Simplified Space Vector Based Discontinuous Variable Delay Random PWM Algorithms for Reduced Total Harmonic Distortion in Induction Motor Drive

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Abstract: - The direct torque control provides precise and quick response and the SVPWM algorithm gives good performance for control of induction motor drive, but these algorithms produce more acoustical noise resulting in increased distortion of harmonics. To reduce these effects various PWM techniques were used in recent. Though the deterministic pulse width modulation (PWM) algorithms give good performance, it also results in more harmonic distortion. Hence, to minimize these anomalies of the drive, this paper presents discontinuous variable delay random pulse width modulation algorithms for direct torque control of induction motor drive. The proposed algorithms randomizes the switching periods by varying the delay of switching cycles with respect to corresponding sampling cycles. In the proposed variable delay random pulse width modulation (VDRPWM) algorithm, the effective time is determined using the concept of imaginary switching times which are proportional to the instantaneous phase voltages in order to avoid the requirement of angle and sector identification. To validate the proposed schemes, simulation studies have been carried out on space vector controlled induction motor drive based on discontinuous variable delay random pulse width modulation algorithms using MATLAB/SIMULINK. Further, the simulation results are presented and compared with conventional DTC and space vector based direct torque control of induction motor drive.

Key Words: - DTC, SVPWM, Total Harmonic Distortion, induction motor drive, VDRPWM, VDRDPWMMIN.

1. INTRODUCTION:

In recent years, the research has been focused to find out different solutions for the induction motor control having the features of precise and quick torque response and reduction of the complexity of field oriented algorithms. The direct torque control (DTC) technique has been recognized as the viable solution to achieve these requirements [1]. The direct torque controlled induction motor drives were developed and presented more than twenty years ago by I.Takahashi and M. Depenbrock [2]. Though the DTC has high dynamic performance, it has few disadvantages such as: 1) Vibrations and acoustical noise due to ripple in torque, 2) Harmonics and power loss due to ripple in current and flux and 3) Variation in switching frequency of the PWM inverter. This technique is based on the space vector approach, in which the torque and flux of an induction motor can be directly and independently controlled without any coordination transformation. The conventional SVPWM is a superior PWM technique for 3-phase inverter drives compared to the traditional regularly sampled triangular comparison technique [3]. Though, the SVPWM based DTC increases the complexity of the control algorithm compared to that of CDTC, this method gives superior performance over CDTC. The SVPWM is a continuous PWM (CPWM) method, the switching losses of the inverter is high [4]. To overcome these anomalies and to minimize the complexity involved in the space vector approach, various PWM algorithms have been developed. By varying either the pulse position or the switching frequency in a random manner, the power spectrum of the output voltage of the converter acquires a continuous part, while the discrete part is significantly reduced. The detailed review of the random PWM algorithms
is given in [5]-[6]. Among, various random PWM algorithms, random pulse position PWM algorithms are easier for implementation [7]. However, a novel algorithm known as variable delay Random PWM (VDRPWM) is reported recently [8]-[9]. A space vector based variable delay random PWM algorithm is implemented for induction motor which uses only conventional space vector approach [10] in which during steady state operation notable torque, flux and current pulsations occur which are reflected in speed estimation and in increased acoustical noise. The VDRPWM algorithm is characterized by a constant switching frequency and a varying switching period (Ts) 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, researchers have developed various PWM algorithms as in [11]-[12] by using the concept of imaginary switching times. This paper presents a simplified discontinuous VDRPWM algorithms for direct torque controlled induction motor drive by using the concept of imaginary switching times for \( \mu = 0.5 \) and 1 to obtain discontinuous VDRSVPWM and VDRPWM MIN algorithms for reduced acoustical noise and harmonic distortion.

2. SIMPLIFIED PWM SEQUENCE:

As the classical SVPWM algorithm uses angle and sector information for the calculation of switching times, the complexity involved in the algorithm is more. To reduce the complexity, a simplified approach is used, 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).

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

The active vector switching times \( T_1 \) and \( T_2 \), if the reference voltage vector falls in sector-1 may be expressed as,

\[
T_1 = T_{an} - T_{bn} \quad ; \quad T_2 = T_{bn} - T_{cn} \quad (2)
\]

Thus, the active voltage vector switching times can be represented by the time difference between the imaginary switching time periods. The zero voltage vectors switching time is calculated as

\[
T_z = T_s - T_1 - T_2 \quad (3)
\]

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 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 \( \mu \) value between 0 and 1, various discontinuous PWM algorithms can be generated. If \( \mu = 0.5 \), then the VDRSVPWM algorithm is obtained which uses 0127-7210 sequence in first sector. When \( \mu = 0 \), any one of the phases is clamped to positive dc bus for 120 degrees over a fundamental interval and then VDRPWM MAX is obtained which uses 721-127sequence. When \( \mu =1 \), any one of the phases is clamped to negative dc bus for 120 degrees over a fundamental interval and then VDRPWM MIN is obtained which uses 012210 sequence.

3. PROPOSED VDRPWM ALGORITHM:

A fixed sampling technique allows optimal use of the processor computational capability. Several papers by various researchers have investigated different methods for maintaining fixed sampling rate by introducing RPWM techniques. Random zero vector and random centre displacement (RCD) has less effectiveness at high-modulation indexes. The Random lead–lag (RLL) does not provide a very good performance with respect to the reduction of acoustical noise and suffers in increased current ripple. In addition, RLL and RCD induce an error in the fundamental component due to average value of the switching ripple. For the above listed reasons, the variable-delay random pulse width modulation (VDRPWM) method was selected for this application. The proposed approach referred to as a variable delay randomization PWM (VDRPWM) algorithm, is characterized by a constant sampling frequency. In VDRPWM approach, the individual switching periods are varied in a random manner. The
resulting switching period will turn out to be too short if a long delay in one sampling cycle is followed by a short delay in the next subsequent cycle, that is, shorter than its minimum allowable value $T_{sw_{minimum}}$. In such case, the switching period is set to that value which results the length of the switching cycle varies between $T_{sw_{minimum}}$ and $2\tau$. The Sampling and switching cycles in the VDRPWM technique is shown in figure 1. As described in the above figure, the individual switching periods are varied in a random manner by randomizing the switching cycle delays with respect to their corresponding sampling cycles. In VDRPWM algorithm, the number of switching cycles is same as that of sampling cycles.

![Sampling and switching cycles in the proposed VDRPWM algorithm](image)

Figure1. Sampling and switching cycles in the proposed VDRPWM algorithm

By varying the $\mu$ value as 0.5, 1 and 0 various PWM algorithms namely discontinuous VDRSVPWM, VDRPWMMIN and VDRPWMMAX algorithms can be generated respectively. However in this paper, the analysis is made for discontinuous variable delay random space vector PWM algorithm for the proposed induction motor drive by selecting the value of $\mu$ as 0.5 and 1. The corresponding possible switching sequences of the above two PWM algorithms in each sector are given in Table1.

<table>
<thead>
<tr>
<th>Sector</th>
<th>SVPWM</th>
<th>DPWMMIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0127-7210</td>
<td>012-210</td>
</tr>
<tr>
<td>II</td>
<td>0327-7230</td>
<td>032-230</td>
</tr>
<tr>
<td>III</td>
<td>0347-7430</td>
<td>034-430</td>
</tr>
<tr>
<td>IV</td>
<td>0547-7450</td>
<td>054-450</td>
</tr>
<tr>
<td>V</td>
<td>0567-7650</td>
<td>056-650</td>
</tr>
<tr>
<td>VI</td>
<td>0167-7610</td>
<td>016-610</td>
</tr>
</tbody>
</table>

Table1. Switching sequences in all sectors

4. Proposed VDRPWM Algorithms Based DTC:

The block diagram of the proposed discontinuous VDRPWM algorithms based DTC induction motor drive is as shown in Fig. 2, from which it is seen that the proposed VDRPWM based DTC scheme retains all the advantages of the DTC. However the complexity is increased as PWM modulator is used to generate the pulses for the inverter. In the proposed method, the position of the reference stator flux vector $\vec{\psi}_s^*$ is obtained by the addition of slip speed and actual rotor speed. The actual synchronous speed of the stator flux vector $\vec{\psi}_s$ is evaluated from the adaptive motor model. After each sampling interval, actual stator flux vector $\vec{\psi}_s$ is erected by the error and it tries to attain the reference flux space vector $\vec{\psi}_s^*$. Thus, the flux error is minimized in each sampling interval.
The Reference and actual values of the d-axis and q-axis stator fluxes compared in the reference voltage vector calculator and the errors in the d-axis and q-axis stator flux vectors are obtained as in (4)-(5).

\[ \Delta \psi_{ds} = \psi_{ds}^* - \psi_{ds} \tag{4} \]

\[ \Delta \psi_{qs} = \psi_{qs}^* - \psi_{qs} \tag{5} \]

The knowledge of flux error and stator ohmic drop allows the determination of appropriate reference voltage space vectors as given in (6)-(7).

\[ V_{ds}^* = R_s i_{ds} + \frac{\Delta \psi_{ds}}{T_{sw}} \tag{6} \]

\[ V_{qs}^* = R_s i_{qs} + \frac{\Delta \psi_{qs}}{T_{sw}} \tag{7} \]

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 vectors are fed to the VDRPWM block, from which, the actual switching times for each inverter leg are calculated.

5. Simulation Results and Discussion:
Matlab-Simulink based simulation studies have been carried out to validate the proposed discontinuous VDRPWM algorithms for direct torque controlled induction motor drive. For the simulation, the reference flux is taken as 1 wb and starting torque is limited to 15 N-m. 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: \( R_s = 7.83 \Omega \), \( R_r = 7.55 \Omega \), \( L_s = 0.4751 \text{H} \), \( L_r = 0.4751 \text{H} \), \( L_m = 0.4535 \text{H} \) and \( J = 0.06 \text{Kg.m}^2 \). The simulation results of conventional DTC and SVPWM algorithm based DTC during starting are shown from Fig 3 to Fig 12 from which, it can be observed that the ripple in torque, flux and current is very less compared to CDTC. Also, the proposed SVPWM based DTC provides constant switching frequency of the inverter.
But, as the amplitudes of dominating harmonics around switching frequency are high in SVPWM algorithm, it produces acoustical noise and harmonic distortion. To reduce acoustical noise and total harmonic distortion further, a discontinuous variable delay random PWM algorithm is proposed with $\mu=0.5$ and 1 to obtain VDRSVPWM and VDRPWMMIN algorithms. The simulation results of the above algorithms based induction motor drive are presented in Fig 13 to Fig 22 which confirms the reduced total harmonic distortion and acoustical noise when compared with conventional DTC and SVPWM based DTC.

Figure 3. Starting transients of conventional DTC based induction motor based drive

Figure 4. Transients during step change in load for conventional DTC based induction motor based drive (a load
torque of 10 N·m is applied at 0.75s and removed at 0.85s)

Figure 5. Transients during speed reversal operation for conventional DTC based induction motor based drive

Figure 6. Locus of the stator flux for conventional DTC

Figure 7. Harmonic spectra of line current of conventional DTC drive
Figure 8. Starting transients of SVPWM based direct torque controlled drive

Figure 9. Transients during step change in load for SVPWM based direct torque controlled drive (a load torque of 10 N-m is applied at 0.75s and removed at 0.85s)
Figure 10. Transients during speed reversal operation for SVPWM based direct torque controlled drive

Figure 11. Locus of the stator flux for SVPWM based DTC

Figure 12. Harmonic spectra of line current of SVPWM based DTC
Figure 13. Starting transients of proposed VDRSVPWM based DTC - induction motor drive

Figure 14. Transients during step change in load for proposed VDRSVPWM algorithm based DTC (a load torque of 10 N-m is applied at 0.75s and removed at 0.85s)
Figure 15. Transients during speed reversal operation of proposed VDRSVPWM algorithm based DTC

Figure 16. Locus of the stator flux for VDRSVPWM based DTC

Figure 17. Harmonic spectra of line current for proposed VDRSVPWM algorithm based DTC drive
Figure 18. Starting transients of proposed VDRPWMMIN algorithm based DTC-I.M drive.

Figure 19. Transients during step change in load for proposed VDRPWMMIN algorithm based DTC (a load torque of 10 N-m is applied at 0.75s and removed at 0.85s)
Figure 20. Transients during speed reversal operation of proposed VDRPWM MIN algorithm based DTC

Figure 21. Locus of the stator flux for proposed VDRPWM MIN algorithm based DTC-I.M drive
5. Conclusions:

The starting and steady state ripples of stator current, torque and flux are very high in CDTC. In order to improve the performance of CDTC in terms of ripples, a SVPWM algorithm is used. 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 total harmonic distortion and acoustical noise of the drive, discontinuous VDRPWM algorithms are proposed in this paper for direct torque controlled induction motor drive. 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 confirmed that the proposed VDRSVPWM and VDRPWMMIN algorithms give less total harmonic distortion. As the magnitude of dominant harmonics around the switching frequency is less in the proposed algorithms, it results in reduced acoustical noise when compared with conventional DTC and SVPWM algorithm based DTC.

References: