Reduction of Torque and Flux Ripples in Direct Torque Controlled Five-Phase Induction Motor Drive based on Instantaneous Voltage Control Technique

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Abstract**—** This paper elaborates the use of instantaneous voltage control method for control of torque in a five phase induction motor drive. In this method, instantaneous time modulating signals are generated, without the feedback of position of rotor, which enhances its easier implementation. These modulating signals being compared with triangular waves gives the required switching states input to the inverter gate triggering circuit, based on the speed, flux and torque errors. Triplet component is added to the fundamental sinusoidal signal and the resultant signal is used as a modulating signal, because of the advantage of getting more effective switching states. This method is achieved by generation of inverter switching states by modulation of the errors in flux, speed and also real time speed control based on the instantaneous error values. A comparison is made with conventional Direct Torque Control (DTC) method and satisfactory results are observed.

Keywords**—** Five-phase inverter, five-phase induction motor, direct torque control, speed control, torque ripple, space vector modulation

I. INTRODUCTION

In today's drive applications multiphase machines are gaining popularity due to their various advantages over classic three phase induction machine such as reducing per phase voltage, reducing the amplitude and increasing the frequency of torque pulsation and high reliability, high fault tolerance [1]. Many control strategies have been suggested so far but Direct torque control method is the most popular and simple method and gave good and fast dynamic torque response [2]. There are mainly two problems with the conventional DTC scheme i.e. high electromagnetic torque ripple and variable switching frequency of the inverter [6]. The reason for variable switching frequency is the use of torque hysteresis comparators. High torque ripple is due to the fact that during the time period of a sector, only one stator voltage vector is ON over a particular switching period, irrespective of the errors in torque and flux. Since the magnitude of torque ripple for an inverter fed electrical machine is inversely proportional to inverter switching frequency, therefore appreciable torque ripple reduction can be achieved by increasing inverter switching frequency [7]. In hysteresis based DTC, torque ripple can be reduced by reducing the width of hysteresis band but it can lead to extremely high switching frequency.

In order to overcome these disadvantages, Space Vector Modulation Direct Torque Control (SVM-DTC) method, using Instantaneous voltage control technique (Kim-Sul's method) was proposed [8]. The SVM-DTC and proposed method with Kim-Sul algorithm are similar in implementation except for the way of generation of modulating signals [9]. SVM-DTC using instantaneous voltage control method is easier to implement than conventional SVM-DTC, since rotor position feedback and look-up table are not required. The main advantage of the proposed method is reduced ripple at low speed. The use of this proposed technique in multi phase machines will enhance their performance and will find more applications in various areas.

This paper presents SVM-DTC using instantaneous voltage control method for 5-phase Induction motor. The conventional and proposed DTC simulation results are presented and compared for steady state response, transient response and speed reversal operation using MATLAB/SIMULINK. The simulation results show the ripples are reduced in all cases in the proposed SVM-DTC method using instantaneous voltage control method.

II. PROPOSED DTC METHOD

A. Control Scheme

Closed loop AC electrical motor drives have a common block diagram consisting of speed and flux error estimator, synchronous to stationary frame convertor, modulating signal generator, induction motor model, etc. Firstly the errors in speed and torque are estimated and are given to a block to generate the modulating signals using instantaneous voltage control algorithm which are then compared with a high frequency triangular signal to generate switching pulses. This signal is given to the inverter with dc-link voltage of 560V and inverter output is supplied to Induction motor. Two voltage signals V_{ds} an V_{qs} in synchronous reference frame are converted into five phases in stationary reference frame as follows

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$$V_a = V_{ds}.\sin\theta + V_{qs}.\cos\theta \qquad (1)$$

$$V_b = V_{ds}.\sin\left(\theta - \frac{2\pi}{5}\right) + V_{qs}.\cos\left(\theta - \frac{2\pi}{5}\right) \qquad (2)$$

$$V_c = V_{ds}.\sin\left(\theta - \frac{4\pi}{5}\right) + V_{qs}.\cos\left(\theta - \frac{4\pi}{5}\right) \qquad (3)$$

$$V_d = V_{ds}.\sin\left(\theta + \frac{4\pi}{5}\right) + V_{qs}.\cos\left(\theta + \frac{4\pi}{5}\right) \qquad (4)$$

$$Ve = V_{ds}.\sin\left(\theta + \frac{2\pi}{5}\right) + V_{qs}.\cos\left(\theta + \frac{2\pi}{5}\right) \qquad (5)$$

The conventional space vector PWM is quite complex due to trigonometric calculations and sector identification. This issue is solved by proposed method which is based on the inverter switching time periods. It uses instantaneous voltage reference signals to generate the switching sequence automatically without any look-up table and sector identification.

To obtain the switching sequence of inverter by this method, the instantaneous voltage signals are converted into time signals as follows

$t_i = \frac{V_i}{V_{dc}} \cdot T_s$ where i= *a, b, c, d, e*. and T_s is sampling time period, $f_s = \frac{1}{T_s} = 2000Hz$

Thus t_a, t_b, t_c, t_d, t_e are the calculated instantaneous time reference signals. The maximum ($T_{\max}$) and minimum ($T_{\min}$) at every instant of sampling time is calculated from these signals to estimate the inverter gate signals. The effective voltage T_{eff} can be calculated as difference between $T_{\max}$ and $T_{\min}$ i.e. $T_{eff} = T_{\max} - T_{\min}$ (7)

Null vector time period T_0 can be calculated as,

$$T_0 = T_s - T_{eff} \qquad (8)$$

This null vector time period is distributed symmetrically over two null vectors, so the offset time can be calculated as

$$T_{off} = \frac{T_0}{2} - T_{\min} \qquad (9)$$

The desired modulating signal for inverter switching is derived as,

$$T_i^* = t_i + t_{off} \qquad \text{where } i = \text{a, b, c, d, e.} \qquad (10)$$

These modulating signals (as in fig.1) are compared with high frequency carrier signal to generate inverter switching logic at each sampling interval.

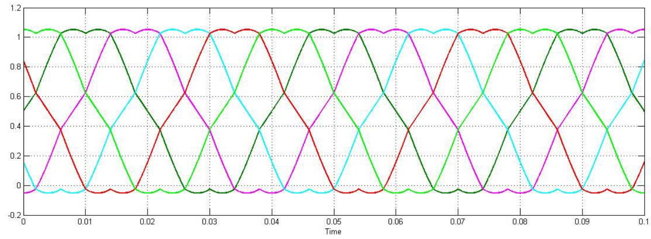


Fig.1: Desired modulating 5-phase signals with triplet components

The error signals in speed and flux are given to a PI controller, where the parameters are set to get the desired steady state error, overshoots and transient time period. The output of this controller is DC component, since it is referred to synchronous frame. When these DC components are transferred to stationary frame, they are converted into AC modulating signals, which are processed to give five AC modulating signals by the SVM block (from equations 1 to 5). These signals are compared with a high frequency (10 kHz) triangular carrier signal, by the comparator circuit, whose output is a DC sequence of 1's and 0's. These signals are the desired pulse width modulated switching signals given to inverter switches to generate five phase AC stator voltages, supplied to 5-phase Induction motor**.**

Based on the error signals, the magnitudes of output of PI controllers will vary and the frequencies of the AC modulating signals also alter. This eventually affects the switching sequence of the inverter circuit. Based on these altered switching states, stator input to the induction motor varies and the errors are rectified. FFT analysis of conventional method (fig.16) shows the ripples of distributed harmonics are present in the given response and these harmonics shift towards the fundamental component as the speed increases. In the proposed method (fig.17), as the switching frequency remains constant, ripples are present near the integral multiples of the fundamental frequency and change in speed doesn't affect this ripple distribution.

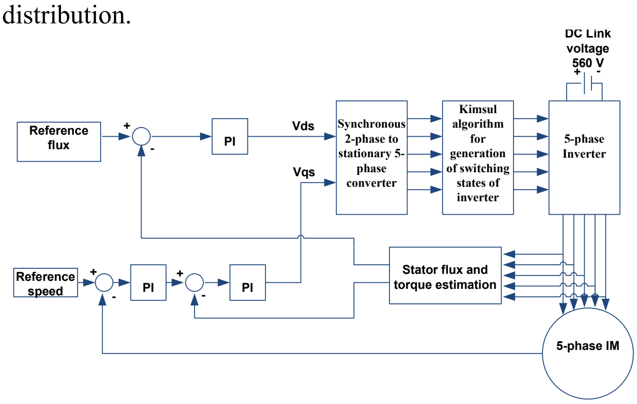


Fig.2: Block diagram of the proposed method.

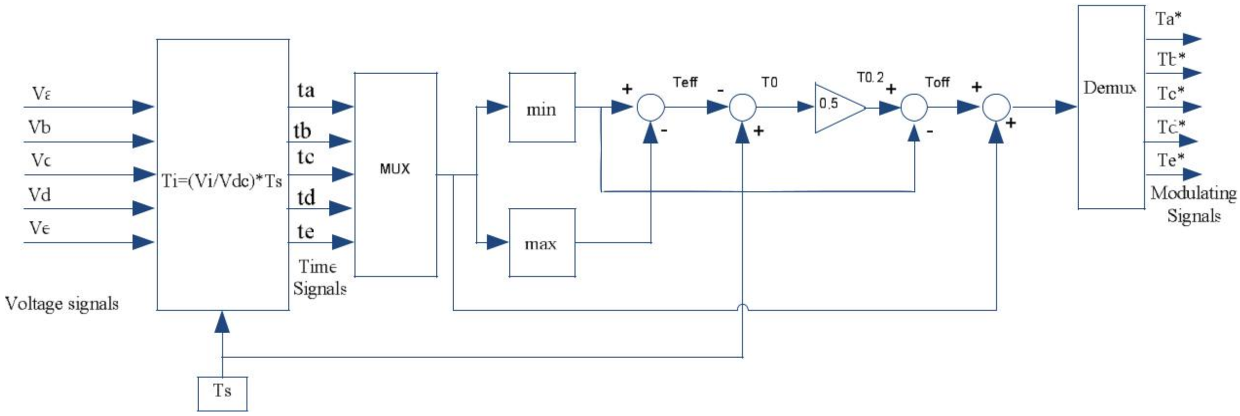


Fig.3: Block diagram for generation of modulating signal (Kim-Sul algorithm)

B. Simulation Results

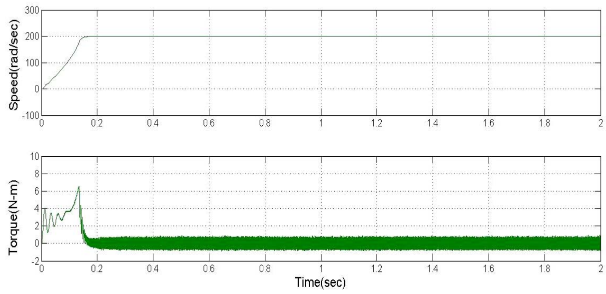


Fig.4: Speed and torque responses for the proposed method at 200 rad/s

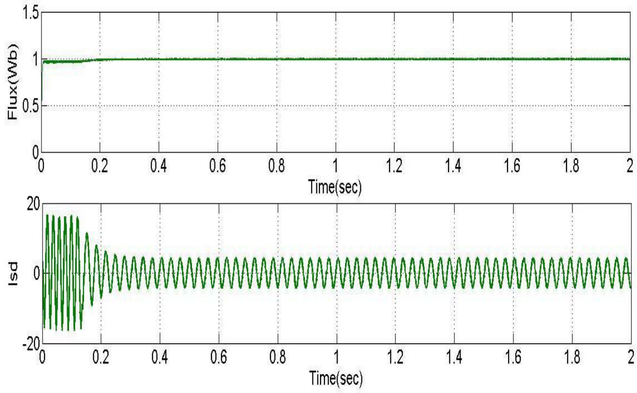


Fig.5: Flux and stator direct-axis current of the proposed method at 200 rad/s

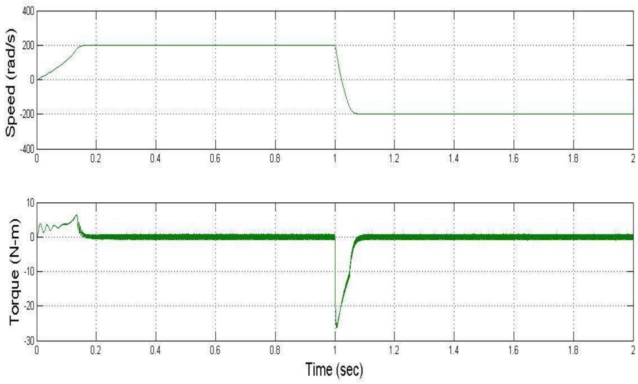


Fig.6: Speed and torque responses for the proposed method at 200 rad/s speed with speed reversal from t=1sec.

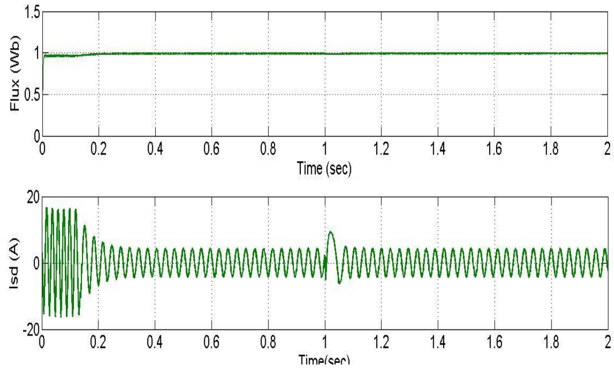


Fig.7: Flux and Stator current of the proposed method for 200 rad/s speed and speed reversal from t=1sec.

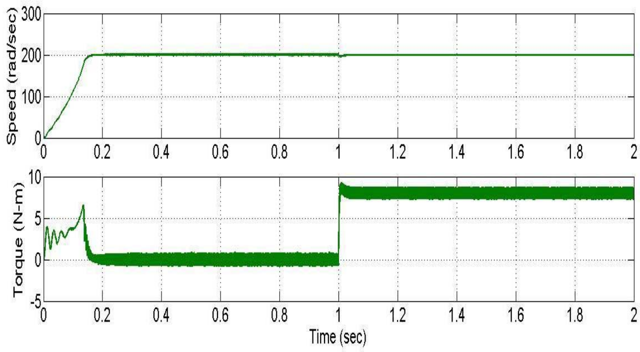


Fig.8: Speed and torque responses of the proposed method with speed 200 rad/s with a load torque of 8 N-m applied at t=1sec.

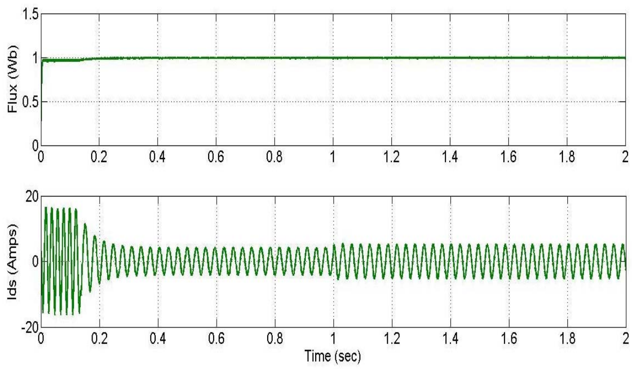


Fig.9: Flux and Stator current responses of the proposed method with speed 200 rad/s and load torque of 8 N-m applied at t=1sec.

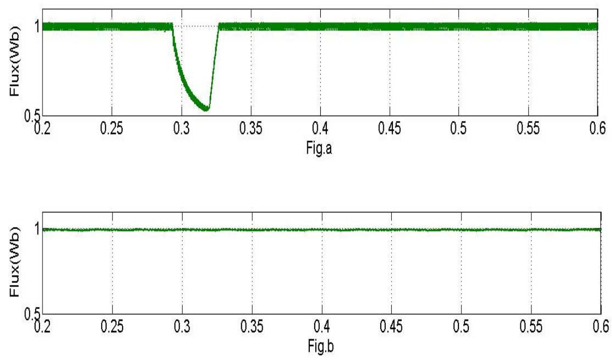


Fig.10: Steady state stator flux response at 20 rad/s in a) conventional DTC method. B) Proposed method.

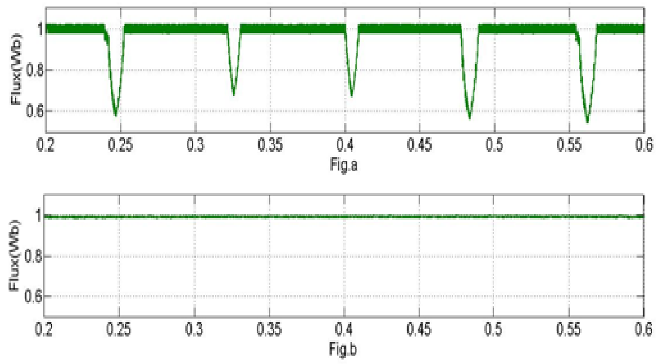


Fig.11: Steady state stator flux response at 80 rad/s in a) conventional DTC method. b) Proposed method

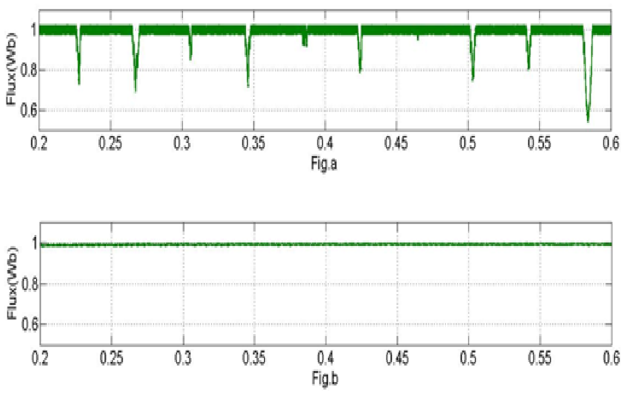


Fig.12: Steady state stator flux response at 160 rad/s in a) conventional DTC method. b) Proposed method

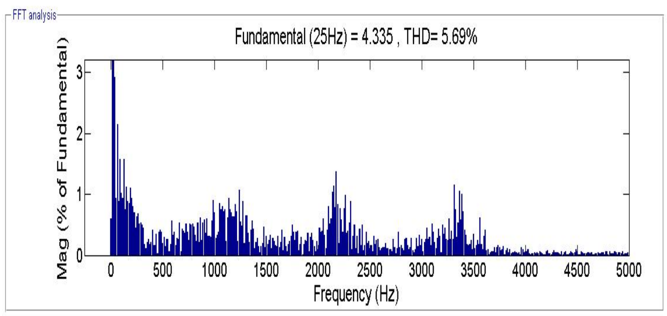


Fig.16: FFT analysis of the conventional method (THD=5.69%).

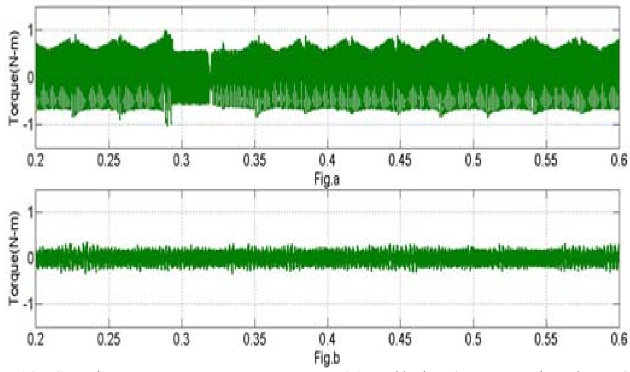


Fig.13: Steady state Torque response at 20 rad/s in a) conventional DTC method. b) Proposed method.

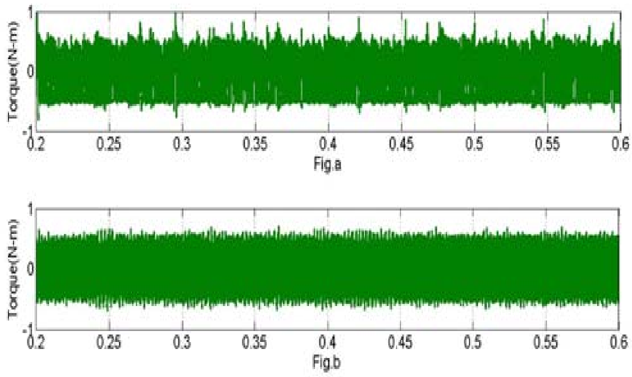


Fig.14: Steady state Torque response at 80 rad/s in a) conventional DTC method. b) Proposed method.

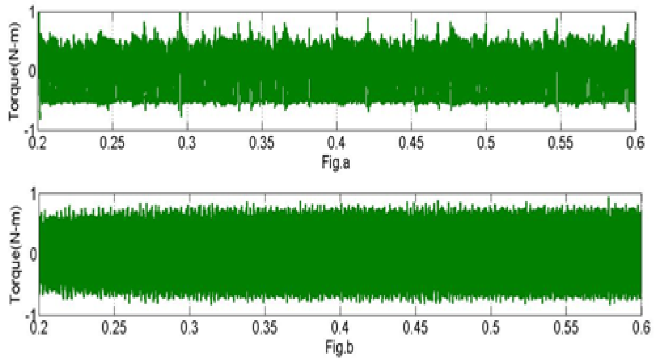


Fig.15: Steady state Torque response at 160 rad/s in a) conventional DTC method. b) Proposed method.

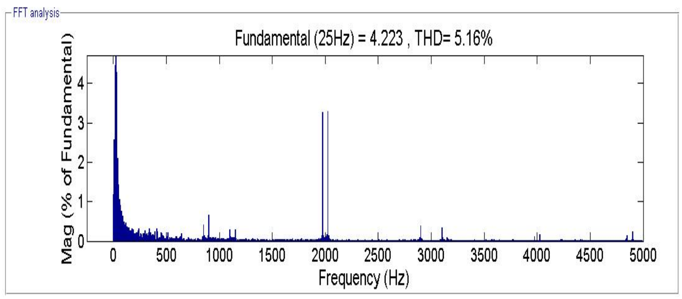
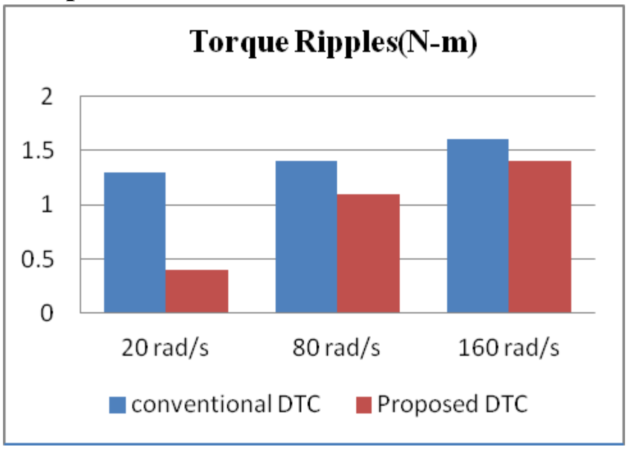
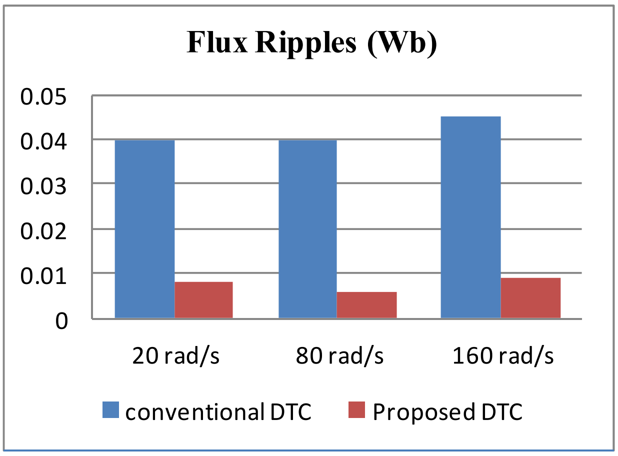


Fig.17: FFT analysis of the proposed method (THD=5.16%).

Comparison:





C. Discussion of Results

At lower speeds in the conventional method, as the null vector time period is increased, more ripples are encountered. Whereas in the proposed method, as the operating frequency is less at low speed, the effective time period of the voltage vector is more and less ripples are observed. As the harmonic content appears across the fundamental component in the form of its side bands, the switching frequency is constant in the proposed method. In speed reversal operation, flux drooping characteristic in conventional method is no longer observed in the proposed method. Also the nature of stator currents approaches towards pure sinusoidal in the proposed method. On the application of load torque, it can be observed that the speed droops and the stator current increases in both the methods in order to meet the load requirements. By the usage of PI controllers in flux and torque ripples, the transient period, overshoots and steady state errors can be altered.

III. CONCLUSIONS

It has been observed that the ripples in torque and flux have been reduced by the proposed algorithm. Inverter switching frequency is constant for all conditions; the harmonics are accumulated near the integral multiples of fundamental as side bands, thereby reducing overall harmonics. At lower operating speeds, the steady state error is low, which increases as the speed increases, but is eventually less than the conventional DTC method. Advantages of the proposed method are- reduced torque ripples, lower flux droops, constant switching frequency, lower THD, etc. Whereas this method suffers from high flux ripples at higher speeds, compared with lower speeds for the same proposed method. If the switching frequency increases, switching losses thus increases.

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