FPGA Implementation of Simplified SVPWM Algorithm for Three Phase Voltage Source Inverter

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Abstract—A resource efficient with low computational overheads SVPWM algorithm for three phase voltage source inverter which is used to supply variable voltage and variable frequency to three phase AC drives is proposed in this paper. Because of its advantages like lower switching losses, higher dc-bus utilization SVPWM scheme becomes the preferred PWM technique for various three-phase power converter applications. Conventional SVPWM algorithm involves complex mathematics and requires more hardware resources to implement and takes more time for its execution. The Field Programmable Gate Arrays (FPGAs) offer high computational ability and flexibility due to their parallel execution and reconfigurable hardware. Hence the scheme suggests the implementation of a resource efficient algorithm with low computational overheads for SVPWM generation using FPGA and obtains higher sampling rates with minimal use of hardware resources. Resource utilization of proposed algorithm obtained is 4% for XILINX XC3S500E processor operating at 50 MHz. The output fundamental frequency can be adjusted from 0.1Hz to 1500Hz and PWM switching frequency can be set from 200 to 50 KHz. The adjustable delay time logic for PWM gating signals is also implemented. The proposed algorithm is tested for 3-phase induction motor with VSI and the experimented results are validated.

Index Terms—Digital Control, FPGA, SVPWM, Xilinx XC3S500E

I. INTRODUCTION

Variable voltage and frequency supply for ac drive is invariably obtained from three-phase Voltage Source Inverter. A number of PWM techniques have been presented to obtain variable voltage and variable frequency supply[4]. Space Vector Pulsewidth Modulation has become one of the most important PWM method for three-phase voltage source inverters[5]. It has an advantages over carrier-based sine tringle pwm such as higher dc bus utilization, lower switching losses and less harmonic distortions [14].

In order to implement SVPWM algorithm DSPs are widely used but the execution of SVPWM algorithm in less number of machine cycles is need of many applications which can not be satisfied with conventioanl DSPs because

they executes instructions sequentially and thus requires more time to compute. Whereas, field programmable gate array (FPGA) performs the entire procedures with concurrent operation by using its reconfigurable hardware and parallel processing. Employing FPGA to realize PWM strategies provides advantages such as rapid prototyping, simple hardware and software design, higher switching frequency and reduction of computational overheads [5]. Computational Complexity and resource utliazation of conventional SVPWM algorithm increases thus the execution time with number of levels of converter [2].

In this paper, a resource efficient SVPWM algorithm is proposed which reduces computational overheads and solves the problem of high sampling time in real time applications. The proposed algorithm uses only adders, subtractors, comparators, shifters,etc to be implemeted using FPGA's and takes less number of resources and execution time than conventional algorithm. Finally, experimental results from an inverter prototype are presented to confirm the validity and performance of the designed SVPWM algorithm. Fig.1 shows the open loop control scheme for three phase induction motor which is used for testing and validation of algorithm.

This paper is organized as follows. Section II introduces conventional SVPWM algorithm and mathematics involved in it. Section III discusses simplified SVPWM algorithm. Section IV describes FPGA implementation of proposed simplified SVPWM algorithm and experimental results. Finally conclusion is in Section V.

Fig. 1 Open loop scheme for three-phase induction motor

II. CONVENTIONAL SVPWM ALGORITHM

To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into

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the stationary d-q reference frame that consists of the horizontal (d) and vertical (q) axis as depicted in Fig. 2

Fig. 2 Relationship between a-b-c reference frame and stationary d-q frame

The relationship is expressed as

$$f_{dq0} = Ks f_{abc} \quad (1)$$

$$\text{Where } Ks = \begin{bmatrix} 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

The transformation is equivalent to an orthogonal projection of a-b-c reference frame onto two dimensional perpendiculars to the equivalent d-q plane in a three dimensional co-ordinate system. As a result six nonzero and two zero vectors are obtained. The six non zero vectors are shape to hexagonal as shown in fig. 3(a). The angle between any two non zero adjacent vectors is 60°. The objective of SVPWM is to approximate reference voltage vector V_{ref} using eight switching pattern. Therefore, space vector PWM can be implemented by following three steps:

- Determining V_d , V_q , V_{ref} and angle α for sector
- Determining the time duration T_1 , T_2 and T_0
- Determining the switching time of each switching devices (S1 ~ S6)

Fig. 3 (a) d-q transformation of Space Voltage Vectors in different sectors

Fig 3 (b) Space Vector time calculations with Vref

The relationship between switching variable vector and phase voltage vector $[V_a \ V_b \ V_c]$ can be expressed as follows.

$$\begin{aligned} V_d &= V_{an} - V_{bn} \cdot \cos 60 - V_{cn} \cdot \cos 60 \\ &= V_{an} - 1/2 V_{bn} - 1/2 V_{cn} \\ V_q &= 0 + V_{bn} \cdot \cos 30 - V_{cn} \cdot \cos 30 \\ &= \sqrt{3}/2 V_{bn} - \sqrt{3}/2 V_{cn} \end{aligned}$$

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (2)$$

From fig. 3 (b), the reference vector V_{ref} is calculated as

$$\begin{aligned} |V_{ref}| &= \sqrt{V_d^2 + V_q^2} \\ \alpha &= \tan^{-1} \left(\frac{V_q}{V_d} \right) \end{aligned} \quad (3)$$

In general, V_{ref} in 'n' sector is obtained by two adjacent non-zero vectors (V_j , V_{j+1}) and two-zero vectors. V_{ref} is expressed as

$$V_{ref} = \frac{T_n}{T_z} \cdot V_n + \frac{T_{n+1}}{T_z} \cdot V_{n+1} \quad (4)$$

where T_n & T_{n+1} are on time of V_n and V_{n+1} during each sampling period (T_z) respectively and 'n' is the sector number in which V_{ref} resides. Fig 3 (b) shows the space vector time representation with V_{ref} for sector 1. The magnitude of non zero sapce vector always $\|V_j\| = 2V_{dc}/3$. The sectors are identifie depending on values of angle ' α '.

The switching time duration T_1 , T_2 and T_0 for a particular sector can be calculated from following equations .

$$\begin{aligned} T_1 &= \frac{\sqrt{3} \cdot T_z}{V_{dc}} \left[\sin \left(\frac{\pi}{3} n \right) V_d - \cos \left(\frac{\pi}{3} n \right) V_q \right] \\ T_2 &= \frac{\sqrt{3} \cdot T_z}{V_{dc}} \left\{ -\sin \left[\frac{\pi}{3} (n-1) \right] V_d + \cos \left[\frac{\pi}{3} (n-1) \right] V_q \right\} \\ T_0 &= T_z - T_n - T_{n+1} \end{aligned} \quad (5)$$

The switching time of each switching devices (S1~ S6) per sector is given as per table I

TABLE I SWITCHING TIME AT EACH SECTOR

SECTOR	S1, S3, S5	S2, S4, S6
1	S1= $T_1 + T_2 + T_0/2$ S3= $T_2 + T_0/2$ S5= $T_0/2$	S4= $T_0/2$ S6= $T_1 + T_0/2$ S2= $T_1 + T_2 + T_0/2$
2	S1= $T_1 + T_0/2$ S3= $T_1 + T_2 + T_0/2$ S5= $T_0/2$	S4= $T_2 + T_0/2$ S6= $T_0/2$ S2= $T_1 + T_2 + T_0/2$
3	S1= $T_0/2$ S3= $T_1 + T_2 + T_0/2$ S5= $T_1 + T_2$	S4= $T_1 + T_2 + T_0/2$ S6= $T_0/2$ S2= $T_1 + T_0/2$
4	S1= $T_0/2$ S3= $T_1 + T_0/2$ S5= $T_1 + T_2 + T_0/2$	S4= $T_1 + T_2 + T_0/2$ S6= $T_2 + T_0/2$ S2= $T_0/2$
5	S1= $T_2 + T_0/2$ S3= $T_0/2$ S5= $T_1 + T_2 + T_0/2$	S4= $T_1 + T_0/2$ S6= $T_1 + T_2 + T_0/2$ S2= $T_0/2$
6	S1= $T_1 + T_2 + T_0/2$ S3= $T_0/2$ S5= $T_1 + T_0/2$	S4= $T_0/2$ S6= $T_1 + T_2 + T_0/2$ S2= $T_2 + T_0/2$

From the above equations and fig 3 (a) and (b), the sector identification criterion of conventional algorithm involves

floating point operations as to get angle that requires calculating inverse tan function. Because of sine function and square root values involved in computation switching time duration i.e. T₁, T₂ and T₀, implementation of conventional algorithm using digital processor becomes difficult. In context with FPGA implementation the floating point operations and trigonometric functions increases resource utilization thus execution time. Attempt to be made to simplify mathematical equations which require only addition, subtraction, shifting, etc. to implement the SVPWM algorithm for three phase VSI.

III. SIMPLIFIED ALGORITHM

The conventional SVPWM algorithm includes d-q transformation of three input voltages V_{an}, V_{bn} and V_{cn} as given by equation (4) this transformation requires value of $\sqrt{3}$ to be calculated it is difficult to implement floating point numbers using FPGA. Hence instead of d-q transformation, intermediate transformation vectors are used. The eq. (3) can be written as:

$$\begin{aligned} V_d &= \frac{2}{3}V_a - \frac{1}{3}V_b - \frac{1}{3}V_c \quad \& \\ V_q &= \frac{1}{\sqrt{3}}V_b - \frac{1}{\sqrt{3}}V_c \end{aligned} \quad (7)$$

$$\begin{aligned} \therefore V_d &= \frac{1}{3}[2V_a - V_b - V_c] \\ V_q &= \frac{1}{\sqrt{3}}[V_b - V_c] \end{aligned} \quad (8)$$

By defining intermediate variables as X_d and X_q, the eq. (7) written as:

$$\begin{aligned} X_d &= 2V_a - V_b - V_c \quad \& \\ X_q &= V_b - V_c \end{aligned} \quad (9)$$

By combining eq. (8) and (9), the V_d and V_q are expressed in terms of intermediate vectors as:

$$\begin{aligned} \therefore V_d &= \frac{1}{3}[X_d] \\ V_q &= \frac{1}{\sqrt{3}}[X_q] \end{aligned} \quad (10)$$

Hence the algorithm needs only to calculate X_d and X_q which requires simple operators namely shifter (for multiplication by 2), adder and subtractor. The corresponding V_d and V_q calculated by normalizing the values with 1/3 and 1/√3 units.

The determination of sector depends only on the sign of X_d and X_q as per following rules. Determination of the sectors can be done by simply checking 3 conditions:

Condition 1: sign of X_d

Condition 2: sign of X_q

Condition 3: |X_d| > |X_q/2|

The rules to find sectors:

Rule 1: if (X_d>0 & X_q>0 & |X_d|>|X_q/2|)

Sector- 1

Rule 2: if (X_d>0 & X_q>0 & |X_d|<|X_q/2|)

Sector- 2

OR

if (X_d<0 & X_q>0 & |X_d|<|X_q/2|)

Sector- 2

Rule 3: if (X_d<0 & X_q>0 & |X_d|>|X_q/2|)

Sector-3

Rule 4: if (X_d<0 & X_q<0 & |X_d|>|X_q/2|)

Sector-4

Rule 5: if (X_d>0 & X_q<0 & |X_d|<|X_q/2|)

Sector-5

OR

if (X_d<0 & X_q<0 & |X_d|<|X_q/2|)

Sector-5

Rule 6: if (X_d>0 & X_q<0 & |X_d|>|X_q/2|)

Sector-6

For a symmetric space vector PWM, the output voltage i.e. X_d and X_q can be in any of the sector 1 to sector 6 is given by the equation

$$\begin{bmatrix} T_n \\ T_{n+1} \end{bmatrix} = T_{PWM} M_0 \begin{bmatrix} X_d \\ X_q \end{bmatrix} \quad (11)$$

Eq. (11) shows that every PWM period, the output voltages are approximated as (T_z/V_{dc}) by switching between the two non zero basic vectors that border the sector of the current output voltages. The sum of T_n and T_{n+1} should be less than or equal to T_{PWM} and rest of period the switching time should be T₀. The M₀ is called as decomposition matrix, given as

$$M_0 = \begin{bmatrix} M_{00} & M_{01} \\ M_{10} & M_{11} \end{bmatrix}$$

Applying equation (10) to (6), the switching time can be calculated as

$$= \begin{bmatrix} \frac{2}{\sqrt{3}} \sin\left(\frac{\pi}{3}n\right) & -\cos\left(\frac{\pi}{3}n\right) \\ -\frac{2}{\sqrt{3}} \sin\left[\frac{\pi}{3}(n-1)\right] & \cos\left[\frac{\pi}{3}(n-1)\right] \end{bmatrix} \quad (12)$$

If V_{dc} is normalized with $\sqrt{3}$ per unit, and T_z is set to $\sqrt{3}$ per unit, the four coefficients in eq. (12) will alter their values according to the sector 'n'. If reference vector is located in sector I, then 'n'=1, then M₀₀ = 1, M₀₁ = -1/2, M₁₀ = 0 and M₁₁ = 1.

The coefficients of decomposition matrix according to sector is given in Table II

TABLE II COEFFICIENTS OF DECOMPOSITION MATRIX

Sector 'n'	1	2	3	4	5	6
M ₀₀	1	1	0	-1	-1	0

M_{01}	-1/2	1/2	1	1/2	-1/2	-1
M_{10}	0	-1	-1	0	1	1
M_{11}	1	1/2	-1/2	-1	-1/2	1/2

So from eq. (11) the switching times are calculated as

$$\begin{aligned} [T_n'] &= [M_{00} \ M_{01}] \begin{bmatrix} X_d \\ X_q \end{bmatrix} \\ [T_{n+1}'] &= [M_{10} \ M_{11}] \begin{bmatrix} X_d \\ X_q \end{bmatrix} \\ [T_0'] &= \sqrt{3} - T_n' + T_{n+1}' \end{aligned} \quad (13)$$

The calculation for eq. (13) will requires simple operators such as shifters, adders and subtractors including X_d , and X_q . Thus the proposed algorithm reduces the complexity of conventional SVPWM algorithm.

IV. FPGA IMPLEMENTATION

Fig. 4 shows the internal architecture of simplified SVPWM algorithm implemented using Spartan 3 FPGA (XILINX XC3S500E)

Fig. 4 Internal Architecture of Simplified SVPWM Algorithm

The architecture mainly consists of five major blocks

1.3-2 Transformation Module:

Values of three phase voltages i.e. V_a , V_b , V_c is input to this block. This module transforms three phase voltage reference frame to two phase voltage reference frame using equations (10). To implement in FPGA the resources requires are only adders, and subtractors.

2.Sector determination module:

The input to this module is X_d and X_q values generated by three to two phase transformation module. This module checks three conditions as explained earlier and the corresponding sectors get determined as per the rules explained earlier.

Result of condition $X_d > 0$ is stored in 1 bit variable as C1.

Result of condition $X_q > 0$ is stored in 1 bit variable as C2

And result of condition $|X_d| > |X_q/2|$ is stored as C3.

These variables are appended to form a three bit array named as sect. The array $\text{sect} = \{C1, C2, C3\}$. The sector can be determined from the value of sect according to following table:

TABLE III VALUES OF ARRAYS ACCORDING TO SECTOR

Sector	Array value
1	7
2	2,6
3	3
4	1
5	0,4
6	5

For example, if $X_d > 0$, then $C1=1$ and $X_q < 0$, $C2=0$ and for $|X_d| > |X_q/2|$, $C3=1$. So $\text{sect} = \{1,0,1\}=5$.

So according to table III, the sector 6 will get selected.

3. Switching time calculation module:

Switching time calculation requires values of X_d , X_q and sectors. These values are calculated by two blocks as explained earlier. The values of parameters T_n' and T_{n+1}' are determined from equation (13). The coefficients of decomposition matrix and their values are obtained from table II based on sector number.

4. Symmetrical PWM generation module:

This module is the heart of this algorithm which is responsible for generation of six symmetrical PWM signals. This module requires sector number and switching time values calculated by previous blocks. The PWM switching frequency can be adjusted in this module. Dead time generation module is a part of this module.

Figure 5(a) and 5(b) shows the waveform produced for sector I and II as a sample.

Figure 5 (a) Symmetrical PWM for sector I

Figure 5 (b) Symmetrical PWM for sector II

Each waveform has following properties

1. Each PWM channel switches twice per PWM period except when duty cycle is 0 or 100%

2. There is fixed switching order among the three PWM channels for each sector

According to figure 5 (a) and 5 (b) the values of different PWM outputs are changes only for the states S2, S3, S5, and S6 out of which the pattern of S2 and S6 are always same as well the pattern of S3 and S5 are always same, Hence 3 bit array (S2ar and S3ar) is created each for S2 (same for S6) and S3 (same for S5) respectively. Values are assigned to these arrays based on sector of V_{ref} according to table IV.

TABLE IV SYMMETRICAL PWM OUTPUTS ACCORDING TO STATES

STATES	N	1	2	3	4	5	6
S2,S6	PWMA	1	0	0	0	0	1
	PWMB	0	1	1	0	0	0
	PWMC	0	0	0	1	1	0
S3,S5	PWMA	1	1	0	0	1	1
	PWMB	1	1	1	1	0	0
	PWMC	0	0	1	1	1	1

The value of switching time T_z is kept equal to V_{dc} for normalization.

A counter is set to 0 at the beginning of each switching period which counts up to T_z . The time step to this counter is adjustable. Larger time step means smaller frequency and vice versa. Thus the PWM frequency can be adjusted by adjusting the time step. For $C < T_0/4$, PWMA, PWMB and PWMC are off. (Refer S1 state of fig.5). Then for $T_0/4 \leq C < T_0/2$, the PWMA, PWMB and PWMC are assigned values of S2ar which are sector dependent (state S2 of Fig.5). For state S3, the values of PWMA, PWMB and PWMC are assigned as given by S3ar.

This procedure is continued till the counter reaches T_z . Thus PWM signals for one switching period are generated. Now the counter is set to zero and again same procedure is repeated for new values of V_{ref} . Thus symmetrical PWM signals are continuously generated.

The table shows the comparison of resource utilization for conventional SVPWM and simplified SVPWM algorithm implemented using Xilinx Spartan 3 FPGA (XC3S500E) operating at 50MHz.

TABLE V
COMPARISON OF SVPWM SCHEMES IMPLEMENTED USING SPARTEN 3 FPGA OPERATING AT 50MHZ

Scheme	Multipliers	Dividers	Adders /Subtractors	CLB's	% Utilization
Conventional	8	2	24+	1796	15%
Proposed	0	0	32+	490	4%

5) Dead time generation module

In ideal conditions, the gating signals to the power switches of same phase leg of the PWM inverter should be complementary. However, the turn-off time of a power switch is usually longer than its turn-on time. So, if the switching is carried out simultaneously, the device turns on quickly as compared to other device which is supposed to be

turned off. This can cause short circuit due to both switches of the same leg being on at the same time. This can damage the switches as well as coil of motor. So this condition must be avoided. It is done by delaying the switching on of a device than switching off of its complementary device. An appropriate delay time must be inserted between these two gating signals. The length of this delay time is usually about 1.5 to 2 times the maximum turn-off time. The following diagram shows how the dead-time is inserted between two PWM signals of the same leg. Dead time generation module is the part of the symmetric PWM generation algorithm.

Figure 6 Dead time generation for PWMA

The scheme shown in figure (6) is implemented in the algorithm. As seen from the figure, the switching on of upper switches of VSI is delayed by dead time value which is configurable. The switching off of lower switches of VSI is delayed by dead time value. Thus short circuiting is prevented.

V. EXPERIMENTAL VERIFICATION OF ALGORITHM

The scheme implemented for testing of the algorithm is as shown in figure (1). Figure (7) shows experimental setup. The DAQ card from National Instruments is used for generation of three 120 degree phase shifted variable frequency sine waves as V_a , V_b and V_c interfaced with Lab VIEW software. These voltage waveforms are given to SPI based 12-bit ADC MCP3204. It is set to scan three channels continuously. The ADC continuously samples the three sine wave inputs by its minimum sampling time and digital values are continuously accepted by FPGA. Thus FPGA gets the values of V_a , V_b and V_c i.e. after calculation V_{ref} for SVPWM generation.

The SVPWM generation algorithm is executed in FPGA. It produces six PWM signals output. The PWM signals from FPGA act as switching signals for IGBT's of VSI. In place of motor, star connected resistive-inductive load is used. The output of VSI is given to this resistive load. To filter the load voltage, low pass RC filters are used. To observe the outputs, Tektronix DSO with 4 input channels is used which has waveform storage function. After testing on R-L load, the algorithm is tested on three phase induction motor. The result matches those of the simulated R-L load.

Motor Parameters

Rated Voltage	:	230V
Three Phase rating	:	1.5KW

No of poles (P)	:	4
Frequency (f)	:	50Hz
Power rating	:	3hp
Stator Resistance (Rs)	:	4.6933 Ohm
Rotor Resistance (Rr)	:	4.4374 Ohm
Stator Leakage reactance (Xls)	:	4.85737Ohm
Rotor Leakage reactance (Xlr)	:	7.12623Ohm
Moment of inertia	:	0.01218

Figure 7 shows the SVPWM pulses of 6.25 KHz frequency. Figure 8 and 9 shows the line-to line voltage and line-to-neutral voltage waveforms respectively.

Figure 7 Experimental results of output SVPWM pulses

Figure 8 Experimental result of line-to-line voltage

Figure 9 Experimental result of line-to-neutral voltage

Figure 10 Experimental result of filtered load current

Figure 11 shows the comparison between expected fundamental frequency in Hz and output fundamental frequency in Hz at the step size of 5Hz, the graph shows the output frequency is matching with expected fundamental frequency.

Figure 11 Experimental result of Output fundamental frequency versus expected fundamental frequency with step size of 5Hz

Figure 12 Experimental results of dead time generation module

Figure 13 Experimental set-up

VI. CONCLUSION

In context with digital implementation of Space Vector PWM algorithm for three phase inverter used for 3-phase induction motor, a simplified and resource efficient algorithm is proposed in this paper. Experimental results are provided to verify the feasibility and validity of proposed algorithm. The algorithm is implemented using Xilinx Spartan 3 FPGA and tested for the fundamental frequency ranging from 0.5Hz to 1500Hz and switching frequency ranging from 200Hz to 50 KHz. The algorithm is so simple to digitally implement as it uses only adders, subtractors and decoders. The same can be implemented using conventional Microcontrollers or DSP processors and will get faster execution time. The VSI model used to test the algorithm is two-level VSI but the same can be used for multilevel VSI with some modifications in algorithm.

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