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Simple Model and PI Controller to Improve the Performance Characteristics of PMSM under Field Oriented Control with Using SVPWM

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Abstract— Voltage source inverter is widely used in many industrial applications such as robot, electric vehicle and machine tool. The performance of the drive system depends upon the method of control for converter and motor control method. From the most performance method is a space vector pulse width modulation technique. Here the field oriented control of permanent magnet synchronous motor with using space vector modulation is used to controlling the inverter and improving the performance characteristics of the motor such as speed, currents and the electric torque by reducing their ripples. This occurs through adding PI controller for flux and simple model to track the torque and speed when varying load is applied. In the PI controller, the d-axis flux is compared to rotor permanent magnet flux to solve the problem arises from non-sinusoidal of the magnetic flux. The output of the PI controller is added to the reference d-axis current. The new d-axis current will reach the best value of THD. The simple model is used to generate new q axis torque current controller comes from lookup table and adding to reference q axis current controller to control the motor speed. The effect of improvement can be seen through the torque ripples, THD and motor speed. This work is simulated by matlab simulink.

Index Terms—Matlab simulink, PI, PMSM and SVM.

I. INTRODUCTION

In the past DC motors are used to get accurate speed, fast dynamic response and high performance characteristics nearer zero speed but these motors have drawn back such as need regular maintenances due to presence of brushes and commutators. With development of power electronics and microcontroller, the DC motors are replaced with AC motors.

Here the PMSM is used this is because this motor has many advantages such as high torque to inertia ratio, high torque to current ratio, high power factor, rotor lossless and high efficiency. The performance of these motors (PMSMS) in drive systems depend upon the motor control and method of current 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. To get good power waveform this depends upon switching frequency of the PWM, modulation method and current waveform. 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. To solve this problem, the machine design and control technique are used. The first method is complicated and high cost so the other method is preferable[1-3]. Many control techniques are used to solve this such as:

Space Vector Pulse Width Modulation (SVPWM) which has some features such as, [4,5]

1. Its can able to adjust with the varying fundamental frequency to switching frequency ratio.
2. Its hardware implementation is very simple
3. It has lower base band harmonics than regular PWM
4. Fifteen percent more output voltage than conventional modulation.
5. More efficient use of dc supply and avoids unnecessary switching.

Also some programs are used to cancelation the harmonics but these methods require full knowledge about the machine parameters. These methods become undesirable if the operating point changes [6-7]. The current control scheme with an adaptive internal model is proposed in many researches as [8]. Passive filter is used to reducing the ripples in [9] but higher circulating current arises between filter and inverter. Active filter is used to reducing the ripples but this method is higher cost [10].

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 [11-13]. 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

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variation such as motor parameters, disturbance and temperature variations. So In this study new proportional integrator corrector controller are used to optimize conventional PI controllers with using space vector pulse width modulation to control the inverter and simple model is used to tracking the motor speed and motor torque. The PI controller is used to reduce the noise, distortion and ripple in the stator currents and torque this can be done by reducing the distortion in the stator flux. The estimated torque is used to track the motor torque and speed. This system is simulated through matlab simulink. The simulated model with proposed new PI controllers is compared with conventional SVPWM to investigate the advantages of the new proposed modle. This paper is organized as follows. Section I introduction. Section II mathematical model of PMSM. Section III SVM. In section IIIV proposed field oriented control with SVM is introduced. Section V for PI controller. Section VI is for simulation. Section VII is for conclusion.

II. 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 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

$$v_d = r_s i_d + L_d \frac{d}{dt} i_d - \omega_e \lambda_q. \qquad (1)$$

$$v_q = r_s i_q + L_q \frac{d}{dt} i_q - \omega_e \lambda_d. \qquad (2)$$

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

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

$$J \frac{d}{dt} \omega_m = T_e - T_L - \beta \omega_m. \qquad (5)$$

$$T_e = \frac{3P}{4} [\lambda_m + (L_d - L_q) i_d] i_q. \qquad (6)$$

$$\theta_e = \frac{P}{2} \int \omega_m dt. \qquad (7)$$

Where v_d-v_q dq axis stator voltages, i_d-i_q dq axis stator current, λ_d-λ_q dq axis stator flux, λ_m rotor permanent magnet flux, L_d-L_q dq stator axis inductance, r_s stator resistance, $\frac{d}{dt}$ is derivative, T_e electrical torque T_L load torque, J moment of inertia, β frictional viscous, ω_m mechanical speed, P number of poles and θ_e electrical position.

With applying the field oriented control, i_d^* becomes zero so the electrical torque becomes

$$T_e = \frac{3P}{4} \lambda_m i_q. \qquad (8)$$

III. Space Vector Modulation

Space vector modulation technique is used to switching the three phase inverter in drive system. This can be seen in Fig.1. It is consists of six switches that shape the output voltages. When any upper switch is on, the lower switch in the same arm is off so by known the upper switched case the output voltage can be determined. The relation between the line to line voltages and switching state can be calculated from the following relation

$$\begin{pmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{pmatrix} = v_{dc} \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} \qquad (9)$$

The relation between the phase voltages and switching state can be calculated from the following relation

$$\begin{pmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{pmatrix} = \frac{v_{dc}}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} \qquad (10)$$

From Fig.1 it is found that, eight possible connections state (on off patterns) these pattern states ($V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7$) are given in table1.

From this table, the eight switching vector can be represented as Fig.2. Each of these space vectors in Fig.2 resulted from two adjacent vectors and any zero vectors (V_0, V_7).

Space vector pulse width modulation (SVPWM) can be implemented in the following steps:

1. Calculate v_α, v_β, v_{ref} and angle α
2. Calculate the time duration T_1, T_2 and T_s
3. Calculate the switching time of each switches (T1 to T6)

A. *Calculating v_α, v_β, v_{ref} and angle α*

Depending upon Fig.3 the v_α, v_β, v_{ref} and angle α can be calculated as

$$v_{ref} = \sqrt{v_\alpha^2 + v_\beta^2} \qquad (11)$$

$$\alpha = \arctan\left(\frac{v_\beta}{v_\alpha}\right) \qquad (12)$$

B. *Calculating time duration T_1, T_2 and T_s*

Depending upon Fig.3 to calculate the time duration in sector1 on the real and imaginary axes it is found that;

$$\frac{T_1}{T_s} V_1 + \frac{T_1}{T_s} V_2 \cos 60 = m v_{ref} \cos \alpha \qquad (13)$$

$$\frac{T_2}{T_s} V_2 \sin 60 = m v_{ref} \sin \alpha \qquad (14)$$

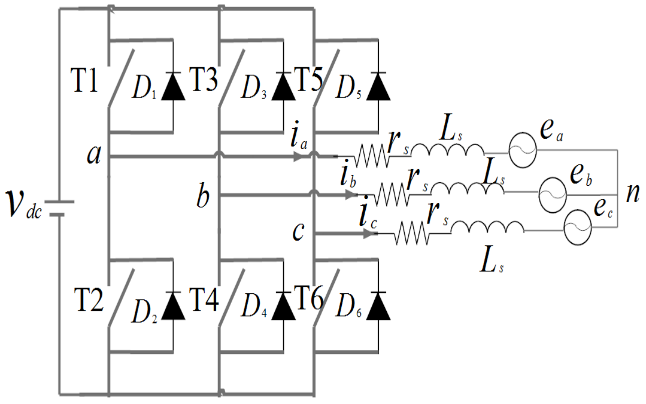

Fig.1. Power circuit inverter and PMSM

Voltage vector	Switching on	Line to neutral voltages			Line to line voltages		
		v_{an}	v_{bn}	v_{cn}	v_{ab}	v_{bc}	v_{ca}
V_0	T1,T3,T5	0	0	0	0	0	0
V_1	T2,T3,T5	2/3	-1/3	-1/3	1	0	-1
V_2	T2,T4,T5	1/3	1/3	-2/3	0	1	-1
V_3	T1,T4,T5	-1/3	2/3	-1/3	-1	1	0
V_4	T1,T4,T6	-2/3	1/3	1/3	-1	0	1
V_5	T1,T3,T6	-1/3	-1/3	2/3	0	-1	1
V_6	T2,T3,T6	1/3	-2/3	1/3	1	-1	0
V_7	T2,T4,T6	0	0	0	0	0	0

Table 1. modes of operations of three phase voltage source inverter (the voltage in term of v_{dc})

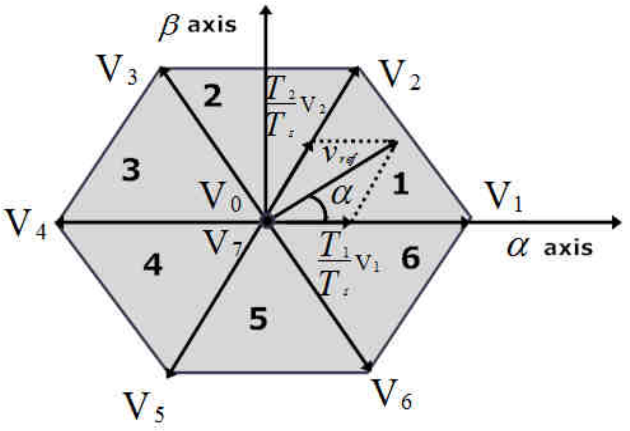

Fig.2. Switching space vector and sector

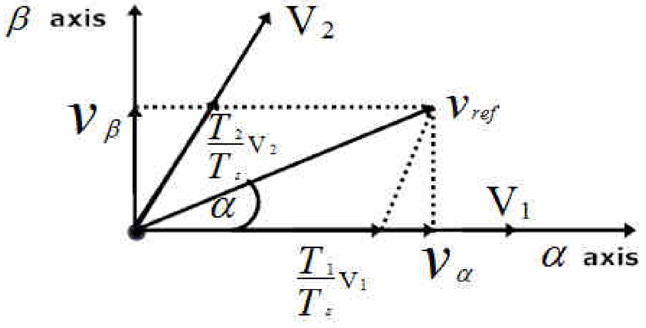

Fig.3. voltage vector v_{ref}

From eq13 and eq14 it is found that;

$$T_1 = \frac{\sqrt{3}}{2} m T_s \sin(60 - \alpha) \qquad (15)$$

$$T_2 = \frac{\sqrt{3}}{2} m T_s \sin\alpha \qquad (16)$$

$$T_0 = T_s - (T_1 + T_2) \qquad (17)$$

Where $T_s = \frac{1}{f_s}$, f_s is switching frequency and m is modulation index

From that the switching time duration at any sector can be calculated as:

$$T_1 = \frac{\sqrt{3}}{2} m T_s \sin(n\frac{\pi}{3} - \alpha) \qquad (18)$$

$$T_2 = \frac{\sqrt{3}}{2} m T_s \sin((n-1)\frac{\pi}{3} - \alpha) \qquad (19)$$

Where n is number of sector

C. Calculating the switching time of each switches

Table2 shows the switching time in inverter

IV. PROPOSED FIELD ORIENTED CONTROL SVM

The conventional structure of the field oriented control is shown in Fig.4. The error in q axis current is introduced to PI current controller to produce q axis voltage reference also the error in d axis current is delivered to PI current controller to produce d axis voltage reference. These voltages are transformed with help of electrical rotor position into two dimensional voltages varying in time which used to generate gating signals to drive the inverter through SVM. In this 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. 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. So this paper introduced modified structure controller to improve these problems.

The modified structure of the field oriented control is shown in Fig5. In this structure, the modified block can be seen in details in Fig6 and simple model is shown in Fig7.To minimize the ripple and noise in the torque and controlling the speed so simple estimated model is used; this model estimated the load torque and deduced from that new q axis current controller through lookup table which is added to reference q axis current controller this new q axis current is comparing to measure q axis current and the error is used to generating q axis voltage through PI controller.

With this enhanced in the q-axis current component, the distortion of the current doesn't reach the best value. 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. This new d axes current is compared to actual d axis current and introduced to PI controller to regulate d axis voltage .

The d axis voltage and q axis voltage are transformed with help of electrical rotor position into two dimensional voltages varying in time which used to generate gating signals to drive the inverter through SVM.

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sector	Upper switches (T1,T3,T5)	Lower switches (T2,T4,T6)
1	$T1=T_1+T_2+\frac{T_0}{2}$ $T3=T_2+\frac{T_0}{2}$ $T5=\frac{T_0}{2}$	$T2=\frac{T_0}{2}$ $T4=T_1+\frac{T_0}{2}$ $T6=T_1+T_2+\frac{T_0}{2}$
2	$T1=T_1+\frac{T_0}{2}$ $T3=T_1+T_2+\frac{T_0}{2}$ $T5=\frac{T_0}{2}$	$T2=T_2+\frac{T_0}{2}$ $T4=\frac{T_0}{2}$ $T6=T_1+T_2+\frac{T_0}{2}$
3	$T1=T_1+T_2+\frac{T_0}{2}$ $T3=T_2+\frac{T_0}{2}$ $T1=\frac{T_0}{2}$	$T2=T_1+T_2+\frac{T_0}{2}$ $T4=\frac{T_0}{2}$ $T6=T_1+\frac{T_0}{2}$
4	$T1=\frac{T_0}{2}$ $T3=T_1+\frac{T_0}{2}$ $T5=T_1+T_2+\frac{T_0}{2}$	$T2=T_1+T_2+\frac{T_0}{2}$ $T4=T_2+\frac{T_0}{2}$ $T6=\frac{T_0}{2}$
5	$T1=T_2+\frac{T_0}{2}$ $T3=\frac{T_0}{2}$ $T5=T_1+T_2+\frac{T_0}{2}$	$T2=T_1+\frac{T_0}{2}$ $T4=T_1+T_2+\frac{T_0}{2}$ $T6=\frac{T_0}{2}$
6	$T1=T_1+T_2+\frac{T_0}{2}$ $T3=\frac{T_0}{2}$ $T5=T_1+\frac{T_0}{2}$	$T2=\frac{T_0}{2}$ $T4=T_1+T_2+\frac{T_0}{2}$ $T6=T_2+\frac{T_0}{2}$

Table 2. Switching time duration

V. 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

$$G(s)=k_p+\frac{k_i}{s}$$

Proportional gain is used to improving the rise time and integral gain which 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.

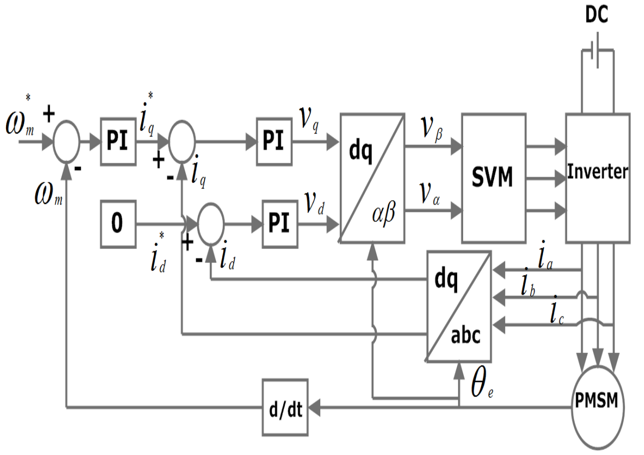

Fig.4. Conventional structure field oriented control

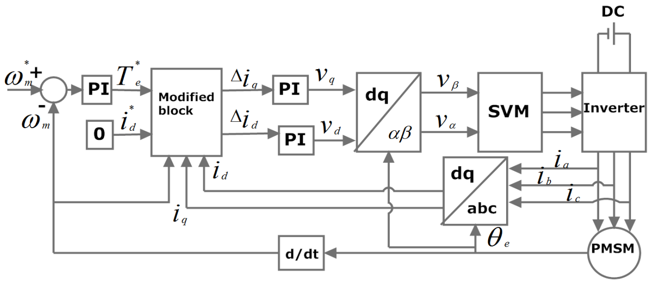

Fig.5. Modified field oriented control

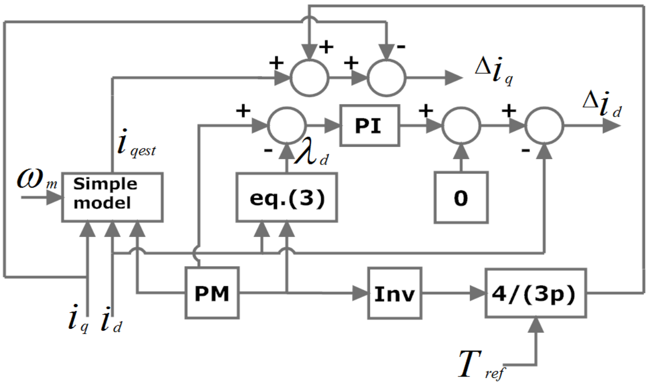

Fig.6. Modified block

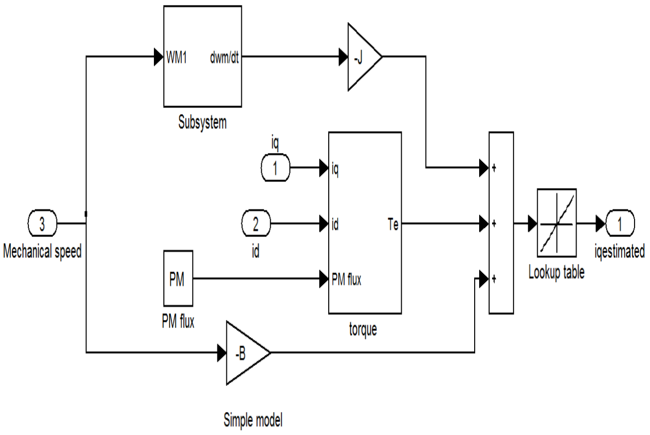

Fig.7. Simple model

The parameters of the PI controller are determined depending upon [15-16].

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VI. SIMULATION STUDY

Here conventional and modified models are compared. These comparisons are used to showing the effectiveness of modified model on the motor speed responses, torque responses and THD in current. Table3 shows the improvement in the torque ripples and THD due to use the simple model and PI controller. Table4 shows the motor parameters. During the simulations, the torque set value is at rated. In all Figs the time axis is in seconds and the following cases are simulated

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

Where it is found that,

A. *The first Case (starting with load)*

In Figs (8-9), dq axes currents are simulated with conventional and modified model respectively. In conventional model (Fig8), the dq axes currents have some distorted. In modified model (Fig9), both q-axis current component and d-axis current component are enhanced.

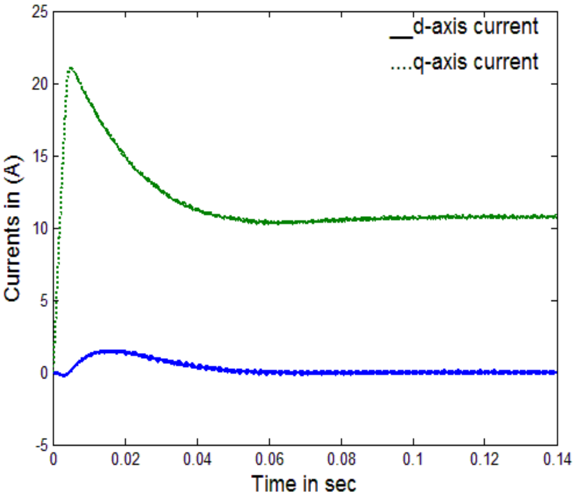

Fig.8. Idq-axis current with conventional method

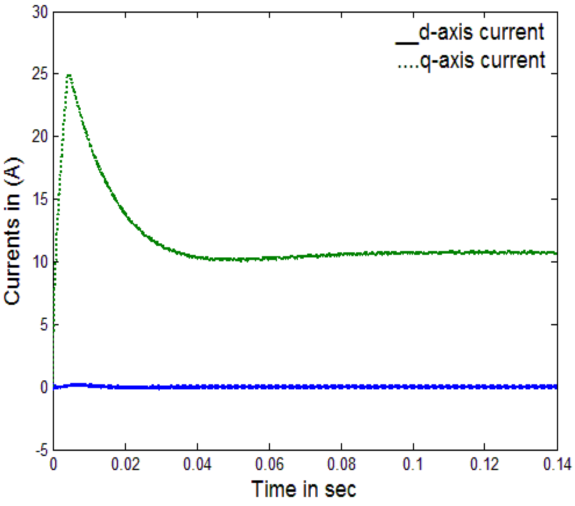

Fig.9. Idq-axis current with modified method

The torque responses in Fig.11 showed that, the torque ripple is improved with modified model if it is compared to the conventional model (Fig.10).

Figs.(12-13) show that the speed with conventional model and the modified model approximately the same.

In Fig.15, the stator currents become smoother with modified model due to improvement in the dq-axes current components. In conventional model (Fig.14), the stator current has some distortion due to noise and electromagnetic interference.

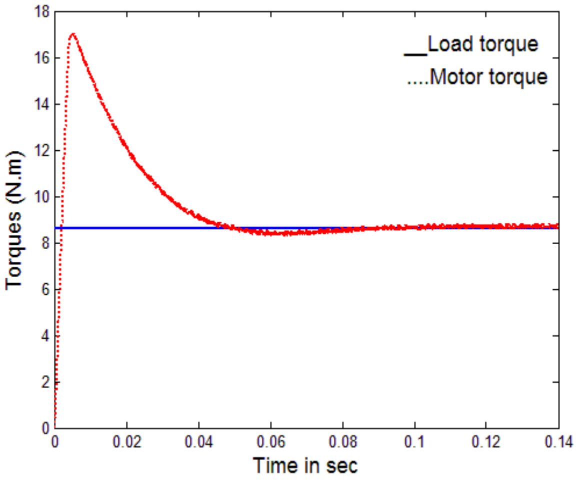

Fig.10. Torque with conventional method

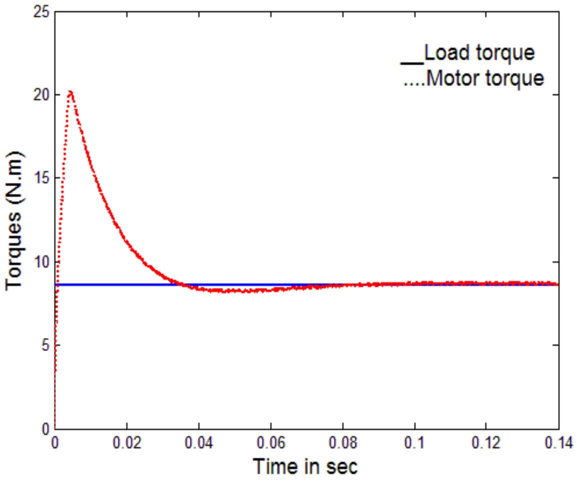

Fig.11. Torque with modified method

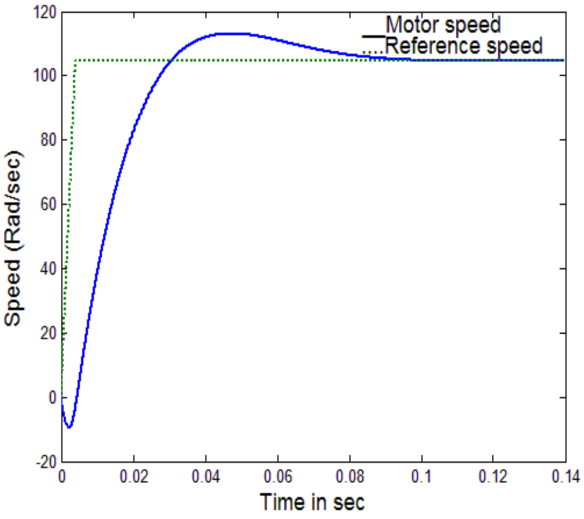

Fig.12. Speed with conventional method

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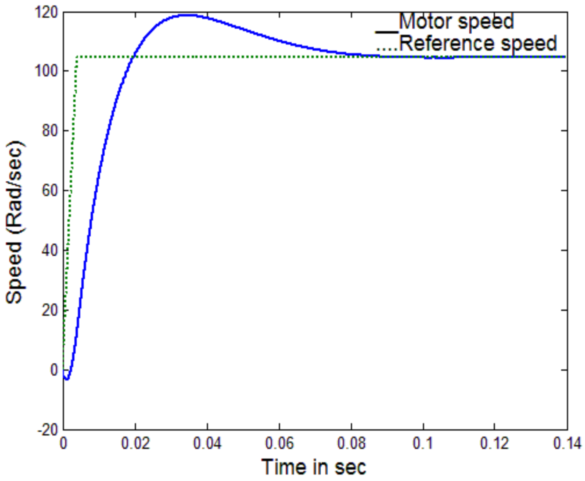

Fig.13. Speed with conventional method

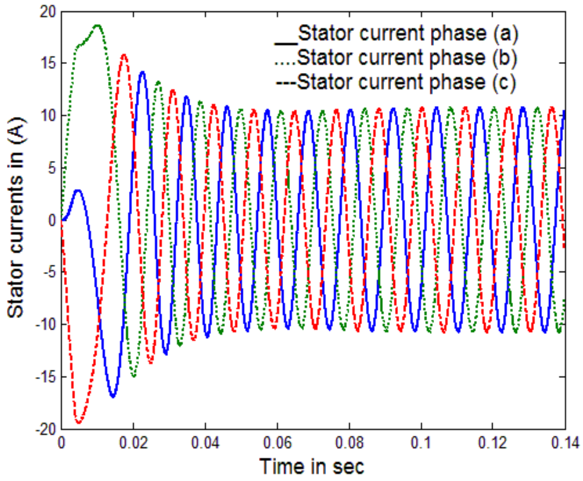

Fig.14. Stator current with conventional method

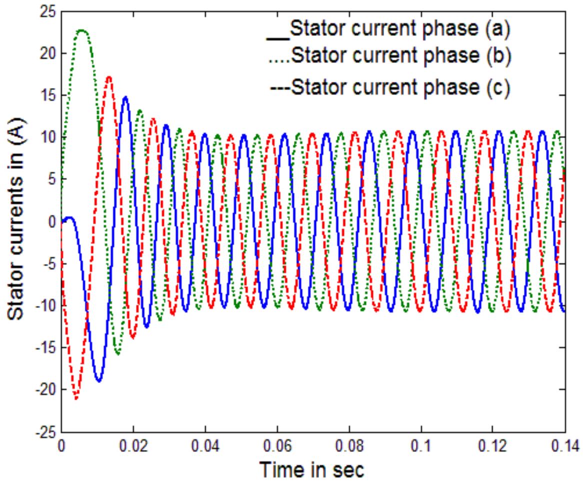

Fig.15. Stator current with modified method

B. The Second Case (sudden applied load)

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,

Fig. 16 shows the oscillation and distortion in the dq-axes currents with conventional method where found that higher oscillations and distortions in both dq axes current while in modulation method the distortion and oscillations are improved as shown in Fig.17.

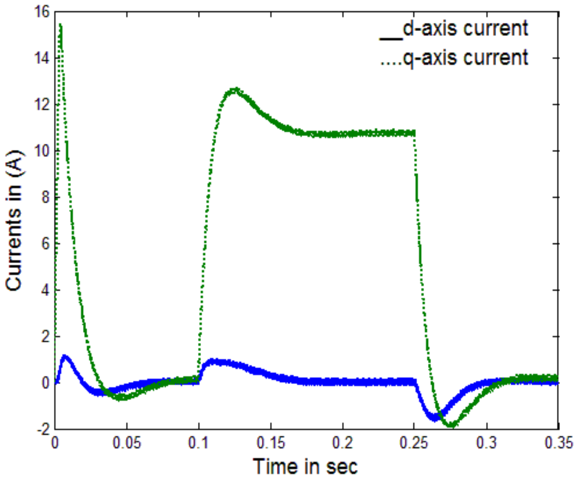

Fig.16. Idq-axis current with conventional method

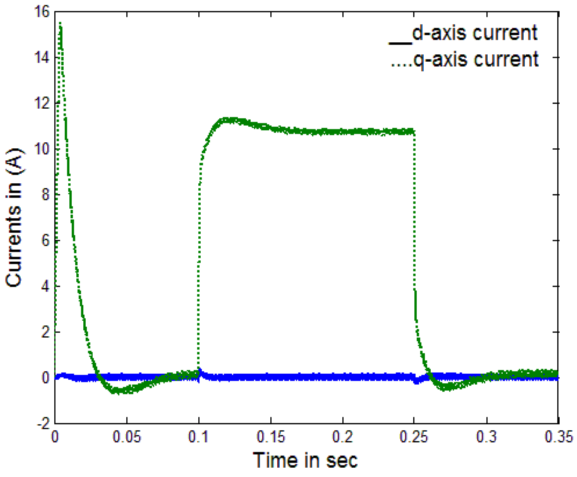

Fig.17. Idq-axis current with modified method

The effect of applied and load removal can bee seen in Figs (18-19). In conventional method (Fig.18), the motor torque is very increasing when suddenly load is applied and decreased when load is removed but in modified model when the load is suddenly applied or removal the effect of this can be neglected i.e. with modified model the motor torque responses is improved (Fig.19).

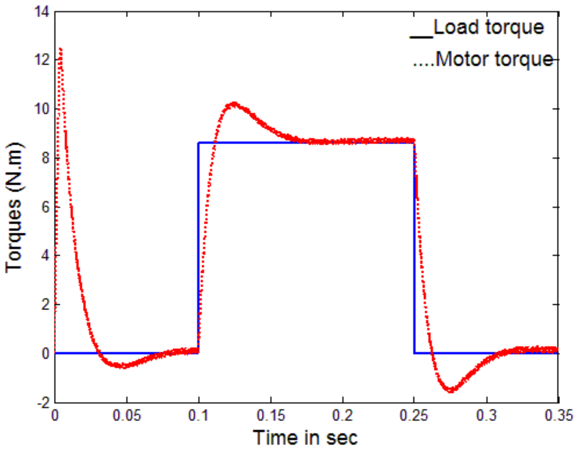

Fig.18. Torque with conventional method

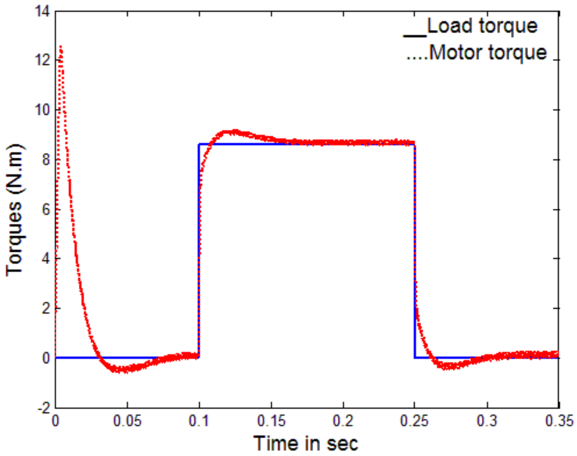

Fig.19. Torque with modified method

The effect of simple model can be seen in Fig.21 with sudden applied or removal the load. The same effect can be studied with conventional method (Fig. 20) where it is found that,

Little change in the motor speed can be seen when suddenly load is applied or removal when compared to conventional model which has higher effect on the motor speed for the same case.

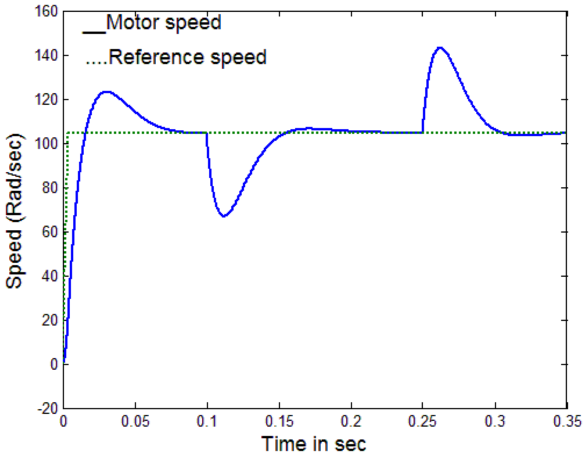

Fig.20. Speed with conventional method

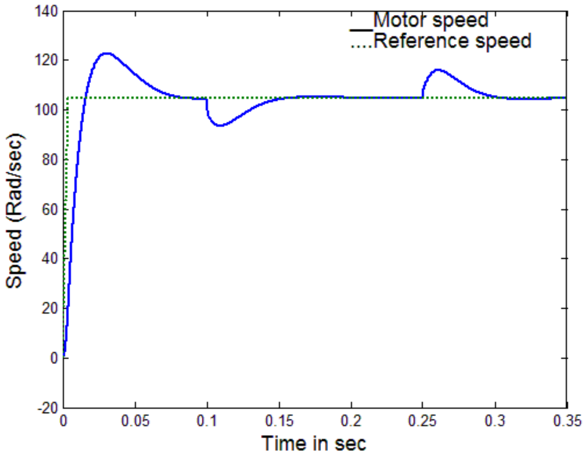

Fig.21. Speed with conventional method

In Fig.23, the stator currents become smoother with modified method due to reduction of the noise in the stator flux and suppresses in electromagnetic interference. With adding PI current controller, the stator currents become less in the total harmonics distortion if it is compared to the conventional model (Fig.22).

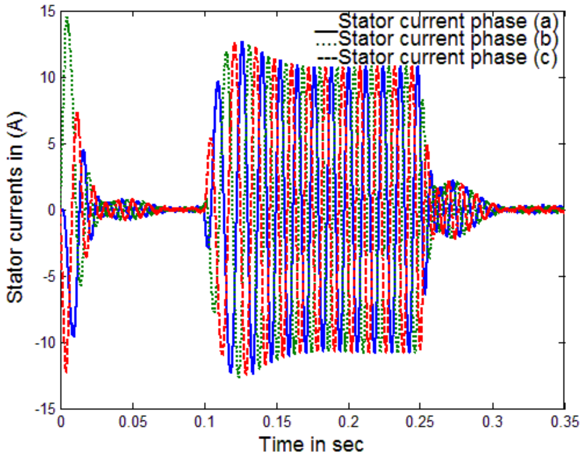

Fig.22. Stator current with conventional method

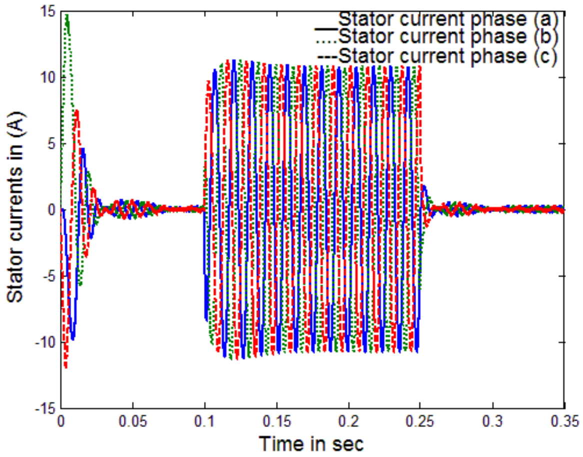

Fig.23. Stator current with modified method

C. *The Third Case (dynamic load)*

Here the motor start with increasing load gradually, at 0.1 sec. the load reached full load, at 0.25 the load is gradually decreased at 0.35 sec. the load reached zero and continuous without load at 0.4 sec.

Oscillations in dq-axes currents with conventional method can be seen in Fig.24. In modulated method the oscillations are improved (Fig.25).

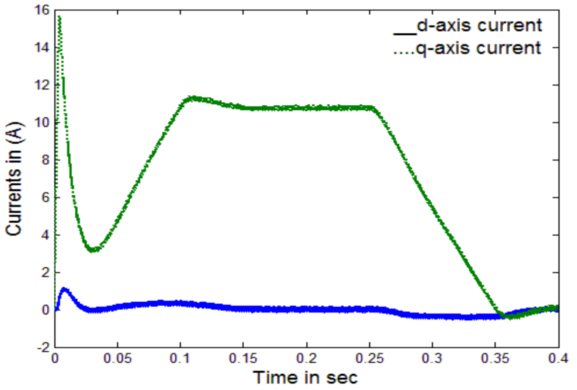

Fig.24. Idq-axis current with conventional method

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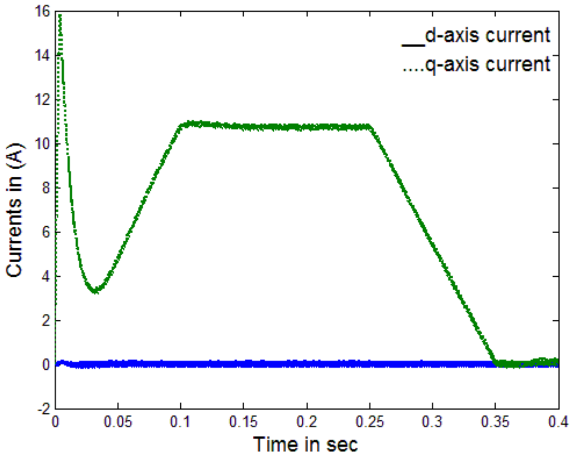

Fig.25. Idq-axis current with modified method

In Fig.26, the ripple torque is reduced with modified methods if it is compared to conventional method (Fig. 27) this occurs due to less in the electromagnet interface and improvement in q-axis current component with modified model.

Fig.28 shows the motor speed with conventional method and Fig.29 shows the motor speed with modified methods. From these Figs. It found that;

The variation of the speed due to varying load can be neglected due to use the simple model where the variation of the motor speed with conventional method can not be neglected.

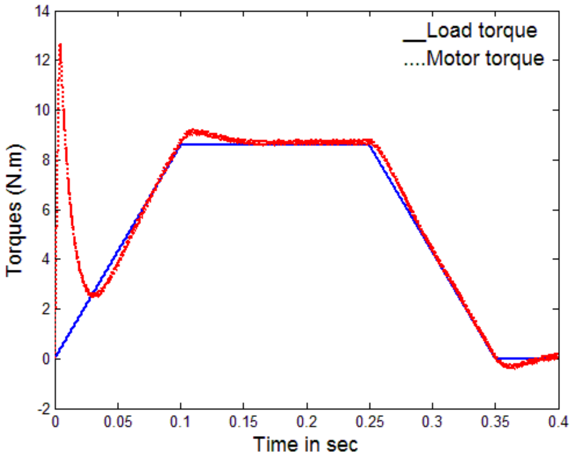

Fig.26. Torque with conventional method

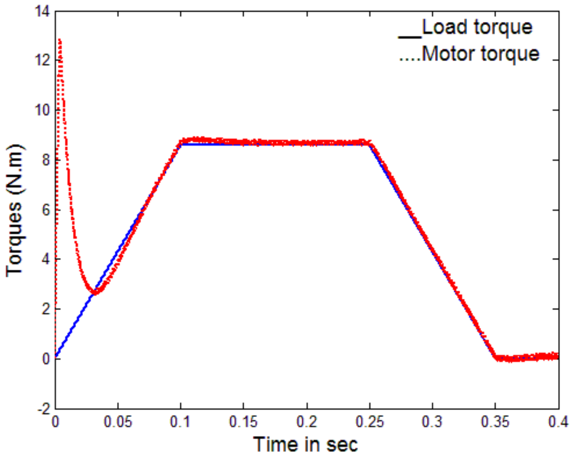

Fig.27. Torque with modified method

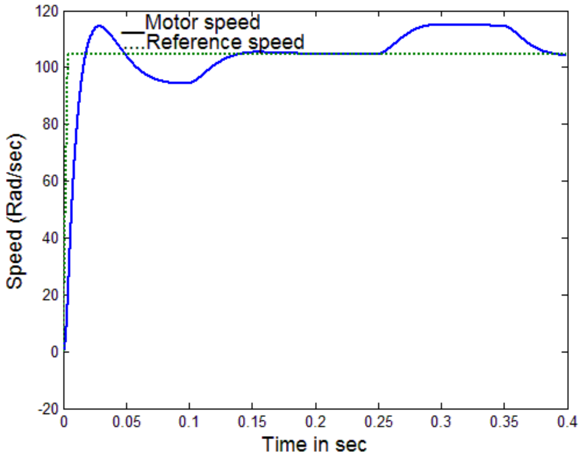

Fig.28. Speed with conventional method

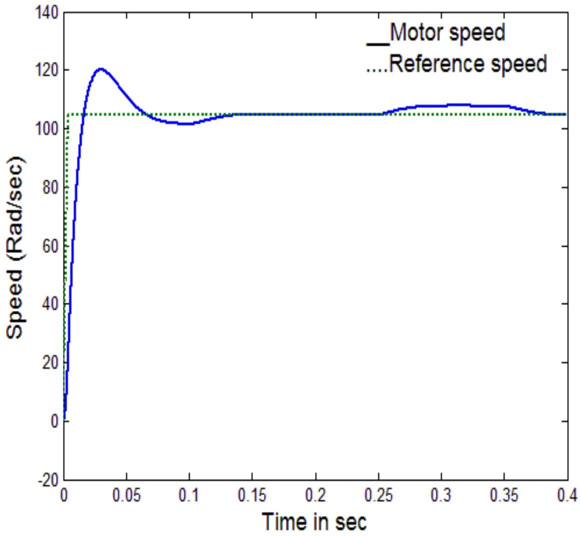

Fig.29. Speed with conventional method

In Fig.31, the stator currents become smoother with modified method due to reduction of the noise in the stator flux and suppresses in electromagnetic interference. With adding PI current controller, the stator currents become less in the total harmonics distortion if it is compared to the conventional model (Fig.30).

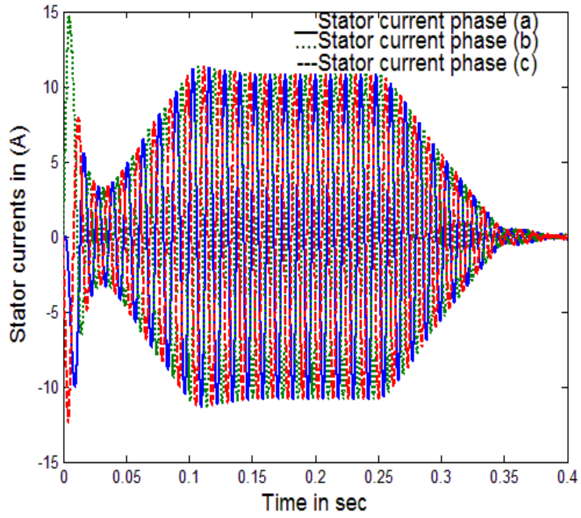

Fig.30. Stator current with conventional method

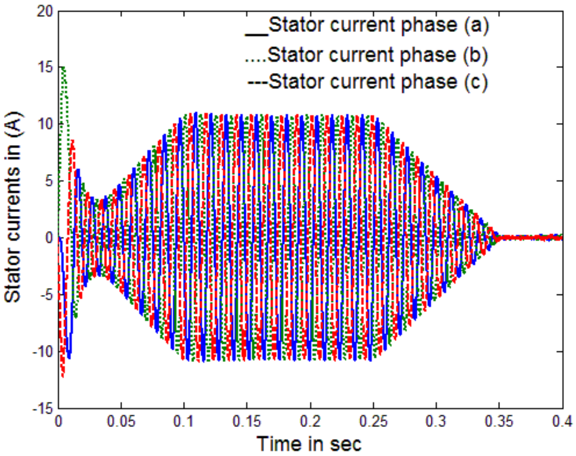

Fig.31. Stator current with modified method

VII. CONCLUSION

This paper is addressed the dynamic performance of permanent magnet synchronous motor under effect of field oriented control with simple model and PI controller with using space vector pulse width modulation. SVPWM is made. Simple model to control the motor torque and motor speed is proposed. PI current controller is used to affect the inverter switching frequency to reduce the ripples in the torque and current. The stator current waveforms become smoother. 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 total harmonic distortion in current. Simple model reduced from effect of sudden applied load, removal load and dynamic load on motor speed and motor torque.

Motor control	Torque ripples	THD in current
Conventional field oriented control	0.62	0.83
Modified field oriented control	0.5	0.71

Table 3. Effect of modified method on torque ripples and THD in current.

Output power in Watts	900
Motor speed in R.P.M.	1000
Line to line voltages in volts	110
Rated torque N.M	8.59
Number of poles	10
Stator resistance in ohm	0.43
d axis stator inductance in Henry	0.00697
q axis stator inductance in Henry	0.00697
Permanent magnet flux in voltage.S/Rad	0.11
Moment of inertia N.m. S^2	0.001118

Table 4. Motor parameters

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