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Space Vector Based Hybrid Random PWM Algorithm for DTC-IM Drive To Achieve Superior Waveform Quality

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Abstract

This paper presents a simplified space vector based hybrid random pulsewidth modulation algorithm for direct torque controlled induction motor drive to achieve superior waveform quality and reduced acoustical noise and harmonic distortion. To reduce the complexity involved in the conventional space vector approach, the proposed pulsewidth modulation (PWM) algorithm uses instantaneous sampled reference phase voltages to calculate the actual switching times of the devices. The proposed PWM algorithm modifies the time duration of application of vector V_0 (000) by using a factor μ. By changing the value of this factor many switching sequences can be derived. The proposed PWM algorithm uses 0127, 012 and 721 switching sequences when μ value takes 0.5, 1 and 0 respectively. In order to achieve superior waveform quality, the harmonic analysis of these sequences is carried out using the notion of stator flux ripple and expressions are derived for mean square flux ripple in terms of imaginary switching times and modulation index. By comparing the instantaneous ripple values in each sampling time interval, the suitable sequence is selected that results in minimum current ripple. Thus, the proposed algorithm gives reduced harmonic distortion when compared with the SVPWM algorithm. 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 acoustical noise when compared with the SVPWM algorithm. The simulation results validate the proposed algorithm.

Key Words: DTC, hybrid RPWM, RPWM, stator flux ripple, SVPWM

1. Introduction

The variable speed drives are finding increasing acceptance in various industrial applications. Nowadays the induction motor drives are attracting many researchers in variable speed drive applications due to their simple and robust construction. The invention of field oriented control (FOC) has brought renaissance in high-performance variable speed applications, due to which the induction motor drives are becoming popular in many industrial applications. Though FOC gives good transient response, it involves more complexity due to reference frame transformations. To reduce the complexity of FOC, a simple control technique known as direct torque control (DTC) is invented by Takahashi in 1980s [2]. 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 [3]. 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 performance of the DTC drive, PWM algorithms have been developed by several researchers. A detailed survey of these PWM algorithms is given in [4]. 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 [5]-[6]. 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 [7]-[11]. The basic principle of the RPWM algorithms is randomization of harmonic spectra by randomizing the pulse pattern or by randomizing the switching frequency. However, the fixed switching frequency RPWM algorithms offer more advantages. The RPWM algorithms randomize the pulse pattern or switching frequency by using a random number generator.

The standard SVPWM algorithm uses equal distribution of zero stat time duration 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 [12]-[22]. Large number of applications requires an efficient PWM algorithm, which gives less total harmonic distortion (THD) in order to reduce acoustical noise and incorrect speed estimations. Hence, in recent years many researchers have been concentrated on the harmonic analysis of PWM algorithms. To calculate the harmonic analysis of the various PWM algorithms a time domain analysis has been given in [12]-[19], [21]-[22] by using the notion of either current ripple or stator flux 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 [20]-[22] by using the concept of imaginary switching times.

This paper presents a simplified space vector based hybrid random PWM algorithm for induction motor drives to achieve superior waveform quality. It uses three switching sequences and selects one sequence in each sampling time period that results in reduced THD.

2. Generation of Proposed Switching Sequences

As the conventional space vector approach uses angle and sector information for the calculation of gating times of the inverter, the complexity involved is more. Hence, to reduce the complexity the proposed switching sequences are developed by using the concept of imaginary switching times, which are proportional to the instantaneous values of sampled reference phase voltages. The imaginary switching times can be calculated as.

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

When the phase voltages are taking negative values, the time values are also negative. Hence, in this paper the times, which are proportional to the phase voltages, are termed as imaginary switching times. To calculate the actual gating times of the inverter, 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 actual active voltage vector and zero voltage vector switching times can be given as in (2)-(4). [21]

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

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

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

Thus, the active and zero state times can be calculated without using the angle and sector information. However, the standard SVPWM algorithm distributes the zero state time equally among two possible zero voltage vectors V_0 (000) and V_7 (111) in each sampling time interval.

By utilizing the unequal distribution of zero state time, various PWM algorithms can be generated [12]-[13]. 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, DPWMMIN and DPWMMAX algorithms can be generated for μ =0.5, 1 and 0 respectively. The possible switching sequences of these PWM algorithms in each sector are given in Table. 1.

Table 1: Switching sequences in all sectors

Sector	SVPWM	DPWMMIN	DPWMMAX
I	0127-7210	012-210	721-127
II	0327-7230	032-230	723-327
III	0347-7430	034-430	743-347
IV	0547-7450	054-450	745-547
V	0567-7650	056-650	765-567
VI	0167-7610	016-610	761-167

In each sampling time interval, the number of switchings of the SVPWM algorithm is three and for remaining algorithms 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 DPWMMIN and DPWMMAX algorithms.

3. Analysis of Harmonic Distortion Using Notion of Stator Flux Ripple

The total harmonic distortion (THD) of the line current (I_{THD}) is a measure for the quality of waveform and is defined as

$$I_{THD} = \frac{I}{I_1}\sqrt{\sum_{n\neq 1} I_n^2} \tag{5}$$

where, I_1 and I_n are the rms values of the fundamental and the nth harmonic components of the no-load current respectively. Alternatively, the quality of the line current can be determined in time domain by integrating the ripple voltages. In the space vector approach, the required reference voltage vector is constructed in the average manner but not in an instantaneous manner. When the voltage vector is applied to the motor, the current is flowing in the stator winding of the induction motor. The actual value of the stator voltage differs from the applied voltage. Hence, there is always an instantaneous error voltage vector, which is also known as ripple voltage vectors. The error voltage vector is defined as given in (6)

$$V_{rip} = V_k - V_{ref}\,, k = 0,1,\ldots 7 \tag{6}$$

where 'k' is the k^{th} voltage vector. The active voltage vectors (V_1, V_2, .. V_6) can be defined as $V_k = \frac{2}{3}V_{dc}e^{j(k-1)\frac{\pi}{3}}$.

Then the stator flux ripple vector can be defined as in (7).

$$\lambda_{rip} = \int_0^t V_{rip}\,dt \tag{7}$$

The ripple voltage vectors and trajectory of the stator flux ripple can be represented in a complex plane as shown in Fig. 1.

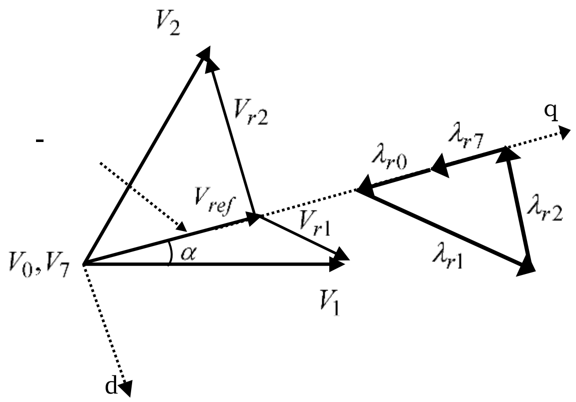

Fig. 1 Ripple voltage vectors and trajectory of the stator flux ripple

The stator flux ripple vectors corresponding to the ripple voltage vectors are given by [22]

$$\lambda_{r1} = \left(\frac{2}{3}V_{dc}\sin\alpha\right)T_1 + j\left(\frac{2}{3}V_{dc}\cos\alpha - V_{ref}\right)T_1 \tag{8}$$

$$\lambda_{r2} = -\left(\frac{2}{3}V_{dc}\sin\left(60^o - \alpha\right)\right)T_2 + j\left(\frac{2}{3}V_{dc}\cos\left(60^o - \alpha\right) - V_{ref}\right)T_2 \tag{9}$$

$$\lambda_{r0} = -jV_{ref}T_0 \tag{10}$$

$$\lambda_{r7} = -jV_{ref}T_7 \tag{11}$$

The above stator flux ripple vectors are normalized to $\lambda_b = \frac{2V_{dc}}{\pi}$ for further simplification. The final expressions of stator flux ripple vectors can be obtained in terms of imaginary switching times and modulation index as given in (12) – (15).

$$\lambda_{r1} = \frac{\pi^2}{6\sqrt{3}M_i}\frac{T_1T_2}{T_s} + j\left(\frac{\pi^2(2T_1^2 + T_1T_2)}{18M_iT_s} - M_iT_1\right) \tag{12}$$

$$\lambda_{r2} = -\frac{\pi^2}{6\sqrt{3}M_i}\frac{T_1T_2}{T_s} + j\left(\frac{\pi^2(2T_2^2 + T_1T_2)}{18M_iT_s} - M_iT_2\right) \tag{13}$$

$$\lambda_{r0} = -jM_iT_0 \tag{14}$$

$$\lambda_{r7} = -jM_i T_7 \tag{15}$$

The mean square stator flux ripple over a sampling time interval can be calculated by using (16).

$$\lambda^2_{(\mathrm{rms})} = \frac{1}{T_s}\int_0^{T_s} \lambda_r^2 dt = \frac{1}{3T_s}\left(\lambda_{11}^2 + \lambda_{12}^2 + \lambda_{13}^2\right) \tag{16}$$

$$\lambda_{11}^2 = \frac{\pi^4}{91(M_i T_s)^2}\left(T_1^5 + 2T_1^3T_2^2 + 2T_1^4T_2 + T_1^2T_2^3\right) \tag{17}$$

$$\lambda_{12}^2 = \frac{\pi^2}{18T_s}\left\{4T_1^4 + 6T_1^3(T_0+T_2) - 2T_1T_2(T_1T_7 - T_1T_2 - T_0T_2) + 7T_0T_1^2T_2 - T_1T_{21}^2T_7\right\} \tag{18}$$

$$\lambda_{13}^2 = M_i^2\left\{(T_0+T_1)^3 + T_7^3 + T_2(T_0^2 + T_1^2) + 2T_0T_1T_2 - T_2T_7(T_0+T_1)\right\} \tag{19}$$

By employing (16), the modulation index and angle dependent mean square stator flux ripple of SVPWM, DPWMMIN and DPWMMAX algorithms can be easily computed and graphically illustrated as shown in Fig. 2 – Fig. 4.

Figs. 2-4 compare the mean square stator flux ripple values of SVPWM, DPWMMIN and DPWMMAX algorithms for different modulation indices. From Fig.2- 4, it can be observed that replacing α by $(60^o - \alpha)$ in the rms stator flux ripple expressions of SVPWM does not change its value. Thus for a given sampling time and V_{ref}, SVPWM algorithm produces equal mean square stator flux ripple at spatial angles α and $(60^o - \alpha)$. However, the rms ripple over a subcycle is not symmetric about the center of the sector for the DPWMMIN and DPWMMAX algorithms. Swapping of T_1 and T_2, in the mean square stator flux ripple expression of DPWMMIN algorithm leads to the rms stator flux ripple expression of DPWMMAX algorithm. Thus, for a given V_{ref} and T_s, these can be given as follows:

$$\begin{aligned}\lambda^2_{(rms)CSVPWM}(\alpha) &= \lambda^2_{(rms)CSVPWM}(60^o - \alpha)\\ \lambda^2_{(rms)DPWMIN}(\alpha) &= \lambda^2_{(rms)DPWMMAX}(60^o - \alpha)\end{aligned} \tag{20}$$

Also, from Fig. 2-4, it can be observed that, DPWMMIN algorithm leads to less rms ripple than DPWMMAX algorithm in the first half of sector-I. Conversely, DPWMMAX algorithm leads to less rms ripple than DPWMMIN algorithm in the second half of sector-I as given in (21).

$$\begin{aligned}\lambda^2_{(rms)DPWMIN}(\alpha) &< \lambda^2_{(rms)DPWMMAX}(\alpha) \text{ if } 0^o < \alpha < 30^o\\ \lambda^2_{(rms)DPWMIN}(\alpha) &> \lambda^2_{(rms)DPWMMAX}(\alpha) \text{ if } 30^o < \alpha < 60^o\end{aligned} \tag{21}$$

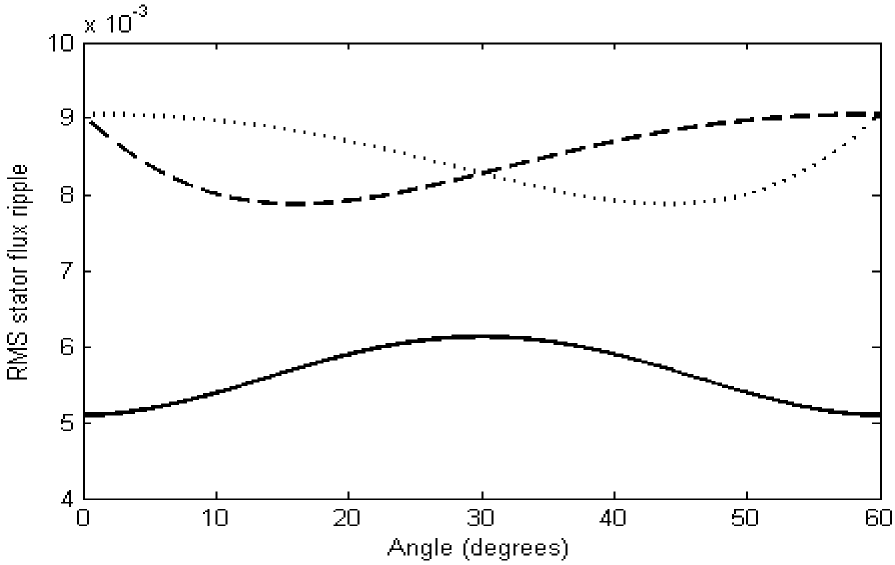

Fig. 2 Variation of stator flux ripple for SVPWM (continuous line), DPWMMIN (dashed line) and DPWMMAX (dotted line) algorithms over the first sector at $M_i = 0.4$

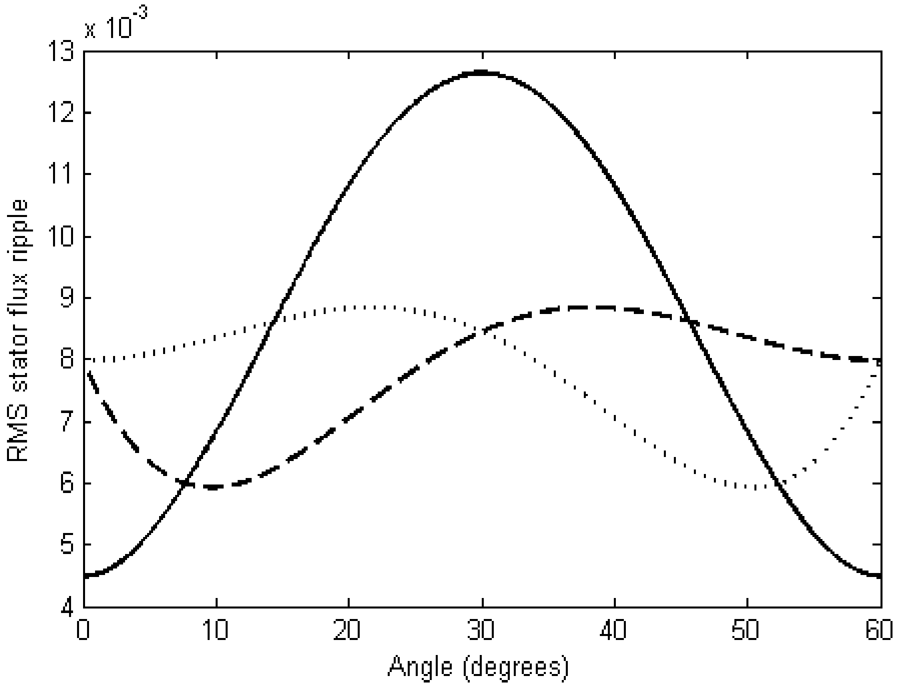

Fig. 3 Variation of stator flux ripple for SVPWM (continuous line), DPWMMIN (dashed line) and DPWMMAX (dotted line) algorithms over the first sector at $M_i = 0.7$

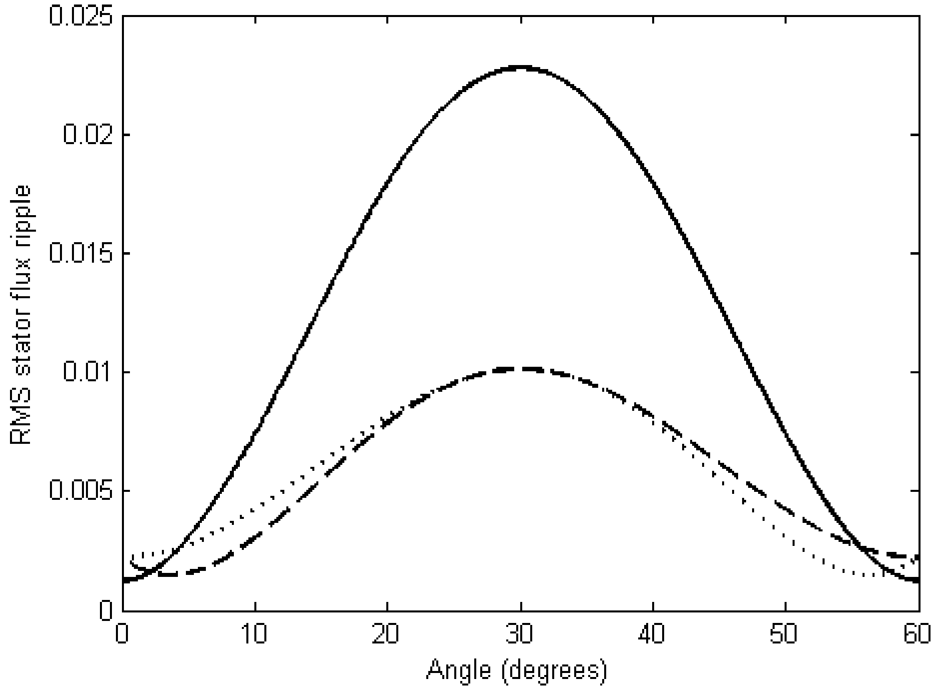

Fig. 4 Variation of stator flux ripple for SVPWM (continuous line), DPWMMIN (dashed line) and DPWMMAX (dotted line) algorithms over the first sector at $M_i = 0.906$

Moreover, from Fig. 2 – Fig. 4, it can be concluded that the SVPWM algorithm has lower harmonic distortion than DPWMMIN and DPWMMAX algorithms, and the difference is more pronounced at low modulation index. The boundary between various PWM algorithms is shown in Fig. 5 – Fig. 7. The overall comparison indicates SVPWM provides superior performance in the low modulation range, however, as modulation index increases, the performance of DPWMMIN and DPWMMAX methods significantly improve and become comparable to SVPWM.

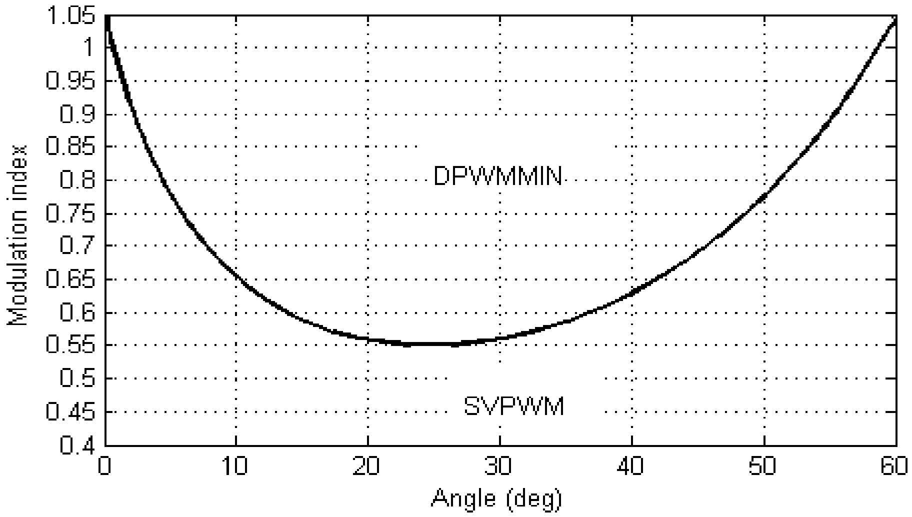

Fig. 5 Boundary between RMS flux ripple of SVPWM and DPWMMIN algorithms

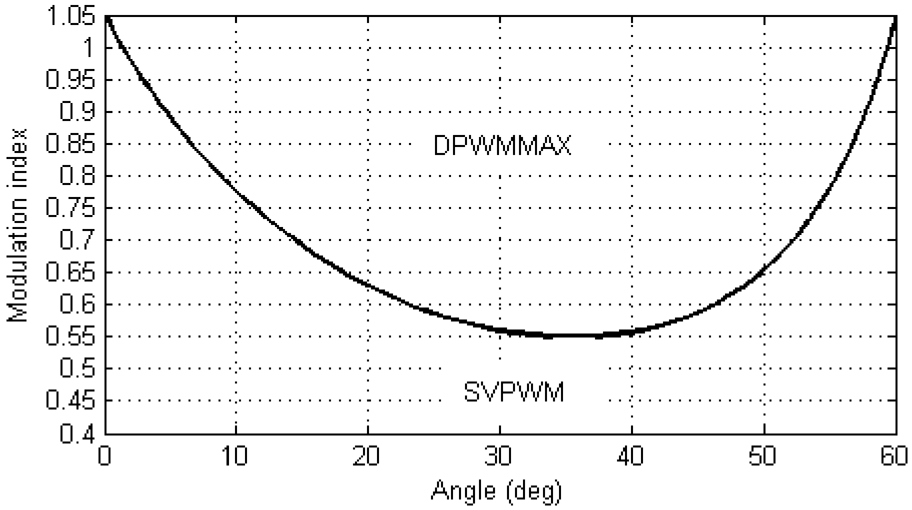

Fig. 6 Boundary between RMS flux ripple of SVPWM and DPWMMAX algorithms

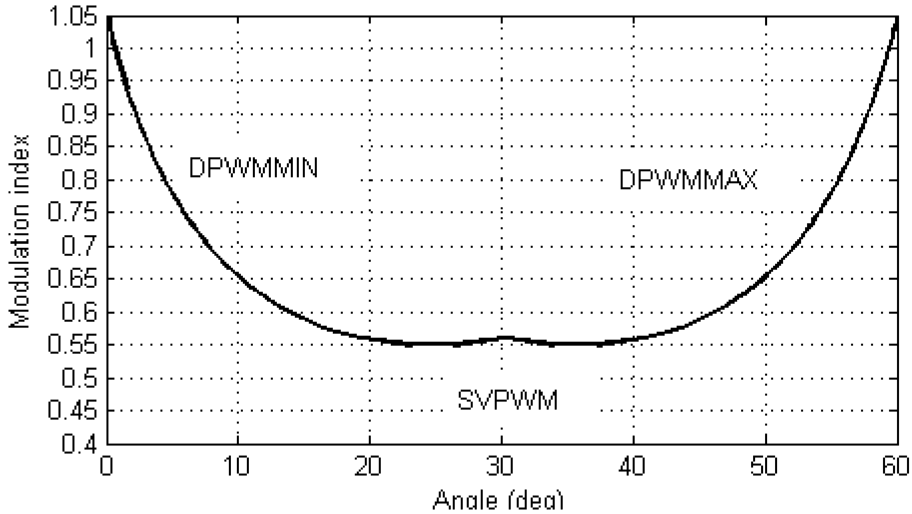

Fig. 7 Boundary between RMS flux ripple of SVPWM, DPWMMIN and DPWMMAX algorithms

4. Proposed Hybrid PWM Algorithm

From Fig. 2 – Fig. 7, it can be observed that at lower modulation indices, the SVPWM algorithm gives superior performance whereas at higher modulation indices the DPWMMIN and DPWMMAX algorithms give superior performance. To minimize the THD of line current at all operating modulation indices, the mean square stator flux ripple over each sampling time interval should be reduced. The proposed hybrid RPWM algorithm employs the best sequence out of the three switching sequences to minimize the mean square current ripple in every sampling time period. The development of proposed PWM technique for reduced harmonic distortion involves determination of superior performance for each sequence. The zone of superior performance for a given sequence is the spatial zone within a sector where the given sequence results in less mean square stator flux ripple than the other sequence considered. In the proposed PWM algorithm, in every sampling time period the rms stator flux ripples are compared with each other and the sequence, which has less rms stator flux ripple is applied to minimize the total harmonic distortion (THD). As the proposed PWM algorithm randomize the time duration of zero state time, it gives spread spectra and gives reduced amplitude for dominating harmonics around switching frequencies. Hence, the acoustical noise of the induction motor also can be reduced. Thus, the proposed PWM algorithm uses the DPWM algorithms in conjunction with CSVPWM algorithm.

5. Proposed Hybrid RPWM Algorithm Based DTC

The block diagram of the proposed hybrid RPWM algorithm based DTC is as shown in Fig. 8.

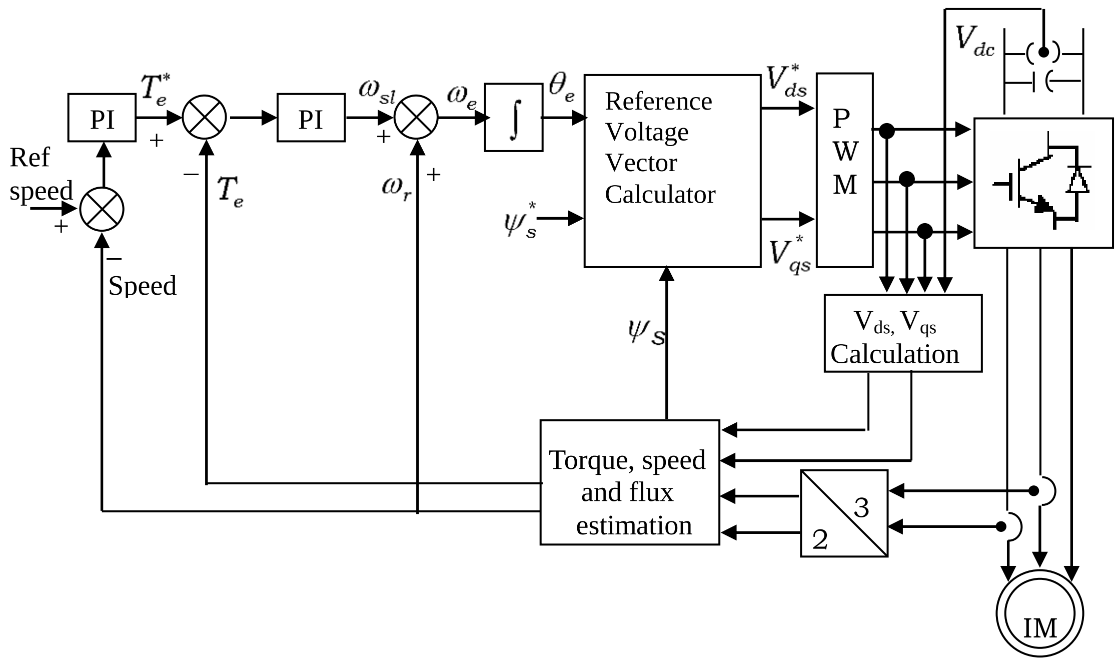

Fig. 8 Block diagram of proposed hybrid RPWM based DTC

In the proposed method, the position of the reference stator flux vector $\bar{\psi}_s^*$ is derived by the addition of slip speed and actual rotor speed. The actual synchronous speed of the stator flux vector $\bar{\psi}_s$ is calculated from the flux estimator. After each sampling interval, actual stator flux vector $\bar{\psi}_s$ is corrected by the error and it tries to attain the reference flux space vector $\bar{\psi}_s^*$. Thus the flux error is minimized in each sampling interval. 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 (22)-(23).

$$\Delta\psi_{ds} = \psi_{ds}^* - \psi_{ds} \tag{22}$$

$$\Delta\psi_{qs} = \psi_{qs}^* - \psi_{qs} \tag{23}$$

The knowledge of flux error and stator ohmic drop allows the determination of appropriate reference voltage space vectors as given in (24)-(25).

$$V_{ds}^* = R_s i_{ds} + \frac{\Delta\psi_{ds}}{T_s} \tag{24}$$

$$V_{qs}^* = R_s i_{qs} + \frac{\Delta\psi_{qs}}{T_s} \tag{25}$$

where, T_s is the duration of subcycle or sampling period and it is a half of period of the switching frequency. This implies that the torque and flux are controlled twice per switching cycle. Further, these d-q components of the reference voltage vector are fed to the PWM block. In PWM block, these two-phase voltages then converter into three-phase voltages. Then, the switching times are calculated.

6. 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 steady state plots of SVPWM algorithm based DTC are given in Fig. 9 and the harmonic spectra of line current is given in 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 acoustical noise/electromagnetic interference. Hence, to reduce the acoustical 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 acoustical noise and reduced harmonic distortion when compared with the SVPWM algorithm.

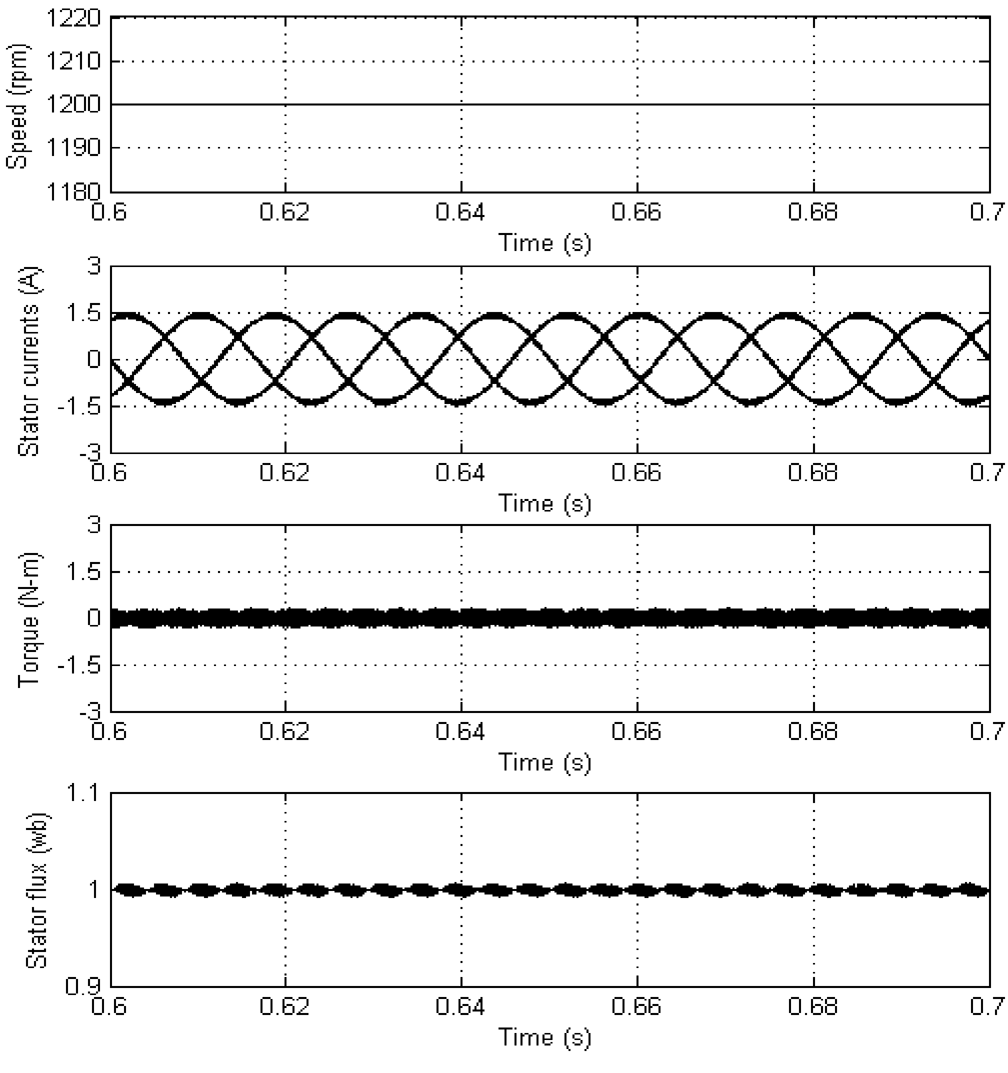

Fig. 9 steady state plots of SVPWM algorithm based DTC drive

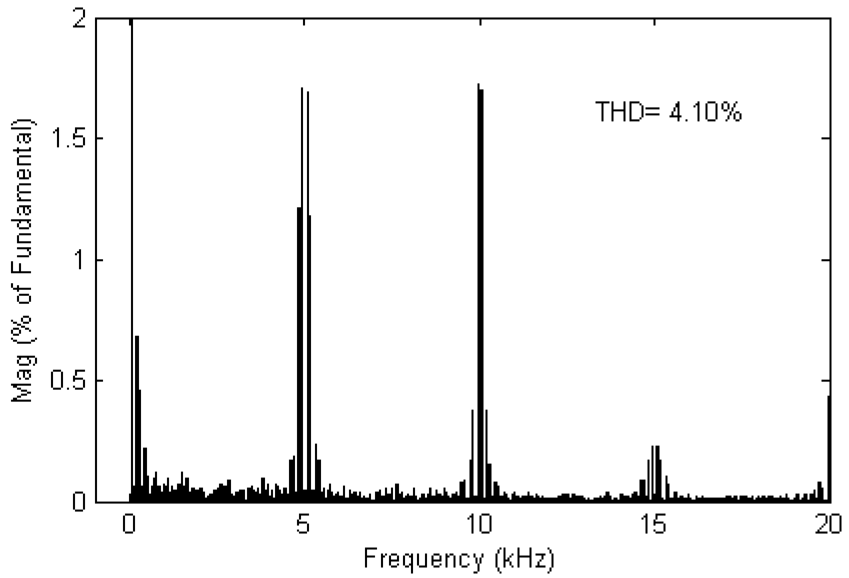

Fig. 10 Harmonic spectra of line current for SVPWM algorithm based DTC drive

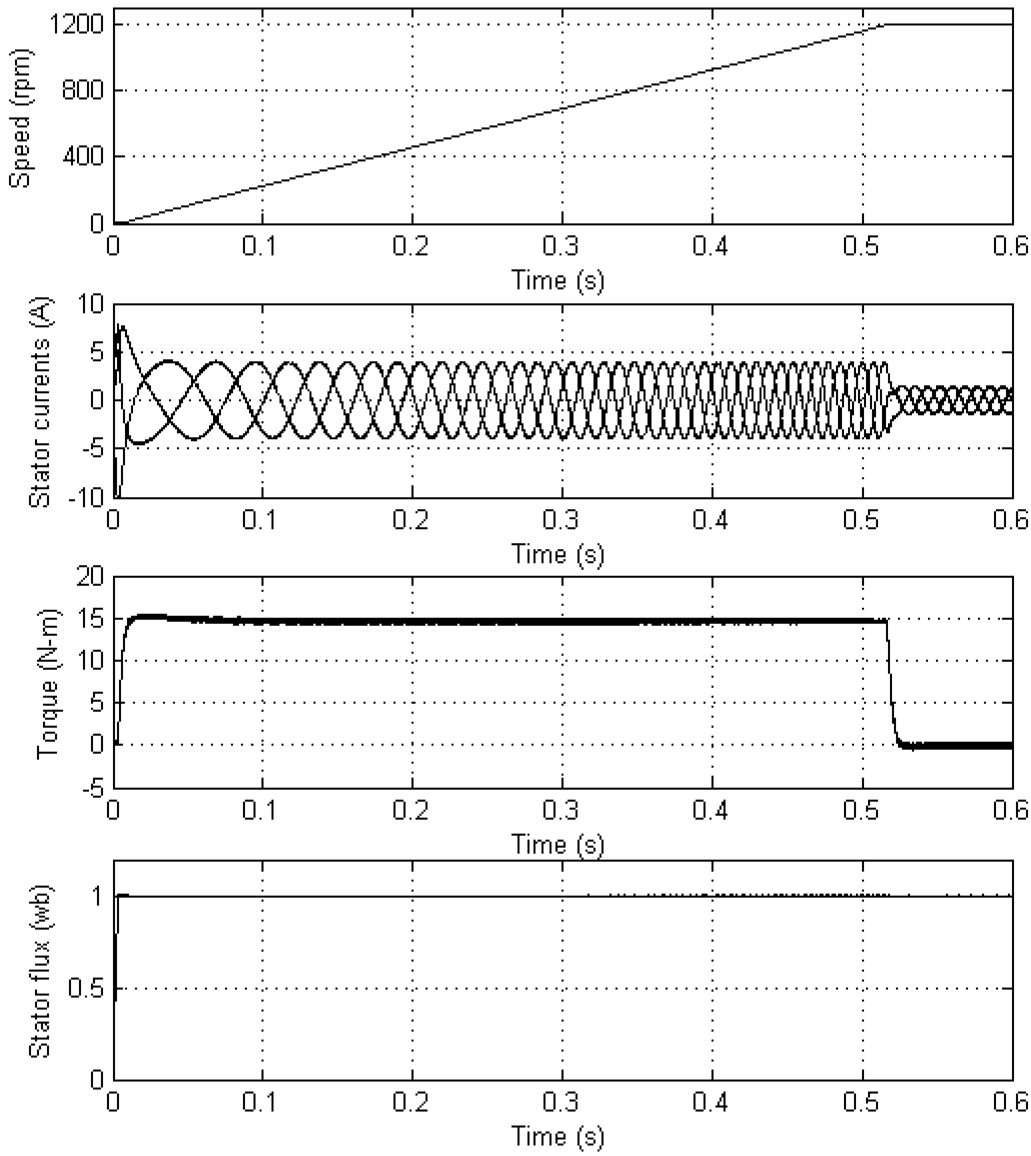

Fig. 11 starting transients for proposed hybrid RPWM algorithm based DTC drive

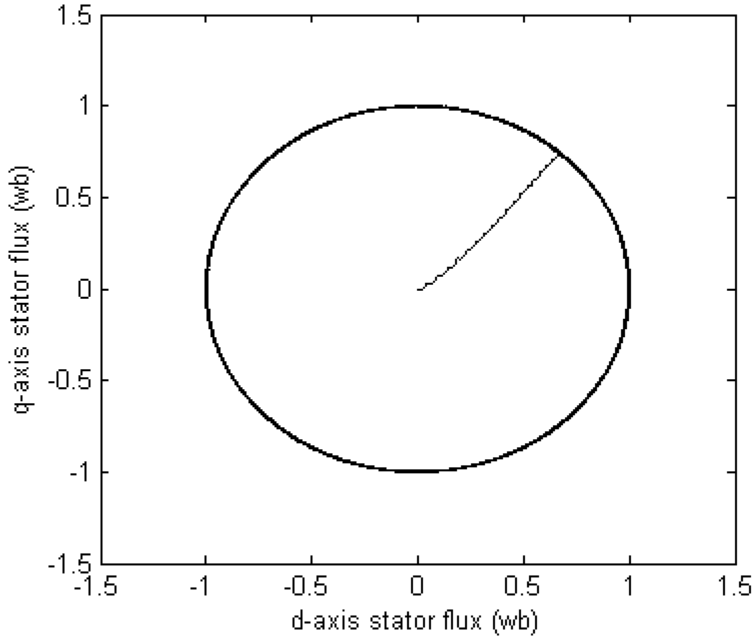

Fig. 12 locus of stator flux for proposed hybrid RPWM algorithm based DTC drive

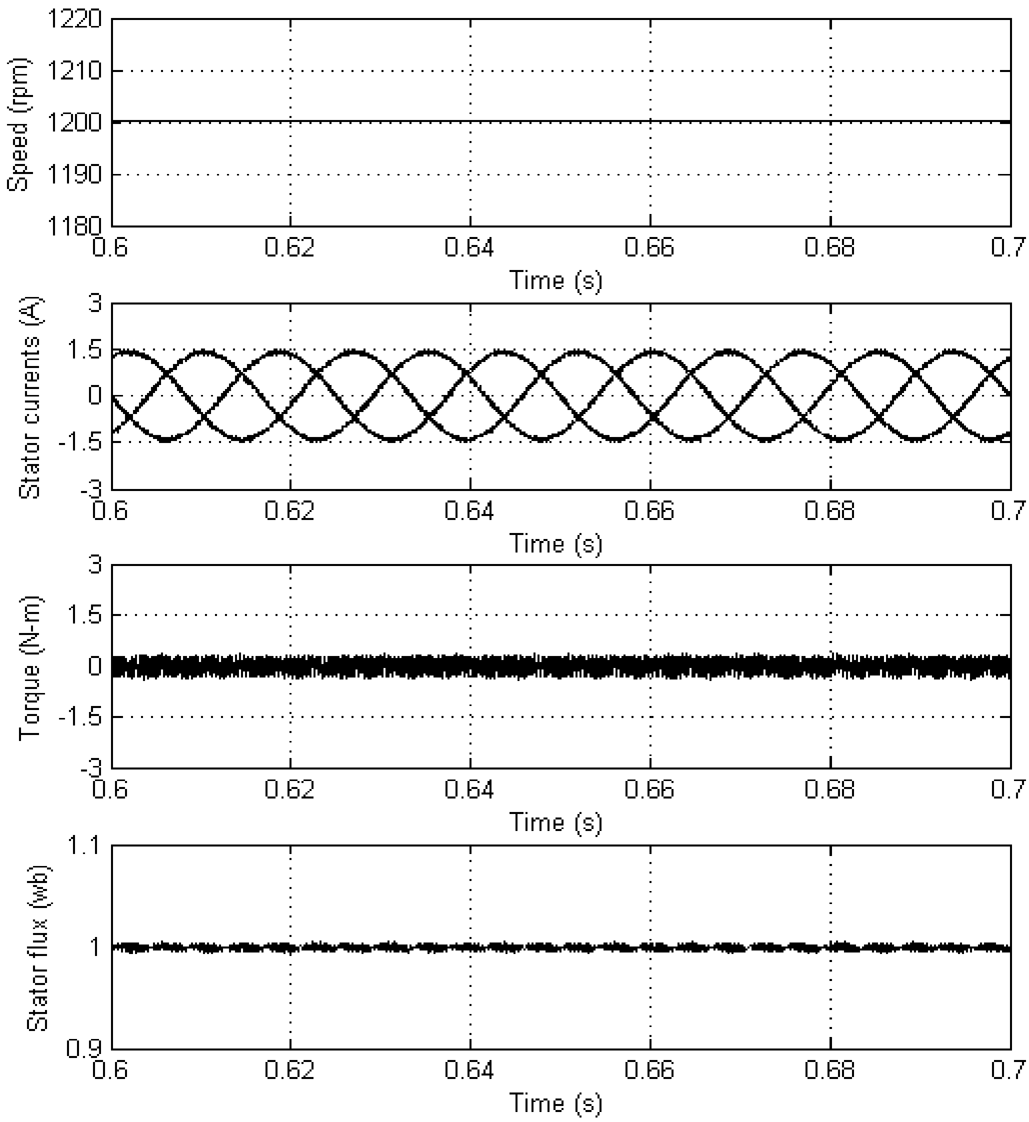

Fig. 13 steady state plots of proposed hybrid RPWM algorithm based DTC drive

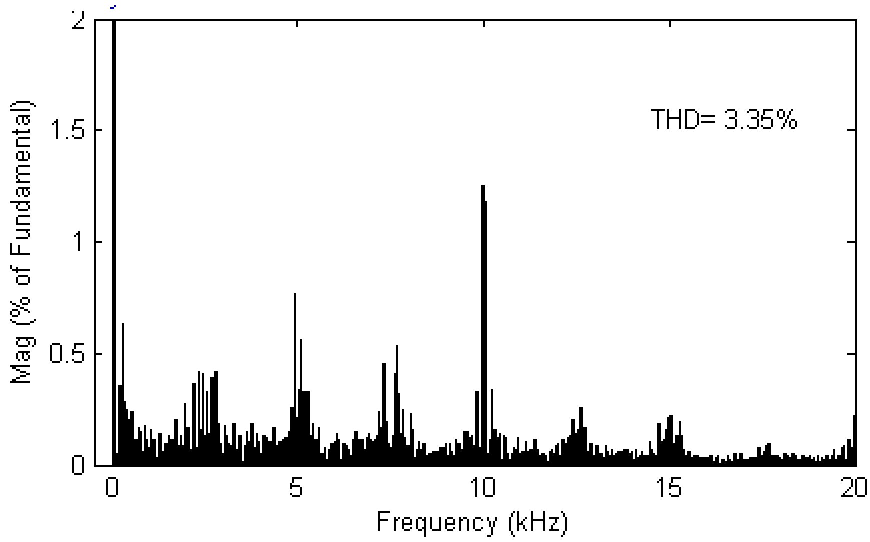

Fig. 14 Harmonic spectra of line current for proposed hybrid RPWM algorithm based DTC drive

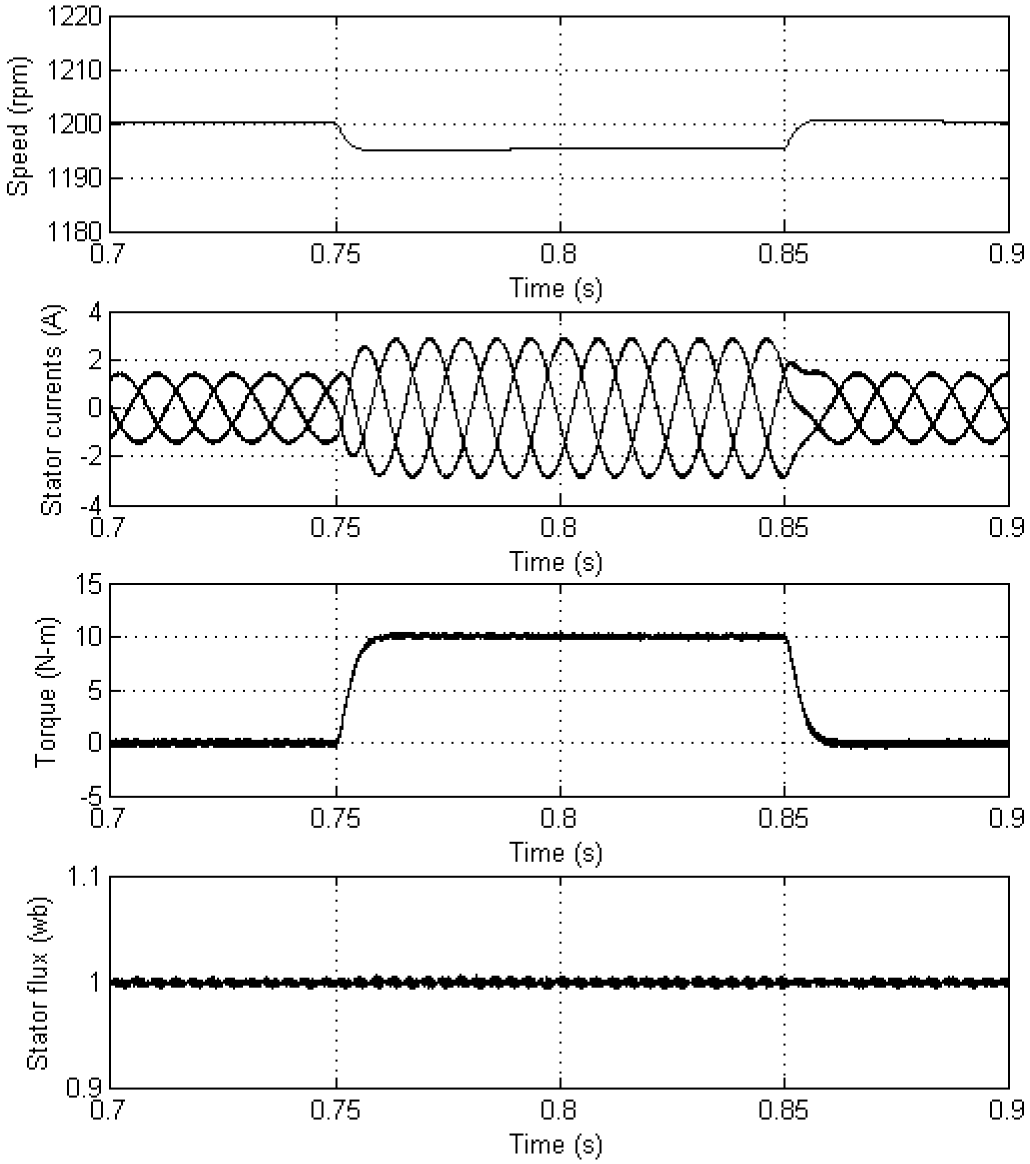

Fig. 15 transients during step change in load condition for proposed hybrid RPWM algorithm based DTC drive (a load torque of 10 N-m is applied at 0.75 s and removed at 0.85 s)

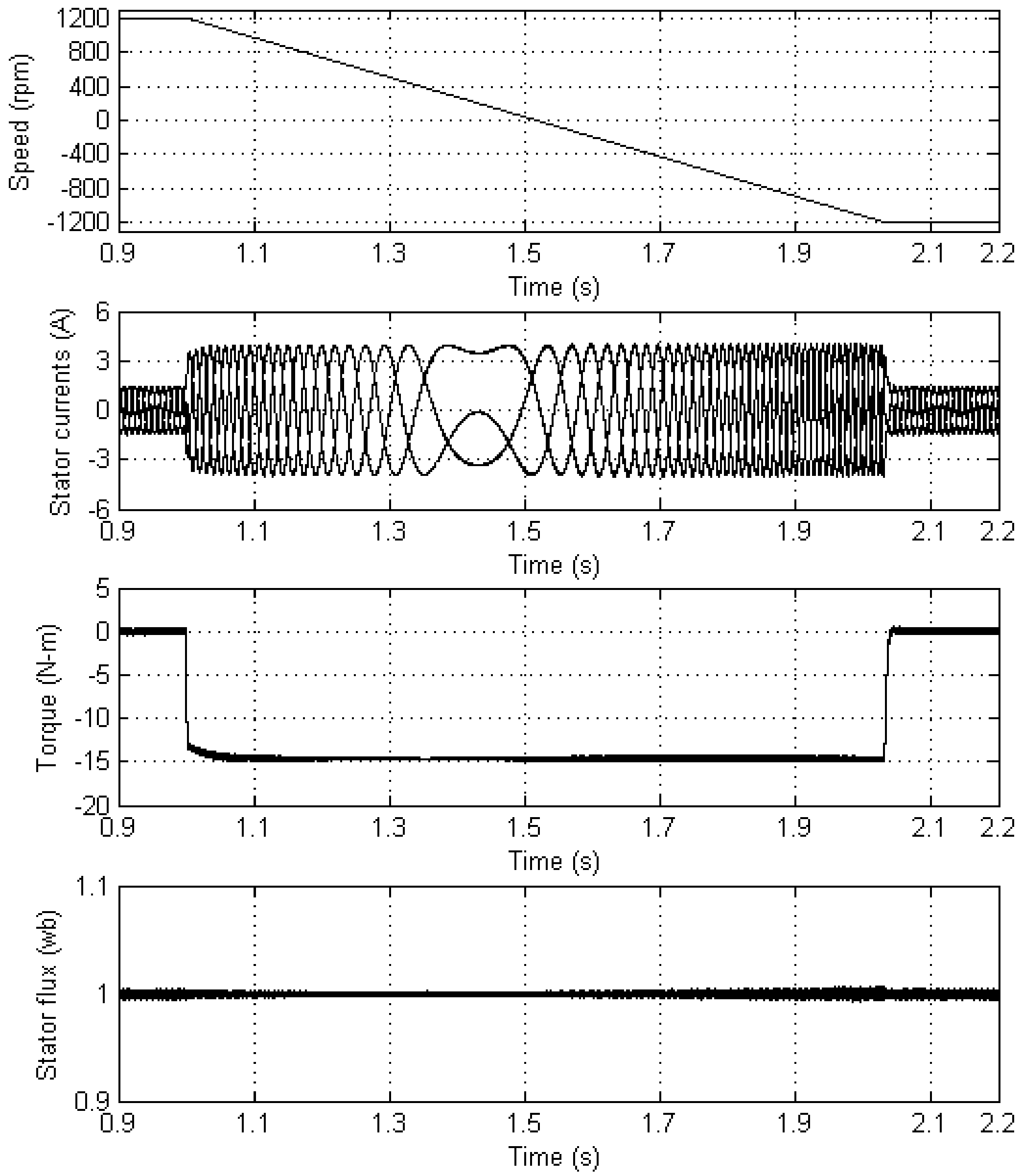

Fig. 16 transients during speed reversal condition for proposed hybrid RPWM algorithm based DTC drive

7. Conclusions

As the SVPWM algorithm gives considerable amplitude of 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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