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Novel Carrier-Based PWM technique for n-Phase VSI

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Abstract

Multiphase machines are nowadays considered for high-power variable-speed drives applications due to numerous advantages when compared to their three-phase counterparts. Multiphase voltage source inverters are invariably used to provide multiphase variable voltage and variable frequency supply with appropriate pulse width modulation (PWM) control. In the proposed work Carrier-based PWM for n-phase VSI is implemented. This method is most common PWM technique for VSI. This paper is aimed at providing a generalised carrier-based PWM for n-phase inverters. The viability of the proposed concept is proved by simulation taking for n-phase (3, 5, 6, 7 and 9) VSI as an example. From the observation the output phase voltage from three phase to nine phase inverter is same. Increasing number of phases percentage increase in THD is observed in the carrier based PWM technique.

Keywords: Carrier-based, n-phase, pulse width modulation, voltage source inverter.

1. Introduction

Variable speed electric drives predominately utilise three-phase machines. However, since the variable speed ac drives require a power electronic converter for their supply, the number of machine phases is essentially unlimited. This has led to an increase in the interest in multi-phase ac drive applications, especially in conjunction with traction, EV/HEVs and electric ship propulsion, since multi-phase machines offer some inherent advantages over their three-phase counterparts. Supply for a multi-phase variable speed drive is in the majority of cases provided by a VSI. A number of PWM techniques are available to control a two-level three-phase VSI. The most widely used pulse PWM techniques for three-phase inverters are the carrier-based sinusoidal PWM (including the offset addition) and the space vector PWM (SVPWM). These techniques have been extensively discussed in the literature (Holmes 2003).The number of voltage vectors of a two-level of phases increases. In principle, there is a lot of flexibility available in choosing the proper space vector combination for an effective control of multi-phase VSIs because of a large number of space vectors. In SVPWM a reference space vector is sampled at a fixed interval to determine the proper switching vectors and their time of application. Application of only large-length active vectors leads to the maximum possible output voltage from a five-phase VSI, of $0.6155V_{dc}$ (peak), but unwanted low-order harmonics appear in the output phase voltages (Shi 2002),Toliyat 2000). A specific problem, encountered in multi-phase drive systems, is that generation of certain low-order voltage harmonics in the VSI output can lead to large stator current harmonics, since these are in essence restricted only by stator leakage impedance (Zhao 1995). For example, if a five-phase machine with sinusoidal winding distribution is supplied with voltages containing the 3rd and the 7th harmonic, stator current harmonics of the 3rd and the 7th order will freely flow through the machine and their amplitude will be restricted by stator leakage impedance only. It is therefore important that the multi-phase VSI output is kept as close as possible to sinusoidal and the SVPWM scheme of (Zhao 1995), for a dual-three phase (asymmetrical six-phase) machine, was developed with exactly this reasoning in mind. On the other hand, five-phase (and in general *n*-phase) machines can be designed with concentrated windings and in such a case it is desirable to utilise the third harmonic stator current injection to enhance the torque production (Xu 2002). Since now both the fundamental and the third stator current harmonic are controlled, it is necessary to have a suitable PWM technique, which enables control of both the fundamental and the third harmonic of the stator supply voltage. A space vector PWM method, proposed in (Ryu 2004) has been developed for this type of a five-phase machine. It is based on the vector space decomposition technique (Zhao 1995) and the inverter output voltages contain the fundamental and the third harmonic, which are both of controllable magnitudes. If a multi-phase machine is with a sinusoidal distributed winding, the output voltages should contain only the fundamental component and they need to be free of low-order harmonics. A lot of effort has been directed in recent times towards development of SVPWM schemes for this type of application (DeSilva 2004 - Kelly 2003). Most of the work has been related to five-phase VSIs (DeSilva 2004 - Casadei 2005), and it has been shown that, by using neighbouring two medium-length and two large-length active vectors, one can achieve sinusoidal output voltages up to 85.41% of the maximum achievable fundamental with application of large-length vectors only (Iqbal 2006). Improvement of dc bus utilisation from 85.41% to 100% inevitably leads to reappearance of unwanted low-order harmonics in the output voltages. These however can be kept at much lower values than when only large vectors are utilised, provided that modified SVPWM schemes of (Iqbal 2006) are applied. Sinusoidal PWM equivalents of SVPWM for multi-phase VSIs have not so far attracted much attention, with the exception of (Ojo 2005), where carrier-based PWM with offset addition was considered. As noted in (Ojo 2005), carrier-based PWM methods are much easier to implement in multi-phase VSIs than SVPWM, since SVPWM requires sector identification and look-up tables to determine time of application of different vectors; this makes the implementation complicated. The aim of this paper is therefore to present a PWM technique for sinusoidal voltage output from a multi-phase VSI, based on sinusoidal carrier-based PWM with continuous sinusoidal harmonic injection. At first a five-phase VSI is considered and fifth harmonic is injected to increase the linear modulation range. It is shown that the maximum achievable sinusoidal output voltage is increased in this way to 85.41% of the maximum fundamental, this being the same as with SVPWM (and giving the full analogy of the equivalence of SVPWM and sinusoidal PWM with harmonic injection that is well known for three-phase VSIs, (Holmes 2003). This is followed by generalisation of the concept and an expression is given that enables determination of the optimum injection level for any *n*-phase (for odd *n*) VSI. An increase in the output fundamental over 85.41% is only possible by injecting other low-order harmonics that will however appear in the output voltages. The multi-harmonic injection concept is therefore considered to extend the operational range of the carrier-based sine-triangle PWM for a five-phase VSI. Some experimental results, collected from a two-motor five-phase series-connected drive (Iqbal 2006), are given to illustrate the use of sinusoidal multi-frequency PWM in a five-phase VSI.

2. Carrier – Based PWM

Carrier-based SPWM is the most popular and widely used PWM technique because of their simple implementation in both analog and digital realization (Ojo 2005). The principle of carrier based PWM true for a three-phase VSI is also applicable to a multiphase VSI. The PWM signal is generated by comparing a sinusoidal modulating signal with a triangular (double edge) or a saw-tooth (single edge) carrier signal. The frequency of the carrier is normally kept much higher compared to the modulating signal. The principle of operation of a carrier-based PWM modulator is shown in Figure.1 and generation of the PWM waveform is illustrated in Figure.2. Modulation signals are obtained using five fundamental sinusoidal signals (displaced in time by $\alpha = 2\pi/n$), which are summed with a zero-sequence signal. These modulation signals are compared with a high-frequency carrier signal (saw-tooth or triangular shape), and all five switching functions (1) for inverter legs are obtained directly. In general, modulation signal can be expressed as

$$v_i(t) = v_i^*(t) + v_n N(t) \tag{1}$$

Where $i = a, b, c, d,$ and n, v_{nN} represents zero-sequence signal,and v_i^* are fundamental sinusoidal signals. Zero-sequence signal represents a degree of freedom (DOF) that exits in the structure of a carrier-based modulator and is used to modify modulation signal waveforms, and thus, to obtain different modulation schemes. Continuous PWM schemes, analyzed in this paper, are characterized by the presence of switching activity in each of the inverter legs over the carrier signal period, as long as peak value of the modulation signal does not exceed the carrier magnitude.

The following relationship hold true in Figure. 2:

$$t_n^+ - t_n^- = v_n t_s \tag{2}$$

$$t_n^+ = \left(\frac{1}{2} + v_n\right) t_s \tag{3a}$$

$$t_n^+ = \left(\frac{1}{2} + v_n\right) t_s \tag{3b}$$

where t_n^+ and t_n^- are the positive and negative pulse widths in the *n*th sampling interval, respectively, and v_n is the normalized amplitude of modulation signal. The normalization is done with respect to *V*dc. Equation (3) is referred as the equal volt–second principle, as applied to a three-phase inverter (Holmes 2003, Blasko 1997).The normalized peak value of the triangular carrier wave is ±0.5 in linear region of operation. Modulator gain has the unity value while operating in the linear region and peak value of inverter output fundamental voltage is equal to the peak value of the fundamental sinusoidal signal. Thus the maximum output phase voltages from a five-phase VSI are limited to 0.5 p.u. This is also evident in (Iqbal 2006). Thus, the output phase voltage from a three-phase and a n-phase VSI are same when utilizing carrier-based PWM.

3. Sinusoidal PWM

The simplest continuous carrier-based PWM is obtained with selection of the zero-sequence signal as $v_n N(t) = 0$.Modulation signals for all five inverter legs are equal to five sinusoidal fundamental signals. Thus, while operating in the linear region, maximum value of the modulation index of the SPWM has the unity value, $M_{\mathrm{SPWM}} = 1$. Modulation index is defined as the ratio of the fundamental component amplitude of the phase-to-neutral inverter output voltage to one-half of the available dc bus voltage. Thus,

$$M = \frac{v}{0.5v_{dc}} \tag{4}$$

Where V is the fundamental output phase voltages.

$$\begin{aligned}
v_a &= v\cos wt \\
v_b &= v\cos(wt-\alpha) \\
v_c &= v\cos(wt-2\alpha) \\
v_d &= v\cos(wt-3\alpha) \\
v_e &= v\cos(wt-4\alpha) \\
v_f &= v\cos(wt-5\alpha) \\
&. \\
&. \\
v_n &= v\cos(wt-n\alpha)
\end{aligned} \tag{5}$$

Here

$$\alpha = \frac{2\pi}{n}$$

Where M is the modulation indices of the fundamental. In the linear modulation range is M is restricted to $0 \le M \le 1$. Equation (5) gives fundamental reference phase voltages. For sinusoidal carrier-based PWM the fundamental peak magnitude of the output voltage for M= 1 is $0.5V_{dc.}$

4. Simulation results

A simulation is performed in order to prove the increase in the maximum fundamental modulation index by the proposed scheme. The dc link voltage is set to 0.5 p.u. and the modulation index M is set to 1. The switching frequency of the VSI is chosen as 1 kHz and the reference fundamental frequency is kept equal to 50 Hz. The simulation results are depicted in Figure. 3 to Figure.7, respectively. As is evident from the upper part of Fig. 3 to Fig.7 shows the, inverter leg reference voltages and carrier signals at the fundamental modulation index M = 1. Bottom parts show the output phase a voltage and its spectrum. In Figure. 3 to Figure.7 show the corresponding value is only 0.353 p.u. (0.5 p.u. peak). Fig.8 shows the when number phases increases total harmonic distortion (THD) increases correspondingly.

9. Conclusion

Carrier-based n-phase VSI, aimed at sinusoidal output voltage generation were analyzed and compared using the analytical and simulation approach. The carrier based PWM method is simple approach and easy to implement in the simulation. In the proposed work aimed at providing a generalised carrier-based PWM for n-phase inverters. The viability of the proposed concept is proved by simulation taking for n-phase (3, 5, 6, 7 and 9) VSI as an example. From the observation the output phase voltage from three phase to nine phase inverter is same. Increasing number of phases percentage increase in THD is observed in the carrier based PWM technique.

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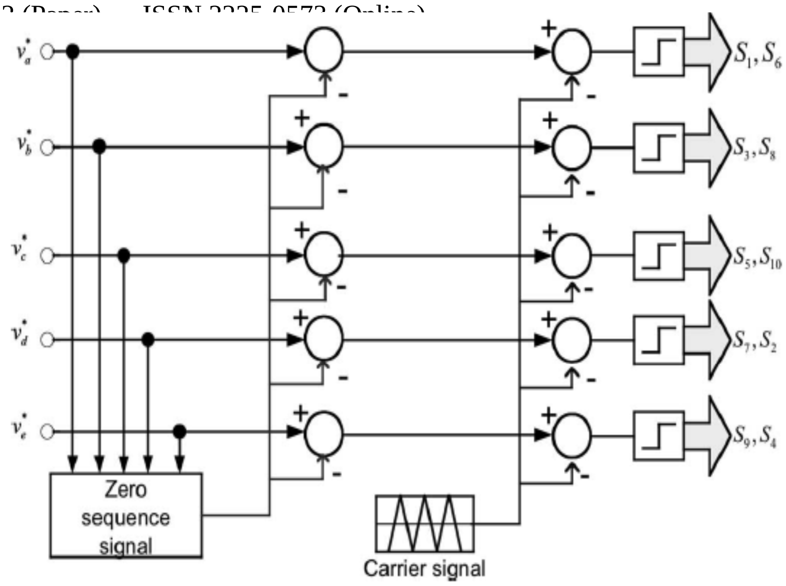

Figure 1. Switching pulses of carrier-based PWM technique.

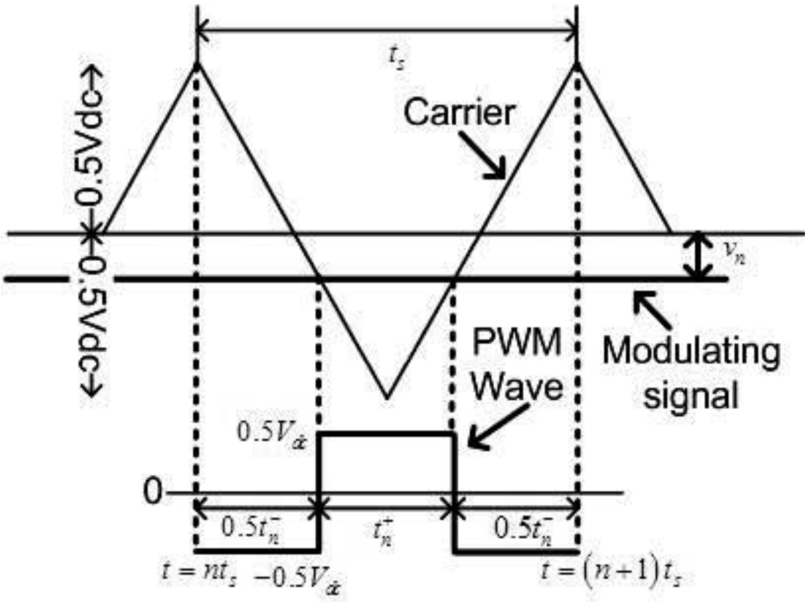

Figure 2. PWM waveform generation in carrier-based sinusoidal method.

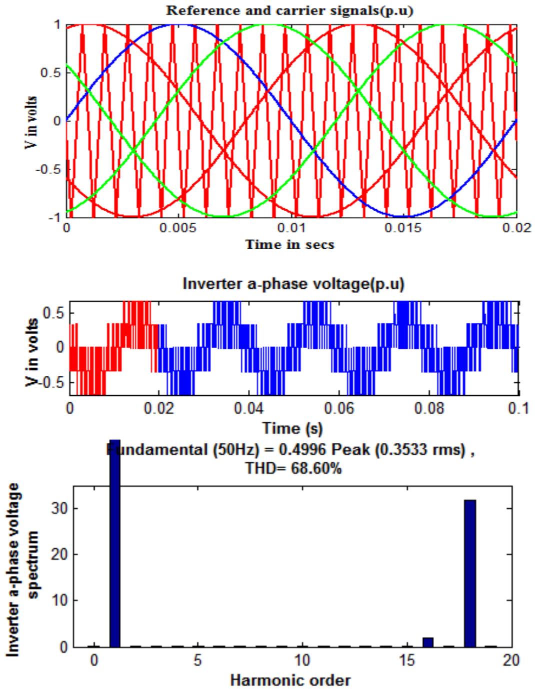

Figure 3.Three phase inverter leg reference voltages and carrier (upper), and output phase *a* voltage and its spectrum of three phase inverter for $M_1 = 1$ (lower).

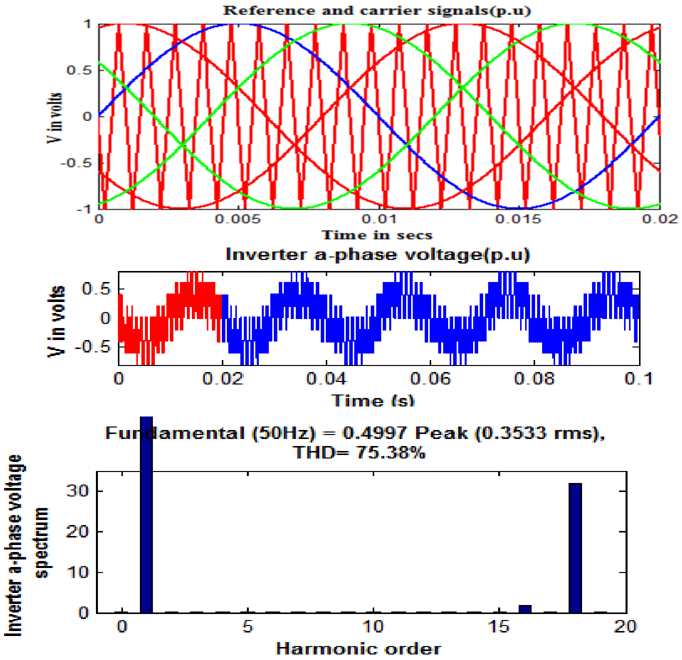

Figure 4. Five phase inverter leg reference voltages and carrier (upper), and output phase *a* voltage and its

spectrum of five phase inverter for $M_1 = 1$ (lower)

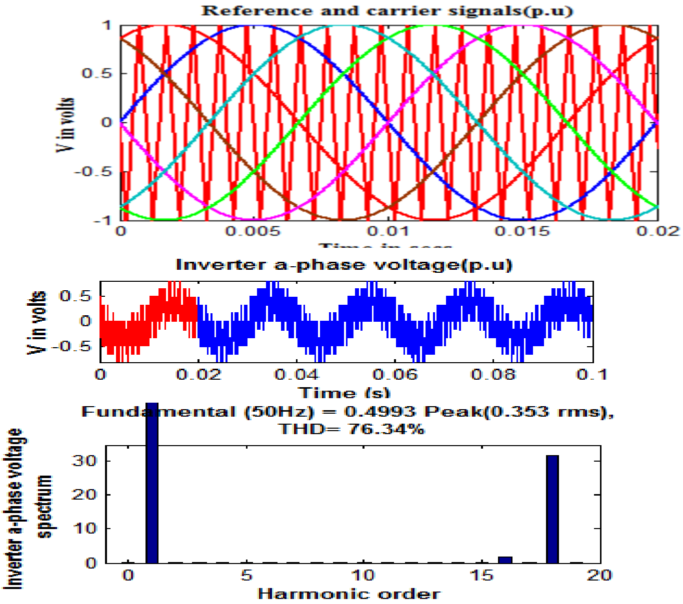

Figure 5. Six phase inverter leg reference voltages and carrier (upper), and output phase *a* voltage and its spectrum of six phase inverter for $M_1 = 1$ (lower)

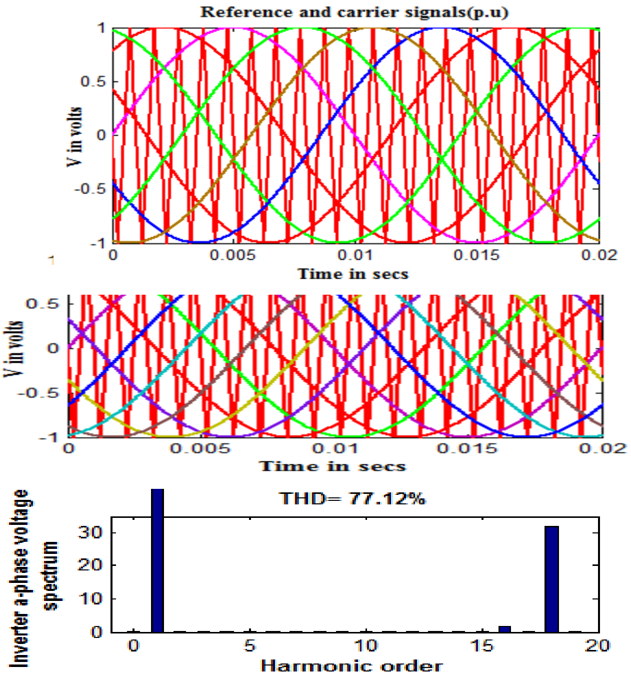

Figure 6. Seven phase inverter leg reference voltages and carrier (upper), and output phase *a* voltage and its spectrum of seven phase inverter for $M_1 = 1$ (lower)

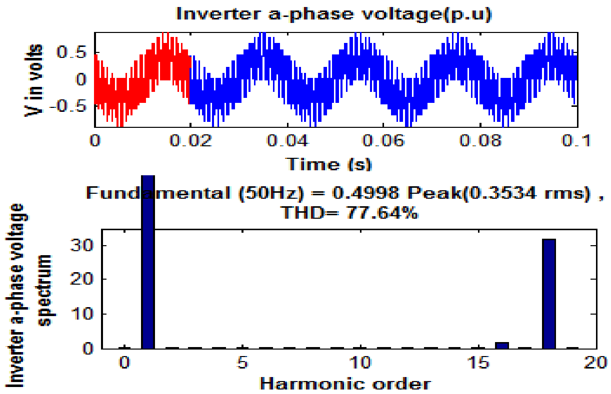

Figure 7. Nine phase inverter leg reference voltages and carrier (upper), and output phase *a* voltage and its spectrum of nine phase inverter for $M_1 = 1$ (lower)

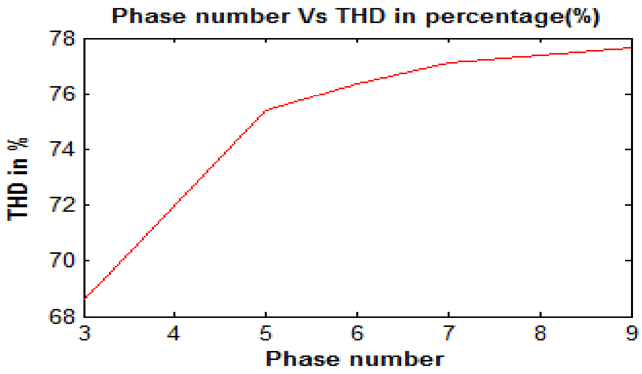

Figure 8. Percentage increase in the THD vs. phase number.

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