

Implementation of SHE-PWM technique for single-phase inverter based on Arduino

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ABSTRACT

This paper presents design and practical implementation of single-phase inverter based on selective harmonic elimination-pulse width modulation (SHE-PWM) technique. Microcontroller mega type Arduino used as a controller for producing the gate pulses. The optimized switching angles determination results in wide range of output voltage. Depending on number of switching angles, the lower order harmonics (LOHs) can be eliminated to improve the output voltage waveform. A comparison study using MATLAB/Simulink for sinusoidal-PWM and SHE-PWM techniques, which shows for the same LOH in the output voltage waveform, the SHE-PWM has less number of pulses per half cycle than sinusoidal-PWM strategy. The reduction in number of pulses results less switching losses. The simulation done using ten switching angles to drive R-L load. A prototype of SHE-PWM inverter with R-L load is used to validate the simulation results.

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1. INTRODUCTION

In recent years, single-phase inverter is widely utilized in numerous applications such as uninterruptible power supply for the residential consumers, single-phase micro-grid, with the vast fields of renewable energy grid-integration conversion, AC motor drives, and single-phase vehicle to grid system. A full bridge inverter is as shown in Figure 1 [1, 2]. Harmonics appear at the output voltage of single-phase inverter. LOHs mainly contribute to the distortion effects in the system. Conversely, the higher order harmonics have less effect in the system. So LOHs content should be minimized or eliminated to improve the load performances [3, 4].

There are many techniques for minimizing or removing these LOHs from single-phase inverter output voltage. The most common and simplest technique is the sinusoidal PWM technique. However, this technique is implemented with high switching frequency which increases switching losses and reduces the system efficiency [5, 6]. Therefore, the switching at the fundamental frequency is very desirable. Space vector PWM (SV-PWM) are also used to eliminate the distortion effect created by the LOHs especially with three phase inverters, it is considered better than sinusoidal-PWM according to DC bus utilization. But this method also operates at high switching frequency and its operation performance improves with increased switching frequency, in addition to its difficulty of implementation [7, 8]. SHE-PWM is the best technique with a basic fundamental frequency (i.e. it works with low switching frequencies) in addition to it has higher utilization of DC input voltage than sinusoidal-PWM technique. SHE-PWM produces a fundamental wave at

the desired value, where the dominant LOHs are removed from the baseline [9]. Thus, SHE-PWM technique is considered in this work to obtain the double advantages of minor switching losses and the elimination of LOHs. The challenge of the SHE-PWM technique is to estimate the switching angles specially with increasing number of switching angles which requires solving (n) number of non-linear equations. Different types of digital controllers are utilised for the production of modulating signals for inverters; as PIC microcontroller [10, 11], digital signal processors (DSPs) TMS320F2812 kit [12], complex programmable logic device (CPLD) [13], field-programmable gate array (FPGA) [14, 15], and Arduino [16, 17]. Arduino is preferred and it employed in this work as its availability, simplicity, its low cost, in addition to its easy programming and re-program.

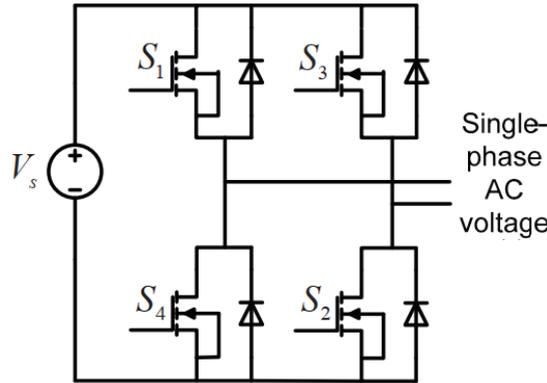


Figure 1. Single phase H-bridge inverter

2. SELECTIVE HARMONIC ELIMINATION

The fundamental output voltage and the undesirable harmonics of the single phase inverter can be controlled. Depending on the number of switching angles (N) per quarter wave symmetry (i.e. chopped N times per quarter-cycle). The low order harmonics can be eliminated and what remains is only the high order harmonics. The fundamental voltage is obtained with the simultaneous elimination of undesirable harmonics. The output voltage waveform V_{out} shown in Figure 2 is produced by firing the inverter switches S_1 to S_4 at the predetermined (offline) angles $\alpha_1, \alpha_2, \dots, \alpha_N$ [18-20].

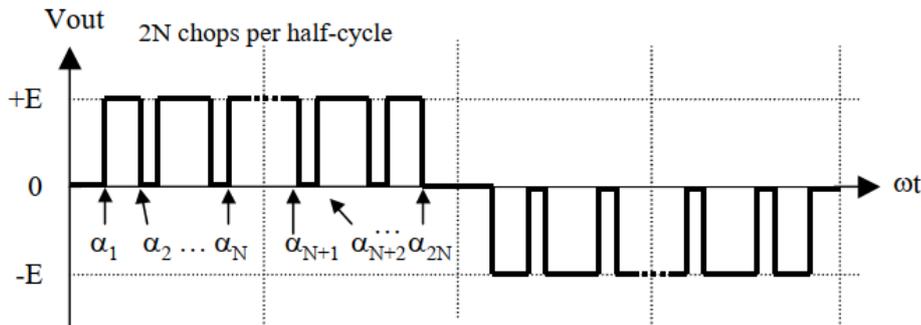


Figure 2. Output voltage waveform of the SHE-PWM inverter

Because of odd quarter-wave symmetry along x-axis of the waveform of the SHE-PWM inverter, the dc component (a_0) and the even harmonics (a_n) are equal to zero. So the Fourier series of the output voltage waveform of the SHE-PWM inverter as in (1), (2) [21-23]:

$$V_{out}(t) = \sum_{n=1}^{\infty} b_n \sin n\omega t \tag{1}$$

$$b_n = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} V_{out}(t) \sin(n\omega t) d\omega t = \frac{4}{\pi} \left[\int_{\alpha_1}^{\alpha_2} V_{dc} \sin n\omega t + \int_{\alpha_3}^{\alpha_4} V_{dc} \sin n\omega t + \int_{\alpha_5}^{\alpha_N} V_{dc} \sin n\omega t + \dots \dots \right] \tag{2}$$

It can be written as:

$$b_n = \begin{cases} \frac{4V_{dc}}{n\pi} \sum_{K=1}^N (-1)^K \cos n\alpha_K & \text{for } n = 1, 3, 5, \dots \\ 0 & \text{for } n = 2, 4, 6, \dots \end{cases} \tag{3}$$

$$V_{out} = \frac{4V_{dc}}{n\pi} \sum_{K=1}^N (-1)^{K+1} \cos n\alpha_K \sin n\omega t \quad n=1, 3, 5, \dots \tag{4}$$

where V_{dc} is the dc input voltage of the bridge inverter, and n is the harmonic order. The switching angles constrain is:

$$0 < \alpha_1 < \alpha_2 < \alpha_3 < \dots < \alpha_N < \pi/2 \tag{5}$$

For example: The 5 unknown switching angles ($\alpha_1, \alpha_2, \alpha_3, \alpha_4,$ and α_5) (N=5) necessity to be estimated from 5 non-linear equations based on (3) for elimination (N-1) odd harmonics that are the (3rd, 5th, 7th, and 9th harmonics) and as in (6)-(10):

$$\frac{4V_{dc}}{n\pi} [\cos \alpha_1 - \cos \alpha_2 + \cos \alpha_3 - \cos \alpha_4 + \cos \alpha_5] = V_1$$

$$[\cos \alpha_1 - \cos \alpha_2 + \cos \alpha_3 - \cos \alpha_4 + \cos \alpha_5] = \frac{M\pi}{4} \tag{6}$$

$$[\cos 3 \alpha_1 - \cos 3 \alpha_2 + \cos 3 \alpha_3 - \cos 3 \alpha_4 + \cos 3 \alpha_5] = H3 = 0 \tag{7}$$

$$[\cos 5 \alpha_1 - \cos 5 \alpha_2 + \cos 5 \alpha_3 - \cos 5 \alpha_4 + \cos 5 \alpha_5] = H5 = 0 \tag{8}$$

$$[\cos 7 \alpha_1 - \cos 7 \alpha_2 + \cos 7 \alpha_3 - \cos 7 \alpha_4 + \cos 7 \alpha_5] = H7 = 0 \tag{9}$$

$$[\cos 9 \alpha_1 - \cos 9 \alpha_2 + \cos 9 \alpha_3 - \cos 9 \alpha_4 + \cos 9 \alpha_5] = H9 = 0 \tag{10}$$

Where M is the modulation index = $\frac{V_1}{V_{dc}}$, where V_1 is the fundamental component of the output voltage, $H3, H5, H7, H9$ are the 3rd, 5th, 7th, and 9th harmonics components respectively [24, 25]. An m-file using MATLAB platform is used to solve these nonlinear (6)-(10) based on "Newton-Raphson Method". Table 1 lists the switching angles for different cases of SHE. For ten angles (α_1 to α_{10}), the number of eliminated harmonics (odd harmonics) equal to nine (3rd to 19th). The LOH will be 21st (21×50=1050 Hz), Figure 3 shows the relation between modulation index M and the switching angles.

Table 1. Switching angles at $M = 1$

Type	Harmonics Eliminated										
Square Wave	Non										
Quasi-square wave	3 rd only										
Four SHE	3 rd , 5 th , 7 th , and 9 th	$\alpha_1 =$ 22.580	$\alpha_2 =$ 33.600	$\alpha_3 =$ 46.640	$\alpha_4 =$ 68.500	$\alpha_5 =$ 75.100					
Six SHE	3 rd , 5 th , 7 th , 9 th , 11 th , and 13 th	$\alpha_1 =$ 19.791	$\alpha_2 =$ 26.973	$\alpha_3 =$ 35.232	$\alpha_4 =$ 47.471	$\alpha_5 =$ 54.185	$\alpha_6 =$ 80.335	$\alpha_7 =$ 82.052			
Nine SHE	3 rd , 5 th , 7 th , 9 th , 11 th , 13 th , 15 th , 17 th , and 19 th	$\alpha_1 =$ 14.000	$\alpha_2 =$ 17.390	$\alpha_3 =$ 28.230	$\alpha_4 =$ 42.830	$\alpha_5 =$ 52.420	$\alpha_6 =$ 58.100	$\alpha_7 =$ 70.240	$\alpha_8 =$ 70.240	$\alpha_9 =$ 74.370	$\alpha_{10} =$ 88.220

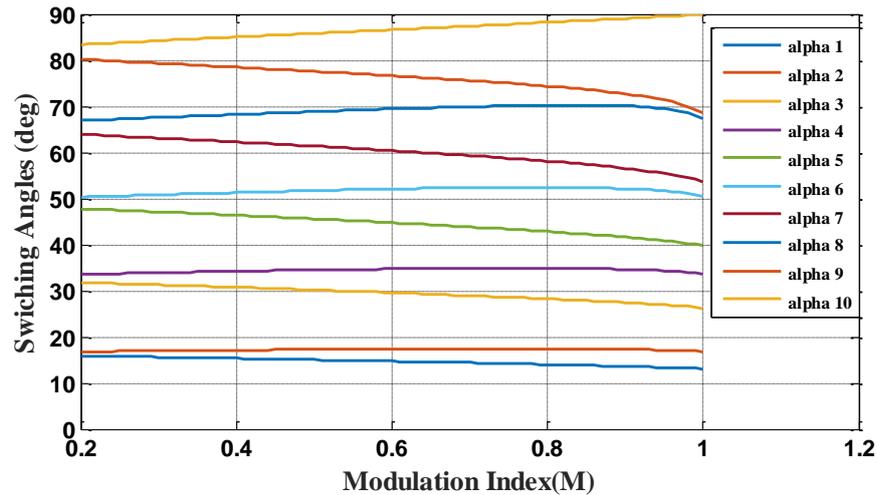


Figure 3. Relation between modulation index and switching angles

3. ARDUINO CODE

The proposed Arduino codes for generation the required trigger signals for inverter switches based on SHE-PWM technique for elimination LOHs are realized according to switching angles in Table 1 and as follows:

- The proposed Arduino codes are developed and edited using Arduino IDE software version 1.8.10 then verified and uploaded to Arduino Mega 2560 type via serial port.
- Selecting the pin mode of the utilized Arduino pins as an "OUTPUT".
- The firing pulses are made ON and OFF for certain intervals depending upon the switching angles presented in Table 1. These angles are normalized to time formula to deal with it as a time delay inside the void loop using "delay Microseconds" function and after each time delay a trigger signal is turned ON (HIGH) or OFF (LOW) using "digital Write" function according to Table 2, as shown in Figures 4 and 5.
- Both power semiconductor switches in the same leg of the H-bridge may be ON at the same time due to the OFF times of the semiconductors greater than the ON times. This case reasons a short circuit in the H-bridge and thus high currents flow in the semiconductors. So, dead time should be inserted between each complement gate signals of the same leg. So in our work 4 micro seconds dead time is inserted after turned OFF each switch using "delayMicroseconds" function again.

Table 2. Switching state of the SHE-PWM inverter per positive half period cycle

S1	S2	S3	S4	V_{out}	Angle Amplitude	Time (μ sec)	Angle
ON	OFF	ON	OFF	0	α_1	777.778	14°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_2 - \alpha_1$	188.333	3.39°
OFF	ON	OFF	ON	0	$\alpha_3 - \alpha_2$	602.222	10.84°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_4 - \alpha_3$	367.222	6.61°
ON	OFF	ON	OFF	0	$\alpha_5 - \alpha_4$	443.889	7.99°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_6 - \alpha_5$	532.778	9.59°
OFF	ON	OFF	ON	0	$\alpha_7 - \alpha_6$	315.556	5.68°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_8 - \alpha_7$	674.444	12.14°
ON	OFF	ON	OFF	0	$\alpha_9 - \alpha_8$	229.444	4.13°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_{10} - \alpha_9$	769.444	13.85°
OFF	ON	OFF	ON	0	$\pi - (2 * \alpha_{10})$	197.778	3.56°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_{10} - \alpha_9$	769.444	13.85°
ON	OFF	ON	OFF	0	$\alpha_9 - \alpha_8$	229.444	4.13°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_8 - \alpha_7$	674.444	12.14°
OFF	ON	OFF	ON	0	$\alpha_7 - \alpha_6$	315.556	5.68°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_6 - \alpha_5$	532.778	9.59°
ON	OFF	ON	OFF	0	$\alpha_5 - \alpha_4$	443.889	7.99°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_4 - \alpha_3$	367.222	6.61°
OFF	ON	OFF	ON	0	$\alpha_3 - \alpha_2$	602.222	10.84°
ON	ON	OFF	OFF	(+Vdc)	$\alpha_2 - \alpha_1$	188.333	3.39°
ON	OFF	ON	OFF	0	α_1	777.778	14°
						10000.000	180°

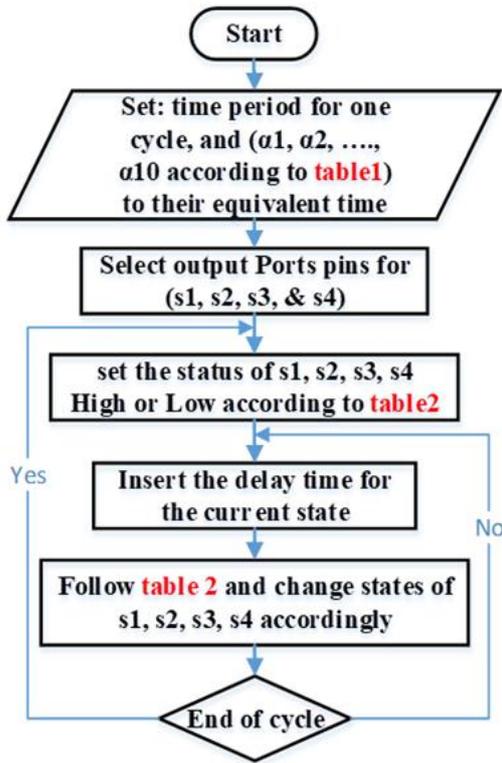


Figure 4. Flow chart of the proposed Arduino code

```

sec_10_withoutdt$
float T = 20000.0; // Time Period in microsecond (T =20 milliseconds)
float alpha_1=14.0; float alpha_2 =17.39; float alpha_3 = 28.23;//Angles
float alpha_4=34.84;float alpha_5 = 42.83;float alpha_6=52.42; // in
float alpha_7= 58.1; float alpha_8=70.24;float alpha_9 = 74.37;// Degree
float alpha_10 =88.22 ;
float alpha1 = (14.00* T)/360;float alpha2 =(17.39*T)/360;//Converting
float alpha3 = (28.23* T)/360;float alpha4 =(34.84*T)/360;//angles from
float alpha5 = (42.83* T)/360;float alpha6 =(52.42*T)/360;//Degree to
float alpha7 = (58.10* T)/360;float alpha8 =(70.24*T)/360;//Time
float alpha9 = (74.37* T)/360;float alpha10 =(88.22*T)/360;
float pi = (180* T)/ 360; float dt =4; // dt = dead time
int S1=6; int S2=7; int S3=8; int S4=9; // Specified the pin number
void setup () {
pinMode (S1,OUTPUT); pinMode (S2,OUTPUT);//Configures the specified pin
pinMode (S3,OUTPUT); pinMode (S4,OUTPUT);} //to behave as an output
void loop () {
digitalWrite (S1, HIGH);digitalWrite (S2, LOW);
digitalWrite (S3, HIGH);digitalWrite (S4, LOW);delayMicroseconds(alpha1);
digitalWrite (S3, LOW);delayMicroseconds(dt);
digitalWrite (S2, HIGH);delayMicroseconds((alpha2-alpha1)-dt);
digitalWrite (S1, LOW);delayMicroseconds(dt);
digitalWrite (S4, HIGH);delayMicroseconds((alpha3-alpha2)-dt);
digitalWrite (S4, LOW);delayMicroseconds(dt);
digitalWrite (S1, HIGH);delayMicroseconds((alpha4-alpha3)-dt);
digitalWrite (S2, LOW);delayMicroseconds(dt);
digitalWrite (S3, HIGH);delayMicroseconds((alpha5-alpha4)-dt);
    
```

Figure 5. Arduino code

4. EXPERIMENTAL IMPLEMENTATION

To validate the results obtained in the theoretical and simulation analysis, a prototype of single phase inverter has been experimentally developed as shown in Figure 6. Power MOSFET IRFP460 is used as a main power switch in the H-bridge. A gate drive circuit based on TLP350 optocoupler is used as shown in Figure 7 for providing isolation between power switches and the Arduino, also it employed for normalize the switching pulses signals to be sufficient to trigger the power switches.



Figure 6. Prototype of the developed inverter

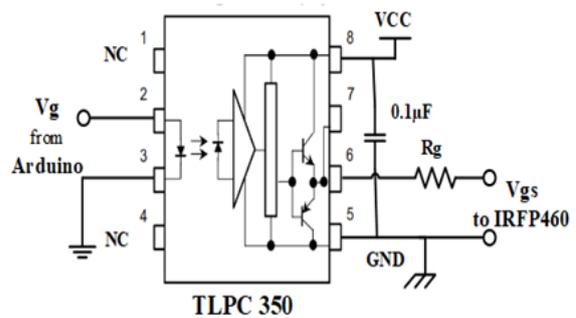


Figure 7. Gate drive circuit

5. DEVELOPMENT OF THE WORK AND RESULTS

Practically, several codes were proposed and carried out in Arduino board for elimination different number of harmonic based on SHE technique. For instance, the first one considers a simple code for producing square wave output voltage (i.e. with 180° conduction angle) of the inverter as shown in Figure 8. This figure also shows the spectral analysis that assures the presence of the fundamental and all accompanying odd harmonics. The second code involves implementation code for quasi-square inverter; which considered as modified of square wave inverter. The quasi-square wave eliminates the 3rd harmonics

as shown in Figure 9. The load is (R-L) load with $R=3.6$ ohm, and $L=5$ mH. The elimination four of LOH (3^{rd} , 5^{th} , 7^{th} and 9^{th} harmonics) after solving five non-linear equations as shown in Figure 10. Adopting this procedure the elimination of five harmonics (3^{rd} , 5^{th} , 7^{th} , 9^{th} and 11^{th} harmonics) is shown in Figure 11. The output terminal voltage and the load current of the inverter for ten switching angles are shown in Figure 12(a) and Figure 12(b) respectively, which shows that the LOH is 21^{st} in its spectral analysis.

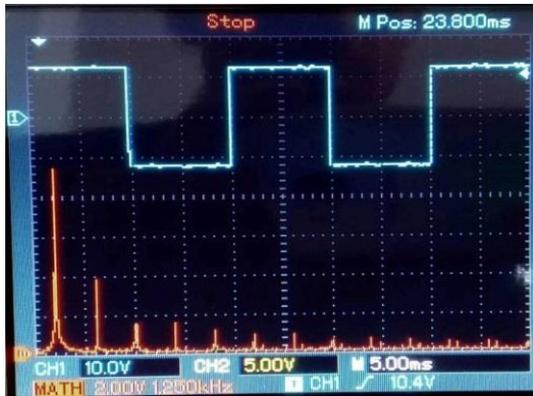


Figure 8. Square wave output terminal voltage



Figure 9. Quasi-square wave output terminal voltage



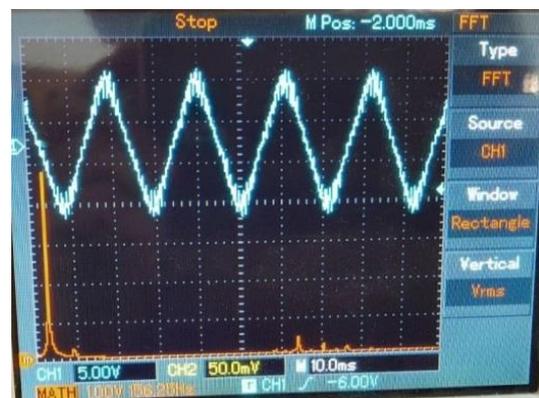
Figure 10. Output terminal voltage with four SHE



Figure 11. Output terminal voltage with five SHE



(a)



(b)

Figure 12. Spectral analysis: (a) Terminal output voltage, (b) Load current with R-L load with nine harmonics eliminated

Its clear that the number of eliminated harmonics in the spectrum analysis of terminal voltage are nine harmonics, where the eliminated harmonics are from 3rd up to 19th in SHE-PWM inverter while the 21st harmonic order (at 1050 Hz) appears as the first harmonic as shown in the spectrum analysis of terminal voltage and load current. To validate the practical results a Simulink MATLAB model is built and according to Figure 3, ten switching angles is used in MATLAB simulation. The modulation index $M=1$, $V_{dc}=300$ V and the inverter frequency $f = 50$ Hz with R-L load of $R=3.6$ ohm, and $L=5$ mH. Figure 13 show the terminal O/P voltage and load current with their harmonics spectral analysis.

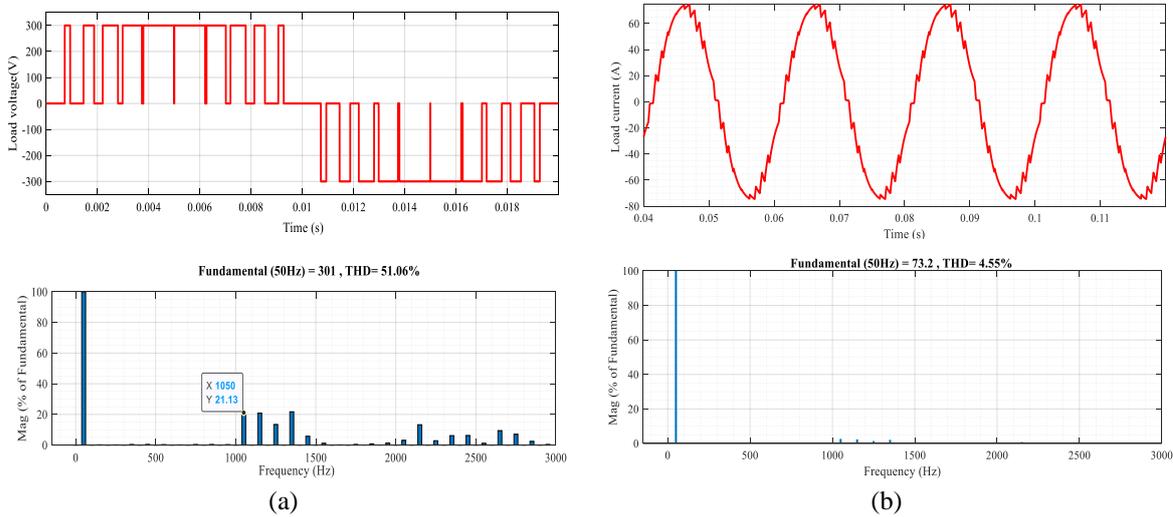


Figure 13. Output voltage and load current with their harmonics spectral analysis for SHE-PWM converter

The LOH as in Figure 13 is the 21st. A comparative study used for sinusoidal-PWM (SPWM) technique, the same spectrum can be obtained by setting the carrier frequency $f_c = 1300$ Hz, the load voltage and current are shown in Figure 14. The simulation shows the number of pulses per half cycle Q equal ten pulses in SHE-PWM technique since ten switching angles per half cycle are used as in Figure 13. While Figure 14 shows Q equal to thirteen pulses where Q equal the ratio between carrier frequency to the fundamental frequency, $Q = f_c/2f = (1300/2*50)$ in SPWM. It is obvious that SPWM results in higher switching losses compared with SHE-PWM strategy. Also a slightly increase in utilization of dc input voltage for SHE-PWM compare with sinusoidal-PWM.

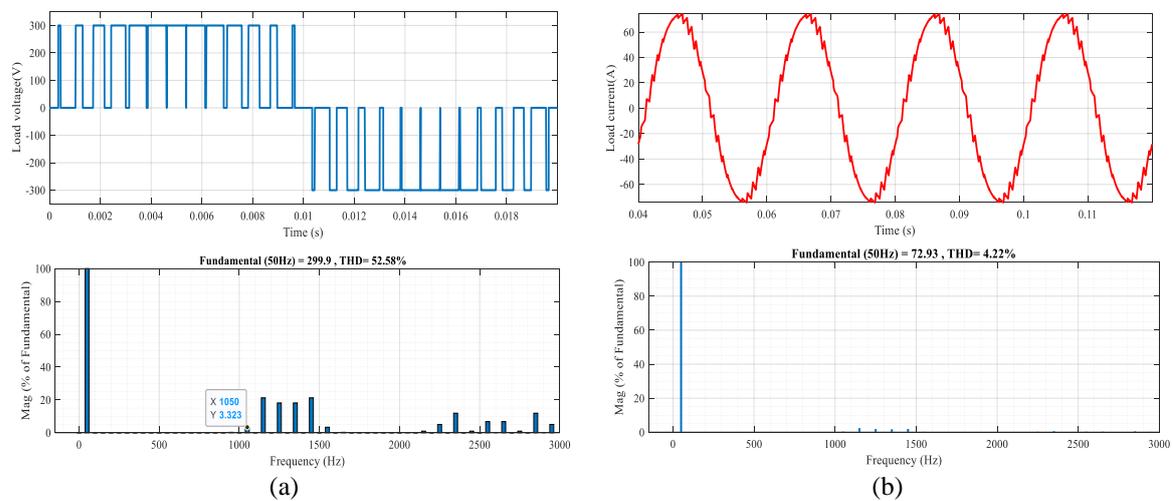


Figure 14. Terminal voltage and load current with their spectrum harmonics analysis for sinusoidal-PWM

6. CONCLUSION

Experimental prototype for single phase inverter based on Arduino is built to verify the software analysis and the MATLAB/Simulink of the inverter based on SHE-PWM technique. As the number of the harmonics eliminated are increased as the THD value is decreased. On the other way the switching losses are increased. Comparison study using same LOH in the output waveform between SHE-PWM and SPWM shows that number of pulses in the gate signal and output waveform in SHE-PWM strategy are less than the number of pulses in the SPWM strategy. Thus the switching losses in SHE-PWM is less than SPWM, also in the practical implementation the dead time that is inserted in the gate signals is reduced due to the reduced number of pulses. Since this dead time result in distortion in the output waveform. A modified Newton Raphson m-file in MATLAB platform is used to calculate a wide range of switching angles according to variation of modulation index. In future work, real time variation of switching angles based on SHE-PWM technique can be adopted. Also, this technique can be applied for three-phase inverter and implemented practically based on Arduino microcontroller.

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