Indonesian Journal of Electrical Engineering and Computer Science
Vol. 2, No. 3, June 2016, pp. 607 ~ 616
DOI: 10.11591/ijeecs.v2.i3.pp607-616

Harmonic Analysis of a Single Phase Modulated Inverter

Md Imran Azim, SM Mohiuddin
Rajshahi University of Engineering and Technology (RUET)
Rajshahi-6204, Bangladesh
*Corresponding author, e-mail: imran.azim89@gmail.com

Abstract

This paper portrays an approach of an analysis that provides information regarding the presence of harmonics at the inverter output terminal. It is certainly true that harmonics cause unbalance and excessive neutral currents, interference in nearby communication networks and disturbance to other consumers. More importantly, torque pulsations in electric motor drives are caused by them. Thus, the minimization of the harmonics contained in the output of a single phase current controlled inverter undergoing hysteresis modulation technique is important so as to get rid of these detrimental effects. A model of an LC low pass filter has been provided in this paper for harmonics reduction purpose, as it blocks the harmonics and passes approximately a sinusoidal output. Moreover, the paper contains the method of Fast Fourier Transform (FFT) for fulfilling the desire of understanding not only the fundamental component but also the harmonics component flawlessly. It has been found from the simulation that the Total Harmonic Distortion (THD) in ideal case is 0%. On the other contrary, during the presence of harmonics, it steeps to 41.415% that can be mitigated to 0.0092% by implementing an LC low pass filter in a precise manner.

***Keywords**: Single Phase Inveter, IGBT, Harmonics Analysis, FFT, THD, LC low pass Filter*

1. Introduction

An inverter can be defined as dc to ac converter which symbolizes the change of dc voltage into a symmetric ac output voltage of desired magnitude and frequency as shown in Figure 1. The output voltage could be fixed or variable at a fixed or variable frequency. A variable output can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. The output waveforms of an ideal inverter should be sinusoidal. However, the waveforms of practical inverters are non-sinusoidal and contain certain harmonics which can be seen with ease in frequency domain. Due to the availability of high speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching technique. IGBTs can be used as ideal switches to explain the power conversion techniques [1].

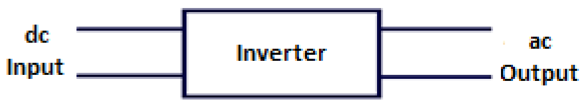

Figure 1. General Block Diagram of Inverter

Some typical applications are variable speed ac drives, induction heating, standby power supplies, uninterruptible power supplies (UPS), traction and HVDC [2].

Current Controlled Inverter is a special kind of inverter in which the output current can be controlled though hysteresis modulation techniques. Hysteresis current control is a kind of instantaneous feedback control model. The basic idea is to compare the given current signal which is detected by the converter with actual inverter current signal [3].

Received February 28, 2016; Revised April 20, 2016; Accepted May 6, 2016

FFT is a linear algorithm that can take a time domain signal into the frequency domain and back. Fourier analysis allows a more intuitive look at an unknown signal in frequency domain helping to understand the fundamental component and the harmonic components without any difficulties [4].

Total Harmonic distortion (THD) is a measure of closeness in shape between a waveform and its fundamental component.

It is given by the expression

$$THD = \sqrt{\frac{Im^2 - Im_1^2}{Im_1^2}} \quad (1)$$

Where, Im_1 is the RMS value of fundamental current component and Im is the RMS value of Current components.

Therefore, it is needless to say that THD can be defined as the ratio of the RMS value of all odd number of non-fundamental frequency terms to the RMS value of the fundamental.

For improvement of THD, a LC Low pass filter is appended at the output terminal that provides low harmonic impedance to ground [5]. In this paper, filering arrangement is made in a way that both the output voltage and current responses become sinusoidal.

2. Hysteresis Modulation Technique

In this modulation, the output current can be controlled by Compelling the inverter line current to track a sinusoidal reference current within a specified error margin in order to attain an adequate switching optimization, excellent dynamic responses and high accuracy in steady-state operation regarded as a hysteresis modulation [6].

Hysteresis Current controlled inverters are used in many low and medium voltage utility applications when the inverter line current is required to track a sinusoidal reference within a specified error margin. Line harmonic generation from those inverters depends principally on the particular switching pattern applied to the valves. The switching pattern of hysteresis inverters is produced through line current feedback and it is not pre-determined unlike the case, for instance, of Sinusoidal Pulse-Width Modulation (SPWM) where the inverter switching function is independent of the instantaneous line current and the inverter harmonics can be obtained from the switching function harmonics [7].

The hysteresis modulation for power electronic converters are preferred for applications, where performance requirements are more demanding such as to achieve good dynamic response, unconditional stability, and wide command-tracking bandwidth [8].

For simplicity, it is assumed that the dc voltage supplied by the DG source is divided into two constant and balanced dc sources, as in the Figure 2, each of value V_c, equal to 23V. The RL element on the AC side represents the combined line and transformer inductance and losses.

The inverter line current *i*, in Figure 2, tracks a sinusoidal reference current
and the inverter line voltage tracks, *v* also tracks a sinusoidal reference voltage through relay band action and fundamental frequency voltage at the inverter ac terminals when the line current equals the reference current is the reference voltage [9]. Referring to Figure 2, when valve Q_1 is turned on, the inverter voltage is $v = v_c > v_{ref}$; this forces the line current *i* to slope upward until the lower limit of the relay band $e_a(t) = -\varepsilon$ is reached . At that moment, the relay switches on Q_2 and the inverter voltage becomes $v = -v_c < v_{ref}$; this forces the line current *i* to slope downward until the lower limit of the relay band is reached $e_a(t) = \varepsilon$

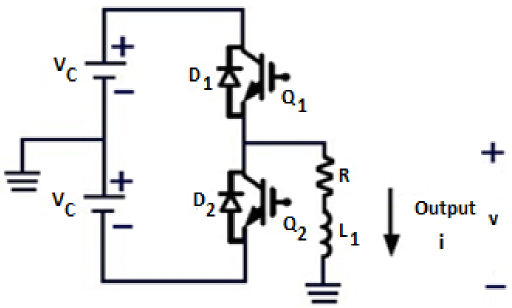

Figure 2. Single Phase Half Bridge Inverter

The operation of the circuit illustrated in Figure 2, has been visualized in Figure 3.

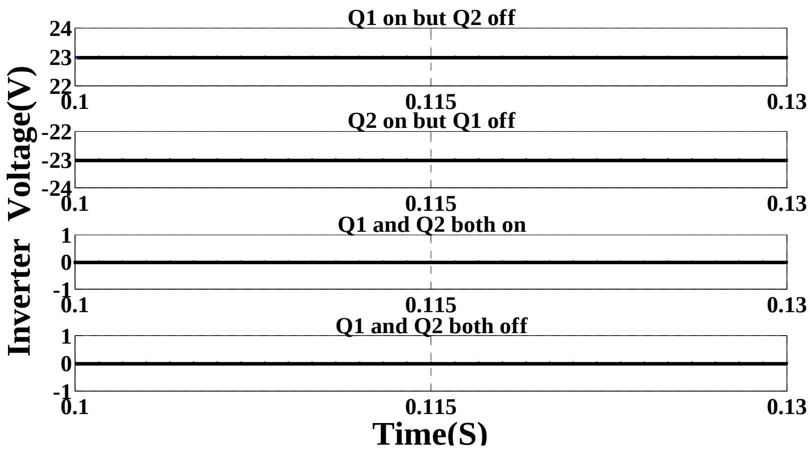

Figure 3. Inverter Voltages under Various Switching Conditions

Inverter output voltage can be regulated in a preferable manner by controlling the switching state of two valves Q_1 and Q_2. As is observed in Figure 4, Q_1 is made turned on for a particular time. After that Q_2 is allowed to operate within a specified time period and this process continues. It has been seen that the inverter voltage becomes V_c and $-V_c$ alternatively during the conduction interval of the two valves Q_1 and Q_2. For more convincing performance, care must be taken not to have two switches on together meaning that a dead time must be provided between them, otherwise, there is a high chance of shorting out of the DG source [10].

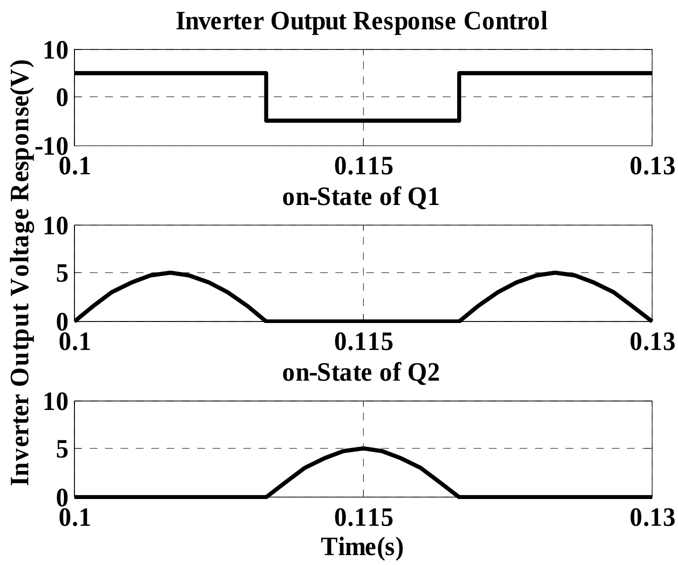

Figure 4. Inverter Voltage Control by Changing the Switching State of the Valves

Instantaneous inverter output voltage,

$$v = \sum_{n=1}^{\infty} 2\frac{2v_C}{n\pi}\sin(nwt) \tag{2}$$

Instantaneous inverter output current,

$$i = \sum_{n=1}^{\infty} 2\frac{2v_C}{n\pi\sqrt{R^2+(nwL)^2}}\sin(nwt-\theta n) \tag{3}$$

where, θn is the lagging or leading angle depending upon the connected load.

If the actual signal is more than the given value, then it is decreased by changing the switching state and vice versa. So, the actual response, S_{act} changes around the reference waveform, S_{ref} and hysteresis control makes the deviation within a certain range [11].

The mathematical expression for modulated output is

$$e_a(t) = S_{ref} - S_{act} \tag{4}$$

It goes without saying that the basic hysteresis technique is affected by the drawbacks of a variable switching frequency, large ripple current in steady state, generation of sub harmonic components and so on [13] that urges the necessity of filtering the output response [14]. An LC low pass filter is connected across the RL load represented in Figure 2. The implementation of an LC filter having L=0.0002H and C=1000F at the inverter ac terminals could trigger a parallel resonance which tends to amplify the harmonic voltages and currents in ac network leading, in some cases, to potential harmonic instabilities owing to the fact that the filter capacitance has a profound impact on the harmonic performance. This filter brings the harmonics into a lower state [15].

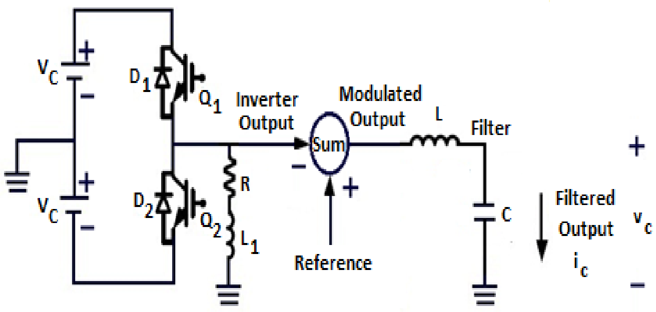

Figure 5. Single Phase Half Bridge Inverter with Filter

Now, output is taken across the capacitor with 1000F capacitance. In this case the inverter output current becomes,

$$i_C = \sum_{n=1}^{\infty} 2\frac{2v_C}{n\pi\sqrt{(-1/nwc)^2}}\sin(nwt-\theta c) \quad (5)$$

where, θc is the current leading angle of the capacitor.

$$v_C = \frac{1}{C}\int i_c\,dt \quad (6)$$

3. Results and Analysis

For making the simulation possible, necessary parameters like supply voltage = 23 V, frequency = 50 Hz, load resistor = 12 Ω and load inductor = 0.0032 H are considered deliberately with assuming that there is no harmonics prevalent at the output which means output response is forecasted to be sinusoidal.

According to the depiction, Figure 6 and Figure 7 deal with the time domain and frequency domain responses of the inverter output voltage and current respectively while there is no existence of harmonics (resistive load). Whereas, Figure 8 and Figure 9, indicate the modulated voltage and current implying the difference between reference and inverter current both in time domain and frequency domain under the same condition. Here, the obtained THD is 0%. But in practical situations it is cumbersome to get 0% THD.

Later on harmonic analysis is taken into account. Generally speaking, a harmonic is a signal or wave whose frequency is an integral multiple of the frequency of some reference signal or wave. The term can also refer to the ratio of the frequency of such a signal or wave to the frequency of the reference signal or wave [12].

Harmonics are considered so that the performance of hysteresis current controlled inverter under harmonics state can be realized and it is predicted that up to 7^{th} order odd harmonics exist at the output indicating the value of n = 1, 3, 5 and 7.

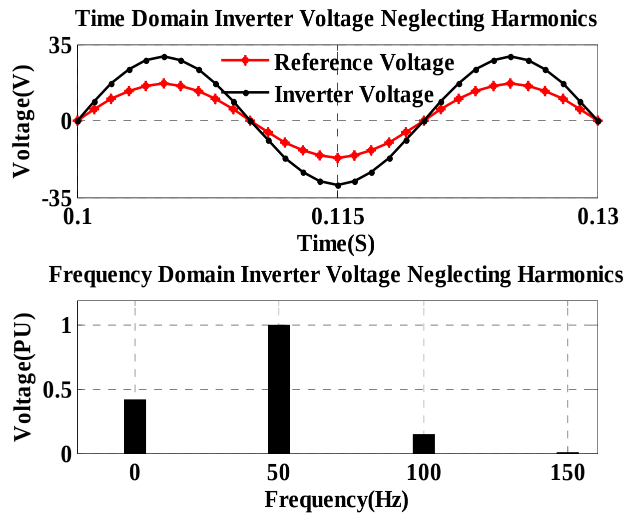

Figure 6. Ideal Response of Inverter Output Voltage (R-load)

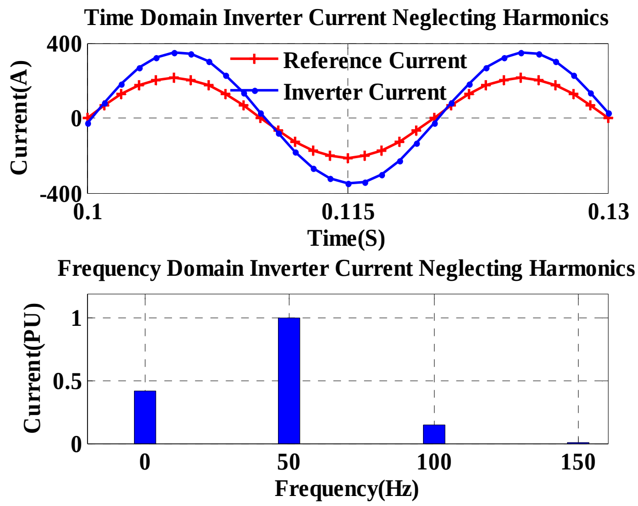

Figure 7. Ideal Response of Inverter Output Current (R-load)

Figure 10, Figure 11, Figure 12 and Figure 13, reveal the responses of hysteres current controlled inverter with RL-load when harmonics are present at the output terminal; in which output voltage and current are demonstrated in the first two figures. On the other hand, later two, reprent the modulated output. According to the expectation, none of these figures show sinusoidal time domain responses due to the existence of unwanted frequencies called harmonics.

Using Equation 1, under these circumstances THD is evaluated and is found 41.415% which is not satisfactory at all. There is no denial that for better performance it is important to evade harmonics.

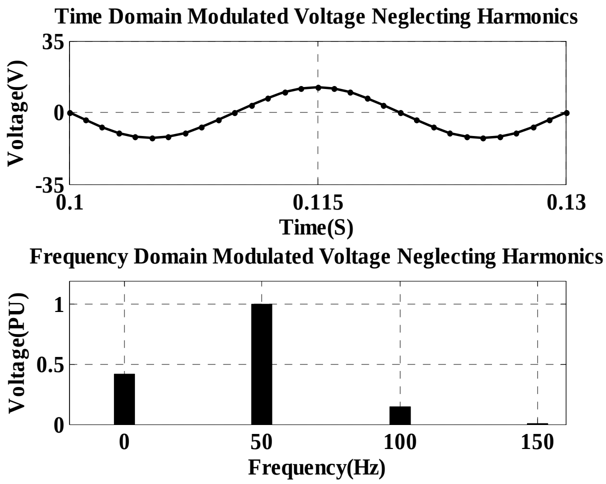

Figure 8. Modulated Voltage without Harmonics (R-load)

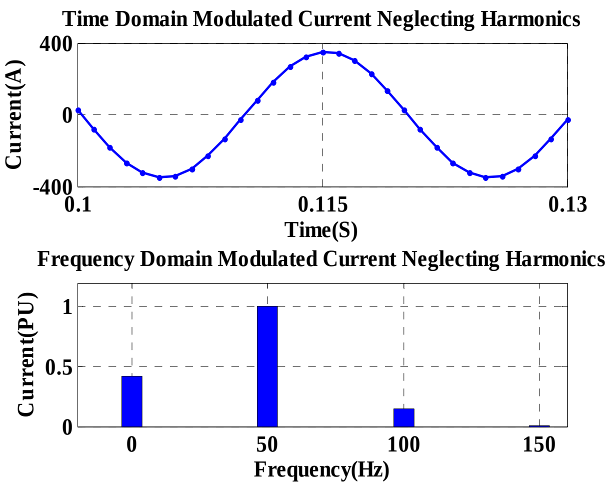

Figure 9. Modulated Current without Adding Harmonics (R-load)

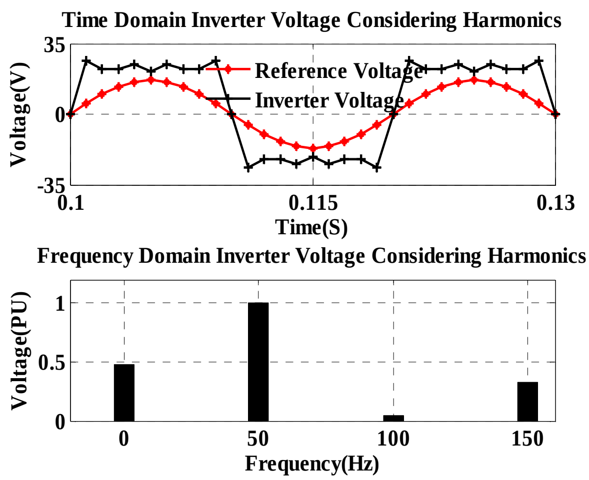

Figure 10. Inverter Ouput Voltage with Harmonics (RL-load)

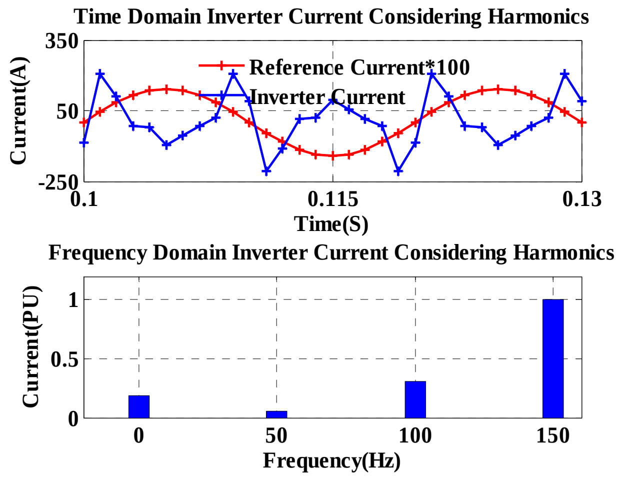

Figure 11. Inverter Ouput Current with Harmonics (RL-load)

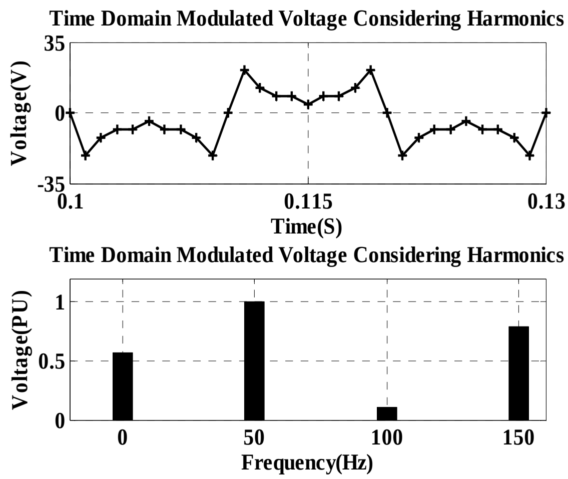

Figure 12. Modulated Ouput Voltage with Harmonics (RL-load)

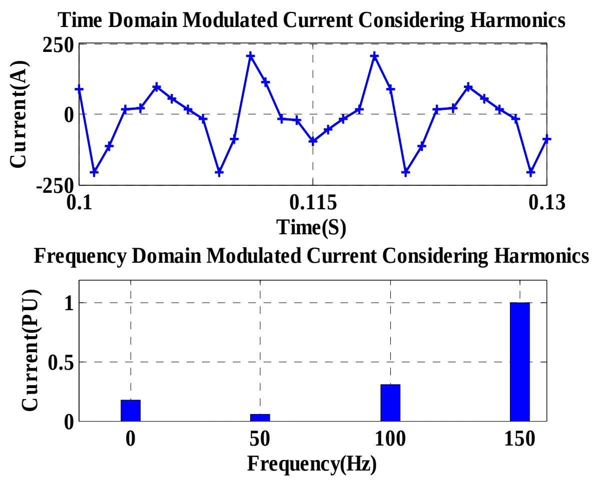

Figure 13. Modulated Output Current with Harmonics (RL-load)

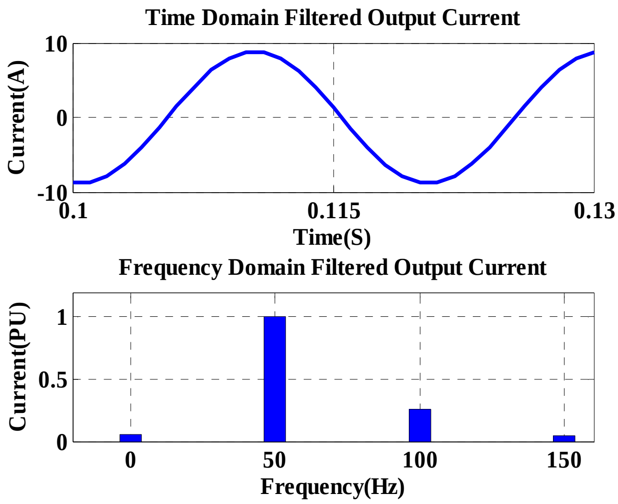

Figure 14. Output Current after Filtering (RLC-load)

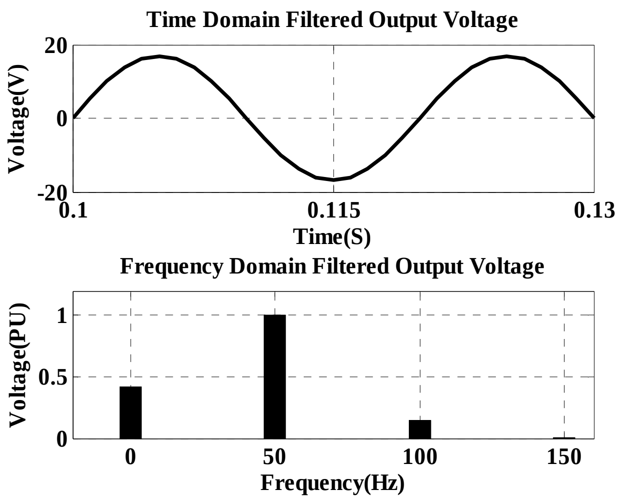

Figure 15. Output Voltage after Filtering (RLC-load)

Finally, in order to visualize the noteworthy performance of the filter having leading current capability, the output response derived from Figure 5, are simulated. As far as Figure 14, and Figure 15, are concerned, as is expected, only desired sinusoidal output responses are obtained , it is noticed that the fundamental components have the highest amplitude.

Lastly, Equation 1 is once again utilized and calculated THD is 0.0092% that can be regarded as a negligible amount. Thence, harmonics have been suppressed to a great extent.

4. Conclusion

When ideal response has been estimated, THD is 0% which is not plausible in real life utilities. At normal condition, harmonics have to be taken into consideration. If up to 7th order harmonics are considered then there exists 41.415% THD that is undisputedly beyond the satisfaction. But as soon as an LC low pass filter is appended, it has been dropped to 0.0092% notifying a vast improvement. This is because of the capacitance having a great effect on the harmonics performance.

It has been found from experimental results [16] that the Total Harmonic Distortion (THD) of three level, five level, seven level and nine level inverter systems are 10.95%, 4.82%, 4.65% and 3.09% respectively referring THD is declining with the enhancement of the level of inverter.

In contrast, only 0.0092% THD is derived in case of single phase inverter mentioned in this paper. Therefore, a remarkable improvement has been achieved with the prescribed modeling when it comes to compare with respect to THD.

In coming days, using this concept, the output responses of single phase full bridge current controlled inverter undergoing hysteresis modulation can be observed as well as the harmonics occurred at the output can be minimized. The implementation of second order LC low pass filter would be an interesting choice in this case.

References

[1] Muhammad H Rashid. Power Electronics Circuits. *Devices, and Applications*, Third Edition. Dorling Kindersley Pvt. Ltd. 2006: 226-299.
[2] MI Azim, MF Zaman, M Rahman. *Beneficial Effect of Filtering in Current Controlled Inverter*. 16th Int'l Conf. Computer and Information Technology, Khulna, Bangladesh. 2014: 30-33.
[3] W Zhao-an, Huang Jun. Power Electronic Technology. Beijing China Machine Press. 2000: 47-50.
[4] C Langton. *Fourier Transform made Easy Part 1*, Edition. 2011: 1.
[5] AJ Onah. Harmonics: Generation and Suppression in AC System Networks. *Nigerian Journal of Technology*. 2012; 31(3): 293-299.
[6] M Mahalakshmi, V Kumaresan. Hysteresis Modulation of Cascaded Inverter. *International Journal of Emerging trends in Engineering and Development*. 2012; 2(3).
[7] A Albanna. Modeling and Simulation of Hysteresis Current Controlled Inverters Using MATLAB. In Tech. 2011: 98-120.
[8] MP Kazmierkowski and L Malesani. Current control techniques for three-phase voltage-source PWM converters: A survey. *IEEE Trans. Ind. Electron*. 1998; 45(5): 691–703.
[9] A Albanna and Hatziadoniu. Harmonic Modeling of Hysteresis Inverters in Frequency Domain. *IEEE Trans. on Power Electronics*. 2010.
[10] D Fewson. Introduction to Power Electronic. Oxford University Press, Inc., Newyork. 1998: 81.
[11] Y Wang, Q Guo. Hysteresis Current Control technique based on Space Vector Modulation for Active Power Filter. *International Journal of Power Electronics and Drive System*. 2011; 1(1): 1-6.
[12] Z Salam. *Power Electronics and Drives*. Version 2. 2002: 1-54.
[13] L Malesani, P Mattavelliand, P Tomasin. High-Performance Hysteresis Modulation Technique for Active Filters. *IEEE Trans. On Power Electronics*. 1997; 12(5).
[14] I Azim, H Rahman. Harmonics Reduction of a Single Phase Half Bridge Inverter. *Global Journal of Research in Engineering*, Version 1. 2013; 13(4): 9-12.
[15] B Singh, K Al-Haddad, A Chandra. A Review of Active Filters for Power Quality Improvement. *IEEE Trans. on Industrial Electronics*. 1999; 46(5): 960-971.
[16] G Mahesh, M Kumar, SR Reddy. Simulation and Experimental Results of 7-Level Inverter System. *Research Journal of Applied Sciences, Engineering and Technology*. 2011; 3(2): 88-95.