SIMPLIFIED AND INNOVATIVE HYBRID RANDOM PWM ALGORITHM FOR DTC-INDUCTION MOTOR DRIVE FOR REDUCED NOISE

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Abstract: *A simple and novel hybrid random PWM algorithm for direct torque controlled induction motor drive for reduced noise and harmonic distortion is presented in this paper to reduce the complexity of the classical space vector approach, the proposed algorithm is developed by using the imaginary switching times, which does not require angle and sector information. In order to get the randomization effect, the proposed algorithm uses DPWMMAX algorithm in conjunction with the SVPWM algorithm. The harmonic analysis of the two switching sequences is carried out and by comparing each other in each sampling time interval, the proposed algorithm selects a suitable switching sequence that results in reduced harmonic distortion. In the proposed algorithm by changing the factor* μ *, which is proportional to the time duration of zero voltage vector* V_0 *(000) the switching sequences of SVPWM and DPWMMIN algorithms are generated. As the zero state time is varied randomly according to the operating sequence, randomization effect will occur, which results in reduced dominating harmonics and hence gives reduced acoustical noise. To validate the proposed PWM algorithm, the numerical simulation studies have been carried out and results are presented and compared. The simulation results confirm the effectiveness of the proposed algorithm.*

Key words: *DTC, imaginary switching times, random PWM, stator flux ripple, SVPWM*

1. Introduction

Research interest on induction motor drives using sensorless drives [1] has grown significantly over the past few years due to some of their advantages, such as mechanical robustness, simple construction, and maintenance. The important issue for a sensorless drive is the flux, torque, and speed estimation [2]. After the invention of field oriented control (FOC) [3] algorithm, the induction motor drives are becoming popular in many industrial applications. But, the FOC is more complex due to the usage of reference frame transformation. To reduce the complexity of FOC, a simple control technique known as direct torque control (DTC) is invented by Takahashi in 1980s [4]. Though the operating principles of FOC and DTC are different, both techniques give effective control of flux and torque. These two control strategies have been implemented in many industrial applications successfully. The detailed comparison between FOC and DTC is given in [5]. Due to the absence of reference frame transformations, DTC is simple when compared with the FOC. Though DTC gives superior torque performance, it gives variable switching frequency of the inverter and large steady state ripple in torque, current and flux.

To improve the torque and current ripple, several pulsewidth modulation (PWM) algorithms have been developed by several researchers. A detailed survey of these PWM algorithms is given in [6]. These PWM algorithms can be classified into two categories such as triangular comparison approach and space vector approach. However, the space vector approach is more popular as it offers more advantages when compared with the triangular comparison approach [7]-[8]. Hence, the space vector PWM (SVPWM) algorithm is attracting many researchers nowadays. Though the SVPWM algorithm based DTC gives reduced harmonic distortion when compared with the conventional DTC, it gives dominating harmonics around the switching frequency. Hence, the acoustical noise of the motor is more. To reduce the acoustical noise of the drive, recently, random PWM (RPWM) algorithms are becoming popular. Various type of RPWM algorithms have been discussed in [9]-[12]. The RPWM algorithms randomize the pulse pattern or switching frequency by using a random number generator.

The standard SVPWM algorithm distributes the zero state time equally among the two possible zero voltage vectors. By utilizing the freedom in zero state time distribution various PWM algorithms can be generated as explained in [13]-[21]. In many applications an efficient PWM algorithm is required, which gives less harmonic distortion and acoustical noise. Hence, in recent years many researchers have been concentrated on the harmonic analysis of PWM algorithms. To calculate the harmonic analysis of the algorithms a time domain analysis has been given in [13]-[18], [20]-[22] by using the notion of stator flux ripple and current ripple. However, the PWM algorithms, which are discussed so far, use the angle and sector information, which increase the complexity involved in the algorithm. To reduce the complexity, a novel approach is presented in [19]-[21] by using the concept of imaginary switching times.

This paper presents a simplified hybrid random PWM algorithm, which uses two switching sequences and selects one sequence in each sampling time period that results in reduced harmonic distortion.

2. Proposed switching sequences

To reduce the complexity involved in the SVPWM, the proposed switching sequences are developed by using the concept imaginary switching times. The imaginary switching times are proportional to the instantaneous values of the sampled reference phase voltages. These can be calculated as.

$$T_{an} = \frac{T_s}{V_{dc}} V_{an} \; ; T_{bn} = \frac{T_s}{V_{dc}} V_{bn} \; ; T_{cn} = \frac{T_s}{V_{dc}} V_{cn} \qquad (1)$$

To calculate the switching times of the active and zero voltage vectors, in every sampling time period maximum ($Max(T_{an}, T_{bn}, T_{cn})$), minimum ($Min(T_{an}, T_{bn}, T_{cn})$) and middle values ($Mid(T_{an}, T_{bn}, T_{cn})$) of imaginary switching times are evaluated. Then the active voltage vector and zero voltage vector switching times can be given as in (2)-(4). [18]

$$T_1 = T_{\max} - T_{mid} \qquad (2)$$

$$T_2 = T_{mid} - T_{\min} \qquad (3)$$

$$T_z = T_s - T_1 - T_2 \qquad (4)$$

Thus, the active state and zero state times can be calculated in a simple by using imaginary switching times.

However, the SVPWM algorithm distributes the zero state time equally in every sampling time period. By utilizing the unequal distribution of zero voltage vector switching times, various PWM algorithms can be generated. To generate the proposed switching sequences, the zero state time durations can be modified as $T_0 = \mu T_z$ for V_0 voltage vector and $T_7 = (1-\mu)T_z$ for V_7 voltage vector. By varying the μ value between 0 and 1, various PWM algorithms can be generated. The SVPWM and DPWMMAX algorithms can be generated for μ=0.5 and 0 respectively. These algorithms use 0127-7210 and 721-127 sequences in the first sector and so on. In each sampling time interval, the SVPWM algorithm has three number of switchings and whereas for the DPWMMAX algorithm is two. Hence, to get the same average switching frequency of the inverter, a sampling time interval is taken as $T_s = T$ for the SVPWM algorithm, while $T_s = (2T/3)$ for the DPWMMAX algorithm.

3. Proposed hybrid RPWM algorithm

3.1 Analysis of harmonic Distortion

The total harmonic distortion (THD) of the line current is a widely used measure for the quality of current waveform. The quality of the line current waveform can be directly determined in time domain by integrating the ripple voltages. This method of analysis can be applied for any PWM switching sequences. In the space vector approach, the reference voltage vector is constructed in an average manner but not in an instantaneous manner. The actual value of the stator voltage differs from the applied voltage. Hence, there is always an instantaneous error voltage vector. The error voltage vector is defined as given in (6)

$$V_{rip} = V_k - V_{ref}, k = 0, 1, ...7 \qquad (5)$$

where 'k' is the k^{th} voltage vector. The active voltage vectors (V_1,V_2,..V_6) can be defined as

$V_k = \frac{2}{3} V_{dc} e^{j(k-1)\frac{\pi}{3}}$.

The trajectory of the stator flux ripple vector tip is along the direction of the ripple voltage vector as stator flux ripple vector is time integral of voltage ripple vector. The ripple voltage vectors and trajectory of the stator flux ripple can be represented in a complex plane as shown in Fig. 1.

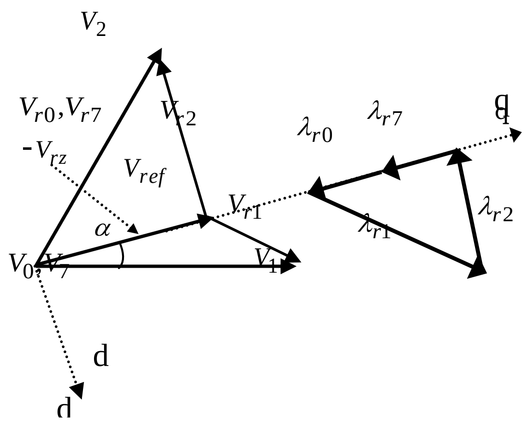

Fig. 1 Ripple voltage vectors and trajectory of stator flux ripple

The stator flux ripple vectors corresponding to the voltage ripple vectors are given by [19]

$$\lambda_{r1} = \left(\frac{2}{3} V_{dc} \sin\alpha\right) T_1 + j\left(\frac{2}{3} V_{dc} \cos\alpha - V_{ref}\right) T_1 \quad (6)$$

$$\lambda_{r2} = -\left(\frac{2}{3} V_{dc} \sin\left(60^o - \alpha\right)\right) T_2 + j\left(\frac{2}{3} V_{dc} \cos\left(60^o - \alpha\right) - V_{ref}\right) T_2 \quad (7)$$

$$\lambda_{r0} = -jV_{ref} T_0 \quad (8)$$

$$\lambda_{r7} = -jV_{ref} T_7 \quad (9)$$

The above stator flux ripple vectors are normalized to $\lambda_b = \frac{2V_{dc}}{\pi}$ for further simplification. The final flux ripple vectors expressions can be obtained in terms of imaginary switching times and modulation index as given in (10) – (13).

$$\lambda_{r1} = \frac{\pi^2}{6\sqrt{3} M_i} \frac{T_1 T_2}{T_s} + j\left(\frac{\pi^2 (2T_1^2 + T_1 T_2)}{18 M_i T_s} - M_i T_1\right) \quad (10)$$

$$\lambda_{r2} = -\frac{\pi^2}{6\sqrt{3} M_i} \frac{T_1 T_2}{T_s} + j\left(\frac{\pi^2 (2T_2^2 + T_1 T_2)}{18 M_i T_s} - M_i T_2\right) \quad (11)$$

$$\lambda_{r0} = -jM_i T_0 \quad (12)$$

$$\lambda_{r7} = -jM_i T_7 \quad (13)$$

Then the rms stator flux ripple over a sampling time period can be calculated as

$$\lambda^2_{(rms)} = \frac{1}{T_s} \int_0^{T_s} \lambda_r^2 dt = \frac{1}{3T_s}\left(\lambda_{11}^2 + \lambda_{12}^2 + \lambda_{13}^2\right) \quad (14)$$

where

$$\lambda_{11}^2 = \frac{\pi^4}{91\left(M_i T_s\right)^2}\left(T_1^5 + 2T_1^3 T_2^2 + 2T_1^4 T_2 + T_1^2 T_2^3\right) \quad (15)$$

$$\lambda_{12}^2 = \frac{\pi^2}{18T_s}\begin{Bmatrix} 4T_1^4 + 6T_1^3 (T_0 + T_2) \\ -2T_1 T_2 (T_1 T_7 - T_1 T_2 - T_0 T_2) \\ +7T_0 T_1^2 T_2 - T_1 T_{21}^2 T_7 \end{Bmatrix} \quad (16)$$

$$\lambda_{13}^2 = M_i^2 \begin{Bmatrix} (T_0 + T_1)^3 + T_7^3 + T_2 (T_0^2 + T_1^2) \\ +2T_0 T_1 T_2 - T_2 T_7 (T_0 + T_1) \end{Bmatrix} \quad (17)$$

By employing (14), the modulation index and angle dependent mean square stator flux ripple of SVPWM and various discontinuous PWM algorithms can be easily computed.

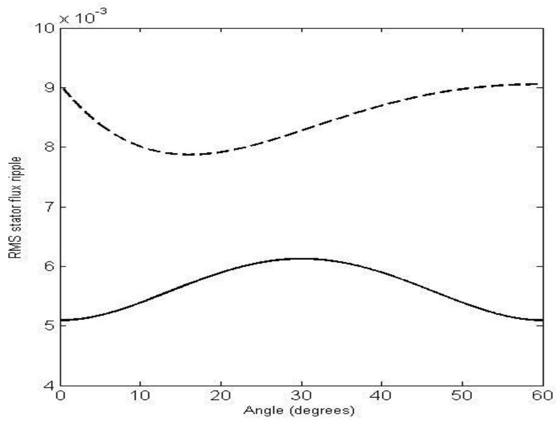

Fig.2. Variation of RMS stator flux ripple for SVPWM (continuous line) and DPWMMIN (dashed line) algorithms over the first sector at $M_i = 0.4$

3.2 Proposed Hybrid RPWM Algorithm

The proposed HRPWM algorithm uses SVPWM and DPWMMIN algorithms. By comparing the RMS stator flux ripple of these two algorithms in each sampling time period, boundary between these two algorithms can be found as shown in Fig.3. from which, it can be observed that the SVPWM algorithm gives superior performance at lower modulation indices and DPWMMIN gives less harmonic distortion at higher modulation indices. Hence, the proposed HRPWM algorithm selects a suitable sequence between the SVPWM and DPWMMIN algorithms that results in less THD in each sampling time period. Thus, the HRPWM algorithm reduces THD and also gives randomization of zero state based on the modulation index.

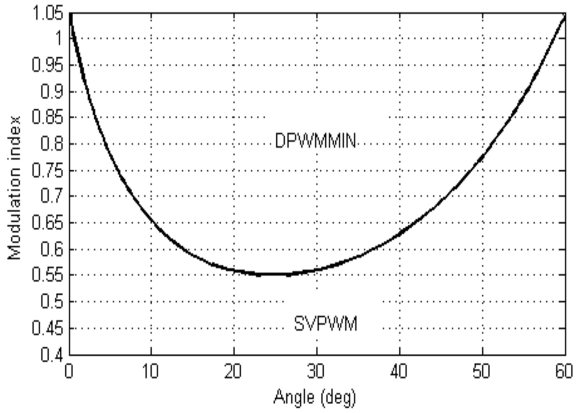

Fig.3. Boundary between RMS flux ripple of SVPWM and DPWMMIN algorithms

4. Proposed Hybrid RPWM Based DTC

The block diagram of the proposed hybrid RPWM algorithm based DTC is as shown in Fig.4. The reference voltage space vector can be constructed in many ways. But, to reduce the complexity of the algorithm, the required reference voltage vector, to control the torque and flux cycle-by-cycle basis is constructed by using the errors between the reference d-axis and q-axis stator fluxes and d-axis and q-axis estimated stator fluxes sampled from the previous cycle. In the proposed method, the d-axis and q-axis components of the reference voltage vector can be obtained as follows: Reference values of the d-axis and q- axis stator fluxes and actual values of the d-axis and q-axis stator fluxes are compared in the reference voltage vector calculator block and hence the errors in the d-axis and q-axis stator flux vectors are obtained as in (18)-(19).

$$\Delta\psi_{ds} = \psi_{ds}^{*} - \psi_{ds} \tag{18}$$

$$\Delta\psi_{qs} = \psi_{qs}^{*} - \psi_{qs} \tag{19}$$

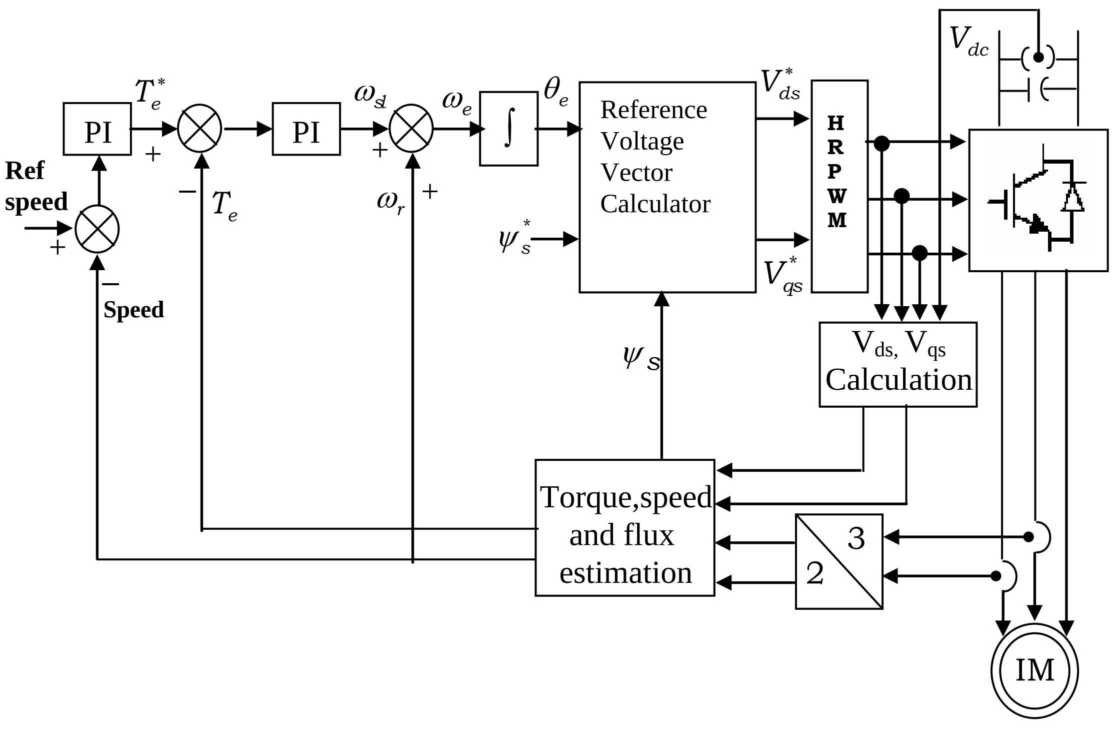

Fig. 4 Block diagram of proposed RPWM based DTC

The knowledge of flux error and stator ohmic drop allows the determination of appropriate reference voltage space vectors as given in (20)-(21).

$$V_{ds}^{*} = R_s i_{ds} + \frac{\Delta\psi_{ds}}{T_s} \tag{20}$$

$$V_{qs}^{*} = R_s i_{qs} + \frac{\Delta\psi_{qs}}{T_s} \tag{21}$$

where, T_s is the duration of subcycle or sampling period and it is a half of period of the switching frequency. These d-q components of the reference voltage vector are fed to the HRPWM block. In HRPWM block, these two-phase voltages then converter into three-phase voltages. Then, the switching times are calculated.

5. Simulation results and discussion

To verify the proposed hybrid RPWM algorithm, the

numerical simulation studies have been carried out using MATLAB. For the simulation studies, the average switching frequency of the inverter is taken as 5 kHz. The induction motor used in this case study is a 4 kW, 400V, 1470 rpm, 4-pole, 50 Hz, 3-phase induction motor having the following parameters:
R_s= 1.57Ω, R_r = 1.21Ω, L_s = 0.17H, L_r = 0.17H, L_m = 0.165 H and J = 0.089 Kg.m^2.

The plot of conventional DTC method and corresponding line current harmonic spectra is shown in Fig.5-Fig7 from which it can be observed that the conventional DTC gives large ripple in torque, flux and current. Moreover, the harmonic distortion is also high. To overcome these drawbacks, SVPWM algorithm is used for DTC. The corresponding plots of SVPWM algorithm based DTC and the harmonic spectra of line current are given in Fig.8 Fig 10. From the harmonic spectra, it can be observed that the SVPWM algorithm gives considerable amplitude of dominating harmonics around switching frequency. Hence, the SVPWM algorithm gives more noise/electromagnetic interference. Hence, to reduce the noise and harmonic distortion, a simplified hybrid RPWM algorithm is proposed in this paper. The simulation results at various conditions such as starting, steady state, step change in load change and speed reversal for proposed hybrid RPWM algorithm based DTC are shown from Fig. 11 to Fig. 16. From the simulation results, it can be observed that the proposed PWM algorithm gives good performance when compared with the SVPWM algorithm. Moreover, the proposed hybrid RPWM algorithm gives wide spread harmonic spectrum and gives reduced amplitudes of dominating harmonics. Hence, the proposed PWM algorithm gives reduced noise and reduced harmonic distortion when compared with the SVPWM algorithm.

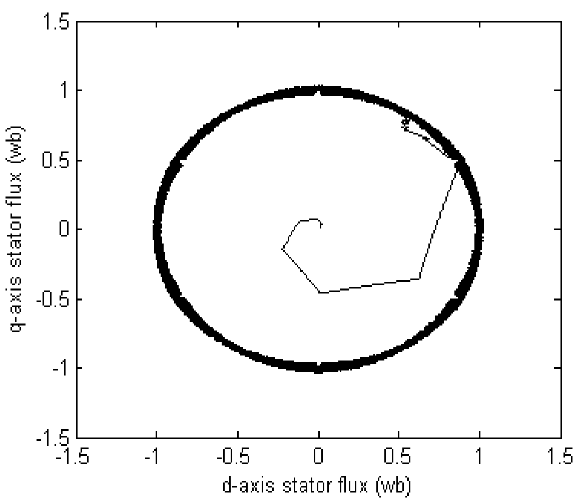

Fig.5. stator flux locus of conventional DTC

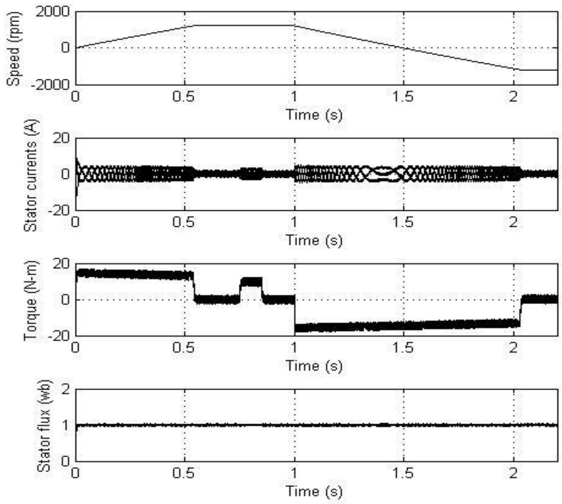

Fig. 6 starting, steady state, load change and speed reversal plots of conventional DTC

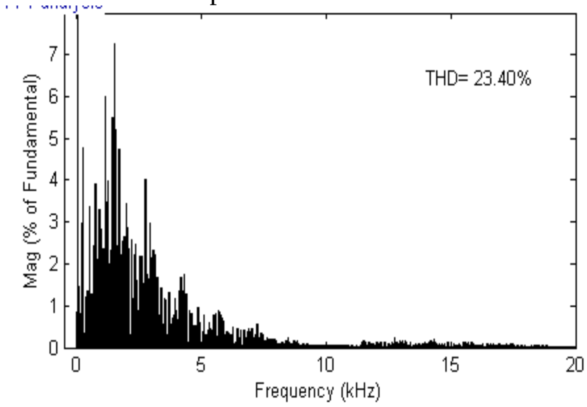

Fig. 7 harmonic spectra of line current of conventional DTC

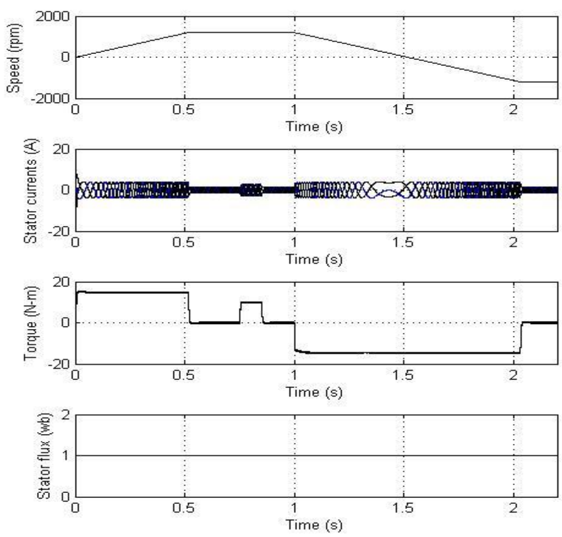

Fig. 8 starting, steady state, load change and speed reversal plots of SVPWM based DTC

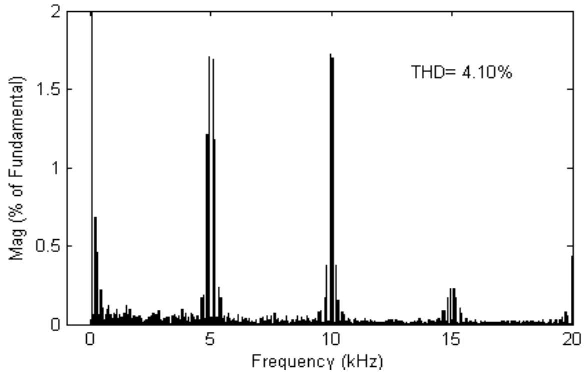

Fig. 9 harmonic spectra of line current of SVPWM based DTC

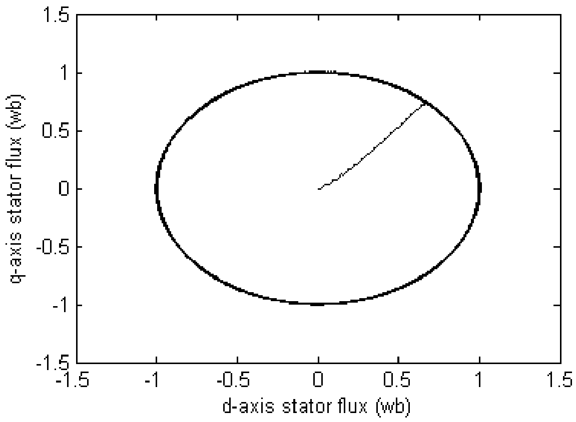

Fig.10 stator flux locus of SVPWM based DTC

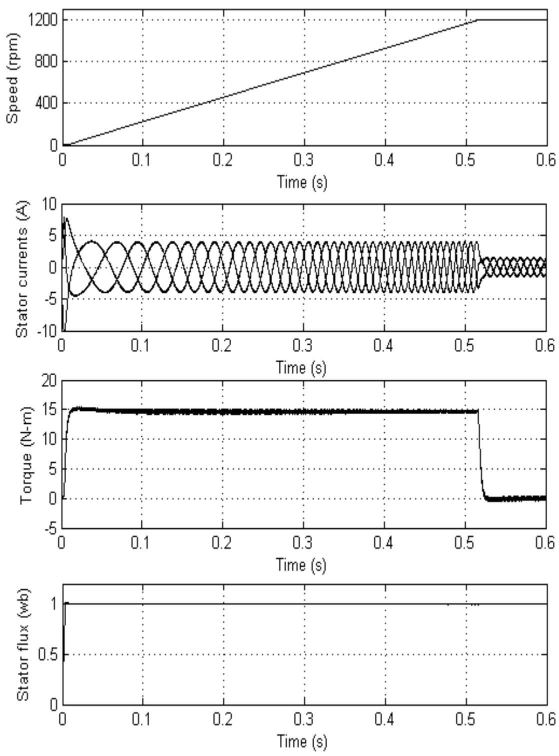

Fig. 11 starting transients proposed RPWM algorithm based DTC

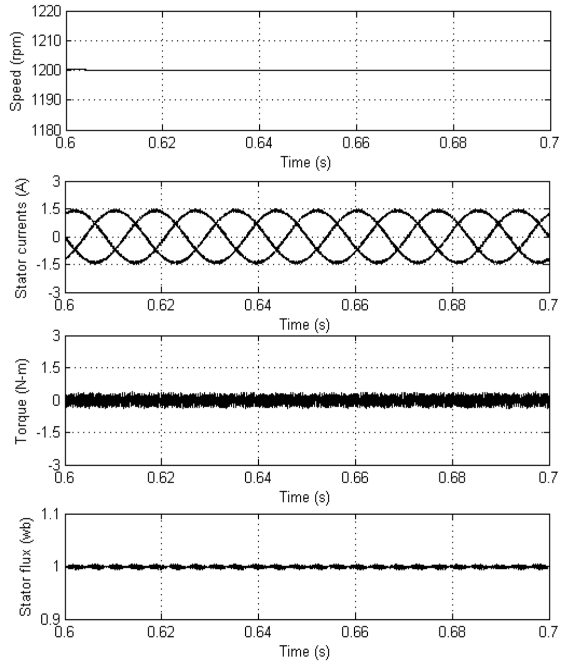

Fig.12 steady state plots of proposed RPWM algorithm based DTC

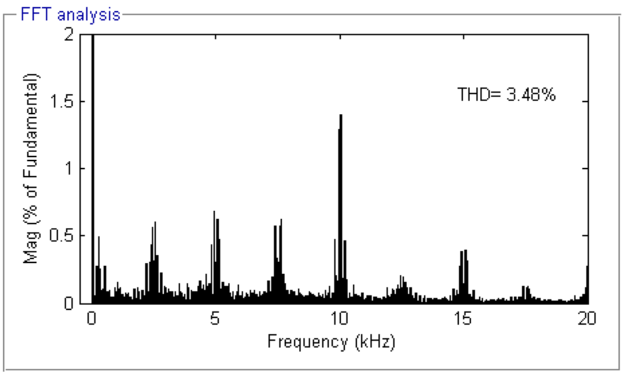

Fig. 13 harmonic spectra of line current of proposed RPWM based DTC

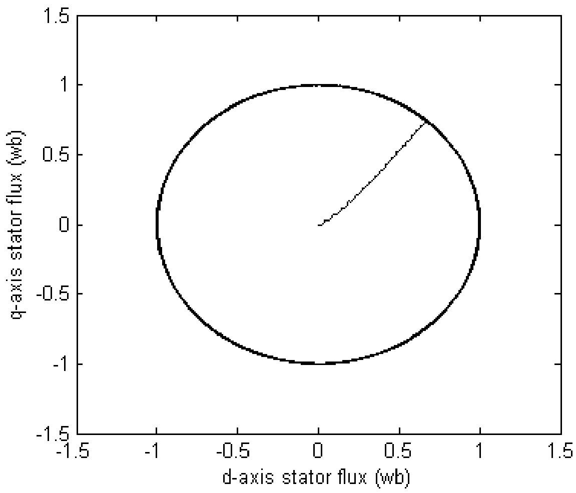

Fig.14 stator flux locus of SVPWM based DTC

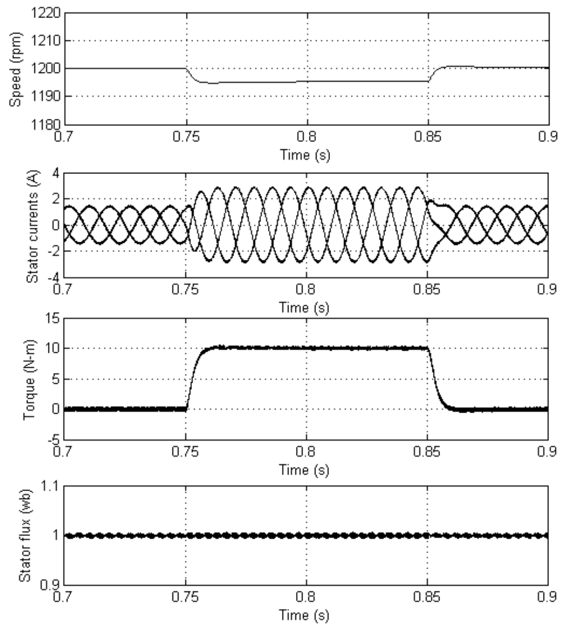

Fig. 15 Transients during step change in load for proposed RPWM based DTC (a load torque of 10 N-m is applied at 0.75s and removed at 0.85s)

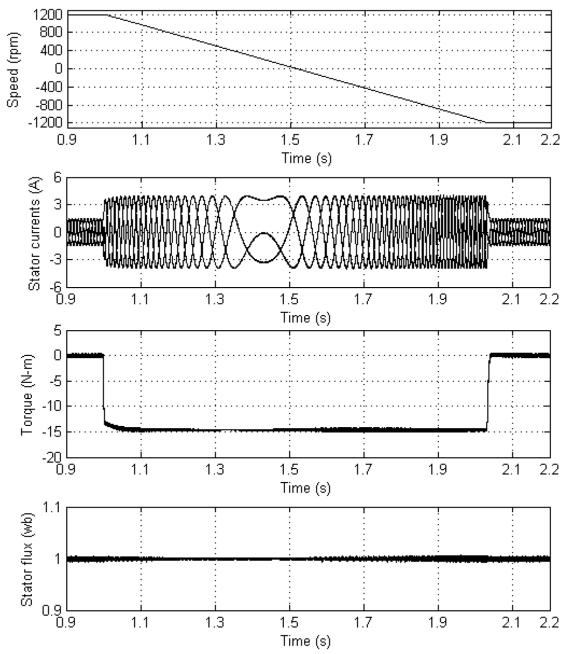

Fig. 16 Transients during speed reversal operation of proposed RPWM based DTC (a load torque of 10 N-m is applied at 0.75s and removed at 0.85s)

6. Conclusions

In earlier days to reduce the drawbacks of conventional DTC technique, SVPWM algorithm is used. As the SVPWM algorithm gives considerable dominating harmonics around switching frequency, it generates more acoustical noise and gives more harmonic distortion. Hence, to reduce the acoustical noise and harmonic distortion, a simplified hybrid RPWM algorithm is presented in this paper for direct torque controlled induction motor drive. The proposed PWM algorithm selects suitable switching sequence based on the stator flux ripple value. Thus, the proposed PWM algorithm gives randomization of zero state time. Hence, the proposed PWM algorithm gives spread spectra and gives reduced amplitude of dominating harmonics when compared with the SVPWM algorithm. The simulation results confirm the superiority of proposed PWM algorithm when compared with the SVPWM algorithm.

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