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Performance Investigation of Multi-phase VSI with Simple PWM Switching Techniques

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ABSTRACT

This paper presents the performance of multi-phase voltage source inverter (VSI) with simple PWM switching techniques, namely the harmonic injection and offset injection method. The technique discussed in this paper is easy to implement and avoid complicated controlling algorithm adapted in SVPWM technique. The generalized switching techniques are proposed in this paper. A generalized algorithm suitable for odd number of phases is developed in Matlab/Simulink environment and discussed in detail for both the switching methods. The performance of the 5, 7 and 9-phase VSI is studied with the above-said switching methods. The results of the simulation are presented for different modulation indices and a comparison in terms of fundamental voltage and THD identifies the better scheme suitable for multi-phase inverter fed drives.

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1. INTRODUCTION

Multi-phase machine drives are increasing rapidly in recent years, due to their several inherent benefits such as lower torque pulsation, reduction in harmonic currents, and increase in current per phase without the need to increase the phase voltage, greater reliability, fault tolerant feature and increased power in the same frame as compared to three phase machine. They are mostly used in high power applications, such as ship propulsion, electric aircraft, and electric/hybrid electric vehicles, etc. Multi-phase motors require multi-phase voltage source inverter (VSI) for their input supply. An inverter topology uses two switches connected in series as one inverter pole. The number of inverter poles depends on number of phases. For example, a three-phase inverter will have three inverter poles whereas a nine-phase inverter will have nine inverter poles. The switching pattern of the three phase inverter should be modified according to the number of phases. For three phase inverters, the sinusoidal pulse width modulation (SPWM) method, space vector pulse width modulation (SVPWM), harmonic injection method and offset injection method have been extensively discussed in literature [1-21].The SPWM and SVPWM techniques are extended for multi-phase VSI [1-16]. The SPWM schemes are more flexible and easy to implement. However, the output waveforms contain more harmonics resulting in reduced fundamental component and efficiency. To achieve the better output voltage, the several space vector pulse width modulation (SVPWM) techniques are discussed, such as conventional SVPWM, space vector disposition SVPWM, discontinuous SVPWM and multi-dimensional SVPWM [4-17]. The complexity involved in the SVPWM technique is more for higher number of phases. The inverter output voltage space vectors changes to 2^n states, since there are 2^n different switching configurations. Hence, the SVPWM has complicated controlling algorithm for sector identification, look up table, angle information and voltage space vector amplitude measurements. Therefore, a simple and efficient switching technique is needed for multi-phase voltage source inverter which would overcome the complexity involved with higher number of phases. In this paper, to investigate the performance of the multi-phase VSI with the improved PWM techniques, namely harmonic injection method and offset injection method, which are commonly used for three phase VSIs can be

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used for multi-phase VSIs. In the harmonic injection method the linear modulation range is extended by adding the m^{th} harmonic component with respective phase of the reference phase voltages and the fundamental output voltage increases without moving into the over-modulation region [18-21]. In the offset injection method, signal generation depends upon the sampled reference phase amplitude and sampling period [5, 22-24]. A comparative study of these two techniques for 5, 7 and 9 phases is considered in this paper.

The simulink model of the multi-phase VSI is presented. The switching schemes based on harmonic injection method and offset injection method are discussed in detail. The performance of the inverter is investigated with these switching techniques and the results are presented for 5, 7 and 9 phases. Based on the simulation results the best scheme is identified in terms of THD and DC bus voltage utilisation.

2. DESCRIPTION OF MULTI-PHASE VSI

The power circuit diagram of *n*-phase VSI is shown in Figure 1. The circuit consists of *n* half-bridges, which are mutually displaced by *2π/n* degrees to generate the n-phase voltage waves. The input dc supply is obtained from a single phase or n-phase utility power supply through a diode-bridge rectifier. The voltages $V_a, V_b, V_c, V_d, V_e, V_f \ldots V_n$ are the inverter pole voltages connected to load terminals. It is seen that the switching states of each pole should be combined with each other pole to create the required *n*-phase output voltages. The load phase voltages and inverter pole voltages is as given in the following relations (1):

$$\begin{aligned}
V_{aN} &= \frac{n-1}{n}V_a - \frac{1}{n}(V_b + V_c + V_d + V_e + V_f + ...+ V_n)\\
V_{bN} &= \frac{n-1}{n}V_b - \frac{1}{n}(V_a + V_c + V_d + V_e + V_f + ...+ V_n)\\
V_{cN} &= \frac{n-1}{n}V_c - \frac{1}{n}(V_a + V_b + V_d + V_e + V_f + ...+ V_n)\\
V_{dN} &= \frac{n-1}{n}V_d - \frac{1}{n}(V_a + V_b + V_c + V_e + V_f + ...+ V_n)\\
V_{eN} &= \frac{n-1}{n}V_e - \frac{1}{n}(V_a + V_b + V_c + V_d + V_f + ...+ V_n)\\
V_{fN} &= \frac{n-1}{n}V_f - \frac{1}{n}(V_a + V_b + V_c + V_d + V_f + ...+ V_n)\\
&.\\
&.\\
&.\\
V_{nN} &= \frac{n-1}{n}V_n - \frac{1}{n}(V_a + V_b + V_c + V_d + V_e + V_f ....)
\end{aligned} \tag{1}$$

The harmonic injection method and offset injection method for different number of phases are discussed detail in the following sections.

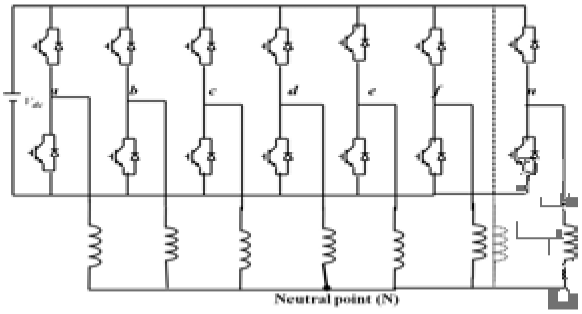


Figure 1. Power circuit diagram of n-phase VSI

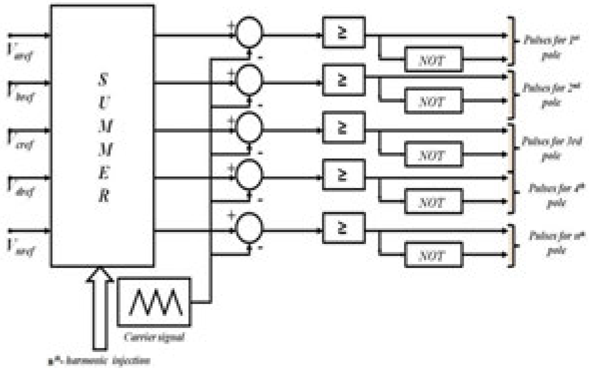


Figure 2. Block diagram of sinusoidal PWM with n^{th} harmonic injection

3. SINUSOIDAL PWM WITH N^{TH} HARMONIC INJECTION FOR MULTI- PHASE VSI

To eliminate the 3rd harmonic component in the output of the three phase voltage source inverter, the 3rd harmonic is injected to the sinusoidal reference voltages [1]. This would increase the maximum fundamental output voltage without moving into the over-modulation region. By analogy, the linear modulation range can be extended by injecting the n^{th} harmonic component for *n*-phase VSI.

The n^{th}-harmonic injection reduces the peak of the *n*-leg reference voltages and hence the modulation index can be moved beyond the unity without entering into over-modulation region.

The block diagram of sinusoidal PWM with n^{th} harmonic injection of a *n*-phase VSI is shown in Figure 2. In the *n*-phase VSI ($V_{aref,}\ V_{bref,}\ V_{cref,}\ V_{dref.....}V_{nref}$) are reference phase voltages displaced by $\alpha = (2\pi/n)$ degrees. The reference sinusoidal signals are added with n^{th} harmonic component to obtain a non-sinusoidal modulating signal. The carrier based modulating signal is compared with the relational operator. The intersections between the modulating signals and the carrier signals give the opening and closing time of inverter switches. The best possible n^{th}-harmonic injection for the *n*-phase VSIs is achieved using (2).

$$\begin{aligned}
v_{a(ref+nthhar)} &= V_{dc}[M\cos wt + M_n \cos nwt] \\
v_{b(ref+nthhar)} &= V_{dc}[M\cos(wt-\alpha) + M_n \cos nwt] \\
v_{c(ref+nthhar)} &= V_{dc}[M\cos(wt-2\alpha) + M_n \cos nwt] \\
v_{d(ref+nthhar)} &= V_{dc}[M\cos(wt-3\alpha) + M_n \cos nwt] \\
&\vdots \\
v_{n(ref+nthhar)} &= V_{dc}[M\cos(wt-n\alpha) + M_n \cos nwt]
\end{aligned} \tag{2}$$

where M–Modulation index $0 \le M \le 1$, M_n–Modulation index of the n^{th} harmonic component. The m^{th} harmonic component has no effect on the value of the reference waveform expression when $wt = [2k+1]\pi/2n$, since $\cos\,[n[2k+1]\pi/2n] = 0$ for all k. where $k=0$ to n Hence, M_n can be chosen to make the peak magnitude of the reference waveform defined in (2) occur where the n^{th} harmonic component is zero, that is $wt = \pi/2n$. This would in turn, assure the maximum possible value for the fundamental component. The reference voltages $v_{a(ref+nthhar)}$ reaches maximum when:

$$\frac{dv_{a(ref+nthhar)}}{dwt} = -MV_{dc}\sin wt - nM_n V_{dc}\sin nwt = 0 \tag{3}$$

where $wt = \pi/2n$. From Equation (3)

$$M_n = -M\,\frac{\sin(\pi/2n)}{n} \tag{4}$$

Under these conditions, the maximum possible non-sinusoidal modulating signal is given by Equation (5)

$$\left|v_{a(ref+nthhar)}\right| = \left|MV_{dc}\cos wt - M\frac{\sin(\pi/2n)}{n}V_{dc}\cos nwt\right| = V_{dc} \tag{5}$$

From Equation (5) M is:

$$M = \frac{1}{\cos(\pi/2n)} \tag{6}$$

4. OFFSET INJECTION METHOD FOR MULTI-PHASE VSI

In the offset injection method signal generation depends upon the sampled reference phase amplitude and sampling period. The time duration for different voltages are maintained completely related to the voltage modulation task according to the equal volt-second principle. Therefore, the modulation task can be greatly simplified by considering the relation between the time duration and the output voltage. For that reason, an imaginary time value will be introduced. This value is directly related to the phase voltage and sampling time (T_s), as defined in Equation (7). Figure 3 shows the matlab/simulink model of multi-phase VSI with different switching techniques. The harmonic injection and offset injection method are written by m-file coding and the inverter switches are also programmed in m-file coding.

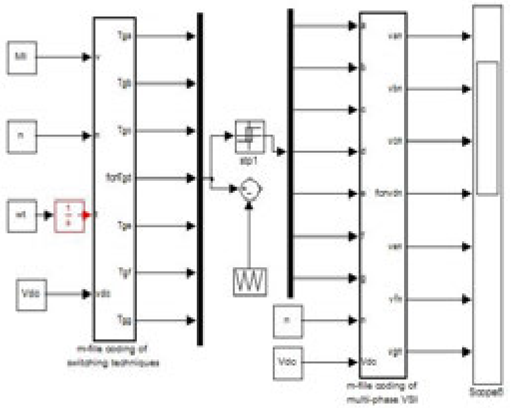


Figure 3. Matlab/Simulink model of multi-phase VSI

$$\begin{aligned}
&V_{as}^{*} : V_{dc} = T_{as} : T_s \Rightarrow T_{as} = \frac{T_s}{V_{dc}} V_{as}^{*} \\
&V_{bs}^{*} : V_{dc} = T_{bs} : T_s \Rightarrow T_{bs} = \frac{T_s}{V_{dc}} V_{bs}^{*} \\
&V_{cs}^{*} : V_{dc} = T_{cs} : T_s \Rightarrow T_{cs} = \frac{T_s}{V_{dc}} V_{cs}^{*} \\
&V_{ds}^{*} : V_{dc} = T_{ds} : T_s \Rightarrow T_{ds} = \frac{T_s}{V_{dc}} V_{ds}^{*} \\
&V_{es}^{*} : V_{dc} = T_{es} : T_s \Rightarrow T_{es} = \frac{T_s}{V_{dc}} V_{es}^{*} \\
&\vdots \\
&V_{ns}^{*} : V_{dc} = T_{ns} : T_s \Rightarrow T_{ns} = \frac{T_s}{V_{dc}} V_{ns}^{*},\ n = a, b, c, d, e...
\end{aligned} \tag{7}$$

where $V_{as}, V_{bs}, V_{cs}, V_{ds}, V_{es}, V_{fs} \ldots V_{ns}$ are the $(a,b,c,d,e,f\ldots n)$ reference phase voltages, respectively. T_{as}, T_{bs}, T_{cs}, T_{es}, T_{fs} ... T_{ns} are the imaginary switching times of respective phases. Now, the effective time or offset time (T_{offset}) can be defined as the time duration between the smallest and the largest of n- imaginary times, as given by:

$$T_{offset} = T_{\max} - T_{\min} \tag{8}$$

$$\begin{aligned}
T_{\max} &= \max\{T_{as}, T_{bs}, T_{cs}, T_{ds}, T_{es} \ldots T_{xs}\} \\
T_{\min} &= \min\{T_{as}, T_{bs}, T_{cs}, T_{ds}, T_{es} \ldots T_{xs}\}
\end{aligned} \tag{9}$$

The offset time T_{offset} *should* satisfy the following constraint

$$0 \le T_{\min} + T_{offset}, T_{\max} + T_{offset} \le T_s \tag{10}$$

Therefore, the range of T_{offset} *can* be computed as follows:

$$T_{\min offset} \le T_{offset} \le T_{\max offset} \tag{11}$$

where

$$\begin{aligned}
T_{\min offset} &= -T_{\min} \\
T_{\max offset} &= T_s - T_{\max}
\end{aligned} \tag{12}$$

$$T_{offset} = 0.5(T_{\max offset} + T_{\min offset}) \tag{13}$$

n = Number of phases

When the actual gating signals for power devices are generated in the PWM algorithm, there is one degree of freedom by which the effective time can be relocated anywhere within the sampling interval. Therefore, a time-shifting operation will be applied to the imaginary switching times to generate the actual gating times $(T_{ga,} T_{gb,} T_{gc,} T_{gd,} T_{ge} \cdots T_{gn})$ for each inverter pole. This task is accomplished by adding the same value to the offset times as follows:

$$\begin{aligned} T_{ga} &= T_{as} + T_{offset} \\ T_{gb} &= T_{bs} + T_{offset} \\ T_{gc} &= T_{cs} + T_{offset} \\ T_{gd} &= T_{ds} + T_{offset} \\ T_{ge} &= T_{es} + T_{offset} \\ &\vdots \\ T_{gn} &= T_{ns} + T_{offset} \end{aligned} \tag{14}$$

5. SIMULATION RESULTS

The n-phase inverter is simulated with the above said firing schemes. The switching frequency of the VSI is chosen as 5 kHz and the fundamental frequency is set to 50 Hz. The simulation results of the individual schemes are discussed and compared in the following sections for different modulation indices.

5. 1. Simulation Results with Harmonic Injection Method

The 5, 7 and 9-phase VSIs are simulated with the pulses obtained by harmonic injection technique. Figures 4 and 5 shows the results for nine-phase VSI.

Figure 4(a) shows the fundamental, 9th harmonic component waveform and the resultant modulating signal for a modulation index of 1. It is seen that the peak value of the modulating signal is less than 1. It will reach ±1, when the modulation index $M = 1/\cos(\pi/2n)$, according to (4). In addition, this would increase the maximum fundamental output voltage without moving into the over-modulation region. Figure 4(b) shows the modulating signal and carrier wave and the corresponding pulses are presented in Figure 4(c).

The output phase voltage and its spectrum are shown in Figure 4(d). It is seen that the output fundamental rms value is 0.3537 p.u. (0.5001 p.u. peak) and THD is 78.01%. The simulation is repeated for the maximum modulation index of 1.01542 and the results are shown in Figure 5(a) to Figure 5(d). It is observed that the output fundamental rms value is 0.3566p.u. (0.5043p.u.peak) and THD is 76.20%. It is seen that the maximum fundamental output voltage is increased by 1.71% for the maximum modulation index. The 5 and 7 phase VSI are also simulated with this switching technique and the fundamental peak voltage is observed to be increased by 5.15% and 2.85%, respectively.

5. 2. Simulation Results with Offset Injection Method

Figures 6 to 9 show the 9-phase VSIs simulated with the pulses obtained by offset injection method.

Figure 6(a) shows the modulating signal and carrier wave and the corresponding pulses are presented in Figure 6(b). The resultant waveform of $T_{maxoffset}$, $T_{minoffset}$ and T_{offset} for the modulation index of 0.9 is presented in Figure 7. The modulation index is varied from 0.2 to 1.01542 and the $T_{minoffset}$ and $T_{maxoffset}$ are observed and shown in Figure 8. The modulation index is varied in steps and the $T_{maxoffset}$ and $T_{minoffset}$ are found for different modulation index.

It is seen that the $T_{maxoffset}$ and $T_{minoffset}$ intersecting at the maximum modulation of 1.01542. The output phase voltage and its spectrum are shown in Figure 9 at this maximum modulation index. It is seen that output fundamental rms value equals 0.3592p.u. (0.508p.u.peak). Thus an increase of 2.28% maximum fundamental output voltage is attained in the offset injection scheme. The simulation is repeated for 5 and 7 phase VSI and an increase of 6% and 3.42% in maximum fundamental output voltage is obtained respectively.

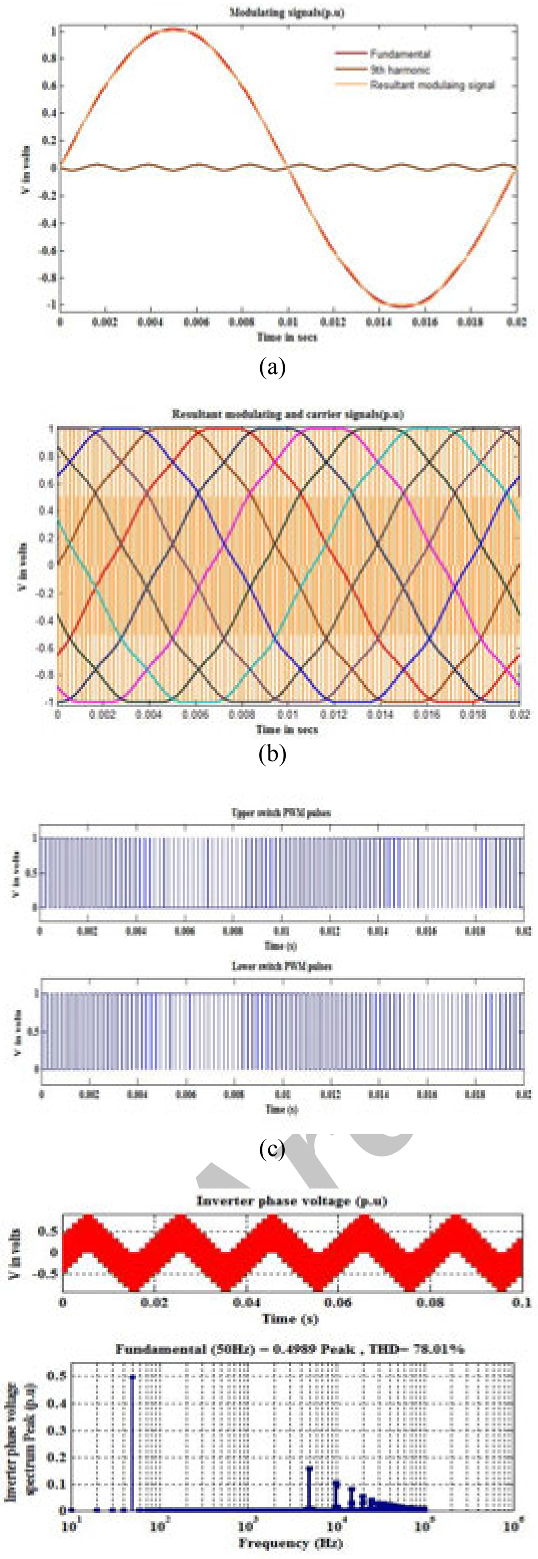
5. 3. Comparison of Harmonic Injection and Offset Injection Method

Simulation results obtained for different number of phases with the above said switching techniques are compared in terms of fundamental voltage and THD.

Table 1 shows the percentage increase of fundamental voltage. It is noted that the fundamental voltage is marginally high with offset injection method also the increase in voltage reduces with increasing phase number. A maximum of 6% increase is achieved for 5-phase VSI.

The variation of percentage increase in voltage with number of phases is presented in Figure 10. Table 2 shows the THD for different switching techniques. It is seen that the THD reduction is observed for offset injection method with increasing modulation index. A minimum THD of 69.63% is obtained for 5-phase VSI at maximum modulation index.

Figure 11 shows the variation of THD for different phase numbers when the modulation index is 1 and 1.01542. Based on the simulation results the minimum THD and maximum fundamental voltage is observed in the offset injection method compared to harmonic injection method.



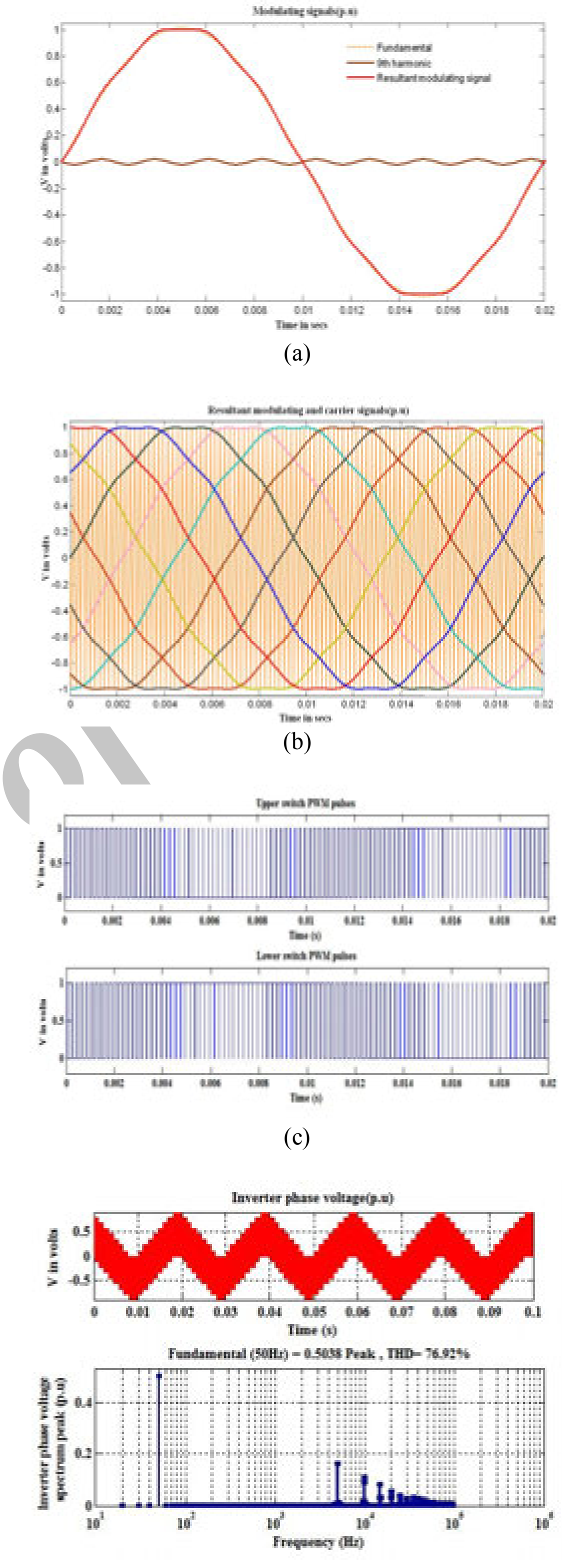
(a)

(b)

(c)

(d)

Figure 4. (a) 9th harmonic injection results of fundamental and modulating signals, (b) Carrier and modulating signal components, (c) PWM pulses and (d) Output phase voltage and its spectrum for *M*= 1



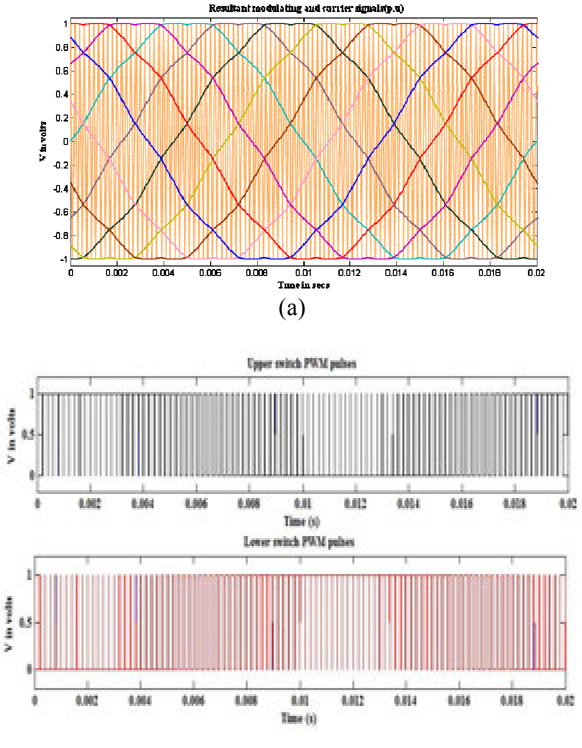
(a)

(b)

(c)

(d)

Figure 5. (a) 9th harmonic injection results of fundamental and modulating signals, (b) Carrier and modulating signal components, (c) PWM pulses and (d) Output phase voltage and its spectrum for *M*= 1.01542



(a)

(b)

Figure 6. (a)Offset injection results of carrier and resultant modulating signal and (b) PWM pulses for 9-phase VSI MI-1

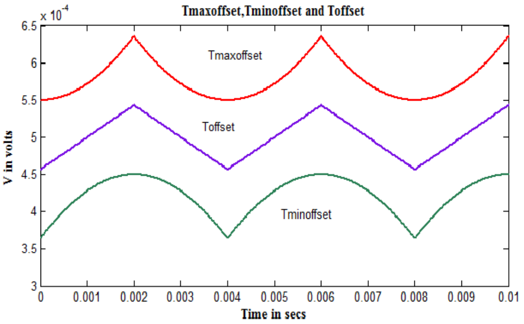


Figure 7. $T_{maxoffset}, T_{minoffset}$ and T_{offset} for MI-0.9

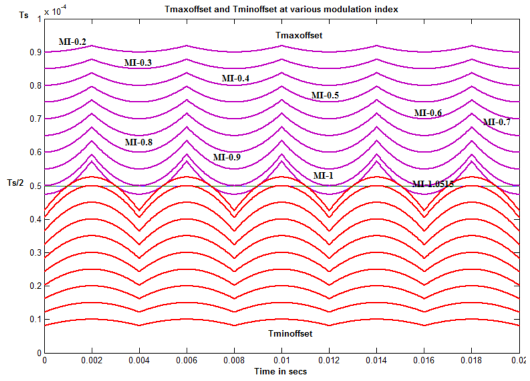


Figure 8. $T_{maxoffset}$ and $T_{minoffset}$ for different modulation indices

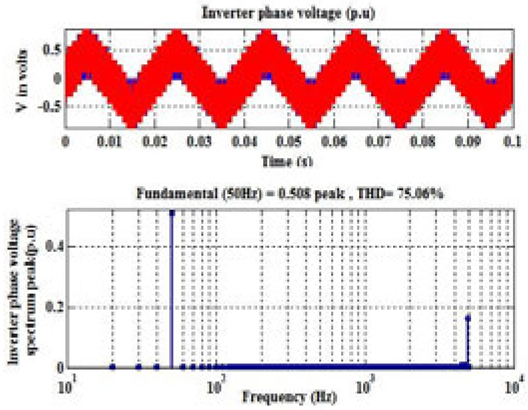


Figure 9. Offset injection results of output phase voltage and its spectrum for 9-phase VSI M=1.01542

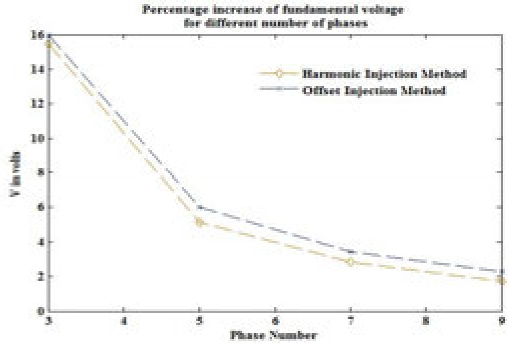


Figure 10. Percentage increase in fundamental voltage for different number of phases

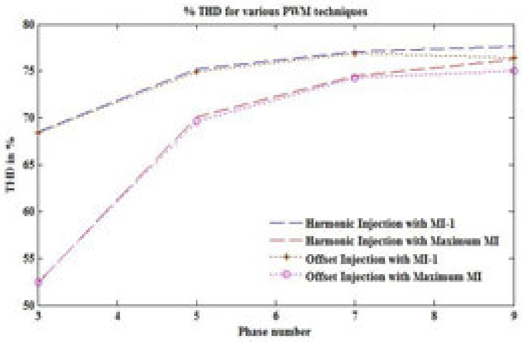


Figure 11. THD vs. phase number

TABLE 1. Percentage increase in fundamental for different phases

No. of phases	Maximum modulation index	% increase in fundamental for harmonic injection	% increase in fundamental for offset injection
5	1.0515	5.15	6
7	1.0257	2.85	3.42
9	1.01542	1.71	2.28

TABLE 2. Comparison of %THD for various PWM techniques

No. of phases	Modulation index	Harmonic injection based PWM THD%	Offset injection THD%
5	0.2	264.61	260.41
	0.4	170.20	169.78
	0.6	126.13	125.52
	0.8	98.67	97.20
	1	75.26	74.96
	1.0515	70.11	69.63
7	0.2	269.04	264.54
	0.4	173.56	172.17
	0.6	128.89	128.48
	0.8	99.31	98.76
	1	77.10	76.89
	1.0257	74.49	74.29
9	0.2	270.06	266.96
	0.4	174.90	173.82
	0.6	129.90	128.21
	0.8	100.41	98.19
	1	78.01	77.43
	1.01542	76.92	75.06

6. CONCLUSION

Two simple PWM techniques namely the harmonic injection and offset injection method suitable for multi-phase VSI are presented. The simulation results are obtained for 5, 7 and 9-phase VSIs. It is found that the linear modulation range is extended without moving into the over-modulation region for both methods. This result is an increase in fundamental voltage. In the offset injection method fundamental voltage is marginally higher than in the harmonic injection method. A maximum of 6% increase in fundamental voltage and minimum THD is observed for 5-phase VSI with offset injection method. The minimum THD and maximum fundamental voltage is obtained for offset injection method in any number of increasing phases. Further the offset injection method eliminates the need for complex control algorithm and its simple calculation makes it easy to implement in digital platform and admirable selection for high power applications.

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APPENDIX

Parameters of the Multi-phase VSI

Parameters	**Values**
DC voltage	*1 p.u*
Fundamental frequency	*50Hz*
Switching frequency	*5KHz*
Modulation index(MI)	*0.2 to1*
Maximum modulation index	*M=1/cos(π/2n)*
Number of phases(n)	*5, 7 and 9*

Performance Investigation of Multi-phase VSI with Simple PWM Switching Techniques

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چکیده

این مقاله به بررسی عملکرد مبدل منبع ولتاژ چند فازی(VSI) با تکنیک‌های سوئیچینگ ساده، PWM، به نام‌های تزریق هارمونیک و روش تزریق آفست می‌پردازد. روش مورد بحث در این مقاله، به آسانی اجرا شده و نیازی به الگوریتم کنترلی پیچیده موجود در روش SVPWM نمی‌باشد. در این مقاله تکنیک‌های سوئیچینگ کلی ارائه شده است. الگوریتم کلی مناسب برای فازهایی با تعداد فرد، در محیط مت‌لب شبیه سازی شده و جزئیات آن برای هر دو روش سوئیچینگ مورد بحث و بررسی قرار گرفته است. عملکرد ۵، ۷ و ۹ فاز VSI، با روش سوئیچینگ ذکر شده،مطالعه شده است. نتایج شبیه سازی برای شاخص‌های مدولاسیون متفاوتی ارائه و از نظر ولتاژ بنیادی و THD مقایسه شده است. طرح مناسب‌تر برای مبدل‌های چند فازی درایوهای fed تعیین شده است.

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