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# Selective Harmonic Elimination in a Conventional Single Phase Full-Bridge Inverter with Adjustable Output

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***Abstract***: *Ordinary single-phase inverter gives a square wave output which when applied to electrical appliances may damage the later, reduce its efficiency as well as life as this inverter output waveform is not sinusoidal and contains lower and higher order harmonics in addition to fundamental. Moreover, the output voltage cannot be controlled. In this paper a single phase full-bridge inverter with controlled output voltage and with selective harmonic elimination from the output voltage waveform is discussed using MOSFETs, which reduces the cost of filter and thus improves the inverter voltage waveform. When this inverter is connected to any electrical appliance, this will not affect the life and efficiency of the same due to absence of dominating lower order harmonics, moreover, it is possible to control the output voltage. The idea can be extended to develop three phase inverter with adjustable output voltage and with improved waveform.*

***Keywords -****Harmonic Factor (HF), inverter, power semiconductor devices, SHE-PWM technique, simulation, total harmonic distortion (THD), transcendental equation.*

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## I. Introduction

Figure 1(a) shows the circuit diagram of a conventional single phase full-bridge inverter using MOSFETS as switching devices with resistive load. A is 0V reference point and load is connected across B and C. D1, D2, D3 and D4 are fly wheel diodes. When a $0^o$ and $180^o$ gating pulses are applied to the gate terminals of switches $S_1$, $S_4$ and $S_2$, $S_3$ respectively the output voltage waveform will be a square wave as shown in Figure 1(b). The magnitude of output voltage normally cannot be controlled. Though it can be controlled by delaying the gating pulses, it will consist of lower and higher order odd harmonics and the removal of which will be a tedious task because it requires series of filters for removing the lower order harmonics for which filter size will be very large and costly. Moreover, while removing lower order harmonics with passive filter, it may filter out fundamental component as its frequency is close to lower order harmonics.

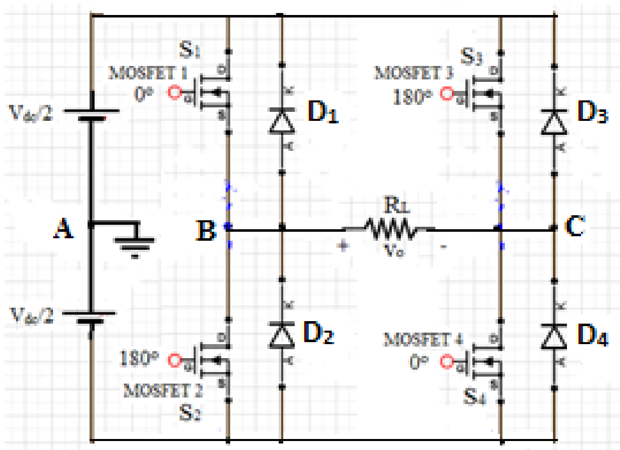



**Fig. 1(a).** Circuit diagram of simple full-bridge Inverter with $0^o$ and $180^o$

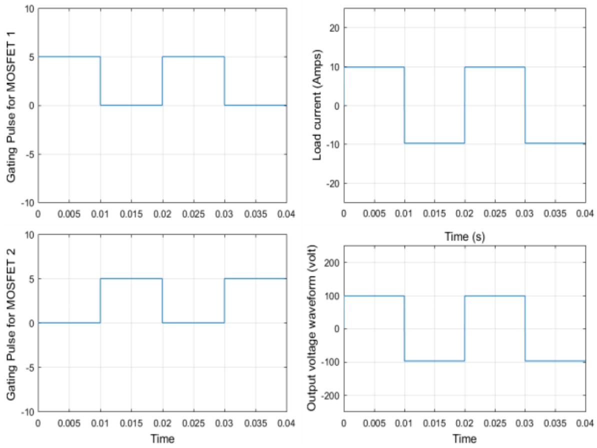


**Fig.1(b).**Gating pulses, output voltage and current waveforms of ordinary full-bridge inverter.

The amplitude of nth order harmonic is given by

$$V_n = \frac{4V_{dc}}{n\pi} = \frac{V_1}{n}, \tag{1}$$

Where n = 1, 3, 5, 7, ….∝, $V_1 = \frac{4V_{dc}}{\pi}$ (amplitude of fundamental waveform) and $V_{dc}$ is the magnitude of dc bus voltage.Harmonic Factor (HF) is defined by, HF = $\frac{V_n}{V_1} = \frac{1}{n}$

Equation (1) indicates that 33% 3rd harmonic, 20% 5th harmonic, 14.3% $7^{th}$ harmonic and 11.1% $9^{th}$ harmonic with respect to the fundamental along with other odd harmonics are present in the output voltage waveform. Except the fundamental, these four harmonics are largest present in the output voltage waveform and are difficult to filter out as these harmonic frequencies are very close to fundamental.

## II. Inverter With No 3rd, 5th, 7th And 9th Harmonics

Essam Hendawi [1] has proposed an idea to eliminate lower order harmonics in single phase full-bridge inverter with fixed output voltage using SHE-PWM technique based on secant method. However, there is no proposal to control the output voltage. The aim of the present paper is to eliminate the four lower order harmonics ($3^{rd}$, $5^{th}$, 7th and $9^{th}$) in a single phase full-bridge inverter with adjustable output voltage. The idea can be extended to develop three phase inverter with adjustable output voltage and with improved waveform.

In a conventional full-bridge inverter, it is seen that there are two commutations per cycle and the output voltage contains all the 'n' number of harmonics (Equation 1). If, however, eighteen commutations of semiconductor switches per cycle i.e., additional sixteen voltage reversals per cycle are made with the load voltage waveform as shown in fig.2, it can be shown using Fourier series analysis of the output voltage waveform that the 3rd, 5th, 7th and 9th harmonics can be eliminated by choosing proper switching time of ($S_1$,$S_4$) and ($S_2$,$S_3$), and only 11th harmonic will be dominating which can be easily filtered out by reduced size filter as this frequency is far from the fundamental [2,3].

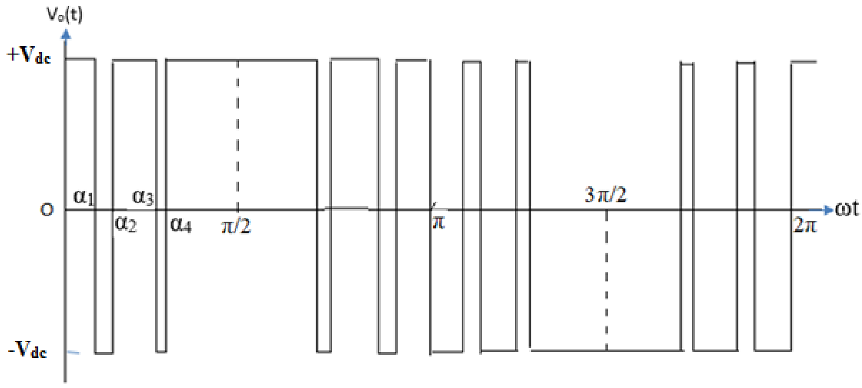



**Fig. 2.** Output voltage waveform with additional sixteen voltage reversals per cycle.

Using Fourier series, the general expression for instantaneous output voltage of this two-level inverter can be given by

$$v_o(t) = \sum_{n=1}^{\infty} (A_n \cos n\omega t + B_n \sin n\omega t),$$

where $n = 1,2,3,5 \ldots \infty$.
Due to quarter-wave symmetry along the x-axis of the waveform of fig.2 [4, 5], we can write
$A_n = \frac{4}{\pi}\int_0^{\pi/2} v_0(t)\cos n\omega t d\omega t = 0$, for n = 0, 1, 2 ….∞.
$B_n = \frac{4}{\pi}\int_0^{\pi/2} v_0(t)\sin n\omega t\, d\omega t$
Or, $B_n = \frac{4}{\pi}[\int_0^{\alpha_1}(+V_{dc})\sin n\omega t d\omega t + \int_{\alpha_1}^{\alpha_2}(-V_{dc})\sin n\omega t\, d\omega t + \int_{\alpha_2}^{\alpha_3}(+V_{dc})\sin n\omega t\, d\omega t + \int_{\alpha_3}^{\alpha_4}(-V_{dc})\sin n\omega t\, d\omega t + \int_{\alpha_4}^{\pi/2}(+V_{dc})\sin n\omega t\, d\omega t] = 0$, for n = 0 or even,
and
$= \frac{4V_{dc}}{\pi}[\int_0^{\alpha_1}\sin n\omega t d\omega t - \int_{\alpha_1}^{\alpha_2}\sin n\omega t\, d\omega t + \int_{\alpha_2}^{\alpha_3}\sin n\omega t\, d\omega t - \int_{\alpha_3}^{\alpha_4}\sin n\omega t\, d\omega t + \int_{\alpha_4}^{\pi/2}\sin n\omega t\, d\omega t]$
$= \frac{4V_{dc}}{n\pi}[1 - 2\cos n\,\alpha_1 + 2\cos n\,\alpha_2 - 2\cos n\,\alpha_3 + 2\cos n\,\alpha_4]$ (2)
for n = 1, 3, 5...... ∞
The amplitude of the output voltage of the fundamental component is
$B_1 = \frac{4V_{dc}}{\pi}[1 - 2\cos\alpha_1 + 2\cos\alpha_2 - 2\cos\alpha_3 + 2\cos\alpha_4]$ (3)
To eliminate the 3rd, 5th, 7th and 9th harmonics from the output voltage, $B_3 = 0$, $B_5 = 0$, $B_7 = 0$, and $B_9 = 0$. i.e.,
$1 - 2\cos 3\,\alpha_1 + 2\cos 3\,\alpha_2 - 2\cos 3\,\alpha_3 + 2\cos 3\,\alpha_4 = 0$ (4)

$1 - 2\cos 5\,\alpha_1 + 2\cos 5\,\alpha_2 - 2\cos 5\,\alpha_3 + 2\cos 5\,\alpha_4 = 0$ (5)

$1 - 2\cos 7\,\alpha_1 + 2\cos 7\,\alpha_2 - 2\cos 7\,\alpha_3 + 2\cos 7\,\alpha_4 = 0$ (6)
and
$1 - 2\cos 9\,\alpha_1 + 2\cos 9\,\alpha_2 - 2\cos 9\,\alpha_3 + 2\cos 9\,\alpha_4 = 0$ (7)
where gating signals, $\alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \pi/2$.
Since the above four transcendental equations are nonlinear in nature, they are required to be solved for $\boldsymbol{\alpha}$ using numerical approach or optimization techniques. There are various numerical methods to solve the above four equations. The Newton-Raphson (N-R) method is one of the fastest iterative methods. The solution for $\alpha_1, \alpha_2, \alpha_3$ and $\alpha_4$ have been obtained using (N-R) iteration technique in MATLAB 2017a, which are as follows:
$\alpha_1 = 15.46°$, $\alpha_2 = 24.33°$, $\alpha_3 = 46.11°$, $\alpha_4 = 49.40°$.
With these switching angles the absolute value of amplitude of fundamental and other harmonics are:
$B_1 \cong \frac{4V_{dc}}{\pi}$ x 0.809, $B_{11} \cong \frac{4V_{dc}}{\pi}$ x 0.234
$B_{13} \cong \frac{4V_{dc}}{\pi}$ x 0..442, $B_{15} \cong \frac{4V_{dc}}{\pi}$ x 0.289.
Table 1 compares the values of the amplitudes of the harmonics normalized with respect to the amplitude of the fundamental for ordinary full-bridge inverter producing square wave shapes as well as the values of the amplitudes of the harmonics normalized with respect to amplitude of the fundamental using selective harmonic elimination (SHE PWM) technique.

**Table no 1:** Comparison of amplitudes for square wave and SHE inverters

| Order of Harmonic ($n$) | Amplitude normalized with respect to Fundamental for Square Wave Inverter | Amplitude normalized with respect to Fundamental (Sq. Wave) for SHE Inverter |
|---|---|---|
| 1 (Fundamental) | 1.000 | 0.809 |
| 3 | 0.333 | 0.0 |
| 5 | 0.200 | 0.0 |
| 7 | 0.143 | 0.0 |
| 9 | 0.111 | 0.0 |
| 11 | 0.091 | 0.234 |
| 13 | 0.077 | 0.442 |
| 15 | 0.067 | 0.289 |

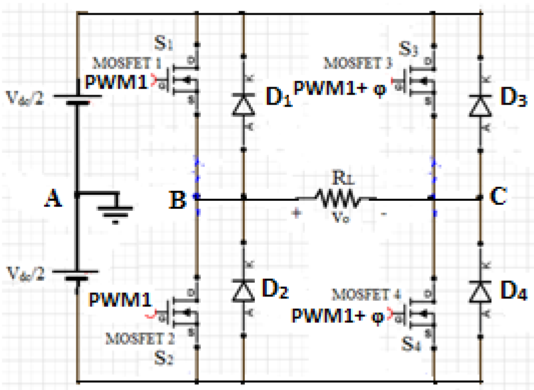
**Table no 2:** Comparison of percentage harmonic voltages (normalized) for square wave and SHE inverters

| Order of Harmonic ($n$) | Percentage Harmonic for Square Wave Inverter | Percentage Harmonic for Selective Harmonic Eliminated Inverter |
|---|---|---|
| 1 (Fundamental) | 100.0 | 100.0 |
| 3 | 33.3 | 0.0 |
| 5 | 20.0 | 0.0 |
| 7 | 14.3 | 0.0 |
| 9 | 11.1 | 0.0 |
| 11 | 9.1 | 28.92 |
| 13 | 7.7 | 54.63 |
| 15 | 6.7 | 35.72 |

In Table1, it can be observed that the absolute value of amplitude of the fundamental component of output voltage of square wave inverter is reduced to 80.9 % in SHE inverter with elimination of 3rd, 5th, 7th and 9th harmonics from 33.3 %, 20 %, 14.3% and 11.1% respectively. Comparing Table 1 and Table 2 it can be observed that, the percentages of the other harmonics using SHE inverter have been increased from 9.1 % to 28.92 % for 11th harmonic, 7.7 % to 54.63 % for 13th harmonic and 6.7 % to 35.72% for 15th harmonic. As these harmonic frequencies are much higher compared to frequency of fundamental component, they can be filtered out easily using reduced size separate filters. However, the disadvantage of this SHE technique is unable to control the output voltage of the inverter e.g., Figure 1(a).

## III. Inverter With Controlled Output And Elimination Of 3rd, 5th, 7th And 9th Harmonics

To control the output voltage, we can use the full-bridge inverter as shown in Figure 1(a) and switches $S_1$ and $S_2$ are gated as before (say PWM 1) to produce voltage wave shape between B and A (where point A is 0V reference) as shown in Figure 2 to eliminate the $3^{rd}$, $5^{th}$, $7^{th}$ and $9^{th}$ harmonics whereas $S_3$ and $S_4$ will be gated with the same gating signal PWM 1 but shifted by an angle φ, as shown in Figure 3(a), to produce a similar voltage wave shape between C and A but shifted by φ (Figure 3(b)), so that the voltage across the load $V_{BC}$ will get reduced depending upon φ.




. **Fig. 3(a).** Circuit diagram of full-bridge inverter with controlled output

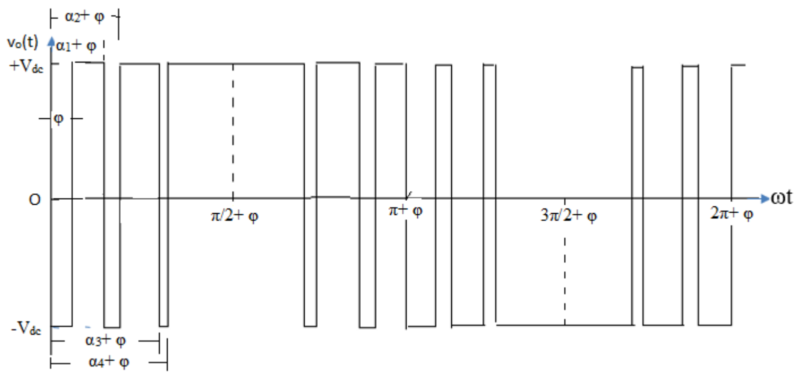



**Fig. 3(b).** Voltage waveform of $V_{CA}$

### 3.1. Working Principle

Let us consider the above full-bridge as a combination of two half-bridges. The switches $S_1$ and $S_2$ (MOSFET 1 and MOSFET 2) are gated as before to produce a voltage wave shape across $V_{BA}$ as shown in Figure 2 where no $3^{rd}$, $5^{th}$, $7^{th}$ and $9^{th}$ harmonics are present. Switches $S_3$ and $S_4$ (MOSFET 3 and MOSFET 4) are gated in the same manner but with a phase shift of angle φ (where $0 \leq \varphi \leq 180°$) with respect to $S_1$ and $S_2$ to produce same voltage wave shape across $V_{CA}$ with a phase shift φ where also no $3^{rd}$, $5^{th}$, $7^{th}$ and $9^{th}$ harmonics are present. With these arrangements, the load voltage $V_{BC}$ (along with fundamental frequency and harmonics) can be controlled by controlling φ where no 3rd, 5th, 7th and 9th harmonics are present as the load voltage $V_{BC}$ is the instantaneous difference between $V_{BA}$ and $V_{CA}$, i.e., $V_{BC} = V_{BA} - V_{CA}$. The load voltage $V_{BC}$ will be maximum, i.e. either $+V_{dc}$ when $S_1$ and $S_4$ are gated in phase (i.e. φ =0) or $-V_{dc}$ when $S_3$ and $S_2$ are gated in phase and 0V when either $S_1$ and $S_4$ or $S_3$ and $S_2$ are gated 180° out of phase (i.e. φ =180°).

The generalized expression for the load voltage amplitude including harmonics, neglecting the voltage drop across the conducting semiconductor devices can be given as a function of n and φ as:

$$v_0(n,\varphi) = \frac{4V_{dc}}{n\pi}[1 - 2\cos n(15.46)^\circ + \cos n(24.33)^\circ - 2\cos n(46.11)^\circ + 2\cos n(49.40)^\circ]\text{x}\cos\frac{n\varphi}{2} \tag{8}$$

Substituting n=1,3,5,7,9,11,13 in equation, we get the amplitudes of the fundamental and harmonic frequency voltages as a function of phase shift angle φ.

i.e.,

$$V_{0,1}(\varphi) = \frac{4V_{dc}}{\pi}[\,0.809]\text{x}\cos\frac{\varphi}{2} \tag{9}$$

$$V_{0,3}(\varphi) = 0 \tag{10}$$

$$V_{0,5}(\varphi) = 0 \tag{11}$$

$$V_{0,7}(\varphi) = 0 \tag{12}$$

$$V_{0,9}(\varphi) = 0 \tag{13}$$

$$V_{0,11}(\varphi) = \frac{4V_{dc}}{\pi}[\,0.234]\text{x}\cos\frac{11\varphi}{2} \tag{14}$$

$$V_{0,13}(\varphi) = \frac{4V_{dc}}{\pi}[\,0.442]\text{x}\cos\frac{13\varphi}{2} \tag{15}$$

Table 3 gives the normalized absolute value of the amplitudes of fundamental and harmonics for different values of phase shift angle.

**Table no 3:** Normalized absolute value of amplitudes of load voltage of fundamental and different harmonic components as a function of phase shift angle.

| Order of Harmonic | Phase Shift Angle φ (in degrees) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 30 | 60 | 90 | 120 | 150 | 180 |
| 1 (Fundamental) | 0.809 | 0.8104 | 0.7266 | 0.5933 | 0.4195 | 0.2171 | 0 |
| 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 |
| 5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 |
| 7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 |
| 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 |
| 11 | 0.234 | 0.2260 | 0.9925 | 0.9832 | 0.9701 | 0.9534 | 0 |
| 13 | 0.442 | 0.9933 | 0.9733 | 0.9403 | 0.2210 | 0.8372 | 0 |

## IV. Simulation Results

A full-bridge inverter circuit similar to Figure 3(a) has been simulated using MATLAB 2017a simulation software with resistive load to verify the results of proposed technique for controlling the output voltage of ordinary full-bridge inverter as well as elimination of 3rd, 5th, 7th and 9th harmonics, with the above-mentioned theoretical values. Table 4 gives the measured values and percentages of harmonic voltages with respect to fundamental up to 13th harmonic considering phase shifts from $0^o$ to $180^o$ for switches $S_3$ and $S_4$ from the phase angles of $S_2$ and $S_1$ respectively. The fundamental frequency and source voltage which have been considered are respectively 50 Hz and 200V.

**Table no 4:** Fundamental and harmonic voltages with resistive load for dc bus voltage $V_{dc}$= 200V and RMS value of output voltage waveform $V_{o(rms)}$= 196V,178.9V, 160V, 138.6V, 113.1V, 79.89V, 0V for phase shift $0^o$,$30^o$, $60^o$, $90^o$, $120^o$, $150^o$ and $180^o$ respectively.

| Frequency (Hz) | Harmonic | Ordinary Inverter | | Phase Shift (Degrees) (SHE Inverter) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0 | | 30 | | 60 | | 90 | | 120 | | 150 | | 180 |
| | | $V_{RMS}$ (volt) | % of Fundamental | $V_{RMS}$ (volt) | % of Fundamental | $V_{RMS}$ (volt) | % of Fundamental | $V_{RMS}$ (volt) | % of Fundamental | $V_{RMS}$ (volt) | % of Fundamental | $V_{RMS}$ (volt | % of Fundamental | $V_{RMS}$ (volt | % of Fundamental | % of Fundamental |
| 50 | 1 | 249.7 | 100 | 206.8 | 100 | 196.5 | 100 | 176.6 | 100 | 144.8 | 100 | 102.2 | 100 | 53.75 | 100 | 0.0 |
| 150 | 3 | 83.23 | 33.33 | 5.159 | 2.49 | 3.011 | 5.92 | 3.775 | 2.13 | 5.008 | 3.46 | 1.341 | 1.31 | 2.995 | 5.57 | 0.0 |
| 250 | 5 | 49.94 | 20 | 2.67 | 1.29 | 2.189 | 5.53 | 2.546 | 1.44 | 2.973 | 2.05 | 2.718 | 2.66 | 1.783 | 3.31 | 0.0 |
| 350 | 7 | 35.68 | 14.3 | 3.888 | 1.88 | 2.934 | 5.76 | 2.895 | 1.63 | 3.217 | 2.22 | 2.892 | 2.83 | 2.938 | 5.47 | 0.0 |
| 450 | 9 | 27.76 | 11.1 | 6.922 | 3.35 | 3.158 | 6.2 | 5.477 | 3.10 | 3.702 | 2.56 | 2.892 | 2.83 | 3.238 | 6.02 | 0.0 |
| 550 | 11 | 22.72 | 9.1 | 59.49 | 28.77 | 56.72 | 28.86 | 50.55 | 28.62 | 43.45 | 30.01 | 30.76 | 30.10 | 15.33 | 28.52 | 0.0 |
| 650 | 13 | 19.24 | 7.7 | 104.5 | 50.53 | 104.8 | 53.18 | 95.46 | 50.05 | 72.48 | 50.05 | 53.37 | 52.54 | 30.7 | 57.11 | 0.0 |

The data presented in Table 4 using the result obtained by simulation has been found to be satisfactory with the theoretical values presented in Table 3. Since the roots for $\alpha_1, \alpha_2, \alpha_3$ and $\alpha_4$ obtained using iteration method is not exactly the same what is required and also due to control circuit limitations during simulation, we find some 3rd, 5th, 7th and 9th harmonic voltages are present in the output voltage waveform. In Table 4, it is seen that the fundamental frequency component of the load voltage decreases with increase in phase shift angle as proposed in this technique. The lower order harmonic voltages do not change much with the increase in phase shift angle. This is the reason for which percentage of lower order harmonic component voltage increases with the decrease of fundamental component voltage. However, with the increase of phase shift the higher order harmonic voltage increases which can be filtered out easily by using reduced size low pass filter. Figure 4 shows the graph of different output voltages for fundamental and harmonics obtained by simulation with respect to different values of phase shift.

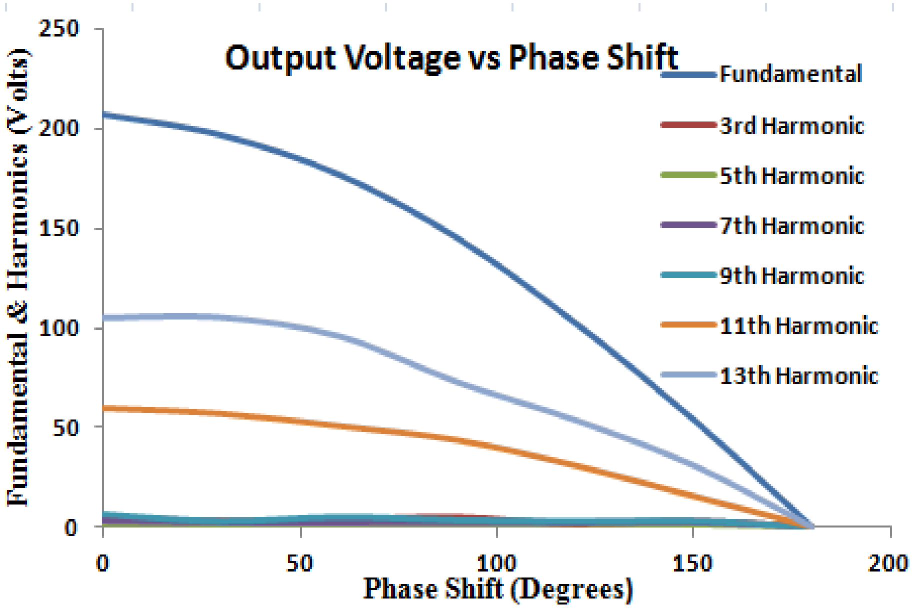



**Fig.4.** Output voltage vs. Phase shift

## V. Conclusion

The paper presents a brief discussion on how a single-phase full-bridge conventional inverter can be converted to produce adjustable output voltages with elimination of 3rd, 5th, 7th and 9th harmonic voltages by selecting proper switching angles of the semiconductor devices from a pre-formulated output voltage waveform. The next lower order dominating harmonic (9.1% of fundamental) can easily be filtered out with reduced size low pass filter. This type of inverter with four-harmonic reduction technique is applicable in those cases where

**i)** the requirement of the ac power system is such that the use of inverters in parallel or use of multilevel inverter is not justified

**ii)** the voltage control range required to maintain a constant value of load voltage during input voltage variations is moderate

**iii)** it is required that the ac output voltage waveform must be sinusoidal. Switching of semiconductor devices per half-cycle do not produce excessive losses

**iv)** the frequency of fundamental component is low enough so that power losses by the semiconductor switches due to the additional voltage reversals per half-cycle is negligible.

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