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Space Vector Based PWM Algorithms to Reduce Current Ripple for an Induction Motor Drive

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ABSTRACT

Conventional space vector pulse width modulation employs conventional switching sequence, which divides the zero vector time equally between the two zero states in every sub cycle .Existing bus-clamping PWM techniques employ clamping sequences, which use only one zero state in a sub cycle. In the present work a new set of Bus clamping pulse width modulation (BCPWM) dealing with a special type of switching sequences, termed as “double-switching clamping sequences”, which use only one zero state and an active vector repeats twice in a sub cycle, will be proposed. It is shown analytically that the proposed BCPWM techniques result in reduced harmonic distortion in the line currents over CSVPWM as well as existing BCPWM techniques at high modulation indices for given a average switching frequency. Simulation is done on v/f controlled Induction Motor drive in MATLAB/SIMULINK environment. To validate the proposed method, simulation results are presented and discussed.

Keywords: Bus clamping pulse width modulation (BCPWM), double switching clamping sequences, harmonic distortion, induction, motor drives, space vector PWM, switching sequences.

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1. INTRODUCTION:

Improvements in fast switching power devices have led to an increased interest in voltage source inverters (VSI) with pulse width modulation (PWM) control. PWM-VSI fed induction motor drives have continuously drawn the attention of many researchers all around the world. Several PWM algorithms exist. Out of several approaches, triangular comparison (TC) approach and space vector (SV) approach are main implementation techniques. Conventional space vector PWM (CSVPWM) is described in (3) is popular and widely used PWM strategy, which has the advantages of lower current harmonics and a possible higher modulation index compared with the sine-triangle PWM method.

In the CSVPWM, the reference voltage vector situated in the appropriate sector is approximated by the time averaging over a sub cycle of the two adjacent active states and the two zero states. The CSVPWM algorithm employs equal division of zero voltage vector times within a sampling interval. However, by utilizing the freedom of zero state division, various DPWM methods can be generated. The DPWM methods give less harmonic distortion at higher modulation indices compared to CSVPWM. Now present work discusses new PWM algorithms for reduced current ripple. The proposed algorithm uses the concept of SVPWM switching times only. The proposed PWM algorithms employs the switching sequence, which results in the lowest harmonic distortion in the current over the given sampling interval. Simulation is done on inverter fed v/f controlled Induction Motor drive.

2. VOLTAGE SPACE VECTOR

The approach to PWM is based on the space vector representation of the voltage in the stationary reference frame. For a given set of inverter pole voltages (Vao, Vbo, Vco), the vector components (Vd, Vq) in the stationary reference frame are found by the forward Clarke transform as

$$V_s = \frac{2}{3}\left[V_{ao} + V_{bo}e^{j\frac{2\Pi}{3}} + V_{co}e^{j\frac{4\Pi}{3}}\right] \qquad (1)$$

The relationship between the phase voltages V_{an}, V_{bn}, V_{cn} and the pole voltages V_{ao}, V_{bo} and V_{co} is given by:

$$V_{ao}=V_{an}+V_{no}; \quad V_{bo}=V_{bn}+V_{no}; \quad V_{co}=V_{cn}+V_{no} \qquad (2)$$

$$\text{Since } V_{an}+V_{bn}+V_{cn}=0, \qquad V_{no} = \frac{(V_{ao}+V_{bo}+V_{co})}{3} \qquad (3)$$

Where, V_{no} is the common mode voltage.

From (1) and (2) it is evident that the phase voltages V_{an}, V_{bn}, V_{cn} also result in the same space vector V_s. The space vector V_s can also be resolved into two rectangular components namely V_d and V_q. It is customary to place the q-axis along the a-phase axis of the Induction Motor. The relationship between V_d , V_q and the instantaneous phase voltages V_{an} ,V_{bn} ,V_{cn} can be given by the conventional three-phase to two-phase transformation as follows:

$$\begin{bmatrix} Vq \\ Vd \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Van \\ Vbn \\ Vcn \end{bmatrix} \qquad (4)$$

The set of balanced three-phase voltages can be represented in the stationary reference frame by a space vector of constant magnitude, equal to the amplitude of the voltages, and rotating with angular speed ω=2πf. The space vector locations for the switching states may be evaluated using (1). Then, all the possible switching states of an Inverter may be depicted as voltage space vectors as shown in Fig 1. The space vector locations for a two-level inverter form the vertices of a regular hexagon, forming six symmetrical sectors as shown in Fig 1.

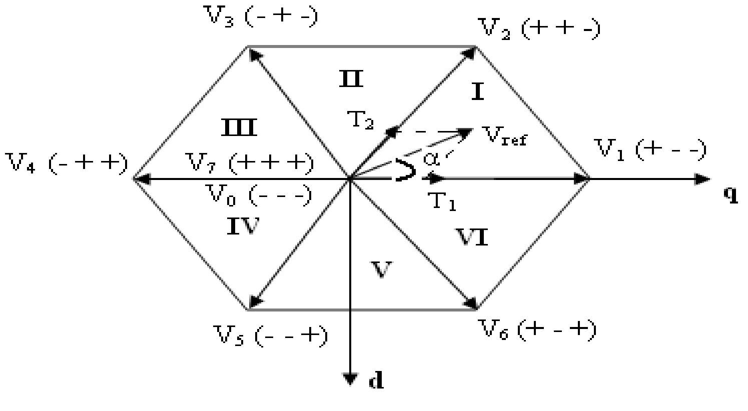


Fig 1 Inverter states and voltage vectors of three-phase inverter

From (1), it is shown that the active voltage vectors or active states can be represented as

$$V_k = \frac{2}{3} V_{dc} e^{j(k-1)\frac{\Pi}{3}} \qquad \text{Where k (sector)} = 1, 2. . 6 \qquad (5)$$

SWITCHING STATES OF THREE-PHASE INVERTER

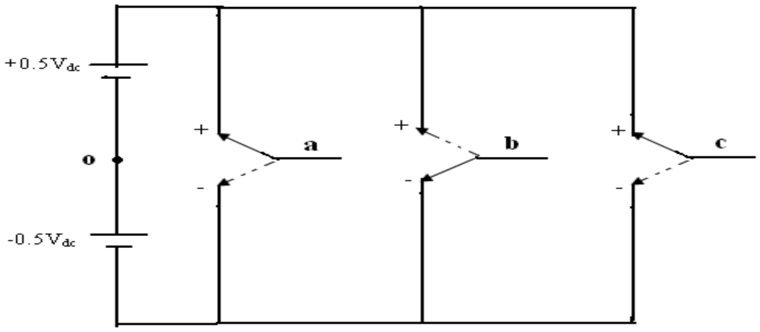


Fig 2Three-Phase Voltage Source Inverter

A three-phase voltage source inverter has eight Switching States as shown in Fig 2. The two zero states (- - - and + + +), which short the motor terminals, produce a voltage vector of zero magnitude as shown in the figure. The other six states, or the active states, produce an active voltage vector each. These active vectors divide the space vector plane into six sectors and are of equal magnitude as shown. The magnitudes are normalized with respect to the dc bus voltage $V_{dc.}$

3. SWITCHING SEQUENCES

In space vector-based PWM, the voltage reference, is provided by revolving reference vector (see Fig 1), which is sampled once in every subcycle, T_S. Given a sampled reference vector of magnitude V_{REF} and angle α in sector I as shown in Fig. 1, the dwell times of active vector 1, active vector 2 and zero vector in the subcycle are given by T_1, T_2, and T_z, respectively.In CSVPWM divides T_z equally between 0 and 7, and employs the switching sequence 0-1-2-7 or 7-2-1-0 in a sub cycle in sector I. The conditions to be satisfied by a valid sequence in sector I are as follows.

1. The active state 1 and the active state 2 must be applied at least once in a sub cycle.
2. Either the zero state 0 or the zero state 7 must be applied at least once in a sub cycle.
3. In case of multiple application of an active state, the total duration for which the active state is applied in a sub cycle must satisfy (1).
4. The total duration for which the zero vector (either using the zero state 0 or the zero state 7) is applied in a sub cycle must satisfy (1).
5. Only one phase must switch for a state transition.
6. The total number of switching‘s in a sub cycle must be less than or equal to three.

Conditions 1 to 4 ensure volt-second balance. Condition 5 avoids unwanted switching’s to keep the switching losses low. Condition 6 ensures that the average switching frequency is less than or equal to that of CSVPWM for a given sampling Frequency.

Principle of volt-second balance:

The reference vector is sampled at equal intervals of time, referred to as sampling time period. Different voltage vectors that can be produced by the inverter are applied over different durations with in a sub cycle such that the average vector produced over the sub cycle is equal to the sampled value of the reference vector, both in terms of magnitude and angle.

As all the six sectors are symmetrical, here the discussion is limited to sector-I only. Let $T_1$and T_2 be the durations for which the active states 1 and 2 are to be applied respectively in a given sampling time period T_S . Let T_z be the total duration for which the zero states are to be applied.

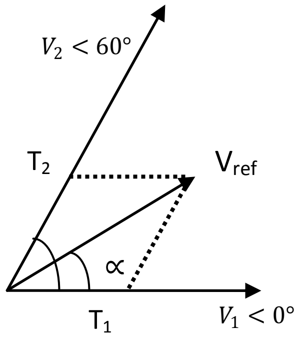
From the principle of volt-time balance T_1, T_2 and T_z can be calculated as:

$$V_{ref}\angle\alpha^\circ * T_s = \frac{2}{3}V_{dc}\angle 0^\circ * T_1 + \frac{2}{3}V_{dc}\angle 60^\circ * T_2 + 0 * T_z$$

$$V_{ref}(\cos\alpha + j\sin\alpha) * T_s = \frac{2}{3}V_{dc} * T_1 + \frac{2}{3}V_{dc}(\cos 60^o + j\sin 60^o) * T_2$$

$$T_1 = \frac{2\sqrt{3}}{\pi}M_i(\sin(60^o - \alpha))T_s \qquad T_2 = \frac{2\sqrt{3}}{\pi}M_i(\sin\alpha)T_s$$

$$Tz = Ts - T1 - T2$$



Where **'M_i '** is the modulation index, given by $M_i = \dfrac{Vref}{\frac{2}{\pi}Vdc}$

In the SVPWM algorithm, the total zero voltage vector time is equally distributed between V_0 and V_7. Also, the zero voltage Vector time is distributed symmetrically at the start and end of the sub cycle in a Symmetrical manner. Moreover, to minimize the switching frequency of the inverter, it is desirable that switching should take place in one phase of the inverter only for a transition from one state to another.

A typical switching sequence when the sample is situated in sector-I Switching sequences in all the sectors for SVPWM:

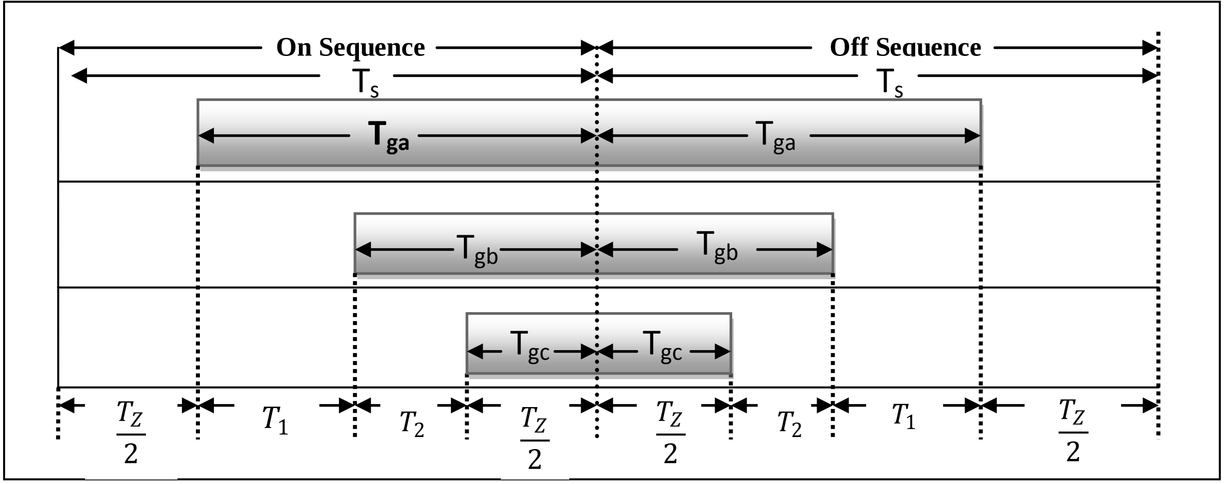


Fig.3. PWM Gate signals when the reference vector in sector-I (0127)

Possible Switching sequences in sector- I

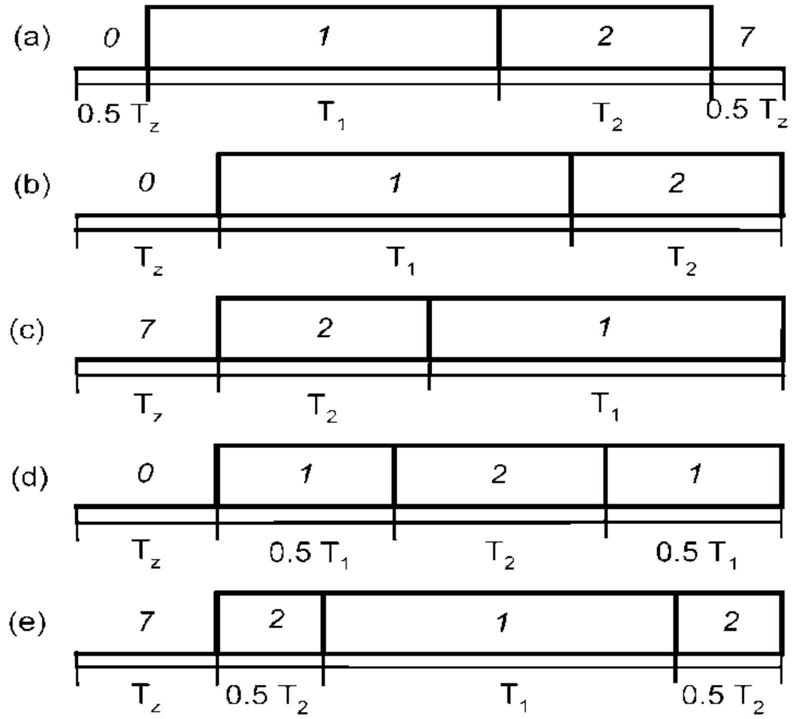


Fig 4 (a)-(e) Different possible switching sequences in sector I

T_1, T_2 and T_Z can be applied in different sequences within a subcycle as shown in Fig4. All these sequences involve only one switching per state transition. The multiplicity of possible switching sequences in a subcycle can be attributed to the following two factors.

First, the zero voltage can be applied either using the zero state 0 or the zero state 7. Conventional sequence 0127 applies the zero states 0 and 7 for equal durations of time. Clamping sequences 012 and 721 as shown in Fig.4 (b) & (c) use only one zero state for the entire duration Tz in a subcycle. This results in clamping of a phase to one of the dc buses.

Second, a given active vector need not be applied continually for the required duration. For example, the active vector 1 can be applied over two intervals of time within the subcycle adding up to T_1. Such multiple application of an active vector within a subcycle leads to sequence 0121 and 7212 shown in Fig.4 (d) and (e). These sequences, respectively, divide T_1 and T_2 into equal halves. More such sequences are also possible. Sequence 7212 leads to clamping of R-phase to the positive dc bus, while sequence 0121 results in clamping of B-phase to the negative dc bus. Both sequences result in Y-phase switching twice in a subcycle. Hence, sequences 0121 and 7212 are termed “double-switching clamping sequences”.

The sequences illustrated in Fig. 4 are employed in sector I. The equivalent sequences in the other sectors are as listed in Table I. The PWM gating signals for the CSVPWM is shown in Fig 3.

Table 1 Switching sequences in all the sectors for SVPWM

Sector	Conventional sequence	Clamping sequences	Double-switching Clamping sequences
I	(0127, 7210)	(012, 210), (721, 127)	(0121, 1210), (7212, 2127)
II	(7230, 0327)	(723, 327), (032, 230)	(7232, 2327), (0323, 3230)
III	(0347, 7430)	(034, 430), (743, 347)	(0343, 3430), (7434, 4347)
IV	(7450, 0547)	(745, 547), (054, 450)	(7454, 4547), (0545, 5450)
V	(0567, 7650)	(056, 650), (765, 567)	(0565, 5650), (7656, 6567)
VI	(7610, 0167)	(761, 167), (016, 610)	(7616, 6167), (0161, 1610)

4. INDUCTION MOTOR MODELLING

The most popular method of Speed control is V/F control. The Flux and Torque are also function of frequency and voltage respectively the magnitude variation of control variables only. The air gap voltage of induction motor is

$$E_{ag} = k\ f\ \Phi_{ag}$$

$$\Phi_{ag} = \text{constant} = \frac{Eag}{f} = \frac{v}{f}$$

Speed is varied by varying the frequency; maintain v/f constant to avoid saturation of flux. With constant v/f ratio, motor develops a constant maximum torque. Among the various reference frames, V/F uses the stationary reference frame. Hence, in this work, the induction motor model is developed in the stationary reference frame, which is also known as Stanley reference frame. The stator and rotor flux linkages in stator reference frame are defined as.

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$

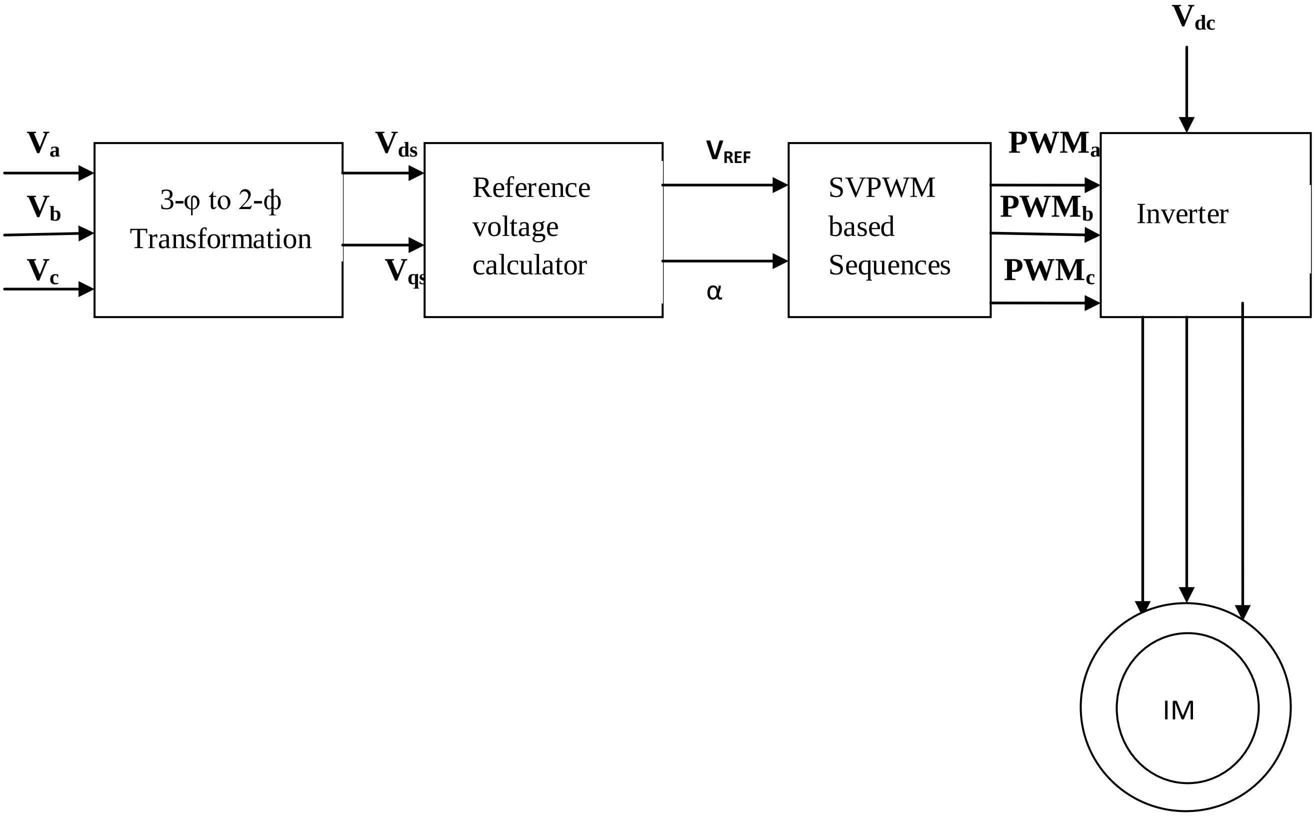
$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt}$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt}$$

$$0 = R_r i_{dr} + \omega_r \lambda_{qr} + \frac{d\lambda_{dr}}{dt}$$

$$0 = R_r i_{qr} - \omega_r \lambda_{dr} + \frac{d\lambda_{qr}}{dt}$$

BLOCK DIAGRAM



In the above circuit the three pwm techiniques are used and the total harmonic distortion are simulated in matlab:

The different pulses given are:

1. Convention sequence
2. Clamping sequences
3. Double-switching Clamping sequences

5. SIMULATION RESULTS:

To validate Space Vector Based PWM Algorithms to Reduce Current Ripple for an Induction Motor Drive .Simulation test can be done using Matlab/Simulink model. The parameters used for simulation and output results will be given below
The induction motor used in this case study is a 4 KW, 1470 rpm, 4-pole, 3-phase induction motor having the following parameters:

R_s =7.83 Ω R_r = 7.55 Ω
L_m = 0.4535 H L_s = 0.475 H; L_r = 0.475 H
J = 0.06 Kg - m^2 B=0.01 N-m.sec/rad

For Space Vector based PWM algorithms to reduce current ripple for an induction motor drive in this various sequences harmonic distortion are compared. The results for CSVPWM are shown

Output Waveforms for CSVPWM

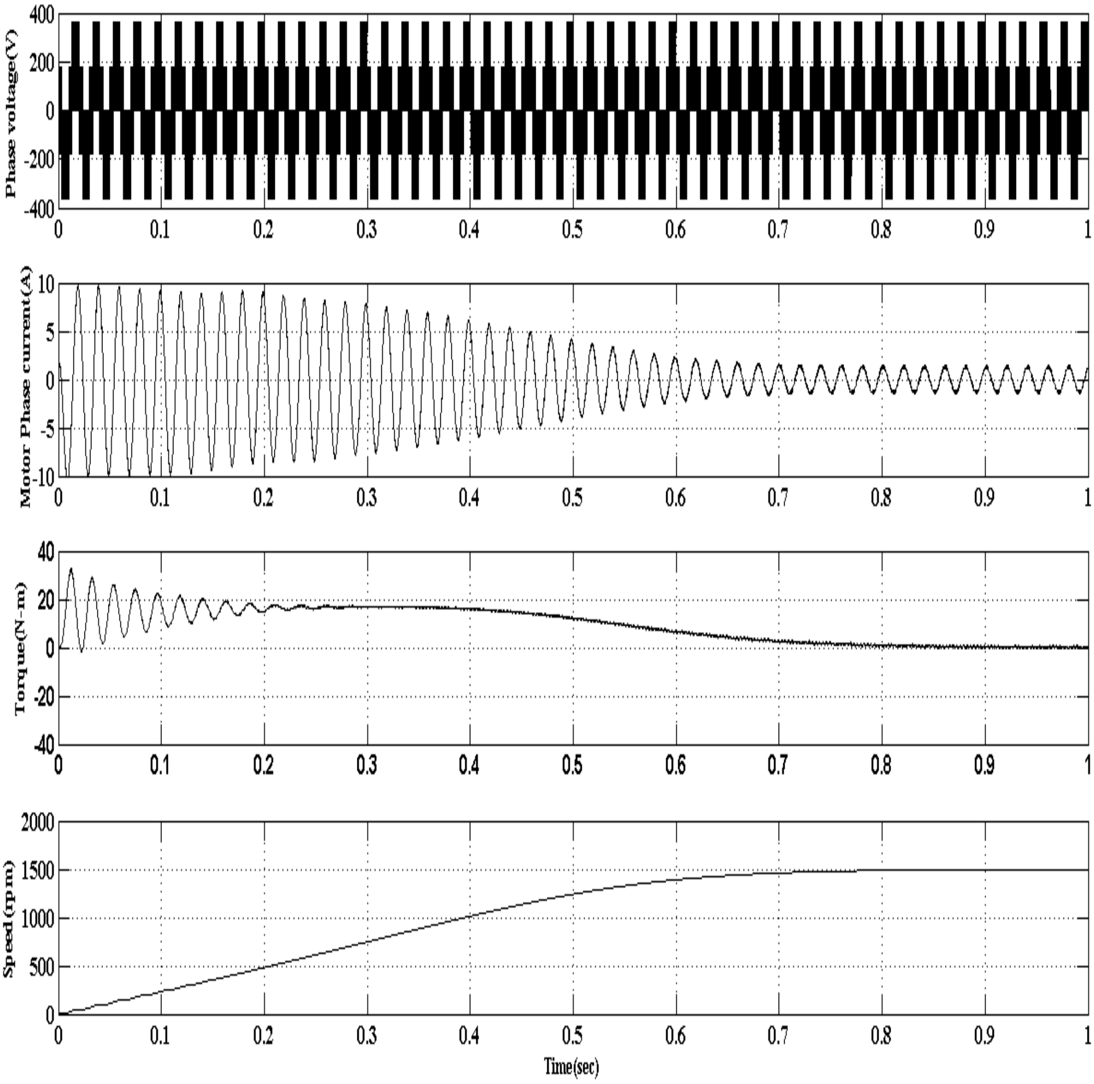


Fig 5: Output Waveforms for CSVPWM

The operation of the induction motor fed with output of the inverter operated by different PWM algorithms like CSVPWM(0127) ,Clamping Sequences (012&721),Double - Switching Clamping Sequences (0121 &7212),are shown and the output voltage waveform is similar to all the sequences the dc voltage considered for inverter is 540Vand the output voltage obtained at inverter is 2/3Vdc=360V,initially when the motor is started due to the large inertia in the rotor it posses large amount of torque so it take large amount of current .Form the Fig5 it can be observed that upto 0.8sec the starting transients are shown during this period the speed starts from 0 rpm and reaches nearly 1500rpm ,that means steady state during this time ,Tα1/N condition is satisfied and before reaches to the steady state the current waveform gradually reduce and reaches to the min value of the current less than 4 amps in steady state .That means after 0.8sec the torque reaches zero and current reaches min value this min value current appears because of steady state/no load effect.

Simulation results of Space vector based pwm algorithms to reduce current ripple for an induction motor drive

1 CONVENTION SEQUENCE

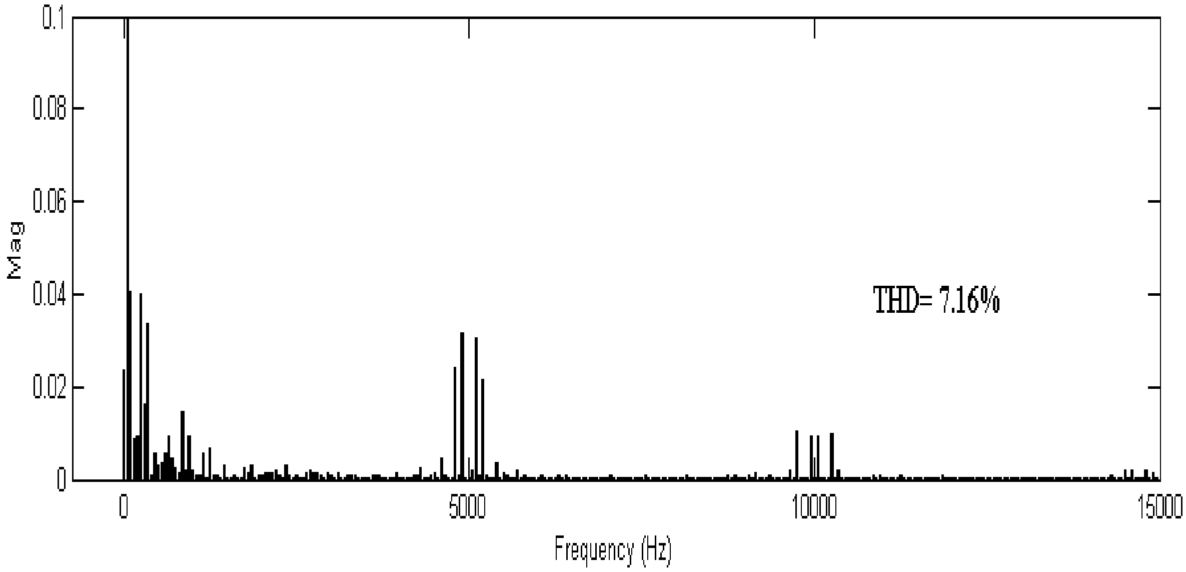


Fig 5.1 Simulation results for CSVPWM at Mi =0.815

2 CLAMPING SEQUENCESE (012 & 721)

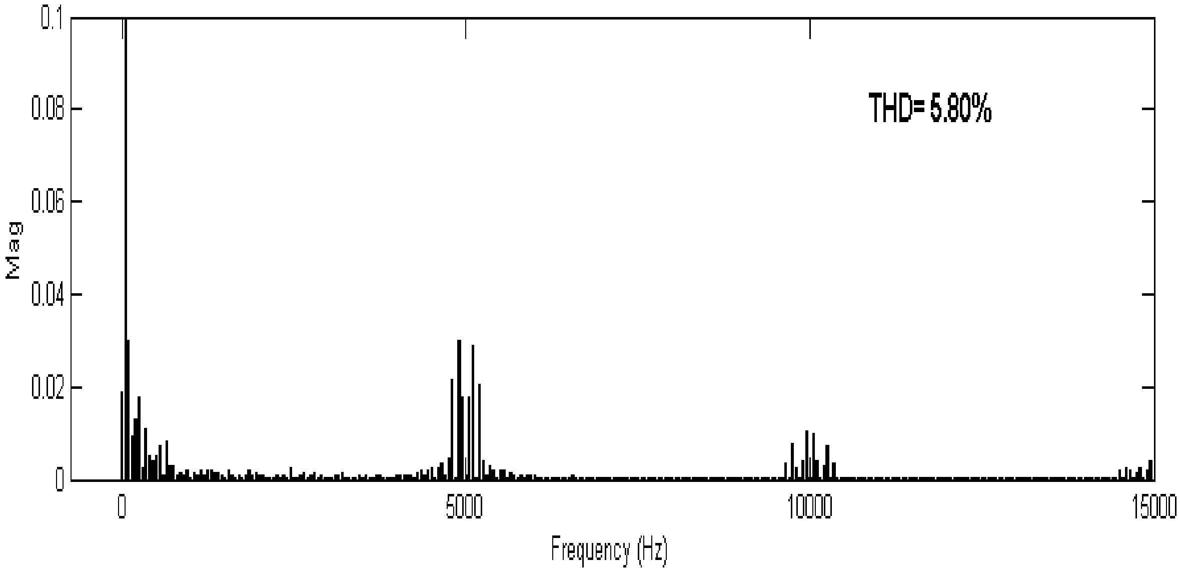


Fig 5.2 Simulation results for Clamping sequence 012 at Mi =0.815

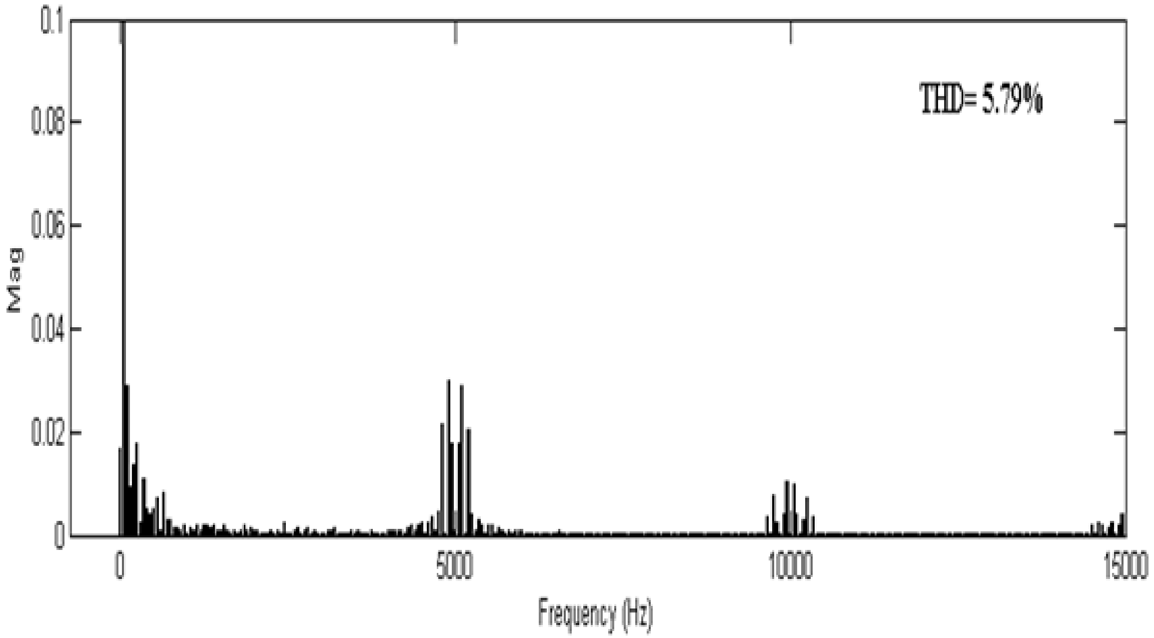
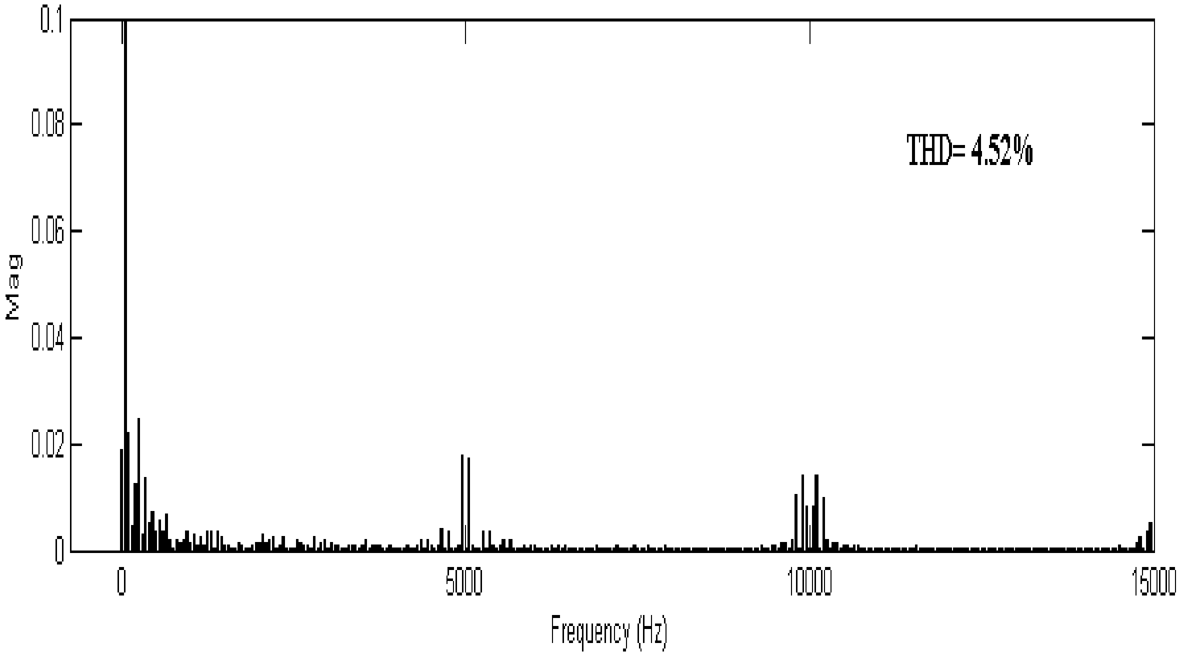
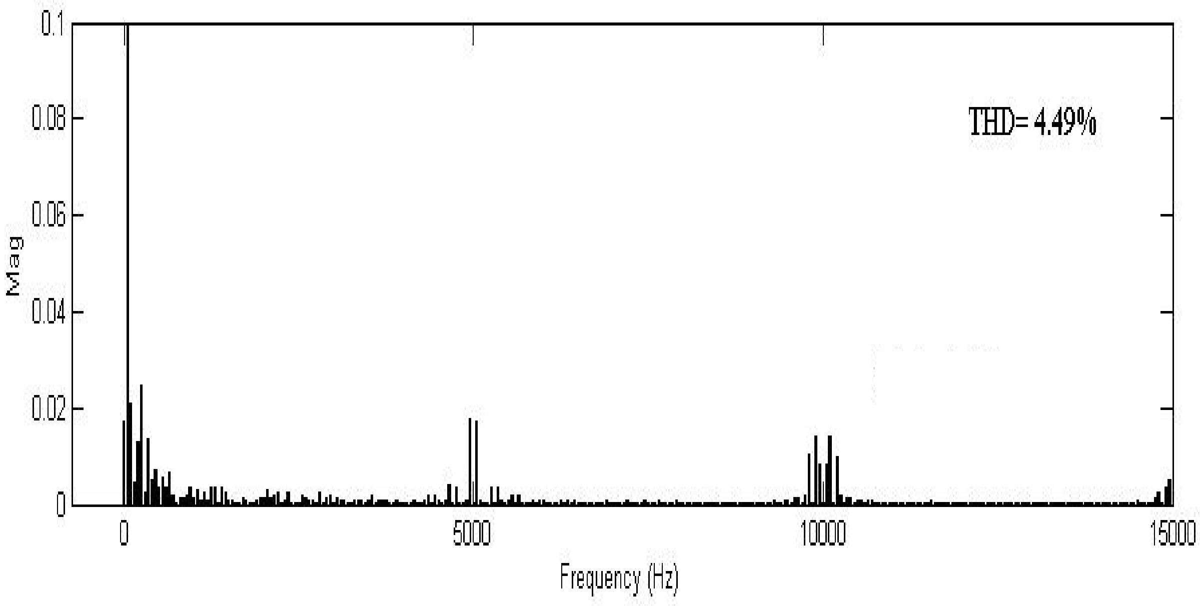


Fig 5.3 Simulation result for Clamping sequence 721 at Mi =0.815

3 DOUBLE-SWITCHING CLAMPING SEQUENCES: (0121 & 7212)



5.4 Simulation result for Double-Switching Clamping sequence 0121 at Mi =0.815



5.5 Simulation result for Double-Switching Clamping sequence 7212 at Mi =0.815

PERFORMANCE OF DIFFERENT SEQUENCES TOTAL HARMONIC DISTORTION AT Mi=0.815

S.NO	SEQUENCES	TOTAL HARMONIC DISTORTION
1	CSVPWM 0127	7.16%
2	CLAMPING SEQUENCES 012 721	5.80% 5.79%
3	DOUBLE-SWITCHING CLAMPING SEQUENCES 0121 7212	4.52% 4.49%

From the above table when CSVPWM sequences are applied the harmonic distortions are more compared to the clamping and double switching clamping sequences at higher modulation indices. Fig 5.1 to Fig 5.5 shows the harmonic distortion of these sequences at modulation index Mi=0.815 at this modulation index double switching clamping sequence 0121 and 7212 are with less harmonic distortion.

6. CONCLUSION

In CSVPWM the ripples in current are very high. In order to improve the performance of Inverter fed Induction motor drive in terms of ripples, in this paper Space Vector based PWM algorithms for Induction motor has been developed. A class of bus-clamping PWM (BCPWM) techniques, which employ only the double-switching clamping sequences, is proposed. The proposed BCPWM techniques are studied, and are compared against conventional space vector PWM (CSVPWM) and existing BCPWM techniques at a given average switching frequency. The proposed families of BCPWM techniques result in less current distortion than CSVPWM and the existing BCPWM techniques at high modulation indices .The simulations of different sequences have been carried out using Matlab/Simulink software to validity the proposed algorithms.

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