

An SMC based RZVDPWM Algorithm of Vector Controlled Induction Motor Drive for Better Speed Response with Reduced Acoustical Noise

M Veera Chandra Kumar, K. Satyanarayana, M.N.V.V. Brahmam

Abstract: In this paper, an sliding mode controller (SMC) based Random Zero vector Distribution PWM (RZVDPWM) algorithm of vector controlled induction motor drive for better speed response with reduced Acoustical Noise is analyzed. In order to mitigate the difficulty faced in the conventional Space Vector PWM (SVPWM) approach, the proposed RZVDPWM algorithm is created by taking the concept of Simplified PWM sequence. This algorithm is developed by using the concept of random number generation technique. Simulation studies are carried out to validate proposed RZVDPWM algorithm, the results obtained are presented and compared. The simulation results shows that the overall performance of SMC based RZVDPWM drive is better when compared to SVPWM technique under different conditions of operation.

Index Terms: Simplified PWM sequence, SVPWM, RZVDPWM, Vector control, SMC

I. INTRODUCTION

The voltage source inverter fed induction motor drives give more harmonic distortion. The harmonic distortion can be reduced by going in for more complex topologies like multilevel inverters, etc. Alternatively, it is possible to achieve an improved performance even with a two-level inverter by designing suitable high-performance PWM algorithms. Nowadays, the variable speed drives are most prominently being used for industrial applications. The creation of vector control algorithm has brought revolution in the high-performance variable speed drives. The vector control or field oriented control (FOC) algorithm enables the isolating control of torque and flux of an asynchronous motor drive. Using this vector control, the asynchronous motor can be rotated in the permissible limits like a separately excited dc motor [1]. Anyways, the classical vector control algorithm considers the hysteresis controllers that produce variable

switching frequency operation of the inverter. To obtain consistent switching frequency operation, the space vector PWM (SVPWM) algorithm is considered in vector controlled asynchronous motor drives. The standard SVPWM algorithm considers zero state time distribution equal of both the zero vectors, and giving constant switching frequency operation [2]. Although SVPWM approach gives better performance compared to classical algorithms it also produces acoustical noise and harmonic distortion. In order to minimize the acoustical noise produced by the proposed SVPWM approach, numerous random PWM (RPWM) algorithms are introduced and are presented in literature [3]-[5]. RPWM algorithms family is shown in [3]. A random pulse position PWM algorithm is presented in [4] to minimize the acoustical noise. A random pulse position PWM approach is given in [4] to minimize the acoustical noise. A part of the RPWM approach is given in [5] which randomizes the sampling time period. The previous RPWM algorithms makes use of classical space vector algorithm, which needs the angle and sector data to build the reference voltage vector at each sampling time period. To minimize difficulty in the SVPWM algorithm, a new potential difference modulation algorithm is given in [6] by considering the theory of offset time. In order to mitigate the difficulty of Space Vector PWM algorithm, a new concept of simplified PWM sequence is given in [7]-[8]. The details of SMC based induction motor with Conventional methods like Proportional Integral (PI) with simulations results presented in [9].

In this paper, a sliding mode controller (SMC) based Random Zero vector Distribution PWM (RZVDPWM) algorithm of vector controlled asynchronous motor drive for better speed response with reduced Acoustical Noise is analyzed. The proposed RZVDPWM algorithm produces gating pulses by the reference voltages which are sampled. Hence it mitigates the difficulty which is presented in the conventional SVPWM approach.

II. SVPWM ALGORITHM

Voltage source inverters (VSI) are used in numerous applications. The 3- ϕ , 2-level VSI has a basic format and produces a low-frequency yields output voltage with allowable amplitude and frequency by programming highest-recurring gate pulses. For a 3- ϕ , 2-level VSI, 8 voltage vectors are obtained, and are represented in.

Manuscript published on 30 October 2016.

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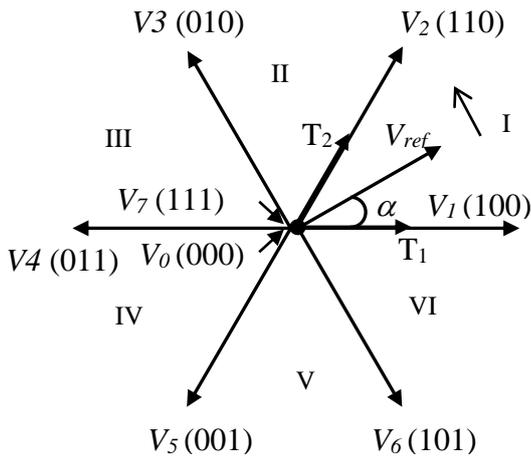
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Fig. 1. From these eight voltage vectors, V_1 to V_6 vectors are known as active states or voltage vectors and the remaining two vectors are known as zero voltage vectors or zero states. The sample voltage or reference voltage space vector which is shown in Fig. 1 also depicts the desired value corresponding to it of the fundamental components for the output phase voltages. In an average manner the space vector approach can be constructed. At equal intervals of time the reference voltage vector (V_{ref}) is sampled, T_s is used to denote the sampling time period. Various vectors of voltage which can

be generated by VSI are given at various time periods with time period of sampling (T_s) so that the average vector generated on the reference voltage V_{ref} , both in magnitude



and angle. So, in order to get any of the sampled reference voltage V_{ref} the vector which are to be considered are both the Zero state vectors and 2 active state vectors thus forming a boundary of the sector in which the sample is present. All the sectors which are specified in the Fig. 1 are symmetrical. The first sector explanation is only given in the paper.

Fig. 1 The Possible voltage space vectors and sector definition in SVPWM algorithm

For the obtainable reference voltage vector V_{ref} , the zero and Active voltage vector times can be calculated as given by (1), (2) and (3).

$$T_1 = \frac{2\sqrt{3}}{\pi} M_i \sin(60^\circ - \alpha) T_s \quad (1)$$

$$T_2 = \frac{2\sqrt{3}}{\pi} M_i \sin(\alpha) T_s \quad (2)$$

$$T_z = T_s - T_1 - T_2 \quad (3)$$

Where M_i is modulation index and is presented in [1]. In the Space Vector approach, the total zero state time is divided equally between V_0 and V_7 and is distributed symmetrically at start and at the end of the each sampling time period T_s . Thus, the pattern used in SV approach is 0127-7210 in the first sector, 0327-7230 in the second sector and so on.

III. PROPOSED RZVDPWM ALGORITHM

a. Modified PWM sequence:

Angle calculation and the transformation of reference frames are widely used in standard SVPWM approach. So, the difficulty is observed and is increased in the standard SVPWM algorithm. For generation of the gating times, the

proposed RZVDPWM algorithm uses sampled reference phase voltages which are instantaneous. In view of explanation of proposed algorithm the basics of simplified PWM sequence will be introduced. The Simplified PWM sequence is in the same way to the instantaneous phase voltages and is formulated as follows [7]:

$$T_{an} = \frac{T_s}{V_{dc}} V_{an}; T_{bn} = \frac{T_s}{V_{dc}} V_{bn}; T_{cn} = \frac{T_s}{V_{dc}} V_{cn} \quad (4)$$

V_{an} , V_{bn} and V_{cn} are the instantaneous reference phase voltages and T_{an} , T_{bn} and T_{cn} are the related Simplified PWM sequence. As these times are proportional to instantaneous potential differences, these times can be negative where voltages are negative. Hence, these times are given identification as Simplified PWM sequence. The active vector switching times T_1 and T_2 , if the reference potential difference vector V_{ref} comes in I sector and can expressed as [7]-[8]:

$$T_1 = T_{an} - T_{bn}; T_2 = T_{bn} - T_{cn} \quad (5)$$

When the reference potential vector V_{ref} comes in the first sector, the switching time which is imaginary is proportional to a-phase (T_{an}) has a maximum value, the switching time which is imaginary corresponding to c-phase (T_{cn}) has a minimum value and the switching time which is imaginary corresponding to b-phase (T_{bn}) has a neither minimum nor maximum value in the conventional SVPWM approach. So, in order to calculate the active vector switching times, the minimum (T_{min}), middle (T_{mid}) and maximum (T_{max}) values of Simplified PWM sequence in every sampling time are calculated. Such that the active vector switching times T_1 and T_2 are expressed as

$$T_1 = T_{max} - T_{mid}; T_2 = T_{mid} - T_{min} \quad (6)$$

The zero voltage vectors switching time is calculated as

$$T_z = T_s - T_1 - T_2 \quad (7)$$

b. Proposed Random Zero Vector Distribution Algorithm:



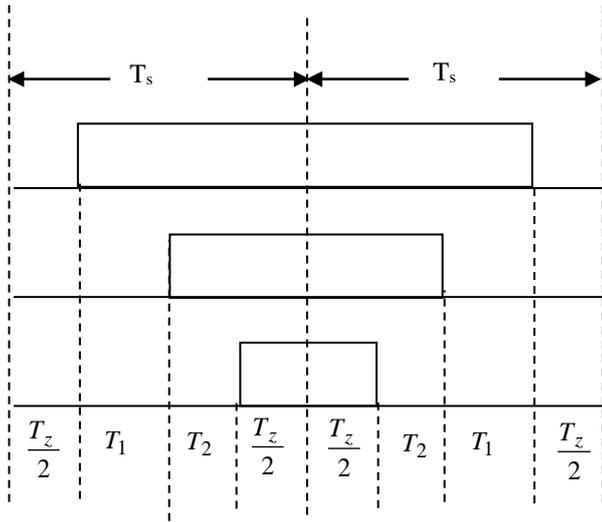


Fig. 2(a) Gating times in first-sector of SVPWM algorithm

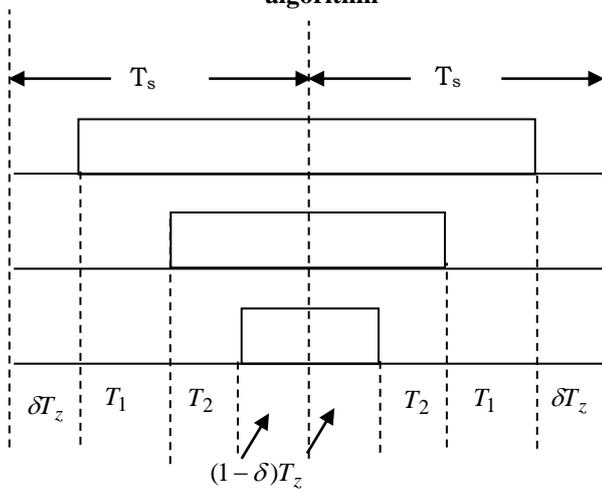


Fig. 2(b) Gating times in first-sector of modified RZVDPWM algorithm

In the standard SVPWM algorithm the total zero state vector time is distributed equally in between the both the zero voltage vectors. But, the modified random zero vector distribution PWM (RZVDPWM) algorithm distributes the zero state time between the two zero voltage vectors as given in (8) and (9).

$$T_0 = \delta T_z \tag{8}$$

$$T_7 = (1 - \delta) T_z \tag{9}$$

δ is a number which is picked in random manner. Its value ranges from 0.1 to 1 (i.e., 0% to 100%). Also, its value is less than one. The order and gating times of applications of active and zero state vectors in the sector-I are as shown in the Fig.2. In Fig. 2, the conventional and the proposed algorithm gating times are shown. As shown in the Fig. 2, the proposed algorithm approach of RZVDPWM randomizes the time of the zero voltage vectors in every sampling time interval but, the pulses are centre aligned as in standard SVPWM algorithm.

c. Sliding mode controller

A sliding mode control (SMC) which is basically an adaptive control that gives solid performance of a drive with parameter variation and load torque disturbance. In SMC the Induction motor drive response is forced to tract sliding along a predefined reference model in a phase plane by a switching

control algorithm, parameter variation and load disturbance. The design and implementation of smc is simpler. SMCS applied induction motors, servo with dc motors, synchronous motors such as controlling of machine tools, robots etc. The electromechanical equation of induction motor is described as

$$J \frac{d\omega_m}{dt} + B \omega_m + T_L = T_e \tag{10}$$

Where J is moment of inertia constant and B is the viscous friction coefficient of the induction motor drive, T_L is load torque, T_e is the electromagnetic torque of induction motor and ω_m is the mechanical speed of the rotor in angular frequency, which is related to rotor electrical speed by $\omega_m = \frac{2\omega_r}{P}$.

The electromechanical equation can be modified further as $\dot{\omega}_m + a\omega_m + d = bT_e$ (11)

Where $a = \frac{B}{J}$, $b = \frac{1}{J}$ and $d = \frac{T_L}{J}$.

By Considering the equation (12) with disturbances as $\dot{\omega}_m = -(a + \Delta a)\omega_m - (d + \Delta d) + (b + \Delta b)T_e$ (12)

Δa , Δb and Δd represents the disturbances or uncertainties of the terms a , b and d respectively introduced by system parameters J and B . Further, considering the error of speed tracking as given in (13)

$$e(t) = \omega_m(t) - \omega_m^*(t) \tag{13}$$

Here ω_m^* is the command of reference speed of the rotor in angular frequency. Then, by taking the differentiation of (13) with respect to time gives,

$$\dot{e}(t) = \dot{\omega}_m(t) - \dot{\omega}_m^*(t) = -ae(t) + f(t) + x(t) \tag{14}$$

Where the following terms have been collected in the signal $f(t)$,

$$f(t) = bT_e(t) - a\omega_m^* - d(t) - \dot{\omega}_m^*(t) \tag{15}$$

And the $x(t)$, lumped uncertainty, defined as

$$x(t) = -\Delta a\omega_m(t) - \Delta d(t) + \Delta bT_e(t) \tag{16}$$

Now, the sliding variable with integral component can be defined as

$$S(t) = e(t) - \int_0^t (h - a)e(\tau) d\tau \tag{17}$$

Here h is the gain constant.

To obtain the tracking of speed trajectory the following assumptions are made

Assumption-1: The gain constant h must be chosen so that the term $(h-a)$ is strictly negative and hence $h < 0$.

Then main sliding surface can be derived as given in (18)

$$S(t) = e(t) - \int_0^t (h - a)e(\tau) d\tau = 0 \tag{18}$$



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Basing on the developed switching surface, the sliding mode switching control is defined from a speed controller given by

$$f(t) = h e(t) - \beta \text{sgn}(S(t)) \quad (19)$$

Where β is the switching gain and $\text{sgn}(\cdot)$ is the sign function given as,

$$\text{sgn}(S(t)) = \begin{cases} +1, & \text{if } S(t) > 0 \\ -1, & \text{if } S(t) < 0 \end{cases} \quad (20)$$

Assumption-2: The gain β must be taken so that $\beta \geq |x(t)|$ for all the time.

Consider the Lyapunov function candidate as given in (21).

$$V(t) = \frac{1}{2} S(t) \dot{S}(t) \quad (21)$$

Its time derivative is calculated as:

$$\dot{V}(t) = S(t) \dot{S}(t) = S(t) (\dot{e} - (h - a)e) \quad (22)$$

by substituting (17) in (22)

$$\dot{V}(t) = S(t) ((-ae + f + x) - (he - ae)) = S(t) (f + x - he) \quad (23)$$

By using (18) in (23)

$$\dot{V}(t) = S(t) (h e - \beta \cdot \text{sgn}(S) + x - he) = S(t) (x - \beta \cdot \text{sgn}(S)) \quad (24)$$

Using second assumption in (21), then

$$\dot{V}(t) \leq -(\beta - |x|)|S| \leq 0 \quad (25)$$

By making use of the Lyapunov's direct method, as the $V(t)$ is clearly a value of '+ve sign, $\dot{V}(t)$ is '-ve value and $V(t)$ reaches to ∞ as $S(t)$ reaches to ∞ , and then the stability at the origin $S(t) = 0$ is globally asymptotically stable. Therefore as t tends to infinity then $S(t)$ tends to zero. Moreover, all trajectories starting from the sliding surface $S=0$ should reach the surface in finite time and then will remain on this surface. Sliding mode is the term used to represent the system's behavior on the sliding surface. When the sliding mode occurs on the sliding surface, then, $S(t) = \dot{S}(t) = 0$ and then there is a convergence of the tracking error $e(t)$ to zero exponentially. Finally, the reference torque command T_e^* can be obtained by substituting (18) in (12) as given in (26)

$$T_e^*(t) = \frac{1}{b} [(h \cdot e) - \beta \text{sgn}(S) + a \omega_m^* + \dot{\omega}_m^* + d] \quad (26)$$

Therefore, the sliding mode speed control resolves the problem of speed tracking for vector controlled induction motor drive, with some uncertainties or disturbances in the load torque.

IV. PROPOSED SMC BASED RZVDPWM ALGORITHM OF VECTOR CONTROLLED INDUCTION MOTOR DRIVE

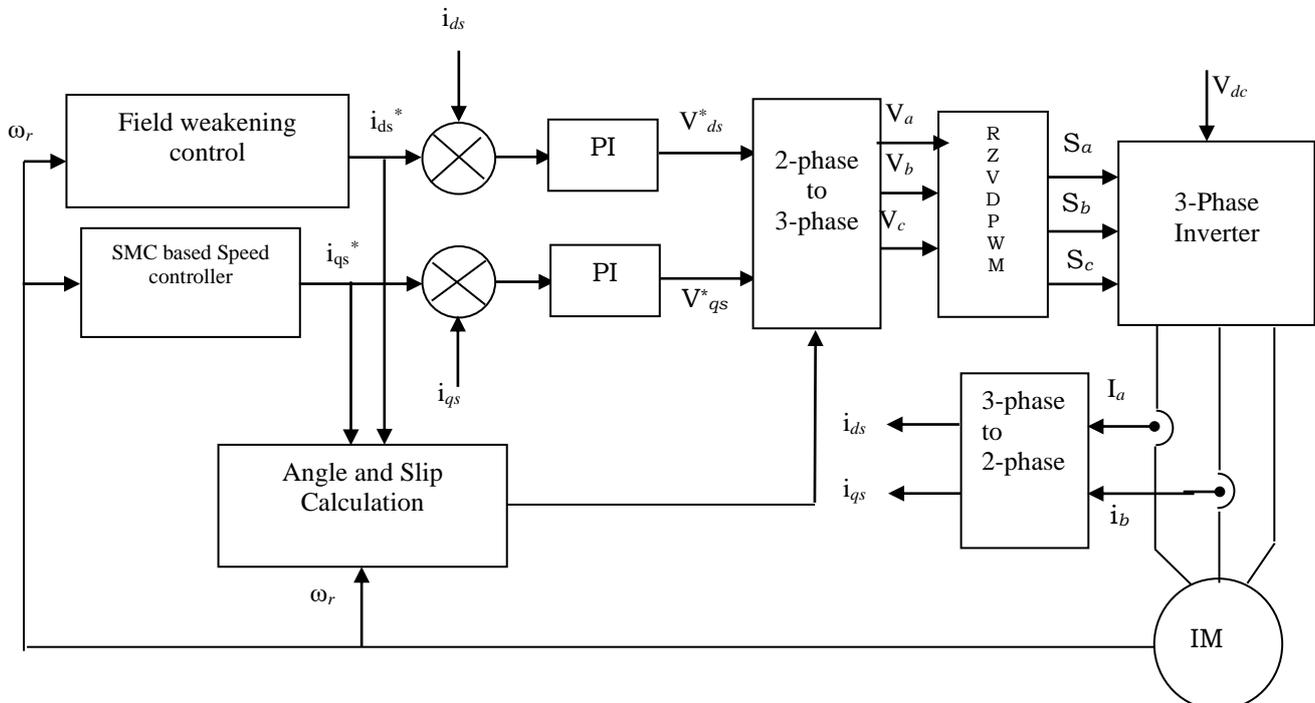


Fig. 3 Block diagram of SMC based RZVDPWM vector controlled induction motor

In VCIMD, Induction motor is driven by using VSI such that slip frequency can be changed according to a specific requirement. The slip speed is derived in the feed-forward manner by assuming the rotor speed is measured. From the decoupling control, the rotor flux is aligned onto the d-axis of synchronously rotating reference frame,

then $\lambda_{qr} = 0$ and $\lambda_{dr} = \lambda_r = L_m i_{ds}$. Then, the slip can be given as in (27).

$$s = \frac{L_m R_r}{L_r \lambda_r} i_{qs}$$

The Block diagram of SMC based RZVDPWM vector controlled induction motor is as shown in Fig. 3. So that the positions of rotor flux linkages are obtained by integration of addition of the rotor and actual speed. The main objectives in the Vector control scheme is to regulate λ_r and rotor speed to desired values. Flux linkages and rotor speed are not directly linked to the stator voltages which generates the both the variables. Here SMC Speed controller is used for controlling the speed. The input to the speed controller is angular reference speed and actual speed. The actual q- and d-axis stator currents are regulated to the two reference currents to get the stator voltages. The inverse two phase to three phase transformation is done and the three phase voltages are given to the RZVDPWM block, and thus the gating pulses are generated to VSI.

V. SIMULATION RESULTS AND DISCUSSIONS

To show the discussed random PWM approach, the numerical simulation studies are done using MATLAB. For the simulation results, 5KHz is taken as the switching Frequency (f_s) of the inverter. 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: $R_s = 1.57\Omega$, $R_r = 1.21\Omega$, $L_s = 0.17H$, $L_r = 0.17H$, $L_m = 0.165 H$ and $J = 0.089 Kg.m^2$.

The simulation results of SMC based SVPWM and RZVDPWM algorithms of vector controlled drive are as shown from Fig. 4 to Fig. 9.

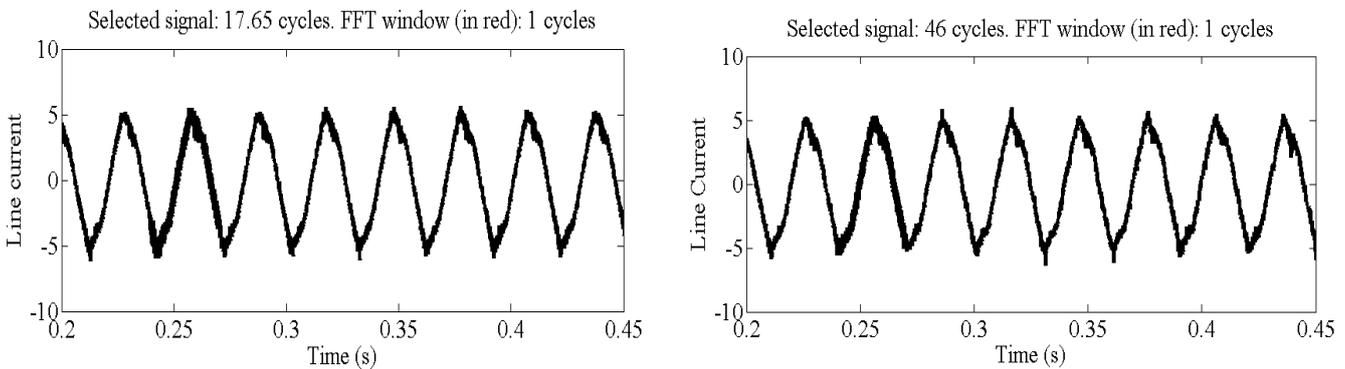


Fig. 4 Performance of steady state Line current of SMC based SVPWM and RZVDPWM algorithms of vector controlled drive

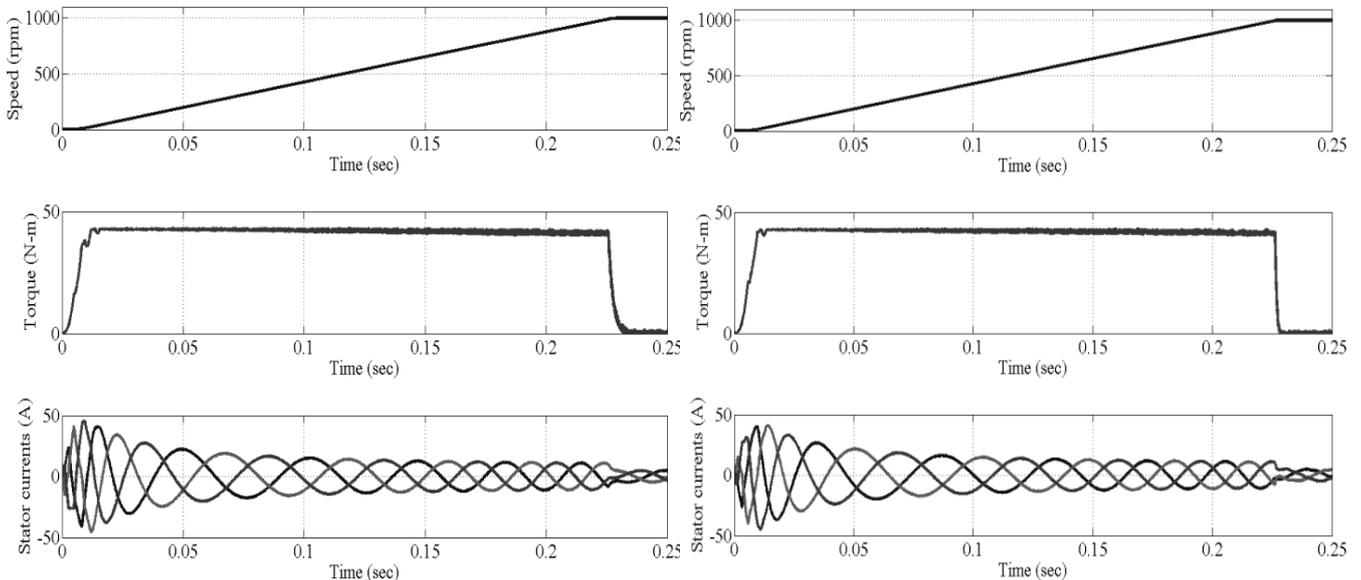


Fig. 5 Starting transients of smc based SVPWM and RZVDPWM algorithms of vector controlled drive

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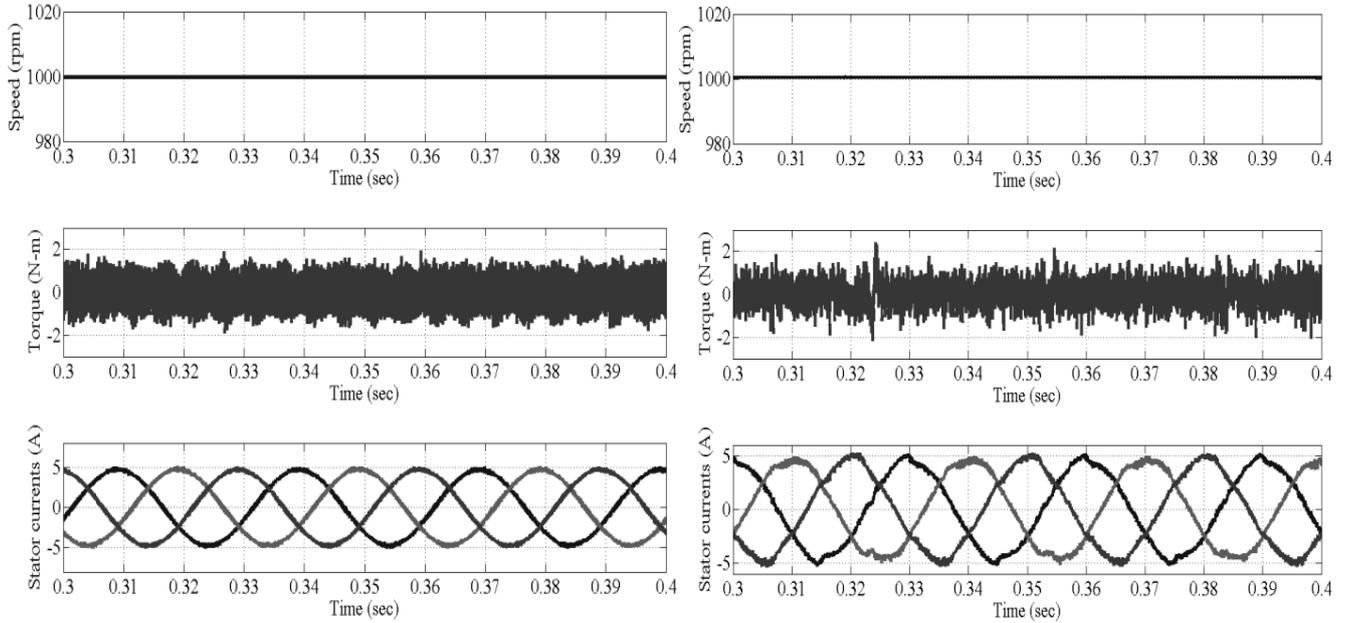


Fig. 6 Steady state plots of SVPWM and RZVDPWM algorithms of vector controlled drive

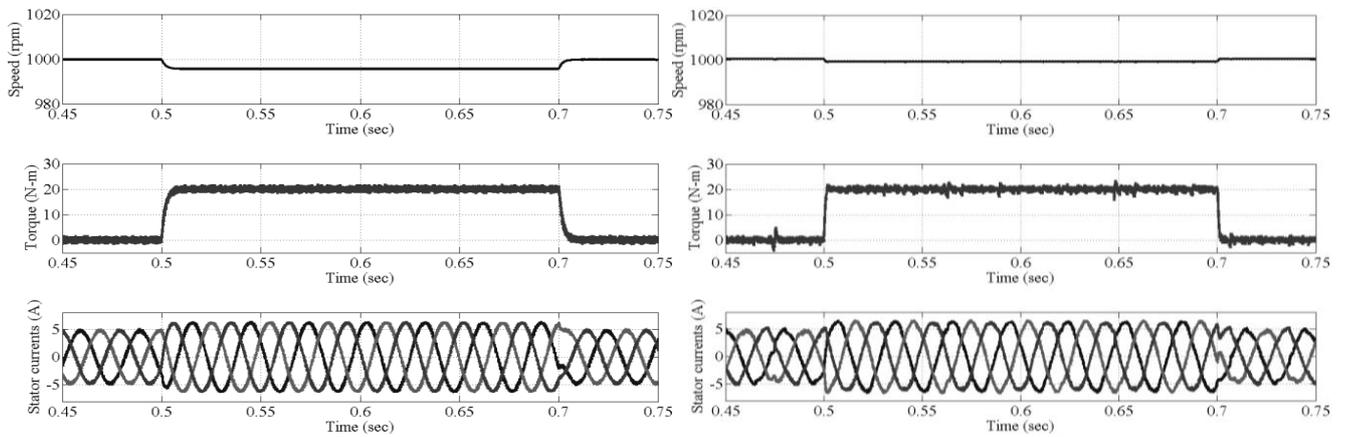


Fig. 7 Performance during step change in load torque (a load torque of 20 N-m is applied at 0.5 s and removed at 0.7 s) of SMC based SVPWM and RZVDPWM algorithms of vector controlled drive

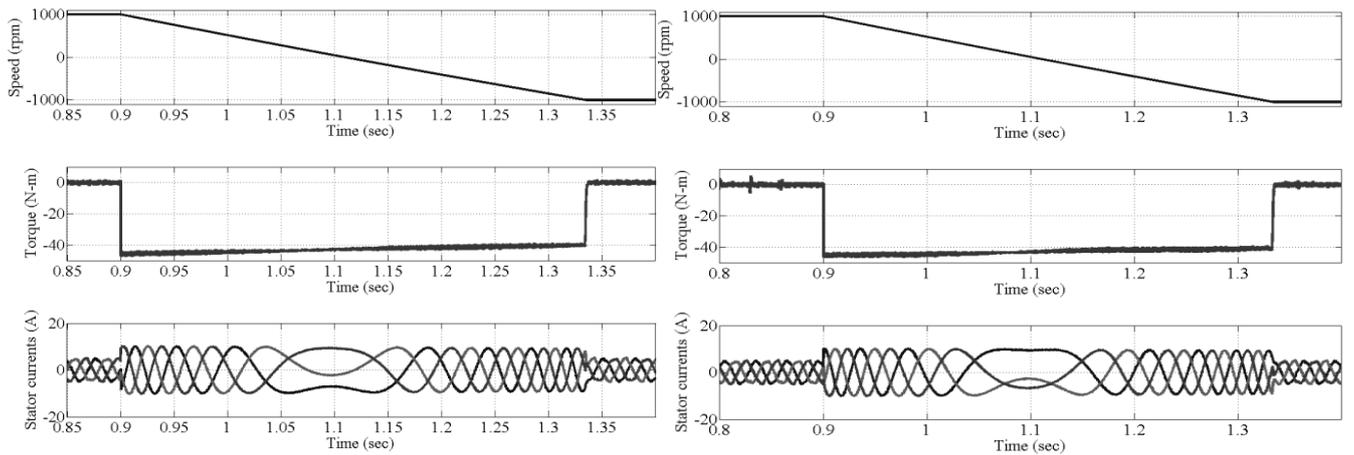


Fig. 8 Performance during speed reversal operation (Speed is changed from (+1000 rpm to -1000 rpm) of SMC based SVPWM and RZVDPWM algorithms of vector controlled drive

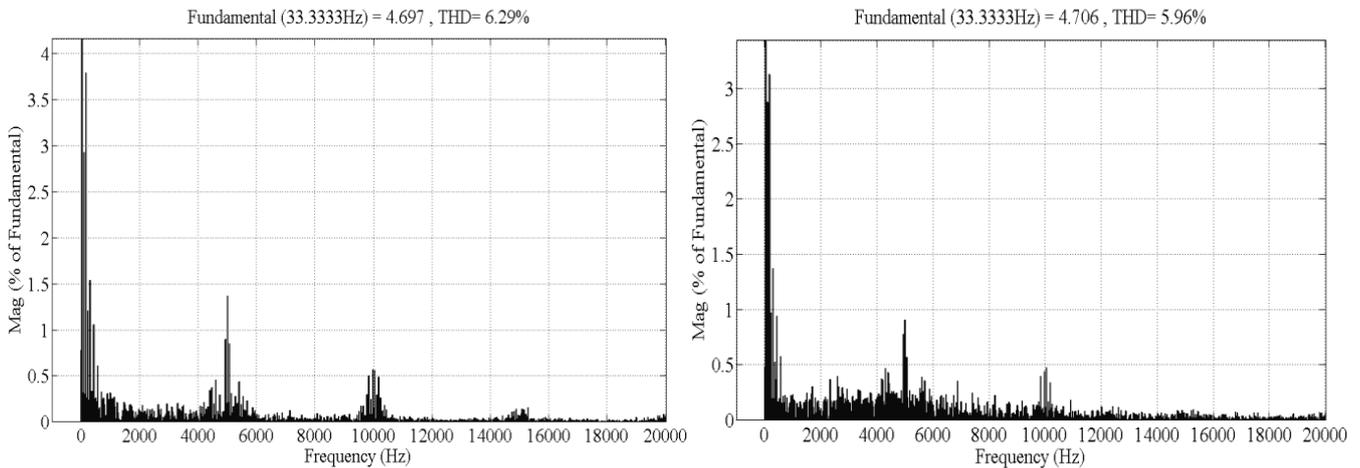


Fig. 9 Harmonic spectra of steady state line current in SMC based SVPWM and RZVDPWM algorithms of vector controlled drive

By seeing the results it can be concluded that the proposed algorithm gives good performance during the transient and steady state conditions. The proposed algorithm has been developed by using Simplified PWM sequence along with SMC controller in order to improve the performance of the speed during step change in load. The harmonic spectra of steady state line current of RZVDPWM technique gives spread spectra which is necessary to reduce the acoustical noise when compared to the SVPWM technique.

VI. CONCLUSION

In this paper, an sliding mode controller (SMC) based Random Zero vector Distribution PWM (RZVDPWM) algorithm of vector controlled induction motor drive for better speed response with reduced Acoustical Noise is analyzed. As the proposed approach eliminates the angle calculation, it is characterized by low computational overhead and easy for implementation. From the simulation results, it can be observed that the proposed algorithm gives superior waveform quality when compared with the SVPWM algorithm. Moreover, as the proposed algorithm gives distributed harmonic spectra, it reduces the acoustical noise of the induction motor. Moreover performance of the speed during step variation in the load (a load torque of 20 N-m is applied at 0.5 s and removed at 0.7 s) is maintained at the same level (1000 rpm) without any deviation. Hence the proposed concept reduces harmonic distortion and acoustical noise effectively when compared with SVPWM technique.

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FOC techniques.

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