

Evaluation effective parameters on the output current harmonics of SHE-PWM voltage source inverters

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Abstract

Many important parameters are effective on the output current of voltage source inverter (VSI) that among them load type, frequency, and load connection can be mentioned. In VSI, the current waveform is affected from mentioned parameters. Variation of these parameters can change the output current total harmonic distortion (THD). It is desired that the output current waveform to be close to sinusoidal. In this paper, by constructing a VSI, effect of load connection, frequency, and load type such as resistive, resistive-inductive, and inductive on VSI output current harmonics are investigated. For this purpose, different operational modes are defined for two structures of VSI, and effects of these parameters on output current are evaluated. Also, this voltage source inverter is simulated in PSpice that verify the experimental results.

Keywords: Power Quality, SHE-PWM, Voltage Source Inverter, Selective Harmonic Elimination, Modulation Index, Load Type and PSpice

Introduction

With advanced technology, make and structure of the high voltage and high current equipments with fast switching capability and industrial electronic converters with various features is possible. One of these converters is voltage source inverter. This converter is used for converting DC voltage to AC voltage. Today voltage source inverters are used in UPS, inductance furnaces drives, small and large induction motors and etc. A lot of papers have been published about industrial and power inverters that numbers of these papers are about switching devices (Ogasawara & Hirofumi, 1991) and other papers are about parallel or serial connection of two or more inverters (Fukuda & Matsushita, 1998; Netzold, 1998). One of the inverter subjects is their active or passive protection against short circuit and another subject is their snubber protection (Salmon, 1992; Blaabjerg *et al.*, 1994; Musumeci *et al.*, 2002). But various load influences on operation of the inverter with SHEM control method has not been attended yet.

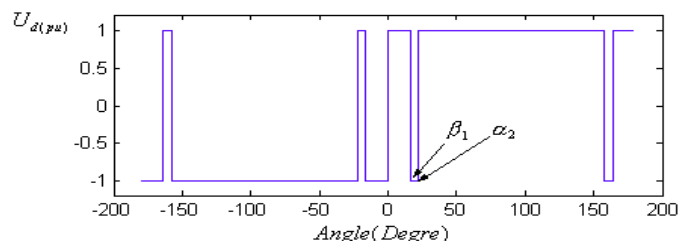
Welchko *et al.* (2002) studied special loads for example reluctance or inductance motors which have been used in inverter output: but the load influences on inverter operation and the output current quality have not been investigated. Vander *et al.* (2002) evaluated operation of switching devices in inverters at starting of induction motors, but they did not consider frequency and load type. Halasz *et al.* (1994) reported one of the modulation methods without consideration of various loads that influences on inverter operation. The other switching strategy which is usually used for DC/AC converters is selective harmonic elimination (SHE) (Farahani, 2008; Farahani & Rashidi 2010; Farahani, 2011). In this paper at first, the effects of SHE-PWM modulation method have been investigated on inverter output voltage and current and then the impacts of

changing various loads and frequencies have been investigated on inverter output quality. To decrease output current harmonics, a passive filter has been used at output. Constructed laboratory inverter has been simulated in PSPICE software completely and experimental results and simulation results have been compared and tested.

SHE-PWM modulation switching angles

If real and periodic function $f(\theta)$ includes DC component then by consideration of Fourier series, $F(\theta)$ will be the same as following expression: (Fig.1.)

Fig. 1. The switching angle for elimination of 3rd and 5th harmonic.



$$F(\theta) = \sum_{n=1}^{\infty} [A_n \cos(n\theta) + B_n \sin(n\theta)] \quad (1)$$

Harmonic components are sum of sinuous and cosine expressions. Therefore, they can be investigated in frequency amplitude. In other words, it is supposed that harmonic component A_n and B_n are on two perpendicular axis that their total consequence is:

$$U_n = \sqrt{A_n^2 + B_n^2} \quad (2)$$

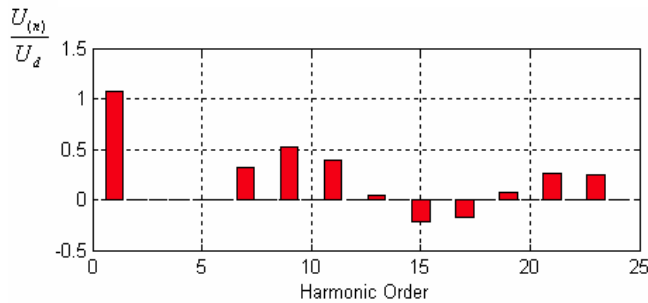
By attention to (1) and (2), amplitude of harmonic components will be like expression (3):

$$|U_n| = \frac{4U_d}{n\pi} [1 - 2\cos(n\beta_1) + 2\cos(n\alpha_2)] \quad (3)$$

To eliminate third and 5th harmonic components, U_3 and U_5 should be zero. Hence, expression parameters are calculated as:

$$\begin{aligned} \beta_1 &= 23.62^\circ \\ \alpha_2 &= 33.3^\circ \end{aligned} \quad (4)$$

Fig. 2. The frequency spectrum with the elimination of the third and 5th harmonics



Fourier series components (frequency spectrum) will be like Fig. 2. According to this figure, it is clear that 9th component has the highest frequency. With elimination of 3rd harmonic order, some of 3rd factors like 9th and 15th harmonic components can be removed from output.

Voltage Inverter operational modes

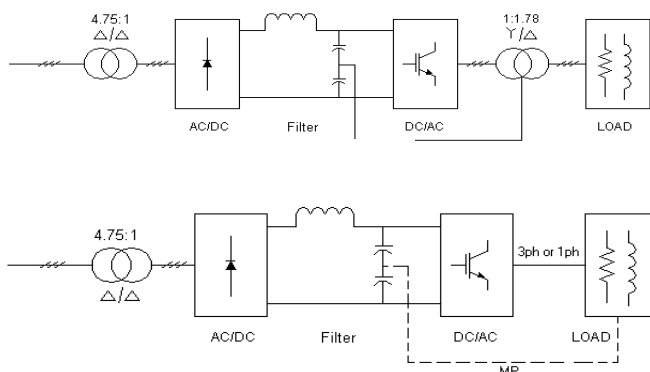
Experimental circuit (Fig. 3a) is used to investigate and evaluate the output current and voltage of VSI.

According to these circuits, if the 3rd harmonic component is not eliminated with SHEM switching, this harmonic component and its factors will exist in line to line voltages of three-phase VSI. To eliminate these harmonic components, a 3-phase transformer according to Fig. 3b with appropriate connections can be used.

To investigate load and frequency influences on operation and output current quality of 3-phase SHE-PWM VSI, two operational modes have been defined:

- Mode I: SHE-PWM with elimination of 3rd and 5th harmonic components (using Fig. 3a)

Fig. 3. Experimental circuit of VSI. (top) without transformer (bottom) with transformer



- Mode II: SHE-PWM with elimination of 5th and 7th harmonic components (using Fig. 3b)

For mode I and II, 3 and 2 cases have been tested and investigated respectively which are listed in Table.1. The THD values for these modes and cases are obtained and compared. To have the suitable and correct

Table.1. The variant operating modes and their cases in the inverter

Mode	case	Load/ frequency	load
Mode I	Case1	Load	2.3mH , 2.6Ω
		Freq	50 Hz
	Case2	Load	2.3mH , 2.6Ω
		Freq	330 Hz
	Case3	Load	2.3mH
		Freq	250 Hz
Mode II	Case1	Load	2.3mH , 2.6Ω
		Freq	50 Hz
	Case2	Load	2.3mH
		Freq	330 Hz

comparison between modes and cases, these tests have been done in different loads and frequencies. In the following sections, each of these cases has been investigated. To have better comparing between simulation and experimental results, both waveforms are shown.

Mode I- case 1: In this case, for eliminating 3rd and 5th harmonic components from output voltage (load voltage) waveform, switching angles are selected according to (4) ($\beta_1 = 23.62^\circ$ and $\alpha_2 = 33.3^\circ$). The load voltage waveform and its harmonic components at 50 Hz in simulation and experimental results are shown in Fig. 4a and Fig. 4b respectively.

Fig. 5 shows the spectrum frequency of output voltage which by attention to this figure, one can see that the 3rd and 5th harmonic orders (150 Hz and 250 Hz) have been eliminated. But the 9th harmonic (450 Hz) and the factors of 3rd harmonic exist in both load voltage and current waveforms yet. In this case, the first remained harmonic is 7th harmonic (350 Hz). For this case, the load current waveform is plotted in Fig. 6 which due to the existence of small inductance, the current harmonics has not eliminated as well. In this case, output voltage THD is equal to 0.4. In VSI with resistive load, the voltage and current waveforms will be interphase. By attention to Fig. 6, it is viewed that by increasing L/R ratio, THD of current will be decreased more.

Mode I - case 2: In this test, load consists of a series 2.3mH inductor and 0.2 Ω resistor. To investigate the effects of frequency on the output voltage and current and their THD, output frequency is considered equal to 300 Hz. Current waveform of this case is shown in Fig. 7.

In this case, L/R ratio is the same as previous case and just frequency has been increased. The current wave is more similar to sinusoidal current, while the 3rd harmonic and its factors remained in the current waveform. Also, THD has been decreased and reached to 0.1.

Fig. 4. Output voltage in mode I - case 1 (top) from PSpice simulation (bottom) from experimental

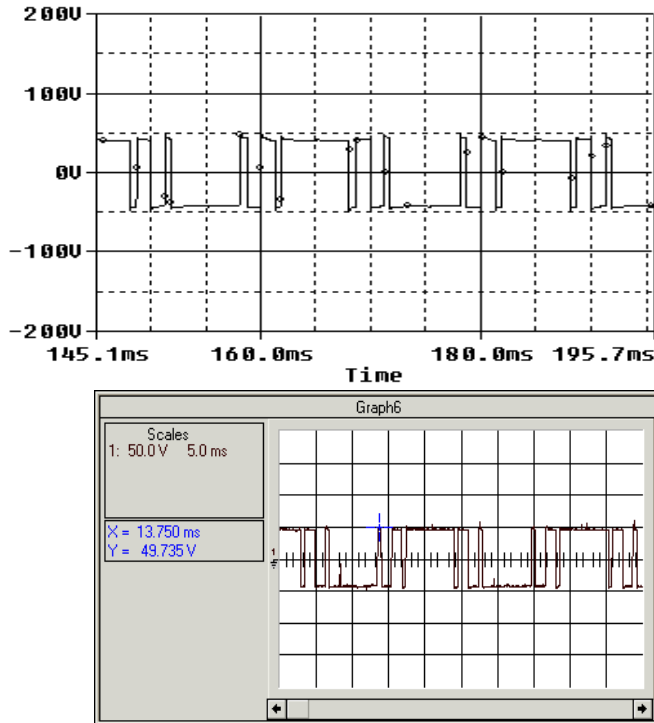


Fig. 6. Output current in mode I - case 1 (top) from PSpice simulation (bottom) from experimental measured with a 0.2Ω shunt resistor

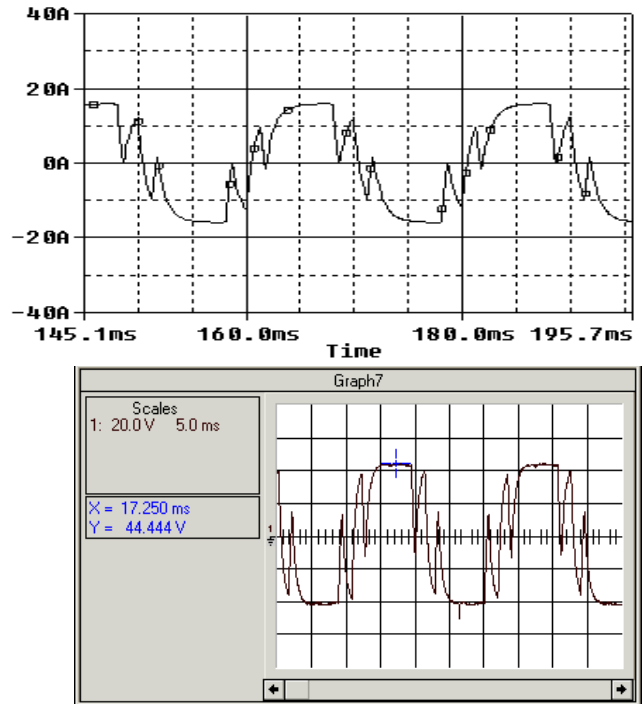


Fig. 5. Spectrum frequency of output voltage in mode I - case 1 a) from PSpice simulation (bottom) from experimental

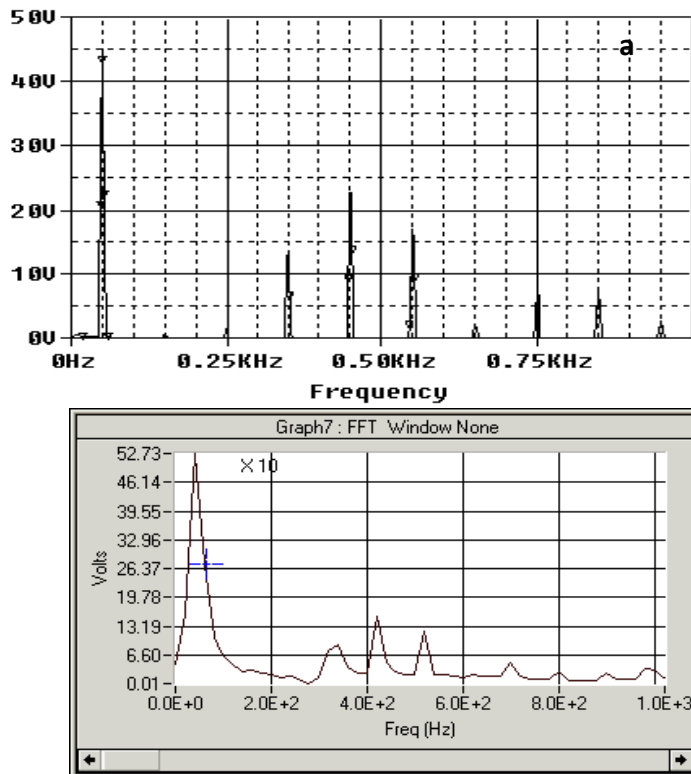


Fig. 7. Output current in mode I - case 2 obtained from experimental with 0.2Ω shunt resistor

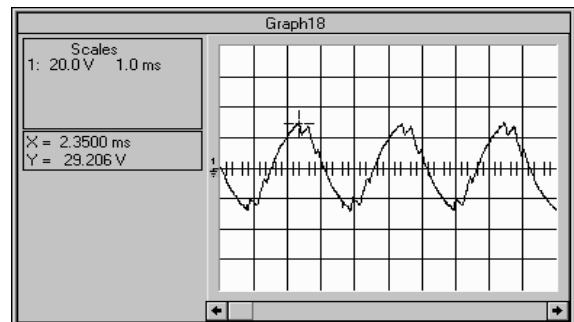
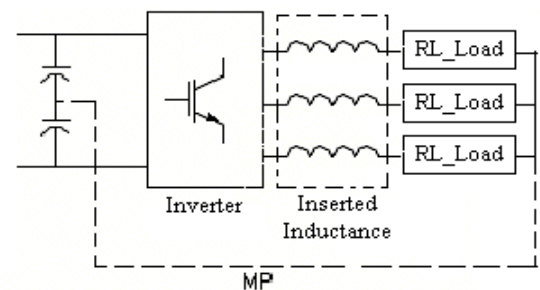


Fig. 8. Inverter, RL load and inductive passive filter



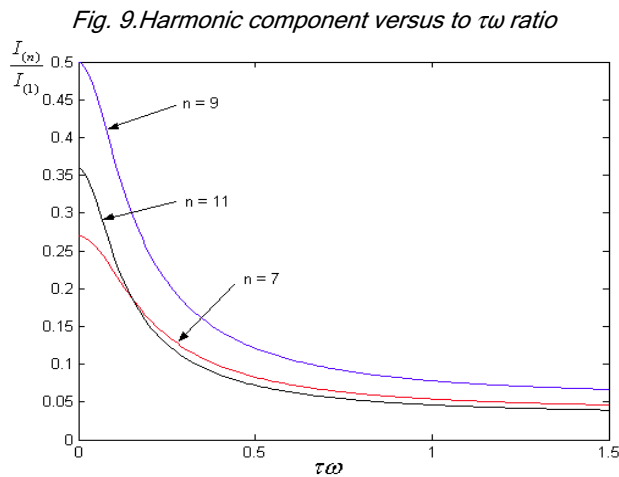


Fig. 9. Harmonic component versus to $\tau\omega$ ratio

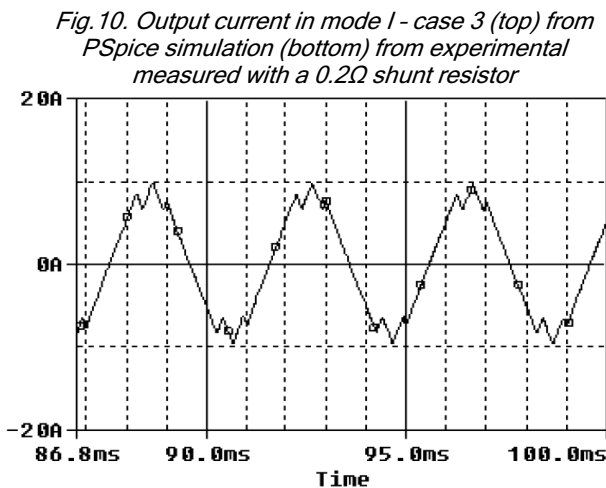


Fig. 10. Output current in mode I - case 3 (top) from PSpice simulation (bottom) from experimental measured with a 0.2Ω shunt resistor

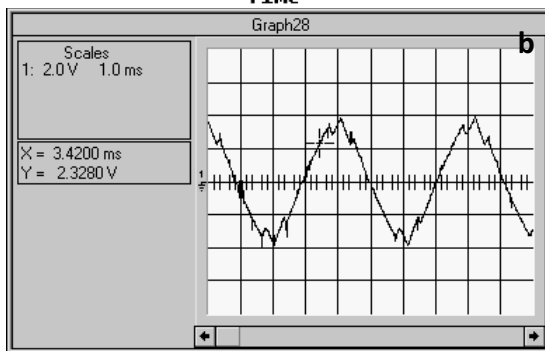


Fig. 11. Waveforms of a) Output line - line voltage

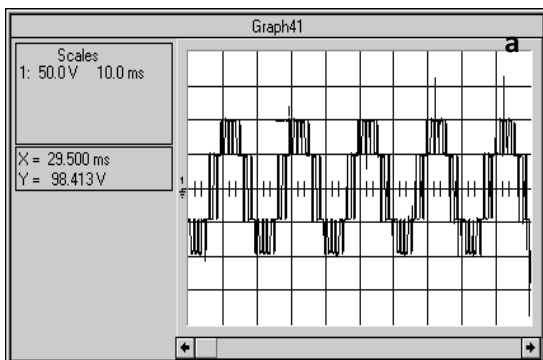


Fig. 11. Waveforms of b) frequency spectrum in mode II - case 1 obtained from experimental

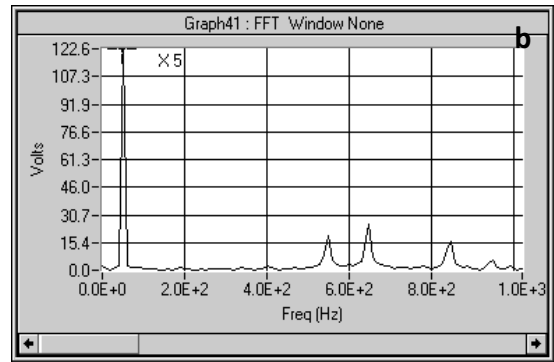


Fig. 12. Output current obtained from excremental using 0.2Ω shunt resistor

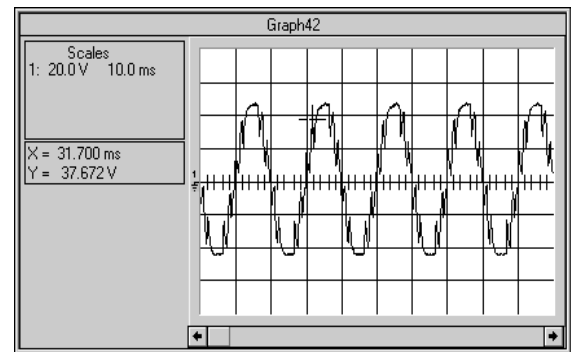
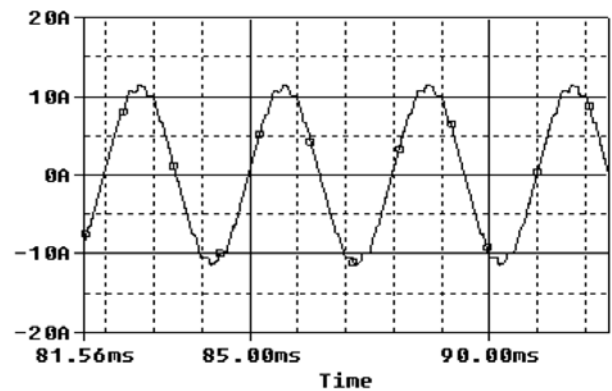


Fig. 13. Output current in mode II - case 2 (top) from PSpice simulation (bottom) from experimental measured with a 0.2Ω shunt resistor



If increasing of operational frequency is impossible, then implementing of inductive passive filter (series with RL load) will be helpful to reduce current THD. One of disadvantages of using this inductor is voltage drop. To compensate this voltage drop, input voltage must be increased. Fig. 8 illustrates the inverter, RL load and inductive passive filters.

For single phase circuit, time constant and ratio of I_n/I_1 and V_n/V_1 can be respectively written as:

$$\tau = \frac{L + L_f}{R} \quad (5)$$

$$\frac{I_n}{I_1} = \frac{V_n}{V_1} \cdot \frac{1 + j\tau\omega}{1 + jn\tau\omega} \quad (6)$$

Where ω is angular frequency and n is number of current harmonics. In order to decrease I_n/I_1 , for each harmonic component, by increasing of filter inductance (L_f) or operational frequency (ω), $\tau\omega$ can be increased in acceptable range. In Fig. 14, the 7th, 9th and 11th harmonic components respect fundamental component versus $\tau\omega$ is plotted which shows that by increasing $\tau\omega$, harmonic component will be decreased about 0.05 (Fig.9.)

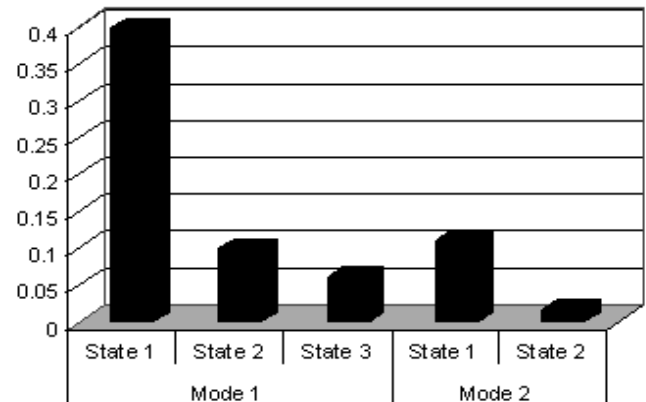
Mode I - case 3: In order to evaluate inductive load and frequency increase effects on THD decreasing, a pure inductive load ($L/R \rightarrow \infty$) has been used as a load. Fig. 10 shows VSI output current. By attention to this figure, it can be seen that by increasing of frequency and L/R ratio, current harmonics is decreased and THD is reached to 0.062.

Mode II - case 1 : By elimination of output voltage harmonic, the output current harmonic will be decreased. In tests of mode I, the 7th harmonic and the 3rd harmonics factors remained in the voltage waveform. In mode II tests, 3rd harmonics factors are eliminated from output voltage as well. This switching method (SHEM) is very effective on decrease of inverter output current harmonics. In order to prove this acclaim, a constructed inverter has been tested with resistive-inductive load in 50 Hz (similar to case 1 - mode I). Line to line secondary voltage of transformer and its frequency spectrum is plotted in Fig. 11. According to these figures, the 3rd, 5th, 7th and the third factors harmonic orders has been eliminated. Fig. 11b indicates that the first remained harmonic in the line - line output voltage is 11th harmonic (550 Hz).

Fig. 12 illustrates the load current which in comparison with case 1 in mode I, current harmonics have significant decrease and close waveform to sinusoidal waveform. This property is obtained from eliminating of 3rd harmonic and its factors. In this case, THD is reached to 0.11 that when compared with case 1 - mode I, it is decreased considerably.

Mode II - case 2: To investigate the effect of inductive

Fig. 14. Comparing THD values in different cases and modes



load on the output voltage/current and its THD, an inductive load is used in the output of VSI. Output current is plotted in Fig. 13. In this figure, the effect of inductive load on the current wave form can be seen. According to Fig. 13, current harmonics values have been considerably decreased compared with previous cases. In this case, current waveform is very close to sinusoidal waveform and current THD is reached to 0.015.

Comparison between mode i and mode ii

To compare the VSI output current quality for each case and mode, the obtained THD values are plotted in Fig. 14. By attention to this figure, case 2 in mode II has the least THD value. In this case, many harmonics such as 3th, 5th, 7th, 9th ... 3k, k=1, 2, 3... are eliminated from output current.

Conclusions

In this paper, effects of frequency and load type have been investigated on the current and voltage waveform of VSI. For this purpose, different modes and cases have been defined which cover all of effects. To have best and accurate comparing among these cases and modes, many tests have been done. Furthermore, each case and mode has been simulated. Two circuits with transformer and without transformer have been used for this study. Obtained results have shown that eliminated harmonics have not been appeared in output current. In the case of using transformer, the 3rd harmonic and its factors have been removed from output current whereas in the case of not using transformer, the 3rd harmonics have been remained in the output current. The results also show that the current harmonics considerably depend on load type, inverter operational frequency and connection type of inverter to load. The current harmonics is decreased by increasing of frequency and inductive load and also by using interface transformer. It has been stated that sometimes because of load types or limitation of power switches and their drivers, frequency increasing is not possible. Therefore, elimination of lower harmonic orders is recommended by implementing SHE-PWM switching method. By using inductor in the output, higher harmonic order can be removed from output current and current waveform is closed to sinusoidal one.



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