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Implementation of Selective Harmonics Elimination for Single Phase Inverter using Arduino and Simulink MATLAB model

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This paper presents Arduino controller implementation and Simulink model in MATLAB to eliminate a selected number of harmonics in a single phase inverter. A MATLAB code is written to solve the nonlinear trigonometric that arises in the Fourier analysis of the output of the inverter. Newton's Raphson method is adopted to find the triggering angles for the four electronic switches in the inverter. All possible combinations of these triggering instants are then computed for period of one cycle. To validate the model a practical set using Arduino controller is implemented. Frequency spectrums of the output of the inverter for both the Simulink model and the practical set are shown for the elimination of certain selected harmonics. Any other selected harmonics can be eliminated using the proposed model.

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تنفيذ ازالة التوافقيات بطريقة انتقائية للعكس احادي الطور باستخدام الاردوينو مع بناء نموذج صندوق في برنامج الماتلاب

طه احمد حسين / قسم هندسة التقنيات الكهربائية / الكلية التقنية الهندسية / الجامعة التقنية الشمالية / العراق
ابراهيم اسماعيل شيت / قسم هندسة التقنيات الكهربائية / الكلية التقنية الهندسية / الجامعة التقنية الشمالية / العراق

الخلاصة

يقدم البحث تنفيذ المتحكم الاردوينو مع نموذج صندوق في برنامج الماتلاب لإزالة عدد مختار من التوافقيات للعكس احادي الطور. تم كتابة شفرة الماتلاب لحل المعادلات المثلثية الغير خطية التي تتكون في تحليل فوريير في خراج العاكس. تم تبني طريقة نيوتن رافسون لإيجاد زوايا التشغيل للمفاتيح الإلكترونية الاربعة الموجودة في العاكس. ثم يتم حساب كل الاحتمالات الأخرى للحظات التشغيل ولفترة دورة عمل كاملة. لغرض تقييم النموذج الكتلي المقترح تم تنفيذ دائرة عملية باستخدام المسبكر الاردوينو. تم عرض الطيف الترددي لأخراج العاكس احادي الطور لإزالة عدد محدد من التوافقيات. من الممكن إزالة أي توافقية أخرى باستخدام النموذج المقترح.

1. INTRODUCTION

Electrical power control using electronic switches like thyristors is used efficiently in variety of applications in industry. However, these switches often generate harmonics which is injected in the electrical power grid. The performance of the grid is severely affected and the

efficiency of the network is noticeably reduced [1]. Therefore, the reduction of these harmonics are the main concern of researchers in order for the power system to work properly. Inverters are DC to AC converters that are found in almost every power system. The output of the inverter is a square wave with high harmonic contents. Harmonics, with amplitudes that are relatively high

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compared with the amplitude of the fundamental, have to be eliminated or at least reduced. Numerical methods are often used for harmonic elimination for inverters. There are various techniques for the elimination of higher order harmonics. The principle of selective harmonics elimination is very powerful in selecting a specific order of harmonics that is designated to have a great influence on the performance of the power system. The output of inverters can be arranged in system of transcendental functions. The solution of these transcendental functions for selected harmonic to be eliminated gives the timing instants for the triggering of thyristors [2, 3]. There are different numerical methods for the solution of such a transcendental nonlinear equation. Newton's method is the best amongst other methods and often used to solve such complicated transcendental functions [4]. Other techniques are found to use Newton's method as implicit teacher to approach their final goals [5]. To validate the simulation part of the work an Arduino Mega set for single phase inverter with 50Hz output is designed and implemented [6]. Selective harmonic elimination (SHE) is a well-known technique to generate PWM signals that can eliminate specific low order harmonics from a given voltage waveform generated by a voltage-source inverter (VSI). Although the method is long established and reported in numerous papers, SHE received new attention (Maswood et al., 2001; [7] Sayyah et al., 2006; [8] and Sundareswaran et al., 2007 [9] due to the advancement in digital signal processing tools and microcontrollers that can be used to implement such algorithms and in some applications such as high speed ac drives where the frequency ratio (switching frequency-to-fundamental frequency) is limited to low values which deteriorates the performance if conventional sine-triangle PWM technique is used [10]. Therefore, selective harmonic elimination is a valuable alternative to other PWM methods, and more suitable for such applications.

2. HARMONIC ELIMINATION

A generalized method for eliminating harmonics can be derived from the two state output wave of the single inverter. The square wave output is chopped at defined positions in order to eliminate selected number of harmonics. The output waveform is chopped N times in such a way to get odd quarter wave symmetry which simplify the analysis. The odd quarter symmetry is actually a half wave symmetry in addition to either even or odd symmetry is

$$f(t) = -f\left(t \pm \frac{T}{2}\right).$$

where T is the period of the signal. The Fourier series of periodic function is

$$f(\omega t) = a_0 + \sum_{n=1}^{\infty} [a_n \sin(n\omega t) + b_n \cos(n\omega t)] \quad (1)$$

Where a_0, a_n and b_n are the Fourier coefficients. Following the above constraints.

The Fourier coefficients were found to be

$$a_0 = 0, b_n = 0 \text{ and } a_n = \frac{4}{n\pi} [1 + 2 \sum_{k=1}^N (-1)^k \cos n\alpha_k] \quad (2)$$

where α_k is the chopping angle. The output of single phase inverter is of the form

$$v_{2k+1} = \frac{4V_{dc}}{(2k+1)\pi} [\sum_{i=0}^N h_i \cos(2k+1)\alpha_k] \quad (3)$$

where $\alpha_1 < \alpha_2 < \alpha_3 < \pi/2$ are the triggering angles, h_i is the waveform level and k is the switching angle

number. Employing this technique yields a bipolar PWM output as shown in Fig. (1).

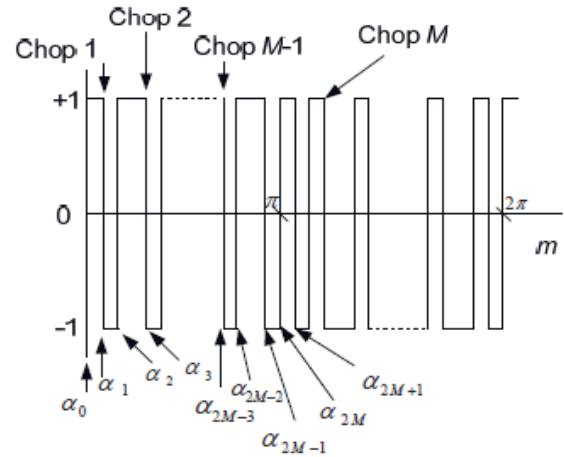


Fig. 1. Single phase inverter chopping points

In order to achieve correct positions for the firing angles, equation (3) is solved for the required number of harmonics to be eliminated. For instance, in order to eliminate 3rd, 5th, 7th, and 9th harmonics, equation (3) can be rewritten as

$\frac{4}{\pi} [(-1 + 2\cos\alpha_1 - 2\cos\alpha_2 + 2\cos\alpha_3 - 2\cos\alpha_4 + 2\cos\alpha_5 - M)]$, where $M \leq 1$ is the modulation index

$-1 + 2\cos 3\alpha_1 - 2\cos 3\alpha_2 + 2\cos 3\alpha_3 - 2\cos 3\alpha_4 + 2\cos 3\alpha_5 = 0$3rd harmonics

$-1 + 2\cos 5\alpha_1 - 2\cos 5\alpha_2 + 2\cos 5\alpha_3 - 2\cos 5\alpha_4 + 2\cos 5\alpha_5 = 0$5th harmonics

$-1 + 2\cos 7\alpha_1 - 2\cos 7\alpha_2 + 2\cos 7\alpha_3 - 2\cos 7\alpha_4 + 2\cos 7\alpha_5 = 0$7th harmonics

$-1 + 2\cos 9\alpha_1 - 2\cos 9\alpha_2 + 2\cos 9\alpha_3 - 2\cos 9\alpha_4 + 2\cos 9\alpha_5 = 0$9th harmonics

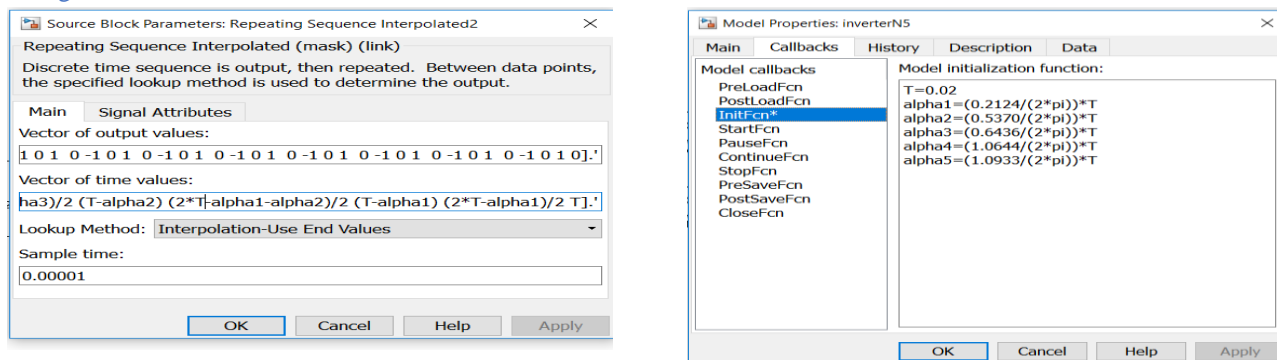
The initial values of the triggering angles are found from the Cauchy problem [4]

$$\alpha_k = \frac{180^\circ \cdot k}{2N+1} \text{ where } k = 1.2.3.4. \dots N.$$

A newton method is then coded in a MATLAB file to produce the firing angles as listed below. The .m file is written for the elimination of the 3rd, 5th, 7th and 9th harmonics and can be rewritten for any other desired harmonics. The Newton-Raphson method, or Newton Method, is a powerful technique for solving equations numerically. Like so much of the differential calculus, it is based on the simple idea of linear approximation. The Newton Method, properly used, usually homes in on a root with devastating efficiency. The MATLAB program codes for the initial triggering angles is shown in appendix A. The output of the file is a vector of the triggering angles given in radian {Alpha= 0.2124 0.5370 0.6436 1.0644 1.0933}. The second step is to divide period of the desired output waveform into all the possible combinations of the triggering instants, then one of a three level magnitudes (i.e. 0, -1 or 1) is assigned against every successive combinations as listed in table (1). Table (1) shows three level magnitudes (i.e. 0, -1 or 1) are assigned against every successive combination. These vectors are the inputs in the main icon of a Simblock called repeating sequence interpolated [11], as shown in the following MATLAB block which associate each output level to its corresponding triggering instant.

Repeating sequence MATLAB block. The initial values are passed to InitFcn box which is popped from the file menu then selecting model properties as follows.

The output of the sequence interpolated block is shown in Fig.2.

**Table .1.**

three level magnitudes (i.e. 0, -1 or 1) is assigned against every successive combinations

Level (0)	Level (-1)	Level (0)	Level (1)	Level (0)	Level (-1)	Level (0)	Level (1)
0	alp1/2	alp1	(alp1+alp2)/2	(alp2)	(alp2+alp3)/2	alp3	(alp3+alp4)/2
alp4	(alp4+alp5)/2	alp5	T/4	(T-2*alp5)/2	(T-4*alp5)/2	(T-2*alp4)/2	(T-4*alp4)/2
(T-2*alp3)/2	(T-2*alp3)/2	(T-2*alp2)/2	(T-2*alp1)/2	(T-2*alp1)/2		0.5*T	(T+alp1)/2
					(T-2*alp1)/2		
(T+2*alp1)/2	(T+alp1+alp2)/2	(T+2*alp2)/2	(T+alp2+alp3)/2	(T+2*alp3)/2	(T+alp3+alp4)/2	(T+2*alp4)/2	(T+alp4+alp5)/2
(T+2*alp5)/2	0.75*T	(T-2*alp5)	(2*T-4*alp5)/2	(T-2*alp4)	(2*T-4*alp4)/2	(T-2*alp3)	(2*T-4*alp3)/2
(T-2*alp2)	(2*T-4*alp2)/2	(T-2*alp1)	(2*T-4*alp1)/2	T			

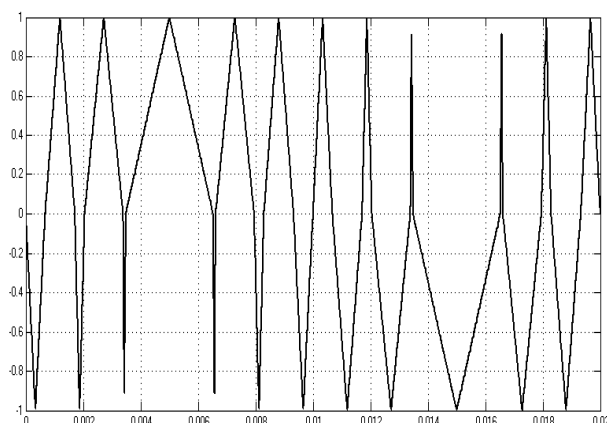


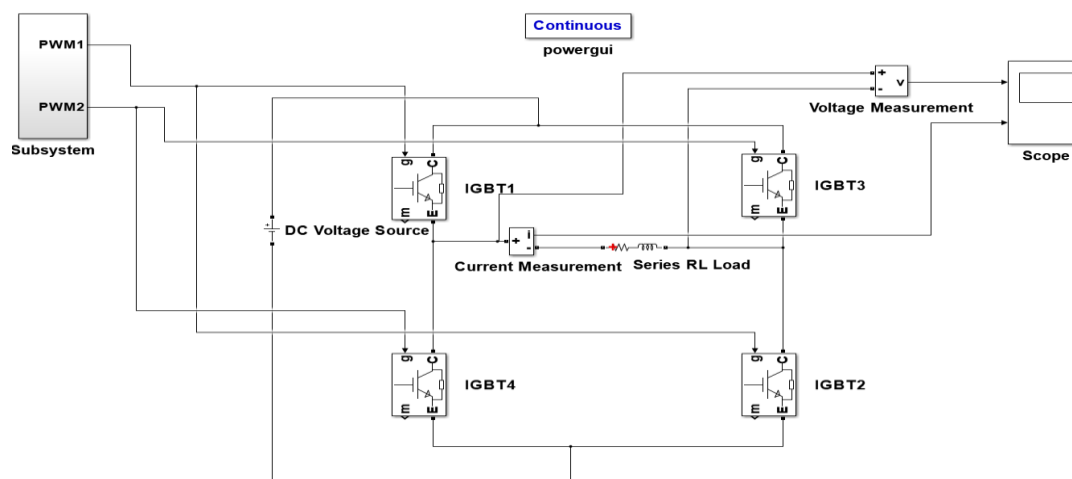
Fig. 2. the output of the sequence interpolated block

3. Model MATLAB

A Simulink model is built for a PWM single phase inverter controlled by the computed values of the possible combinations of the triggering angles is shown in Fig. 3.

4. RESULTS

The Simulink model is tested for 180° square wave triggering angles to monitor the harmonic contents of the inverter. The output wave form and the harmonic contents are shown in Fig. (4) and Fig. (5) respectively.



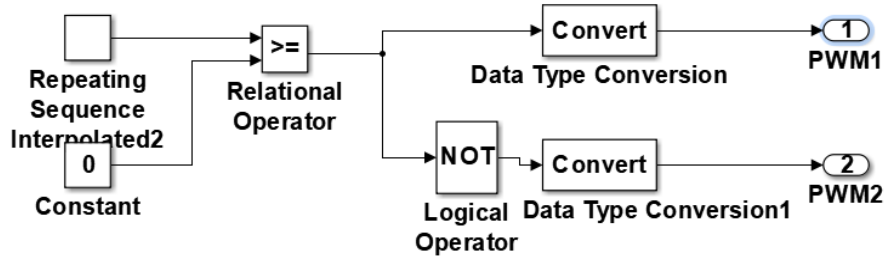


Fig. 3. Simulink model for a single phase inverter

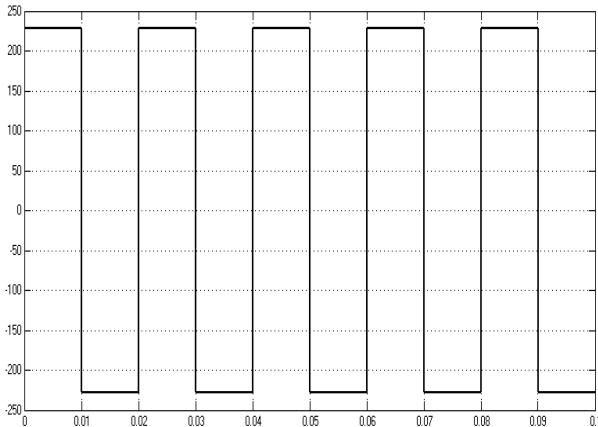


Fig.4. Inverter output for 180° triggering angles

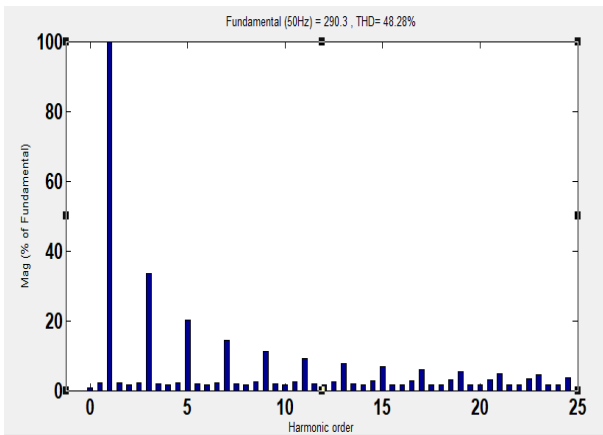


Fig. 5. Harmonics contents (order) for Fig. (4)

To eliminate the 3rd and 5th harmonics, the initial values of the triggering angles are found from equation (4). The MATLAB file is now solved for: $\alpha_1 = 0.2967$, $\alpha_2 = 0.8838$ and $\alpha_3 = 0.9677$. The modulation index is set to be $M=1$ for all the results. These values when passed to the Newton algorithm in the MATLAB file gives the precise values of the instants of triggering angles and are found to be: $\alpha_1 = 0.2916$, $\alpha_2 = 0.8113$ and $\alpha_3 = 0.8976$. All possible combinations within one cycle is then calculated according to table (1). The output wave form and the harmonic contents are shown in Fig. (6) and Fig. (7) respectively for resistive load. The frequency in Fig. (7) Spectrum shows that the 3rd and 5th harmonics are almost vanished. The output spikes are due to the inductive load but the THD values for resistive and inductive loads are almost the same. To eliminate these

spikes a capacitive filter is added and a smooth output is shown in Fig. (9).

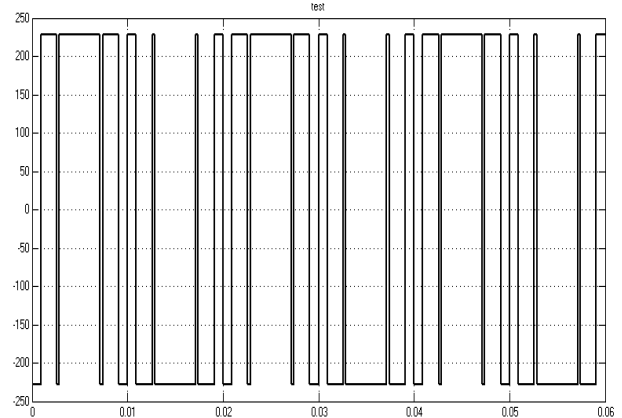


Fig. 6. Inverter output for the elimination of 3rd and 5th harmonics

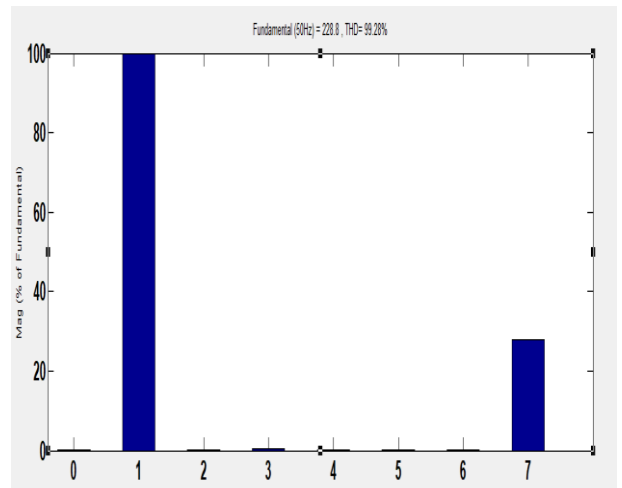


Fig. 7. Frequency spectrum(order) for Fig. (6)

For the elimination of 3rd, 5th and 7th harmonics the Newton's methods gives $\alpha_1 = 0.2533$, $\alpha_2 = 0.6769$, $\alpha_3 = 0.7785$ and $\alpha_4 = 1.5630$. The output wave form and the harmonic contents are shown in Fig.(9) and Fig.(10) respectively. For the elimination of 3rd, 5th and 7th and the 9th harmonics the triggering angles are found to be : $\alpha_1 = 0.2124$, $\alpha_2 = 0.5370$, $\alpha_3 = 0.6436$, $\alpha_4 = 1.0644$ and $\alpha_5 = 1.0933$. The output wave form is and the harmonic contents are shown in Fig.(11) and Fig.(12) respectively.

For each group of selected harmonics to be eliminated the combination of all possible triggering angles are

considered as illustrated for the case of 3rd, 5th, 7th and 9th harmonics in table (1).

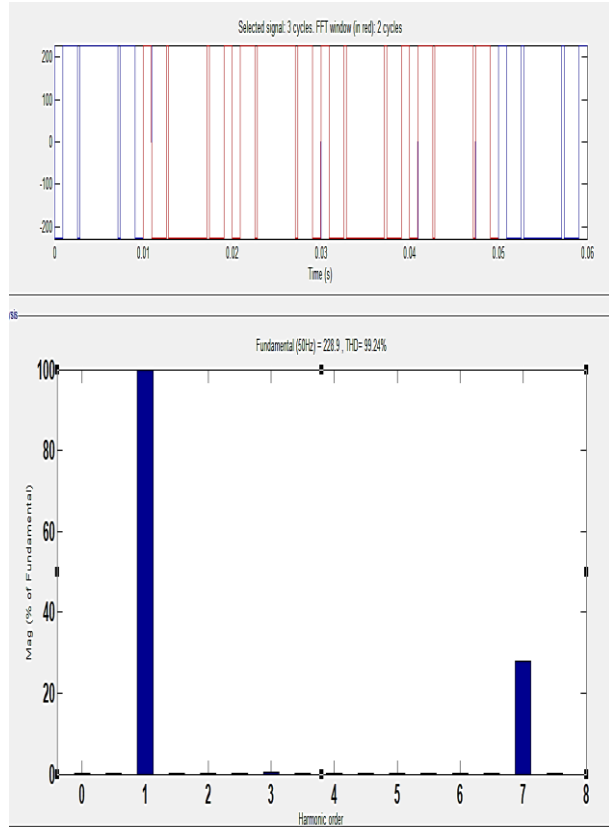


Fig. 8. Frequency spectrum(order) for Fig. (6) with RL load

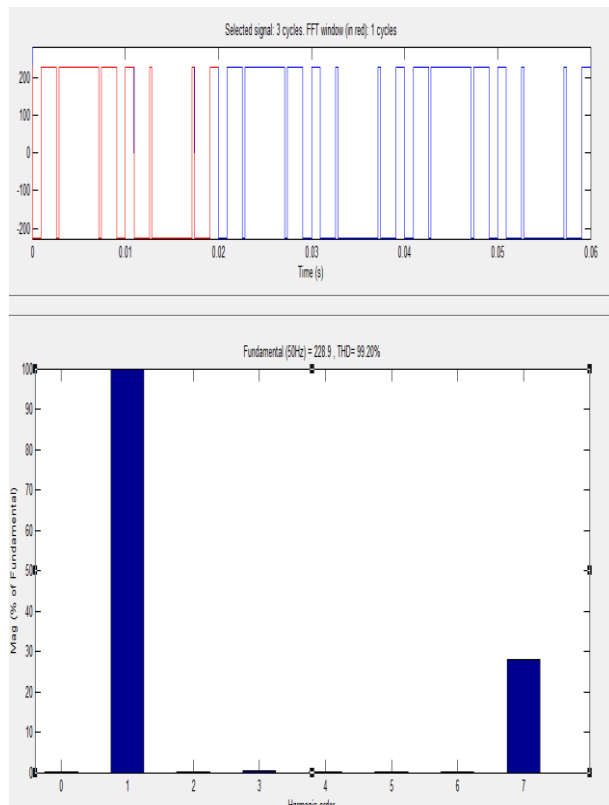


Fig. 9. output voltage and frequency spectrum(order)

for inductive load with capacitive filter
To validate the Simulink, model a practical set for single phase inverter is built. An Arduino Mega 2560 controller

is used for the control of the 50Hz inverter power circuit. An opt isolator is connected between the inverter power circuit and the Arduino controller. The programs for the Arduino are written such that they use the same triggering angles which are employed with the Simulink MATLAB block. At first the circuit is implemented for square wave output. Fig. (14) shows the frequency spectrum that contains the 50Hz fundamental along with a lot of harmonics as expected.

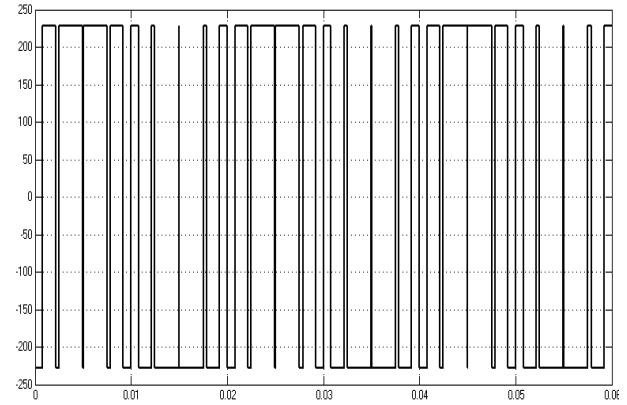


Fig. 10. Inverter output for the elimination of 3rd, 5th and 7th harmonics

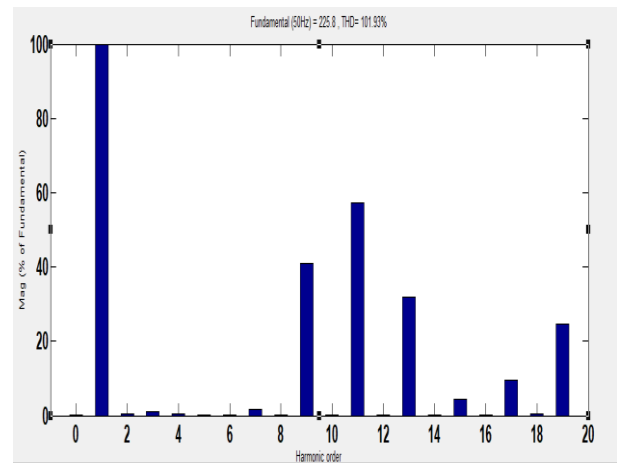


Fig. 11. Frequency spectrum (order) for Fig. (10)

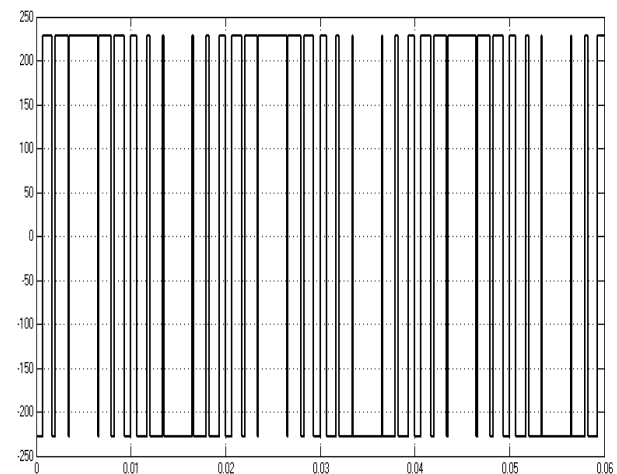


Fig. 12. Inverter output for the elimination of 3rd, 5th, 7th and 9th harmonics

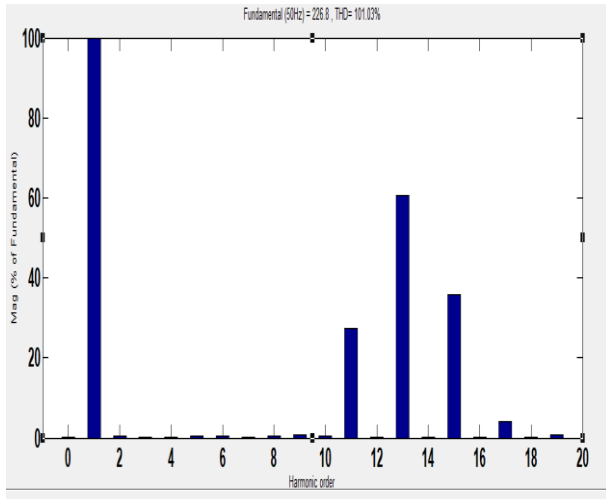


Fig. 13. Frequency spectrum (order) for Fig. (12)



Fig.14. Output voltage and frequency spectrum for square wave output

Secondly, the practical circuit is implemented to eliminate the 3rd, 5th, 7th and 9th harmonics. Fig.(15) shows that the fundamental 50Hz frequency and the frequencies 11th and beyond are exists which assist the results shown by the MATLAB Simulink model. Results shows the agreement between the MATLAB Simulink and the practical set.



Fig. 15. Output voltage and frequency spectrum for elimination of 3rd, 5th, 7th and 9th harmonics. (156.25Hz/div)

Then the elimination of six harmonics is tackled. Fig. (16) shows that the 3rd, 5th, 7th, 9th, 11th and 13th harmonics are eliminated.

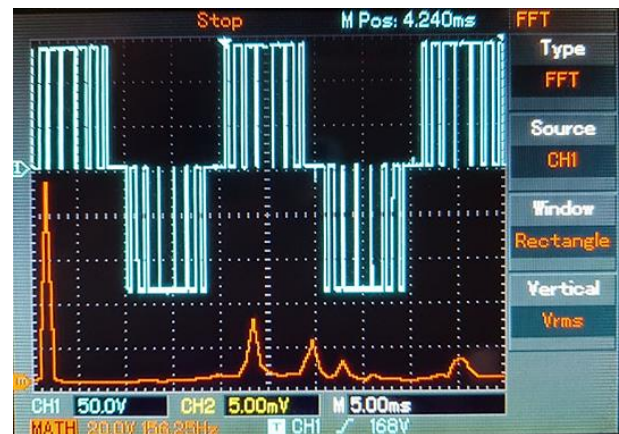


Fig.16. Output voltage and frequency spectrum for elimination of the 3rd, 5th, 7th, 9th, 11th and 13th harmonics (156.25Hz/div)

Any other selected harmonics can be eliminated with appropriate modification in the Arduino code.

5. CONCLUSIONS

PWM control method for single phase inverter using Newton method is used to solve the non-linearity in the harmonic equations. The instants for triggering angles are calculated to eliminate the selected order of harmonics. A MATLAB Simulink model is connected to handle harmonic elimination of 3rd, 5th, 7th and 9th order for a single phase inverter with resistive load. To determine the validity of the study an inductive load is also tried and the harmonics are eliminated in the same manner although spikes are introduced in the output voltage. These spikes are easily eliminated by adding a capacitive filter at the load side. An Arduino mega controller is used for the selective harmonic elimination in the set of practical single phase inverter. Practical results agreed with the MATLAB Simulink model. Any desired orders of harmonics can be eliminated by the suitable modification of the all possible combinations of the triggering angles that have to be passed to the Newton's algorithm via the MATLAB file or to the Arduino code. The Simulink model and the Arduino circuit can be

upgraded easily to multilevel inverter for single and three phase supply.

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Appendix A

% calculate the best triggering angles for single phase %inverter using Newton's method for the elimination %of 3rd ,5th , 7th and 9th harmonics

```
alpha1=0.2856;alpha2=0.5712; alpha3=0.8568;alpha4=1.1424;alpha5=1.4280;M=1;
alpha= [alpha1 alpha2 alpha3 alpha4 alpha5]';
for i=1:30
    alpha1=alpha(1,:);alpha2=alpha(2,:); alpha3=alpha(3,:);alpha4=alpha(4,:);alpha5=alpha(5,:);
    f=[-1+2*cos(alpha1)-2*cos(alpha2)+2*cos(alpha3)- 2*cos(alpha4)+2*cos(alpha5)-pi*M/4;
        -1+2*cos(3*alpha1)-2*cos(3*alpha2)+2*cos(3*alpha3)-2*cos(3*alpha4)+2*cos(3*alpha5);
        -1+2*cos(5*alpha1)-2*cos(5*alpha2)+2*cos(5*alpha3)-2*cos(5*alpha4)+2*cos(5*alpha5);
        -1+2*cos(7*alpha1)-2*cos(7*alpha2)+2*cos(7*alpha3)-2*cos(7*alpha4)+2*cos(7*alpha5);
        -1+2*cos(9*alpha1)-2*cos(9*alpha2)+2*cos(9*alpha3)-2*cos(9*alpha4)+2*cos(9*alpha5)];
    J=[ -2*sin(alpha1) 2*sin(alpha2) -2*sin(alpha3) 2*sin(alpha4) -2*sin(alpha5);
        -6*sin(3*alpha1) 6*sin(3*alpha2) -6*sin(3*alpha3) 6*sin(3*alpha4) -6*sin(3*alpha5);
        -10*sin(5*alpha1) 10*sin(5*alpha2) -10*sin(5*alpha3) 10*sin(5*alpha4) -10*sin(5*alpha5);
        -14*sin(7*alpha1) 14*sin(7*alpha2) -14*sin(7*alpha3) 14*sin(7*alpha4) -14*sin(7*alpha5);
        -18*sin(9*alpha1) 18*sin(9*alpha2) -18*sin(9*alpha3) 18*sin(9*alpha4) -18*sin(9*alpha5)];
    delalpha=inv(J)*f;
    alpha=alpha-delalpha;
end
alpha
```