Modified Space Vector PWM Sequences for High Power Drives

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Abstract
The inbuilt advantage of the space vector based pulse width modulation (SVPWM) strategy lies in the ease in choosing different switching sequences to generate the required reference vector than with the conventional triangle comparison approach. However, SVPWM technique involves various steps which are mathematically intense. In order to reduce this complexity, a simplified algorithm is proposed here. This work aims at reducing of harmonic distortion in high-power drives, which operate at significantly lower switching frequencies. In this paper, conventional SVPWM (CSVPWM) and Modified SVPWM (MSVPWM) sequences are applied to a three level neutral point clamped (NPC) inverter fed V/f controlled induction motor drive. The two performance measuring parameters weighted total harmonic distortion (WTHD) of the line voltages and total harmonic distortion (THD) in no-load stator current for odd and even samples are compared for different sequences employing simplified algorithm.
Keywords:ADPWM, CSVPWM, DPWM, MSVPWM

I. Introduction

The role of multi-level inverters (MLI) increased in industry and academia as one of the preferred choices of power conversion for high power applications. MLI's produce output waveform of better quality than two level inverters for the same device switching frequency. Three-level NPC inverters can handle higher DC bus voltages than two level inverters with same device voltage ratings [1]-[4]. The power circuit of three-level NPC inverter is shown in Fig.1. The pole voltage, V_{AO} is the potential of A-phase with reference to the potential at midpoint of the DC link designated by 'O', and it depends on the position of A-phase switches. The switch position, state and pole voltages are shown in Table I.

The performance of the converter in high-power applications is determined, based on how the output voltage waveform of voltage source inverter is synchronized with its fundamental component. The quality of output waveform of an inverter depends on pulse width modulation (PWM) technique used and one of the performance measures is through THD in line voltages and currents. There are two approaches for the generation of PWM pulses; triangle comparison approach and SVPWM approach [5]. Among these two, SVPWM has greater flexibility in terms of switching sequence selection in which numerous switching states can be applied to generate the given reference vector. Such switching sequences involve clamping of a phase or discontinous PWM (DPWM) sequences, double switching of a phase or advanced DPWM (ADPWM) sequences etc and are appropriate to reduce the harmonic distortion at high modulation indices, [4], [5]. Employing these sequences improve the efficiency of the converter with reduced switching losses. Also, through proper switching states choice, it is possible to get synchronization and symmetry in SVPWM algorithm.

In order to further improve the performance of the converter MLI's are generally used in high-power applications where the switching frequency is less than 1 kHz [1]. At low switching frequencies, the pulse number P, defined as the ratio of switching frequency, f_{sw} to the fundamental frequency, f is low. To make sure that the waveform quality is good under such conditions, all the waveform symmetries and synchronization has to be maintained [2], [3], [5]. In case of synchronized PWM, pulse number should be an integer. Three phase symmetry (TPS) and half wave symmetry (HWS) require further restraint on P. In case of synchronized CSVPWM, the pulse number belongs to series 2,5,8,11,…..if the above supposed symmetries are to be preserved [2], [3]. Conversely, by taking the advantage of the flexibilities in terms of switching sequences offered by SVPWM, MSVPWM approach relaxes this restriction on P considerably. This approach can produce PWM waveforms of any integral pulse number, P maintaining all the waveform symmetries [2], [3].

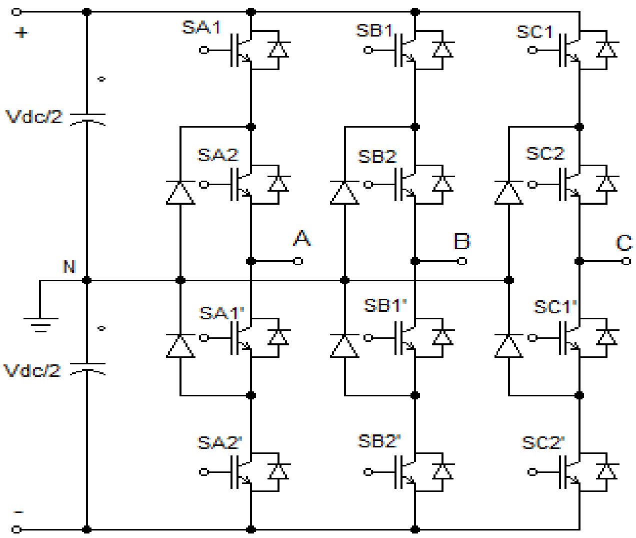

Fig.1. Neutral point clamped (NPC) three-level inverter

Besides the advantage in terms flexibility in sequence selection, SVPWM based approach is computationally incommodious [2], [3]. The main objective of this paper is to reduce the computational complexity in SVPWM algorithm. The simplified algorithm reduces computational burden and memory requirement of the controllers and hence low cost micro-controllers can be used for executing the algorithm. The steps involved in simplified algorithm are explained in section III. CSVPWM and MSVPWM sequences for odd and even samples are considered in this paper. Simulation results are compared for a switching frequency of 1.65KHz.

II. EXISTING ALGORITHM FOR SVPWM

The space phasor diagram for three-level NPC inverter is shown in Fig. 2. There are six states corresponding to six vectors each of magnitude V_{dc}, six states corresponding to six vectors each of magnitude $0.866V_{dc}$, twelve states corresponding to six vectors each of magnitude $0.5V_{dc}$ and three states corresponding to a zero vector. The space plane containing all the possible states and their corresponding vectors are shown in Fig. 2.

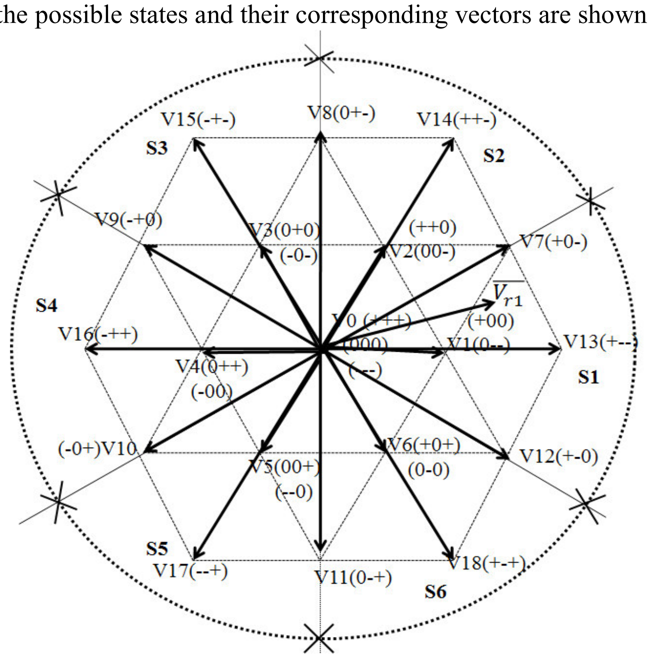

Fig.2. Space vectors of a three-level inverter with sector identification

In SVPWM approach the reference vector $\overline{V_r}$, is synthesized by time averaging the three nearest vectors $\overline{V_x}$, $\overline{V_y}$,

TABLE I
SWITCH STATUS, STATE AND POLE VOLTAGE

Switch position	State	Pole voltage, v_{AO}
SA1=ON, SA2=ON	+	Vdc/2
SA1=OFF, SA2=ON	0	0
SA1=OFF,SA2=OFF	-	-Vdc/2

$\overline{V_z}$ in a subcycle as given in (1).

$$\overline{Vr}\overline{Ts} = \overline{Vx}Tx + \overline{Vy}Ty + \overline{Vz}Tz \quad (1.1)$$

$$T_s=T_x+ T_y + T_z \quad (1.2)$$

Here $T_{x,}$, $T_y$and T_z are the dwell time of the inverter legs in the nearest states corresponding to $\overline{V_x}$, $\overline{V_y}$, and $\overline{V_z}$ respectively. So identifying the three nearest states and computation of the dwell times, of each state is crucial in this approach. Also selecting the opt state out of available redundant states corresponding to 0.5Vdc and zero states is another problem to be addressed. Both issues are considered in this paper.

The vectors of magnitudes $0.5V_{dc}$ are here referred as 'pivot vectors', as state space plane of a two level inverter pivots around these states in a three level inverter. The pivot vector nearest to $\overline{V_r}$ is traced out and is subtracted from $\overline{V_r}$. The resultant is the new reference vector, $\overline{V_r'}$ to be synthesized by the equivalent two-level inverter, with in the three-level inverter. This is explained with the aid of Fig.3. To synthesize $\overline{V_r'}$, the inverter has to dwell for T_x' time in state x′, T_y' time in state y′, and the remaining time, T_z' equally in Z_x' and Z_y'. With reference to the instantaneous position of $\overline{V_r'}$ from Fig.3, Vx′, Vy′, $Z_x'$and Z_y' are V_7(+0-), V_{13}(+--), V_1(0--) and V_1(+00) respectively. These nearest states, V_x' and V_y' are the two active states and Z_x' and Z_y' are the two inactive or zero states, can be applied in different ways to form different sequences that can synthesize the same reference vector. A few popular among them CSVPWM, DPWM and ADPWM sequences. The dwell times of each inverter states are calculated as in the case of two-level inverter and this involves trigonometric functions and are computationally intense [2] – [4].

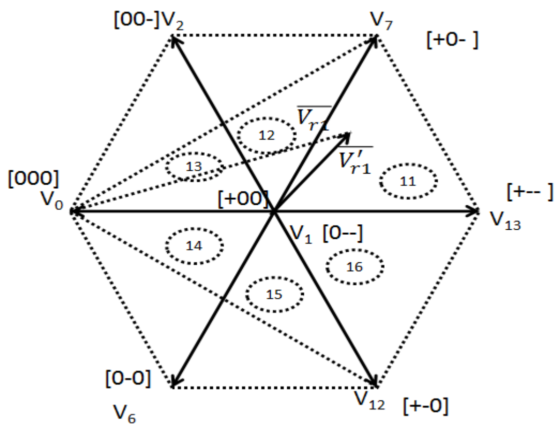

Fig.3. Space vector diagram of an equivalent two level inverter

TABLE II
SEQUENCES FOR CSVPWM

sample	N=odd		N=even	
1^{st}	$z_x \to x \to y \to z_y$	$z_y \to y \to x \to z_x$	$z_x \to x \to y \to z_y$	$z_y \to y \to x \to z_x$
2^{nd} to $(N\text{-}1)^{th}$	$z_y \leftrightarrow y \leftrightarrow x \leftrightarrow z_x$	$z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$	$z_y \leftrightarrow y \leftrightarrow x \leftrightarrow z_x$	$z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$
N^{th}	$z_x \to x \to y \to z_y$	$z_y \to y \to x \to z_x$	$z_y \to y \to x \to z_x$	$z_x \to x \to y \to z_y$
Pulse Number (P)	$\frac{3N+1}{2}$	$\frac{3N+1}{2}$	$\frac{3N+1}{2}$	$\frac{3N+1}{2}$

TABLE III
SEQUENCES FOR MSVPWM

sample	N=odd		N=even	
1^{st}	$z_x \to x \to y \to z_y$	$z_y \to y \to x \to z_x$	$z_x \to x \to y \to z_y$	$z_y \to y \to x \to z_x$
2^{nd} to $(N\text{-}1)^{th}$	$z_y \leftrightarrow y \leftrightarrow x \leftrightarrow z_x$	$z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$	$z_y \leftrightarrow y \leftrightarrow x \leftrightarrow z_x$	$z_x \leftrightarrow x \leftrightarrow y \leftrightarrow z_y$
N^{th}	$z_x \to x \to y$	$z_y \to y \to x$	$z_y \to y \to x$	$z_x \to x \to y$
Pulse Number (P)	$\frac{3N-1}{2}$	$\frac{3N-1}{2}$	$\frac{3N-1}{2}$	$\frac{3N-1}{2}$

To achieve synchronization in PWM schemes, the number of samples per sector (N) must be an integer. This assures synchronization, HWS and TPS [2], [3]. Also, the samples will be placed symmetrically within the sector. This achieves quarter wave symmetry (QWS) in addition to the above conditions [2], [3]. The present work investigates the performance of different sequences for odd and even values of N. The sequences considered are shown in Fig. 4. The sequences utilizing only 0127 or 7210 are desiganted as 0127, 7210 respectively and those utilizing 012 and 721in addition to the 0127 and 7210 are designated as 012 and 721 respectively. 0127 and 7210 are considered as CSVPWM sequences and 012 and 721 are termed as MSVPWM sequences and the order of execution in different samples is tabulated in Table II, III.

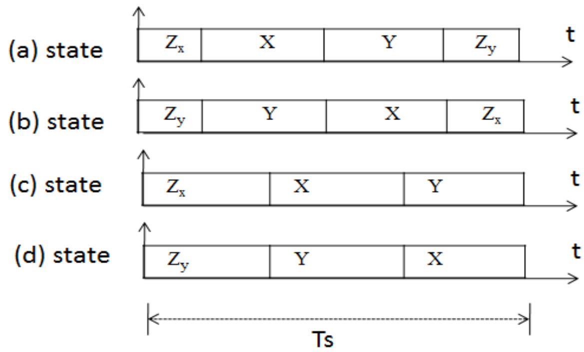

Fig.4.a) 0127 b) 7210 c) 012 and d) 721 switching sequences for realization of the same reference vector

In 0127 sequence, for odd number of samples there exists one transition during sector change over whereas for even samples there occurs three transitions during sector change over. With 7210, same is the case with odd samples but with even samples number of state transitions reduces by one. For every sample in the CSVPWM strategy must start with one of the zero states and ends with other. The final state of the present sample must be initial state for the next sample. There are three switching transitions in every subcycle. During the sector change over, the zero state z_x, of the old sector, is the state x, for the next sector. This includes additional switching during sector change over [2], [3]. Hence, the total number of switchings in CSVPWM is 3N+1and the pulse number is given by $P = \frac{3N+1}{2}$. For N=1,3,5… P takes values 2,5,8,….[2], [3].

In order to reduce the additional switching with CSVPWM during sector change over, MSVPWM is proposed.

In MSVPWM the number of samples per sector can be odd or even. The pulse number is given by $P = \frac{3N-1}{2}$. In MSVPWM the switching sequence used for the last sample is modified as indicated in Table III.

The extra switching involved is therefore avoided [3] in the MSVPWM. From the table, *P* can take any integral value. Based on pulse number, the number samples per sector, *N* can be calculated from the equations as given in Table II, III. The sequence for the N^{th} sample is modified in MSVPWM as $z_y \rightarrow \ y \rightarrow x$ [6]. The simplified algorithm has been considered to reduce the computation effort and is presented in the following section.

III. Simplified Algorithm for SVPWM

In MSVPWM algorithm three phase sinusoidal reference modulating waves (m_a, m_b and m_c) are used in estimating the instantaneous position, thereby sector in which $\overline{V_r}$ is located, is identified. This is done based on the angle information in CSVPWM algorithm. The condition to be satisfied by the reference modulating wavesfor estimating the sector is tabulated in Table IV.

As the space vector plane is symmetrical, recurring computations involved in calculating the dwell times in each sector is avoided by shifting $\overline{V_r}$ to first sector using (3) but this is again computationally implicated as it is associated with exponential term.

$$\overline{V_{r1}} = V_r \, e^{\,j*(\text{sector}-1)\pi/3} \qquad (3)$$

TABLE IV
INDETIFICATION OF SECTOR

Condition	Sector
$\lvert m_a\rvert = max\,(\lvert m_a\rvert,\lvert m_b\rvert,\lvert m_c\rvert);\ m_a>0$	1
$\lvert m_a\rvert = max\,(\lvert m_a\rvert,\lvert m_b\rvert,\lvert m_c\rvert);\ m_a<0$	4
$\lvert m_b\rvert = max\,(\lvert m_a\rvert,\lvert m_b\rvert,\lvert m_c\rvert);\ m_b>0$	3
$\lvert m_b\rvert = max\,(\lvert m_a\rvert,\lvert m_b\rvert,\lvert m_c\rvert);\ m_b<0$	6
$\lvert m_c\rvert = max(\lvert m_a\rvert,\lvert m_b\rvert,\lvert m_c\rvert);\ m_c>0$	5
$\lvert m_c\rvert = max\,(\lvert m_a\rvert,\lvert m_b\rvert,\lvert m_c\rvert);\ m_c<0$	2

For reducing these implications, an alternative method is carried in MSVPWM algorithm summarized in Table V. M_a, M_b and M_c are the new modulating waves that represent the shifted reference vector. This is always positioned in first sector but the subsector in which the tip of the shifted $\overline{V_{r1}}$ lies depends on the magnitude of the $\overline{V_r}$.to apply similar analogy developed for two level inverter, the shifted $\overline{V_{r1}}$ must be decomposed into $\overline{V_{r1}'}$ by subtracting the pivot vector $\overline{V_1}$. Now the new reference vector becomes the reference vector in an equivalent two level inverter shown in fig.3. Hence $\overline{V_{r1}'}$ can be synthsis similar to conventional two level inverter analogy using (1), but disparity due to few redundant states.

To apply MSVPWM algorithm $\overline{V_{r1}'}$ interms of new reference modulating waves denoted as M_a', M_b' and M_c' are derived by swinging down M_a, M_b and M_c by $\frac{V_{dc}}{3}$,$\frac{-V_{dc}}{6}$, $\frac{-V_{dc}}{6}$ respectively as given in (4).

Now the shifted revised reference vector,$\overline{V_{r1}'}$ becomes the voltage vector to be synthesized. The tip of $\overline{V_{r1}'}$ in which it is located decides the subsector and the knowledge of subsector is crucial in identifying theoptswitching state of the available 12 inverter switching states for reduced voltage ripple. The conditions to be satisfied by the new modulating waves for subsector identification are tabulated in Table VI.

TABLE V
SHIFTING THE MODULATING SIGNALS TO FIRST SECTOR

Sector	*Ma*	*Mb*	*Mc*
1	*ma*	*mb*	*mc*
2	*-1*mc*	*-1*ma*	*-1*mb*
3	*mb*	*mc*	*ma*
4	*-1*ma*	*-1*mb*	*-1*mc*
5	*mc*	*ma*	*mb*
6	*-1*mb*	*-1*mc*	*-1*ma*

$$Ma' = Ma - \frac{V_{dc}}{3}; \quad (4.1)$$

$$Mb' = Mb - \frac{-V_{dc}}{6}; \quad (4.2)$$

$$Mc' = Mc - \frac{-V_{dc}}{6}; \quad (4.3)$$

TABLE VI
IDENTIFICATION OF SUBSECTOR

Condition 1	Condition 2	Subsector
$M_a' \geq 0$ and $(M_b' - M_c') \geq 0$	$(M_b' - M_c') \geq 3 * M_a'$	2
	$(M_b' - M_c') < 3 * M_a'$	1
$M_a' \leq 0$ and $(M_b' - M_c') \leq 0$	$(M_b' - M_c') \geq 3 * M_a'$	4
	$(M_b' - M_c') < 3 * M_a'$	5
$M_a' \geq 0$ and $(M_b' - M_c') \leq 0$	$(M_c' - M_b') \geq 3 * M_a'$	5
	$(M_c' - M_b') < 3 * M_a'$	6
$M_a' \leq 0$ and $(M_b' - M_c') \geq 0$	$(M_c' - M_b') \leq 3 * M_a'$	2
	$(M_c' - M_b') > 3 * M_a'$	3

In CSVPWM algorithm subsector identification of equivalent two-level inverter is based on angle of $\overline{V'_{r1}}$. In the proposed MSVPWM algorithm this is done using swinged reference modulating signals as indicated in Table VI. Also, in CSVPWM computation of dwell times using $\overline{V'_{r1}}$ involves trigonometric functions, so implementation of the algorithm requires high-cost controllers as this requires lot of memory and computation time is also high.

In MSVPWM algorithm dwell time of each state is algebraic function of the swinged reference modulating waves that are directly available as Ma′, Mb′ and Mc′. Computation of dwell time is indicated in Table VII.

So, with the proposed MSVPWM algorithm identifying sector, subsector and dwell times computation is based on the reference modulating waves.

TABLE VII
DWELL TIME COMPUTATION IN EACH OF SUBSECTOR

Subsector	Time-x	Time-y	Time-z
1	*2(Ma'- Mb')Ts*	*2(Mb'- Mc')Ts*	*Ts-Tx-Ty*
2	*2(Ma'- Mc')Ts*	*2(Mb'- Ma')Ts*	*Ts-Tx-Ty*
3	*2(Mb'- Mc')Ts*	*2(Mc'- Ma')Ts*	*Ts-Tx-Ty*
4	*2(Mb'- Ma')Ts*	*2(Mc'- Mb')Ts*	*Ts-Tx-Ty*
5	*2(Mc'- Ma')Ts*	*2(Ma'- Mb')Ts*	*Ts-Tx-Ty*
6	*2(Mc'- Mb')Ts*	*2(Ma'- Mc')Ts*	*Ts-Tx-Ty*

The opt switching states corresponding to sector number and its corresponding subsectors are identified

and are shown in TableVIII. To identify the corresponding switching states for synthesizing the $\overline{V'_{r1}}$ in the remaining sectors a reverse procedure need to be followed similar to shifting the modulating waves to the first sector. In other words the states are to be shifted to their original sector as followed in Table V.

TABLE VIII

SWITCHING STATES OF SECTOR 1

Sector	Subsector	State0	State1	State2	State7
1	1	0--	+--	+0-	+00
	2		00-	+0-	
	3		00-	000	
	4		0-0	000	
	5		0-0	+-0	
	6		+--	+-0	

IV. Simulation Results and Discussion

The simulation results are carried out by using Matlab/Simulink software with fixed step of 1µs in ode4 (Runge-Kutta) solver. The IGBT based three level NPC is used and DC bus voltage is maintained at 600V.

TABLE IX

PARAMETERS OF THE MOTOR

PARAMETER	RATING
Stator resistance, Rs	7.83Ω
Rotor resistance, Rr	7.55Ω
Stator Inductance, Ls	0.4751H
Rotor Inductance, Lr	0.4751H
Mutual Inductance, Lm	0.4535H
Moment of inertia, J	0.06 Kg.m^2
Number of poles, P	4

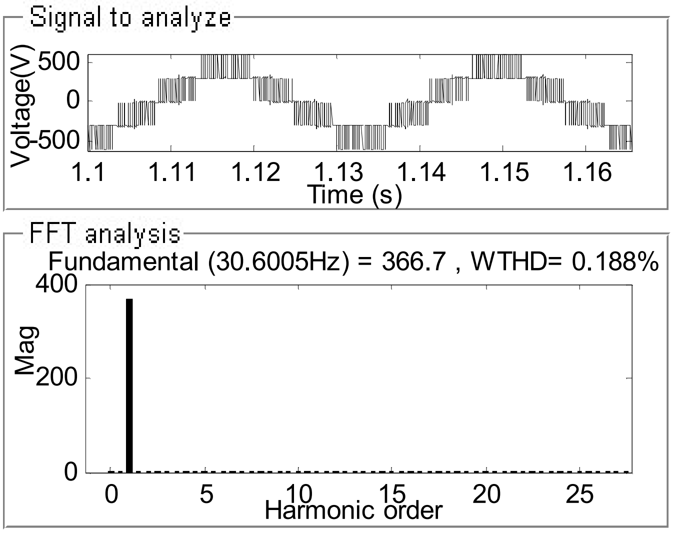

Fig.5.Harmonic spectrum of line voltage for sequence 0127, when N=18

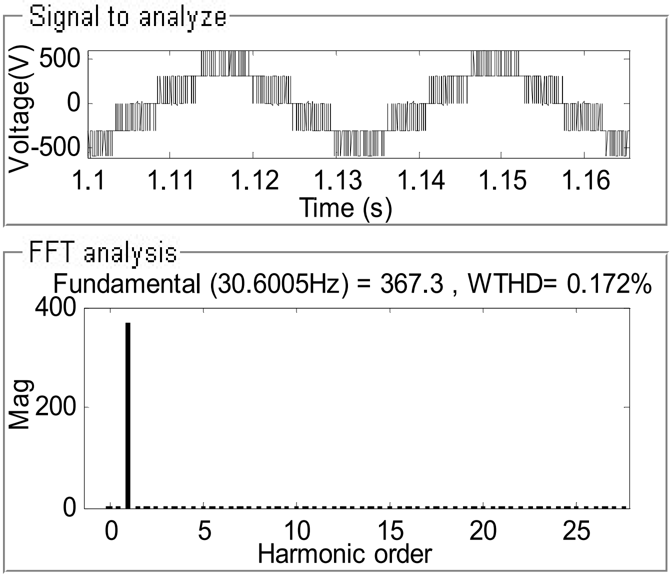

Fig.6. Harmonic spectrum of line voltage for sequence 7210, when N=18

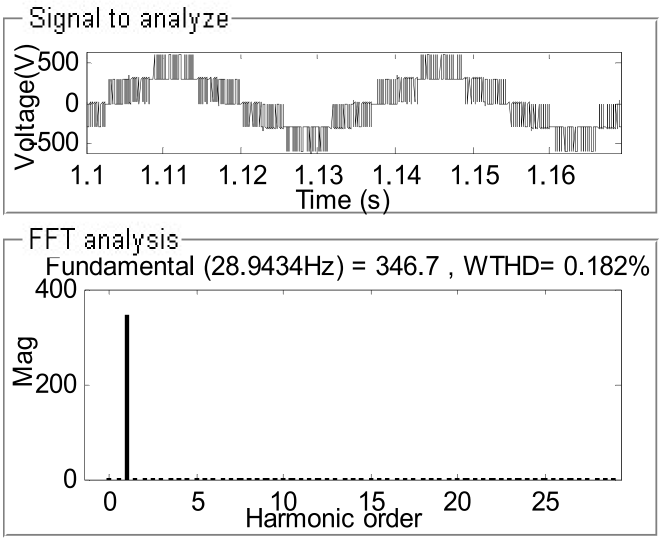

Fig.7.Harmonic spectrum of line voltage for sequence 0127, when N=19

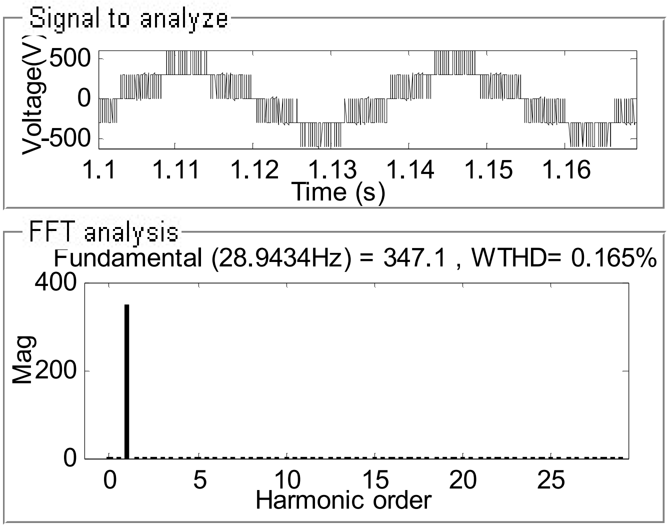

Fig.8.Harmonic spectrum of line voltage for sequence 7210, when N=19

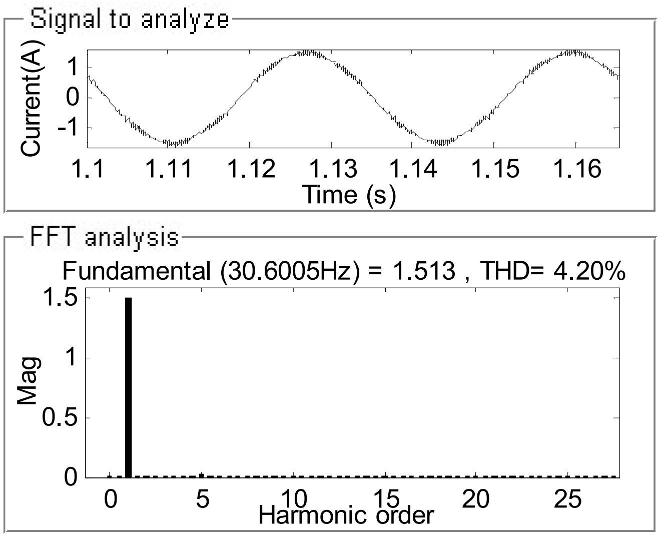

Fig.9.Harmonic spectrum of no-load stator current for sequence 0127, when N=18

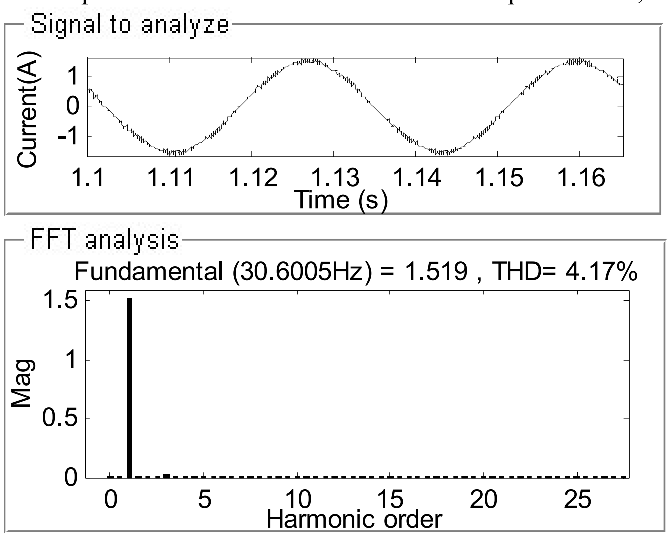

Fig.10.Harmonic spectrum of no-load stator current for sequence 7210, when N=18

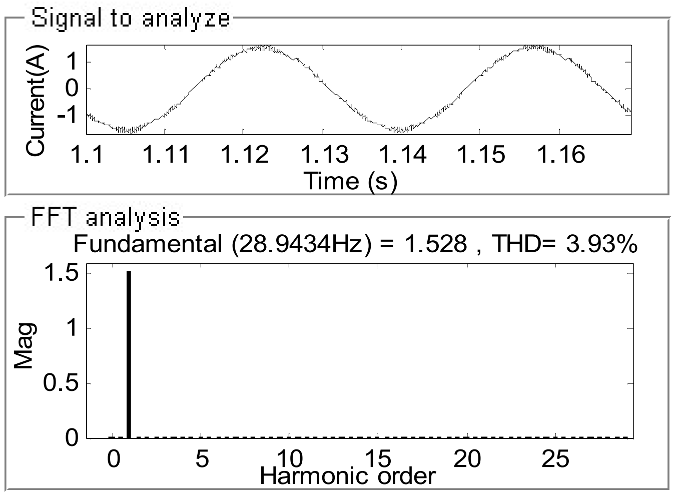

Fig.11.Harmonic spectrum of no-load stator current for seq 0127, when N=19

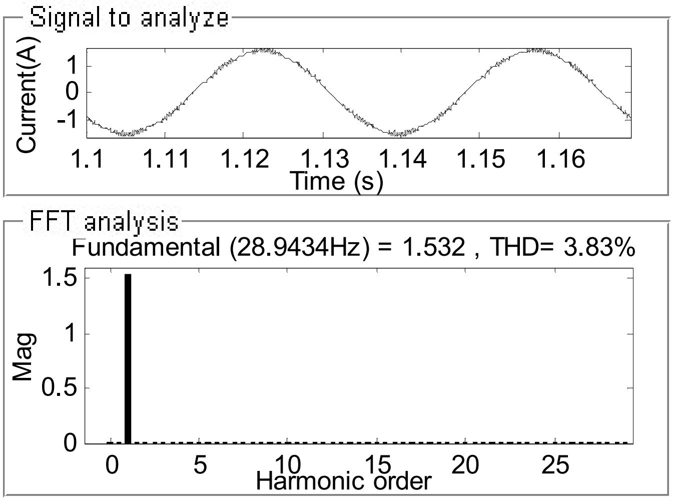

Fig.12.Harmonic spectrum of no-load stator current for seq7210, when N=19

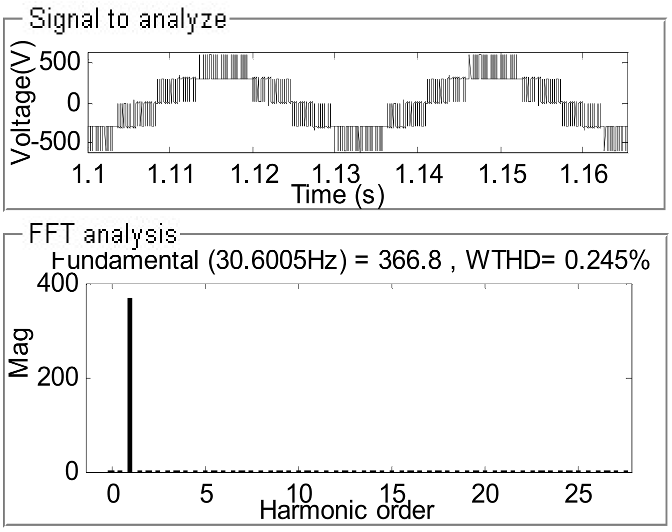

Fig.13.Harmonic spectrum of line voltage for sequence 012, when N=18

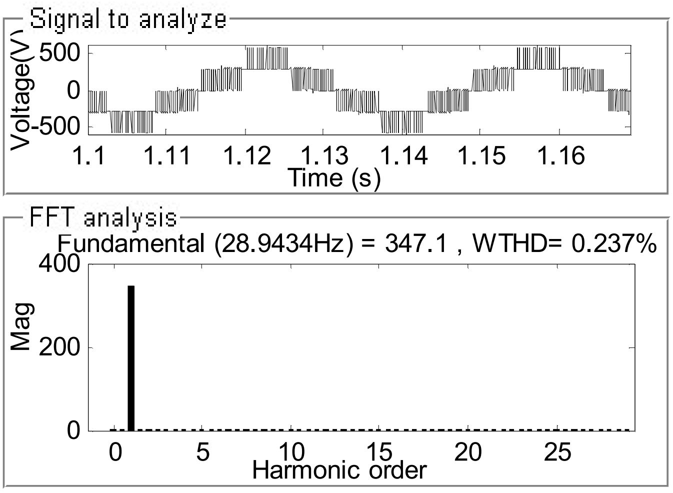

Fig.14.Harmonic spectrum of line voltage for seq 012, when N=19

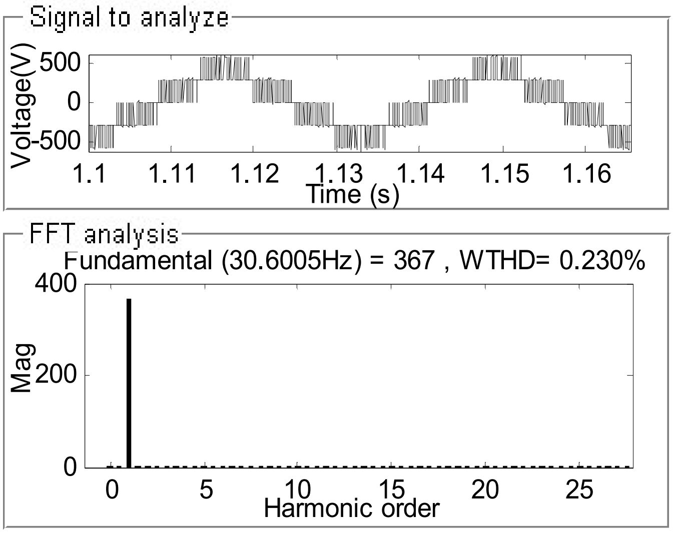

Fig.15.Harmonic spectrum of line voltage for sequence 721, when N=18

TABLE X
RESULTS

Switching sequence	N=18			N=19		
	V_{WTHD} (%)	I_{THD} (%)	*S.T	V_{WTHD} (%)	I_{THD} (%)	*S.T
0127	0.188	4.20	3	0.182	3.93	1
7210	0.172	4.17	2	0.165	3.83	1
012	0.245	4.86	3	0.237	4.35	2
721	0.230	4.43	1	0.218	4.25	0

*S.T= Number of state transitions during sector change over

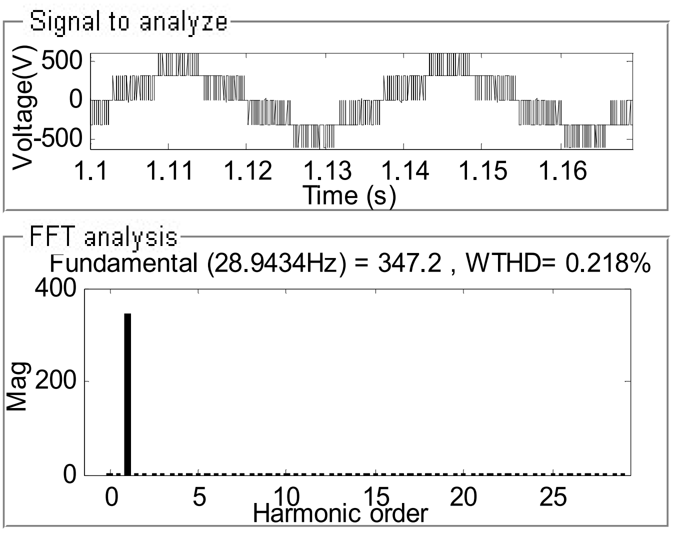

Fig.16.Harmonic spectrum of line voltage for sequence 721, when N=19

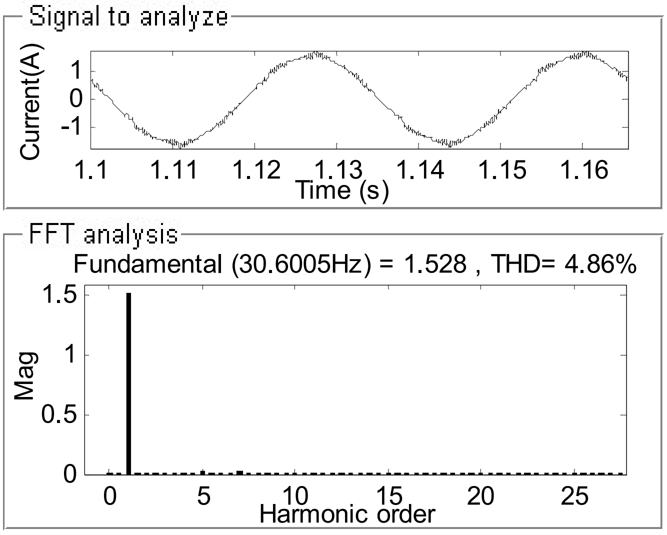

Fig.17.Harmonic spectrum of no-load stator current for sequence 012, when N=18

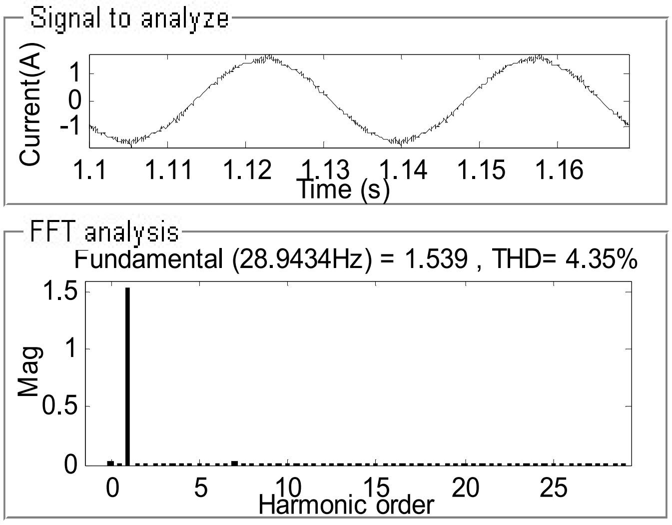

Fig.18.Harmonic spectrum of no-load stator current for sequence 012, when N=19

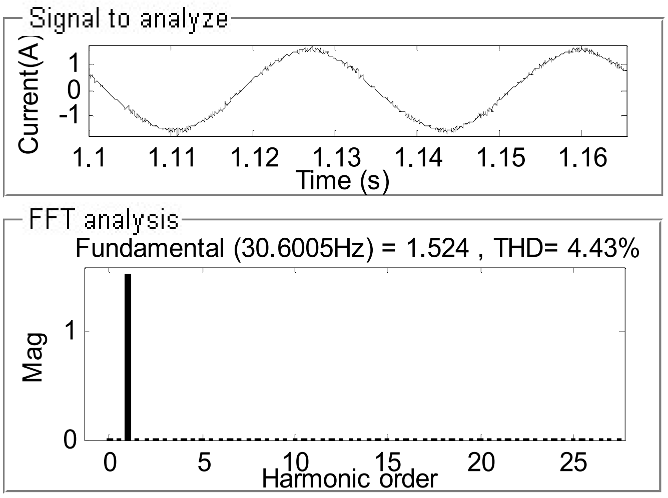

Fig.19.Harmonic spectrum of no-load stator current for sequence 721, when N=18

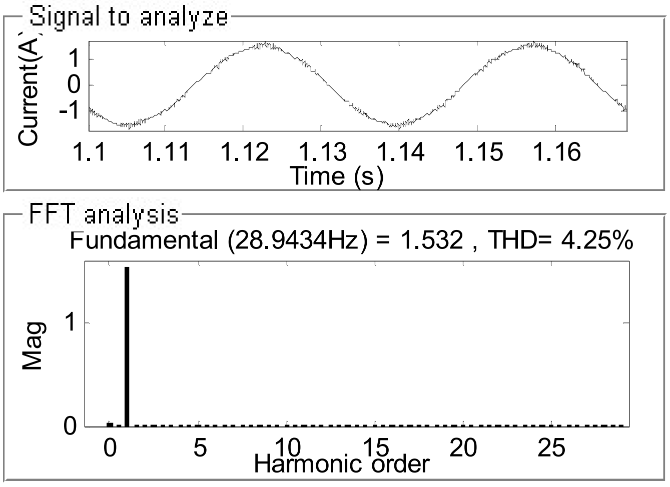

Fig.20.Harmonic spectrum of no-load stator current for sequence 721, when N=19

To simulate the CSVPWM and MSVPWM using proposed algorithm, the motor is operated as a constant V/f controlled drive and the reference voltage is $0.866V_{dc}$ at 50Hz. The maximum switching frequency is 1.65KHz.

Here the sequences CSVPWM and MSVPWM are compared for odd and even samples. The switching sequence to be followed is tabulated in Table II and Table III. For odd value of N, V_{ref}=0.5013Vdc and f_1=28.94, for even value of N, V_{ref}=0.53Vdc and f_1=30.60. The WTHD of the line voltage applied across motor terminals is calculated and the no-load stator current harmonic distortion is measured for all the sequences and concluded in Table X. With all the sequences lower order harmonics are almost zero, since synchronization and all the symmetries are maintained.

With 0127, when N is odd, during sector change over there are three state transitions, and when N is even, it is only one. Hence no-load stator current distortion is reduced for odd N. For 7210, when N is odd, during sector change over there are two state transitions,and when N is even, there is one state transition. Hence THD in no-load stator current is reduced for N to be odd. This is for the same reason 7210 gives lower THD than 0127.
With 012, when N is odd, during sector change over there are three state transitions and when N is even, it is reduced to two. HenceTHD in no-load stator current is reduced when N is odd. For 721, when N is odd, during sector change over there is only one state transition and when N is even, there are no state transitions. Here the no-load stator current is reduced for odd N.

V. Conclusions

The space vector based PWM approach has advantage of generating different possible switching sequences for synthesizing a given reference vector. Moreover, different switching sequences can be used in different subcycles. A simplified algorithm of space vector based PWM strategy for three-level inverter is proposed in this paper. This algorithm reduces the computational efforts required for space vector based PWM strategies. The proposed algorithm is simulated on NPC inverter, feeding a 1.5kW induction motor, controlled as a constant v/f drive.

This paper presents detailed analysis of different sequences maintainings synchronization, QWS, HWS, and TPS for all integer values of P. Detailed analysis of the CSVPWM and MSVPWM sequences for odd and even N is presented with reference to the two performance measures, THD in no-load current and WTHD in line voltage.It is concluded that for add N there is a significant reduction in distortion for even number of samples. This is for the reason that when the number of samples per sector is even, during sector change over there is two or three state transitions whereas when the number of samples per sector is odd, then during sector change over there is two or less state transitions. Hence with the proper selection of switching frequency the switching losses can also be reduced in addition to improving the quality of the waveform.

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