

A FAMILY OF VARIABLE DELAY RANDOM PWM ALGORITHMS FOR DIRECT TORQUE CONTROLLED INDUCTION MOTOR DRIVES FOR REDUCED HARMONIC DISTORTION AND ACOUSTICAL NOISE

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Abstract: *Though the deterministic pulsewidth modulation (PWM) algorithms give good performance, it generates more acoustical noise. Hence, this paper presents a family of variable delay random pulsewidth modulation (VDRPWM) algorithms for direct torque controlled induction motor drives for reduced total harmonic distortion (THD) and acoustical noise. The proposed algorithms randomizes the switching periods by varying the delay of switching cycles with respect to corresponding sampling cycles. This randomization of switching periods has a mitigating effect of the acoustic and electromagnetic noise emitted by the supplied system. Moreover, to reduce the computational effort and complexity involved in the PWM algorithms, the proposed VDRPWM algorithms are developed by using the concept of imaginary switching times, which are proportional to the instantaneous phase voltages. Hence, the implementation of the proposed algorithm is simpler. To validate the proposed PWM algorithms, simulation studies have been carried out and results are presented. The simulation results confirmed the features of proposed PWM algorithms.*

Key words: *Acoustic noise, DTC, imaginary switching times, RPWM, SVPWM, VDRPWM.*

1. Introduction

Research interest in high-performance control algorithms for induction motors received wide attention over the last three decades. The invention of field oriented control (FOC) algorithm by F. Blaschke has brought renaissance in the high-performance applications. Though FOC gives good performance, the complexity involved is more due to the reference frame transformations. To overcome the drawbacks of FOC, a new control strategy renowned as direct torque control (DTC) was developed by Takahashi [1]. Due to the simplicity, it has more applications in the industry [2]. A detailed comparison between FOC and

DTC has given in [3]. Though DTC is simple and easy to implement, it generates substantial steady state ripples in torque and current. Moreover, DTC gives variable switching frequency operation of the inverter. To reduce the steady state ripple and to get the constant switching frequency, several pulsewidth modulation (PWM) techniques were proposed to DTC algorithm. A detailed survey of the various PWM algorithms is given in [4]. Voltage control in PWM-inverter is performed by means of enforcing appropriate duty ratios of the inverter switches. The duty ratio, which is the ratio of the ON-time of the switch to the length of the switching (sampling) interval, does not depend on the location on the ON interval within the switching interval, i.e., the pulse position, or on the length of the switching interval, i.e., the switching frequency. The PWM techniques, which are given in [4] are also known as deterministic PWM algorithms. Among the various PWM algorithms, space vector PWM (SVPWM) algorithm is attracting many researchers due to its advantages. The SVPWM algorithm results in higher line side voltage and less line current harmonic distortion than sine PWM algorithm with constant switching frequency [5]. To reduce the steady state ripple and to get constant switching frequency operation of the inverter, SVPWM algorithm is applied to DTC in [6-7]. Though, the SVPWM algorithm gives good performance, it gives more acoustical noise and harmonic distortion due to the deterministic nature of pulse durations. If either the pulse position or the switching frequency is varied in a random manner, the power spectrum of the output voltage of the converter acquires a continuous part, while the discrete (harmonic) part is significantly reduced. This is the basic principle of the

random pulse width modulation (RPWM) which has in recent years attracted the increasing interest of researchers. The detailed review of the RPWM algorithms is given in [8]-[9]. Among, various RPWM algorithms, random pulse position PWM algorithms are easier for implementation [10]-[11]. However, a novel algorithm known as variable delay RPWM (VDRPWM) is reported recently [12]-[14]. The VDRPWM algorithm is characterized by a constant switching frequency and a varying switching period (T_s) realized by random changes of the delay of switching cycles with respect to the corresponding sampling cycles. However, the existing VDRPWM algorithm requires angle and sector information, which increases the complexity involved in the algorithm. To reduce the complexity involved in the conventional space vector approach, various PWM algorithms have been developed in [15]-[16] by using the concept of imaginary switching times.

This paper presents a family of VDRPWM algorithms that include both two-phase and three-phase modulation methods for direct torque controlled induction motor drive by using the concept of imaginary switching times for reduce acoustical noise and harmonic distortion.

2. Simplified Deterministic PWM Sequences

The classical space vector based PWM algorithms use angle and sector information for the calculation of actual gating times of the inverter. Hence, the complexity involved in the classical space vector approach is more. To reduce the complexity involved in the classical space vector approach, this paper presents a simplified approach, which uses the concept of imaginary switching times. The imaginary switching time periods, which are proportional to the instantaneous values of the reference phase voltages, are defined as given in (1) [15]-[16].

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

Then, in each sampling time period, the maximum, minimum and middle values of imaginary switching times are evaluated by using (2)-(4).

$$T_{\max} = \text{Max}(T_{an}, T_{bn}, T_{cn}) \quad (2)$$

$$T_{\min} = \text{Min}(T_{an}, T_{bn}, T_{cn}) \quad (3)$$

$$T_{\text{mid}} = \text{Mid}(T_{an}, T_{bn}, T_{cn}) \quad (4)$$

Then the active voltage vector switching times T_1 and T_2 may be expressed as [16]

$$T_1 = T_{\max} - T_{\text{mid}} ; T_2 = T_{\text{mid}} - T_{\min} \quad (5)$$

The zero voltage vectors switching time is calculated as

$$T_z = T_s - T_1 - T_2 \quad (6)$$

Thus, the active state times and zero states times can be calculated without determining the angle and sector information with the help of imaginary switching times.

The space vector PWM (SVPWM) algorithm

employs equal division of zero voltage vector time within a sampling time period. However, by utilizing the unequal distribution of zero voltage vector switching times, various discontinuous PWM (DPWM) algorithms, which are also known as bus-clamping PWM (BCPWM) 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, DPWMMIN and DPWMMAX algorithms can be generated for $\mu = 0.5$, 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. The SVPWM algorithm is also known as three-phase modulation algorithms and remaining DPWM algorithms are known as two-phase modulation algorithms.

3. Proposed VDRPWM Algorithms

The ideal random PWM (RPWM) algorithm should possess reduced acoustic noise over the full operating range, easier implementation, reduced complexity, acceptable switching losses and minimal impact on the system dynamics and basic motor control functionality. The RPWM algorithms can be classified into two categories as random switching frequency PWM (RSFPWM) and fixed switching frequency PWM algorithms. In the RSFPWM algorithms, both the sampling and PWM periods are synchronized. The major drawback of the RSFPWM algorithm is the limitation of the maximum code size by the minimum sampling time period. The fixed switching frequency RPWM algorithms can be classified as random zero state distribution PWM (RZSDPWM), random center distribution PWM (RCDPWM) and random lead-lag PWM (RLLPWM) algorithms. Though the fixed switching frequency RPWM algorithms allow optimal use of the processor computational capability due to

fixed sample rate, these suffer from few limitations. RZSDPWM and RCDPWM algorithms lose effectiveness at higher modulation indices. The RLLPWM algorithm does not offer a very good performance with respect to the reduction of acoustic/EMI emissions and suffers an increased current ripple as well. Additionally, both RLLPWM and RCDPWM introduce an error in the fundamental component of current due to a per-cycle average value of the switching ripple. Hence, VDRPWM algorithms are used in this paper for direct torque controlled induction motor drive. However, the existing VDRPWM algorithm uses sector and angle information for the calculation of gating times, which increase the complexity. Hence, to reduce the complexity involved in the algorithm, the concept of imaginary switching times is used and the gating times are calculated as explained in the previous section.

This paper presents a family of VDRPWM algorithms, namely variable delay random SVPWM (VDRSVPWM), variable delay random DPWMMIN (VDRDPWMMIN) and variable delay random DPWMMAX (VDRDPWMMAX) algorithms. All the proposed simplified VDRPWM algorithms use fixed sample rate for optimal usage of processor computational power while providing quasi-random PWM output for good spectral spreading. This algorithm introduces a random delay into the trailing edge of the next PWM output cycle. Since two consecutive edges determine the PWM output period, a quasi-random PWM output is created as shown in Fig. 1. The detailed flowchart of the proposed VDRPWM algorithms is shown in Fig. 2, which illustrates the computation of the delay and switching period within the processor. In the proposed VDRPWM algorithms, a random number is generated between 0 and 1. Then, this is multiplied by sample time period to obtain the random delay time. Hence, the delay time is varied from zero to sampling time period. To avoid very short output PWM periods, a lower limit on the switching period is defined as minimum sampling time period (T_{swmin}). If the initial switching period calculation is less than the T_{swmin} , it will be clamped to T_{swmin} . Hence, the final delay must be recalculated after the limiting function. Thus, the resultant switching period may vary from T_{swmin} to 2 times the sampling time period. The average switching period will equal the sample period over time.

The VDRPWM algorithms do not affect the basic motor control algorithm or type of space vector modulation employed. Thus, the VDRPWM algorithms consist of two steps. First, the duty cycles of various PWM algorithms are computed as given in previous section with fixed frequency. In second step, the delay is now computed as well. Then the duty cycles and delay are passed to the PWM modulator. Thus, the VDRPWM algorithms can be added to the inverter with minimal impact on the motor control algorithm. The switching loss of the inverter is also

same as existing deterministic PWM algorithms. Moreover, as it uses fixed sample rate, it avoids the updating of filter and regulator gains, which is necessary when using variable sample rate techniques.

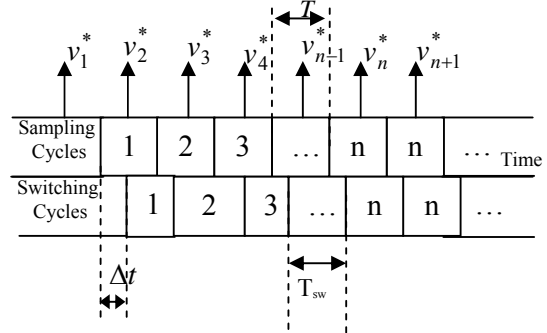


Fig. 1 sampling and switching cycles in the proposed VDRPWM algorithms

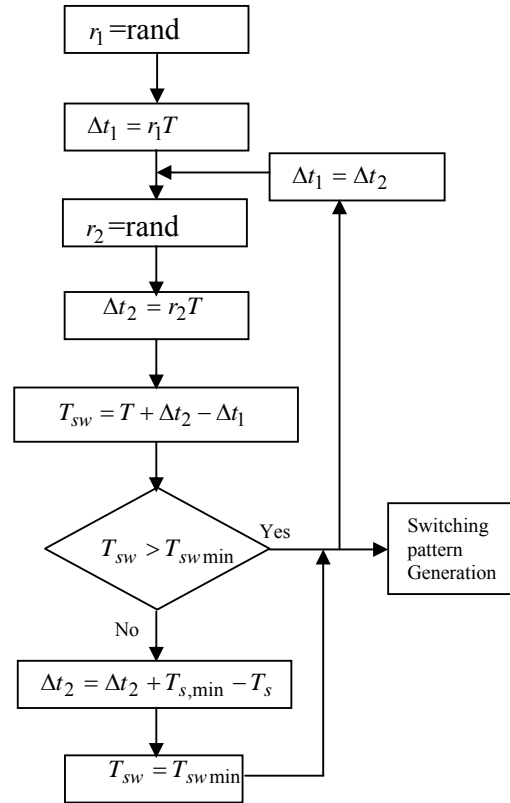


Fig.2 flowchart of the proposed VDRPWM algorithms

4. Proposed VDRPWM Algorithms Based DTC

The block diagram of the proposed VDRPWM algorithms based DTC is as shown in Fig. 3. From Fig. 3, it is seen that the proposed VDRPWM based DTC scheme retains all the advantages of the CDTC, such as no co-ordinate transformation and robust to motor parameters. However a PWM modulator is used to generate the pulses for the inverter, therefore the complexity is increased in comparison with the

classical DTC method. 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 adaptive motor model. 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 (7)-(8).

$$\Delta\psi_{ds} = \psi_{ds}^* - \psi_{ds} \quad (7)$$

$$\Delta\psi_{qs} = \psi_{qs}^* - \psi_{qs} \quad (8)$$

The knowledge of flux error and stator ohmic drop allows the determination of appropriate reference voltage space vectors as given in (9)-(10).

$$V_{ds}^* = R_s i_{ds} + \frac{\Delta\psi_{ds}}{T_{sw}} \quad (9)$$

$$V_{qs}^* = R_s i_{qs} + \frac{\Delta\psi_{qs}}{T_{sw}} \quad (10)$$

where, T_{sw} 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 as explained in previous sections.

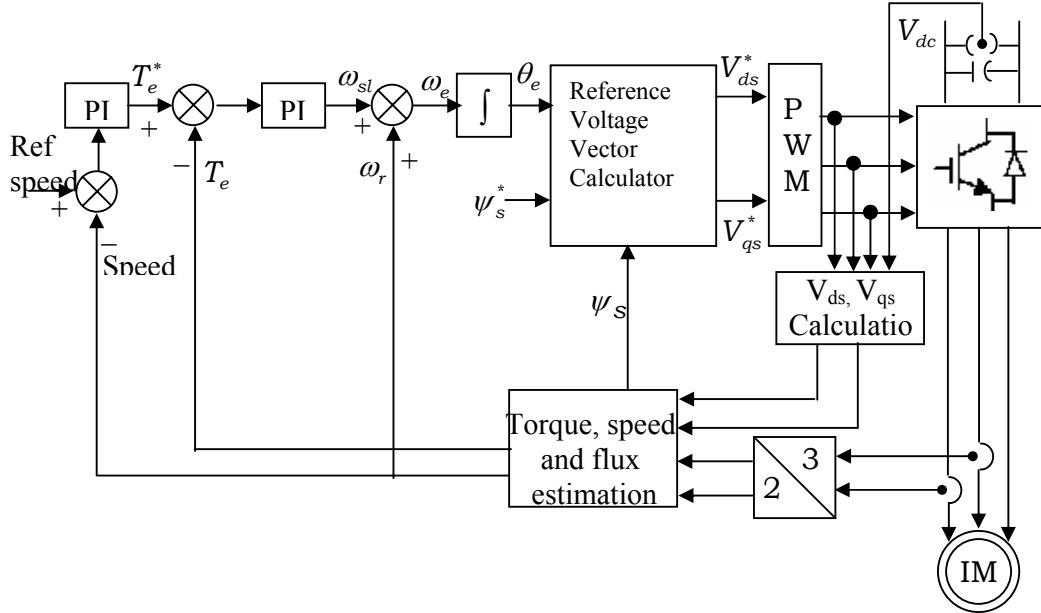


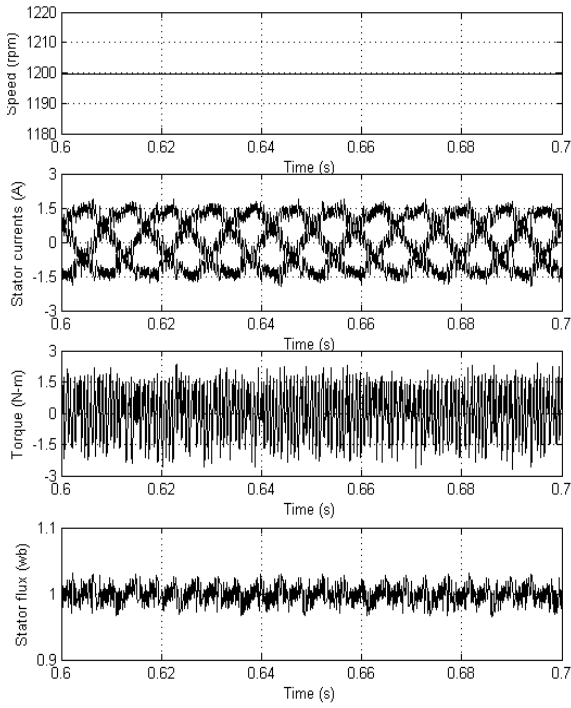
Fig. 3 Block diagram of proposed VDZPWM based DTC

5. Simulation Results and Discussion

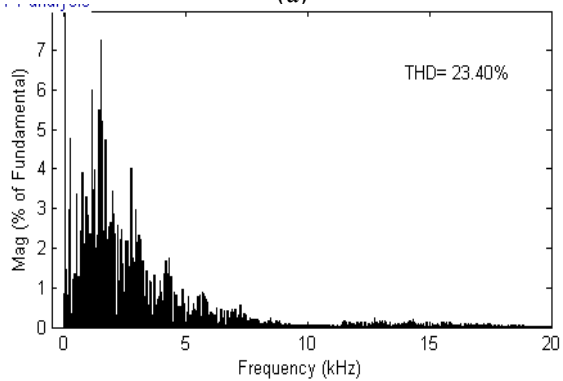
To verify the proposed scheme, numerical simulation studies have been carried out by using Matlab/Simulink. For the simulation, the reference flux is taken as 1wb and starting torque is limited to 15 N-m. The average switching frequency of the inverter is taken as 5 kHz. The induction motor used in this case study is a 1.5 kW, 1440 rpm, 4-pole, 3-phase induction motor having the following parameters:

$R_s = 7.83\Omega$, $R_r = 7.55\Omega$, $L_s = 0.4751H$, $L_r = 0.4751H$, $L_m = 0.4535H$ and $J = 0.06\text{ Kg.m}^2$
The steady state simulation results of conventional DTC and SVPWM algorithm based DTC are shown in

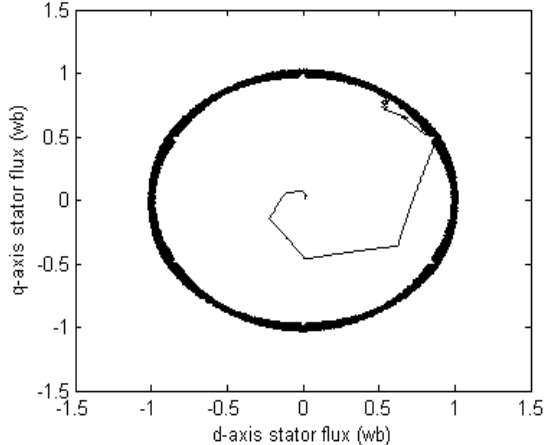
Fig. 4 and Fig. 5. From which, it can be observed that the total harmonic distortion (THD) of SVPWM algorithm based DTC is less when compared with the conventional DTC algorithm. As the amplitudes of dominating harmonics around switching frequency are high in SVPWM algorithm based DTC, it gives more acoustical noise and harmonic distortion. To reduce acoustical noise, the simplified VDRPWM algorithms are proposed in this paper. The steady state simulation results of proposed VDRSVPWM, VDRDPWMMIN and VDRDPWMMAX algorithms are shown in from Fig. 6 to Fig. 8.



(a)

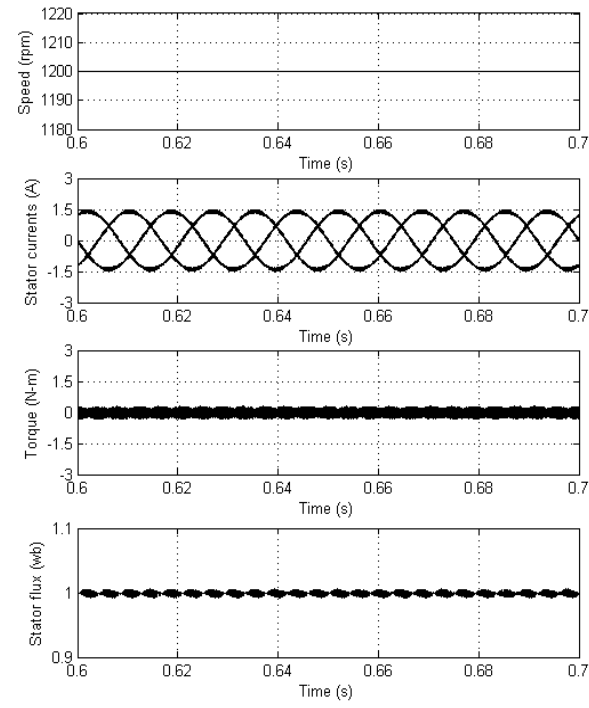


(b)

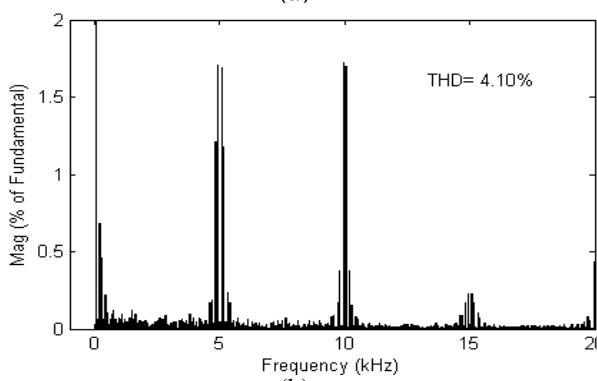


(c)

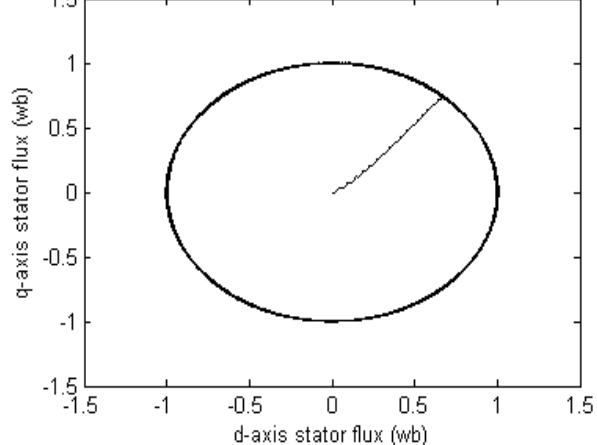
Fig. 4 Steady state plots of conventional DTC based drive (a) speed, currents, torque and flux plots (b) harmonic spectra of line current (c) locus of stator flux



(a)

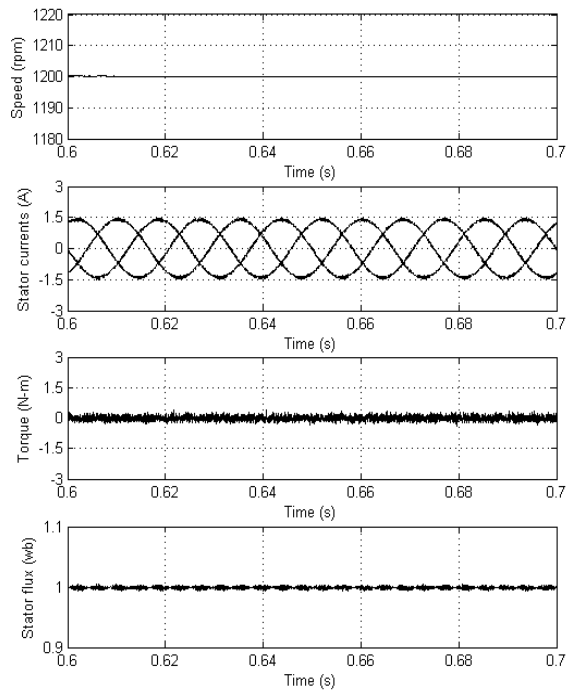


(b)



(c)

Fig. 5 Steady state plots of SVPWM based DTC drive (a) speed, currents, torque and flux plots (b) harmonic spectra of line current (c) locus of stator flux

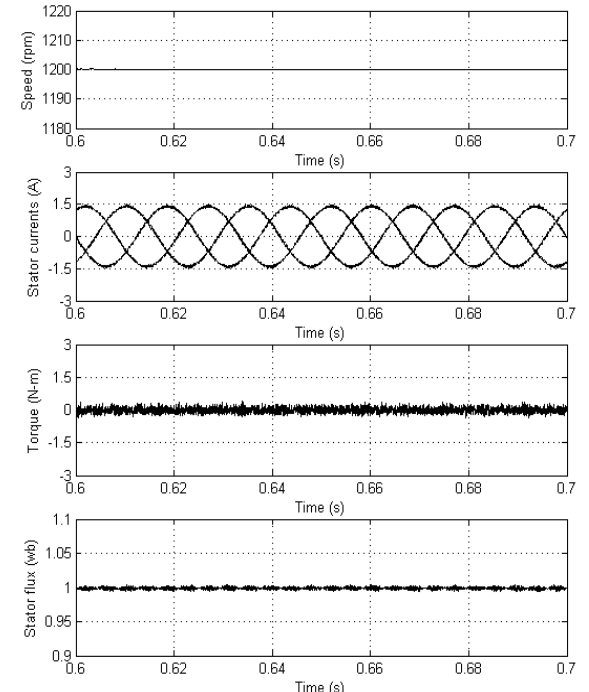


(a)

(b)

(c)

Fig. 6 Steady state plots of VDRSVPWM based DTC drive (a) speed, currents, torque and flux plots (b) harmonic spectra of line current (c) locus of stator flux



(a)

(b)

(c)

Fig. 7 Steady state plots of VDRDPWMMIN based DTC drive (a) speed, currents, torque and flux plots (b) harmonic spectra of line current (c) locus of stator flux

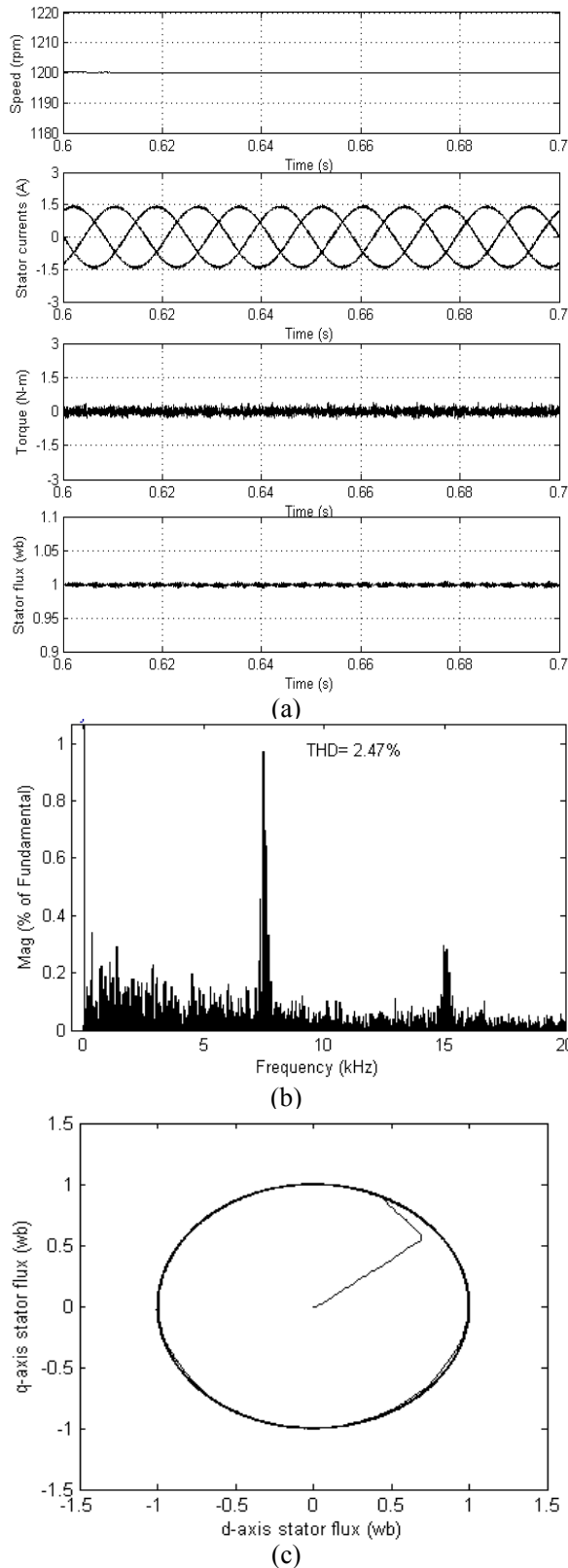


Fig. 8 Steady state plots of VDRDPWMMAX based DTC drive (a) speed, currents, torque and flux plots (b) harmonic spectra of line current (c) locus of stator flux

From the simulation results, it can be observed that the proposed VDRPWM algorithms give reduced THD when compared with the SVPWM algorithm. Moreover, as the amplitude of dominating harmonics is less when compared with the classical SVPWM algorithm, the proposed VDRPWM algorithms give less acoustical noise. Moreover, the proposed VDRPWM algorithms give spread spectra when compared with the SVPWM algorithm. From Fig. 6 to Fig. 8, it can be observed that the two-phase modulation VDRPWM algorithms (VDRDPWMMIN and VDRDPWMMAX) give less THD when compared with the three-phase modulation VDRPWM (VDRSVPWM) algorithm.

6. Conclusions

Though the SVPWM based direct torque controlled induction motor drive gives good performance, it generates more acoustical noise and harmonic distortion due to the dominating harmonics around the multiples of switching frequency. Hence, to reduce the harmonic distortion and acoustical noise of the drive, simplified VDRPWM algorithms are proposed in this paper for direct torque controlled induction motor. As the proposed algorithm uses the concept of imaginary switching times, it reduces the complexity involved in the algorithm. From the simulation results, it can be observed that the proposed VDRPWM algorithms give less harmonic distortion. As the magnitude of dominant harmonics around the switching frequency (5 kHz for three-phase modulation method and 7.5 kHz for two-phase modulation methods) is less in the proposed VDRPWM algorithms, it gives less acoustical noise when compared with the SVPWM algorithm.

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