Space Vector vs. Sinusoidal Carrier-Based Pulse Width Modulation for a Seven-Phase Voltage Source Inverter

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Abstract—The paper presents an extensive comparison between two pulse width modulation (PWM) control schemes, namely carrier-based and space vector based PWM for a seven-phase voltage source inverter. Sinusoidal carrier-based PWM and space vector PWM techniques are employed to control multiphase power converters supplying variable speed multiphase motor drive systems. Implicit relationships that exist between the two PWM techniques are comprehensively explored; this paper, reveal the underlying relationship between the two PWM techniques in terms of several parameters such as modulating signals and space voltage vectors, modulating signals and space voltage vector sectors, switching pattern of space vector and type of carrier. Furthermore, sharing of zero vectors among different chosen space vectors is elaborated that leads to the formulation of different types of modulation. Digital implementation of the two modulation schemes is elaborated. Simulation results are validated using experimental investigation.

Index Terms—Carrier-based pulse width modulation (PWM), multiphase motor drive system, space vector PWM, voltage source inverter.

NOMENCLATURE

a^*	The transposition of 'a'.
$d-q$	The fundamental stationary reference frame.
k	Number of sectors of output voltage vectors.
n	Total number of output phases.
$\xi(t)$	Duty ratio.
V_i	Output phase voltage ($i = 1, 2, \dots, 7$, in volt).
I to XIV	Sector of voltage space vector.
M	Maximum modulation index.
m	Even numbered sector of voltage space vectors.
S_k ($k \rightarrow 1$ to 4)	Inverter switches.
t_{a1}, t_{a2} and t_{a3}	Application time of the inverter voltage space vectors (in sec).
t_{b1}, t_{b2} and t_{b3}	Application time of the inverter phase opposed voltage vectors (in sec).
t_s	Switching period (in sec).
N	Zero sequence voltage signal.
V_{DC}	DC voltage source of the inverter (in volt).

v_{sm}, v_m, v_l

Small, medium and large length voltage vector.

V_{max}, V_{min}

Maximum and minimum voltage max, out of V_1 to V_7 .

x_1-y_1 and x_2-y_2

The auxiliary orthogonal planes.

I. INTRODUCTION

Variable speed motor drives find widespread industrial applications ranging from manufacturing sectors, process plants, oil & gas plants and electric and hybrid transportations. Since variable speed drives are supplied by power electronic converters to obtain variable voltage and variable frequency supply, adding extra legs become a parameter of choice. This has led to the development of multiphase power conversion and control system. A large literature is available on multiphase motor drive system modeling, analysis and control. Few review papers are available to comprehend the development in the field of multiphase motor drive systems. The first review was reported in 2002 [1] and since then work on the area has been accelerated and two reviews appeared in 2007 and 2008 [2], [3], most recently new reviews are reported in 2016 [4]–[6].

Multiphase motor drive system is known to offer numerous advantages over corresponding three-phase motor drive system. The major advantages include: 1) lower torque ripple amplitude, 2) higher frequency of torque ripple, 3) higher torque density due to injection of lower order harmonics that modulate the shape of the air-gap flux, 4) less noise, 5) lower per-leg converter rating for same power output 6) higher redundancy and better fault tolerance characteristics, 7) greater control flexibility and 8) possibility of independent control of more than one machine supplied by one power converter [1]–[6].

Multiphase power converters are used to feed multiphase ac machines. Power converters used in three-phase drive are extended by adding extra legs to use in multiphase drives. Traditional two-level inverters and multilevel inverters are explored for multiphase drives. Numerous PWM techniques are used to control multiphase power converters including sinusoidal carrier-based and space vector approaches [7], [8]. Application of carrier-based PWM technique in multiphase converter is straightforward; using multiphase sinusoidal modulating signals with appropriate phase shifts and comparing with triangular high frequency signal. However, space vector PWM when applied to multiphase converter is completely different from the three-phase counterpart. When applied to an n -phase voltage source inverter (VSI), the total number of switching states are $2n$ [6], [7]. The space vectors are obtained

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corresponding to the available switching states and are mapped in a polygon with $2n$ sectors each spanning $2\pi/n$ degree. The space vectors of a three-phase VSI when transformed in $d-q$ plane, they are spread in two-dimensional plane [7]. However, the space vectors of n -phase VSI can be transformed into $(n-1)/2$ orthogonal planes. The $d-q$ plane vectors when used to implement space vector PWM, produces fundamental frequency component output with sinusoidal waveforms. While other plane vectors (auxiliary planes) e.g. $x-y$ in a five-phase and x_1-y_1, x_2-y_2 in a seven-phase VSIs are responsible for producing low-order harmonics and as a result distortion in the output voltage waveforms. Hence the implementation of space vector PWM require careful selection of space vectors and computation of dwell time in such a way to cancel out the effect of auxiliary plane vectors [6], [7].

Space vector PWM methods are successfully realized to cancel out the effect of auxiliary plane vectors for five-phase [9]–[12], six-phase [13]–[16], seven-phase [17], [18], nine-phase [19], [20], eleven-phase [21], thirteen-phase [22], and fifteen-phase [23], [24] VSIs. Sinusoidal carrier-based PWM technique is applied to control a five-phase VSI and analyzed in [25], [26]. The maximum output voltage magnitude available when using sinusoidal carrier-based PWM technique is $0.5 V_{DC}$ (V_{DC} is the DC link voltage), irrespective of the number of phases of VSIs. The lower dc bus utilization can be improved by modifying the modulating signal either by injection n th harmonic or by offset addition (which is in essence multiple of n th harmonics) [27], [28]. This causes an increase in the range of the linear modulation.

Although the approach of both the sinusoidal carrier-based PWM and space vector PWM techniques are entirely different, however, they have an underlying relationship; this relationship is elaborated in [29], [30]. The two methods are different because of the application time of zero vectors. The zero vectors are symmetrically placed in a sample time using space vector PWM contrary to sinusoidal carrier-based PWM. When the modulating signal is modified by adding n th harmonic, the zero vector application is symmetrically placed and the two methods yield similar results. More comprehensive relationship between the two PWM methods are illustrated for three-phase VSI in linear modulation region [31] and over modulation region [32]. The similar approach was adopted and the relationship between carrier-based PWM and space vector is established for a five-phase VSI [33]. This paper is an extension of [34], here the relationship between the two PWM schemes is established for a seven-phase VSI. Although the extension of sinusoidal carrier-based PWM when applied to multiphase VSI is simple, while the same is not true for space vector PWM. As in the case of multiphase space vector PWM, the total number of possible space vectors increases exponentially. There is not only increment in the number of space vectors but new subspaces are also recorded. These subspaces cause the lower order harmonics if they are not eliminated and the requirement of producing sinusoidal output voltage waveform need special considerations. Hence, the analysis presented for five-phase VSI [35], [36] cannot be easily extended to the

Fig. 1. Power circuit of a seven-phase voltage source inverter.

seven-phase VSI. Also the different harmonic content injection has been studied and it is experimentally validated in [37], where a third harmonic injection sinusoidal PWM method based on alternating carrier polarity is compared with the space vector PWM. The harmonic injection modulation has common mode voltage with lower frequency as compared to the space vector modulation method. Moreover, synchronization of the reference voltage and phases of injected third harmonic must be there. Whereas, in [38], the relative study on various types of carrier-based PWM techniques for multiphase induction motor drive have been presented. It is obtained that the torque pulsations in drives are intensified by the higher magnitude of space harmonics in airgap. Space harmonics can be reduced by carrier phase-shifted space vector PWM technique in which the lower centre band harmonics are cancelled and the remaining sidebands are shifted to six times of the carrier frequency. Thus, the multilevel voltage can reduce time harmonics. Better performance of the drive can be obtained by giving an optimum phase shift angle to the carriers.

II. SEVEN-PHASE VSI MODEL

A seven-phase voltage source inverter is presented in Fig. 1. The input DC link voltage is assumed constant. The output phase voltages are represented as v_i ($i = 1, 2, 3, 4, 5, 6, 7$), in the seven-phase star-connected and the pole voltages are denoted in capital letter (A, B, C, D, E, F, G). The inverter leg/pole voltage and phase-to-neutral voltage are related as (here leg and phase voltage have the same expression [9]);

$$v_i = \left(\frac{6}{7} \right) V_j - \left(\frac{1}{7} \right) \left(\sum_{\substack{k=A \\ k \neq j}}^G V_k \right) \quad (1)$$

where, if $i = 1, 2, \dots, 7$, then $j = A, B, \dots, G$, respectively. It is seen from Fig. 1 that the pole/leg voltage varies from $+0.5V_{DC}$ to $-0.5V_{DC}$. The power switches can be either ON (represented by 1) or OFF (represented by 0), and hence in total $2^7=128$ possible states exist.

These switching states can yield 128 number of space vectors. These 128 space vectors are classified as active (126) and zero (2). Space vectors when mapped, form nine concentric tetra-decagon in the $d-q$ plane with zero space vectors at the origin [17]. In a seven-phase VSI, the space vector in the $d-q$

TABLE I
LENGTHS AND POSITION OF PHASE VOLTAGE SPACE VECTORS [32]

Space vectors	Set number in planes			Space vectors lengths and position planes
	$d-q$	x_1-y_1	x_2-y_2	
$v_{1\text{phase}}$ to $v_{14\text{phase}}$	1	8	7	$(2/7)V_{DC}/[2 \cos(3\pi/7)]\exp(jk\pi/7)$
$v_{15\text{phase}}$ to $v_{28\text{phase}}$	2	5	9	$2(2/7)V_{DC} \cos(\pi/7)\exp(jk\pi/7)$
$v_{29\text{phase}}$ to $v_{42\text{phase}}$	3	3	4	$\sqrt{2} (2/7)V_{DC} \exp(j 0.3052 k\pi/7)$
$v_{43\text{phase}}$ to $v_{56\text{phase}}$	4	4	3	$\sqrt{2} (2/7)V_{DC} \exp(j 0.6948 k\pi/7)$
$v_{57\text{phase}}$ to $v_{70\text{phase}}$	5	9	2	$2(2/7)V_{DC} \cos(2\pi/7)\exp(jk\pi/7)$
$v_{71\text{phase}}$ to $v_{84\text{phase}}$	6	6	6	$(2/7)V_{DC} \exp(jk\pi/7)$
$v_{85\text{phase}}$ to $v_{98\text{phase}}$	7	1	8	$(2/7 V_{DC})/[2 \cos(2\pi/7)]\exp(jk\pi/7)$
$v_{99\text{phase}}$ to $v_{112\text{phase}}$	8	7	1	$(2/7 V_{DC})/[2 \cos(\pi/7)]\exp(jk\pi/7)$
$v_{113\text{phase}}$ to $v_{126\text{phase}}$	9	2	5	$2(2/7) V_{DC} \cos(3\pi/7)\exp(jk\pi/7)$ for $k = 0, 1, 2, \dots, 13$
$v_{127\text{phase}}$ to $v_{128\text{phase}}$	-	-	-	0

plane is defined as:

$$v_{dq} = \frac{2}{7} (v_1 + av_2 + a^2 v_3 + a^3 v_4 + a^{*3} v_5 + a^{*2} v_6 + a^* v_7) \quad (2a)$$

where $a = e^{j2\pi/7}$. Using general decoupling transformation matrix voltage space vectors in the other two orthogonal planes namely x_1-y_1 and x_2-y_2 are given with,

$$v_{x_1y_1} = \frac{2}{7} (v_1 + a^2 v_2 + a^4 v_3 + a^6 v_4 + av_5 + a^3 v_6 + a^5 v_7) \quad (2b)$$

$$v_{x_2y_2} = \frac{2}{7} (v_1 + a^3 v_2 + a^6 v_3 + a^2 v_4 + a^5 v_5 + av_6 + a^4 v_7)$$

The zero-sequence component is not considered since they are zero because of ungrounded neutral. The space voltage vectors are spanned over 14 sectors with each sector is spread over 25.714286° ($\pi/7$ radians). Table I provide the detail lengths and positions of all possible 128 space vectors [32]. From Table I, it is noticed that the space vectors of $d-q$ plane are harmonics of order $14k \pm 1, k = 0, 1, 2, 3, \dots, (1, 13, 15, \dots)$.

The space vectors of x_1-y_1 plane are harmonics of the order $7k \pm 2, k = 1, 3, 5, \dots, (5, 9, 19, \dots)$ while the space vectors of x_2-y_2 plane are harmonics of the order $7k \pm 4, k = 1, 3, 5, \dots, (3, 11, 17, \dots)$.

III. MODELLING AND VECTORIAL REPRESENTATION OF DIFFERENT PWM SCHEMES AND RELATION BETWEEN THEM

A. Space Vector Pulse Width Modulation Sinusoidal Output

In a three-phase VSI, two neighboring space vectors are used to synthesize the reference while using space vector PWM. However, in the case of multiphase VSI, several space vectors are available in each sector. In general, implementing SVPWM require an $n-1$ number of neighboring space vectors

in order to yield sinusoidal output voltage waveform [17]. This implies that six active vectors are required in each switching period in a seven-phase VSI. The time of application of space vectors should be chosen in such a way as to eliminate vectors of both x_1-y_1 and x_2-y_2 planes in order to obtain a sinusoidal output voltage. Thus six active vectors (In sector I, active vectors no. 1, 2, 15, 16, 71, 72 are used) and one zero vector is chosen to implement the SVPWM. The chosen vectors belong to 1st, 2nd and 6th sets. The space vectors used in all fourteen sectors are given in [32]. Each power switch of inverter leg changes its states twice (ON to OFF and then OFF to ON), hence in total twenty-eight switching takes place in one switching period.

The space vector spread in sector I is shown in Fig. 2 for $d-q, x_1-y_1$ and x_2-y_2 orthogonal planes. Considering equal volt-second principle, the following relations are obtained for sector I [32]; The lengths of space vectors from Table I is obtained as:

$$|v_1|_{1-14} = \frac{V_{DC}}{7 \cos\left(\frac{3\pi}{7}\right)} |v_m|_{15-28} = \frac{4V_{DC} \cos\left(\frac{\pi}{7}\right)}{7} |v_{sm}|_{71-84} = \frac{2V_{DC}}{7}$$

$$k_1 = \frac{|v_{sm}|}{|v_1|} = 0.44504$$

$$k_2 = \frac{|v_m|}{|v_1|} = 0.8019377$$

$$k_3 = k_1 + k_2 + 1 = 2.246979$$

From [18],

$$t_a = \frac{|v_s^*| \sin\left(k \frac{\pi}{7} - \theta\right)}{|v_1| \sin\left(\frac{\pi}{7}\right)} t$$

$$t_b = \frac{|v_s^*| \sin\left[\theta - (k-1) \frac{\pi}{7}\right]}{|v_1| \sin\left(\frac{\pi}{7}\right)}$$

where $k = 1, 2, \dots, 13, 14$.

Let t_{a3}, t_{a2} and t_{a1} be the time of application for vectors numbers sets 71–84, 15–28 and 1–14, respectively. Similarly, let the times of applications t_{b3}, t_{b2} and t_{b1} be the dwell time for another side of vectors number sets 71–84, 15–28 and 1–14, respectively. Therefore, the time of applications of space vectors can be written in (3)–(4). The time of application of (4) completely agree with [17], [18]. The zero space vector application time is t_{a1}, t_{a2} and t_{a3} are application times of space vectors 1, 15, and 71, respectively and t_{b1}, t_{b2} and t_{b3} are applications times of space vectors 2, 16 and 72, respectively in sector I. Fig. 3 shows the switching sequence and decomposition of vectors in sector I.

B. Carrier-Based Sinusoidal PWM (CBSPWM)

CBSPWM techniques are simple in implementing analogically and digitally, hence, they are popular and widely used [26].

Fig. 2. Space vector disposition in sector I. (a) d - q plane. (b) x_1 - y_1 plane. (c) x_2 - y_2 plane.

Fig. 3. (a) Switching pattern and space vector disposition for one cycle of operation. (b) Sketch of vector decomposition on volt.sec principle to eliminate/reduce harmonics.

The principle of application of CBSPWM to a multiphase VSI is the same as that for a three-phase VSI. The sinusoidal modulating signals are compared with a triangular or a saw-tooth carrier signal to generate PWM signals. The frequency of carrier signal is kept much higher than that of the modulating signals.

$$\begin{aligned} t_{a1} &= \frac{|v_s^*| \sin\left(k \frac{\pi}{7} - \theta\right)}{k_3 |v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\ t_{a2} &= \frac{k_2 |v_s^*| \sin\left(k \frac{\pi}{7} - \theta\right)}{k_3 |v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\ t_{a3} &= \frac{k_1 |v_s^*| \sin\left(k \frac{\pi}{7} - \theta\right)}{k_3 |v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\ t_{b1} &= \frac{|v_s^*| \sin\left[\theta - (k-1) \frac{\pi}{7}\right]}{k_3 |v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\ t_{b2} &= \frac{k_2 |v_s^*| \sin\left[\theta - (k-1) \frac{\pi}{7}\right]}{k_3 |v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\ t_{b3} &= \frac{k_1 |v_s^*| \sin\left[\theta - (k-1) \frac{\pi}{7}\right]}{k_3 |v_1| \sin\left(\frac{\pi}{7}\right)} t_s \end{aligned} \quad (3)$$

Substituting the values of k_1 , k_2 and k_3 in (3) one get,

$$\begin{aligned}
 t_{a1} &= 0.445 \frac{|v_s^*| \sin\left(k \frac{\pi}{7} - \theta\right)}{|v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\
 t_{a2} &= 0.3569 \frac{|v_s^*| \sin\left(k \frac{\pi}{7} - \theta\right)}{|v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\
 t_{a3} &= 0.19806 \frac{|v_s^*| \sin\left(k \frac{\pi}{7} - \theta\right)}{|v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\
 t_{b1} &= 0.445 \frac{|v_s^*| \sin\left[\theta - (k-1) \frac{\pi}{7}\right]}{|v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\
 t_{b2} &= 0.3569 \frac{|v_s^*| \sin\left[\theta - (k-1) \frac{\pi}{7}\right]}{|v_1| \sin\left(\frac{\pi}{7}\right)} t_s \\
 t_{b3} &= 0.19806 \frac{|v_s^*| \sin\left[\theta - (k-1) \frac{\pi}{7}\right]}{|v_1| \sin\left(\frac{\pi}{7}\right)} t_s
 \end{aligned} \quad (4)$$

1) Sinusoidal Pulse Width Modulation (SPWM)

The SPWM becomes simple when the zero-sequence signal is set to zero. PWM signals for all legs are as per sinusoidal fundamental signals. The highest modulation index in the linear region is unity, it is defined as:

$$M = \frac{V_1}{0.5V_{DC}} \quad (5)$$

where, V_1 is the fundamental output phase voltage.

2) Seventh Harmonic Injection PWM-SHIPWM

To enhance the output voltage magnitude in a carrier-based PWM, modulating signal is augmented by injecting n -th harmonic. This causes a reduction in peak of the modulating signal providing further room for pushing the modulation index. In general, the amount of n -th harmonic to be injected into the fundamental is given as [25].

$$V_n = \pm V_1 \frac{\sin(\pi/2n)}{n} \quad (6)$$

where (6) takes the positive sign for $n=3, 7, 11, 15, \dots$ and negative sign for $n=5, 9, 13, 17, \dots$ (number of phases). Hence in a seven-phase system, the injected 7th harmonic is in phase with the fundamental. The zero-sequence signal is thus defined as:

$$v_{nN}(t) = V_7 \sin(7\omega t) + \frac{V_1}{7} \sin\left(\frac{\pi}{14}\right) \sin(7\omega t) \quad (7)$$

Using (7), the generalized resulting modulating signals have

Fig. 4. Characteristics signals of carrier-based PWM. (a) With seventh harmonic injection. (b) With triangular harmonic injection.

the form

$$V_i = M \cdot 0.5V_{DC} \left[\sin\left(\omega t - \frac{m\pi}{7}\right) + 0.0318 \cdot \sin(7\omega t) \right] \quad (8)$$

where $i = 1, 2, \dots, 7$; $m = 0, 2, 4, \dots, 10, 12$. In the linear region, when n -th harmonic injected, the maximum modulation index (M) is expressed as [25]:

$$M = \frac{1}{\cos\left(\frac{\pi}{2n}\right)} \quad (9)$$

where $n = 7$, the maximum modulation index $M_{SHIPWM} = 1.0257$. Thus there is 2.57% increase in the DC bus utilization comparing SPWM.

3) Offset Addition PWM or Triangular Injection PWM (TIPWM)

Another prevalent approach to enhance the output voltage magnitude in a carrier-based PWM scheme is by adding an offset signal into the fundamental signal. The modulating signal is modified in such a way that its peak shrinks providing an additional room for pushing the reference value. The offset signal is given as:

$$v_{nN} = -\frac{1}{2}(V_{\max} + V_{\min}) \quad (10)$$

where, $V_{\max} = \max(V_1, V_2, V_3, V_4, V_5, V_6, V_7)$ and $V_{\min} = \min(V_1, V_2, V_3, V_4, V_5, V_6, V_7)$. The voltage v_{nN} (the modulating signal) contains all multiple of 7th harmonics. If the same modulating signal is used to generate the gating signals the maximum achievable modulation index would be $M_{TIPWM} = 1.0257$. To illustrate the effects of 7th harmonic and offset signal injection the overall modulating signals are shown in Fig. 4.

C. Relationship Between Carrier-Based and Space Vector PWM

Fig. 5 shows the generated PWM switching signals when the triangular carrier signal interacts with the sinusoidal signals. It can be seen that the CBPWM (Fig. 5) and SVPWM (Fig. 6) have the similar pattern in sector I as well as in other sectors too. From the switching pattern, the relationship between space vector application time in different sectors and the modulating

TABLE II
RELATIONSHIP BETWEEN MODULATING SIGNALS AND SPACE VECTOR APPLICATION TIME

Signals sectors	V_1	V_2	V_3	V_4	V_5	V_6	V_7
I	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$
II	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$
III	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$
IV	$(V_{DC}/2t_s)(t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} + t_{a3} - t_{b3})$
V	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} + t_{b3})$
VI	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} - t_{b3})$
VII	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} - t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(t_{a1} + t_{b1} + t_{a2} + t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} + t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3})$	$(V_{DC}/2t_s)(-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} + t_{b3})$

Fig. 5. SVPWM and CBPWM signals in sector I.

Fig. 6. Relationship between space vector sectors and fundamental signals.

signals can be found. They are tabulated in Table II. The same relationship exists for the sectors from VIII to XIV but with opposite polarity to that of sectors I to VII, respectively. The zero-sequence signal can then be found as given in (11).

$$v_{nN} = \frac{1}{7} (V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7) \quad (11)$$

The relationships can be obtained between the zero-sequence signal and space vector application time using (11) and the switching pattern for all fourteen sectors. They are listed in Table III for sectors I to VII. Again, the same relationship exists for the sectors from VIII to XIV but with opposite polarity to that of sectors I to VII, respectively. The general expression for zero-sequence signal in even and odd sectors can be expressed as in (12) and (13), respectively.

$$v_{nN} = \frac{V_{DC}}{2t_s} (t_{a1} - t_{b1} - 3t_{a2} + 3t_{b2} + 5t_{a3} - 5t_{b3} - 7t_{127} + 7t_{128}) \quad (12)$$

$$v_{nN} = \frac{V_{DC}}{2t_s} (-t_{a1} + t_{b1} + 3t_{a2} - 3t_{b2} - 5t_{a3} + 5t_{b3} - 7t_{127} + 7t_{128}) \quad (13)$$

D. Relationship Between Space Vectors and Line-to-Line Voltages

In a seven-phase system three systems of line-to-line voltages namely adjacent, 1st non-adjacent, and 2nd non-adjacent, exist. The relationship between line-to-line voltage and space vectors can be obtained using equations of Table II and equation (14), given in Table IV for sectors I and II;

$$v_{ij} t_s = (v_i - v_j) t_s = \frac{V_{DC}}{2} (v_i^* - v_j^*) t_s \quad (14)$$

where $i, j = 1, 2, 3, 4, 5, 6, 7$ and $i \neq j$. Once again, the same

TABLE III
ZERO-SEQUENCE SIGNALS IN DIFFERENT SECTORS

Sector No.	Switching period	Zero-sequence signal
I	$t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3} - t_{127} + t_{128}$	$v_{nN} = \frac{V_{DC}}{2t_s} (-t_{a1} + t_{b1} + 3t_{a2} - 3t_{b2} - 5t_{a3} + 5t_{b3} - 7t_{127} + 7t_{128})$
II	$t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} - t_{b3} - t_{127} + t_{128}$	$v_{nN} = \frac{V_{DC}}{2t_s} (t_{a1} - t_{b1} - 3t_{a2} + 3t_{b2} + 5t_{a3} - 5t_{b3} - 7t_{127} + 7t_{128})$
III	$t_{a1} + t_{b1} + t_{a2} - t_{b2} + t_{a3} - t_{b3} - t_{127} + t_{128}$	$v_{nN} = \frac{V_{DC}}{2t_s} (-t_{a1} + t_{b1} + 3t_{a2} - 3t_{b2} - 5t_{a3} + 5t_{b3} - 7t_{127} + 7t_{128})$
IV	$t_{a1} - t_{b1} - t_{a2} + t_{b2} + t_{a3} - t_{b3} - t_{127} + t_{128}$	$v_{nN} = \frac{V_{DC}}{2t_s} (t_{a1} - t_{b1} - 3t_{a2} + 3t_{b2} + 5t_{a3} - 5t_{b3} - 7t_{127} + 7t_{128})$
V	$-t_{a1} - t_{b1} + t_{a2} - t_{b2} - t_{a3} + t_{b3} - t_{127} + t_{128}$	$v_{nN} = \frac{V_{DC}}{2t_s} (-t_{a1} + t_{b1} + 3t_{a2} - 3t_{b2} - 5t_{a3} + 5t_{b3} - 7t_{127} + 7t_{128})$
VI	$-t_{a1} - t_{b1} - t_{a2} - t_{b2} + t_{a3} - t_{b3} - t_{127} + t_{128}$	$v_{nN} = \frac{V_{DC}}{2t_s} (t_{a1} - t_{b1} - 3t_{a2} + 3t_{b2} + 5t_{a3} - 5t_{b3} - 7t_{127} + 7t_{128})$
VII	$-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} - t_{b3} - t_{127} + t_{128}$	$v_{nN} = \frac{V_{DC}}{2t_s} (-t_{a1} + t_{b1} + 3t_{a2} - 3t_{b2} - 5t_{a3} + 5t_{b3} - 7t_{127} + 7t_{128})$

TABLE IV
SPACE VECTORS AND LINE-TO-LINE VOLTAGES

Adjacent line-to-line voltages	1st non-adjacent line-to-line voltages	2nd non-adjacent line-to-line voltages
Sector I		
$V_{12} = \frac{V_{DC}}{t_s} (t_{a3})$	$V_{13} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b2} + t_{a1})$	$V_{14} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3})$
$V_{23} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b2})$	$V_{24} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{a2} + t_{b2})$	$V_{25} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{b3})$
$V_{34} = \frac{V_{DC}}{t_s} (t_{b1} + t_{a2})$	$V_{35} = \frac{V_{DC}}{t_s} (t_{b1} + t_{a2} + t_{b3})$	$V_{36} = \frac{V_{DC}}{t_s} (t_{b1})$
$V_{45} = \frac{V_{DC}}{t_s} (t_{b3})$	$V_{46} = \frac{V_{DC}}{t_s} (-t_{a2})$	$V_{47} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{a2})$
$V_{56} = \frac{V_{DC}}{t_s} (-t_{a2} - t_{b3})$	$V_{57} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{a2} - t_{b3})$	$V_{51} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3} - t_{b3})$
$V_{67} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1})$	$V_{61} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{b2} - t_{a3})$	$V_{62} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{b2})$
$V_{71} = \frac{V_{DC}}{t_s} (-t_{b2} - t_{a3})$	$V_{72} = \frac{V_{DC}}{t_s} (-t_{b2})$	$V_{73} = \frac{V_{DC}}{t_s} (t_{a1})$
Sector II		
$V_{12} = \frac{V_{DC}}{t_s} (-t_{b3})$	$V_{13} = \frac{V_{DC}}{t_s} (t_{a2})$	$V_{14} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{a2})$
$V_{23} = \frac{V_{DC}}{t_s} (t_{a2} + t_{b3})$	$V_{24} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{a2} + t_{b3})$	$V_{25} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3})$
$V_{34} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1})$	$V_{35} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{b2} + t_{a3})$	$V_{36} = \frac{V_{DC}}{t_s} (t_{a1} + t_{b1} + t_{b2})$
$V_{45} = \frac{V_{DC}}{t_s} (t_{b2} + t_{a3})$	$V_{46} = \frac{V_{DC}}{t_s} (t_{b2})$	$V_{47} = \frac{V_{DC}}{t_s} (-t_{a1})$
$V_{56} = \frac{V_{DC}}{t_s} (-t_{a3})$	$V_{57} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b2} - t_{a3})$	$V_{51} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{a3})$
$V_{67} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b2})$	$V_{61} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{a2} - t_{b2})$	$V_{62} = \frac{V_{DC}}{t_s} (-t_{a1} - t_{b1} - t_{a2} - t_{b2} - t_{b3})$
$V_{71} = \frac{V_{DC}}{t_s} (-t_{b1} - t_{a2})$	$V_{72} = \frac{V_{DC}}{t_s} (-t_{b1} - t_{a2} - t_{b3})$	$V_{73} = \frac{V_{DC}}{t_s} (-t_{b1})$

TABLE V
SPACE VECTOR SECTORS AND FUNDAMENTAL SIGNALS

Sector I	Sector II
$V_1 > V_2 > V_7 > V_3 > V_6 > V_4 > V_5$	$V_7 > V_1 > V_3 > V_7 > V_4 > V_6 > V_5$
Sector III	Sector IV
$V_2 > V_3 > V_1 > V_4 > V_7 > V_5 > V_6$	$V_3 > V_2 > V_4 > V_1 > V_5 > V_7 > V_6$
Sector V	Sector VI
$V_3 > V_4 > V_2 > V_5 > V_1 > V_6 > V_7$	$V_4 > V_3 > V_5 > V_2 > V_6 > V_1 > V_7$
Sector VII	Sector VIII
$V_4 > V_5 > V_3 > V_6 > V_7 > V_1 > V_2$	$V_5 > V_4 > V_6 > V_3 > V_7 > V_2 > V_1$
Sector IX	Sector X
$V_5 > V_6 > V_4 > V_7 > V_3 > V_1 > V_2$	$V_6 > V_5 > V_7 > V_4 > V_1 > V_3 > V_2$
Sector XI	Sector XII
$V_6 > V_7 > V_5 > V_1 > V_4 > V_2 > V_3$	$V_7 > V_6 > V_1 > V_5 > V_2 > V_4 > V_3$
Sector XIII	Sector XIV
$V_7 > V_1 > V_6 > V_2 > V_5 > V_3 > V_4$	$V_1 > V_7 > V_2 > V_6 > V_3 > V_5 > V_4$

Fig. 7. Application time of zero vector in sector I.

relationship exists for the sectors from VIII to XIV but with opposite polarity to that of sectors I to VII, respectively. A direct relationship between line-to-line voltages and space vectors is thus evident from Table IV. Further, it can be noted that the line-to-line voltages are determined by only active vectors. Hence line-to-line output voltage can be obtained directly using the time of application.

E. Space Vector Sectors and Fundamental Signals

The space vectors and the fundamental signals are shown in Fig. 6 and their relationship is listed in Table V. The sectors are shown in Roman letter I to XIV and the fundamental signals are seven-phase sinusoidal waveform.

F. Distribution of Zero-Sequence Signal and Zero Vectors

In SVPWM the two zero vectors timings t_{127} , t_{128} can be distributed as per choice depending upon the type of PWM to be used. That means the timings are flexible in SVPWM whereas timings are fixed in CBPWM. Depending on the choice of t_{127} and t_{128} various space vector PWM are possible. The expression for t_{127} (0000000) can be written as (15)–(17). Fig. 7 shows the variation of zero vector application time in

Fig. 8. Variation of t_{127} with angle in sector I for sinusoidal Carrier-based PWM.

sector I for maximum possible reference of 0.61 p.u. The switching frequency is assumed as 5 kHz. The general form of distribution of t_{127} and t_{128} can be written as:

$$t_{127} = \xi(t)t_o \quad (15)$$

$$t_{128} = [1 - \xi(t)]t_o \quad (16)$$

$$t_{127} + t_{128} = t_s - (t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3}) \quad (17)$$

where, $0 \leq \xi(t) \leq 1$ A degree of freedom that exists in CBPWM is the shape of zero-sequence signal. In general, the zero-sequence signal can be expressed as [23]:

$$v_{nN} = \xi(t)(1 - V_{\max}) + [1 - \xi(t)](-1 - V_{\min}) \quad (18)$$

By using (18) for arbitrary zero-sequence signal, the timings of application of zero space vectors t_{127} and t_{128} can be obtained.

1) Sinusoidal Pulse Width Modulation (SPWM)

This is the result of $v_{nN}(t) = 0.0$ which leads to SPWM with modulation index $M_{\text{SPWM}} = 1$. The equivalent distribution of t_{127} and t_{128} is obtained using (17). Considering switching period of 0.2 ms, the variation of application time of in sector I without harmonic injection is shown in Fig. 8.

$$t_{127} = \frac{t_s}{2} \left[1 - \frac{1}{2} \left(\frac{6k_1 + 4k_2 + 2}{k_3} \right) \left| v_s^* \right| \cos(\theta) \right] \quad (19)$$

$$t_{128} = t_s - (t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3} + t_{127}) \quad (20)$$

2) Seventh Harmonic Injection PWM (SHIPWM)

This is the result of $v_{nN} = V_1 \frac{\sin(\pi/14)}{7}$ which leads to SHIPWM with maximum modulation index $M_{\text{SHIPWM}} = 1.0318$. The corresponding distribution of t_{127} and t_{128} is

$$t_{127} = \frac{t_s}{2} \left\{ 1 - \frac{1}{2} \left(\frac{6k_1 + 4k_2 + 2}{k_3} \right) \left| v_s^* \right| \left[\cos(\theta) + \frac{\sin(\frac{\pi}{14})}{7} \cos(7\theta) \right] \right\} \quad (21)$$

Fig. 9. In sector I, the variation of t_{127} with angle for SHIPWM.

$$t_{128} = t_s - (t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3} + t_{127}) \quad (22)$$

Fig. 9 shows, in sector I, the variation of application time of t_{127} with harmonic injection.

3) Offset Addition or Triangular Zero-Sequence Injection PWM (TIPWM)

This is the result of $v_{nN}(t) = -\frac{1}{2}(V_{\max} + V_{\min})$ which leads to TIPWM with maximum modulation index 1.0318. This is due to the application of zero vectors. The corresponding distribution of t_{127} and t_{128} is

$$t_{127} = t_{128} = \frac{1}{2} [t_s - (t_{a1} + t_{b1} + t_{a2} + t_{b2} + t_{a3} + t_{b3})] \quad (23)$$

IV. SWITCHING PATTERN OF CARRIER-BASED PWM AND SPACE VECTOR PWM

Carrier-based PWM is characterized by the type of high carrier signals that are used to compare with low frequency modulating signals. Performance of the modulation scheme heavily relies on the shape of carrier signals. Usually triangular (double edge) and saw-tooth (single edge) waveforms are used as carrier signals. In contrast space vector method optimally determines the active and zero vector pulse width to satisfy the volt-second balance. The proper sequencing of the active and zero vectors determine the performance of space vector modulator. For triangular carrier signal, the equivalent switching pattern corresponds to the one used in space vector PWM (Fig. 5). Thus the two modulation schemes yield similar performance. Considering saw-tooth waveform as the carrier signal the equivalent switching pattern is illustrated in Fig. 10.

V. EXPERIMENTAL RESULTS

A seven-phase VSI is built using fourteen insulated gate bipolar transistor (IGBT) power modules. The gate pulses were generated from the Matlab/Simulink model, using dSPACE DS1103 control board. A star-connected seven-phase R-L load ($R = 75 \Omega$, $L = 78 \text{ mH}$) is connected to each output phase of the seven-phase inverter. DC link voltage is adjusted to $V_{DC} = 200 \text{ V}$ for all PWM schemes from a regulated DC power supply. The

Fig. 10. Switching pattern for carrier based PWM with saw tooth carrier.

Fig. 11. Experimental setup.

dead time between switching on the lower leg switch and switching off the upper leg switch is kept at $2 \mu\text{s}$ by dead time code in the FPGA Vertex-5 board (connected externally to the dSpace board DS 5203) which is used in conjunction with dSpace-1006. The minimum sampling time used is $10 \mu\text{s}$ for dspace and 100 ns for the FPGA. The experimental set-up is shown in Fig. 11, where, experiments were performed with CBPWM, SHIPWM, SVPWM, and TIPWM and results are shown in Figs. 12–14.

DC link voltage is adjusted to $V_{DC} = 200 \text{ V}$ from a regulated DC power supply for controlling the load with voltage/frequency = constant. Fig. 12 shows experimental results of four PWM schemes with a unity modulation index, where from the top, 1st trace gives the phase-A voltage, 2nd trace gives the A-B line voltage, 3rd trace gives the A-C line to voltage and the 4th trace gives the phase-A current. The current is shown for phase-A, but other phase currents will have same magnitude but phase shifted by $\frac{2\pi}{7}$ degrees. Fig. 12(a), (b), (c)

Fig. 12. With modulating Index $m = 1$, phase voltage, adjacent line voltage (V_{AB}), second adjacent voltage (V_{AC}), and phase current. (a) CBPWM. (b) SVPWM. (c) SHIPWM. (d) TIPWM.

and (d) show the experimental results for CBPWM, SHIPWM, SVPWM, and TIPWM, respectively. The output voltage at a modulation index of unity is presented in Fig. 12; the RMS of phase voltage is seen as 87 V for the CBPWM while the theoretical value is 85.2 V that amounts to an error of 3.7%. This difference appears due to dead time in the experimental realization and higher sampling rate.

In this paper, due to the laboratory constraints, the experiment has been done on a 7-phase R - L load instead of 7-phase induction motor. However, all PWM techniques have been validated for different modulation index values with constant voltage/frequency = constant control. The experimental results for the under modulation ($M.I = 0.4$) and over modulation ($M.I = 1.2$) for all four PWM techniques are presented in Fig. 13, where the phase-A voltage, A-B line to line voltage, A-C line to line voltage and phase-A current are shown. From this figure it is observed that because of the $V/f = \text{constant}$ control the line-line voltage and frequency is maintained constant for 0.4 and 1.2 M.I values. With CBPWM, the RMS line to A-B line voltage and frequency of the load are 42 V and 20 Hz, respectively for 0.4 M.I, as shown in Fig. 13(a). Similarly, A-B line voltage and frequency of the load are 120 V and 60 Hz respectively for M.I = 1.2, as shown in Fig. 13(b). The set of results for 0.4 and 1.2 M.I values with SHIPWM, SVPWM, and TIPWM

are shown in Fig. 13(c) to (f), respectively. Since the SVPWM and TIPWM will generate same modulating waveform, so the phase voltage and the currents will be the same. Because of this, the results are shown for SVPWM in Fig. 13(c) and (d).

The experimental phase voltage, current waveforms and associated harmonic spectrum with CBPWM technique for different modulation index values are presented in Fig. 14. The percentage THD values of phase voltage and phase current for M.I = 1 with CBPWM are shown in Fig. 14(b), where it is observed that the current and voltage THD is 1.8% and 7.2%, respectively. However, the percentage THDs for remaining carrier-based PWMs are clearly mentioned in Table VI. Outputs of all carrier-based PWMs are similar with slight difference. This difference is due to the modulation index is in over-modulation region.

VI. CONCLUSION

The sinusoidal output is achieved using CBPWM and SVPWM schemes, both are analyzed/compared using analytic, simulation and experimental approaches. A transformation between arbitrary CBPWM and SVPWM is shown by relating space vectors and modulation signals. The line-to-line voltage and space vectors are shown to be related directly. It establishes that only active vectors give the line-to-line voltage. The line-

Fig. 13. Phase voltage, adjacent line voltage (V_{AB}), second adjacent voltage (V_{AC}), and phase current. (a) At $m = 0.4$, CBPWM. (b) At $m = 1.2$, CBPWM (over modulation). (c) At $m = 0.4$, SVPWM (under modulation). (d) At $m = 1.2$, SVPWM (over modulation). (e) At $m = 0.4$, SHIPWM (under modulation). (f) At $m = 1.2$, SHIPWM (under modulation).

TABLE VI
COMPARISON OF EXPERIMENTAL RESULTS

Sl. No.	PWM type	Mod. index	V_{phase} (V)	I_{phase} (A)	Current THD (%)
1	SVPWM	$V_{\text{ref}}=1.0318$	91	2.1	1.4
3	CBPWM	1.0	87	2	2.8
5	SHIPWM	1.0318	90	2.1	2.2
7	TIPWM	1.0318	91	2.1	1.4

to-line voltage is independent of zero vectors. The space vector in various sectors and modulation signals are related. The distribution of zero vectors application times for SPWM,

SHIPWM and TIPWM are expressed analytically. In terms of THD as performance modulator for triangular and saw-tooth carrier signals are shown. Finally, it is concluded that during implementation similarities do exist between space vector PWM and carrier-based PWM, and shown to have underlying relationships in a seven-phase VSI similar to three-phase VSI. With the increase of phase numbers the space vector PWM method becomes more and more complex and the gain the output voltage reduces. It is further concluded that the third harmonic injection and triangular injection methods give similar results as that of SVPWM, however, they are simple to implement. Hence for the practical purposes, instead of using SVPWM, triangular injection and 3rd harmonic injection method should be preferred.

Fig. 14. Harmonic analysis of the CBPWM at different modulation indices and in V/f control mode. (a) At 50 Hz operation. (b) Lower order harmonics. (c) At 20 Hz operation. (d) At 60 Hz operation.

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