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Improvement the Current Control Methods for Three Phase Voltage Source Inverter to Drive the Permanent Magnet Synchronous Motor

Hamdy Mohamed Soliman, S. M. EL. Hakim

Abstract— ***Three phase pluse width modelation voltage soruce inverter are widly used in many industrial application such as the drive system. The performance of the 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. This paper aims to improve the performance of Ac drives through the improvement the different methods of the current controlled. Here the classical hysteresis controller, ramp type controller and delta modulator controller are discussed and improvement by general design of PI current controller for each phase. The improvement can be seen through the torque ripple and total harmonic distortion. The proposed model is compared to classical model to show the effectiveness of the proposed model. This work is simulated through matlab simulink.***

Index Terms— ***hysteresis controller, delta modulator controller, ramp type controller, matlab simulink.***

I. INTRODUCTION

Inverter-fed AC-machines are widely used in industrial applications. In particular, to achieve fast torque responses and high-performance operation, Permanent magnet synchronous motors (PMSM) are often used together with high performance current controls. These motors (PMSM) become popular in various applications due to have some advantage 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. So 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].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 [2-3]. Field oriented control technology makes high-performance PMSM be widely applied. However, the control performance of PMSM is still influenced by the uncertainties of the plant, which include plant parameter variations and external load disturbances. Internal model control (IMC) can offer many good properties, such as easy design, good ability of disturbance rejection, and so on. Due to the advantages motioned above, IMC has been used widely in the field of AC motor drive systems [4-5].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 [6-7]. PMSM with field oriented control 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, under perfect field oriented control, with constant flux operation, applying the principles operation of the field oriented control, 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 oriented 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 [8]. Here PWM hysteresis current control, ramp type control and delta modulator are discussed. In these methods of current control, the load currents are measured and compared with the reference currents. The error is used as the input to the PWM which is used to drive the switching frequency of inverter.

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***** Correspondence Author (s)
Hamdy Mohamed Soliman*, General Manger in cairo Merto Gereater, Hellwan, Egypt.
S. M.EL. Hakim, Department of Electrical Power and Machines Engineering, Cairo University/ Engineering College, Giza, Egypt.

In this paper adaptive hysteresis current controller, ramp type controller and delta modulator controller are 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, section three basics of the current controlled PWM, hysteresis current controller in section four, ramp current controller in section five, section six discusses the delta modulated current controller, section seven shows the simulation results and conclusion in section eight.

II. MATHEMATICAL MODEL OF PMSM

The stator voltages equation can be written as,

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

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,

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

The dynamic equation

$$\frac{d\omega_e}{dt} = \frac{p}{J}[T_e - T_L - \beta\omega_e] \qquad (3)$$

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. BASICS OF THE CURRENT CONTROLLED PWM

The concept of current controlled PWM can be seen through Fig.1. The voltage source inverter controls the motor current by controlling the switching frequency of the inverter across the motor. The motor current is compared to the reference current and the error between them is used to drive the inverter. During the operation, the main task of this method of control is to force the motor current to follow the reference signals.

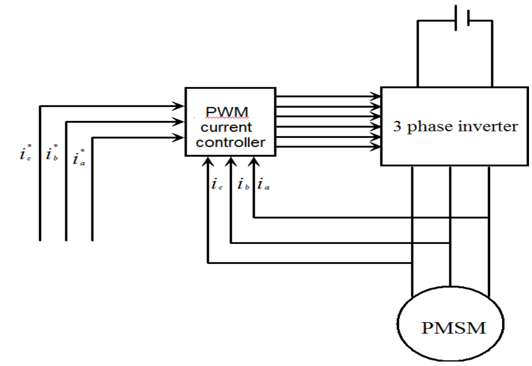


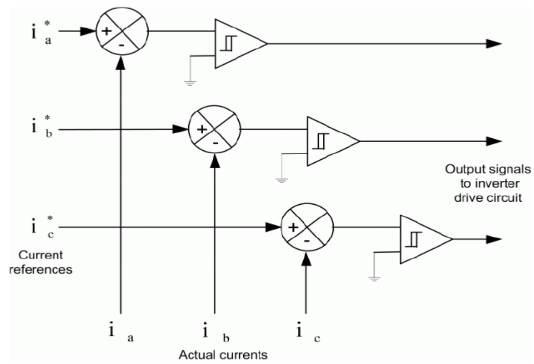
Fig.1. Basics circuit of PWM current controlled

IV. HYSTERESIS CURRENT CONTROLLED PWM

Number The hysteresis current controller is used due to simple, fast dynamic response and insensitive to load parameters. Figure 2. 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 [9]. 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

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

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.



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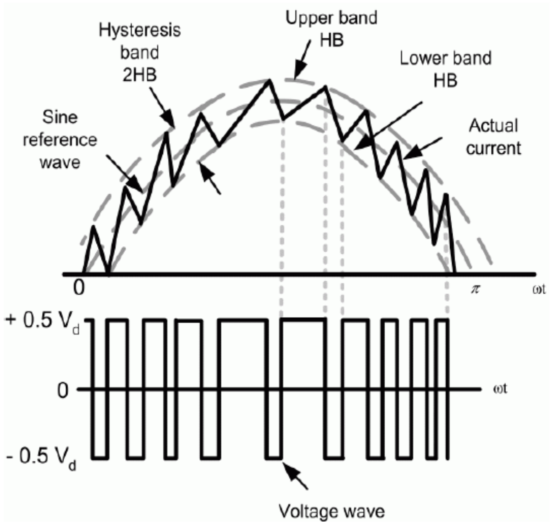

Fig 2. Hysteresis current controller basic structure and concept

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.3. 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 [10].

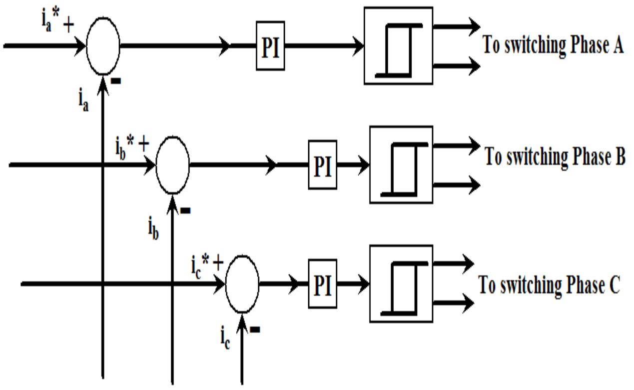

Fig.3. Proposed hysteresis current controller

V. RAMP CURRENT CONTROLLED PWM

In this type of control the switching frequency is constant which means that lower content of harmonics. In the classical ramp type current control, the motor current is compared to reference current and the errors signals is compared to fixed frequency triangular waveform. If this error is positive and larger than triangular wave positive voltage (Vdc) is applied to the motor and if the error is positive and smaller than triangular wave negative voltage (-Vdc) is applied to the motor [11]. Hysteresis band is added to avoid multiple crossing of error signal with triangular waveform. This technique suffers from errors in the magnitude and phase shift which means the motor disconnected several times. To repair this problem, triangular waveform is shifted by 120^0 between these phases to get the balance and get red from these errors. This can be done by phase shifter as shown in Fig. 4.

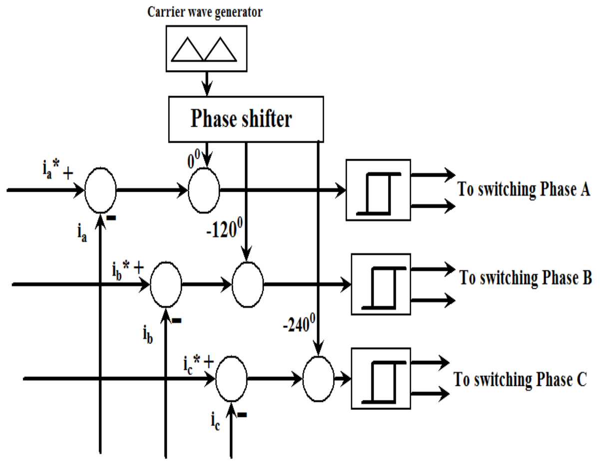

Fig.4 Modified ramp current controller

With this modification the harmonics became less but the remaining harmonics still effect on performance drive so the PI current controller is proposed as shown in Fig. 5 to suppress the harmonics, noise, torque ripple and total harmonic distortion. The error of the current used as the input for PI current controller which minimize the error at steady state and increase the performance of the drives and inverter as will be seen when simulation studying.

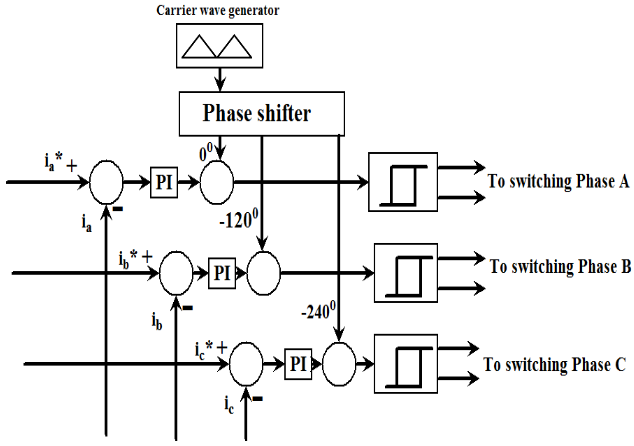

Fig.5 Proposed ramp current controller

VI. DELTA MODILATOR CURRENT CONTROLLER

In this type of current control (Fig. 6), the measured currents are compared to the reference currents and errors comes from comparing between the phase shifter and the errors in the current are used to compare with output of integrator filter. The integrator filter (Fig. 7) is used as the feed back. The feed back pass consists of integrator filter and the forwarded pass consists of hysteresis quantizer which used to calculate the error signal to produce the modulated wave to control the switching frequency [12-13]. This error can be controlled by controlling the time constant of the filter and cut of frequency which can be calculated as

$$\frac{G_o(S)}{G_i(S)} = K\frac{1}{1+\tau S} \qquad (5)$$

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Where K ($K = -\frac{R_2}{R_1}$) is the gain of filter and τ ($\tau = R_2 C$) is the time constant of filter

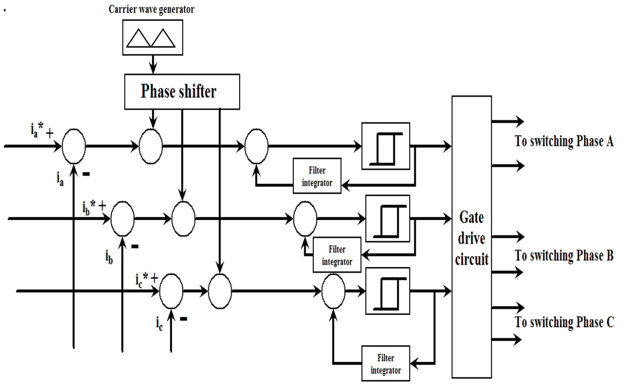

Fig. 6 Delta modulator current controller

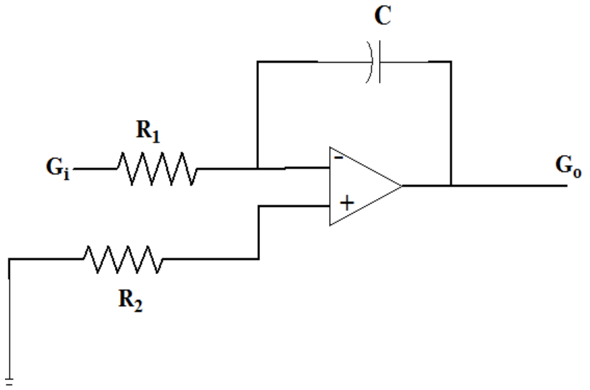

Fig. 7 Integrator filter

With this modification the harmonics became less but the drive systems still effected by unwanted things so the PI current controller is proposed as shown in Fig. 8. to improve the performance of the drives and inverter as will be seen when simulation studying.

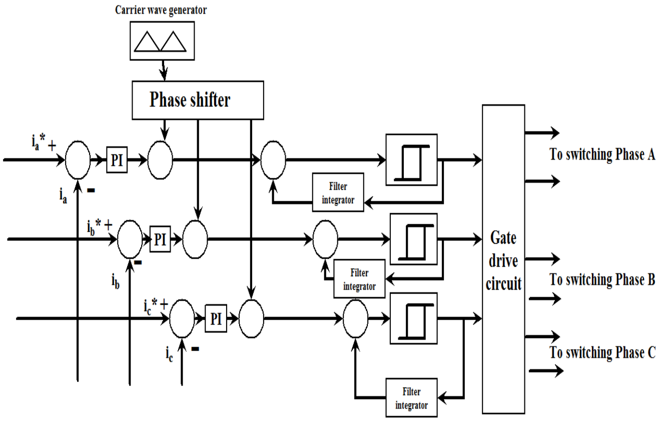

Fig. 8 Proposed delta modulator current controller

VII. SIMULATION STUDING

Here the proposed models are compared to conventional models to show the effectiveness of proposed models. Tables 1&2 show the effectiveness the proposed models in suppressing the ripples, noise and THD if it is compared to classical models. Appendix 1 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 operation of the motor under effect the full load also the effect of different current control methods and proposed control method when the motor starting with load is studied. Where it is found that

7.1. Hysteresis current controller

Here the conventional method means hysteresis current controller and the proposed model; it is hysteresis current controller with adding PI controller.

In figures (9-10), dq axes currents are simulated. In conventional model (Fig. 9), the dq axes currents is highly distorted but in proposed model with PI current controller (Fig. 10) both q-axis current component and d-axis current component are closest to the best value.

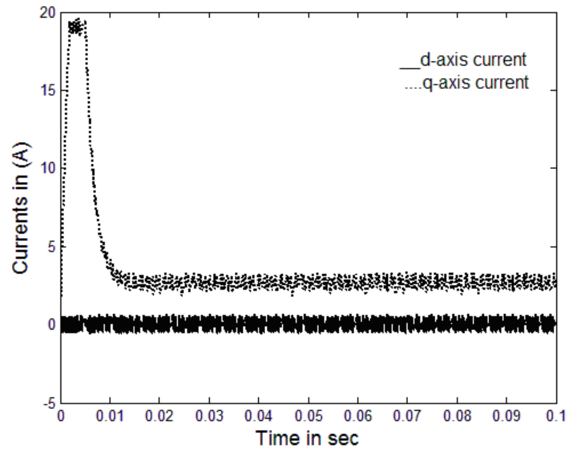

Fig. 9. Idq-axis current with conventional method

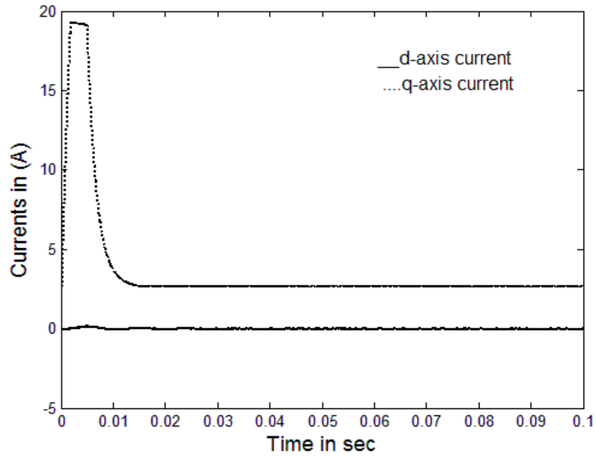

Fig. 10. Idq -axis current with proposed model

The torque response in Fig.12 showed that, the torque ripple is approximately vanished with proposed model if it is compared to the conventional model (Fig. 11).

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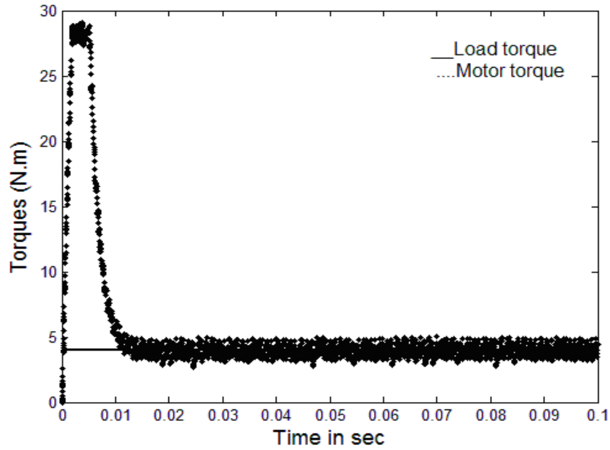

Fig. 11. Torque with conventional method

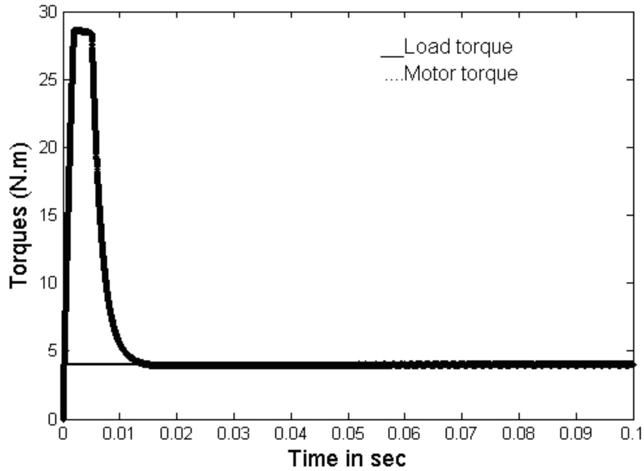

Fig. 12. Torque with proposed model

Figure 13 shows some noise in the speed with conventional model if it is compared to the proposed model (Fig. 14). This is because the torque ripple reaches the best value with proposed model due to improvement in q-axis current component.

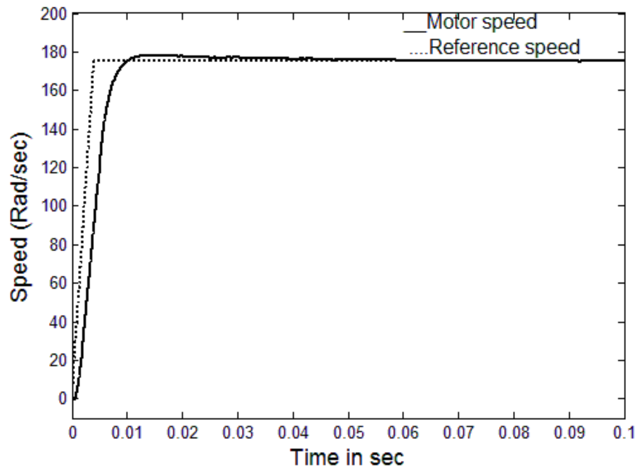

Fig. 13. Speed with conventional method

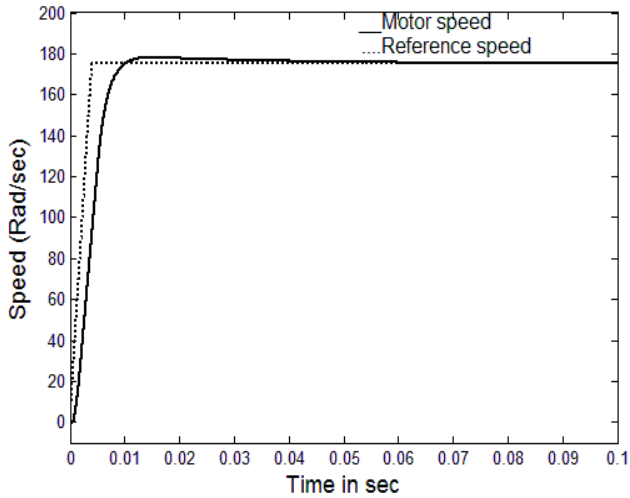

Fig. 14. Speed with proposed method

In figure.16, the stator currents become smoother with proposed model due to improvement in the dq-axes current components. In conventional model (Fig.15), the stator current is highly distorted due to noise and electromagnetic interference.

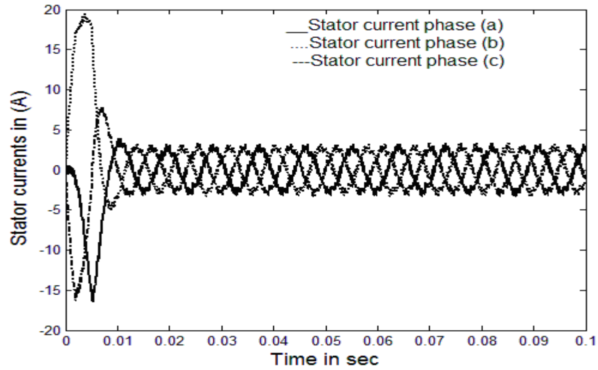

Fig. 15. Stator current with conventional method

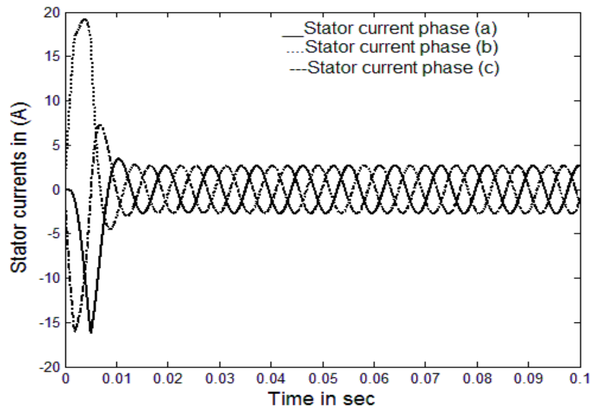

Fig. 16. Stator current with proposed method

Error in current signal with conventional method is shown in Fig. 17. while the same signal for proposed method is shown in Fig. 18.

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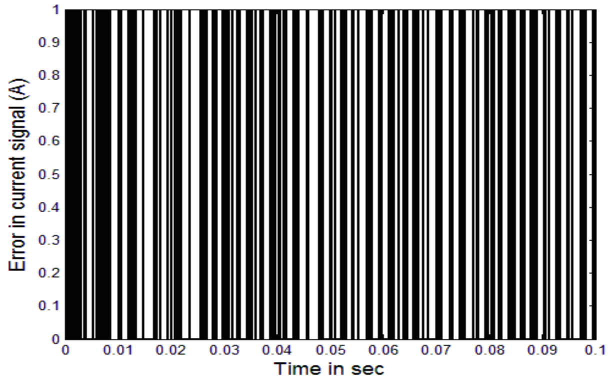

Fig. 17. Error in current signal with conventional method

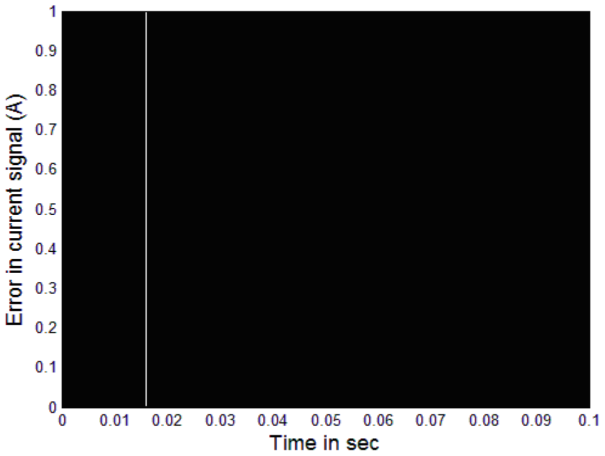

Fig. 18. Error in current signal with proposed method

7. 2. Ramp modulation current controller

Here the conventional method means ramp modulation current controller and the proposed model means ramp modulation current controller with adding PI controller.

Highly distorted in dq-axis currents with conventional method (Fig. 19) are shown. In modulated method the distortion is vanish (Fig.20) i.e. in the proposed method with PI current controller, the dq-axes current becomes improvement.

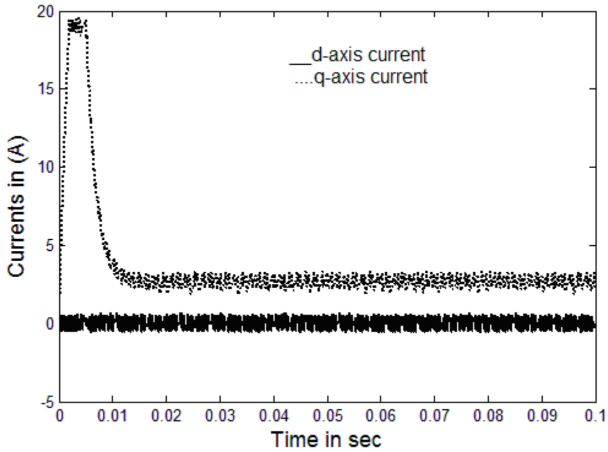

Fig. 19. Idq-axis current with conventional method

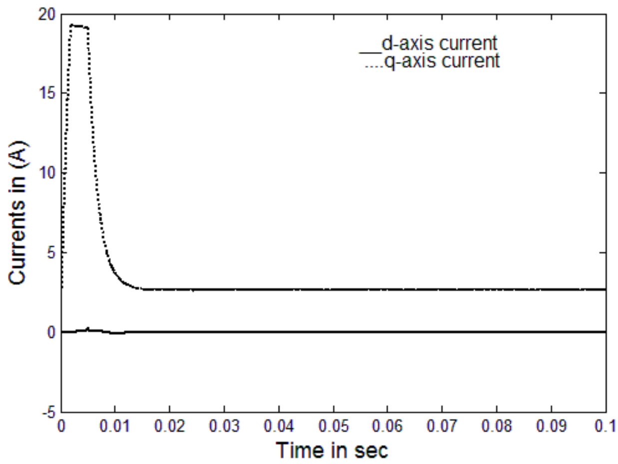

Fig. 20. Idq -axis current with proposed model

In figure.22, the ripple torque is reduced with proposed methods if it is compared to conventional method (Fig. 21) this occurs due to less in the electromagnet interface and improvement in q-axis current component with proposed model.

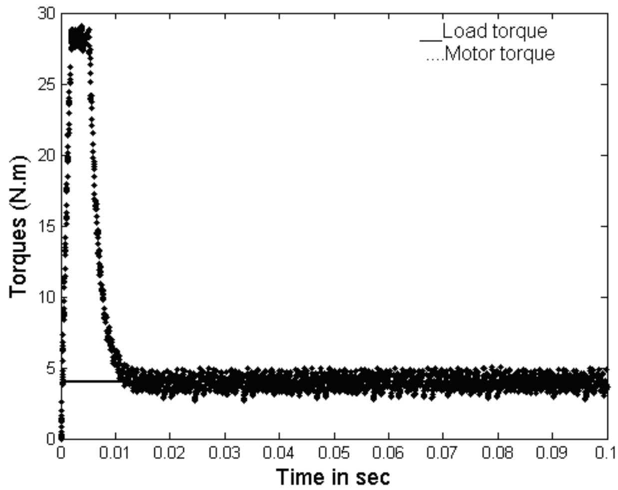

Fig. 21. Torque with conventional method

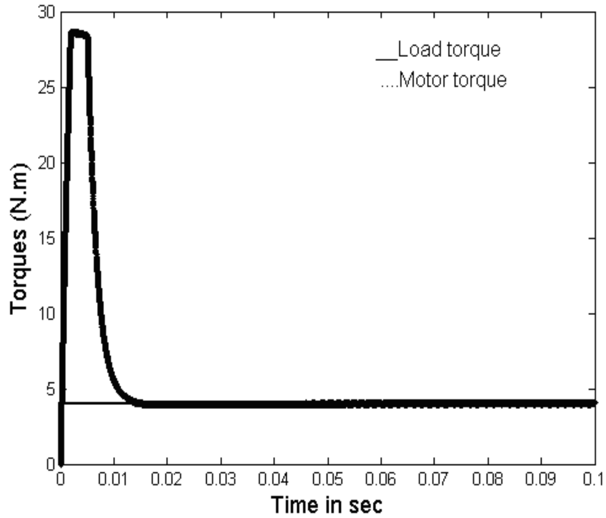

Fig. 22. Torque with proposed model

Figure 23 shows little noise in the speed with conventional method if it is compared to the proposed methods (Fig.24).

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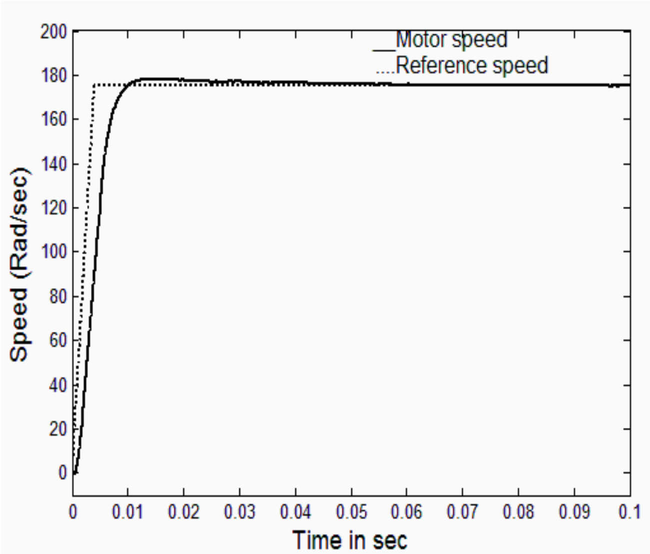

Fig. 23. Speed with conventional method

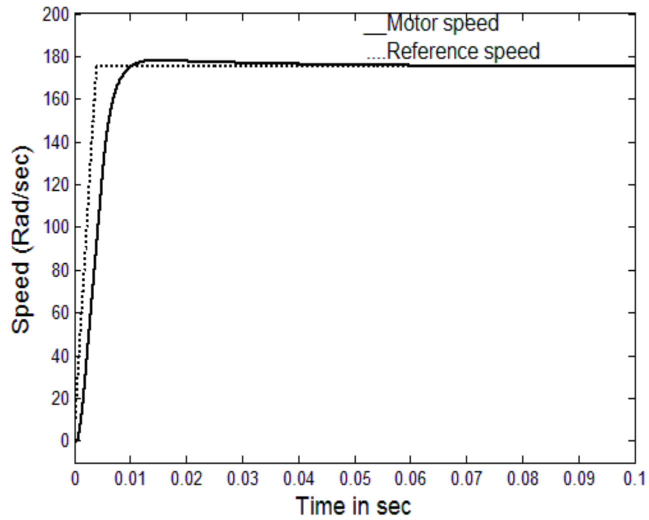

Fig. 24. Speed with proposed method

In Fig.26, the stator currents become smoother with proposed model due to reduction of the noise, improvement in the dq-axes current components. In conventional model (Fig.25), the stator current is highly distorted due to noise and electromagnetic interference.

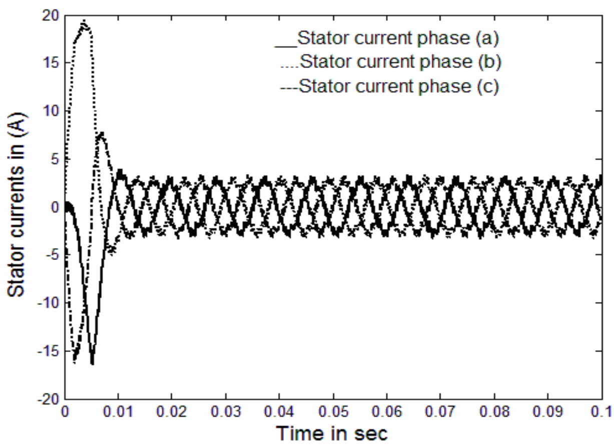

Fig. 25. Stator current with conventional method

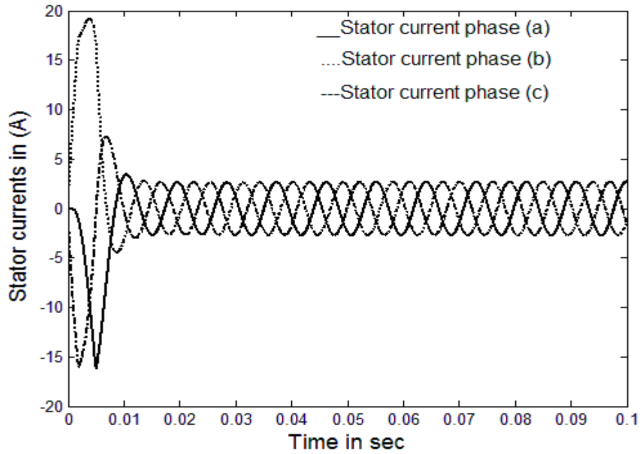

Fig. 26. Stator current with proposed method

Error in current signal with conventional method is shown in Fig. 27. while the same signal for proposed method is shown in Fig. 28.

Fig. 27. Error in current signal with conventional method

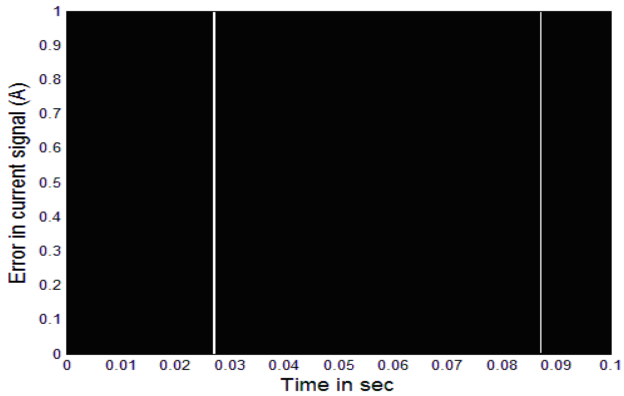

Fig. 28. Error in current signal with proposed method

7.3. Delta modulation current controller

Here the conventional method means delta modulation current controller and the proposed model means delta modulation current controller with adding PI controller.

In figures (29-30), dq axes currents are simulated. In conventional model (Fig. 29), the dq axes currents is highly ripple and highly distorted but in proposed model with PI current controller (Fig. 30) both q-axis current component and d-axis current component are closest to the best value.

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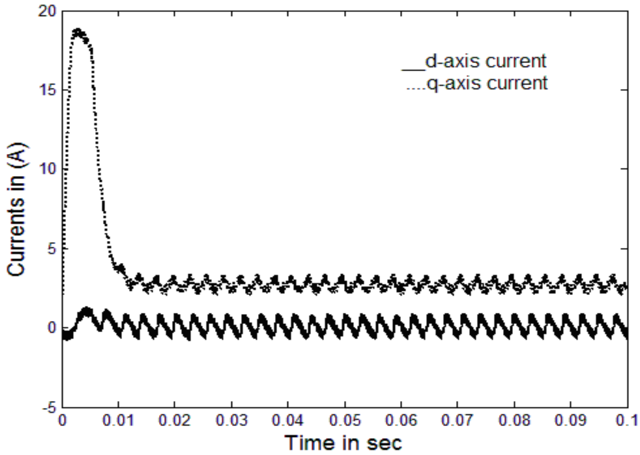

Fig. 29. Idq-axis current with conventional method

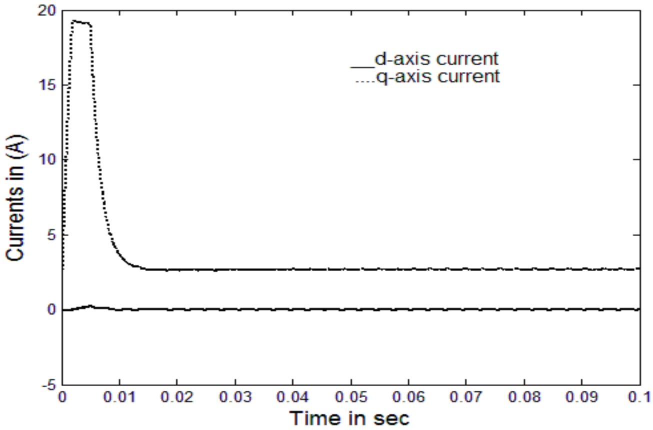

Fig. 30. Idq -axis current with proposed model

The torque response in Fig.32 showed that, the torque ripple is approximately vanished with proposed model if it is compared to the conventional model (Fig. 31). The ripple torque is reduced with proposed methods due to less in the electromagnet interface and improvement in q-axis current component if it compared to conventional model.

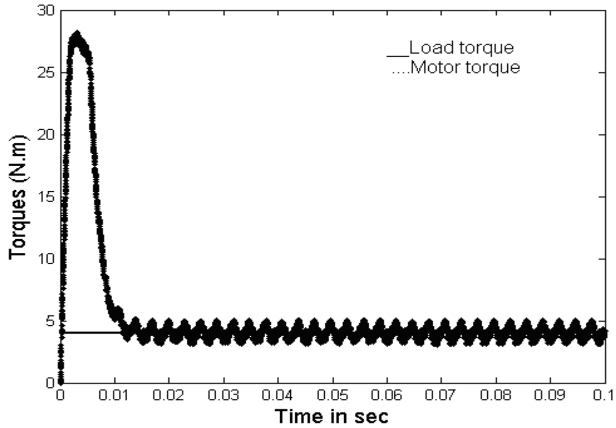

Fig. 31. Torque with conventional method

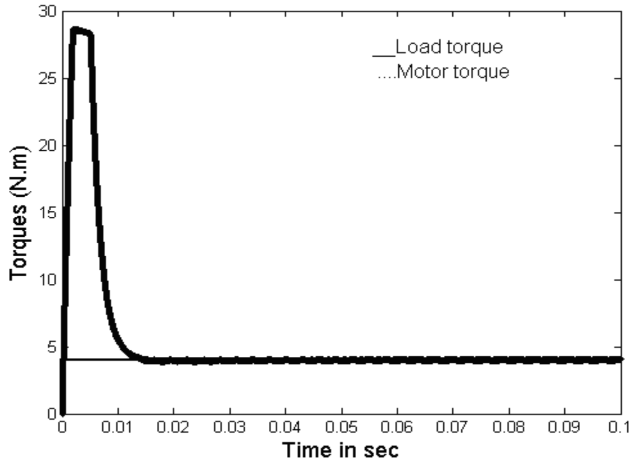

Fig. 32. Torque with proposed model

Figure 33 shows some noise in the speed with conventional model if it is compared to the proposed model (Fig. 34). This is because the torque ripple reaches the best value with proposed model due to improvement in q-axis current component.

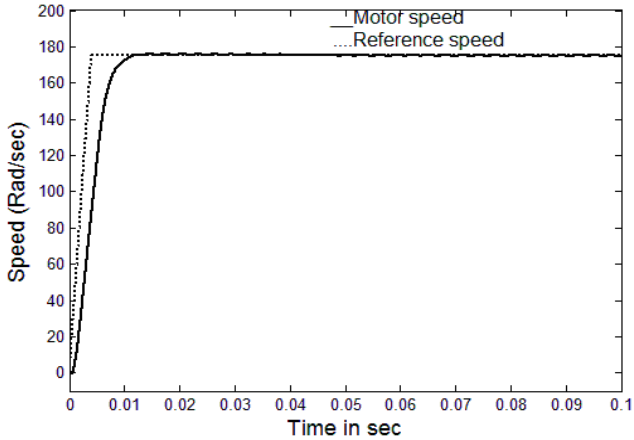

Fig. 33. Speed with conventional method

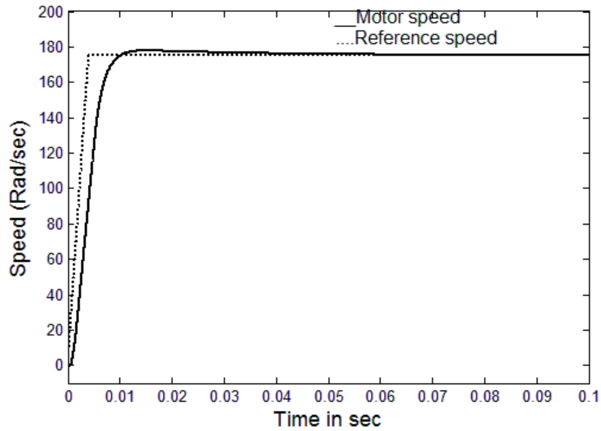

Fig. 34. Speed with proposed method

The stator currents become smoother with proposed method (Fig.36) if it is compared to conventional method (Fig.35) due to reduction of the noise, improvement in dq-axes current components and suppresses the electromagnetic interference.

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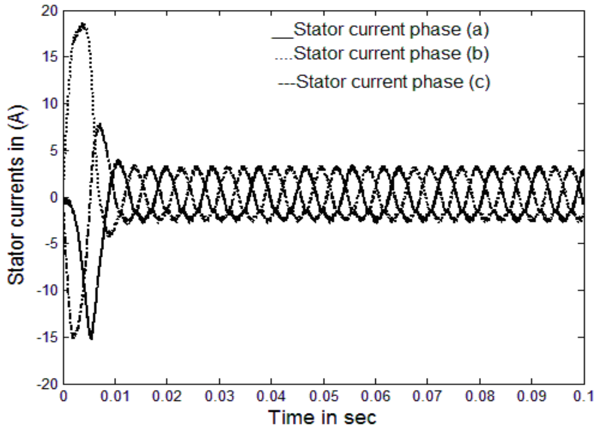

Fig. 35. Stator current with conventional method

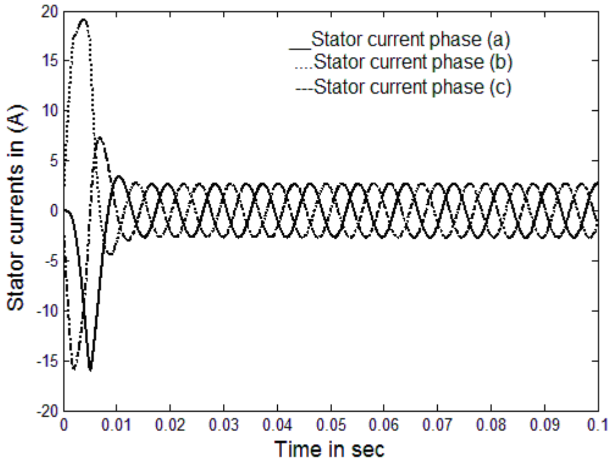

Fig. 36. Stator current with proposed method

Error in current signal with conventional method is shown in Fig. 37. while the same signal for proposed method is shown in Fig. 38.

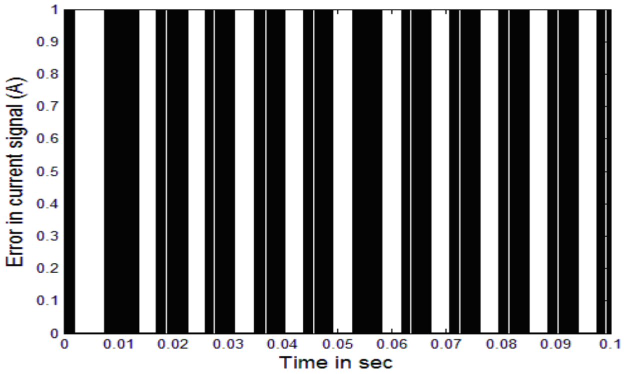

Fig. 37. Error in current signal with conventional method

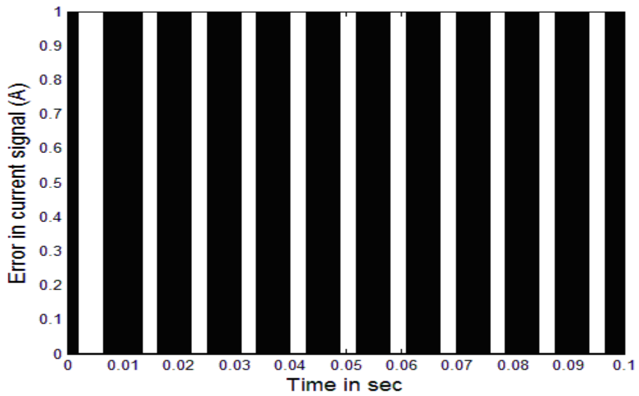

Fig. 38. Error in current signal with proposed method

VIII. CONCLUSION

This paper is addressed the torque problem, noise and total harmonic distortion by adding PI controller to the conventional current control methods as, hysteresis current controller, ramp current controller and delta modulated current controller. PI controller is introduced to suppress the harmonics, torque ripples, noise and electromagnetic interference in the previous methods of control. 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. Also this paper is compared between these current controller methods in case of conventional method where it is found that, the different methods of current controllers provide good dynamic response and the ramp current controller is found less in total harmonic distortion where delta modulated current controller is higher but in torque ripple the delta modulated current controller is less and ramp current controller is higher also in proposed models the dynamic response, the torque ripple and total harmonic distortion become excellent.

"Table 1"

Type of control	***Ripple torque %***	
	Conventional control	***Proposed control***
Hysteresis current control	***10.88***	***0.822***
Ramp current control	***11.36***	***0..83***
Delta current control	***10.82***	***0.933***

"Table 2"

Type of control	***THD in the current %***	
	Conventional control	***Proposed control***
Hysteresis current control	***15.77***	***1.19***
Ramp current control	***15.69***	***1.21***
Delta current control	***18.28***	***1.41***

IX. APPENDIX 1

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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