Improved Hysteresis Current Controller to Drive Permanent Magnet Synchronous Motors through the Field Oriented Control

Hamdy Mohamed Soliman, S.M.EL. Hakim

Abstract— ***Hysteresis current controller is used in many industrial applications because it has many advantages as fast, high dynamic performance and doesn't require any information about load parameters. The draw back of this current controller is varying switching frequency. This paper presents adaptive hysteresis current controller to control the inverter. It is used to reduce the ripple, total harmonic distortion and improvement the switching frequency through design of PI current controller. The performance of the drive system due to improvement in the hysteresis current controller is simulated through the matlab simulink. The modified hysteresis current controller is compared to conventional hysteresis controller under steady state and transient conditions with fixed load, sudden applied and sudden removal load and reversing load to show the effectiveness of this modification.***

Index Terms— ***Hysteresis Current Controller, PI Controller, PMSM, Torque Ripple.***

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM), it is a synchronous motor which the rotor windings are replaced by high resistivity permanent magnet material so no induced current in the rotor i.e. the rotor is lossless. Also it has some advantages such as: high power density and efficiency, high power factor, high torque to inertia ratio, high reliability, low rotor inertia, efficient heat dissipation structure, and reduced motor size. Due to these advantages, it has received widespread appeal in industrial applications such as aero space, nuclear power plant, robotics, adjustable speed drives and electric vehicles. In these motors (PMSM) the permanent magnet material is placed on the rotor by many methods. Among these methods, surface mounted magnets, inset magnets and buried magnets [1]. Depending on these configurations, different properties of the machine are obtained. In case of surface mounted magnets, the rotor iron is approximately round and the stator inductance is low, as well as independent of the rotor position. The control of the machine becomes simple and the reluctance effect can be neglected. The operation of that motor in field weakening is difficult due to generate higher d-axis current this is because the low value of stator inductance [2]. The method of motor control is very important in the drive system. This is because the operation of the PMSM under some methods of control is suffered from complicated coupling and nonlinear dynamic performance. This problem can be solved by field oriented control (FOC) [3-4]. To achieve the field-oriented control of PMSM, knowledge of the rotor position is required. Usually the rotor position is measured by a shaft encoder, resolver, or Hall sensors. [5-6]. 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, uunder perfect field orientation, with constant flux operation, applying the principles operation of the FOC, the linear relation can be described the motor torque. However, the control performance of PMSM drive is still influenced by uncertainties, which usually are composed of unpredictable plant parameter variations, external load disturbances and nonlinear dynamics of the plant and harmonics in both motor and inverter. These problems shaped difficult in getting robust control. They lead to problems in torque and oscillation in the speed as the secondary problem comes from torque problem. There are many methods of control tried to get rid these problem by design robust current control of the drive system. The dynamic performance of voltage source inverter (VSI) fed PMSM drive system largely depends on the applied control strategy. The quality control of these methods depend upon the quality of the waveform is generated by method control of converter. Good power waveform depends upon the switching frequency of PWM, modulation index and the shape of current or voltage wave forms. The control method in inverter is voltage control or current control. The current control is preferable due to simple. PWM current-controlled voltage source inverters are widely used in high performance ac drives for quick response and accurate control. It has substantial advantage in eliminating stator dynamics in high performance ac drive systems under field orientation control. There many methods of current control such as: linear and non-linear current controllers. Linear controller includes PI controller, state feed back controller and predictive current controller. Nonlinear controller includes bang-bang controllers (Hysteresis control, ramp type control and delta modulator) and predictive controllers with online-optimization [7]. Here PWM hysteresis current control is used due to easily implemented with no complex hardware, fast dynamic response and doesn't require any information about the system parameters but this technique has suffered from some disadvantage as, switching frequency of inverter varies within a band because peak - to – peak current ripple is required to be controlled at all points of the fundamental frequency wave [8]. Variable switching frequency has been recognized as solution for motor drive systems to minimize mechanical noise [9], but it is not recommended for power system applications due to generation of sub harmonics and low order harmonics which affect the quality of the power system.

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Many methods are suggested adjustable speed drives by adapting the hysteresis current controller as in [10-11] the hysteresis band is programmed as a function of load current drive system. The performance with these methods doesn't reach to best value due to some noise, torque ripple and it takes large computation time. In this paper adaptive hysteresis current controller is proposed. This can be done by design PI current controller in each phase of the inner loop of current controlled inverter. It is approximately vanish the torque ripple and improvement the total harmonic distortion at any load conditions, besides it takes less computation time. This system is simulated by MATLAB Simulink. The simulated model with proposed new PI controllers is compared to conventional controller in order to investigate the advantages of the new proposed control. This paper is organized as follows. Section one introduction, section two the mathematical model of PMSM, classical hysteresis current controller in section three, design adaptive hysteresis current controller is made in section fourth, design PI speed controller in section five, section six shows the simulation results and conclusion in section seven.

II. MATHEMATICAL MODEL OF PMSM

The stator voltages equation can be written as,

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{pmatrix} \frac{d}{dt} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} - \omega_e \psi_m \begin{pmatrix} \sin\theta_e \\ \sin(\theta_e - 120^\circ) \\ \sin(\theta_e - 240^\circ) \end{pmatrix} \quad (1)$$

Where v_a, v_b, v_c are the phase voltages, i_a, i_b, i_c are the phase currents, R_s the stator phase resistance, L_s is the synchronous inductance, ω_e is an electrical radiant speed, ψ_m rotor permanent magnet and θ_e is an electrical rotor position.

The electromagnetic torque can be written as,

$$T_e = -\frac{P}{2}\psi_m [i_a \sin\theta_e + i_b(\sin\theta_e - 120^\circ) + i_c(\sin\theta_e - 240^\circ)] \quad (2)$$

The dynamic equation

$$\frac{d\omega_e}{dt} = \frac{p}{J}[\mathrm{T}_e - \mathrm{T}_L - \beta\omega_e] \quad (3)$$

Where T_e is the developed torque, T_L is load torque, J is inertia torque, β is the friction torque and p is the number of poles pair for the motor

III. CLASSICAL 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. Figure1. 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

$$\text{distortion} = \frac{100}{I_{rms}}\sqrt{\frac{1}{T}\int (i_{act} - i_{ref})^2 dt}\ \% \quad (4)$$

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.

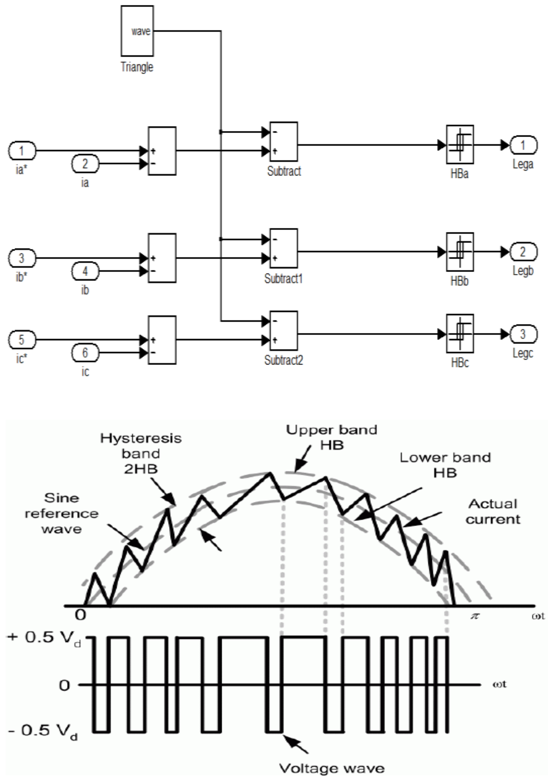

Fig.1. Hysteresis current controller basic structure and concept

IV. PROPOSED HYSTERESIS CURRENT CONTROL DESIGN

PI current controller is proposed to overcome undesirable drawbacks of classical hysteresis current controller. This PI controller is used to adapt the hysteresis controller. The input of PI controller is the error in the current between the reference current and motor current for each phase as shown in Fig.2.

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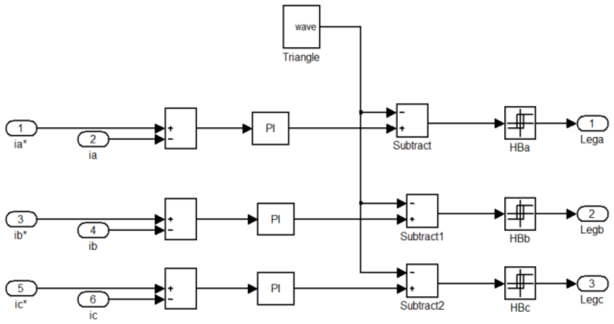

Fig.2. Proposed hysteresis current controller

The parameters of PI current controller can be designed as the follows:

The motor voltage can be written as

$$v = R_s i + L_s \frac{di}{dt} + e \qquad (5)$$

The Laplace transformed equation of a PI current controller is given by:

$$\frac{i(s)}{v_d(s)} = \frac{1/R_s}{ST_m + 1} \qquad (6)$$

Where T_m is electrical motor time constant

The delays in inner current loop arise due to control algorithm which has time constant (T_s) 0.5 ms, holding element which has time constant 0.25 ms and inverter which has time constant 0.25 ms. Each delay can be represented by first order transfer function. These transfer functions can be collected in one transfer function which is represented the total delay time as shown in Fig. 3. It (Fig.3) is represented the current loop

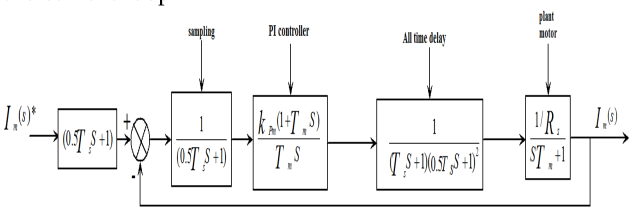

Fig.3. Design current loop

The transfer function of PI current controller depending upon [12] can be written as

$$PI_m = \frac{k_{Pm}(1 + T_m S)}{T_m S} \qquad (7)$$

Depending upon Fig.3 the open loop transfer function current loop is

$$C_{open} = \frac{k_{Pm}}{R_s T_m S} \frac{1}{(2T_s S + 1)} \qquad (8)$$

The parameters of PI current controller can be deduced depending upon generic open loop transfer function with damping factor $\xi = 0.707$ which has the following form

$$C_{open} = \frac{1}{2\xi S(\xi S + 1)} \qquad (9)$$

So $k_{Pm} = \frac{R_s T_m}{4T_s}$, $k_{im} = \frac{k_{Pm}}{T_m}$

Where k_{Pm} and k_{im} are proportional gain and integral gain of current controller respectively

V. DESIGN OF SPEED LOOP

The transfer function of dynamic equation is

$$\frac{p}{JS} = \frac{\omega_e(S)}{\Delta T(S)} \qquad (10)$$

The delays in outer speed loop arise due to control algorithm which has time constant 0.5 ms, sampling which has time constant 0.25 ms, current loop which has time delay 1ms and filter measured speed which has time constant 0.25 ms. Each delay can be represented by first order transfer function These transfer functions can be collected in one transfer function which is represented the total delay time as shown in Fig. 4. It (Fig.4) is represented the speed loop.

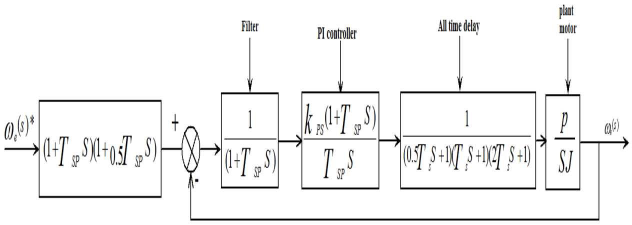

Fig. 4. Design of the speed loop

The transfer function of PI speed controller depending upon [12] can be written as

$$PI_{SP} = \frac{k_{SP}(1 + T_{SP} S)}{T_{SP} S} \qquad (11)$$

Where T_{SP} is motor speed time constant

Depending upon Fig.4 the open loop transfer function speed loop is

$$C_{SPO} = \frac{k_{SP}}{(1 + T_C S)} \frac{p}{J} \qquad (12)$$

Where T_C is the sum time delay due to speed loop

Depending upon generic open loop transfer function the parameters of speed loop are

$$k_{SP} = \frac{J}{2T_C}, \quad k_{iSP} = \frac{k_{SP}}{4T_C} \qquad (13)$$

Where k_{SP} and k_{iSP} are proportional gain and integral gain of speed controller respectively

VI. SIMULATION RESULTS

Here the modified model is compared to conventional model to show the effectiveness of modified model. Table 1 shows the effectiveness the modified model in suppressing the ripples, noise and THD if it is compared to classical model. Table 2 shows the motor parameters. During the simulations, the torque set value is limited to 4 N.m. In all figures the time axis is in seconds. Here the simulation studies the following cases

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

Where it is found that,

6.1. The first case (motor starting with loading)

In Figs. (5-6), dq axes currents are simulated. In conventional model (Fig. 5), the dq axes currents is highly distorted but in modified model with PI current controller (Fig. 6) both q-axis current component and d-axis current component are closest to the best value.

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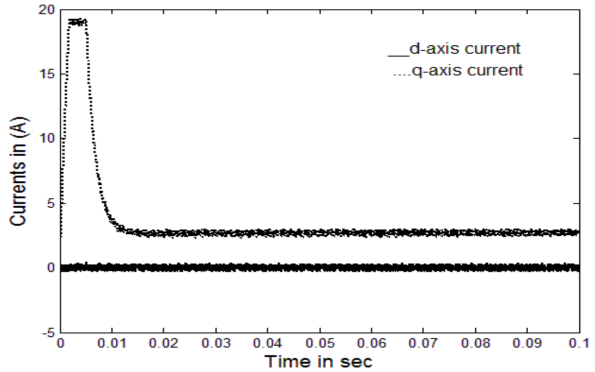

Fig. 5. Idq-axis current with conventional method

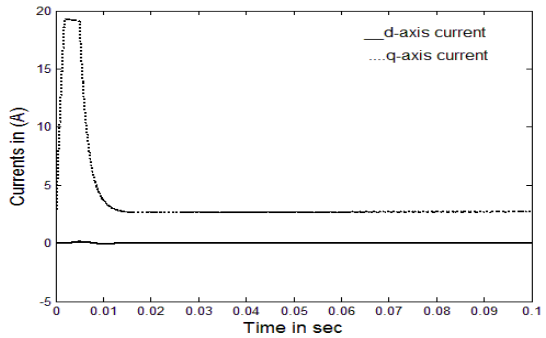

Fig. 6. Idq -axis current with modified model

The torque response in Fig.8 showed that, the torque ripple is approximately vanished with modified model if it is compared to the conventional model (Fig. 7).

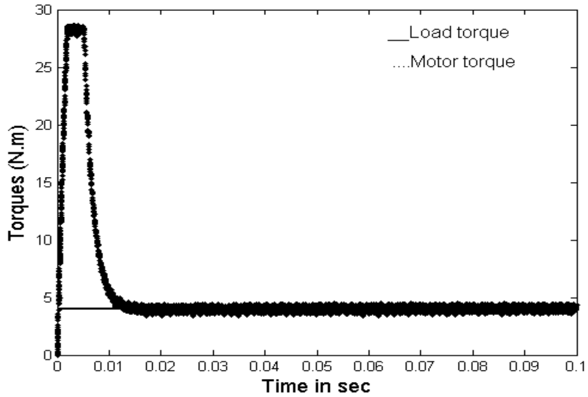

Fig. 7. Torque with conventional method

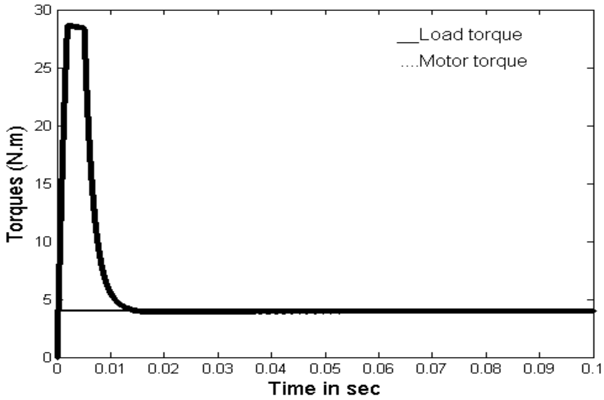

Fig. 8. Torque with modified model

Figure 9 shows some noise in the speed with conventional model if it is compared to the modified model (Fig. 10). This is because the torque ripple reaches the best value with modified model due to improvement in q-axis current component.

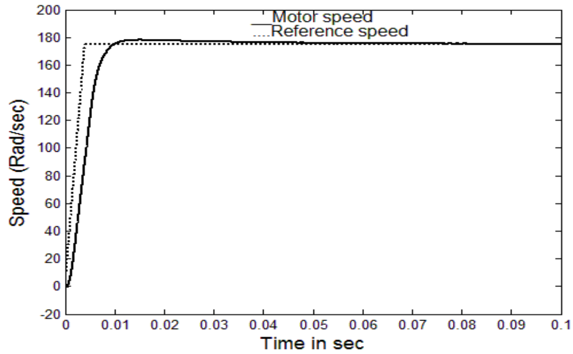

Fig. 9. Speed with conventional method

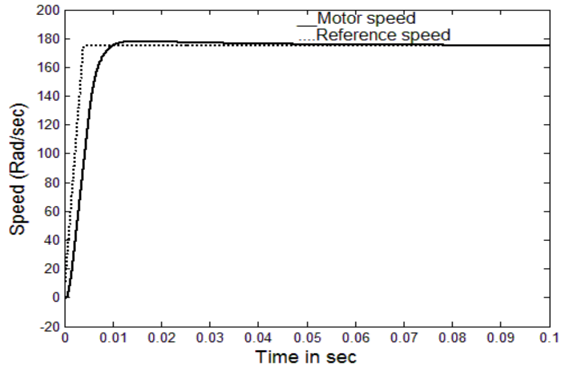

Fig. 10. Speed with modified method

In Fig.12, the stator currents become smoother with modified model due to improvement in the dq-axes current components. In conventional model (Fig.11), the stator current is highly distorted due to noise and electromagnetic interference.

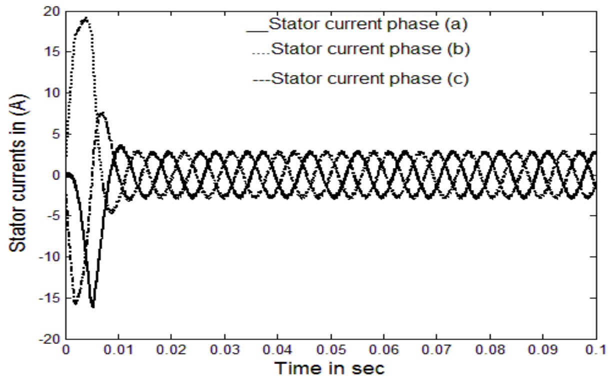

Fig. 11. Stator current with conventional method

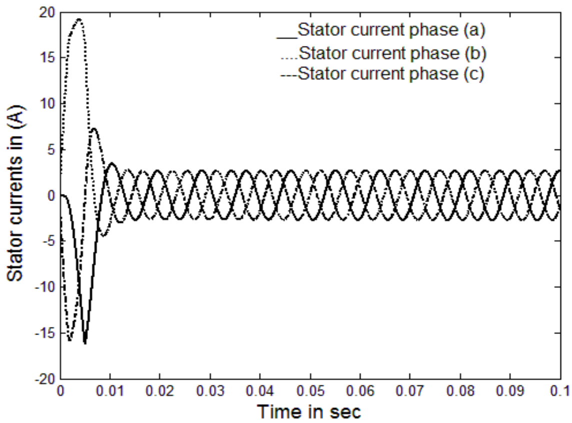

Fig. 12. Stator current with modified method

6.2. 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, highly distorted in dq-axis currents with conventional method even with starting without load (Fig. 13). In modulated method the distortion is vanish (Fig.14). In the modified method with PI current controller, the dq-axes current becomes improvement.

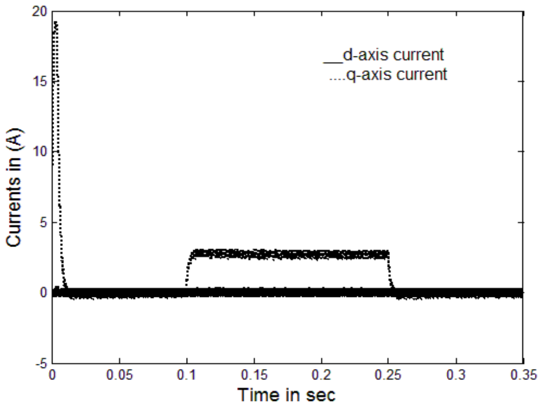

Figure 13. Idq-axis current with conventional method

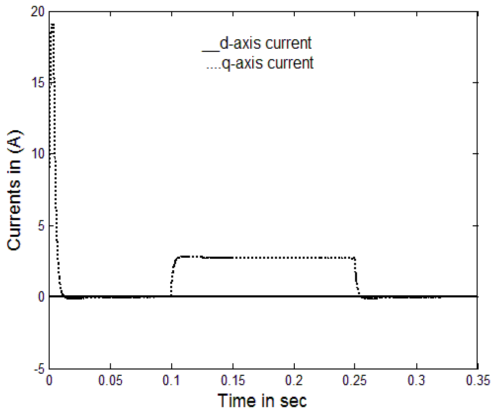

Fig. 14. Idq -axis current with modified model

In Fig.16, the ripple torque is reduced with modified methods if it is compared to conventional method (Fig. 15) this occurs due to less in the electromagnet interface and improvement in q-axis current component with modified model.

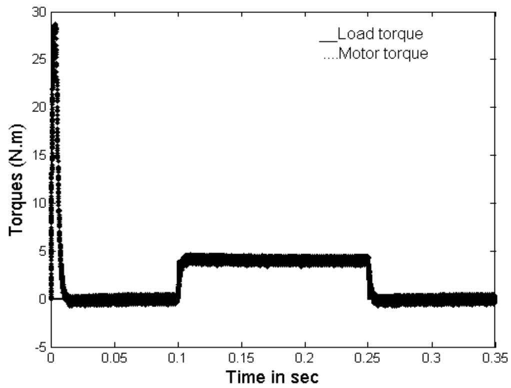

Fig. 15. Torque with conventional method

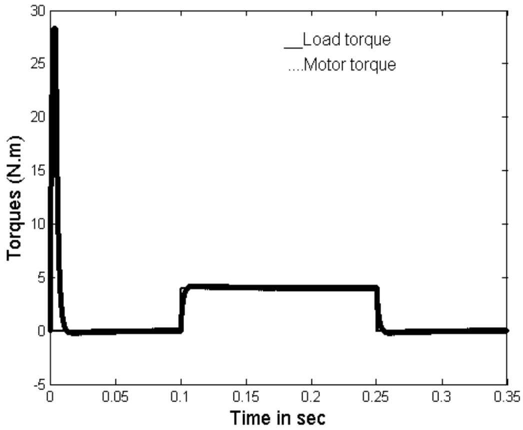

Fig. 16. Torque with modified model

Figure 17 shows some noise in the speed with conventional method if it is compared to the modified methods (Fig.18).

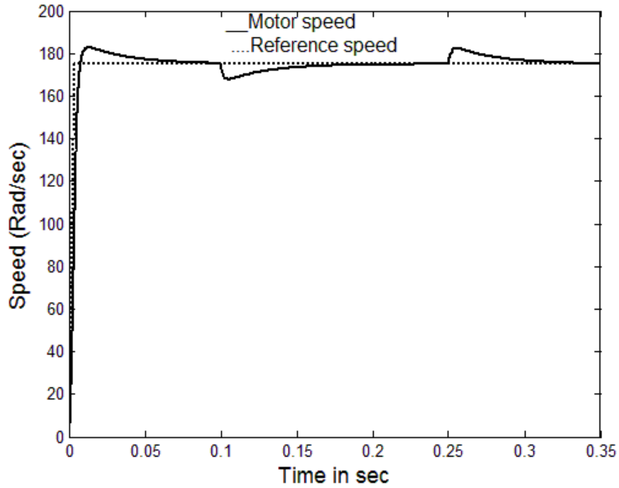

Fig. 17. Speed with conventional method

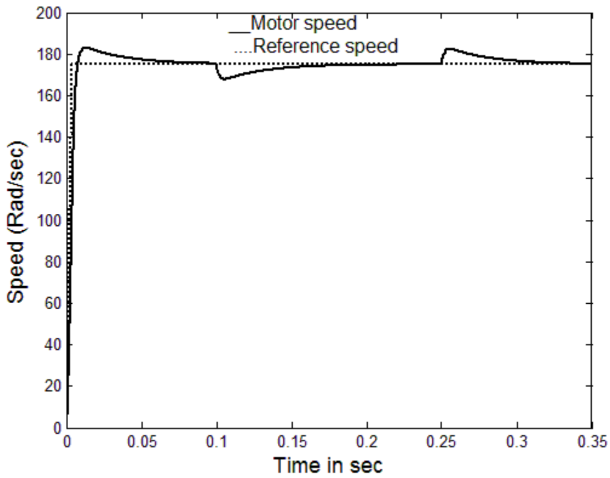

Fig. 18. Speed with modified method

In Fig.20, 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 approximately zero under no load but with conventional method these currents don't equal to zero due to noise, harmonics and electromagnet interface (Fig.19).

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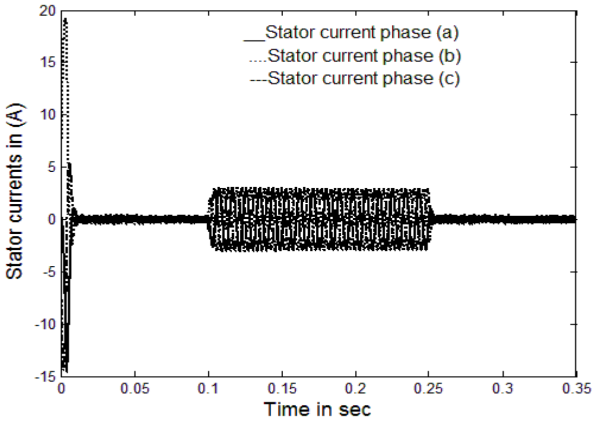

Fig. 19. Stator current with conventional method

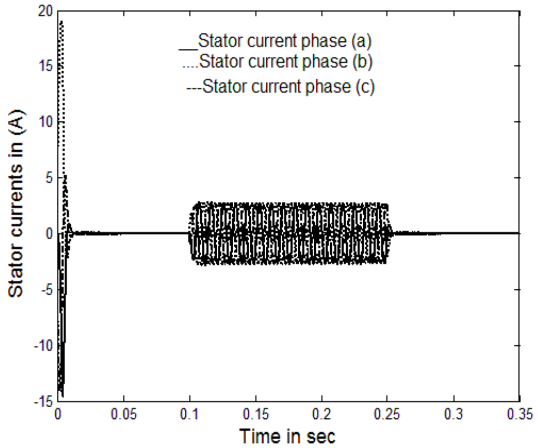

Fig.20. Stator current with modified method

6.3. The third case (reversing load)

The effects of reversing load are studied here. The motor starting with load, at 0.18 sec. the load is reversed where it is found that:

When the load is reversed, the q-axis current is responded by reversing in the proposed model and in the conventional model. The dq-axes current are smoother with modified model (Fig. 22) if it is compared to conventional model (Fig. 21).

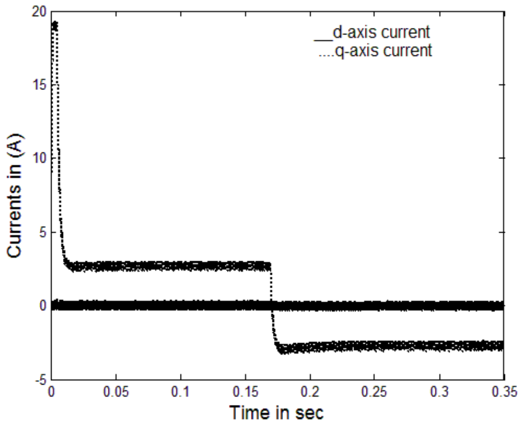

Fig. 21. Idq-axis current with conventional method

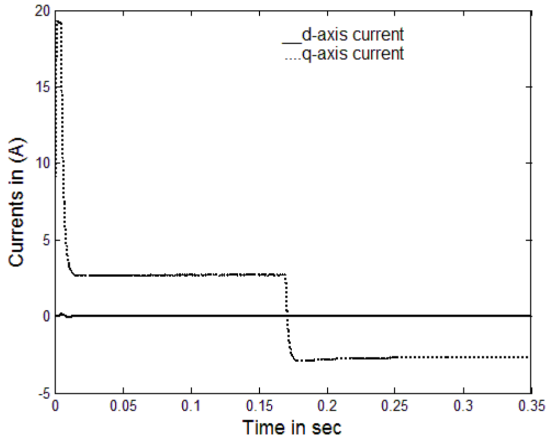

Fig. 22. Idq -axis current with modified model

The ripple torque is reduced with modified methods this occurs due to less in the electromagnet interface and improvement in q-axis current component (figure 24) if it compared to conventional model (figure 23).

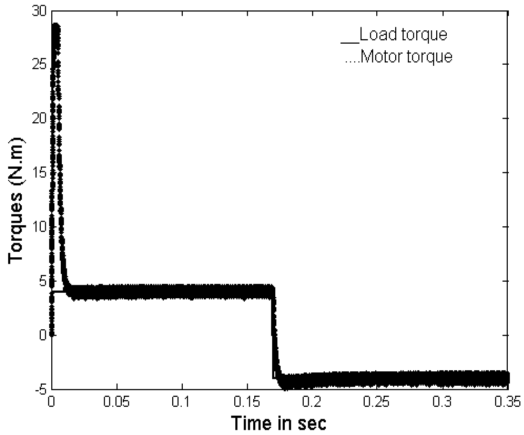

Fig. 23. Torque with conventional method

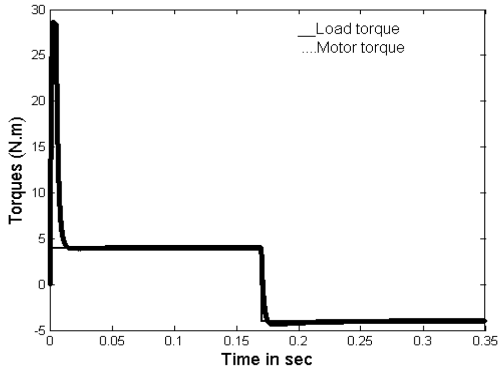

Fig. 24. Torque with modified model

The variation of the speed with two models approximately the same due to the motor is surface mounted and this is shown in Figs (25-26).

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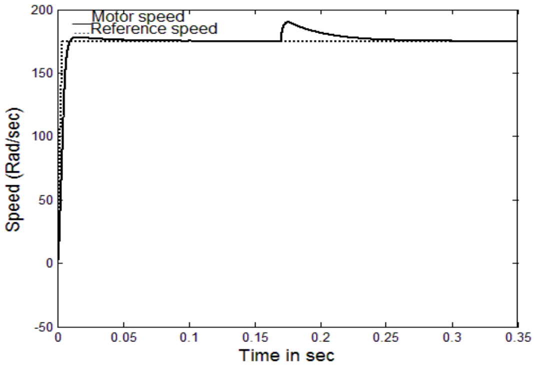

Fig. 25. Speed with conventional method

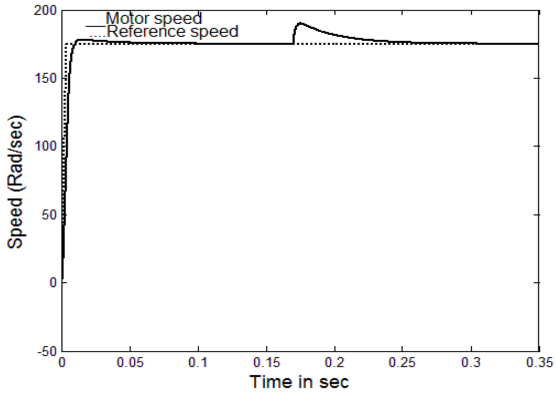

Fig.26. Speed with modified method

The stator currents become smoother with modified method (Fig.28) if it is compared to conventional method (Fig.27) due to reduction of the noise, improvement in dq-axes current components and suppresses the electromagnetic interference.

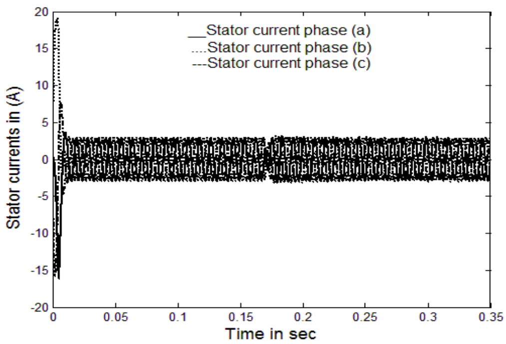

Fig. 27. Stator current with conventional method

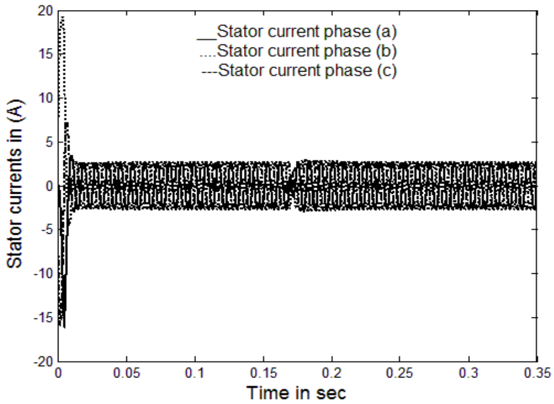

Fig. 28. Stator current with modified method

VII. CONCLUSION

This paper is addressed the torque problem, noise and total harmonic distortion. It introduced PI controller to suppress the harmonics, torque ripples, noise and electromagnetic interference in the hysteresis band. The design of PI current controller and speed controller are made. The PI current controller is affecting 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.

"Table 1"

Type of control	Ripple torque %	THD in the current %
Traditional method	9.62	10.2
Proposed method with modified PI controllers	0.23	0.54

APPENDIX I

Rated torque 4 N.M, Rated speed 175 Rad/Sec, Permanent magnet flux 0.175 Wb, phase stator resistance 2.875Ω, phase self inductance 12.5 mH, phase mutual inductance 4.5 mH, and rotor inertia 0.0008 Kg.m^2

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