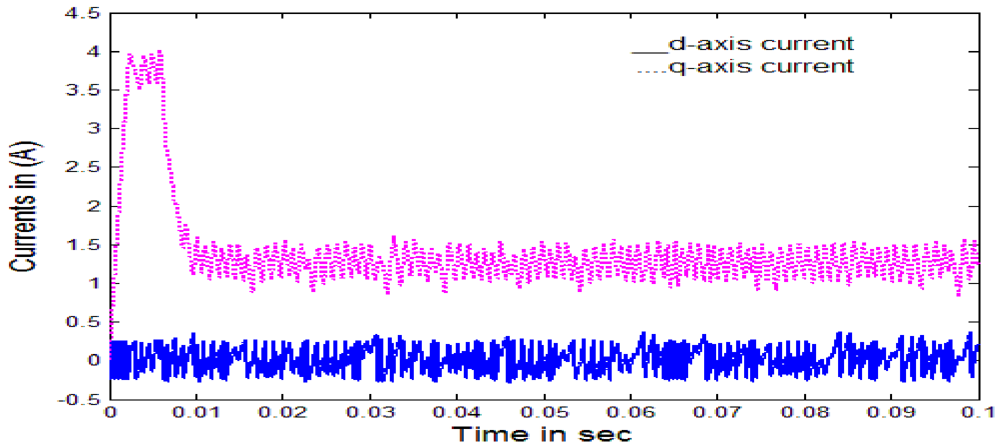


Figure 6. (a) Idq-axis current with conventional method

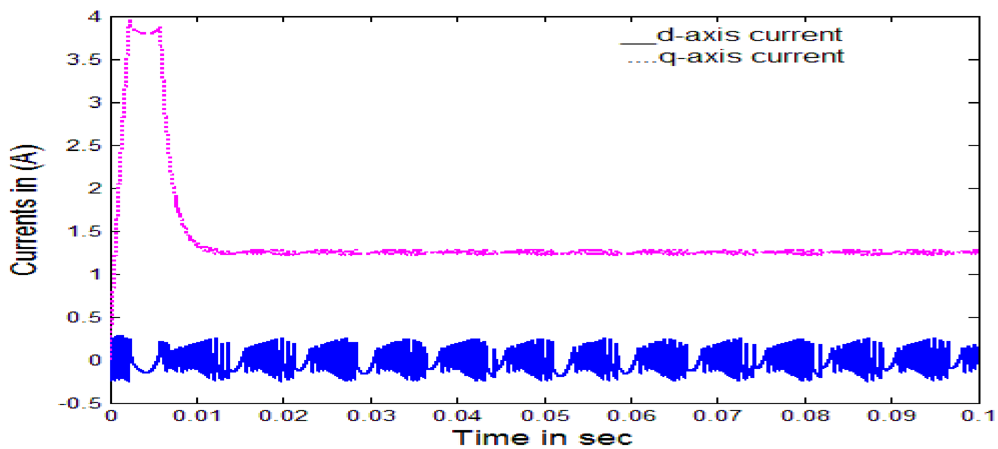


Figure 6. (b) Idq -axis current with modified PI controller for torque only

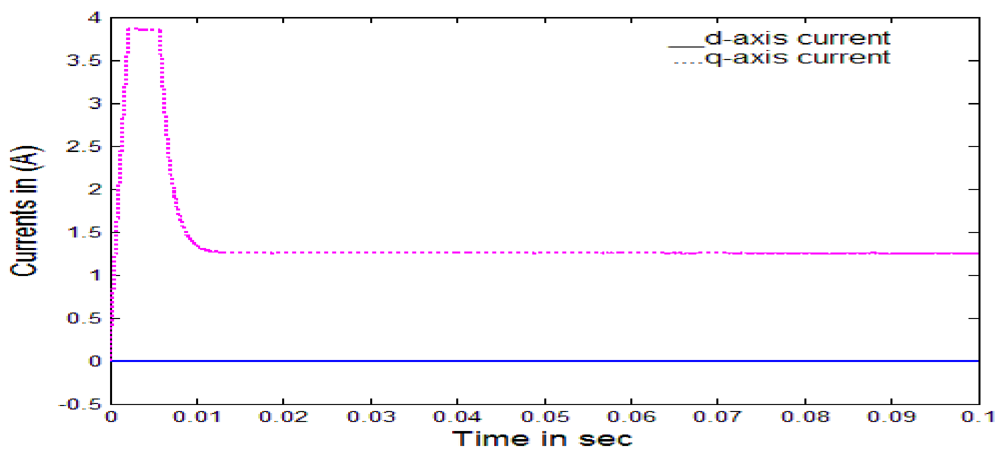


Figure 6. (c) Idq -axis current with modified PI controllers for torque and flux

In figure7, the stator flux is simulated. With modified control (PI controllers for torque and flux) figure 7. (c), the distortion in the flux is suppressed if it is compared to conventional method figure 7. (a), and modified method with one PI controller (torque current controller) figure 7. (b).

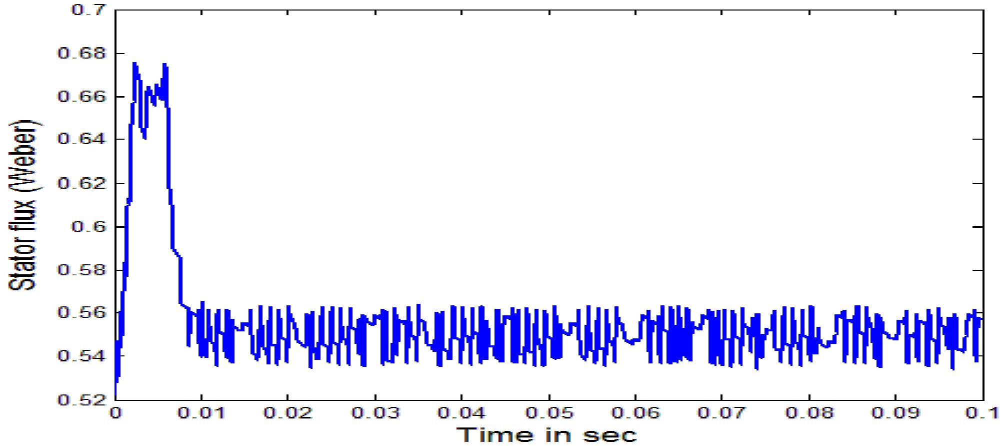


Figure 7. (a) Stator flux with conventional method

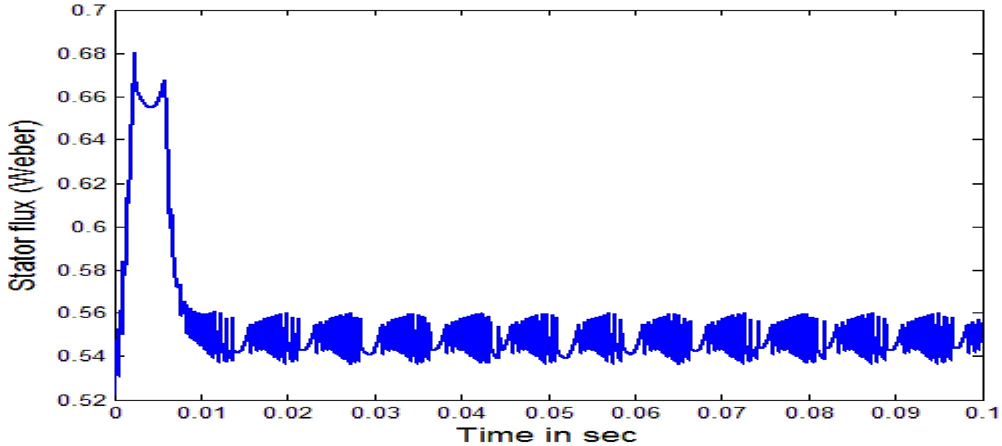


Figure 7. (b) Stator flux with modified PI controller for torque only

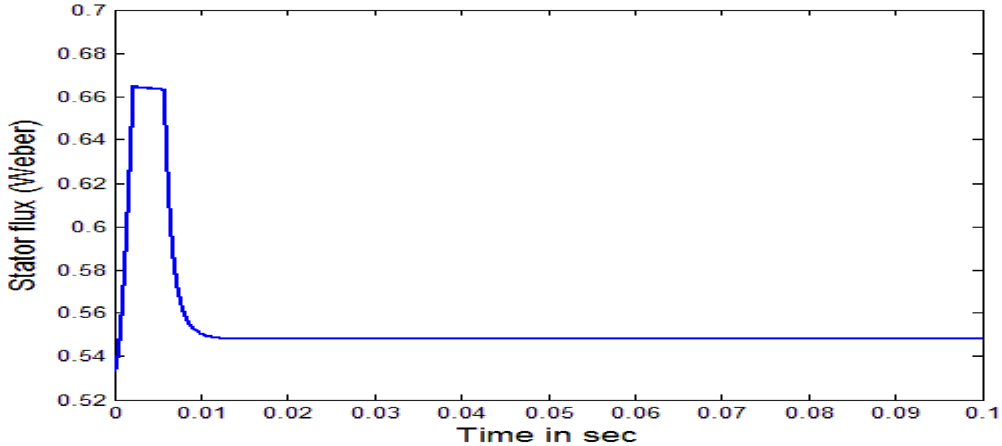


Figure 7. (c) Stator flux with modified PI controller for torque and flux

The torque response in figure 8 showed that, the torque ripple is approximately vanished with two modified control (two PI controllers and one PI controller) figure 8. (c) and figure 8. (b) if it is compared to the conventional method figure 8. (a). This is because the improvement occurred in q-axis current component.

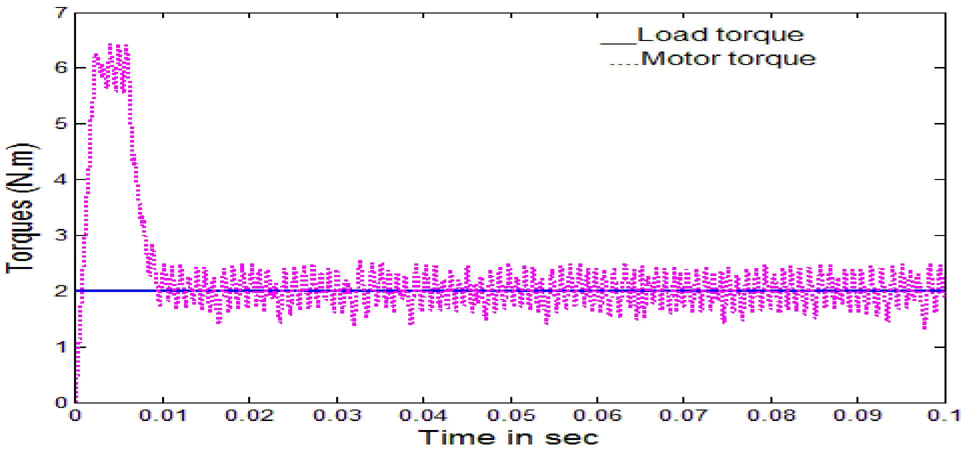


Figure 8. (a) Torque with conventional method

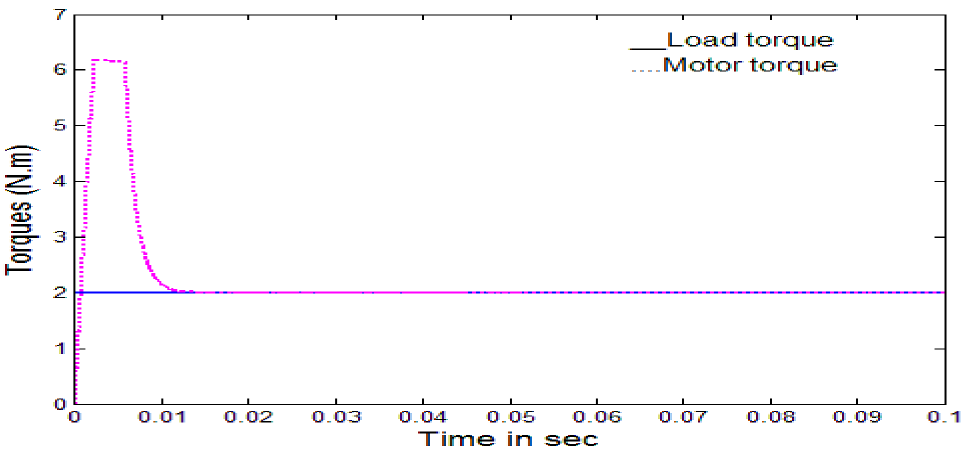


Figure 8. (b) Torque with modified PI controller for torque only

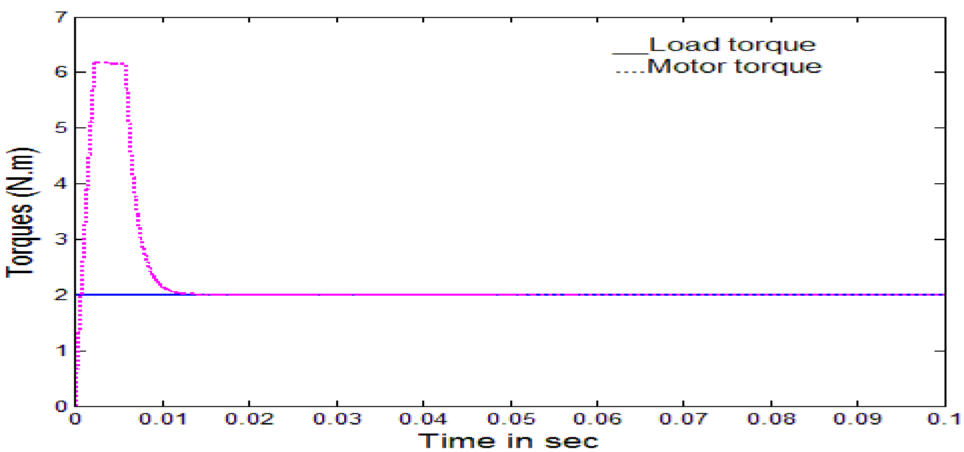


Figure 8. (c) Torque with modified PI controller for torque and flux

Figure 9 shows some noise in the speed with conventional method figure 9. (a) if it is compared to the modified method (two PI controllers and one PI controller) figure 9. (c) and figure 9. (b). This is because the torque ripple reaches the best value with modified methods.

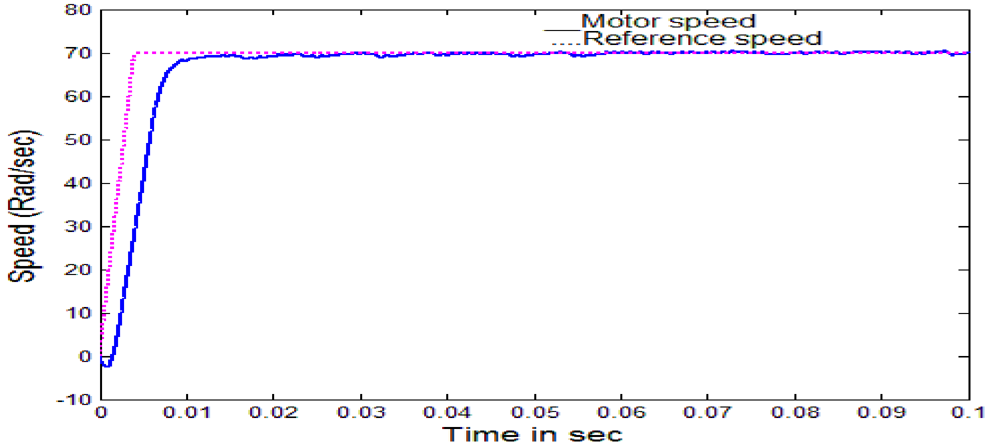


Figure 9. (a) Speed with conventional method

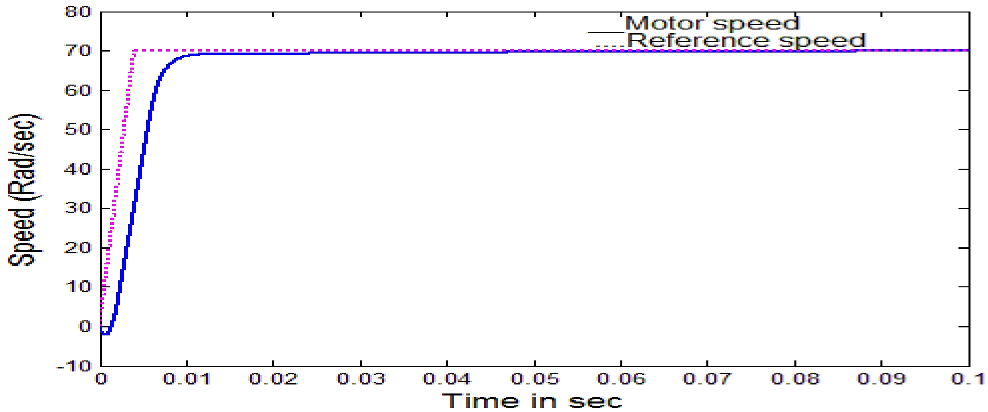


Figure 9. (b) Speed with modified PI controller for torque only

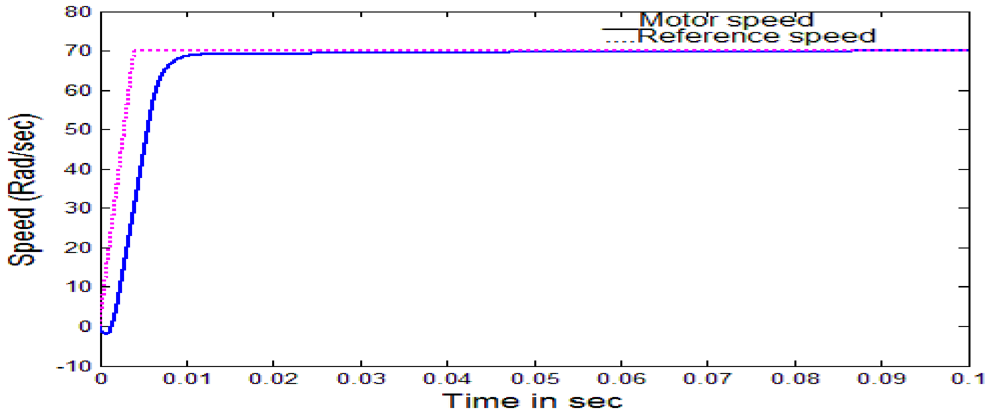


Figure 9. (c) Speed with modified PI controller for torque and flux

In figure 10, the stator currents become smoother with modified method (PI controllers for torque and flux) figure 10. (c) but with using torque current controller only figure 10. (b), the modified in the current is less smoother. This occurs due to highly reduction of the noise in the stator flux and suppresses in electromagnetic interference with two PI controllers. In conventional method figure 10. (a), the stator current is highly distorted due to noise in the stator flux and electromagnetic interference.

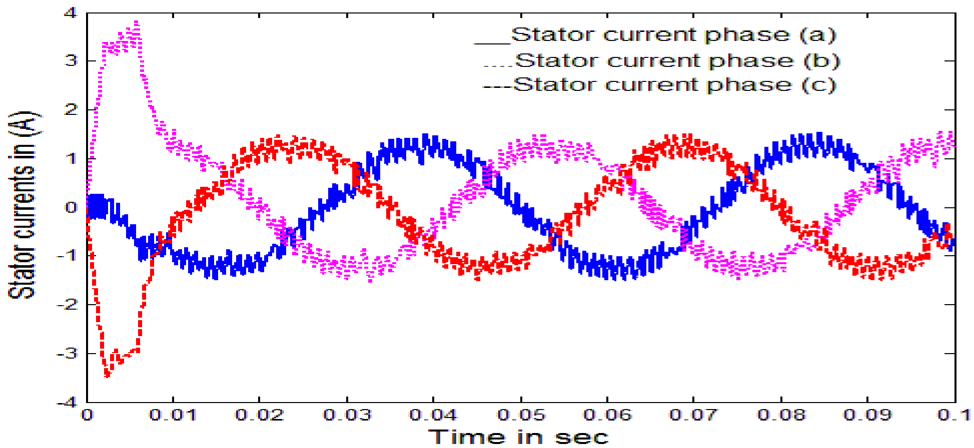


Figure 10. (a) Stator current with conventional method

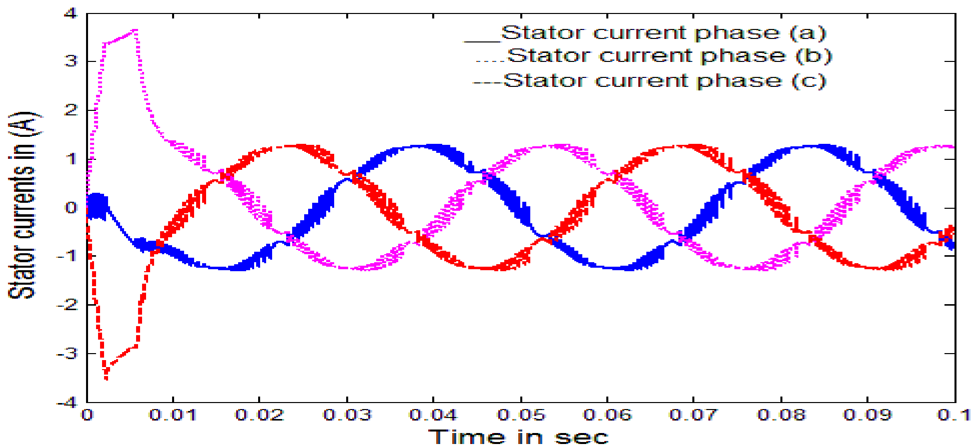


Figure 10. (b) Stator current with modified PI controller for torque only

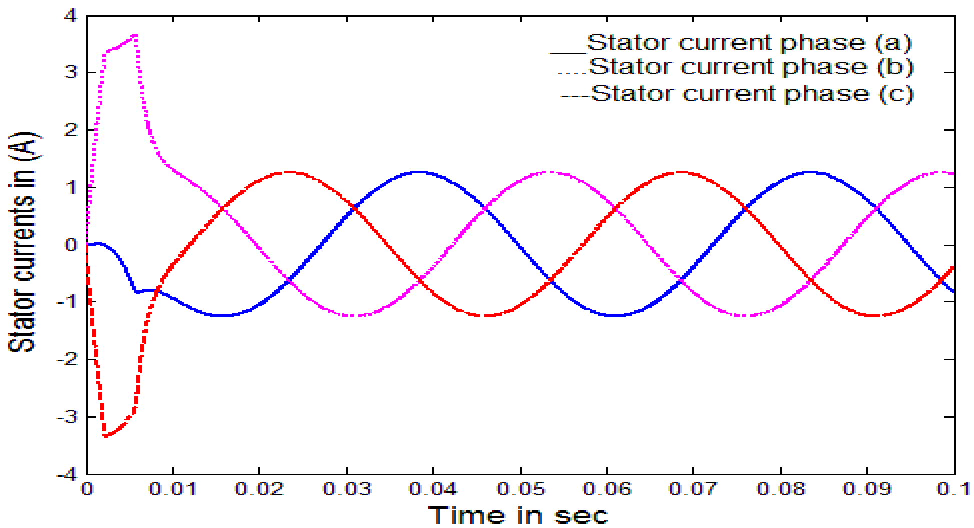


Figure 10. (c) Stator current with modified PI controller for torque and flux

8.2. The second case

Here the motor start without load, at 0.1 sec. sudden load is applied, at 0.25 the load is suddenly removed where it is found that, highly distorted in dq-axis currents with conventional method even with starting without load but with modulated method (PI controllers for torque and flux) the distortion is vanish. In the modified method with one PI torque current controller, the q-axis current becomes improvement but the improvement in the d-axis current component is limited. This is shown in figure 11.

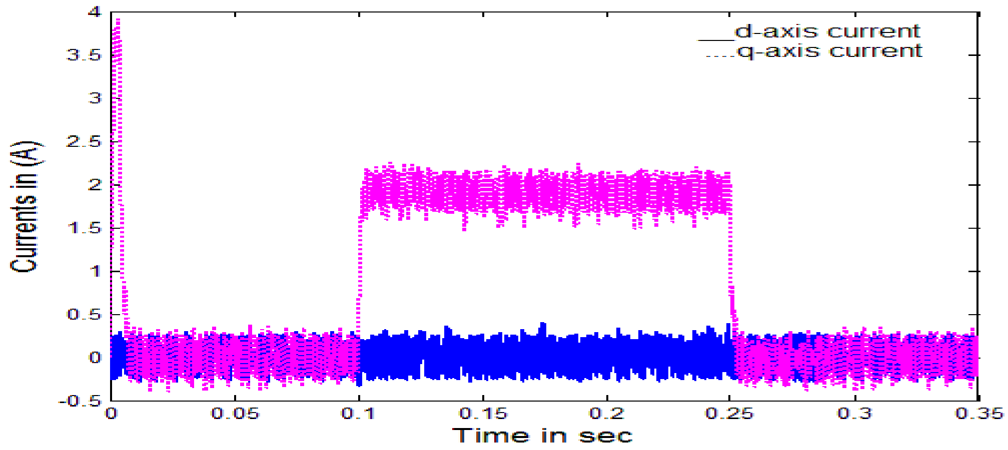


Figure 11. (a) Idq -axis current with conventional method

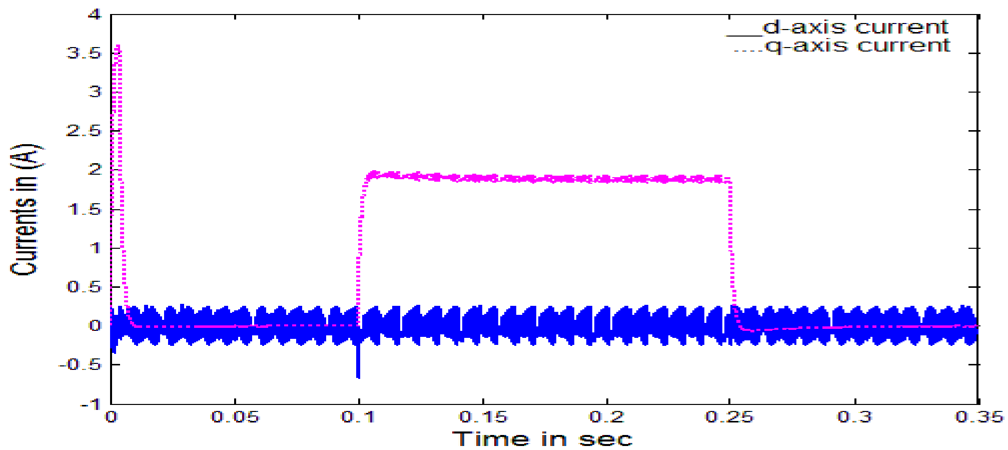


Figure 11. (b) Idq -axis current with modified PI controller for torque only

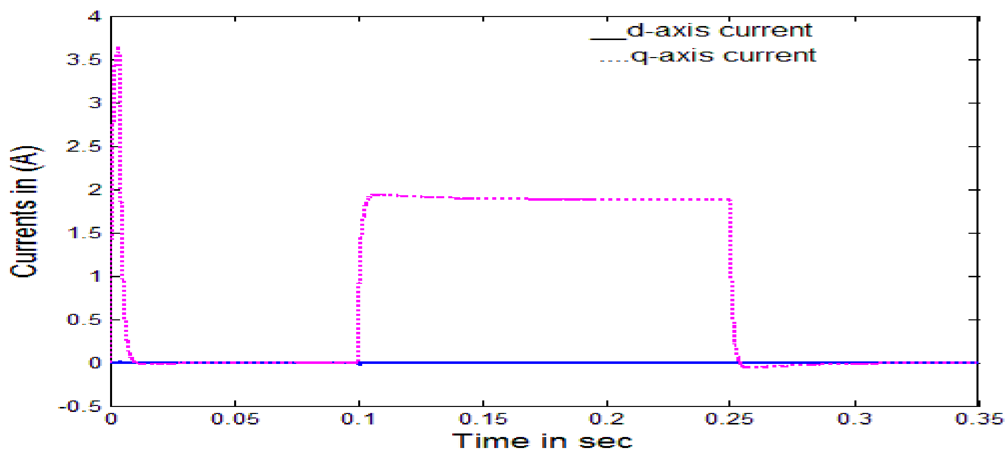


Figure 11. (c) Idq -axis current with modified PI controller for torque and flux

In figure 12 when compared to the stator flux with three methods under discussion(conventional field oriented control, field oriented control with PI torque current control and field oriented control with two PI controllers for torque and flux), it is best improvement occurring with PI controllers for torque and flux.

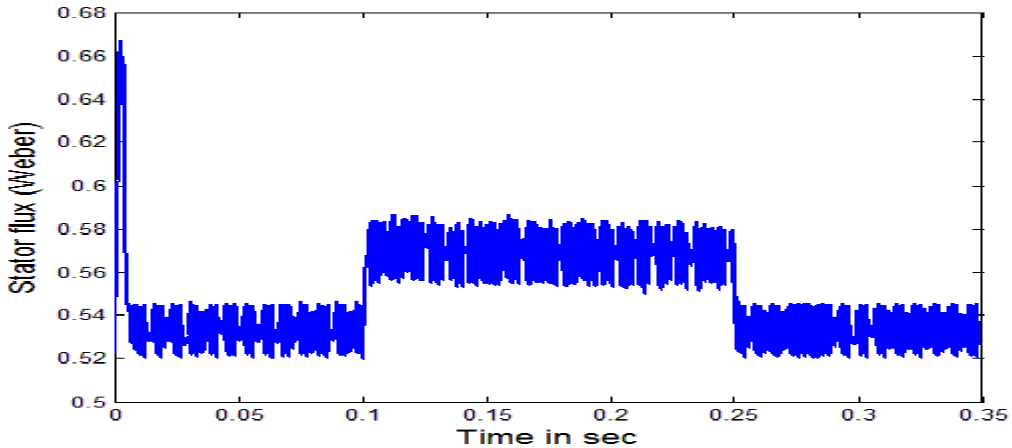


Figure 12. (a) Stator flux with conventional method

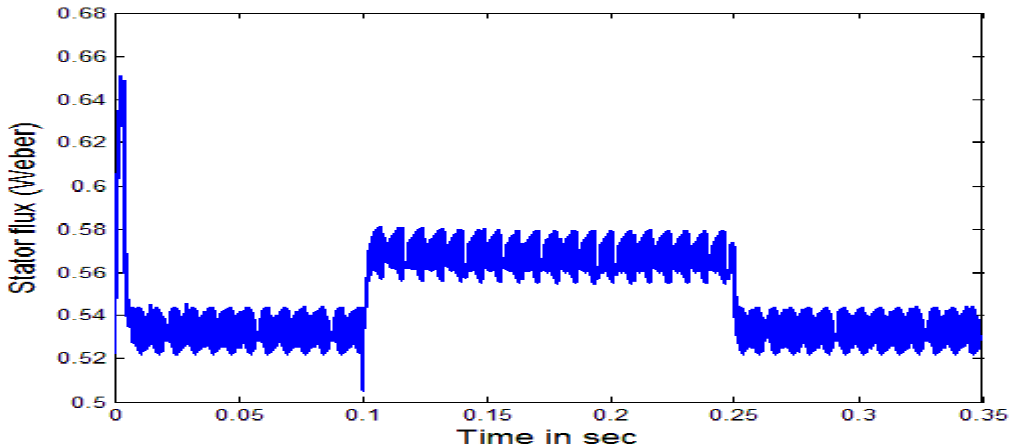


Figure 12. (b) Stator flux with modified PI controller for torque only

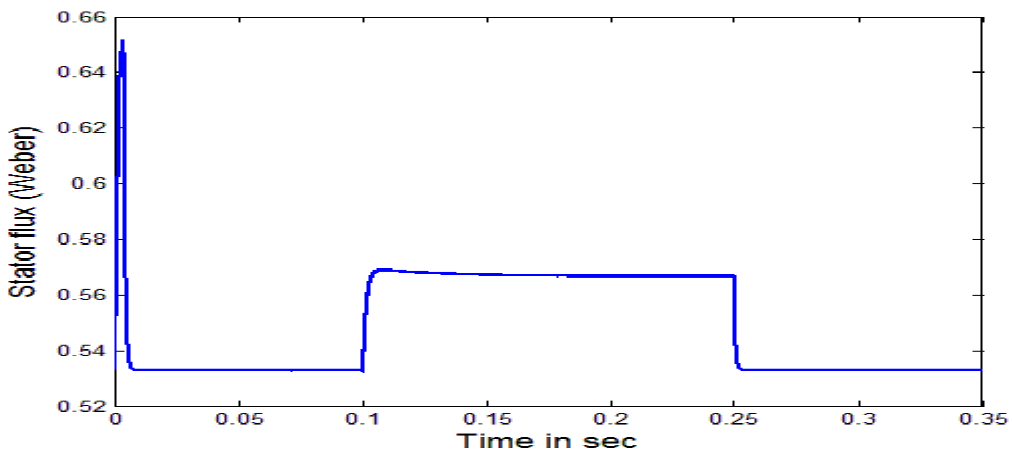


Figure 12. (c) Stator flux with modified PI controller for torque and flux

In figure 13. The ripple torque is reduced with modified methods this occurs due to less in the electromagnet interface.

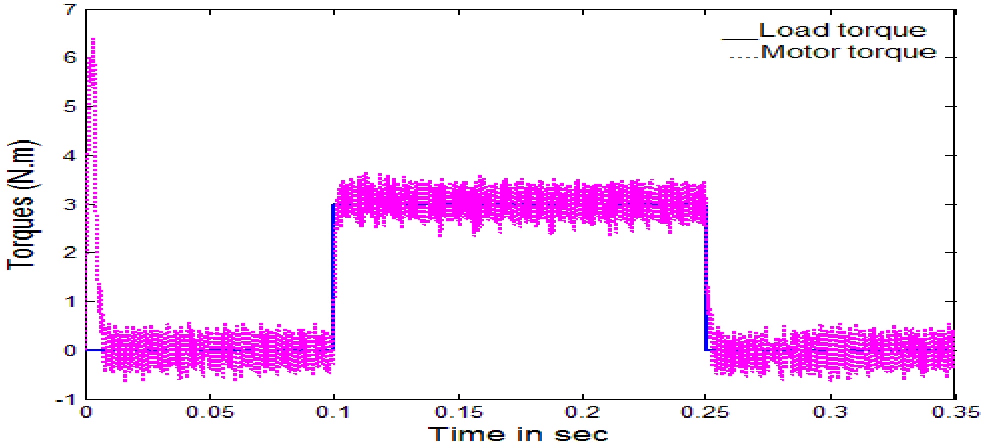


Figure 13. (a) torque with conventional method

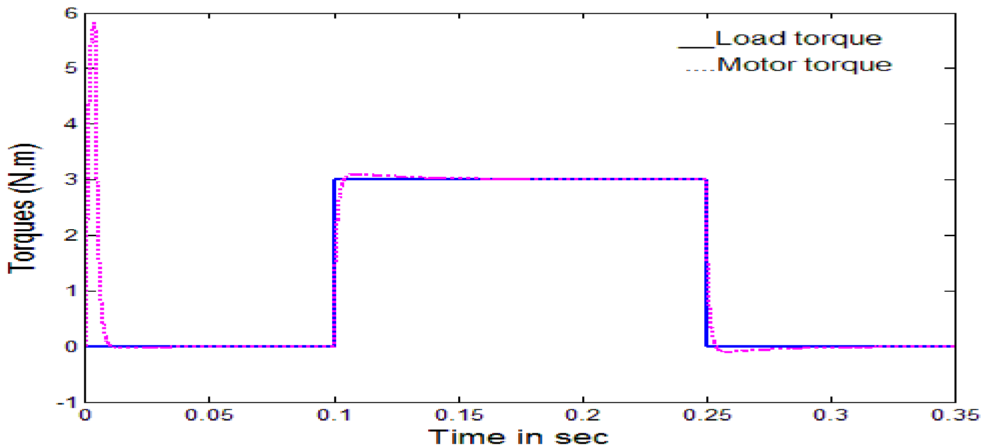


Figure 13. (b) torque with modified PI controller for torque only

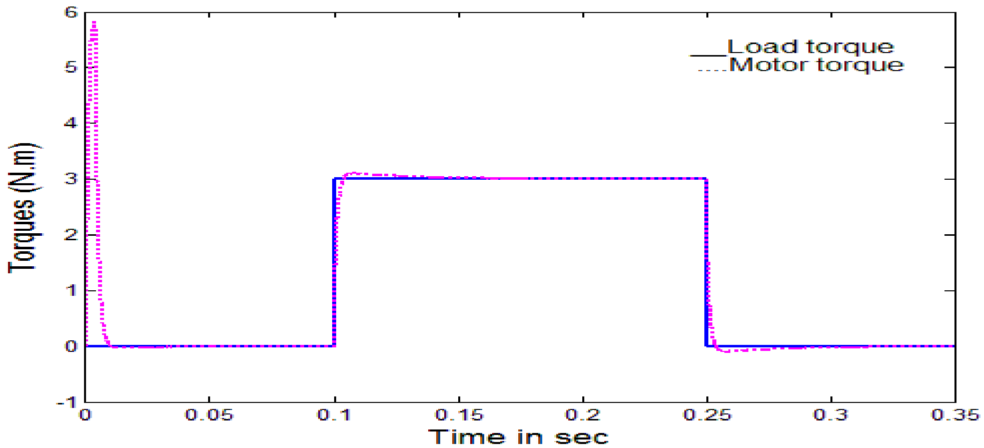


Figure 13. (c) Torque with modified PI controllers for torque and flux

Figure 14 shows some noise in the speed with conventional method if it is compared to the modified methods.

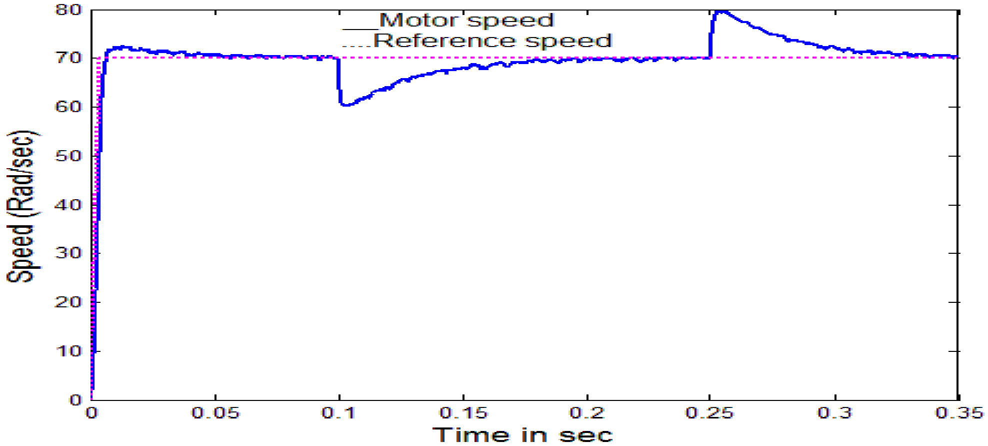


Figure 14. (a) speed with conventional method

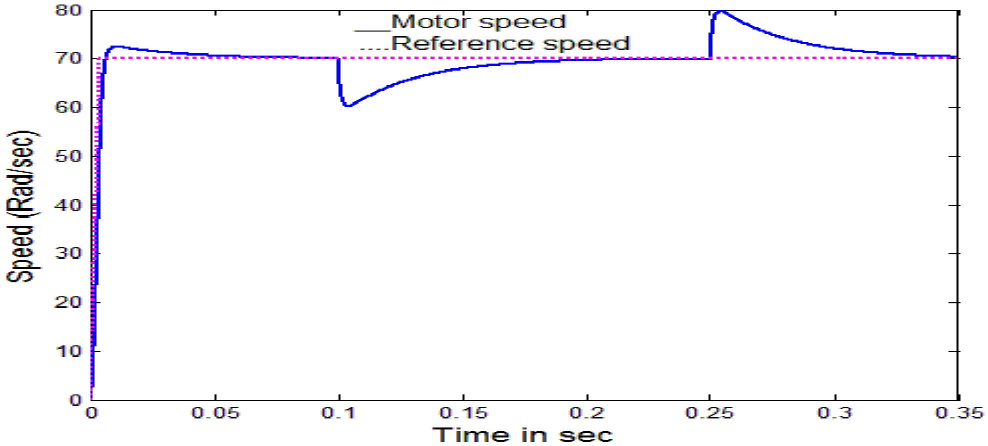


Figure 14. (b) Speed with modified PI controller for torque only

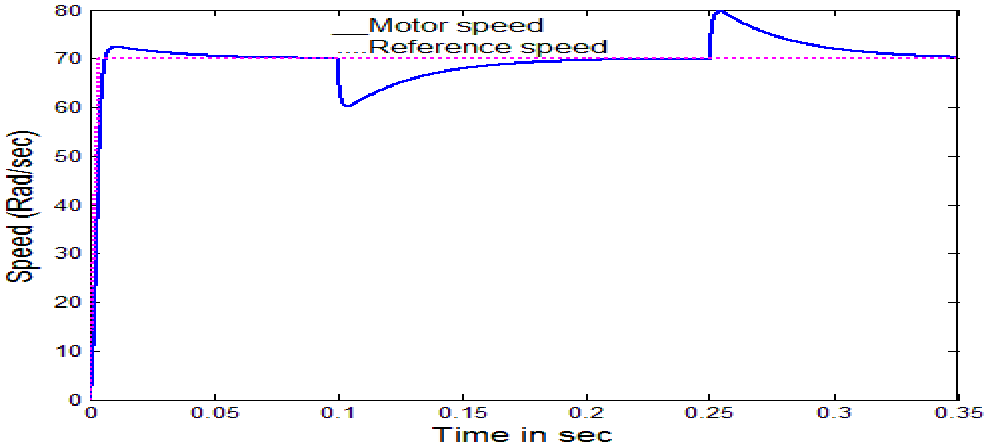


Figure 14. (c)Speed with modified PI controller for torque and flux

In Figure 15, the stator currents become smoother with modified method (PI controllers for torque and flux) due to reduction of the noise in the stator flux and suppresses in electromagnetic interference. With two PI controllers, the stator currents become approximately zero under no load but with conventional method these currents don't equal to zero due to noise, harmonics and electromagnet interface.

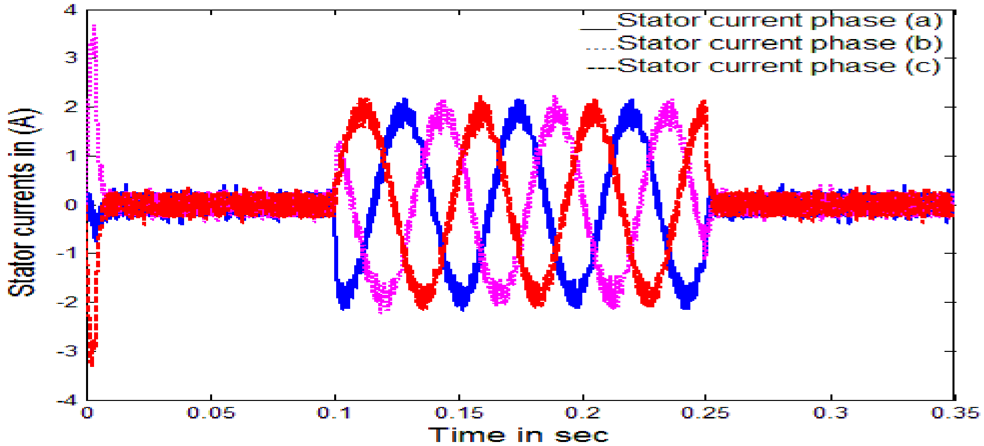


Figure 15. (a) Stator current with conventional method

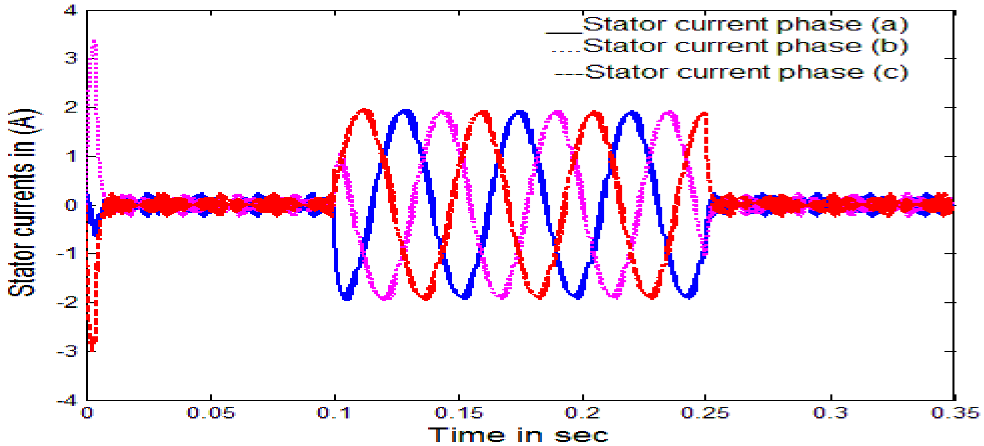


Figure 15. (b) Stator current with modified PI controller for torque only

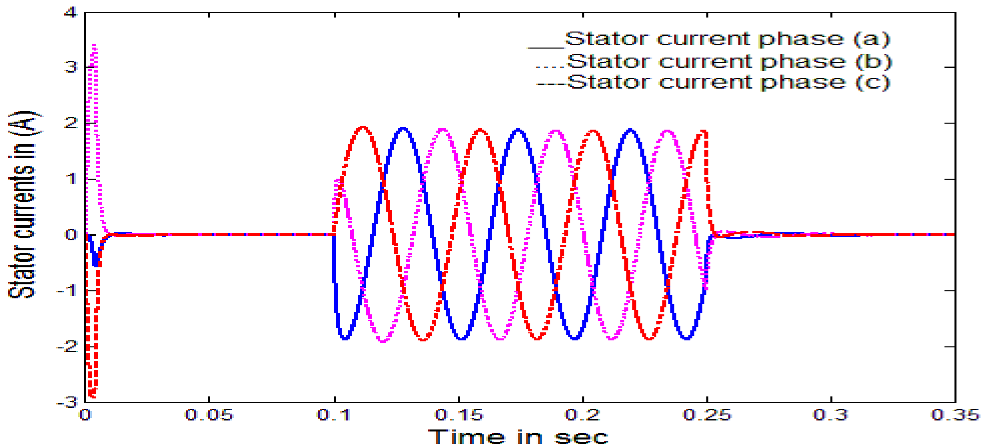


Figure15. (c) Stator current with modified PI controller for torque and flux

9. CONCLUSION

This paper is introduced two new PI controllers to suppress the harmonics, torque ripples, noise and electromagnetic interference. These PI controllers are affecting the inverter switching frequency. These controllers are reducing the ripples in the torque and current. The stator currents become smoother wave form. The results show that, the q-axis current becomes smoother which reflects on the motor torque to keep quit operation. The d-axis current reduced to zero which reflects on the stator flux linkage. It becomes distortion less and leads to reducing the cogging torque.

"Table 1"

Type of control	*Ripple torque %*	*THD in the current %*
Traditional method	12.22	15.43
Proposed method with modified PI controller for torque only	0.1868	9.269
Proposed method with modified PI controllers one for the torque and other for flux	0.1177	0.537

"Table 2"

Number of pole P	*4*
Stator resistance r	5.8 Ohm
d-axis inductance L_d	44.8 mH
q-axis inductance L_q	102.7 mH
Permanent magnet flux ψ_m	533 mWb
Inertia constant J	$0.000329 N.m\,S^2$
Friction constant β	*0*
Load torque T_L	*2 N.m*
Reference speed ω_m	70 rad/s

Abbreviations:
DC: Direct current motor.
FOC: Field oriented control.
PM: Permanent magnet.
PMSM: Permanent magnet synchronous motor.
List of symbol

i_{as}, i_{bs}, i_{cs} : The instantaneous stator phase currents.

i_d : d-axis stator current referred to rotor.

i_d^* : d-axis stator reference current referred to rotor.

i_q : q-axis stator current referred to rotor.

i_q^* : q-axis stator reference current referred to rotor.

J : Moment of inertia

k_p : Proportional gain

k_i : integral gain

L_d : d-axis inductance.

L_q : q-axis inductance.

P : Number of pole

r : Stator resistance

T_m : Developed torque.

T_{em} : Mutual torque.

T_L : Load torque.

T_{e6h} : Six harmonics torque

β : Friction constant

$\frac{d}{dt}$: differentiation operator.

ω_m : mechanical speed of the motor.

ω_e : The electrical frequency.

ω_r : The electrical rotor speed.

ψ_m : Permanent magnet flux

ψ_{d6}, ψ_{d12} : Six and twelve d-axis flux

ψ_{q6}, ψ_{q12} : Six and twelve q-axis flux

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