MODELING AND SIMULATION OF MULTI PULSE CONVERTER SYSTEM FOR HARMONIC REDUCTION WITH NON-LINEAR LOAD

DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT

FOR THE AWARD OF DEGREE OF

MASTER OF TECHNOLOGY
IN
POWER SYSTEM

Submitted by:-

TIKAM BHARDWAJ

(2K13/PSY/22)

Under the supervision of

Dr. Priya Mahajan

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

2015

CERTIFICATE

I, **TIKAM BHARDWAJ**, Roll No. 2K13/PSY/22 student of **M. Tech. (Power System)**, hereby declare that the dissertation/project titled **"MODELING AND SIMULATION OF MULTI PULSE CONVERTER SYSTEM FOR HARMONIC REDUCTION WITH NON-LINEAR LOAD"** under the supervision of Dr. Priya Mahajan, Assistant Professor, Department of Electrical Engineering Department, Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

Place: Delhi **TIKAM BHARDWAJ**

Date: 02.12.2015

Dr. PRIYA MAHAJAN
Assistant Professor
Electrical Engineering Department
Delhi Technological University
Bawana Road, Delhi-110042

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Dr. Priya Mahajan for her guidance and assistance in the thesis. The technical discussions with her were always been very insightful, and I will always be indebted to her for all the knowledge she shared with me. Her prompt responses and availability despite her constantly busy schedule were truly appreciated. She always helped me in all the technical and non-technical issues during the production of this thesis. Without her consistent support, encouragement and valuable inputs, this project would not have become possible.

I would like to express my deep gratitude to Prof. Madhusudan Singh, Head, Department of Electrical Engineering for providing his support during my project.

I would like to thank Prof. Vishal Verma for his invaluable and lively discussions during the tenure of this research work.

I would also like to thank Mr. Ramesh Singh, Mr. Amritesh, my batch-mates and friends who encouraged and helped me in completing the thesis work.

Finally, I express my deep sincere thanks to my Parents my brother and sister who motivated and encouraged me for higher studies, without which it wouldn’t have been possible.

TIKAM BHARDWAJ
(2K13/PSY/22)
M.Tech (Power System)
Delhi Technological University, Delhi

ABSTRACT

Often power electronic converters generate harmonics in power system which affects the system adversely different manner such as increased rms current which results in heating, resonance in current with connected transformer, interference with communication lines, equipments operating on zero crossing detection etc. Such unwanted harmonics should be avoided while conversion of power from AC-DC, to sustain ideal conditions in power systems. The present work deals with harmonic reduction using multipulse converter.

The multi-pulse converter, uses a modular architecture, where each power module comprises of a three-phase bridge and specially designed transformer for shifting of phase . The primary windings of the transformers are wound in star and fed by a power source, while the secondary windings of the transformers are connected to individual power converters with relevant phase shifts to realize the desired ouput. By selecting appropriate phase shifts between the primary and secondary sides of the transformers and synchronously switching the three-phase bridges at specified phase relations, low order harmonics can be eliminated in pairs. Thus a very high power quality current waveform can be synthesized even with low switching frequencies of the converters or with thyristor converters.

CONTENTS

LIST OF FIGURES PAGE NO.

LIST OF TABLES **PAGE NO.**

CHAPTER 1

INTRODUCTION

1.1 GENERAL:

Three phase ac-dc converters have been developed not only with better power factor correction ability but also with reduced harmonic distortion at input ac mains, and regulated dc output with various converters like buck, boost, buck-boost, multilevel and multipulse. This research work is mainly based on the design and study of multipulse ac-dc converters for improvement of power quality. The main purpose of presenting this chapter is to show motivation behind the research done in this thesis work. The chapter also contain the main objectives of the research work as well as the thesis organization.

1.2 MOTIVATION:

In HVDC system conversion of electric power is employed widely. In nonconventional energy sources like solar photovoltaic system, battery energy storage system, adjustable speed drives, power supplies for tele communication systems and in many more system three phase ac-dc conversion of electric power is employed. Thyristors and diodes are used as electric power conversion devices, commonly known as rectifiers, which provides controlled and uncontrolled unidirectional and bidirectional dc power. These conventional rectifiers have so many problems like poor power quality in terms of injected current harmonics, resultant voltage distortion along with poor power factor at input ac mains and slowly varying rippled dc output at load end, due to this they have low efficiency and there is also a requirement of large size of ac and dc filters. In view of their increased applications, a new breed of rectifiers has been developed using new solid-state self-commutating devices such as MOSFETs, insulated gate bipolar transistors (IGBTs), gate turn off thyristors (GTOs), etc. Such converters are generally classified as switch-mode rectifiers, power factor correctors, pulse width-modulation rectifiers, multilevel rectifiers, and multipulse rectifier. Several standards have been developed to fulfil the strict requirement of power quality at input ac mains side. Passive filters, active filters and hybrid filters along with conventional rectifiers have been extensively developed as another option to overcome the severity of power quality problem, especially in large rating and already existing installations. But these filters are quite bulky further, use of these filters results in reduced overall efficiency of complete system because of losses in these type of filters. So it is preferred to use converters based on modern solid state device as they provide reduced size, high efficiency, and well controlled regulated dc to provide efficient operation of the system. AC-DC-AC power conversion topology with 3 phase bridge rectifier for power conversion is utilized by standard AC drive. The total harmonic distortion (THD) are found to be 32% in a 6 pulse type current generated by three phase VSC. The improvement technique of converter systems by use of multipulse transformer are well reported nowadays.

The three phase multipulse AC- DC conversion system uses a phase-shifting transformer, and a bridge converter between the supply end and load end of the system. Each converter of this type provides 6 pulse AC- DC conversion. In this order for producing more sets of 6-pulse systems, an appropriate phase-shift is required. Hence, with proper phase-shifting, 12, 18, 24, 30, and higher pulse systems can be generated. By increasing the no of pulse total harmonic distortion can be optimized to very less content, also it leads to less dc voltage ripple and form factor.

1.3 ORGANISATION OF THESIS :

CHAPTER 2 – In this chapter literature review on multipulse converter system, HVDC transmission system, VSC based converter system, and the inverter system is represented.

CHAPTER 3- This chapter deals with design and simulation of multipulse converter system with uncontrolled converter.

CHAPTER 4 – This chapter deals with design and simulation of multipulse converter system with controlled converter.

CHAPTER 5 – This chapter consists of design and simulation of multipulse back to back converter system with nonlinear load.

CHAPTER 6 - This chapter contains the main conclusion of this research work and scope of further works in this area.

1.4 SCHEME OF WORK

In this work multipulse converter for nonlinear load is designed and simulated. Overall scheme of this work can represented in block diagram form as shown in figure 1.1

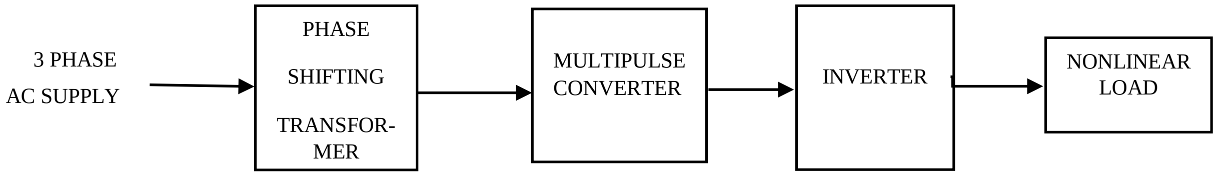


Fig. 1.1 representation of overall system

1.5 CONCLUSION

In this chapter, a brief outline on the introduction of this project work is given.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter contains a complete literature survey on various modules related to this thesis work. Various books and research papers related to multipulse converter system, power quality, HVDC transmission system, issues with nonlinear load have been studied, which forms the back bone of the present thesis work.

2.2 MULTIPULSE CONVERTER SYSTEM

Multipulse methods involve multiple converters connected so that the harmonics generated by one converter are cancelled by harmonics produced by other converters. By these means certain harmonics, related to the number of converters, are eliminated from the power source. Multipulse converters give a simple and effective technique for reducing power electronic converter harmonics**.**

D A Paice et al [1] stated about requirement of harmonics, multipulse method and all the novel connection of transformers that may be practically possible.

Bhim Singh and Ambarish Chandra et al [2] studied the improved power quality ac-dc converter (IPQCs) configurations, their control strategies, selection of components, recent trends, comparative factors, their suitability, and their selection for specific applications. They have presented the state of art of the IPQC technology to the application engineers, designers and researchers dealing with 3 phase ac-dc converter.

Bhim Singh and S. Gairola et al [3] studied that the delta/fork connection based transformer utilized for a multipulse ac –dc converter has a huge performance in terms of correction of harmonics power factor and ripple at output voltage and less than 2% line current harmonics and almost sinusoidal line current wave form and in phase with line voltage. They have also carried out the comparison of the parameters of multipulse pulse AC-DC converter at light load and full load. Then exhibits the results of multipulse that they are superior in every respect. But this fork connection is not so much popular with high power and high voltage AC-DC converters.

Bhim Singh et al [4] studied and have stated that to mitigate the current harmonics and improve the efficiency of the system as well as the power factor multipulse ac-dc converter is to be used. The power quality at both side that is dc output side and ac mains side is improved by these multiple converter. The multipulse converters are useful to reduce EMI, RFI, noise and low switching losses and low cost.

Bhim Singh et al [5] studied the design and analysis of a novel multipulse ac–dc converter for reduction of harmonics harmonic under varying loads. In this proposed multipulse ac-dc converter, polygon-connected autotransformer based converter with reduced magnetics is used. This ac–dc converter is able to eliminate system harmonics lower than 29th order in the ac supply current. The autotransformer is so designed that it is suitable for retrofit applications.

2.3 BACK TO BACK SYSTEM

A back-to-back HVDC arrangement is used when two asynchronous AC systems need to be interconnected for bulk power transmission or for AC system stabilization reasons. Back-to-Back system gives your own system more flexibility and can prevent you from having to build a new generation network. The power flow is fast and accurate and prevents widespread blackouts from occurring.

Dr Madan Mohan and Bhim Singh et al [6] dealt with 24-pulse three-level VSC design and control, harmonic reduction with switching of fundamental frequency for a high-voltage DC transmission system. By selecting the proper dead angle of the three-level VSC the level of harmonics in converter is optimized.

Makoto Hagiwara, and Hirofumi Akagi et al [7] presented the features of continuous and reliable operation even during faults in power line of a voltage-source BTB system for the purpose of obtaining power flow control and change in line frequency in the transmission systems.

Makoto Hagiwara, and Hirofumi Akagi et al [8] stated technique, for achieving the control in power flow in transmission system, also the experimental verifications has to be done for the self-commutated BTB system.

Rakesh Maurya, Pramod Agarwal and S.P.Srivastava et al [9] presented the various topologies of multipulse ac–dc converter for low voltage high current (LVHC) applications. And also they have investigated the performance of these converters. They compared these converter with respect to power quality aspects, and suitability for the Low Voltage High Current (LVHC) applications.

Dr Madan Mohan and Bhim Singh et al [10] dealt with the optimum dead angle operation of a three level 18-pulse voltage source converter (VSC) for power quality improvement in high voltage dc (HVDC) transmission system. The harmonics level of VSC is optimized by selecting proper dead angle (β) of a three level 18-pulse voltage source converter operated at fundamental frequency switching. The effect of varying dead angle (β) is also studied in detail and it is compared with two-level voltage source converter.

Giampaolo Buticchi, Emilio Lorenzani and Claudio Bianchini et al [11] presented a complete solution based on back-to-back topology. This solution includes the sensor less vector control for the PMSG, the Maximum Power Point Tracker (MPPT) algorithm, the d-q vector control of the single-phase grid connected inverter and the power flow control strategies from the PMSG to the grid. It is worth noticing that the two full-bridge power converters are controlled by two different DSP which can exchange information only through the value of the DC Link voltage.

Song Xu, Haifeng Wang et al [12] presented a back-to-back pulse width modulation (PWM) converter for the flywheel energy storage system (FESS), which store energy in the form of kinetic energy. The permanent magnet brushless DC machine (BLDCM) is used for energy conversion. Back-to- back PWM converter used in FESS improves power factor, reduces the harmonic content and controls the bidirectional flow of energy. The principle of operation and control strategies are analysed.

2.4 CONTROL OF INVERTER AND FILTER DESIGN

There has been an increase in the number of sources that are natural dc sources or whose ac frequency is either not constant or is much higher than the grid frequency. In some of these cases three-phase inverters have been used. So far, only small-scale power applications have used inverters because of limited component availability, heat dissipation problems, reliability concerns and cost. High-power semiconductor switches with reasonable switching frequency have become more available. Power quality standards for connection of an inverter to the grid are still under development, since previously there have been few similar high power applications. It is well known that the power quality is determined by the voltage quality, when the voltage is a controlled variable. If there is connection to an existing (stiff) grid, then the voltage cannot be controlled. The power quality is then defined by the current quality. Control of inverter provides high quality of current injected into a voltage grid and, therefore, high power quality.

Milan Prodanovic and Timothy C. Green et al [13] described a filter, designed to incorporate an isolating transformer and the design of a complementary controller that rejects grid disturbance, maintains good waveform quality and achieves real and reactive power control.

Abad Lordly, Antonio Lazaro, Andrés Barrado et al [14] presented the optimized control of a three phase grid connected inverter, considering as basis of analysis the observation of the dynamics of the system with two inputs and two outputs (TITO SYSTEM).This model allows the design of the inverter control in a direct way, by means of two PI controllers to control the instantaneous active and reactive power.

Xiaorui Wang, Hao Ma et al [15] proposed a three phase inverter to guarantee symmetric output voltage with asymmetric load for three-phase inverter, a feedback linearization based on inverse system, which can improve system adaptability and stability under complex load conditions and disturbances.

Sangita R Nandurkar, Mini Rajeev et al [16] dealt with design and simulation of a three phase inverter in MATLAB SIMULINK environment which can be a part of photovoltaic grid connected systems. The converter used is a Voltage source inverter (VSI) which is controlled using synchronous d-q reference frame to inject a controlled current into the grid. Phase lock loop (PLL) is used to lock grid frequency and phase. The design of low pass filter used at the inverter output to remove the high frequency ripple is also discussed and the obtained simulation results are presented.

Leonardo Augusto Serpa, Srinivas Ponnaluri,Peter Mantovanelli Barbosa and Johann Walter Kolar et al [17] proposed a novel approach to adapt a conventional direct power control (DPC) for high-power applications, where a third-order *LCL* filter is frequently required. The *LCL* filter can cause a strong resonance and requires additional effort for system control. The addition of an active damping strategy, together with a harmonic rejection control loop, to the conventional DPC is proposed and analysed in this paper. The steady-state, as well as the dynamic performance of the proposed system, is verified with simulation results and experimental measurements.

Hirofumi Akagi et al [18] presented the present status of active filters based on state-of-the-art power electronics technology, and their future prospects and directions toward the 21st century, including the personal views and expectations of the author.

Kurt Schenk and Slobodan Cuk et al [19] analysed theoretically the optimal duty-cycle modulation for the lowest possible input current distortion of a single switch three-phase power factor corrector. A simple control strategy which achieves results which are very close to the theoretical optimum is presented. Furthermore problems that arise when an isolation transformer is introduced are explored and a solution is proposed.

Akira nabae, satoshi ogasawara and Hirofumi Akagi et al [20] presented a high-performance current controlled inverter must have a quick current response in transient state and low harmonic current content in steady state. However, in general, these requirements contradict each other. A novel control scheme is proposed which is based on the current deviation vector and satisfies both requirements. Experimental results showed good agreement with the anticipated performance.

Satoshi Ogasawara, Jin Takagaki, Hirofumi Magi,and Akira Nabae et al [21] presented a novel parallel technique for current-controlled PWM inverters. Two voltage source inverters, the output terminals of which are connected in parallel through current balancers, are used as a main circuit. In this scheme, excellent characteristics both in steady states and in transient states are obtained, keeping the average values of the cross current and zero sequence current at zero level. This current control scheme is applicable to large-capacity GTO inverters because good performance is attained even if the switching frequency is only a few hundred Hertz.

2.5 POWER QUALITY IMPROVEMENT

Application for solid state equipments continue to increase, especially because of their ability to converse power and provide better control. The inherent nonlinear nature of solid state equipments places harmonic current demands and extraneous losses upon power system. To avoid these losses, improvement of power quality is needed.

S**.** Kim, P. Enjeti, P. Packebush I. pitel et al [22] proposed a new approach to improve power factor and reduce harmonics generated by a three phase diode rectifier type utility interface. The proposed approach is passive and consists of a novel interconnection of a star delta transformer between the ac and dc sides of the diode rectifier topology. This novel interconnection, in combination with the 120 degree conduction intervals of each diode, is shown to generate a circulating third harmonic current between the ac and dc side of the rectifier bridge. The circulating third harmonic current is then shown to drastically improve the performance of the diode rectifier type interface.

Mukul Rastogi, Rajendra Naik, and Ned Mohan, et al [23] presented a comparative evaluation of harmonic reduction techniques which satisfy the current harmonic limits specified by the IEEE Standard 519, and at the same time provide a regulated dc output voltage. The techniques considered include active and hybrid filters, and various current wave shaping approaches for a three-phase utility interface. These techniques are compared in terms of their complexity (number of switches) and their component ratings. Based on the application requirements and the cost of active and passive components, they estimated the minimum cost topology.

Sewan Choi, Prasad N. Enjeti, and Ira J. Pitel [24] presented polyphase transformer arrangements with reduced kVA capacities for harmonic current reduction in high power diode rectifier-type utility interface systems. Based on the concept of an autotransformer, a 12- pulse rectifier system is realized with a resultant transformer kVA rating of 0.18Po (pu). In this arrangement the 5, 7, 17, 19, etc. harmonics are absent from the utility input line current. In the second scheme an IS-pulse rectifier is realized with the kVA rating of 0.16P0 (pu) and the 5, 7, 11, 13, etc. harmonics are cancelled in the utility line currents. Analytical design equations are presented to facilitate the design of system components. Simulation results verify the proposed concept, and experimental results are provided from a 208 V, 10 kVA 12-pulse rectifier system. The advantage of employing the proposed system for utility interface of rectifier/PWM-inverter motor drive systems is also explained.

Dudi *A.* Rendusara, Annette von Jouanne, Prasad N. Enjeti, and Derek *A.* Paice, et al [25] discussed a design considerations for 12-pulse diode rectifier systems operating under utility voltage unbalance and pre-existing harmonic voltage distortion. For a 12-pulse diode rectifier system connected in parallel to feed a common dc link via an interphase transformer it is shown that a small amount of impedance mismatch, utility voltage unbalance or pre-existing voltage distortion drastically affects the current sharing capability of the rectifier bridges. This in turn generates additional uncharacteristic and characteristic harmonics thereby increasing the THD. In order to mitigate these effects and ensure proper operation of diode rectifiers, specially designed line reactors termed Harmonic Blocking Reactors (HBR's) are introduced. The analysis and design procedure for HBR's are discussed. Simulation results illustrate improved performance. Experimental results from a laboratory prototype system show close agreement with theory.

John Salmon, Alexander Love, Emanuel Bocancea et al [26] presented a resonant harmonic correction networks that lower the line current harmonic distortion of 30 diode rectifiers using a capacitor smoothed dc rail. The basic harmonic correction network consists of line inductors and capacitors connected in parallel with the rectifier. This structure injects resonant current into the ac supply that makes the line current wave shape more sinusoidal. Several modifications can be made to this basic structure that improves the rectifier performance and lowers the size of the line inductors. A 12-pulse rectifier configuration can be used to achieve a line current distortion less than 5% using line inductors rated at around 0.14 p.u. Thyristor networks can be used to improve the rectifier power factor over a wide load range. Split resonant inductors with an IGBT switch can be used to decrease the size of the line inductors and to regulate the output dc-rail voltage over a wide load range and as compensation for fluctuating supply voltages.

Yasuyuki Nishida and Mutsuo Nakaoka et al [27] proposed a new harmonic reducing diode rectifier for high voltage and high power applications. The new rectifier consists of the conventional double sequential (or series connected) three-phase bridge 12-pulse diode rectifier and a particularly designed auxiliary circuit. The double sequential topology is suitable

For high voltage and high power applications because output voltages of the two bridges are added and fed to the load. Harmonics of the utility line currents and ripples of the dc voltage *of* the proposed rectifier are reduced as low as those of the %-pulse rectifier due to the operation of the auxiliary circuit. Since the new rectifier does not require any self-turn off device nor controller and the ratings of the components in the auxiliary circuit are also low, the proposed scheme gives an economical, efficient and reliable solution to obtain high voltage and high power dc from the utility without harmonic pollution.

D. Rendusara K. J. Slater I. Pitel B. *S.* Lee P. Enjeti W. Gray et al [28] discussed an auto-connected multipulse (1 2/24 pulse) rectifier schemes that are cost effective methods for reducing line current harmonics in PWM drive systems. Employing these schemes to enhance utility power quality requires careful attention to several design considerations. They analysed excursion of dc-link voltage at no load, effect of pre-existing voltage distortion, impedance mismatches, unequal diode drops on rectifier current sharing and performance. Several corrective measures to improve the performance of 12/24-pulse rectifier systems are also discussed.

Predrag Pejovic´ and ˇ Zarko Janda et al [29] proposed a novel current injection network for low-harmonic rectifiers that apply the third harmonic current injection. The current injection network requires one inductor, two capacitors, and one 1 : 1 transformer with volt-ampere rating of only 0.16% of the input power. The transformer is introduced to provide complete rejection of harmonic components of the injected currents at even triples of the line frequency, resulting in significant reduction of the input current total harmonic distortion (THD). Dependence of the input current THD on the current injection network factor is computed.

Uffe Borup, Frede Blaabjerg, and Prasad N. Enjeti, et al [30] presented, a new control method which enables equal sharing of linear and nonlinear loads in three-phase power converters connected in parallel, without communication between the converters. The paper focuses on solving the problem that arises when two converters with harmonic compensation are connected in parallel. Without the new solution, they are normally not able to distinguish the harmonic currents that flow to the load and harmonic currents that circulate between the converters. Analysis and experimental results on two 90-kVA 400-Hz converters in parallel are presented

N. R. Raju, A. Daneshpooy and J. Schwartzenberg et al [31] presented a new method to eliminate harmonics drawn by a twelve-pulse rectifier through modulation of the dc bus. A PWM converter with low ratings is inserted in the dc link and controlled in a fashion that results in sinusoidal currents at the input. The bulk of the power transfer is handled by the diode bridges, while the additional PWM converter deals only with a ripple voltage.

Lixiang Wei, Nickolay Guskov, Richard A Lukaszewski, and Gary Skibinski et al [32] stated that 18 pulse rectifier systems have been shown to be a cost effective harmonic solution in many industries where IEEE 519 is specified. A small amount of voltage unbalance can cause a large amount of current harmonic injected back to the input source. Consequently, a stricter pre-existing voltage THD condition has to be specified for an 18 pulse rectifier to meet the IEEE 519 current harmonics requirement. They introduced a DC link passive filtering method to solve this problem. This method greatly reduces the current harmonics caused by the phase unbalance, the 5th, and the 7th order voltage harmonics by adding several series LC resonant loops into the DC link. As a result, the proposed 18- pulse rectifier can still meet IEEE 519 under abnormal source voltage conditions of the AC line. Theory analysis, simulation and experimental result are provided in this paper to verify the effectiveness of this method.

Bang Sup Lee, P. Enjeti, et al [33] proposed a 24-pulse diode rectifier system suitable for utility interface of PWM ac motor drive systems with low kVA components. The proposed 24-pulse system employs an autotransformer and two zero sequence blocking transformers (ZSBT) in the dc link and a tapped interphase reactor. Results produce near equal leakage inductance in series with each diode Rectifier Bridge ensuring equal current sharing and performance improvements. A specially tapped interphase reactor is employed with two additional diodes and is shown to extend the conventional 12-pulse operation to 24-pulse operation from an input current stand point, the voltage across the ZSBT is analysed and the kVA rating of each component in the proposed system is computed. The 5th, 7th, llth, 13th, 17th and 19th harmonics are eliminated in the input line current resulting in clean input power. The dc link voltage magnitude generated by the proposed rectifier system is nearly identical to a conventional 6-pulse system. The proposed system is suitable to retrofit applications as well as in new PWM drive systems.

Sewan Choi, Prasad N. Enjeti, Hong-Hee Lee and Ira J. Pitel, et al [34] proposed a new active interphase reactor for twelve-pulse diode rectifiers. The proposed system draws near sinusoidal currents from the utility. In this scheme, a low %VA [0.02 Po (PU)] active current source injects a triangular current into an interphase reactor of a twelve-pulse diode rectifier. This modification results in near sinusoidal utility line currents with less than 1% THD. It is further shown that a low kVA, 12-pulse system with an autotransformer arrangement [kVA rating of 0.18 P, (PU)] can be implemented with the proposed active interphase reactor. The resulting system draws clean power from the utility and is suitable for powering larger kVA ac motor drive systems. Detailed analysis of the proposed scheme along with design equations is illustrated. Simulation results verify the concept. Experimental results are provided from a 208 V, 10 kVA rectifier system.

Wladyslaw Mielczarski, William B. Lawrance, Rafal Nowacki, and Donald Grahame Holmes, et al [35] described further development of the novel current-injection scheme devised by the authors for attenuating line current harmonics in bridge-rectifier circuits. The previous passive filters are replaced by controlled filters connected between the bridge-rectifier output and the star point of the transformer secondary. These filters are used to inject controlled third harmonic currents into the transformer windings. Variations in bridge working conditions, due to changes in either load or bridge delay angle, lead to corresponding changes in the filter operating conditions if the harmonic attenuation is to remain optimal. The control law for the filters has been derived and the effectiveness of the new method confirmed by both simulation and laboratory tests.

Sewan Choi, Prasad N. Enjeti, Derek A. Paice et al [36] proposes two new passive 24-pulse diode rectifier systems for utility interface of PWM ac motor drives. The first approach employs an extended delta transformer arrangement which results in near equal leakage inductance in series with each diode rectifier bridge. This promotes equal current sharing and improved performance. A specially tapped interphase reactor is then introduced with two additional diodes to extend the conventional 12-pulse operation to 24-pulse operation from the input current point of view. The proposed system exhibits clean power characteristics with 5th, 7th, 11th, 13th, 17th and 19th harmonics eliminated from the utility line currents. The second scheme is a reduced kVA approach employing autotransformers to obtain 24-pulse operation. The kVA rating of the polyphase transformer in the second scheme is 0.18 Po @U). Detailed analysis and simulations verify the proposed concept and experimental results from a 208V, l0 kVA rectifier system are provided.

M.M.R. Ahmed G.A. Putrus L. Ran L. Xiao et al [37] presented a harmonic study on a newly developed solid-state fault current limiter. Using this device, the supply voltage sag is reduced when a short-circuit fault occurs on a cable feeder in the downstream network, hence improving the power quality. The device will eventually isolate the faulted part from the healthy network. Harmonics caused by the fault current limiter are analysed and a method is proposed to prevent undesirable harmonic interactions. Analytical and experimental results are compared with existing regulations. It is verified that, with precautions, the operation of the solid-state fault current limiter will not cause problems to either the supply network or the loads.

Girish R. Kamath, Bruce Runyan and Richard Wood et al [38] presented a compact autotransformer topology suitable for 12-pulse rectification. It differs from conventional schemes by achieving harmonic current reduction without the need for equal current sharing between the diode bridges. This eliminates the need for impedance matching inductors and zero sequence current blocking devices further reducing size and cost. They presented the concept and principle of operation. It establishes guidelines for designing the autotransformer. A simple model is developed and simulated to investigate the concept

F. Javier Chivite-Zabalza, Andrew J. Forsyth, and David R. Trainer et al [39] described a new converter topology for a three-phase multipulse rectifier circuit. This converter draws almost sinusoidal currents from the ac system with very low harmonic content and typically less than 3% total harmonic distortion. The topology uses only passive components and has a lower component count than other rectifier circuits with similar performance. Two six-pulse rectifier bridges are connected in series, fed by a series connection of transformers, to form a 12-pulse system. An additional low power harmonic injection circuit enhances the performance of the circuit to obtain low harmonic current pollution levels that are comparable with those achieved from a 24-pulse rectifier. The circuit operation is explained and experimental results are presented.

Maryclaire Peterson and Brij N. Singh et al [40] presented an active current shaper for a 12-pulse thyristor converter, termed a load compensator (LSTATCOM). The LSTATCOM injects compensation current through a split winding interphase reactor connected on dc bus of the 12-pulse ac-dc converter. It is desired that the LSTATCOM provides sinusoidal shaping of the source currents for variations in the output load as well as changes in the output voltage requirements. For voltage sensitive dc loads, the LSTATCOM should also be capable of compensating voltage sag and voltage swell. To observe the dynamic and steady state performance of the LSTATCOM based 12-pulse thyristor converter, a detailed mathematical model of the system is derived and the corresponding simulation models are developed. A thorough investigation of the performance results reveals that the proposed LSTATCOM provides sinusoidal shaped source currents for a 12-pulse converter operating under a variety of operating conditions and requirements.

Bin Wu, L Umanand, Marcel & Dekker et al [41-43] stated the design of magnetic circuit like phase shifting transformers, their concepts, their connections for power quality improvement.

2.6 CONCLUSION

In this chapter, a brief outline of the literature survey during the course of this project work is given.

CHAPTER 3

SIMULATION AND DESIGN OF 18 PULSE CONVERTER USING DIODE RECTIFIER

3.1 INTRODUCTION

MPCs (multipulse converters) are advanced level converters used for ac–dc conversion [1] with reduced harmonic currents and reactive power burden, low EMI, RFI at input ac mains and good quality reduced rippled dc output with unidirectional and bidirectional power flow for feeding loads from a few kilowatts to several hundred megawatts. The MPCs can be considered better alternatives for power quality improvement because of an inherent integrated converter with simple construction, reduced size of magnetics, and enhanced reliability due to lower components count compared to other means of power quality improvement [32-40]. These converters improve the power quality at both ends, i.e., input ac mains and dc output load. Moreover, the use of these MPCs results in less noise, low EMI and RFI, low switching losses, and low cost due to the use of simple devices In this chapter, 18 pulse converter is simulated and designed using diode rectifier.

3.2 MULTIPULSE CONVERTER

In multipulse system [1-5], multiple converters are connected in such manner so that the harmonics generated by one converter are cancelled by harmonics produced by other converters. In this manner certain harmonics, which are related to the number of converters, are eliminated from the power source. Multipulse converters give simple and effective technique for reducing power electronic converter harmonics.

Multipulse systems have two major advantages. They are achieved simultaneously and are

1. Reduction of ac input line current harmonics
2. Reduction of dc output voltage ripple.

The main impact of the converter on the power system is a reduction of ac input line current harmonics [22-27]. Also, it may be essential to meet harmonic current standards. The use of multiple converters, or multiple semiconductor devices, with a common dc load characterized the mulipulse method. In some applications, unidirectional power flow is required from ac source to dc loads; therefore , these MPCs are developed using diode rectifiers and transformer circuit configurations in isolated and nonisolated topologies starting with 12-pulse to 18,24,30 and higher number of pulses to maintain low total harmonic distortion (THD) of a mains current and ripple –free dc output.

The phase shifting transformers are an essential ingredient and provide the mechanism for cancellation of harmonic current in pairs, for example, the 5th and 7th harmonics, or 11th and 13th, and so on. The major breakthrough in the technology of MPCs is due to phase shifting process through transformer to convert from original three-phase ac supply to multiphase ac supply to result in a higher number of pulse in dc output for reducing in ripple and a high number of step in ac mains current to make it close to sinusoidal with reduced and acceptable THD. The merit of the realized multipulse configuration may not only result in decrease the current harmonics but also increases the dc side voltage due to cascading of converters.

3.3 PROPOSED DESIGN OF 18 PULSE SYSTEM

The concept design [1] proposes, three numbers of three phase transformer with phase shifting angle of $+15^0$, $- 15^0$, $+30^0$ respectively using star-delta and star-star configurations. For 18 pulse converter the degree of phase shift should be $+20^0$, $- 20^0$. The phase shift of $+15^0$, $- 15^0$, $+30^0$ is for 24 pulse converter. In this work we studied the effect of applying this phase shift for 18 pulse converter as it will result in to the reduction of cost. The design is first simulated under MATLAB environment and output of transformer is fed to diode rectifier circuits. After obtaining the satisfactory simulation results the design of transformer is done and the design is realised for each transformer with 2 KVA rating to a total of 6 KVA. The design is realised on T-8B EI three phase core and wound with enamelled copper wire of different gauges. The terminals brought out are connected in such a way so as to realize 18 pulse converter. The prototype 18 pulse converter is tested to satisfactory operation for harmonic reduction.

3.4 SIMULATION OF PROPOSED DESIGN

The multi-pulse converter, uses a modular architecture, where each power module comprises of a three-phase bridge and specially designed transformer for shifting of phase. Fig 3.1 shows the simulation model of proposed design. The primary windings of the transformers are wound in star and fed by a power source, while the secondary windings of the transformers are connected to individual power converters with relevant phase shifts to realize the desired ouput. By selecting appropriate phase shifts between the primary and secondary sides of the transformers and synchronously switching the three-phase bridges at specified phase relations, low order harmonics can be eliminated in pairs.

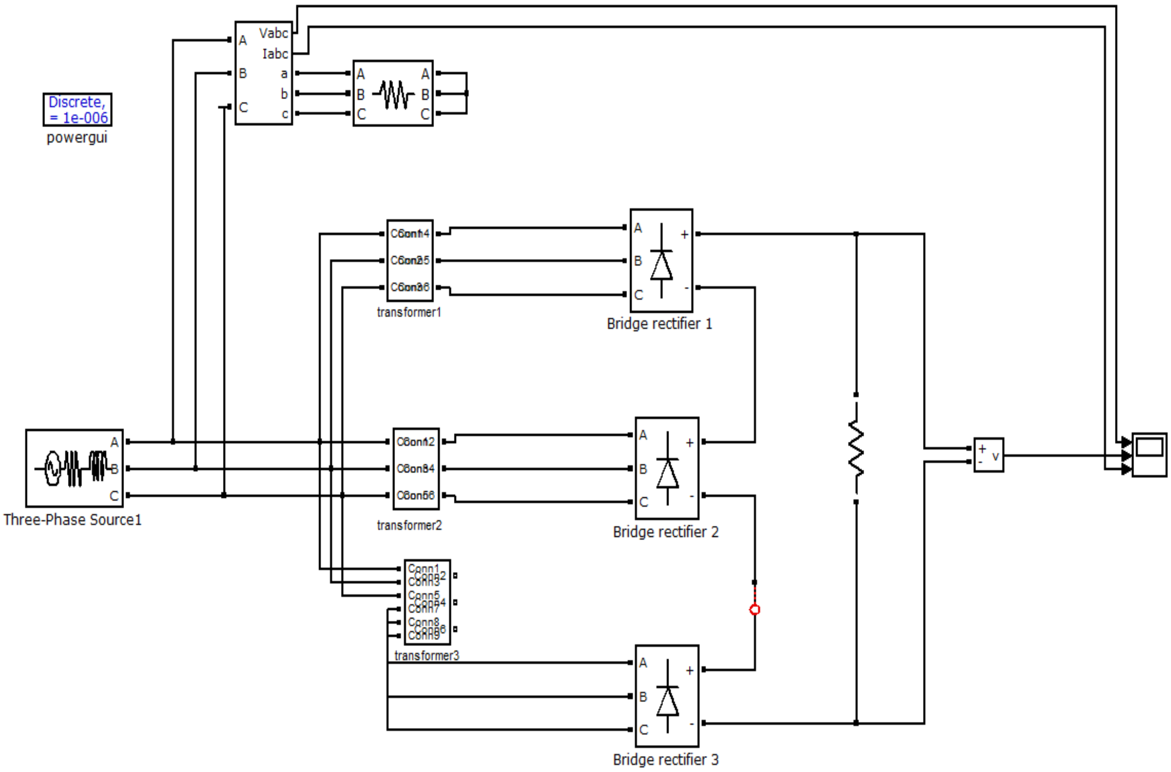


Fig.3.1 simulation model of multipulse converter with diode rectifier

Figure 3.2, 3.3 and 3.4 shows the output of phase shifting transformers for $+15^0$, -15^0 and $+30^0$. It can be clearly seen from the figure that output is shifted from input wave form. Figure 3.5 shows the input current waveform. Figure 3.6 and 3.7 shows the dc waveform of the 18 pulse converter and total harmonic distortion respectively. THD is found to be 6.21%.

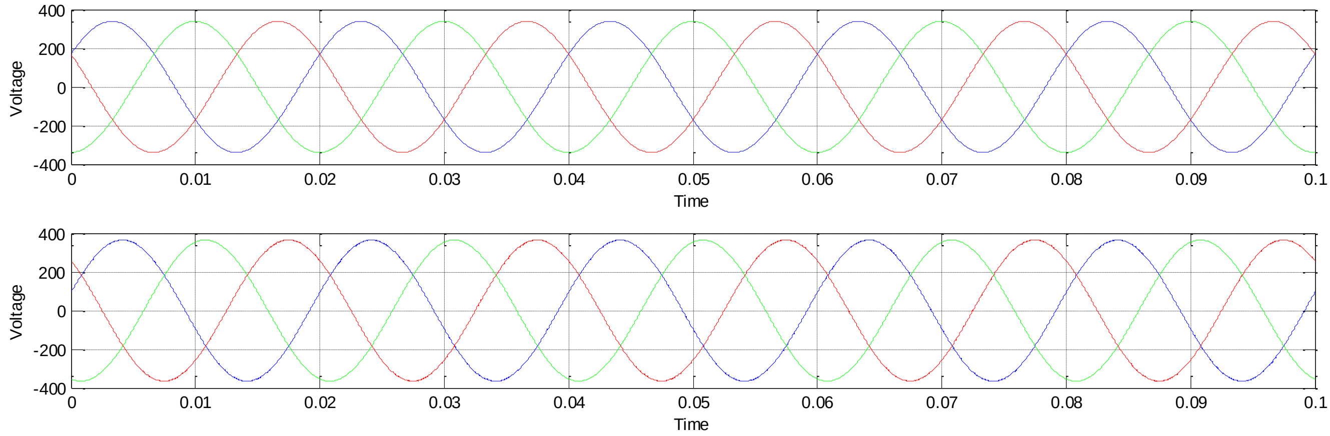


Fig.3.2 $+15^0$ phase shift from input

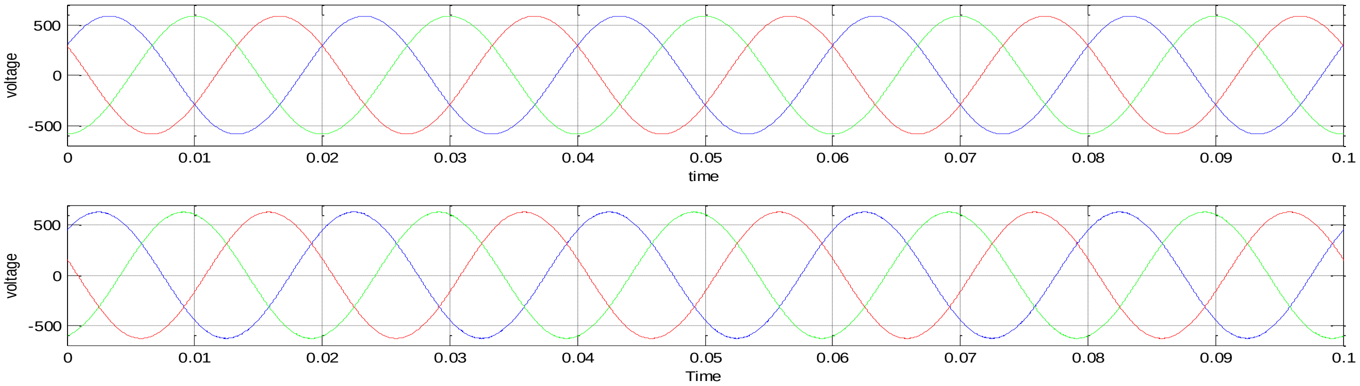


Fig. 3.3 - 15^0 phase shift from input

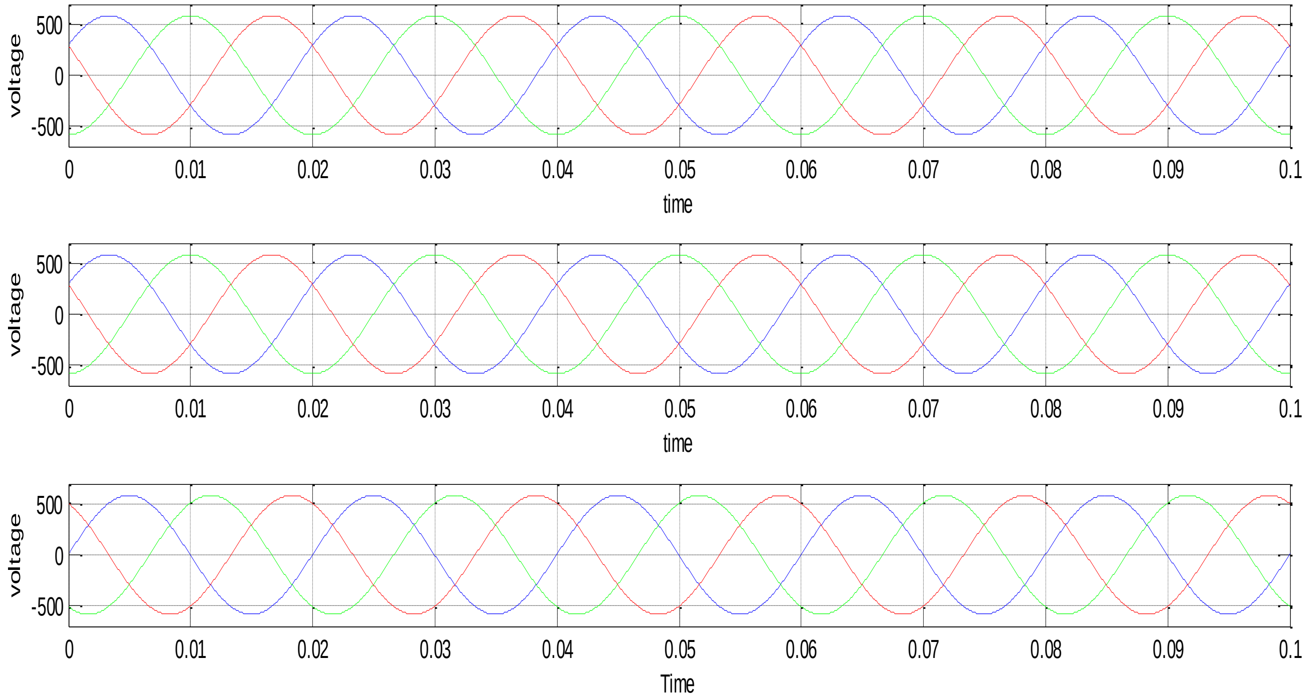


Fig.3.4 0^0 and 30^0 phase shift from input

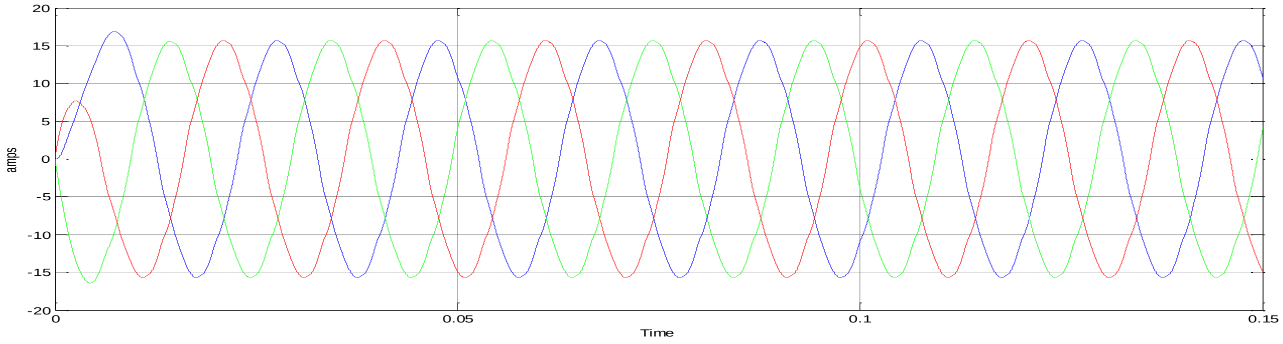


Fig.3.5 Input current waveform

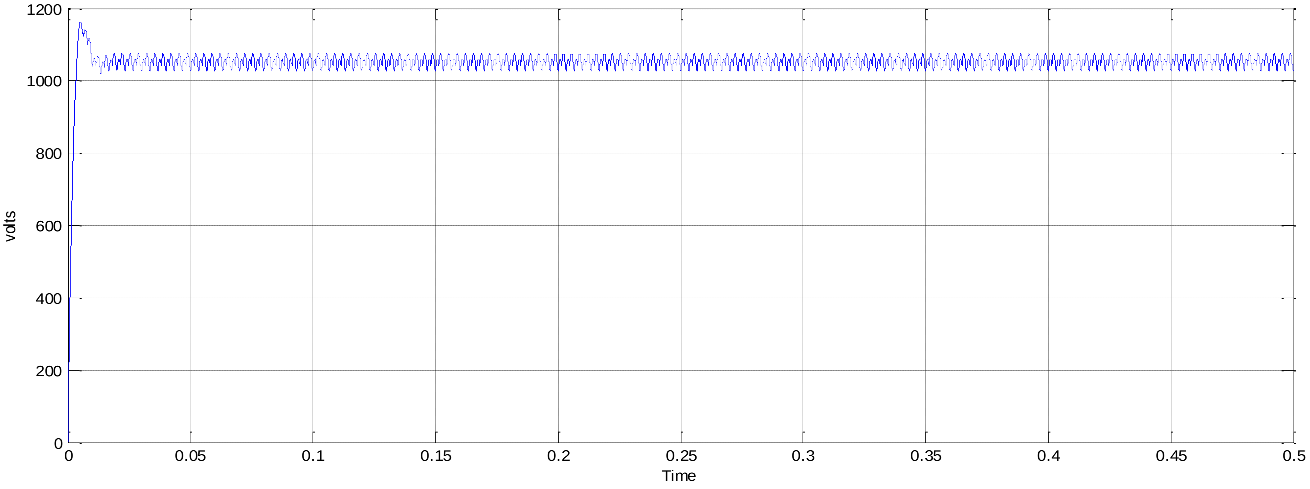


Fig.3.6 DC output of proposed model

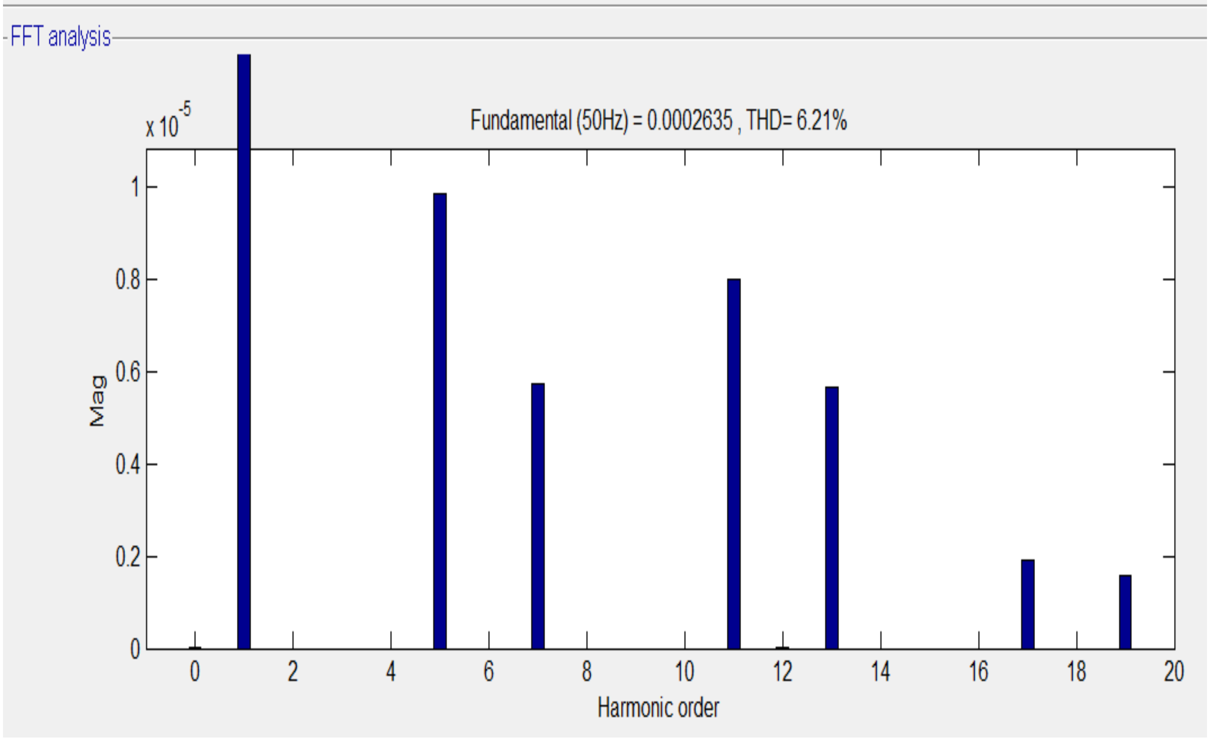


Fig. 3.7 simulation result of current harmonic in ac side

3.5 HARDWARE DESIGN OF MULTIPULSE CONVERTER

After the successful working of matlab model, in which THD is found to be 6.21% , this design is implemented for hardware model. For hardware implementation of this model firstly the phase shifting transformer along with diode rectifier is designed. Their connection as per the software design is implemented to form a multipulse converter. The detail of transformer design is briefly given.

3.5.1 TRANSFORMER DESIGN

The phase shifting transformer is an important device in multipluse diode/SCR rectifiers. It provides a phase displacement between primary side and valve side voltages for harmonic cancellation, supplies a proper valve side voltage, and also makes an electric isolation between the rectifiers and the utility supply. The tertiary winding transformer, which have two secondary windings, is used for this purpose.

For the design of transformer [42-43], transformer core, bobbin, copper wire, frame, terminals, slews, varnish, screw and nut bolts, thimbles, connecting wires etc are the required apparatus

To design transformer of power 2 KVA, line voltage on primary 415 V, frequency 50Hz, winding factor K_w=0.5, flux density B_m=1.4 tesla and current density J= 3.5 A/mm^2 are chosen. The parameters, primary phase current(I_1), secondary phase current(I_2), secondary voltage(V_2), area product(A_p), core area(A_c), number of primary turn(N_1), number of secondary turn(N_2), number of SWG on primary and secondary, wire cross section area, type of core are computed using equations (3.1) – (3.9)

Phase current and line current

$$I_{L1} = \frac{VA}{\sqrt{3} \times V_1} \tag{3.1}$$

$$I_{ph1} = \frac{IL_1}{\sqrt{3}} \tag{3.2}$$

$$I_{L2} = \frac{VA}{\sqrt{3} \times V_2} \tag{3.3}$$

$$I_{ph2} = \frac{IL_2}{\sqrt{3}} \tag{3.4}$$

For star, phase current is equal to line current.

Wire cross section area

$$a_1 = \frac{Iph_1}{J} \tag{3.5}$$

$$a_2 = \frac{Iph_2}{J} \tag{3.6}$$

From the computed value of wire cross section area, the data of appendix-I is used for selecting the SWG (standard wire gauge) .

The area product or net iron core area (A_p)

$$A_p = \frac{VA}{2 \times K_w \times f \times B_m \times J} \tag{3.7}$$

From the computed value of A_p, the data of appendix -II is used for selecting the value of $\boldsymbol{A_c}\ and\ \boldsymbol{A_w}$ and type of core.

Number of turn on primary and secondary winding (N_1 & N_2)

$$N_1 = \frac{E_1}{4.44 \times f \times B_m \times A_c} \tag{3.8}$$

$$N_2 = \frac{E_2}{4.44 \times f \times B_m \times A_c} \tag{3.9}$$

The value obtained are crosschecked using equation 3.10, using the actual conductor areas, check back to see if the turns fit into the window area A_w of the core by checking for inequality

$$A_w\, K_w \geq \sum_{i=1}^{m} \boldsymbol{a_i}\, \boldsymbol{N_i} \tag{3.10}$$

Design is realised on T-8B EI three phase core and wound with enamelled copper wire of different gauges.

PHASE SHIFTING TRANSFORMER

According to the winding arrangements [41], the transformers can be classified into Y/Z and Δ/Z configurations, where the primary winding can be connected in wye (Y) or delta (Δ) while the secondary windings are normally in zigzag (Z) connection. Both configurations can be equally used in the multipulse rectifiers. Depending on winding connections, the line-to-line voltage of the transformer secondary winding may lead or lag its primary voltage by a phase angle ϴ. The Y/Z-1 transformers provide a leading phase angle, while the Y/Z-2 transformers generate a lagging angle. In Y/Z-1transformer, the primary winding is connected in wye with *N*1 turns per phase. The secondary winding is composed of two sets of coils having *N*2 and *N*3 turns per phase. The *N*2 coils are connected in delta and then in series with the *N*3 coils. Such an arrangement is known as zigzag or extended-delta connection. In Y/Z-2 the primary winding remains the same as that in the Y/Z-1 transformer while the secondary delta-connected coils are connected in a reverse order. It is the phase displacement that makes it possible to cancel certain harmonic currents generated by a three-phase nonlinear load.

3.5.2 EXPERIMENTAL SETUP

Table 3.1 shows the specifications of the apparatus used for experimental setup. Figure 3.8 & 3.9 shows the experimental setup of the multipulse converter. In this arrangement a common 3 phase ac supply is given to all the three transformers. Each transformer is connected to 3 phase diode rectifier circuit. The diode rectifier is connected to each other in cascade manner on dc side which is connected to resistive load.

TABLE 3.1 SPECIFICATION OF APPARATUS USED

Apparatus used	specifications
Transformer core	CRNO core, 8B type EI
Copper wires	17, 19, 21 and 24 SWG
Diodes	6 nos, 6A
Connecting wires	0.5 mm^2, 5A, 20 AWG
3 phase analyser	Fluke 435 series
Resistor	230 ohm
Lamination sheet	0.5 mm

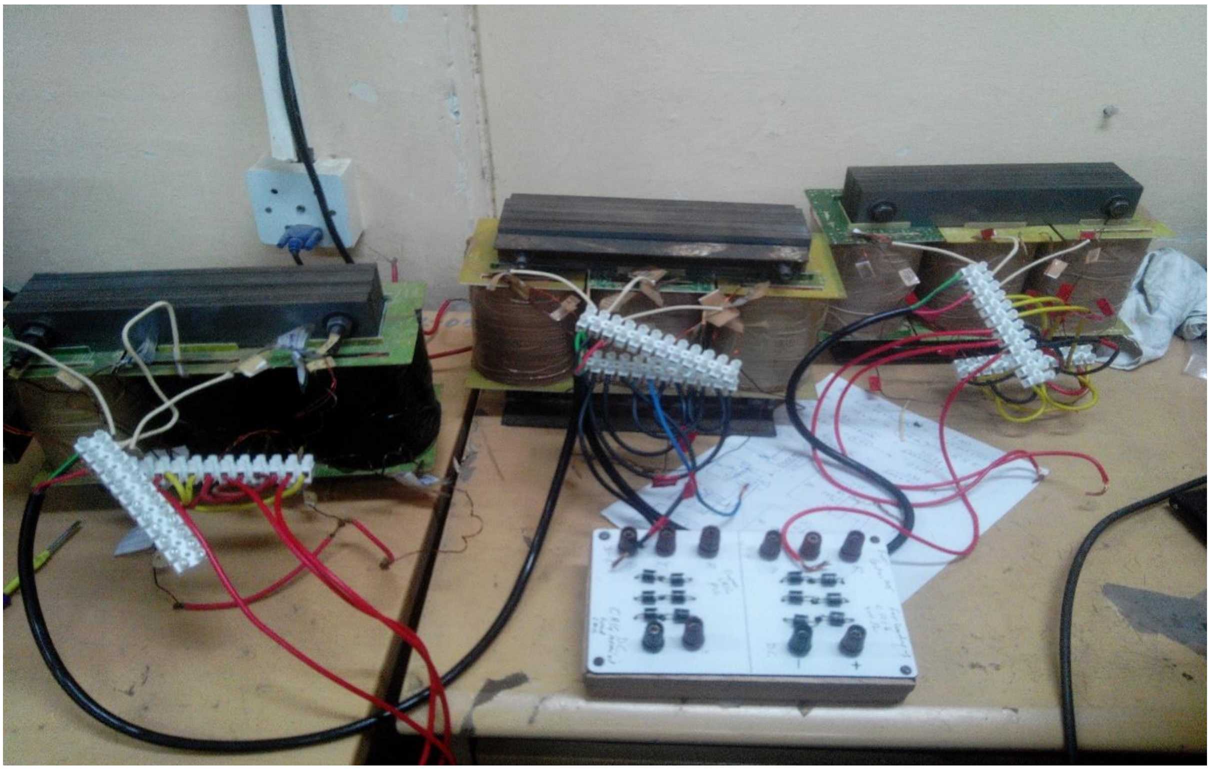


Fig.3.8 experimental setup of multipulse converter

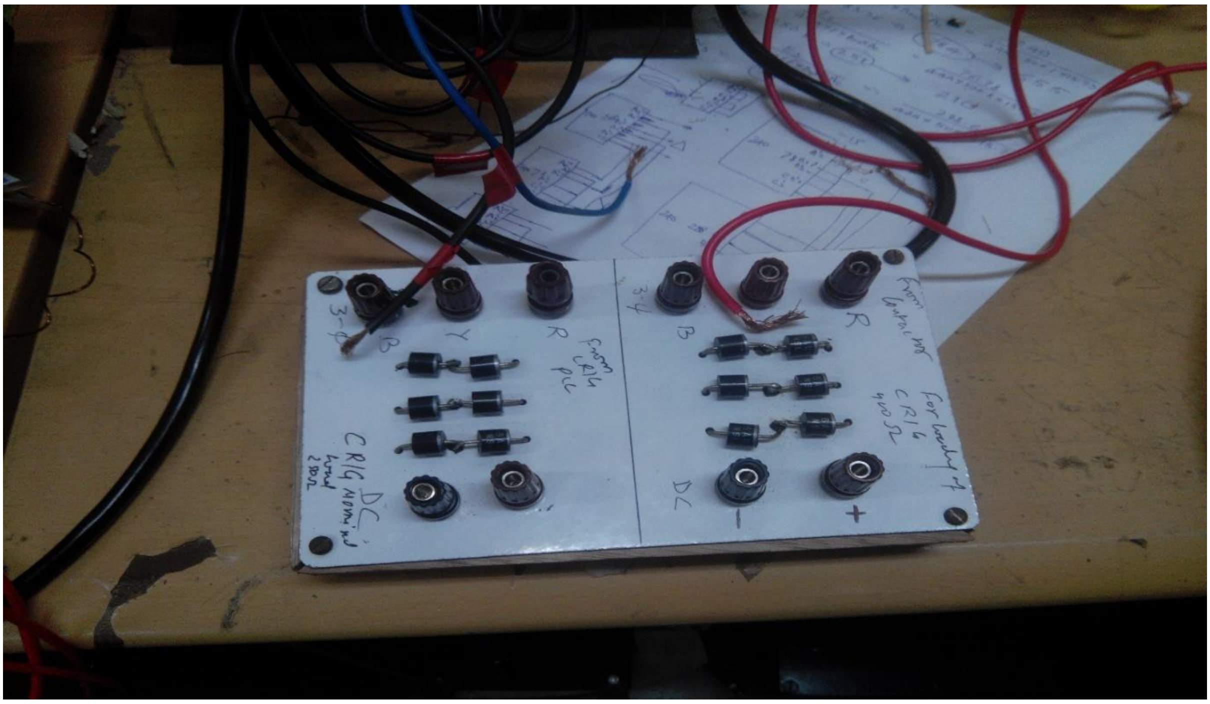
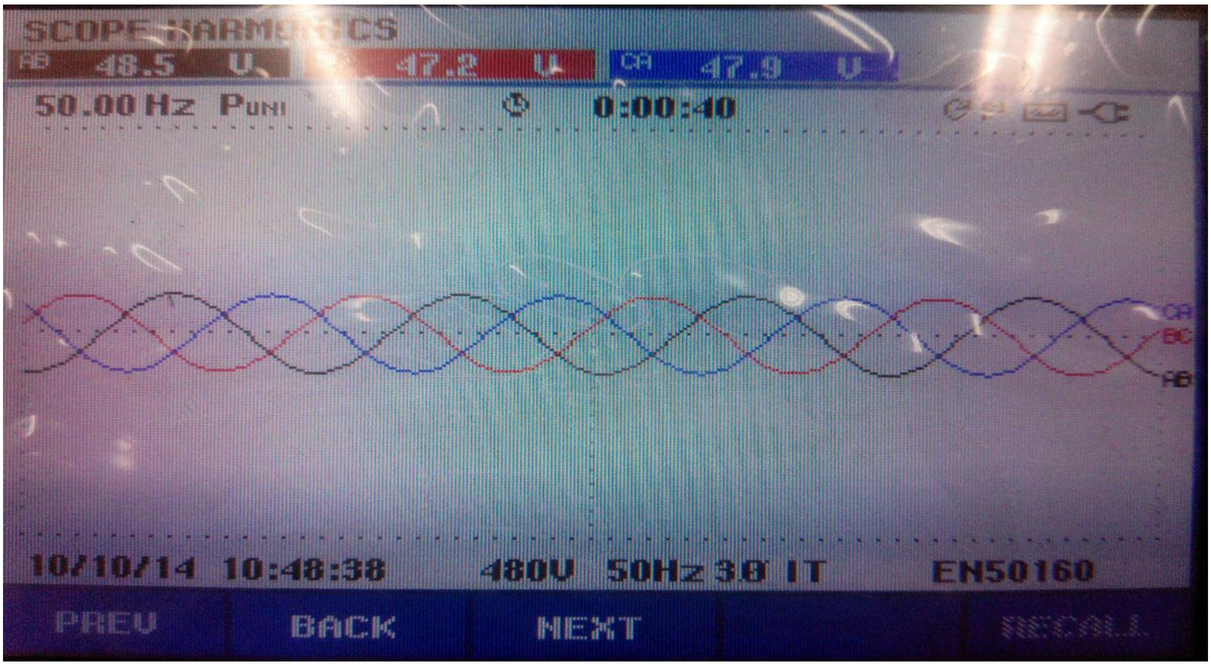


Fig.3.9 arrangement of multipulse bridge rectifier

The input voltage and current waveforms are shown below in the figure 3.10 & 3.11 respectively which are measured through analyser. Figure 3.12 shows the total harmonic distortion at input ac mains side of the system which is observed to be **6.9%**.

Fig.3.10 input voltage waveform



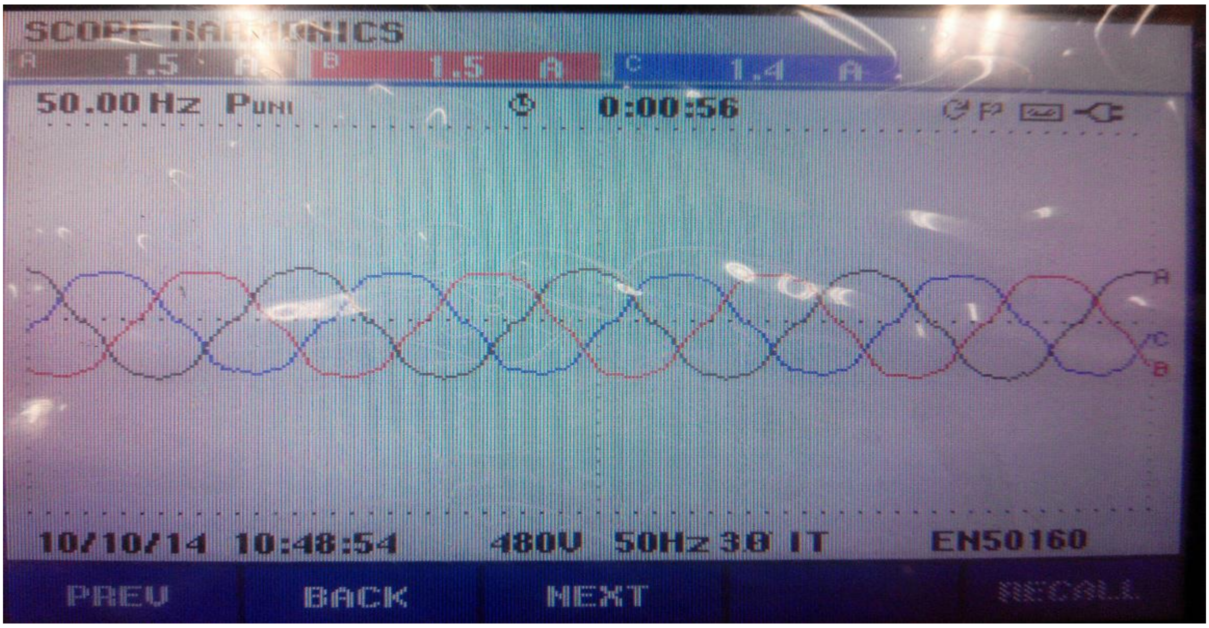


Fig. 3.11 input current waveform

Fig.3.12 experimental result of current harmonics in ac side

3.6 CONCLUSION

In this chapter, design of 18 pulse converter using phase shifting transformer is carried out using simulation. Further, this simulation is realised on hardware model and a comparison between simulink model and practical model is carried out. In this case the THD is observed to be 6.9%. Also, it is observed that there is not much difference between Simulink model and hardware model. The small difference is because of the transformer practical imperfections such as magnetising current and copper losses which are ignored in the basic design but are present in the hardware implementation of the model.

CHAPTER 4

SIMULATION AND DESIGN OF 18 PULSE SYSTEM USING CONTROLLED RECTIFIER

4.1 INTRODUCTION

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable output dc voltage in a single unit instead of a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. The output voltage of a three phase diode rectifier contains multiplies of 6th harmonic of input cycle and the input ac current contain only odd harmonics but no dc component or triplen harmonics.

Three-Phase controlled rectifiers can be classified from the point of view of the commutation process as Line Commutated Controlled Rectifiers (Thyristor Rectifiers) and Force Commutated PWM Rectifiers.

Force commutated rectifiers [10] are built with semiconductors with gate-turn-off capability. This allows full control of the converter, because valves can be switched ON and OFF whenever it is required. Active rectifiers are located in this last category. This allows the commutation of the valves hundreds of times in one fundamental period, which is not possible with line commutated rectifiers, where thyristors are switched ON once a cycle.

The advantages of using this feature are: a) the current or voltage can be modulated (Pulse Width Modulation or PWM), generating less harmonic contamination; b) power factor can be controlled.

There are two types of force-commutated three-phase rectifiers: a) current source rectifier, where power reversal is by dc voltage reversal; and b) as a voltage source rectifier where power reversal is by current reversal at the dc link.

The Active Rectifier is defined as a non-isolated AC-DC converter that uses actively controlled switches such as MOSFETs or IGBTs instead of diodes or thyristors in order to rectify the voltage/current [2]. The two key benefits of active rectifier are;

I. output voltage (DC-link) regulation and
II. AC input harmonic reduction.

The converter is inherently bi-directional, and thus the DC side can be output or input.

In this chapter simulation and design of 18 pulse converter using controlled rectifier is presented.

4.1.1 PROPOSED MODEL FOR 18 PULSE CONVERTER

Figure 4.1 shows the proposed model of 18 pulse converter using controlled rectifier. A common 3 phase 415V input supply is given to primary of all phase shifting transformers, the secondary of transformer is connected with 3 phase controlled rectifier (in this case IGBT is used) circuit. All the bridge circuit are connected in cascade manner to give ripple free, boosted dc output.

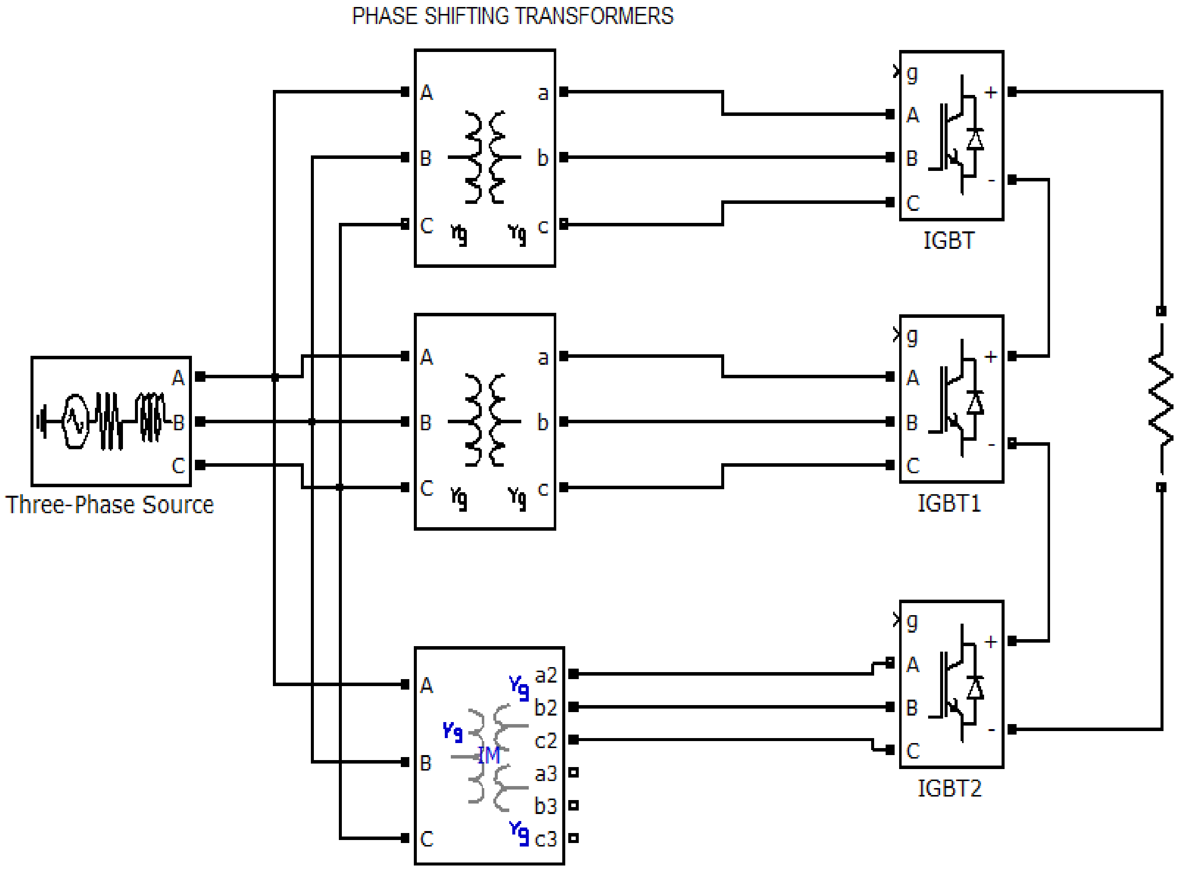


Fig. 4.1 proposed model of 18 pulse converter

4.2 VOLTAGE SOURCE CONVERTER

VSCs utilize self-commutating switches, e.g. gate turn-off thyristors (GTOs) or insulated gate bipolar transistors (IGBTs), which can be turned on or off in a controlled manner[28-29]. VSCs operate at high switching frequency utilizing Pulse-Width Modulation (PWM) technique. It can control the reactive power independent of the active power (to or from the converter) without any need for extra compensating equipment and also there is a little risk of commutation failures in the converter. IGBT has a very low on-state voltage drop due to conductivity modulation and has superior on-state current density. So smaller chip size is possible and the cost can be reduced. It has low driving power and a simple drive circuit due to the input MOS gate structure. It can be easily controlled as compared to current controlled devices (thyristor, BJT) in high voltage and high current applications. It has superior current conduction capability compared with the bipolar transistor. It also has excellent forward and reverse blocking capabilities. Figure 4.2 shows the three phase active rectifier.

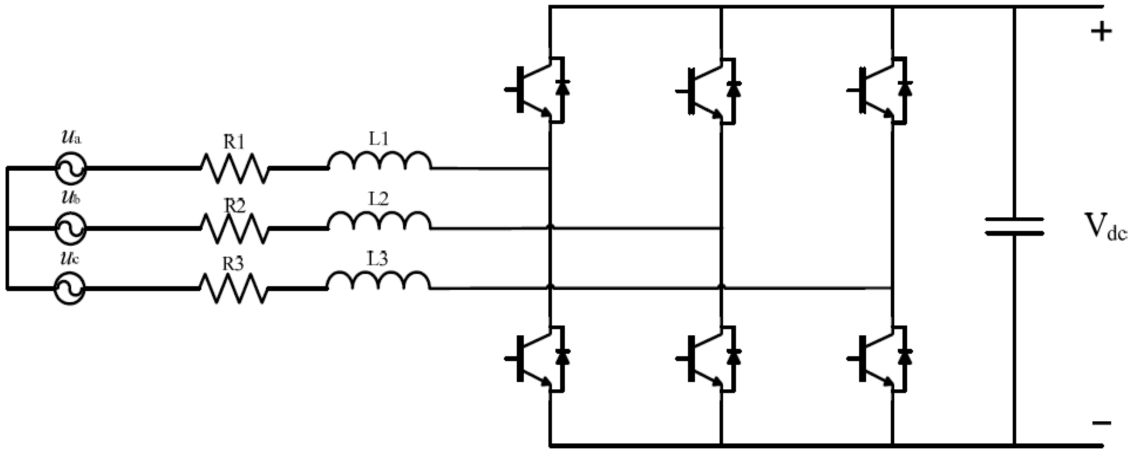


Figure 4.2: Three-Phase Active Rectifier topology: Voltage Source Rectifier.

4.3 GATE PULSE FOR IGBT

Gate characteristic of IGBT gives us a brief idea to operate it within a safe region of applied gate voltage and current.

For systems, that require higher switching frequencies such as inverters and pulsed power applications, fast switching is essential for the optimum performance of the system resulting in reduced Turn-On and Turn-Off losses. The switching behaviour (turn-on and turn-off) of an IGBT module is determined by its structural internal capacitances (charges) and the internal and external resistances. When calculating the output power requirements for an IGBT driver circuit, the key parameter is the gate charge.

The gate drive simplified schematic diagram is shown in figure 4.3. It effectively reduces the collector-emitter peak current, and thus protects the IGBT from being destroyed during soft short circuit conditions at high di/dt

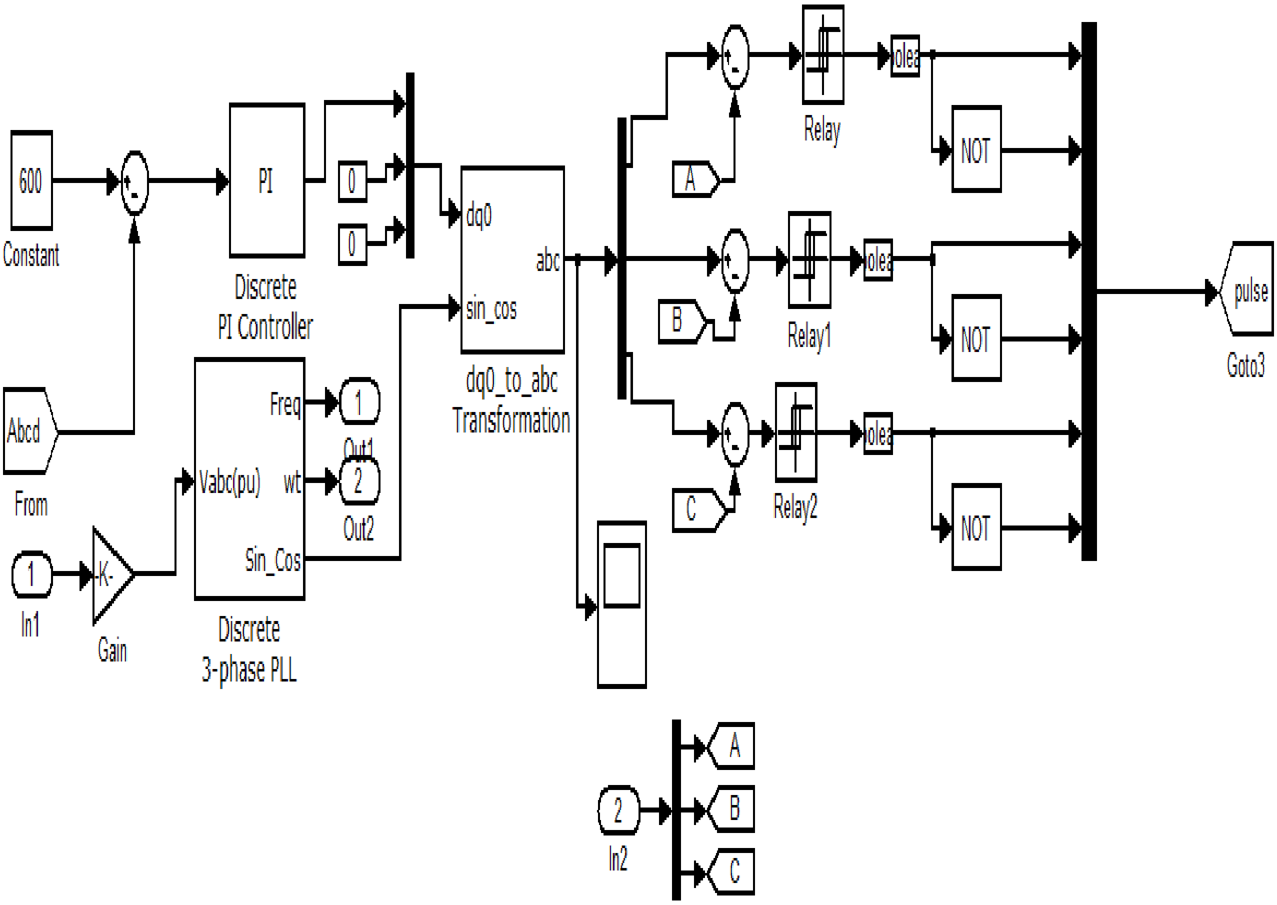


Figure 4.3: Gate triggering circuit of IGBT

4.4 SIMULATION OF PROPOSED MODEL

Figure 4.4 shows the simulation model of vsc based 18 pulse converter. A common 3 phase 415V input supply is given to all three transformers, each transformer is connected with a bridge rectifier circuit. All the 6 pulse converter are connected in cascade manner to give boosted dc output. Gate triggering circuit is represented in the form of subsystem in the simulation. Each converter produces 600V dc output. Resistance of 300 ohm is taken as load at the end of each converter. The proposed model is simulated in MATLAB version 7.10.0.

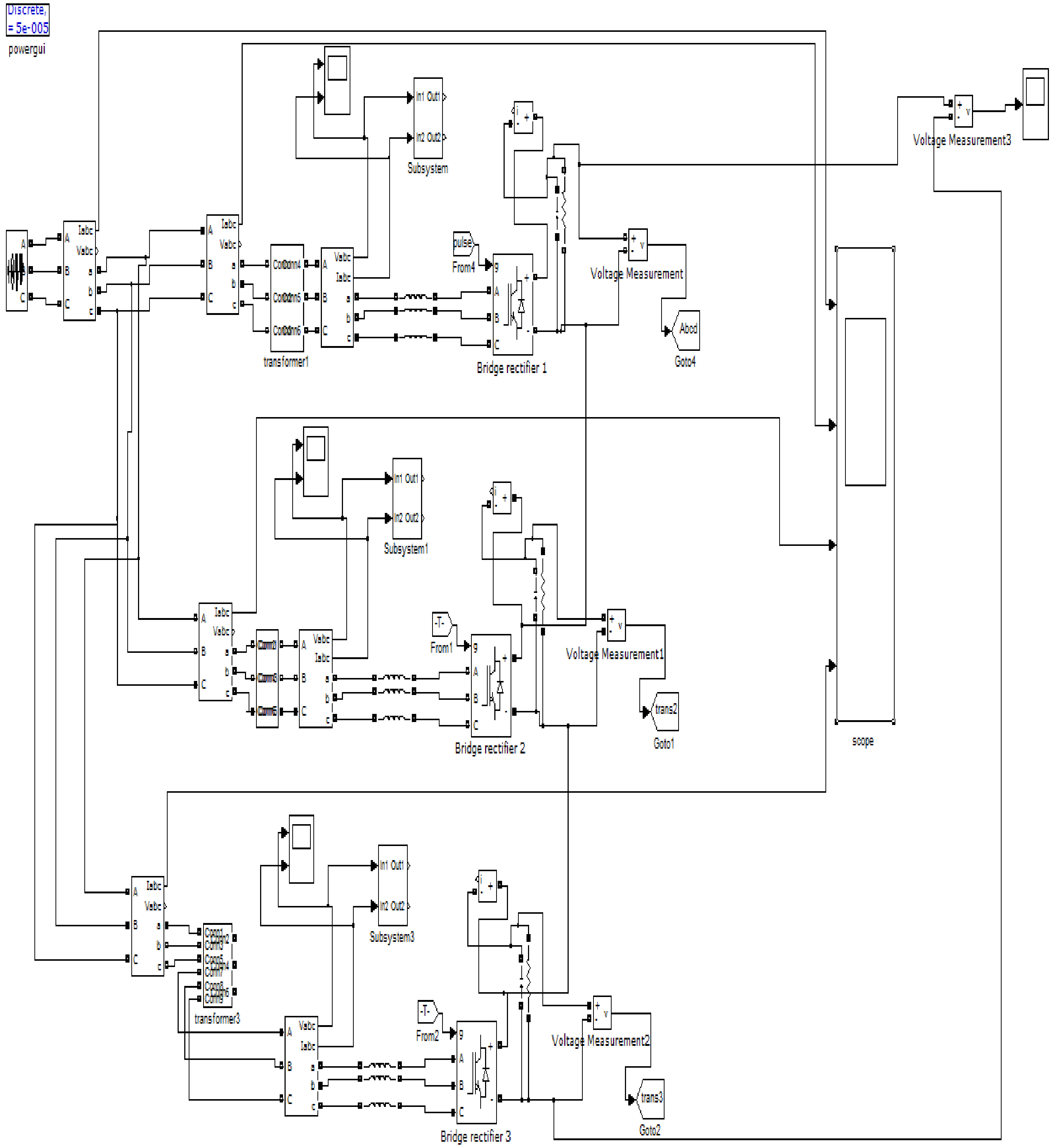
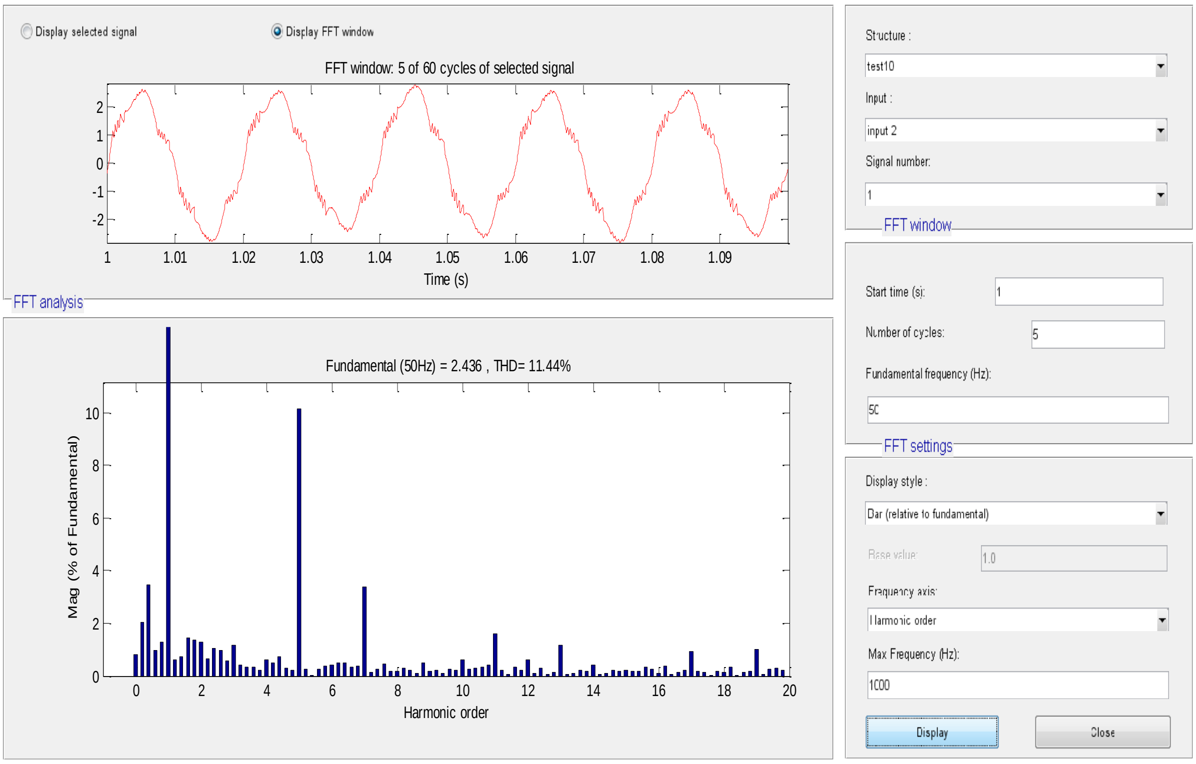


Figure 4.4: Simulation model of VSC based multipulse converter

4.5 RESULT AND CONCLUSION

Figure 4.5, 4.6 and 4.7 shows the total harmonic distortion at ac mains side of all three transformers respectively.



Structure : test10

Input : input 2

Signal number: 1

Start time (s): 1

Number of cycles: 5

Fundamental frequency (Hz): 50

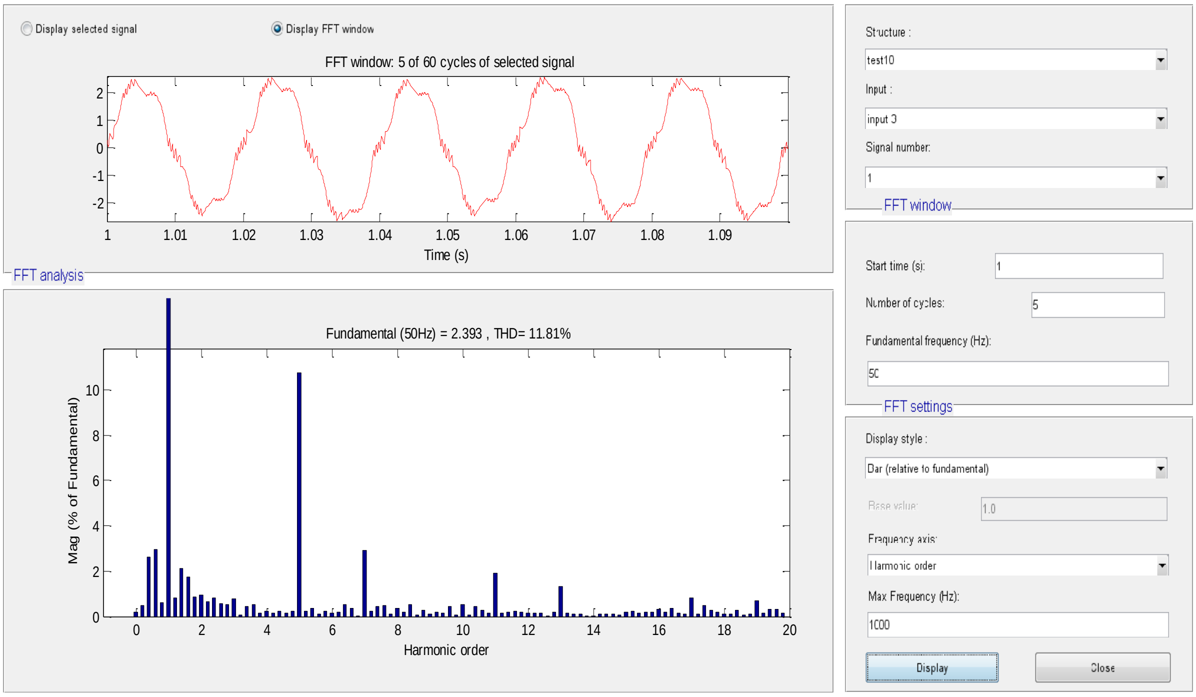
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig. 4.5 THD of transformer 1 at ac mains side



Structure : test10

Input : input 3

Signal number: 1

Start time (s): 1

Number of cycles: 5

Fundamental frequency (Hz): 50

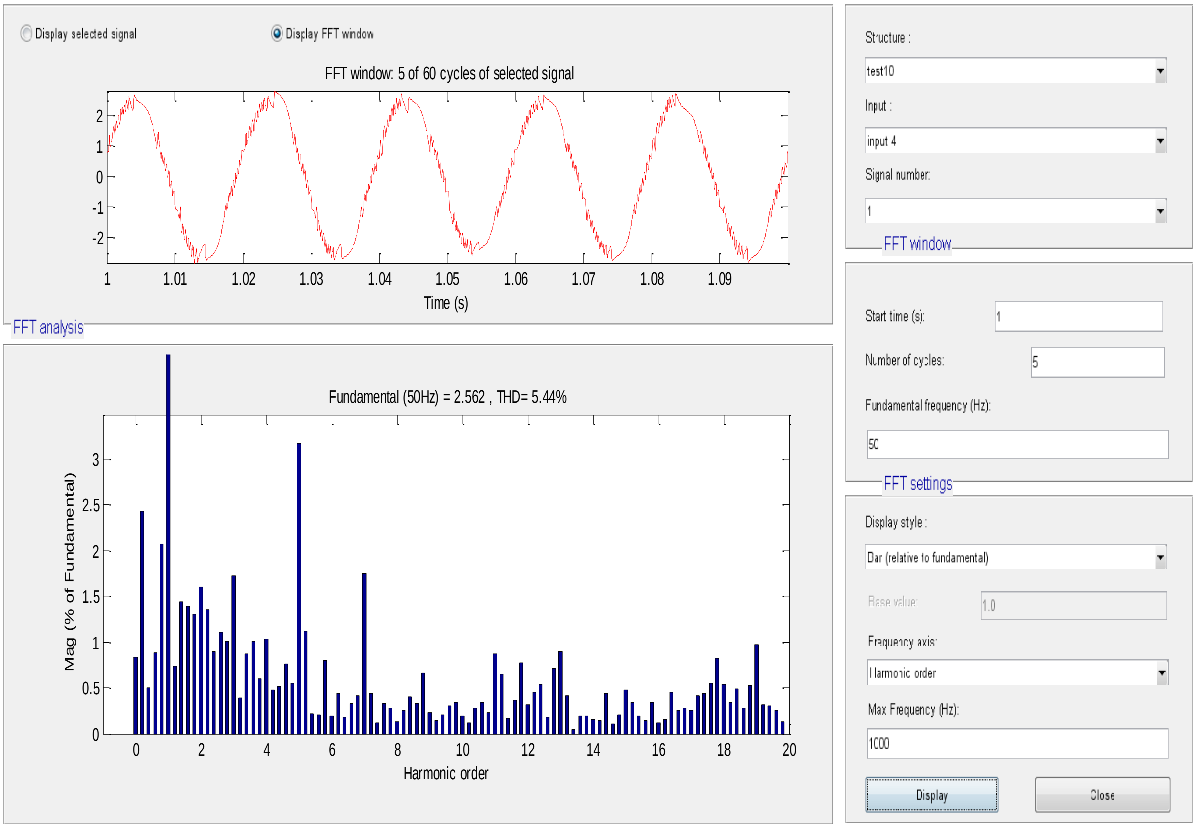
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig. 4.6 THD of transformer 2 at ac mains side



○ Display selected signal

● Display FFT window

FFT window: 5 of 60 cycles of selected signal

Fundamental (50Hz) = 2.562 , THD= 5.44%

Structure : test10

Input : input 4

Signal number: 1

Start time (s): 1

Number of cycles: 5

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig. 4.7 THD of transformer 3 at ac mains side

By cascading the dc output at the end of converters we get boosted and ripple free dc output as well as input ac. Figure 4.8 and 4.9 shows the result for cascade converter.

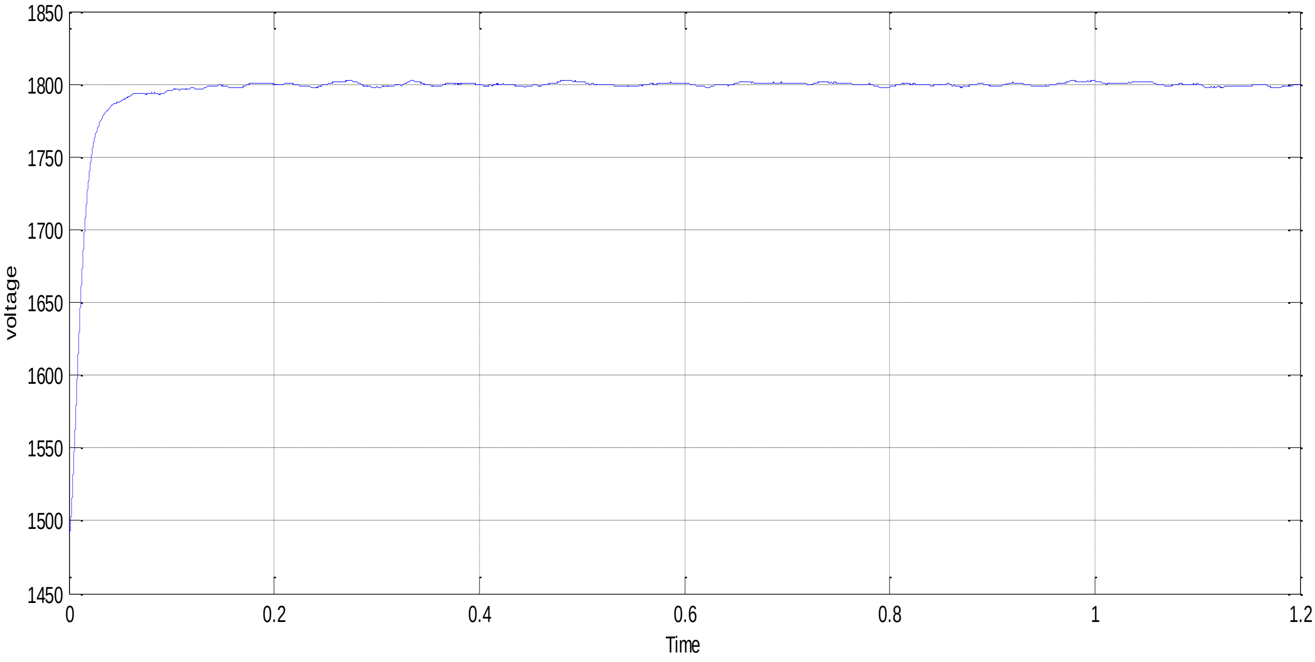


Fig. 4.8 DC output of multipulse converter

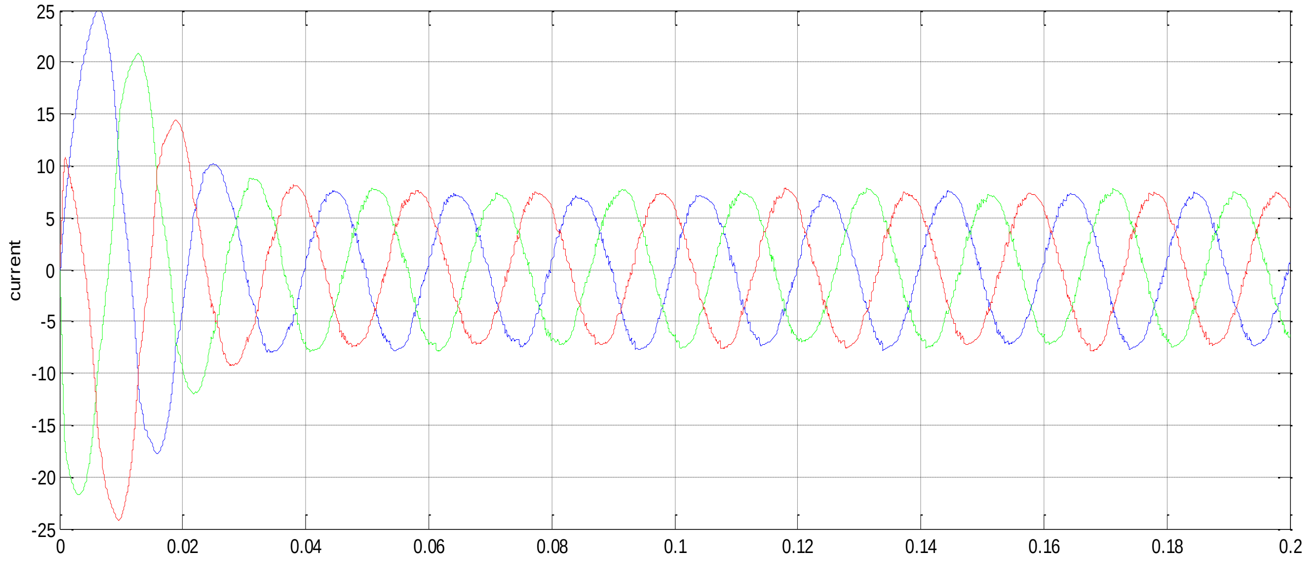
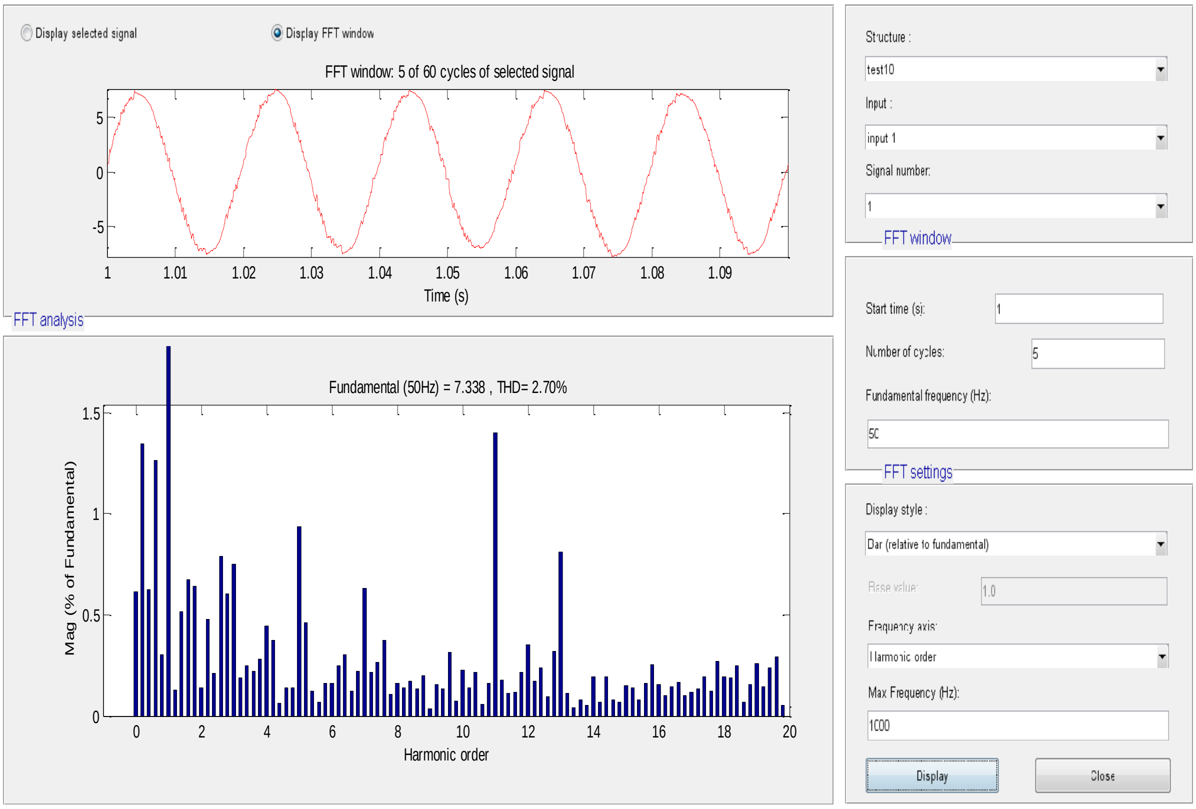


Fig. 4.9 Input current wave form of cascaded converter

The THD of cascaded converter at ac mains is reduced to **2.70 %** as shown below in figure 4.10.



○ Display selected signal ● Display FFT window

FFT window: 5 of 60 cycles of selected signal

Fundamental (50Hz) = 7.338 , THD= 2.70%

Structure : test10

Input : input 1

Signal number: 1

Start time (s): 1

Number of cycles: 5

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig. 4.10 THD of cascaded converter at ac mains side

The analysis of total harmonic distortion (THD) of individual transformer and overall system at ac mains side and corresponding dc voltage at dc side is as shown in the table 4.1.

TABLE 4.1 THD ANALYSIS AT AC MAINS SIDE

	INPUT VOLTAGE	**THD**	**DC VOLTAGE**
TRANSFORMER 1	415 V	11.44 %	600 V
TRANSFORMER 2	415 V	11.81 %	600 V
TRANSFORMER 3	415 V	5.44 %	600 V
CASCADED TRANSFORMERS	415 V	2.70 %	1800 V

CONCLUSION

In this chapter, 18 pulse voltage source converter using IGBT in place of diode rectifier is realised. It has been observed that the total harmonic distortion is reduced to 2.7%, which meets the IEEE standard, by using IGBT converter. It has also been observed that boosted, smooth and reduced rippled DC voltage is obtained at output end.

CHAPTER 5

SIMULATION AND DESIGN OF 18 PULSE AND 24 PULSE BACK TO BACK SYSTEM WITH NONLINEAR LOAD

5.1 INTRODUCTION

Three phase voltage-source inverters (VSIs) are employed in many grid-connected applications [7] such as static var compensators, uninterruptible power systems, and distributed generating systems (e.g., photovoltaic, wind power, etc.). High-power semiconductor switches with reasonable switching frequency have become more available and it is expected that there will be more inverter applications in small-scale power generation (up to 1 MVA). In order to control the VSIs and achieve a proper power flow regulation in a power system, voltage-oriented control, which provides a good dynamic response by an internal current control loop, is widely used [6-12]. This chapter proposes a control solution that provides high quality of current and voltage to the system and, therefore, high power quality. When two asynchronous AC system need to be interconnected for bulk power transmission or for AC system stabilization reason, a back to back high voltage dc arrangement is used. Back to back system gives your own system more flexibility and can prevent you from having to build a new generation network. The power flow is fast and accurate and prevents widespread blackouts from occurring. In recent years, there has been a considerable increase in the use of uninterruptible power supply (UPS) to provide a low output voltage distortion, fast dynamic response, high reliability and continuous power supply system especially for sensitive and critical loads, which cannot afford have unexpected power failure. Critical loads such as computer systems, hospitals and airline reservation systems need UPS. Low total harmonic distortion (THD) and high efficiency are commonly required in high power applications, such as three-phase inverter systems. Nonlinear loads and non-sinusoidal currents can cause more voltage drops on the supply network impedance resulting in unbalanced conditions. They also cause electromagnetic Interference (EMI) and resonances. The harmonics have negative influence on the control and automatic equipment protection systems and other electrical loads, resulting in reduced reliability and availability

In this chapter, simulation and design of 18 and 24 pulse back to back system with nonlinear load is presented.

5.2 PROPOSED SCHEME

Figure 5.1 shows the complete scheme of the system in the form of block diagram three phase inverter is added to the previous system along with nonlinear load. Nonlinear load consists of three phase diode rectifier along with filter capacitor and load resistor. Subsystem block represents gate control of inverter

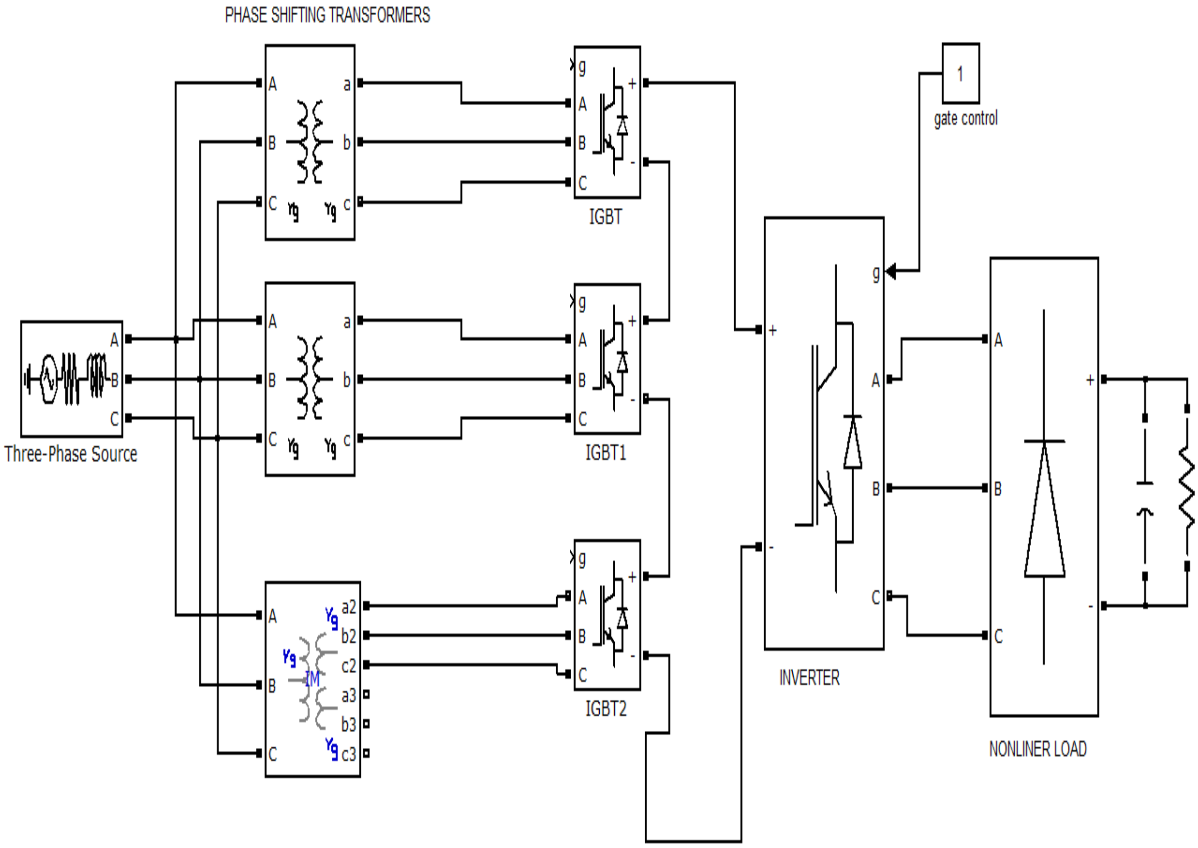


Fig. 5.1 model for 18 pulse converter inverter system

5.3 CONTROL OF INVERTER

Two control loops involved in the inverter control strategy [13-21]. The inner control loop is fast which controls output current and the dc link voltage is controlled by an external voltage loop. For power quality issues like low THD and good power factor the current control loop is responsible, whereas voltage control loop balances the power flow in the system. Synchronous reference frame control which is also called d-q control, uses a reference frame transformation abc to dq which transforms the current and voltages into d-q frame. The phase and frequency are detected by transformed voltage, whereas the current is controlled by transformed current. Thus the control variables becomes dc values, hence filtering and controlling becomes easier. The schematic of the d-q control is shown in Fig.5.2. The DC link voltage sets reference for active current control, whereas reactive power control reference is set to zero, because reactive power control is not done here. A reference must be set in the system if the reactive power has to be controlled.

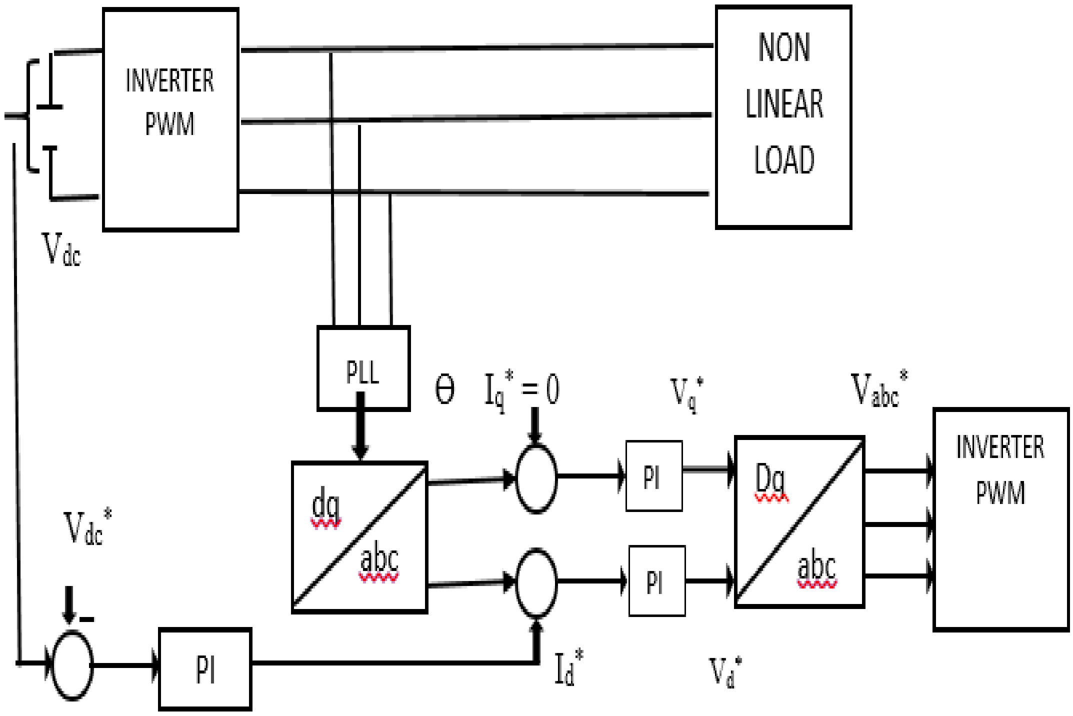


Fig.5.2 General structure for synchronous rotating d-q reference frame control.

Phase lock loop(PLL)

For the inverter control system synchronizations plays important role. Synchronization [16] of the output frequency and phase voltage with current has to be done using different transformation in PLL. PLL techniques causes one signal to track another one. The output signal is synchronized with a reference input signal in frequency and phase. Using the d-q transformation and with a proper design of loop filter PLL can be implemented in three phase grid connected system In PLL Vabc is the sensed grid voltage which is transformed in to DC components using coordinate transformation abc-dq and the PLL gets locked by setting Vd * to zero. The loop filter PI is a low pass filter. It is used to suppress high frequency component and provide DC controlled signal to voltage controlled oscillator (VCO) which acts as an integrator. To obtain inverter phase angle θ, the output of PI controller, which is a inverter output frequency, is integreted. PLL becomes active when the difference betwwen output voltage phase angle and invereter phase angle is reduced tozero.This results in synchronously rotating voltages Vd = 0 and Vq gives magnitude of output voltage.

The inverter output frequency locked by PLL is 314 rad/sec which is 50 Hz. The simulation results of PLL shown in figure 5.3, indicated that the error of output phase detector becomes zero and equal to reference voltage V_d*, when output voltage phase angle equals to inverter phase angle, and lock is set by PLL. *Sinθ* and *Cosθ* required for abc-dq and dq- abc transformation in control loop is generated by the output controlled signal from PI regulator to VCO. Figure 5.4 shows the general structure of 3 phase d-q PLL. To obtain zero phase error and to detect accurate inverter phase angle PI controller gain is varied. By locking PLL at zero crossing and at every instant of time between 0 to 2π, synchronization is achieved between output of inverter phase and output voltage phase angle. The abc to dq current transformation results in dc component of I_d and I_q components. The active current which is necessary to feed active power is controlled by I_d component.

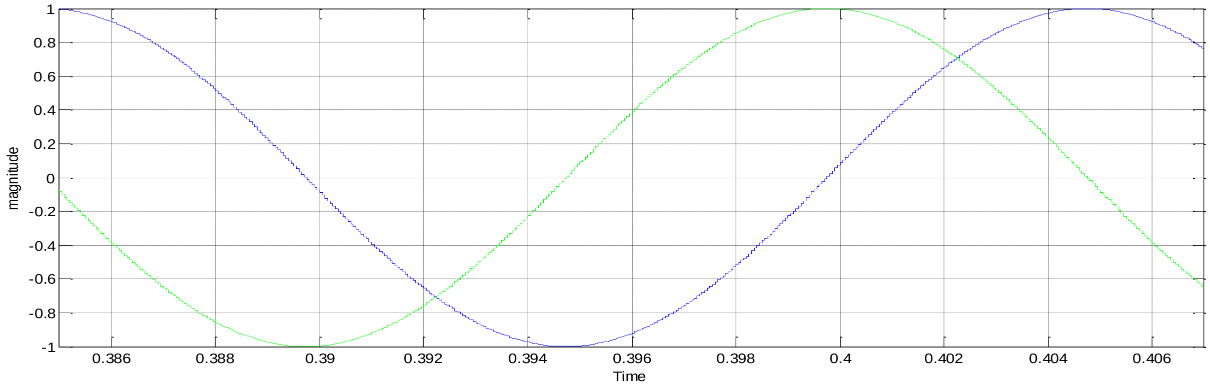


Fig.5.3. Sine and cos wave generated by PLL

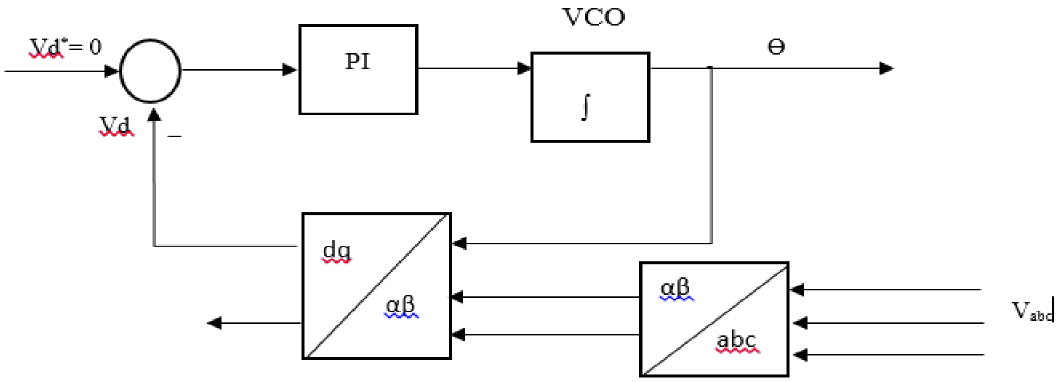


Fig.5.4 General Structure of three phase d-q PLL

5.4 SIMULATION MODEL OF 18 PULSE BACK TO BACK SYSTEM WITH NONLINEAR LOAD

Figure 5.5 shows the proposed simulation model of 18 pulse converter inverter system with nonlinear load. A common 3 phase 415V input supply is given to all three transformers, each transformer is connected with a bridge rectifier circuit. All the 6 pulse converter are connected in cascade manner to give boosted dc output. This dc output is given to inverter which is connected with nonlinear load.

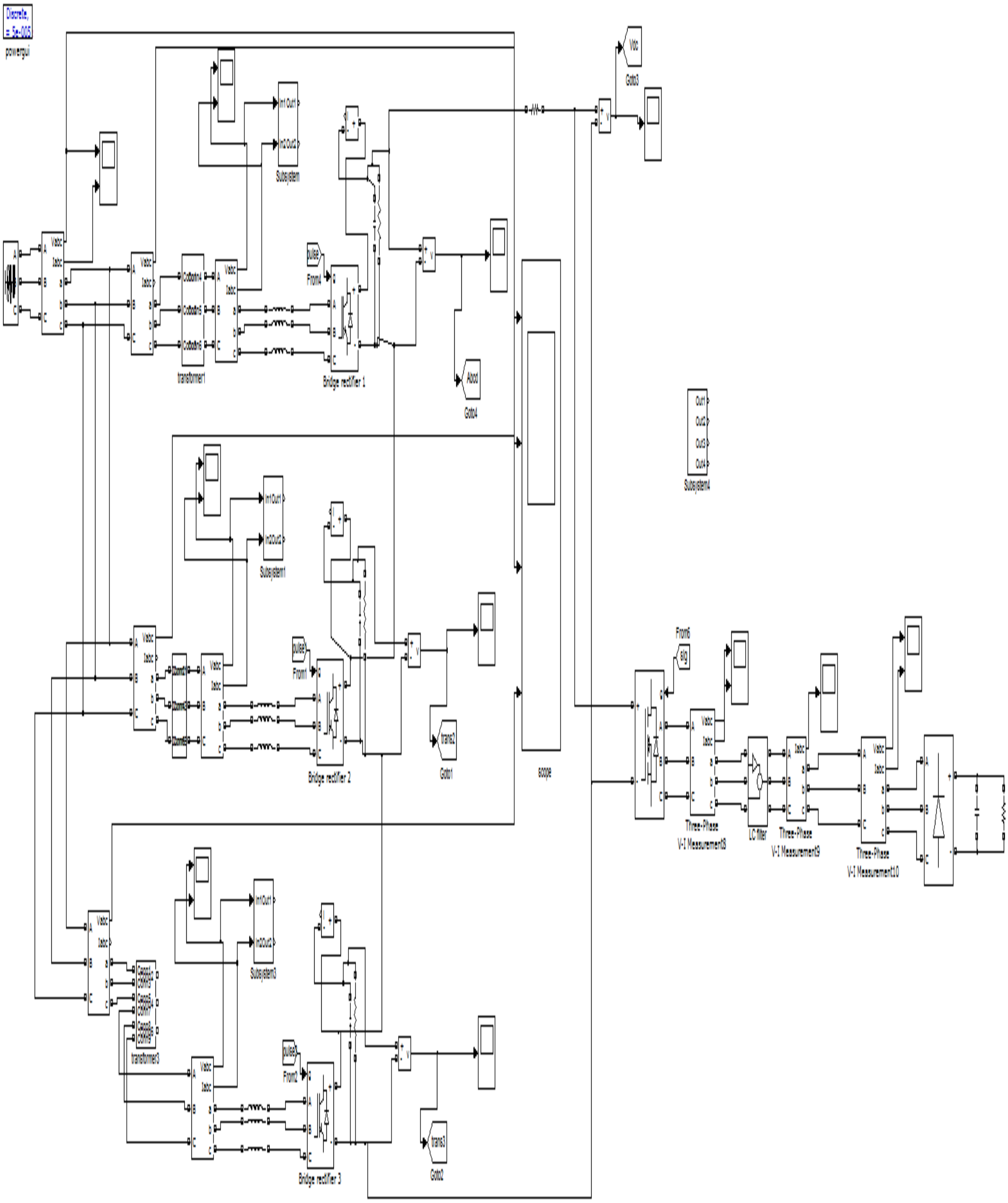
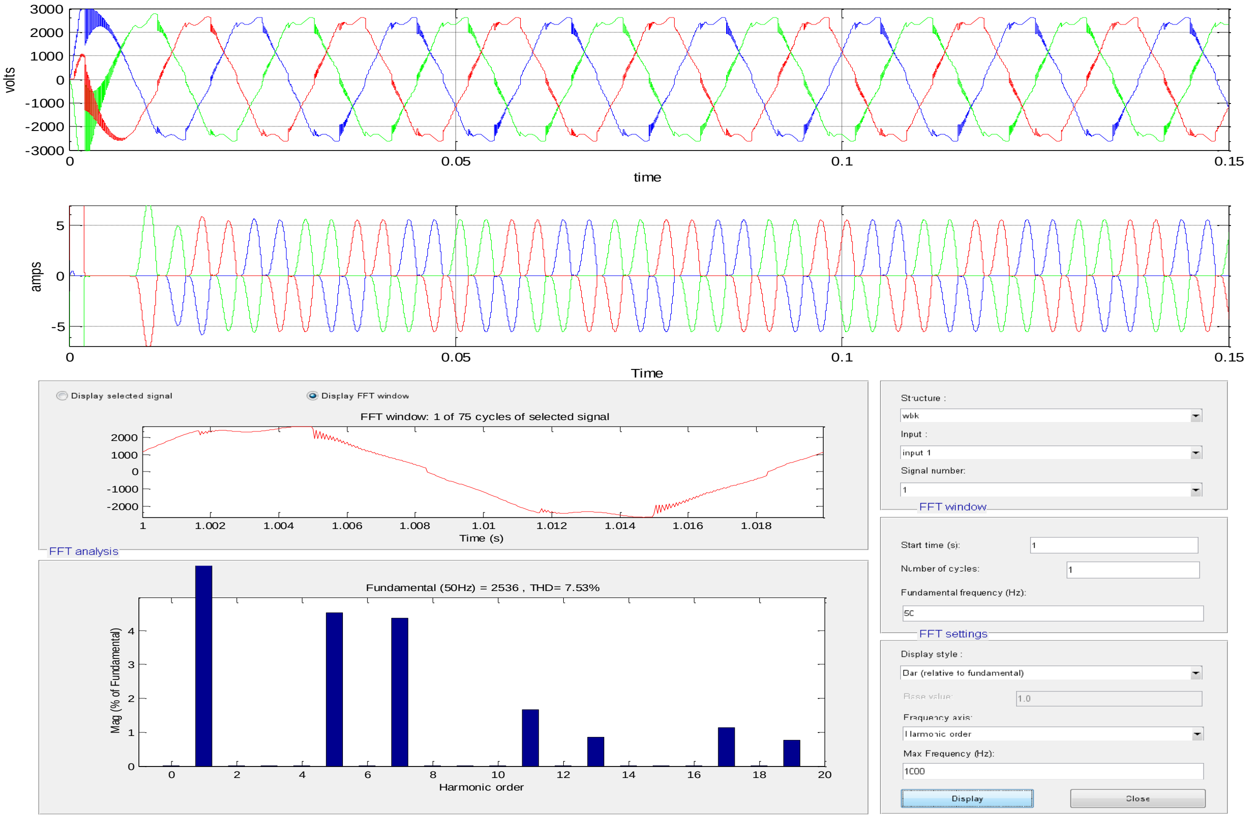


Fig.5.5 Simulink model of 18 pulse system with nonlinear load

5.5 RESULT AND CONCLUSION

The above proposed model is tested with nonlinear load and the results carried out which are shown below. Figure 5.6-5.9 shows, V-I graph and THD with nonlinear load consists of R_L = 1000 Ω, it has been observed that THD is reduced to 2.23% at ac mains side.



Structure : wbk

Input : input 1

Signal number: 1

Start time (s): 1

Number of cycles: 1

Fundamental frequency (Hz): 50

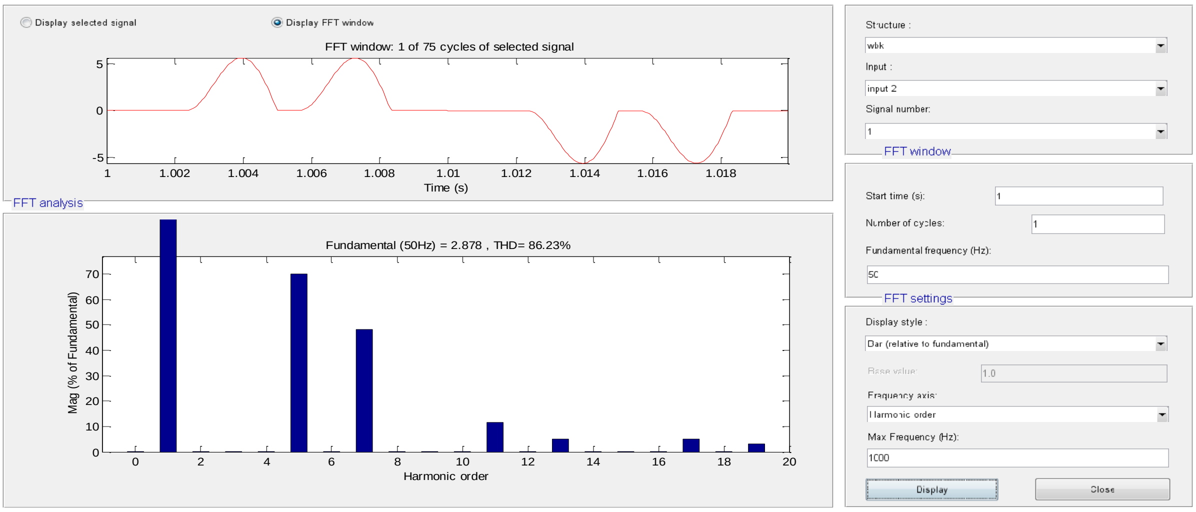
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig 5.6 Load side V-I wave form and voltage THD



Structure : wbk

Input : input 2

Signal number: 1

Start time (s): 1

Number of cycles: 1

Fundamental frequency (Hz): 50

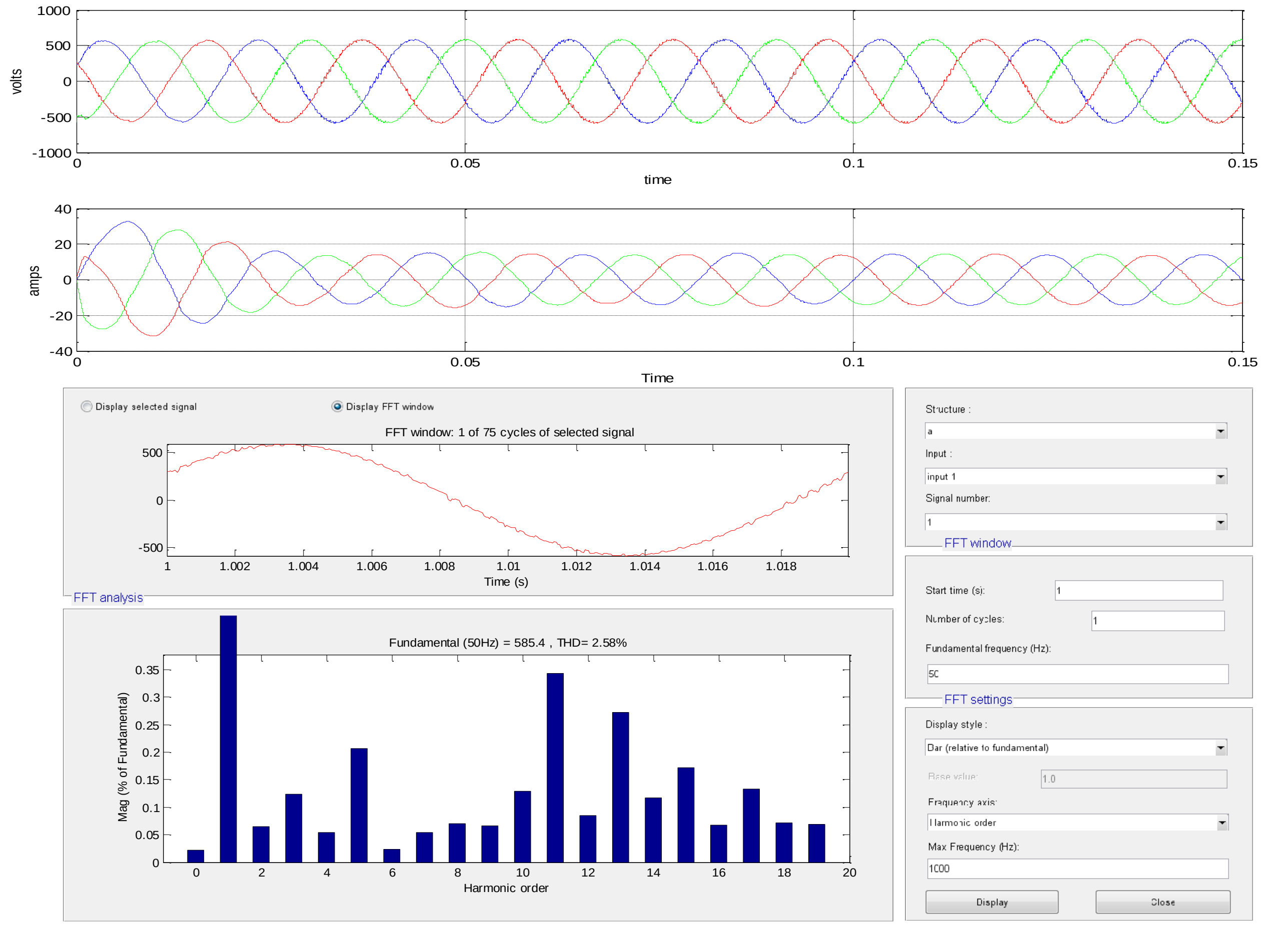
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig 5.7 load side current THD



Structure : a

Input : input 1

Signal number: 1

Start time (s): 1

Number of cycles: 1

Fundamental frequency (Hz): 50

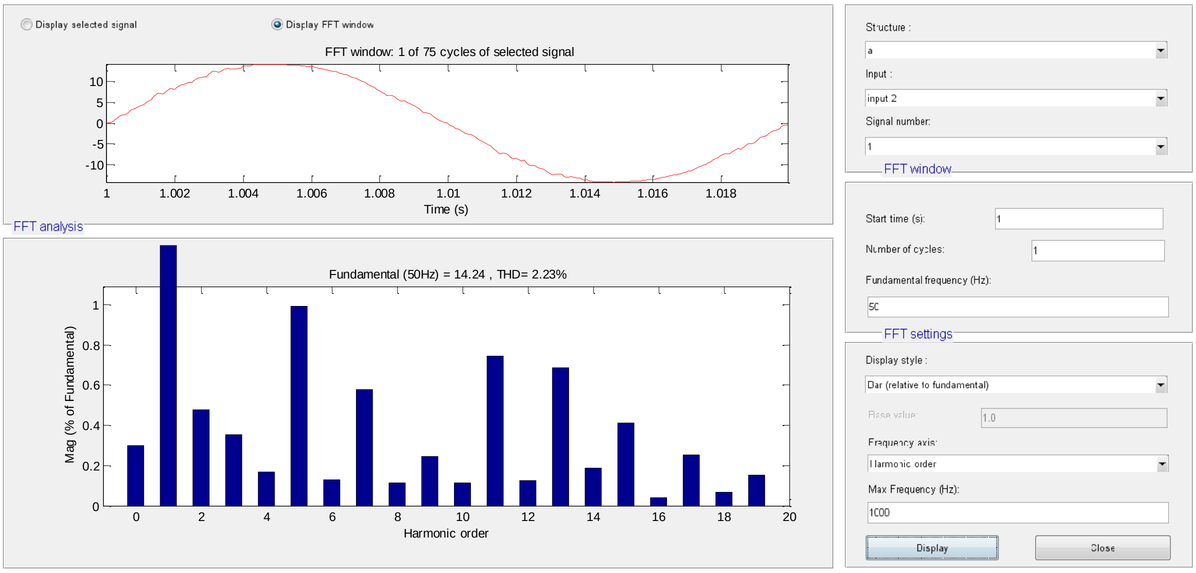
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig 5.8 source side V-I wave form and voltage THD



Structure : a

Input : input 2

Signal number: 1

Start time (s): 1

Number of cycles: 1

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig 5.9 source side current THD

Table 5.1 shows the analysis of THD for the 18 pulse system with nonlinear load consisting of diode rectifier and load resistor of 1000 ohm.

TABLE 5.1 THD OF 18 PULSE SYSTEM AT NONLINEAR LOAD

load side V	load side I	THD % Voltage	THD% current	source side V	source side I	THD% voltage	THD% current
2630	5.6	7.53	86.23	592	14.5	2.58	2.23

5.6 MODEL FOR 24 PULSE BACK TO BACK SYSTEM WITH NONLINEAR LOAD

Figure 5.10 shows the proposed model for 24 pulse system for which phase shifting of $+15^0$, -15^0, 30^0,and 0^0 , in transformers has been implemented. In this model, one extra 6 pulse converter is added to the previous system to make complete 24 pulse system.

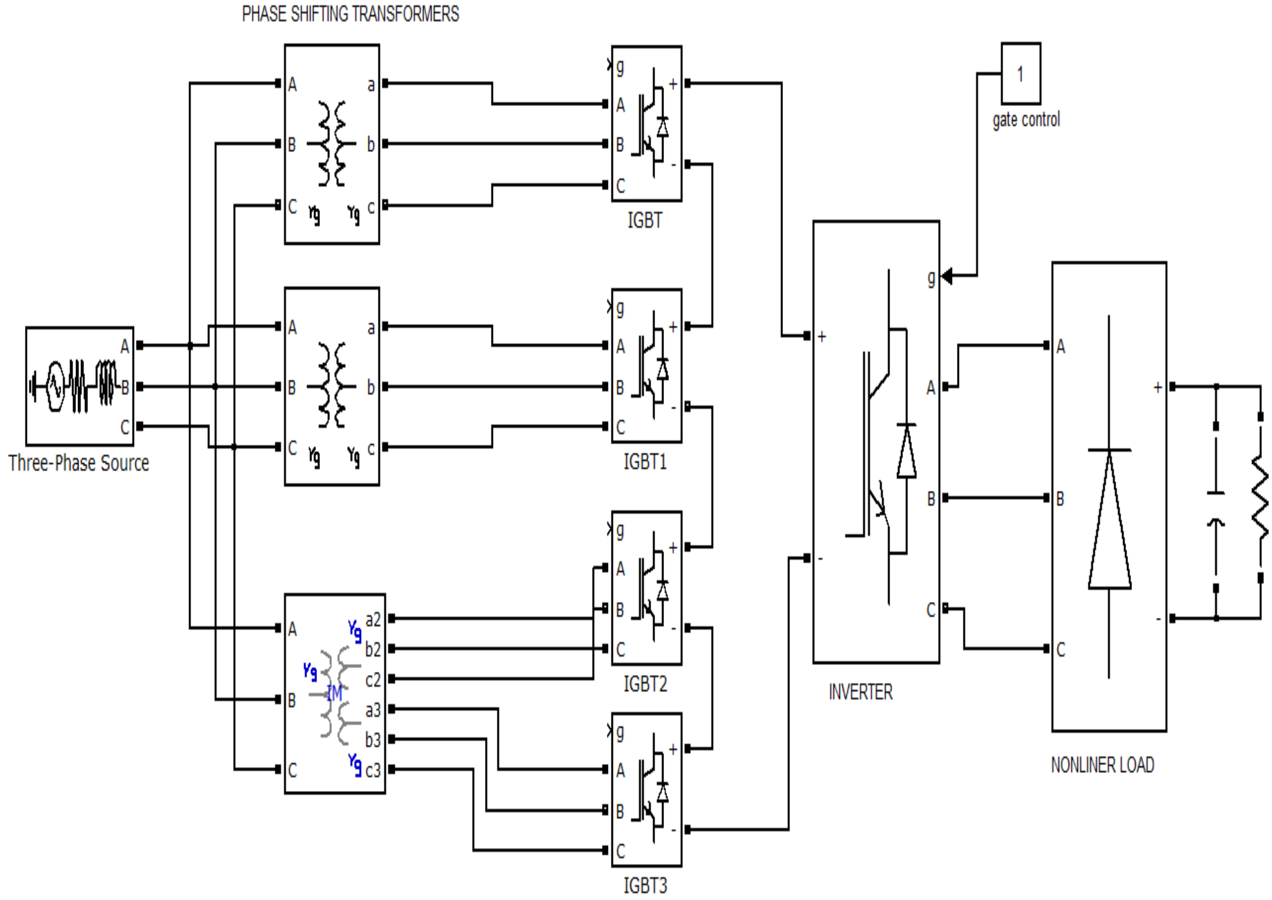


Fig. 5.10. Model for 24 pulse converter inverter system

SIMULINK MODEL

Figure 5.11 shows the simulation model for 24 pulse converter inverter system in which a common 3 phase 415V supply is given to each transformer. The diode rectifier along with load resistor of 1000 ohm is taken as nonlinear load. Subsystem in this model represents the control technique of inverter.

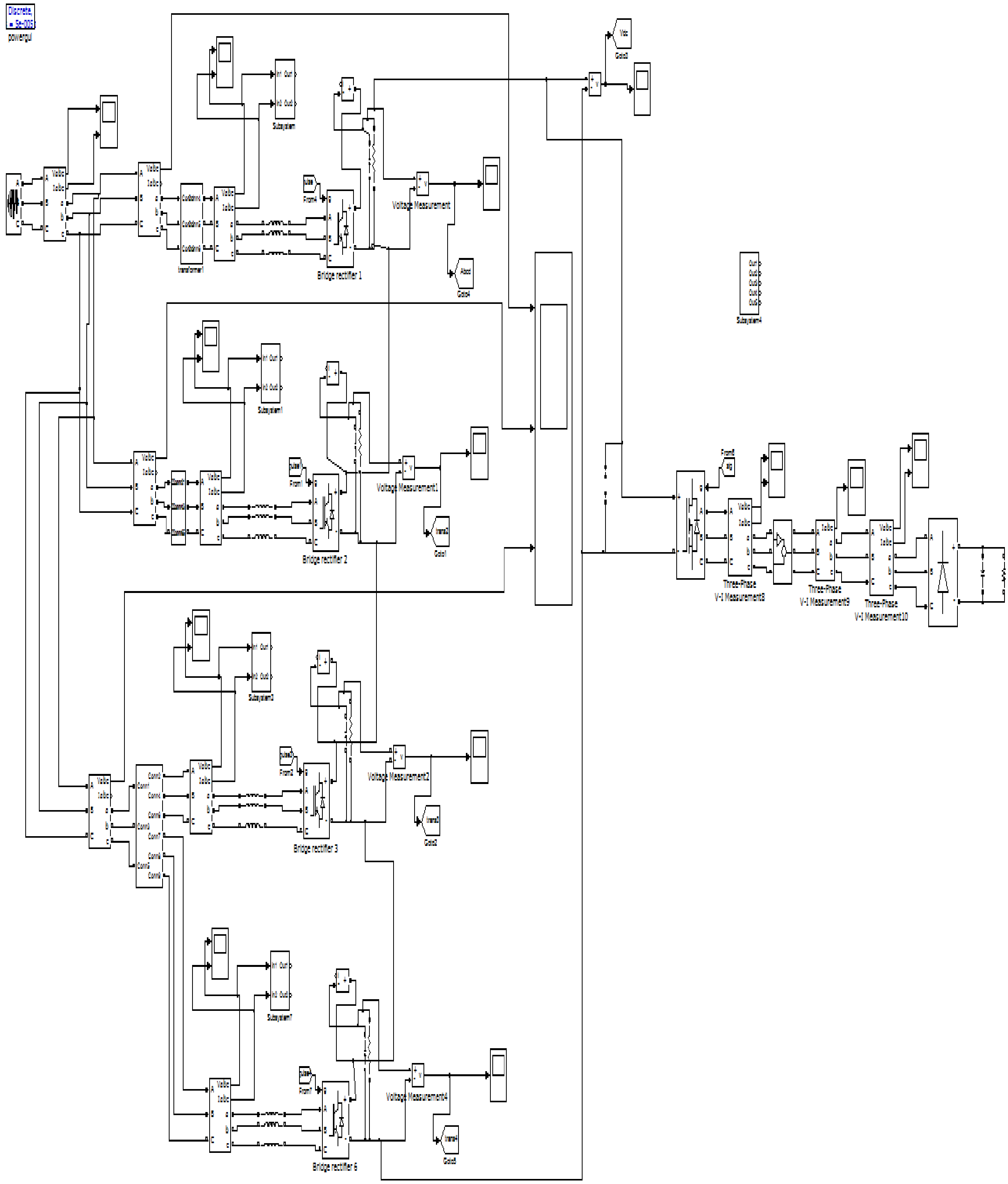


Fig. 5.11.Simulink model for 24 pulse converter inverter system

5.7 RESULT OF 24 PULSE BACK TO BACK SYSTEM WITH NONLINEAR LOAD

Figure 5.12–5.16 shows the result of proposed model at nonlinear load with load resistor R_L=1000Ω

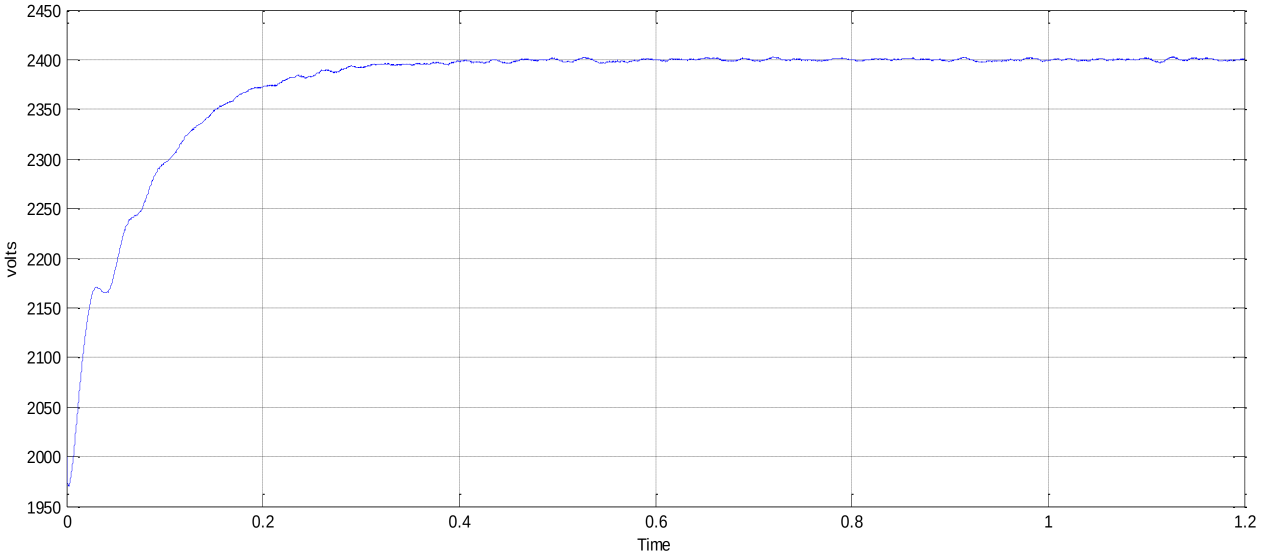
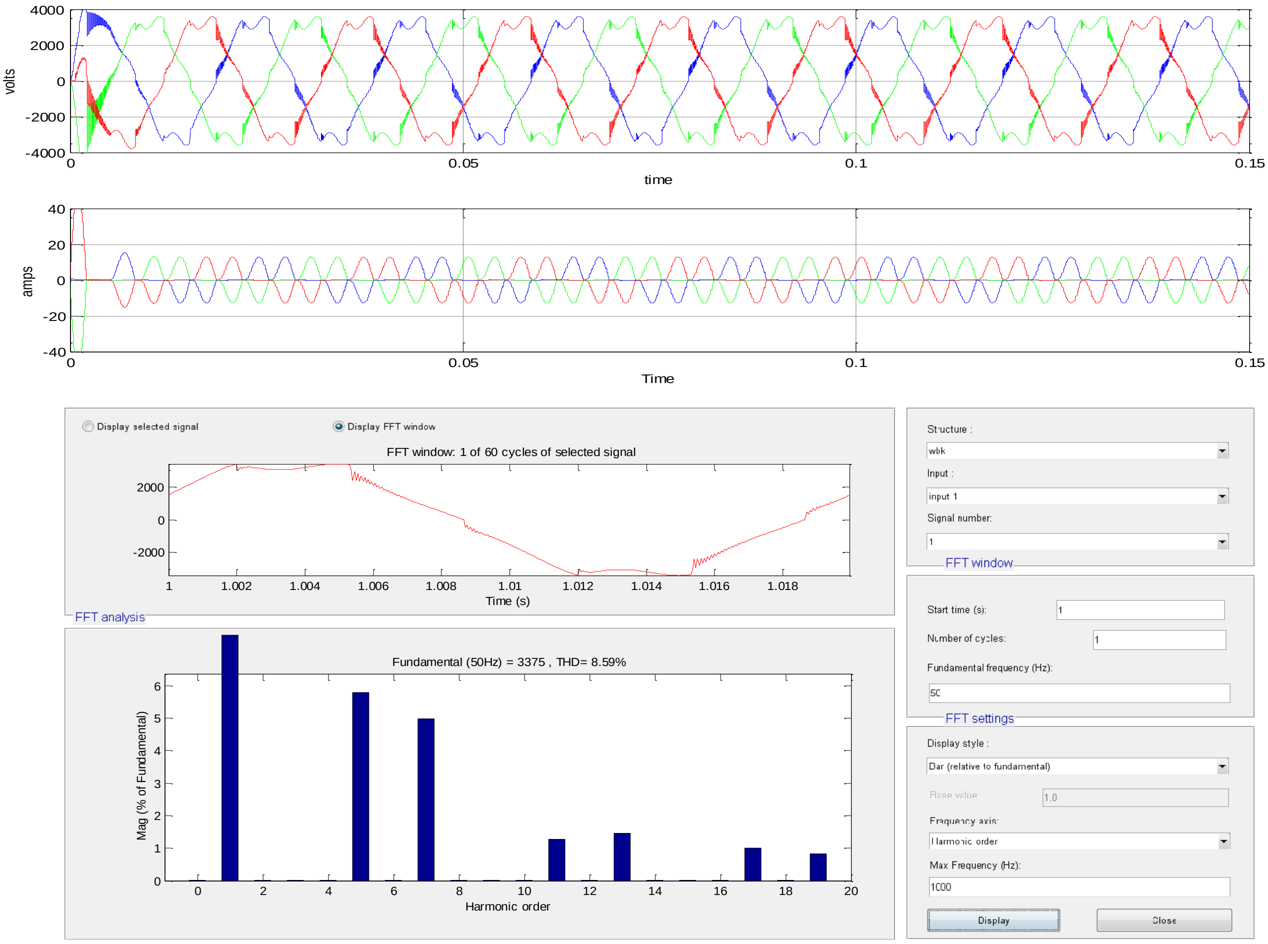


Fig. 5.12 DC output of 24 pulse system



Fundamental (50Hz) = 3375 , THD= 8.59%

Structure : wbk

Input : input 1

Signal number: 1

Start time (s): 1

Number of cycles: 1

Fundamental frequency (Hz): 50

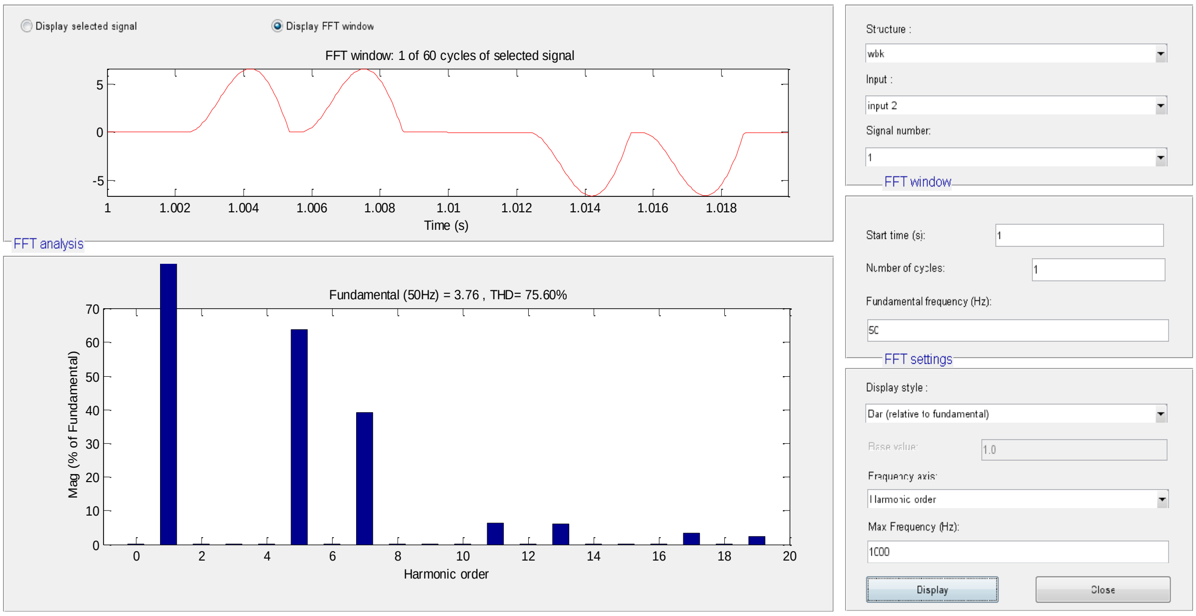
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig. 5.13 Load side V- I wave form and voltage THD graph



Structure : wbk

Input : input 2

Signal number: 1

Start time (s): 1

Number of cycles: 1

Fundamental frequency (Hz): 50

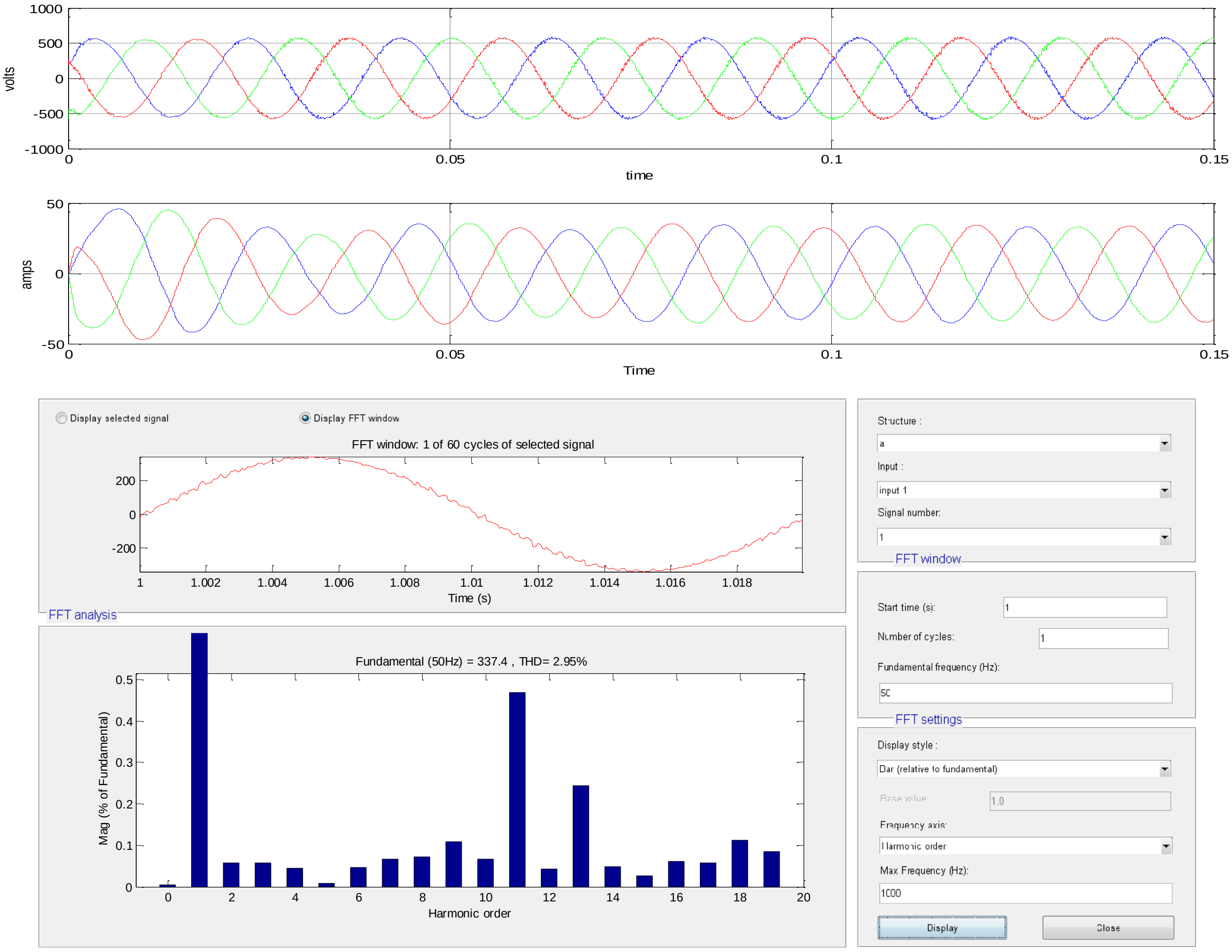
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig 5.14 load side current THD



Structure : a

Input : input 1

Signal number: 1

Start time (s): 1

Number of cycles: 1

Fundamental frequency (Hz): 50

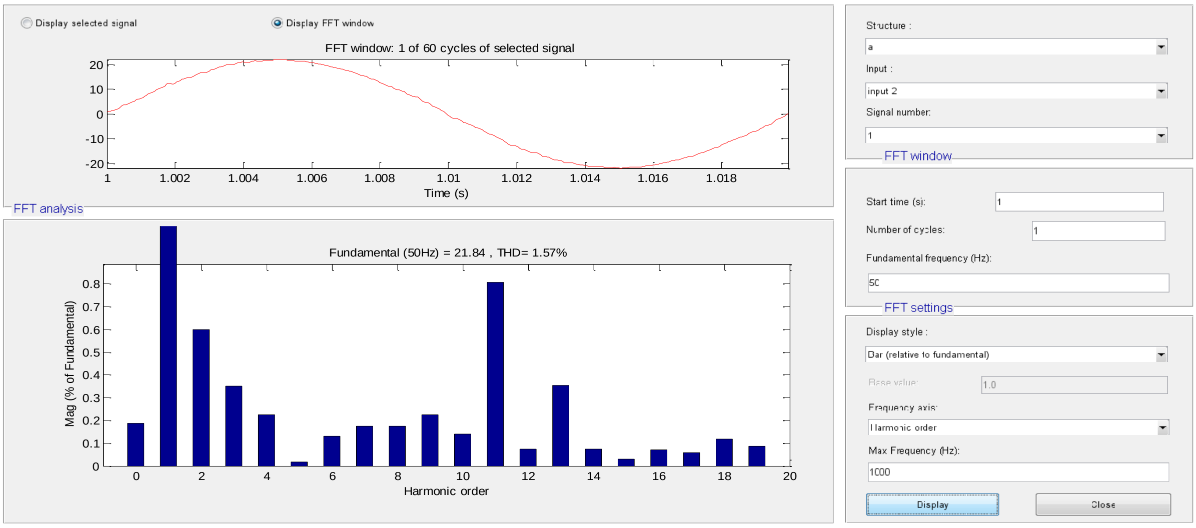
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 1000

Fig. 5.15 source side V-I waveform and voltage THD



○ Display selected signal
● Display FFT window

Structure : a
Input : input 2
Signal number: 1

FFT window
Start time (s): 1
Number of cycles: 1
Fundamental frequency (Hz): 50

FFT settings
Display style : Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order
Max Frequency (Hz): 1000

Fig. 5.16 source side current THD

Table 5.2 shows the analysis of THD for the 24 pulse system system with nonlinear load consisting of diode rectifier and load resistor of 1000 ohm.

TABLE 5.2 THD OF 24 PULSE SYSTEM AT NONLINEAR LOAD

load side V	**load side I**	**THD % voltage**	**THD% current**	**source side V**	**source side I**	**THD% voltage**	**THD% current**
3600 V	6.5 A	8.59	75.60	588 V	22 A	2.95	1.57

5.8 CONCLUSION

In this chapter 18 & 24 pulse back to back converter is designed. It has been observed that the harmonic effect of non linear load on the ac mains side is reduced to 1.57% from 2.23% by switching over from 18 to 24 pulse converter. The quality of power is improved and this was the main aim of this research work. One of the major objective to increase the number of pulse in ac–dc converters is to improve the power quality at input ac mains and output dc load in a wide variety of applications.

CHAPTER 6

CONCLUSION AND SCOPE OF FUTURE WORK

6.1 GENERAL:

The main impact of the multipulse converter on the power system is a reduction of ac input line current harmonics. Certain harmonics, which are related to the number of converters, are eliminated from the power source by connecting these converters in appropriate manner. Multipulse converters give a simple and effective technique for reducing power electronic converter harmonics.

6.2 SUMMARY OF CONCLUSION :

This research work mainly focused on the reduction of the total harmonic distortion on ac mains side in a back-to back configuration with nonlinear load. Some of the main findings in this research are as mentioned below:

- The concept for phase shifting of transformer is presented. Design of 18 pulse diode based converter using phase shifting transformer is carried out using simulation. This simulation is realised on hardware model and a comparison between simulink model and practical model is carried out. In this case the THD is observed to be 6.9%. Further it is seen that there is not much difference between simulink model and hardware model. The small difference is because of the transformer practical imperfections such as magnetising current and copper losses which are ignored in the basic design but must be included when system affects are evaluated. In practical transformer, there is imperfect flux coupling which causes the transformers to exhibit a leakage inductance.
- The main drawbacks of conventional ac–dc converters have been harmonic injection into ac mains. In this work IGBT based 18 pulse Voltage source converter is realised for the conversion of power. It has been observed that the total harmonic distortion is reduced to 2.7%, which meets the IEEE standard, by using IGBT converter. It has been also observed that boosted, smooth and reduced rippled DC voltage is obtained at output end.
- One of the major objective to increase the number of pulse in ac–dc converters is to improve the power quality at input ac mains and output dc load in a wide variety of applications. In this research work it has been observed that the harmonic effect of non linear load on the ac mains side is reduced to 1.57% from 2.23% by increasing the

number of pulse from 18 to 24, which is a great achievement to the researcher. The quality of power is improved and this was the main aim of this research work.

6.3 FUTURE WORK

Future work of the present research work includes:

- Inverter control in case of line voltage asymmetry.
- Design and implementation of the system for dynamic load.
- Design and implementation of the system with grid connected system.

REFERENCES

[1] D. A. Paice, “Power Electronic Converter Harmonics: Multipulse Methods for Clean Power”. *New York: IEEE Press,* 1996.

[2] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, “A review of three-phase improved power quality ac-dc converters,” *IEEE Trans. Ind. Electron.*, vol. 51, no. 3, pp. 641–660, Jun. 2004.

[3] B.Singh, S.Gairola, B.N.Singh, A.Chandra, and K.A.Haddad, “Multi-pulse AC-DC Converter for Improving Power Quality: A Review‖” *IEEE Transactions on Power Delivery*, Vol.23 No.1 January 2008.

[4] D. Madhan Mohan, Bhim Singh and B. K. panigrahi –“Selection of Dead Angle of a Three Level Multipulse Voltage Source Converter for Power Quality Improvement in HVDC System”, 2009 *Third International Conference on Power Systems, Kharagpur, INDIA* December 27-29

[5] B. Singh, G. Bhuvaneswari, and V. Garg, “An improved power-quality 30-pulse ac–dc converter for varying loads,” *IEEE Trans. Power Delivery*, vol. 22, no. 2, pp. 1179–1187, Apr. 2007.

[6] D. Madhan Mohan B. Singh B.K. Panigrahi, “Harmonic optimised 24-pulse voltage source converter for high voltage DC systems”, *IET Power Electron*., 2009, Vol. 2, Iss. 5, pp. 563– 573

[7] M. Hagiwara, H. Fujita and H. Akagi, “Performance of a Self- Commutated BTB HVDC Link System under a Single-Line-to-Ground Fault Condition,” *IEEE Trans. on Power Electronics.* vol. 18, no. 1, pp. 278-285, 2003.

[8] M. Hagiwara, H. Fujita and H. Akagi, “Performance of a Self- Commutated BTB HVDC Link System under a Single-Line-to-Ground Fault Condition,” *IEEE Trans. on Power Electronics.* vol. 18, no. 1, pp. 278-285, 2003.

[9] Rakesh Maurya, Pramod Agarwal and S.P.Srivastava, “Performance Investigation of Multipulse Converter for Low Voltage High Current Applications” *IEEE International Conference on Computer Science and Automation Engineering (CSAE)*, vol.1, pp.211-216, Shanghai, 10-12, June 2011.

[10] D. Madhan Mohan, Bhim Singh and B. K. panigrahi “Selection of Dead Angle of a Three Level Multipulse Voltage Source Converter for Power Quality Improvement in HVDC System”, *2009 Third International Conference on Power Systems, Kharagpur, INDIA* December 27-29

[11] Giampaolo Buticchi, Emilio Lorenzani and Claudio Bianchini, “Optimal system control of back to back power converter for wind grid connected converter” *2^{nd} IEEE ENERGYCON conference & exhibition, 2012 / advance in energy conversion symp*.

[12] Song Xu, Haifeng Wang, “Simulation and analysis of back-to-back PWM converter for flywheel energy storage system”.

[13] Milan Pradanovic& Timothy Green, “Control and filter design of three phase inverter for high power quality grid connection”, *IEEE transactions on Power Electronics,*Vol.18. pp.1- 8, January 2003

[14] Abad Lorduy, Antonio Lázaro, Andrés Barrado, Cristina Fernández, Isabel Quesada and Carlos Lucena, “Simplified Synchronous Reference Frame Control of the Three Phase Grid Connected Inverter”.

[15] Xiaorui Wang, Hao Ma,” Research on Feedback Linearization Control of Three-Phase Inverter Based on Inverse System”. *2012 IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia* June 2-5, 2012,

[16] Miss. Sangita R Nandurkar, Mrs. Mini Rajeev “Design and Simulation of three phase Inverter for grid connected Photovoltic systems”. *Proceedings of Third Biennial National Conference, NCNTE*- 2012, Feb 24-25

[17] Leonardo Augusto Serpa, Srinivas Ponnaluri, Peter Mantovanelli Barbosa, and Johann Walter Kolar, “A Modified Direct Power Control Strategy Allowing the Connection of Three-Phase Inverters to the Grid Through LCL Filters”. *IEEE Transaction on industry application,* vol. 43, no. 5, September/October 2007

[18] M. Hagiwara, H. Fujita and H. Akagi, “Performance of a Self- Commutated BTB HVDC Link System under a Single-Line-to-Ground Fault Condition,” *IEEE Trans. on Power Electronics.* vol. 18, no. 1, pp. 278-285, 2003.

[19] Akira nabae, satoshi ogasawara and Hirofumi Akagi, “A Novel Control Scheme for Current-Controlled PWM Inverters” *IEEE Transactions on industry application,* vol. IA-22, no. 4, july/august 1986

[20] Satoshi Ogasawara, Jin Takagaki, Hirofumi Magi,and Akira Nabae, “A Novel Control Scheme of a Parallel Current-Controlled PWM Inverter” *IEEE Transactions on industry application,* vol. 28, no. 5, sep/oct 1992.

[21] Kurt Schenk and Slobodan Cuk, “A simple three-phase power factor corrector with improved harmonic distortion”.

[22] S. Kim, P. N. Enjeti, P. Packbush, and I. J. Pitel, “A new approach to improve power factor and reduce harmonics in a three-phase diode rectifier type utility interface,” *IEEE Trans. Ind. Applicat.*, vol. 30, no. 6, pp. 1557–1564, Nov./Dec. 1994.

[23] M. Rastogi, R. Naik, and N. Mohan, “A comparative evaluation of harmonic reduction techniques in three-phase utility interface of power electronic loads,” *IEEE Trans. Ind. Applicat.*, vol. 30, no. 5, pp. 1149–1155, Nov./Dec. 1994

[24] Sewan Choi, Prasad N. Enjeti, and Ira J. Pitel, “ Poly phase transformer arrangements with reduced kVA capacities for harmonic current reduction in rectifier type utility interface”. *IEEE Transactions on industry power electronics,* vol. 11, no. 5, September 1996.

[25] Dudi *A.* Rendusara, Annette von Jouanne, Prasad N. Enjeti, and Derek *A.* Paice, “Design Considerations for 12-Pulse Diode Rectifier Systems Operating under Voltage Unbalance and Pre-Existing Voltage Distortion with Some Corrective Measures” *IEEE Transactions on industry application,* vol.. 32, no. 6, nov/dec 1996

[26] J. Salmon, A. Love, and E. Bocancea, “Performance of low distortion 3-phase diode rectifiers using resonant harmonic correction networks,” in *Proc. IEEE IAS’97,* 1997, pp. 1344–1351

[27] Y. Nishida and M. Nakaoka, “A new harmonic reducing three-phase diode rectifier for high voltage and high power applications,” in *Proc. IEEE IAS’97,* 1997, pp. 1624–1632.

[28] D. Rendusara, K. J. Slater, B. S. Lee, and P. Enjeti, “Design considerations for 12/24 pulse connected rectifier for large VA, PWM drive system,” in *Proc. 14th Annu. IEEE Conf.-Appl. Power Electron. Conf. Expo. APEC ’99,* Mar. 14–18, 1999, vol. 2, pp. 903–909

[29] P. Pejovic and Z. Janda, “An improved current injection network for three-phase high-power-factor rectifiers that apply the third harmonic current injection,” *IEEE Trans. Ind. Electron.*, vol. 47, no. 2, pp. 497–499, Apr. 2000.

[30] U. Borup, F. Blaabjerg, and P. N. Enjeti, “Sharing of nonlinear load in parallel-connected three-phase converters,” *IEEE Trans. Ind. Applicat.*,vol. 37, no. 6, pp. 1817–1823, Nov.–Dec. 2001.

[31] N. R. Raju, A. Daneshpooy, and J. Schwartzenberg, “Harmonic cancellation for a twelve pulse rectifier using dc bus modulation,” in *Proc. IAS’02,* Oct. 13–18, 2002, vol. 4, pp. 2526–2529

[32] L. Wei, N. Guskov, R. A. Lukaszewski, and G. Skibinski, “Mitigation of current harmonics for multi-pulse diode front end rectifier systems,” *IEEE Trans. Ind. Applicat.*, vol. 43, no. 3, pp. 787–797, May–Jun. 2007.

[33] B. S. Lee, and P. Enjeti, “Design considerations for 12/24 pulse connected rectifier for large VA, PWM drive system,” in *Proc. 14th Annu. IEEE Conf.-Appl. Power Electron. Conf. Expo. APEC ’99*, Mar. 14–18, 1999, vol. 2, pp. 903–909

[34] S. Choi, P. N. Enjeti, H. H. Lee, and I. J. Pitel, “A new active interphase reactor for 12-pulse rectifiers provides clean power utility interface,” *IEEE Trans. Ind. Applicat.*, vol. 32, no. 6, pp. 1304–1311, Nov./Dec. 1996.

[35] Wladyslaw Mielczarski, William B. Lawrance,Rafal Nowacki, and Donald Grahame Holmes, “Harmonic Current Reduction in Three-Phase Bridge-Rectifier Circuits Using Controlled Current Injection” *IEEE Transactions on industrial electronics,* vol. . 44, no. 5, oct 1997

[36] Sewan Choi, Prasad N. Enjeti, Derek A. Paice “New 24-pulse diode rectifier system for utility of high power ac motors drives” *IEEE Transctions on power electronics*, vol.. 11, NO. 5, September 1996.

[37] M.M.R. Ahmed G.A. Putrus L. Ran L. Xiao “Harmonic Analysis and Improvement of a New Solid-stateFault Current Limiter”, *IEEE Trans. Ind. Electron,*2000

[38] Girish R. Kamath, Bruce Runyan and Richard Wood “A Compact Autotransformer based 12-Pulse Rectifier Circuit” IECON'O1: *The 27th Annual Conference of the IEEE Industrial Electronics Society*

[39] F. J. Chivite-Zabalza, A. J. Forsyth, and D. R. Trainer, “Analysis and practical evaluation of an 18-pulse rectifier for aerospace applications,” in *Proc. PEMD 2nd Int. Conf. (Conf. Publ. no. 498)*, 31 Mar.–2 Apr. 2004, vol. 1, pp. 338–343.

[40] M. Peterson and B. N. Singh, “A novel load compensator for a 12-pulse diode converter,” in *Proc. IEEE Conf. Power Electron., Drives, Energy Syst. PEDES ’06*, Dec. 12–15, 2006, pp. 16.

[41] “High Power Converters and AC Drives,” Bin Wu, Institute of Electrical and Electronics Engineering (2006)

[42] L Umanand and S. R. Bhat, “Design of magnetic component for switch mode power converters”. *Wiley eastern limited publications*, 2007

[43] “Transformer and Inductor design” hand book 3rd edition ,*Marcel and Dekker Inc New York* 2004

APPENDIX – I

WIRE SIZE TABLE

SWG	Dia with enamel, mm	Area of bare conductor, mm^2	R/Km @20oC ohms	Weight Kg/Km
45	0.086	0.003973	4,340	0.0369
44	0.097	0.005189	3,323	0.0481
43	0.109	0.006567	2,626	0.061
42	0.119	0.008107	2,127	0.075
41	0.132	0.009810	1,758	0.0908
40	0.142	0.011675	1,477	0.1079
39	0.152	0.013700	1,258	0.1262
38	0.175	0.018240	945.2	0.1679
37	0.198	0.023430	735.9	0.2202
36	0.218	0.029270	589.1	0.2686
35	0.241	0.035750	482.2	0.3281
34	0.264	0.042890	402	0.3932
33	0.287	0.050670	340.3	0.465
32	0.307	0.059100	291.7	0.5408
31	0.33	0.06818	252.9	0.6245
30	0.351	0.07791	221.3	0.7121
29	0.384	0.09372	184	0.8559
28	0.417	0.11100	155.3	1.014
27	0.462	0.13630	126.5	1.245
26	0.505	0.16420	105	1.499
25	0.561	0.20270	85.1	1.851
24	0.612	0.24520	70.3	2.233
23	0.665	0.29190	59.1	2.655
22	0.77	0.39730	43.4	3.607
21	0.874	0.51890	33.2	4.702
20	0.978	0.65670	26.3	5.939
19	1.082	0.81070	21.3	7.324
18	1.293	1.16700	14.8	10.537
17	1.501	1.589	10.8	14.313
16	1.709	2.075	8.3	18.678
15	1.92	2.627	6.6	23.64
14	2.129	3.243	5.3	29.15
13	2.441	4.289	4	38.56
12	2.756	5.48	3.1	49.22
11	3.068	6.818	2.5	61
10	3.383	8.302	2.1	74
9	3.8	10.51	1.6	94
8	4.219	12.97	1.3	116

APPENDIX – II

TRANSFORMERS AND CHOKE LAMINATIONS - STANDARD TYPES

TYPE No.	A_c, cm^2	A_w, cm^2	A_p, cm^4
17	1.61	1.2	1.95
12A	2.52	1.884	4.75
21	2.52	3.32	8.36
10	2.52	4.43	11.2
10A	2.52	4.43	11.2
1	2.789	6.543	18.2
74	3.063	2.28	6.98
23	3.63	2.72	9.88
11	3.63	7.26	26.4
11A	3.63	9.07	32.9
2	3.63	10.89	39.52
30	4	3	12
31	4.94	3.71	18.3
45	4.94	3.71	18.3
15	6.45	4.84	31.2
44	6.45	4.84	31.2
14	6.45	6.55	42.2
4	6.45	15.85	102.2
33	7.84	5.88	46.1
3	10.08	7.54	76
13	10.08	14.11	142.3
4A	11.12	10.26	114
16	14.5	10.89	158
5	14.5	12.73	184.5
6	14.5	19.35	280.8
7	25.8	18.95	488.9
8	25.8	51.23	1,322
34	2.5	6.68	16.3
9	4.4	9.1	44.9
9A	4.9	7.9	38.9
4AX	5.6	13.07	74.1
75	6.5	15.26	98.4
35A	14.5	39.34	570.4
8B	58.1	65.52	3,804
100	103.2	116.1	11,988