International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 5, No. 2, October 2014, pp. 142~152
ISSN: 2088-8694

Estimation of Harmonics in Three-phase and Six-phase (Multi-phase) Load Circuits

Deepak Kumar, Zakir Husain
Departement of Electrical Engineering, National Institute of Technology, Hamirpur (HP), India

Article Info

Article history:

Received Nov 22, 2013
Revised Jul 10, 2014
Accepted Aug 2, 2014

Keyword:

Fast Fourier Transform
Harmonics
Inverters
Multi phase system
Ripple
Total Harmonic Distortion

ABSTRACT

The Harmonics are very harmful within an electrical system and can have serious consequences such as reducing the life of apparatus, stress on cable and equipment etc. This paper cites extensive analytical study of harmonic characteristics of multiphase (six- phase) and three-phase system equipped with two & three level inverters for non-linear loads. Multilevel inverter has elevated voltage capability with voltage limited devices; low harmonic distortion; abridged switching losses. Multiphase technology also pays a promising role in harmonic reduction. Matlab simulation is carried out to compare the advantage of multi-phase over three phase systems equipped with two or three level inverters for non-linear load harmonic reduction.The extensive simulation results are presented based on case studies.

Corresponding Author:

Deepak Kumar,
Departement of Electrical Engineering,
National Institute of Technology,
Hamirpur, Himachal Pradesh, India-177005.
Email: dkaroraelectrical@gmail.com, timothyarora@gmail.com

1. INTRODUCTION

Owing to the budding benefits resulting from the use of a phase order higher than three in multi-phase transmission and distribution, some interest has also developed in the area of multi-phase system analysis in recent past [1]-[10]. Also, multi-level inverters have emerged as a capable tool in achieving high power ratings with voltage limited devices. This paper presents a functional model of two and three level inverter with multi and three phase load and simulation of the developed model is done with the help of MATLAB/Simulink. Multi-level inverter fed electric machine drive systems have emerged as a promising tool in achieving high power ratings with voltage limited devices [20]. The conventional inverters used are voltage source inverter (VSI) and current source inverter (CSI) which consists of a dc link and Inverter Bridge. Harmonic reduction is achieved to greater extent than conventional inverter such as voltage source inverter, current source inverter in multilevel inverter and multiphase loads. High phase number drives own several advantages over conventional three-phase drives such as: reducing the amplitude and increasing the frequency of torque pulsation, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, lowering the dc link current harmonics, higher reliability and increased power. Harmonics are very detrimental within an electrical system and can have serious consequences. For example, the presence of harmonics reduces the life of apparatus. Harmonics cause things to run hot, which cause stress on the cables and equipment. In the long term, this degrades an electrical system. The presence of harmonics will also mean that although you will get billed for the power that you are supplied, a large percentage of that power may be not viable. Harmonic mitigation is taking action to minimize the presence of harmonics in your electrical system and can achieve great cost savings. Harmonic distortion can cause poor power factor, transformer and distribution equipment overheating, random breaker tripping, or even sensitive equipment failure. Since harmonics affect the overall power distribution system, the power utility may even levy heavy fines when a facility is affecting the utilities' ability to efficiently supply power to all of its customers. These harmonics can be suppressed using multilevel inverter equipped with multi-phase loads.

The multi-phase technology received a substantial worldwide attention by the various R&D's and front-end industries in three very specific application areas, namely electric ship propulsion, traction (including electric and hybrid electric vehicles) and the concept of 'more-electric' aircraft. Irrespective of abundant advantageous multi-phase electric drives are limited to economically viable design, power converter configurations and closed control aspects. Multi-phase power systems can be used to cancel harmonic currents. For higher power rectifier circuits, even 12-phase power systems have been used for further harmonic current reduction. Six phase transmission lines are popular due to its increased power transfer capability by $\sqrt{3}$ times, maintaining the same conductor configuration, better efficiency, better voltage regulation, greater stability and greater reliability.

2. MULTI-LEVEL INVERTER

The power electronics device which converts DC power to AC power at required output voltage and frequency level is known as inverter. Inverters can be broadly classified into two level inverter and multilevel inverter. Multilevel inverter as compared to two level inverters has advantages like minimum harmonic distortion and can operate on several voltage levels. A multi-stage inverter is being utilized for multipurpose applications, such as active power filters, static var compensators and machine drives for sinusoidal and trapezoidal current applications. The drawbacks are the isolated power supplies required for each one of the stages of the multiconverter and it's also lot harder to build, more expensive, harder to control in software.

Multilevel inverters are named after the level of voltages that can be obtained from them. For example a 2-level inverter can take values +V and –V and 3-level inverter can produce voltage levels of +V, 0 and –V where V is the voltage of dc supply.

For 2 level inverter, there are two levels for phase voltage and three levels for line voltage as shown in following figure of matlab.

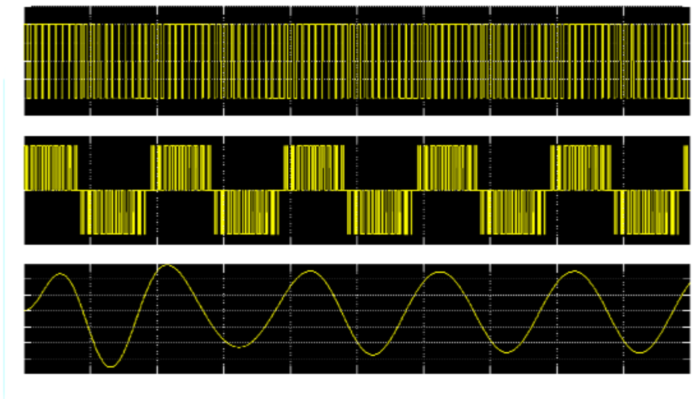

Figure 1. Van: inverter phase output voltage; Vab: Inverter line output voltage; Vab_load: inverter load line voltage after linear transformer shown in the above figures respectively (y axis: Voltage; x axis: Time)

The system consists of two independent circuits illustrating two three-phase two-level PWM voltage source inverters. Each inverter feeds an AC load through a three-phase transformer. Both converters are controlled in open loop with the Discrete PWM Generator block. The two circuits use the same DC voltage, carrier frequency, modulation index and generated frequency (f = 50 Hz). Harmonic filtering is performed by the transformer leakage inductance and load capacitance.

For 3 level inverter, there are three levels of phase voltage and 5 levels for line voltage as shown in following figure of matlab:

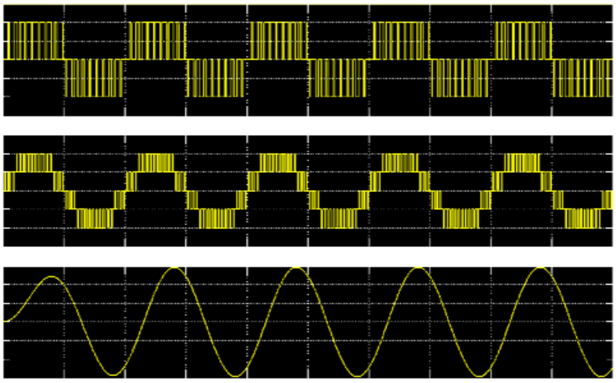

Figure 2. Van: inverter phase output voltage; Vab: Inverter line output voltage; Vab_load: inverter load line voltage after linear transformer shown in the above figures respectively. (y axis: Voltage; x axis: Time)

The system consists of two three-phase three-level PWM voltage source converters connected in twin configuration. The inverter feeds an AC load through a three-phase transformer. Harmonic filtering is performed by the transformer leakage inductance and load capacitance. Each of the two inverters uses the Three-Level Bridge block where the specified power electronic devices are IGBT/Diode pairs. Each arm consists of 4 IGBTs, 4 anti-parallel diodes, and 2 neutral clamping diodes. The inverter is controlled in open loop. Pulses are generated by the discrete 3-Phase Discrete PWM Generator block. This PWM generator or modulator can be used to generate pulses for 3-phase, 2-level, or 3-level converters using one bridge or two bridges The PWM modulator generates two sets of 12 pulses (1 set per inverter). The generator can operate either in synchronized or un-synchronized mode. When operating in synchronized mode, the carrier triangular signal is synchronized on a PLL reference angle connected to input 'wt'. In synchronized mode, the carrier chopping frequency is specified by the switching ratio as a multiple of the output frequency.

3. HARMONICS & FOURIER ANALYSIS

In three-phase power systems, even harmonics cancel out, so only the odd harmonics are of concern. On three-phase systems each phase voltage is 120 degrees out of phase, causing the phase current to be 120 degrees out of phase as well. With a sinusoidal voltage, current harmonics do not lead to average power. However, current harmonics do increase the rms current, and hence they decrease the power factor. The average power is:

$$\mathrm{Pav} = \frac{\mathrm{V1} * \mathrm{I1}}{2} \cos(\Phi 1 - \Phi 2) \quad (1)$$

Where V1 and I1 are the peak values and, and Φ1 and Φ2are the phase angles of fundamental voltage and current respectively. The rms current considering the harmonics is given by (2) as:

$$\text{Rms Current} = \frac{\sqrt{(\mathrm{I0}^2 + \sum_{n=1}^{n=\infty} \mathrm{In}^2)}}{2} \quad (2)$$

Where I_n is the peak current at any harmonic number. With non-linear loads, the third harmonic on all three phases is exactly in phase and adds, rather than cancels, thus creating current and heat on the neutral conductor. Left un-treated, harmonic loads can reduce the distribution capacity and degrade the quality of the power of public utility power systems, increase power and AC costs, and result in equipment malfunctions such as communication errors and data loss.

A nonlinear load in a power system is characterized by the introduction of a switching action and consequently current interruptions. This behavior provides current with different components that are multiples of the fundamental frequency of the system. These components are called harmonics.

THD (Total harmonic distortion) is used as harmonic index for harmonic measurement which is given by:

$$THD = \frac{\sqrt{\sum_{n=2}^{n=\infty} In^2}}{I1} \quad (3)$$

THD is used as the harmonic index and harmonic spectrum is presented for each load using FFT (Fast Fourier Transform) [17], [18]. Fourier analysis of a periodic function refers to the extraction of the series of sines and cosines which when superimposed will reproduce the function. This analysis can be expressed as a Fourier series. The fast Fourier transform is a mathematical method for transforming a function of time into a function of frequency. Sometimes it is described as transforming from the time domain to the frequency domain. It is very useful for analysis of time-dependent phenomena.

One essential application of FFT is for the examination of sound. It is imperative to assess the frequency distribution of the power in a sound because the human ear exercises that capacity in the hearing process. For a sine wave with a single frequency, the FFT consists of a single peak. Combining two sound waves produces a complex pattern in the time domain, but the FFT clearly shows it as consisting almost entirely of two frequencies. For a full-wave rectified sine wave, meaning that the wave becomes positive wherever it would be negative. This creates a new wave with double the frequency. You can see that after rectification, the fundamental frequency is eliminated, and all the even harmonics are present.

Single-phase non-linear loads, like electronic ballasts, PC (Personal Computer) and other electronic apparatus, create odd harmonics (i.e. 3rd, 5th, 7th, 9th, etc.). Triplen harmonics (3rd order and its odd multiples) are bothersome for single phase loads because the A-phase triplen harmonics, B-phase triplen harmonics and C-phase triplen harmonics are all in the phase with each other. They will add rather than cancel on the neutral conductor of a 3-phase, 4-wire system. This can burden the neutral if it is not sized to handle this type of load. In addition, triplen harmonics cause circulating currents on the delta winding of a delta-wye transformer design. The result is transformer heating similar to that created by unbalanced 3-phase current. On the other hand, 3-phase non-linear loads like 3-phase ASDs, 3-phase DC drives, 3-phase rectifiers, etc., do not produce current triplen harmonics so much. These types of loads cause mainly 5th and 7th current harmonics and a minor amount of 11th, 13th, and higher order based on the design of the converter used.

4. THREE PHASE TO SIX PHASE TRANSFORMATION USING TRANSFORMER

Three phase voltages obtained from the inverter is fed to three single phase transformer for converting to six phase system. The circuit diagram for obtaining 6ϕ supply from 3ϕ supply using linear transformer is shown in Figure 3.

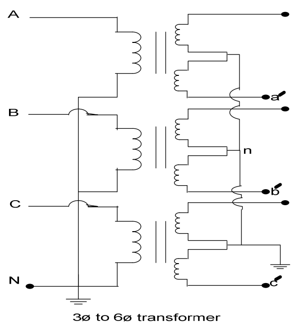

Figure 3. Linear transformer for three phase to six phase transformation

The transformer is called linear if the coils are wound on magnetically linear material (air, plastic, Bakelite, wood, etc.). Flux is proportional to current in the windings.

5. MATLAB MODELS

Four different cases are considered for the harmonic study as shown from Figure 4 to Figure 7 comprising of 2 and 3 level inverter with three phase or six phase rectifier circuit.

CASE I: Two level inverter- Measurement system- Three Phase Transformer- Three Phase Rectifier.

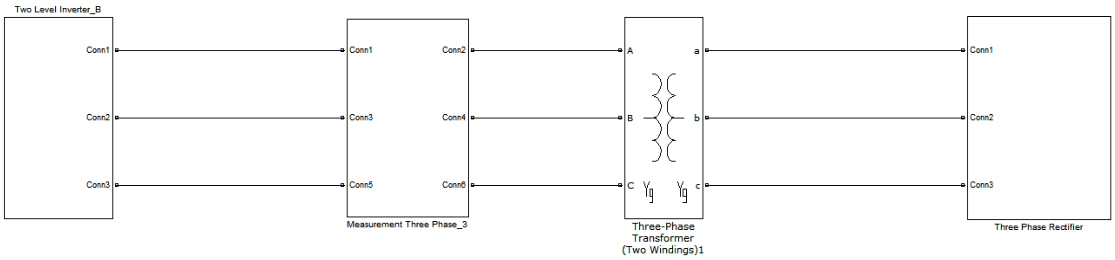

Figure 4. Two level inverter with three phase rectifier

CASE II: Two Level Inverter- Measurement System- Three Phase to six phase transformer- Six Phase Rectifier.

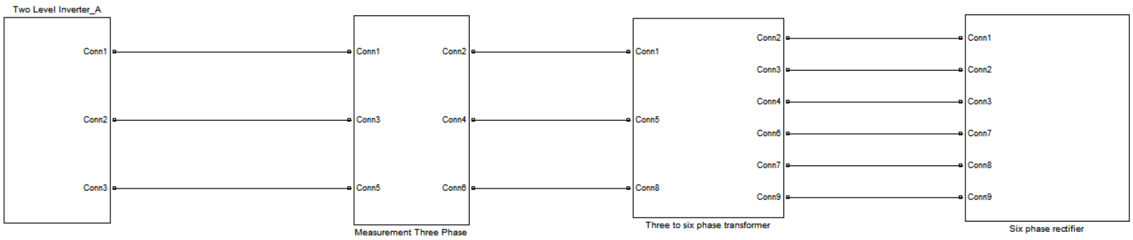

Figure 5. Two level inverter with six phase rectifier

CASE III: Three level inverter- Measurement system- Three Phase Transformer- Three Phase Rectifier.

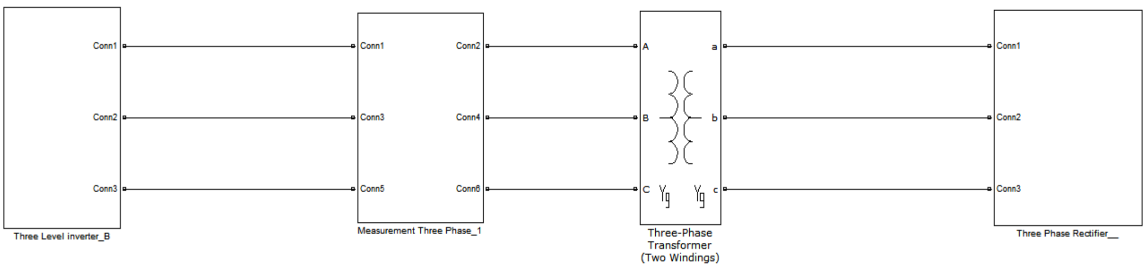

Figure 6. Three level inverter with three phase rectifier

CASE IV: Three level inverter- Measurement system- Three to six Phase Transformer- Six Phase Rectifier.

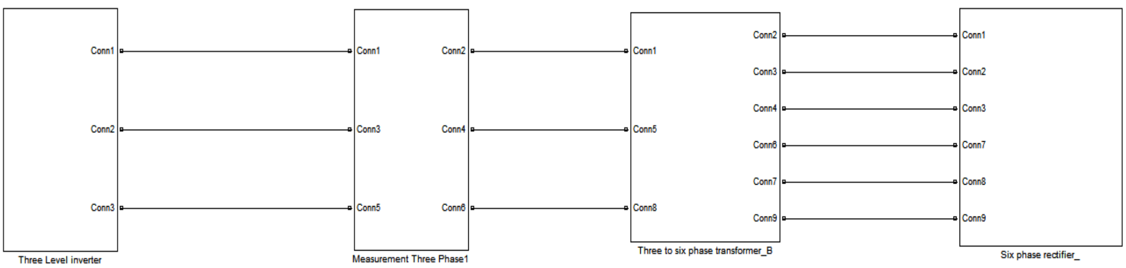

Figure 7. Three level inverter with six phase rectifier

Matlab simulink models of two and three level inverters are shown in Figure 8 and Figure 9 respectively. Three level inverter has advantage over two level inverter that when magnitude of supply is very high, use of filter is superfluous, constraint on the switches are low for the reason that the switching frequency may be low, and reactive power flow can be controlled. Two full-bridges VSI is employed wich contains twelve IGBT which switch on dc source [12]. Twelve pulses are generated for a double bridge three phase inverter. The first six pulses (1 to 6) fire the six devices of the first three arm bridge while the last six pulses (7 to 12) fire the six devices of the second three arm bridges.

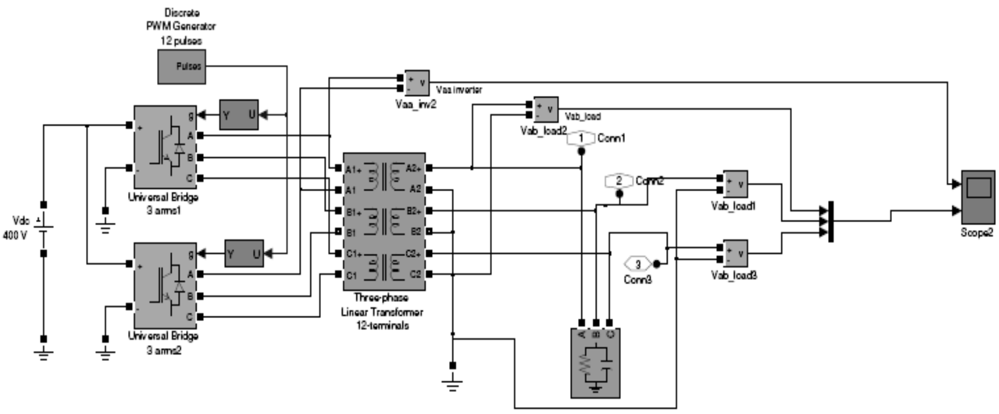

Figure 8. Matlab model of two level inverter

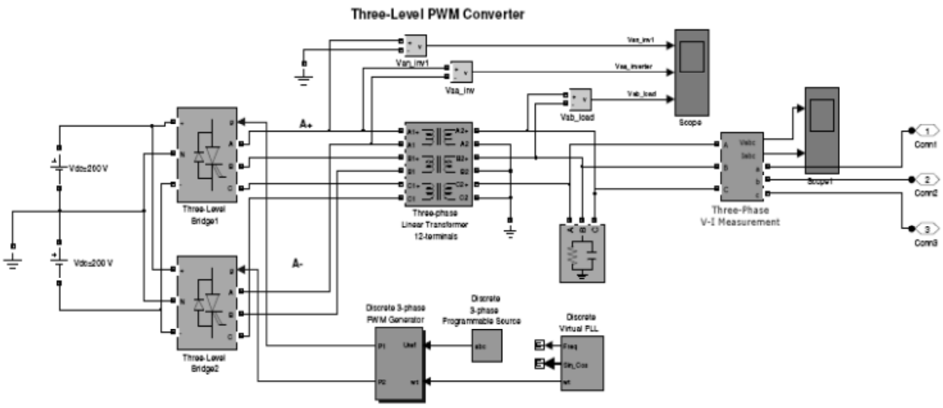

Figure 9. Matlab Model of three level inverter

A non-linear load on a power system is usually a rectifier and some kind of arc discharge device such as a fluorescent lamp, electric welding machine, or arc furnace in which current is not linearly related to the voltage. Current in these systems is interrupted by a switching action; the current contains frequency components that are multiples of the power system frequency and leads to distortion of the current waveform which in turn distorts the voltage waveform. For analysis of three phase non-linear load, RL load is replaced with three phase rectifier circuit. Following is the circuit of three phase rectifier. For six phase non-linear load, six RL load is replaced with two such circuits.

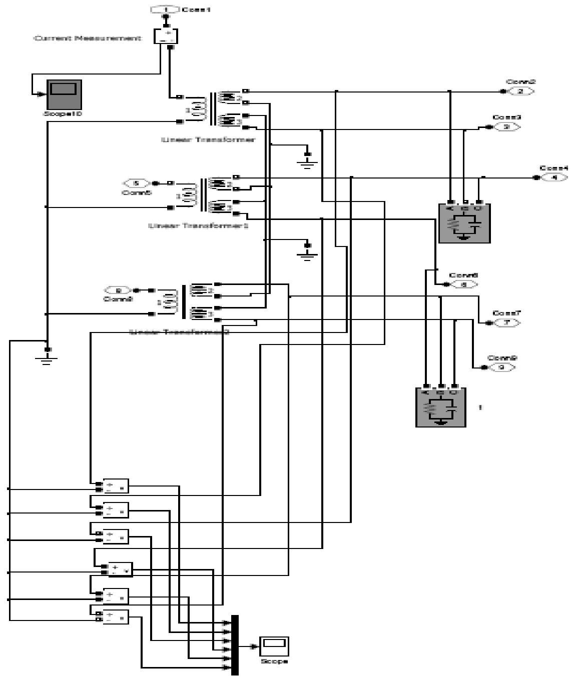

Figure 10. Matlab model of Three to six-phase transformer

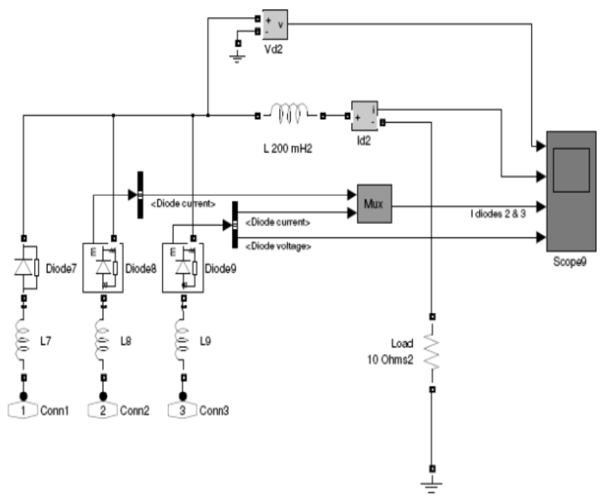

Figure 11. Three-phase rectifier circuit

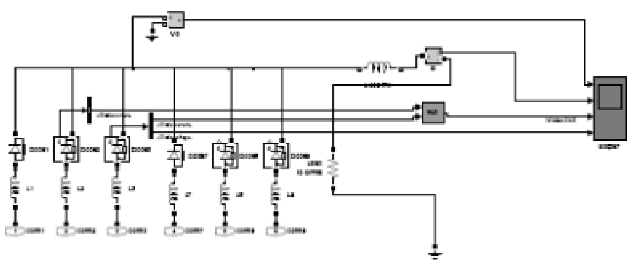

Figure 12. Matlab model of Six-Phase Rectifier

6. SIMULATION RESULTS

A nonlinear load in a power system is characterized by the beginning of a switching action and consequently current interruptions. This behavior provides current with different components that are multiples of the fundamental frequency of the system. These components are called harmonics which if not suppressed will cause severe problems in power distribution system. So, to analyze the effects of non-linear load, FFT analysis is done for the four different cases as mentioned above.

Once the simulation is completed, open the Powergui and select 'FFT Analysis' to display the frequency spectrum of signals saved in the structures. The FFT will be performed on a 2-cycle window starting at t = 0.1 - 2/50 (last 2 cycles of recording). Measurement of phase voltage FFT of load w.r.t ground for a nonlinear Load is shown from Figure 13 to Figure 16:

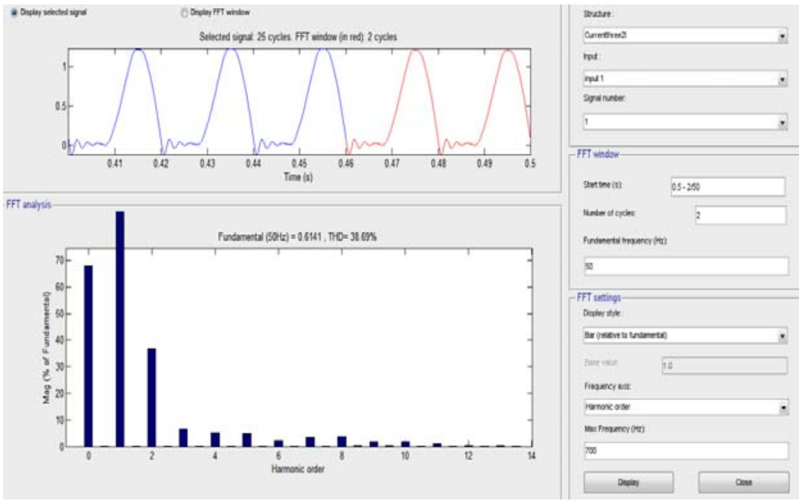

Figure 13. FFT analysis at two level inverter output with three phase rectifier load (Case I)

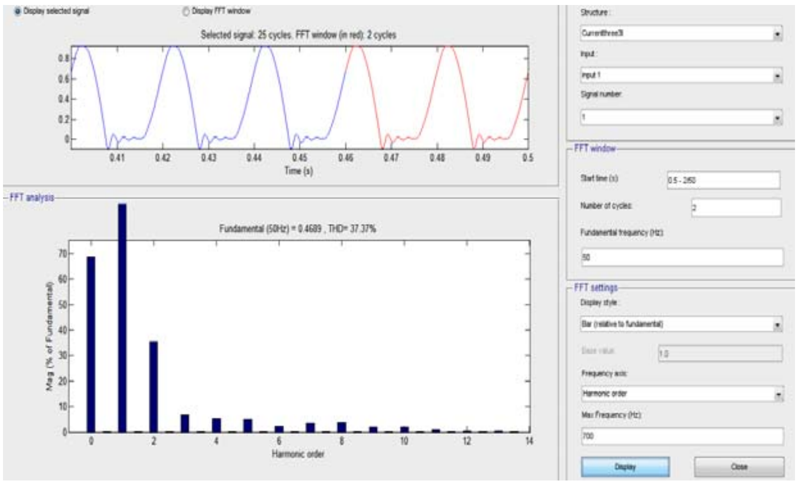

Figure 14. FFT analysis at three level inverter output with three phase rectifier load (Case III)

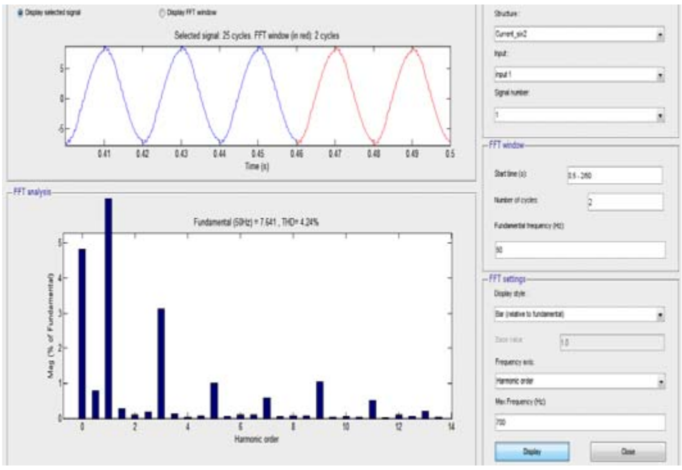

Figure 15. FFT analysis at two level inverter output with six phase rectifier load (Case II)

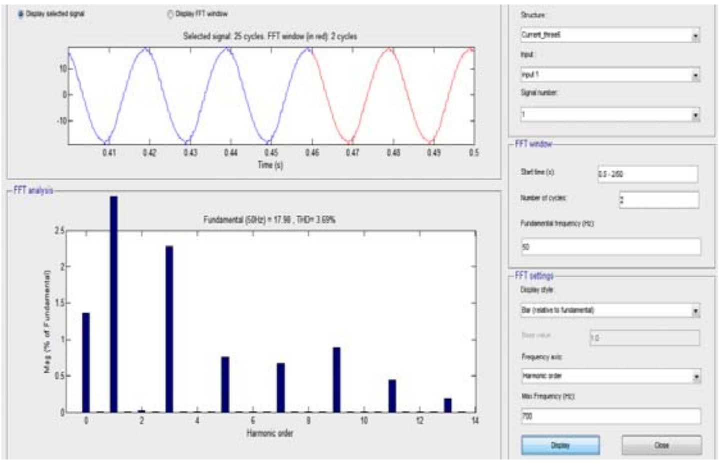

Figure 16. FFT analysis at three level inverter output with six phase rectifier load (Case-IV)

Total harmonic distortion (THD) for two level and three level inverter with three phase and six phase rectifier loads are shown in Table 1.

Type of inverter	**Current THD for 3-phase rectifier load**	**Current THD for Multi-phase (6-phase) Rectifier load**
Two Level Inverter	38.69%	4.24%
Three level inverter	37.37%	3.69%

For nonlinear current T.H.D (Total Harmonic Distortion) in the load current is found to be more in three phase. Power factor compensation requirement is more in three phase load as compared to three phase is also found by simulation. Rectified output voltage under these four different cases is also shown which shows that there are fewer ripples in six phase rectifier circuit.

From Figure 17 to 20, it is noted that ripple in case of six phase rectifier is less which is an undesirable factor in many electronic application as large ripples shorten the life of electrolytic capacitor, reduce the resolution of electronic test and measurement instruments etc.

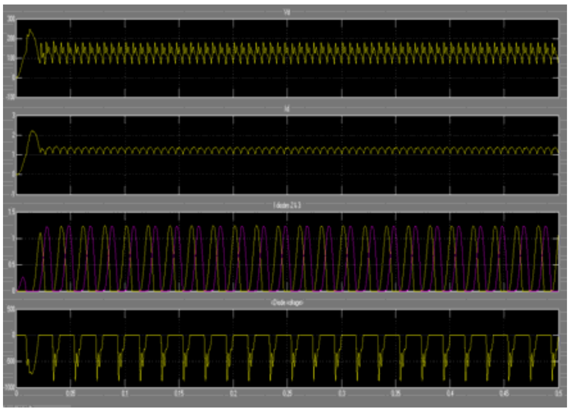

Figure 17. Three-phase load rectifier load output (2 level inverter): Y axis: Rectified output dc voltage, rectified output dc current, Current through diode, voltage across diode ; X axis: time. (Case I)

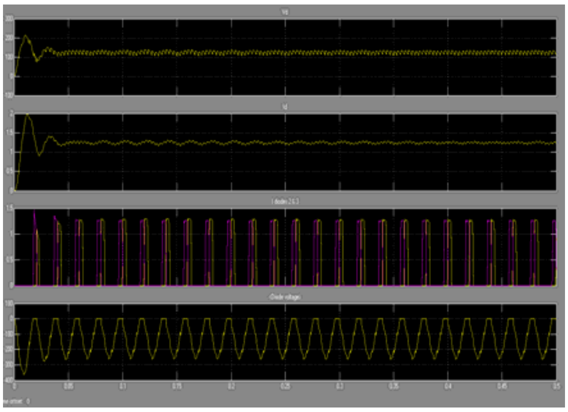

Figure 18 Six-phase load rectifier load output (2 level inverter): Y axis: Rectified output dc voltage, rectified output dc current, Current through diode, voltage across diode; X axis: time (Case II)

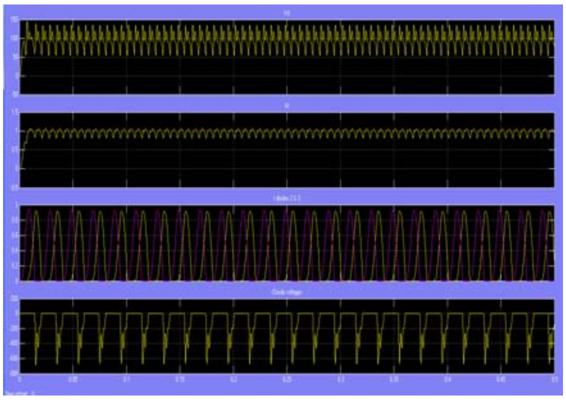

Figure 19 Three-phase load rectifier load output (3 level inverter): Y axis: Rectified output dc voltage, rectified output dc current, Current through diode, voltage across diode; Xaxis: time. (Case III)

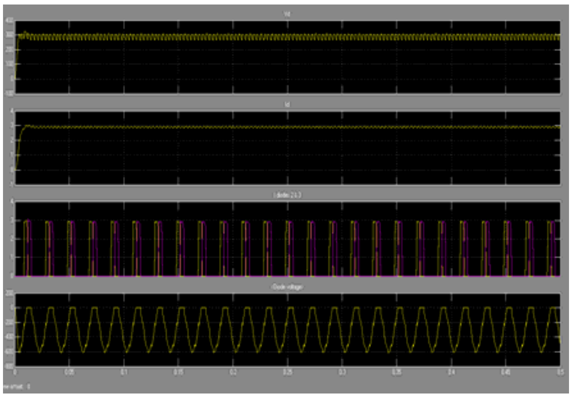

Figure 20 Six-phase load rectifier load output (3 level inverter): Y axis: Rectified output dc voltage, rectified output dc current, Current through diode, voltage across diode; X axis: time. (Case IV)

7. CONCLUSION

This paper presents a quantitative study on reduction of harmonic analysis for six phases as compared to three phases by simulink (MATLAB) for two levels and three levels inverter for non linear loads. Decline in harmonics in load is observed for six phase as compared to three phase load. In addition to harmonic study authors found that ripples of rectified output in case of six phase load circuits is less as compared to its three phase counterpart. As the ratings of various power electronic switches are limited, multilevel voltage source topologies are useful for high voltage and high power applications along with low down harmonics. With the augment of levels of inverter, drop in current THD is observed which further reduces with the increase of three phases to six phases. This implies that there is less requirement of harmonic compensation in case of multiphase load circuit. So, multilevel inverter with multiphase technology pays a promising tool for cost-effective system with effectively reduced harmonics.

REFERENCES

[1] Shantanu Chatterjee. A Multilevel Inverter Based on SVPWM Technique for Photovoltaic Application, *International Journal of Power Electronics and Drive System (IJPEDS)*. 2013; 3(1): 62~73.
[2] Risnidar C, I. Daut, Syafruddin H, N. Hasim, Influence of Harmonics in Laboratory due to Nonlinear Loads, *International Journal of Power Electronics and Drive System (IJPEDS)*. 2012; 2(2): 219~224.
[3] L Srinivas Goud, T Srivani. A Simulation of Three Phase to Multi Phase Transformation using a Special Transformer. *International Journal of Science and Research (IJSR)*, India Online ISSN: 2319-7064. 2013; 2(7).

[4] Srinivasa Rao Maturu, Avinash Vujji. SVPWM Based Speed Control of Induction Motor Drive with Using V/F Control Based 3-Level Inverter in VSRD *International Journal of Electrical, Electronics and Communication Engineering*. VSRD-IJEECE. 2012; 2(7): 421-437.
[5] B Somashekar, B Chandrasekhar, David Livingston D. Modeling and Simulation of Three to Nine Phase Using Special Transformer Connection. *International Journal of Emerging Technology and Advanced Engineering*. 2013; 3(6).
[6] Mika Ikonen, Ossi Laakkonen, Marko Kettunen. Two-level and three-level converter comparison in wind power application. *International Journal of Scientific & Engineering Research*. 2013; 4(1).
[7] Hag Ahmed Y, Zhengming Zhao, Ting Lu. Comparison and analysis of three-level converters versus two-level converters for ship propulsion applications. *IJRRAS.* 2012; 11(2): 168-175.
[8] K Ramash Kumar, D Kalyankumar, Dr V Kirubakaran. An Hybrid Multi Level Inverter Based DSTATCOM Control, *Majlesi Journal of Electrical Engineering*. 2011; 5(2).
[9] Zakir Husain, Ravindra Kumar Singh, Shri Niwas Tiwari. Multi-phase (6-Phase & 12-Phase) Transmission Lines: Performance Characteristics. *International journal of mathematics and computers in simulation.* 2007; 2(1).
[10] GK Singh. Multi-phase induction machine drive research—a survey, Electric Power Systems Research. 2002; 61: 139–147.
[11] Bimal K Bose. Modern Power Electronics and AC Drives, *Prentice Hall of India*, New Delhi. 218-241.
[12] Ovdiu NEAMTU. Three-Phase Inverter with Two Bridges optimized on Simulation. *ACTA Electrotechnica*. 2005; 46(4).
[13] Brendan Peter McGrath, Donald Grahame Holmes. Multicarrier PWM Strategies for Multilevel Inverters. *IEEE transactions on industrial electronics*. 2002; 49(4).
[14] Wenyuan Xu, Jose R Marti, Hermann W Dommel. A multiphase harmonic load flow solution technique. *IEEE transactions on Power Systems*. 1991; 6(1)
[15] Lucian Asiminoaei, Steefan Hansen, Frede Blaabjerg. Predicting Harmonics by Simulations. A Case study for High power Adjustable speed drives. *Electric Power Quality and Utilization*. 2006; 2(1).
[16] Mukhtiar ahmed Mahar, Muhammad Aslamuqaili, And Abdul Sattar Larik. Harmonic Analysis of AC-DC Topologies and their Impacts on Power Systems. *Mehran University Research Journal of Engineering & Technology*. 2011; 30(1) [ISSN 0254-7821]
[17] C Venkatesh, D Srikanth Kumar, DVSS Siva Sarma, M Sydulu, Modelling of Nonlinear Loads and Estimation of Harmonics in Industrial Distribution System. *Fifteenth National Power Systems Conference* (NPSC), IIT Bombay. 2008: 592-597.
[18] Harmonic Current Reduction Techniques for computer systems, *Liebert web notice and conditions* Copyright. Liebert Corporation. 1995-2000.

BIOGRAPHIES OF AUTHORS

Deepak Kumar received the B.E from C.R State College of Engineering, Murthal (Sonepat) and M.Tech from National Institute of Technology, Kurukshetra. He is currently working as Lecturer in NIT Hamirpur. His main areas of interest are Power Electronics and drives, Renewable Energy Resources.

Zakir Husain took his Bechelor and Master degrees in Electrical Engineering from Aligarh Muslim University, Aligar, India. Subsequently he did his Ph.D from Motilal Nehru National Institute of Technology, Allahabad, India. He has been employed as Lecturer in Department of Electrical Engineering, National Institute of Technology, Hamirpur (H.P.), India since 1989 and is working as Associate Professor in the same institute. During 2011 and 20012 he was on Academic pursuit and worked as Head, Department of Electrical Engineering, College of Engineering, Salman Bin Abdulaziz University, Kingdom of Saudi Arabia. His principal research interest is Power system and Drives.