CONTROL AND ANALYSIS OF MULTILEVEL INVERTERS FOR POWER QUALITY IMPROVEMENT

THESIS

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by

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DEDICATION

to

My Role Model and Inspiration, My Mother Pratibha Singla

My Motivation, My Husband Aman Sharma

My beloved son Aadvik And My Family

CANDIDATE'S DECLARATION

I hereby declare that this thesis entitled "**CONTROL AND ANALYSIS OF MULTILEVEL INVERTERS FOR POWER QUALITY IMPROVEMENT" by DEEPSHIKHA SINGLA,** being submitted in fulfillment of requirement for the award of Degree of Doctor of Philosophy in the Department of Electrical Engineering under Faculty of Engineering and Technology of J.C.BOSE University of Science and Technology, YMCA, Faridabad, during the academic year 2020-2021, is a bonafide record of my original work carried out under the guidance and supervision of **Dr. P.R.SHARMA, PROFESSOR, DEPARTMENT OF ELECTRICAL ENGINEERING** and has not been presented elsewhere.

I further declare that the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

(DEEPSHIKHA SINGLA)

Registration No. YMCAUST/PH12/2012

CERTIFICATE

This is to certify that this thesis entitled **"CONTROL AND ANALYSIS OF MULTILEVEL INVERTERS FOR POWER QUALITY IMPROVEMENT" by DEEPSHIKHA SINGLA** submitted in fulfilment of the requirement for the award of Degree of Doctor of Philosophy in **DEPARTMENT OF ELECTRICAL ENGINEERING**, under Faculty of Engineering and Technology of J.C.BOSE University of Science and Technology, YMCA, Faridabad, during the academic year 2020-2021, is a bonafide record of work carried out under my guidance and supervision.

I further declare that to the best of my knowledge, the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

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ABSTRACT

The increased use of renewable energy sources like solar power and its integration in the existing grid provide an effective solution in energy utilization. Modern day power sensitive devices demand clean and quality power and thus, Multilevel Inverters (MLIs) are incorporated into the grid. The performance of multilevel inverters with existing control strategies is quite impressive yet there has been the ever felt need for novel mechanisms for controlling the output of multilevel inverter meeting power quality standards.

Cascaded H-Bridge Inverters produce approximate sinusoidal output waveform with high levels but harmonics are introduced, which can be reduced using different modulation techniques. Most of the control techniques are based upon high frequency Sinusoidal Pulse Width Modulation (SPWM), which involves from high switching losses. Total Harmonic Distortion (THD) minimization methods enable a global minimum THD in voltage though low order harmonics may or may not lie within the harmonic limits. Selective Harmonic Elimination (SHE) aims at eliminating specific lower order harmonics, whereas some higher order harmonics exists which can be removed by filtering, thus increasing the cost. So, the main challenge is to design a control technique for MLIs, which produces low harmonic output voltage.

Harmonic Elimination methods convert the equations involving harmonics into an optimization problem which optimizes a set of switching angles using an optimization algorithm. Optimal value of switching angles yields output voltage with minimum harmonics. The work carried out in this thesis involves introducing an objective function capable of producing optimal values with the help of appropriate optimization algorithm. The function not only aims to minimize harmonics but also minimize the deviation of fundamental component of desired voltage. The proposed function is developed based upon the limitations in the existing functions. The technique can be used with Single-phase as well as Three-phase systems for any level of inverter.

The work also involves the selection of best suited algorithm for optimization of proposed minimization function. An appropriate algorithm for the minimization function is chosen depending upon its performance, which can be obtained in terms of

efficiency, reliability, and quality of solution. Cuckoo Search (CS) Algorithm has been proved showing best performance as the set of optimized switching angles gives minimum harmonic profile. Thus, considering the simplicity and efficiency of the Cuckoo Search algorithm for solving the proposed minimization problem, this research work utilized Cuckoo Search optimization for control of multilevel inverter.

This work is an improvement over the existing works, which has been proved through the simulation of Single-phase Five-level, Nine-level, Thirteen-level and Three-phase Five-level Cascaded H-Bridge Inverter using proposed scheme. The work was further extended to realization of Single-phase Cascaded H-bridge configurations on a hardware prototype using Spartan-6 XC6SLX9 FPGA controller. The observations confirm the simulation results and prove the efficiency of CS Optimized Switching scheme. Further, Three-phase Five-level Cascaded H-bridge Inverter is modelled and studied for the power quality parameters.

The work computes various power quality related parameters for to provide a clear vision of the power quality improvement in MLI. A detailed analysis and comparison of the proposed CS Optimized Switching scheme is done and compared against the most common Pulse Width Modulation scheme. Even after lots of research in the field of harmonic minimization, the search to find the best algorithm for optimal control of multilevel inverter will continue to exist.

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LIST OF ABBREVIATIONS

Abbreviation	Details or Expanded Form
MLI	Multilevel Inverter
CS	Cuckoo Search
THD	Total Harmonic Distortion
DCC	Diode Clamped Converter
NPC	Neutral Point Converter
FCC	Flying Clamped Converter
CHB	Cascaded H-Bridge
PWM	Pulse Width Modulation
GS	Gravitational Search
PSO	Particle Swarm Optimization
HS	Harmony Search
SA	Simulated Annealing
TLBO	Teaching Learning Based Optimization
SHE	Selective Harmonic Elimination
RMS	Root Mean Square
LOH	Low Order Harmonics
PF	Power Factor
DF	Distortion Factor
SPWM	Sinusoidal Pulse Width Modulation
SVM	Space Vector Modulation
OHSW	Optimized Harmonic Stepped Waveform
OMTHD	Optimized Total Harmonic Distortion
GA	Genetic Algorithm
DE	Differential Evolution

SVPWM	Space Vector Pulse Width Modulation
CBPWM	Pulse Width Modulation
PDPWM	Phase Disposition Pulse Width Modulation
PODPWM	Phase Opposition Disposition Pulse Width Modulation
APODPWM	Alternate Phase Opposition Disposition Pulse Width Modulation
PODfPWM	Phase Opposition Disposition with Variable Frequency Pulse Width Modulation
NTV	Nearest Three Vectors
SVFFM	Space Vector At Fundamental Frequency
SVC	Space Vector Control
SHEPWM	Selective Harmonic Elimination Pulse Width Modulation
FFT	Fast Fourier Transform
EA	Evolutionary Algorithm

CHAPTER I

INTRODUCTION

1.1. SCOPE

As the research in power electronic sector is increasing and availability of fossil fuels is depleting rapidly, the need to have high quality power is increasing. This is accomplished primarily by utilizing the available renewable energy resources, and/or by improving the efficiency and power quality of power electronic converters [1]–[3]. Existing modulation strategies do not perform best to enhance the power quality of Multilevel Inverters (MLIs). Therefore, the need arises to devise some new methodologies to enhance the performance of MLIs.

The intention of this research is to contribute in the existing field of modulation techniques in multilevel inverters. More precisely, it addresses the pros and cons along with the difficulties and restrictions that may occur in existing methods. A multilevel fundamental switching scheme is proposed for the control of switches in multilevel inverter. Furthermore, various algorithms have been explored and the best algorithm is chosen to optimize the objective function with much better efficiency, reliability, and quality of solution. Cuckoo Search (CS) Algorithm is recommended as showing the best performance with minimum iterations required, less time and 100% efficiency. The task is accomplishes using a mathematical computing software, *MATLAB and Simulink*, by *MathWorks* which support data analysis, developing algorithms, and simulation.

This thesis present the outcomes attained in the research work "*Control and Analysis of Multilevel Inverters for Power Quality Improvement*" executed and implemented by the author during the period *May 2012 to June 2019*. The simulation and execution results obtained have been already presented and published in reputed journals or conference papers, added at the end of the thesis. The consequence of this research is the proposal of a new modulation technique that has been realized for Single-phase as well as Three-phase systems. An experimental set up has been done for Single-phase 5-level, 9-level and 13-level and Three-phase five-level inverter. Validation of proposed method and results has been made with the help of simulation and practical results.

1.2. BACKGROUND AND MOTIVATION

The need to provide quality power to the sensitive power electronic world led to the growth and evolution of DC/AC power converters in power sector [4], [5]. Unfortunately, the inherent switched nature of modern power electronic converters is accompanied by undesirable harmonics, switching stress, and many other problems. Though, it is obvious that significant improvements in the quality of output voltage and converter losses can be obtained by increasing the voltage levels produced at the output of converter. So, a multilevel converter is a power electronic circuit capable of generating such voltages [6]. In comparison to a two-level converter, a multilevel converter has reduced harmonic distortion and less switching stress. By increasing the number of levels, the output waveform of a multilevel converter becomes smoother and approximate to a sine wave; however with more levels both the circuit component count and complexity increase.

There is a valid requirement of optimal modulation technique to improve the performance of multilevel inverter in terms of less harmonics and better power quality. Nowadays, most of the research is dedicated to harmonic minimization/elimination using pre-designed objective functions to reduce the harmonic content of the output as revealed by the Total Harmonic Distortion (THD) and hence the power quality. The literature discusses such problems as inappropriate objective function, or optimization method, and other problems like switching power losses and filter sizing of the output associated with the proposed control for MLIs. These problems are addressed and worked upon in order to develop more efficient approach to control multilevel inverters, while minimizing the computational effort needed and other factors. However, the desire to find obtain the best optimal strategy for power quality improvement of multilevel inverters will continue to remain the area of interest in the coming years.

1.3. POWER QUALITY

Electrical power is one of the important issues that most effects the economic development of our society. Since the beginning of the use of electricity, the continuous improvement of generation, distribution and use of electricity attempts to meet the ever increasing quality and performance needs of most sectors [7]–[10].

Even then the need for effective control and efficient use of electric power has resulted in massive proliferation of power electronic converters in almost all areas of electric power such as in industry, utility, and commercial applications [11]–[15]. These power electronic converters are basically DC to AC converters that generate a square wave leading to harmonic related problems. However, the ability of Multilevel Inverters to achieve power conversion by synthesizing a staircase voltage waveform has replaced two-level inverters. The attractive features of a multilevel converter can be briefly summarized as staircase waveform quality, minimum harmonic distortion, common-mode voltage, switching frequency, input current, reduced EMI/RFI generation, etc. However, they suffer from certain drawbacks too, like requirement of greater number of power semiconductor switches, complex modulation strategies, and some more. Despite these limitations, multilevel inverters (MLIs) can be viewed as sophisticated power conversion systems for high power medium voltage applications [16]–[19]. Furthermore, the design of effective control for multilevel inverter to ensure minimum total harmonic distortion (THD) and better quality waveform has always been a challenging task.

What exactly is Power Quality? The question can be answered with different perspective, but surely it involves the waveforms of current and voltage in an AC system, the presence of harmonics in bus voltages and load currents, the presence of momentary low voltages, spikes, and other issues of distortion. Possibly the power quality can be defined as, “the provision of voltages and system design so that the user of electric power can utilize electric energy from the distribution system successfully, without interference or interruption” [8]. A broad definition of power quality borders on system reliability, outages, voltage unbalance in three-phase systems, power electronics and their interface with the electric power supply and many other areas. The concern for Power Quality has increased with the growing use of sensitive and susceptive electronic equipment (e.g. personal computers, computer-aided design workstations, printers, uninterruptible power supplies, fax machines, etc) and some other nonlinear loads (e.g. fluorescent lighting, adjustable speed drives, heating and lighting control, arc welders, etc).

As, Power Quality is a worldwide subject, use of related standards becomes mandatory. A number of standards are available which have been provided by various technical organizations like IEEE, IEC, ANSI and more. These standards aid to

monitor and maintain values of power quality parameters such as voltage harmonics, current harmonics, etc. The standards IEC 61000 and IEEE 1159 are mainly related to Power Quality. IEC 61000 discusses safety requirements, limits, testing methods, whereas IEEE 1159 includes details of power quality monitoring devices, application techniques, and the interpretation of monitoring results. The standard ANSI/IEEE 519-1992 (IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems) focus on the harmonic limits recommended for voltage and current signals in power system [20]. It doesn't give any information for determining the harmonic content at Point of Common Coupling (PCC). A revision of this standard has been published in 2014 as IEEE 519-2014 [21]. Table 1.1 shows the individual and total harmonic distortion limits for voltages at a PCC as a function of the bus. Table 1.2 defines limits for current harmonics and Total Demand Distortion (TDD) based on the PCC voltage and bus short circuit capability.

Table 1.1 Voltage Distortion Limits as per IEEE 519-2014

Bus Voltage V at PCC	**Individual harmonic (%)**	**Total Harmonic Distortion THD (%)**
$V \leq 1$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5

Table 1.2 Maximum Harmonic Current Distortion in Percent of I_L as per IEEE 519-2014

Individual Harmonic Order (odd harmonics)						
I_{SC}/I_L	**3≤h<11**	**11≤h<17**	**17≤h<23**	**23≤h<35**	**35≤h<50**	**TDD**
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

1.4. MULTILEVEL INVERTERS

Conventional two-level voltage source converters have been widely used, but the advent of Multilevel Inverters has revolutionized the power electronic sector [2], [22]. MLIs have ability to yield higher voltage levels from lower rating of semiconductor switch resulting in a much better output power than two or three level inverters. A multilevel inverter not only achieves high power ratings, but also enables the use of capacitors, batteries, and even renewable energy voltage sources as the multiple dc voltage sources. J.S.Lai and F.Z.Peng [6], introduces the three common topologies of multilevel-voltage source converters: Diode Clamped, Flying Capacitor, and Cascaded H-Bridge with separate dc sources; their operating principle, features, constraints, and potential applications [16].

1.4.1. Diode Clamped Multilevel Inverter

The first topology of MLIs, by arranging a number of power switches, was introduced by Nabae, Takahashi, and Akagi in 1981[23]. Basically, a three-level diode-clamped inverter was proposed as neutral point converter. Further, the configuration in more levels has been used by several other researchers for many applications. Diode Clamped MLI uses a common DC bus for all the three phases and levels are divided by use of (n-1) capacitors for n-levels. The structure uses diodes to limit the voltage stress of power devices.

The voltage of each capacitor and each switch is V_{dc}. An n level inverter needs (n-1) voltage sources or DC link capacitors, 2(n-1) power switches and (n-1)*(n-2) diodes. A single-phase five-level Diode Clamped Converter (DCC) or Neutral Point Clamped Converter (NPC) is shown in Figure 1.1. Here, the DC-Link voltage is equally shared by all the capacitors used (C_1, C_2, C_3 and C_4). Each voltage level of phase output voltage is produced using conduction of four switches and the possible switching states are shown in Table 1.3. The maximum phase output voltage is only half of the DC source, which is the major drawback of diode clamped multilevel inverter.

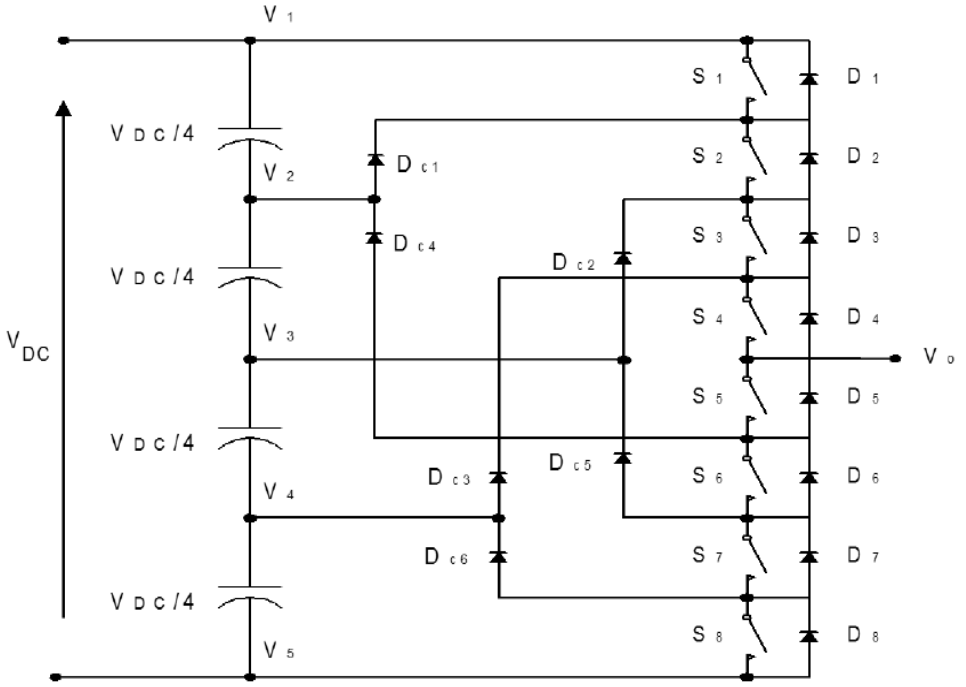


Figure 1.1 Single-Phase Five-Level Diode Clamped Inverter

Table 1.3 Switching States of Five-Level Diode Clamped Inverter

V_0	S_8	S_7	S_6	S_5	S_4	S_3	S_2	S_1
$-V_{dc}/2$	1	1	1	1	0	0	0	0
$-V_{dc}/4$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$V_{dc}/4$	0	0	0	1	1	1	1	0
$V_{dc}/2$	0	0	0	0	1	1	1	1

Advantages and Disadvantages of Diode-Clamped Multilevel Inverters are summarized as:

ADVANTAGES

- There is a common voltage source or DC-Link bus for all phases.
- Use of few capacitors as voltage source minimizes the cost and size of inverter.
- Switching frequency can be as low as fundamental frequency, thus efficiency is high.

DISADVANTAGES

- The possibilities to control the balance of the DC-Link capacitors voltage are limited.
- The number of clamping diodes required is quadratic function of number of levels.
- Diodes used for clamping are more in number, which make layout tedious.

• Reactive current and negative-phase-sequence current can be controlled. • The configuration does not require any transformer. • The capacitors can be pre-charged in a group. • The structure requires relatively simple control method.	• The flow of Real power in a single inverter is difficult as the intermediate DC levels will tend to overcharge or discharge without precise monitoring and control. • Need different (high) rating of diodes to block the reverse voltages.

1.4.2. Flying Capacitor Multilevel Inverter

An alternate configuration of multilevel inverter was introduced by Meynard and Foch, namely flying capacitor inverter in 1992. The arrangement of power switches is similar to diode clamped multilevel inverter. The capacitors are used as clamping device instead of diodes. The configuration forms a ladder structure of DC-link capacitors, where the difference of voltage between two adjacent capacitors gives the levels of voltage in output. The voltage of each capacitor and each switch is V_{dc}. An n level inverter needs (n-1) voltage sources or DC link capacitors, (n-1)*(n-2)/2 clamping capacitors, 2(n-1) power switches and 2(n-1) diodes.

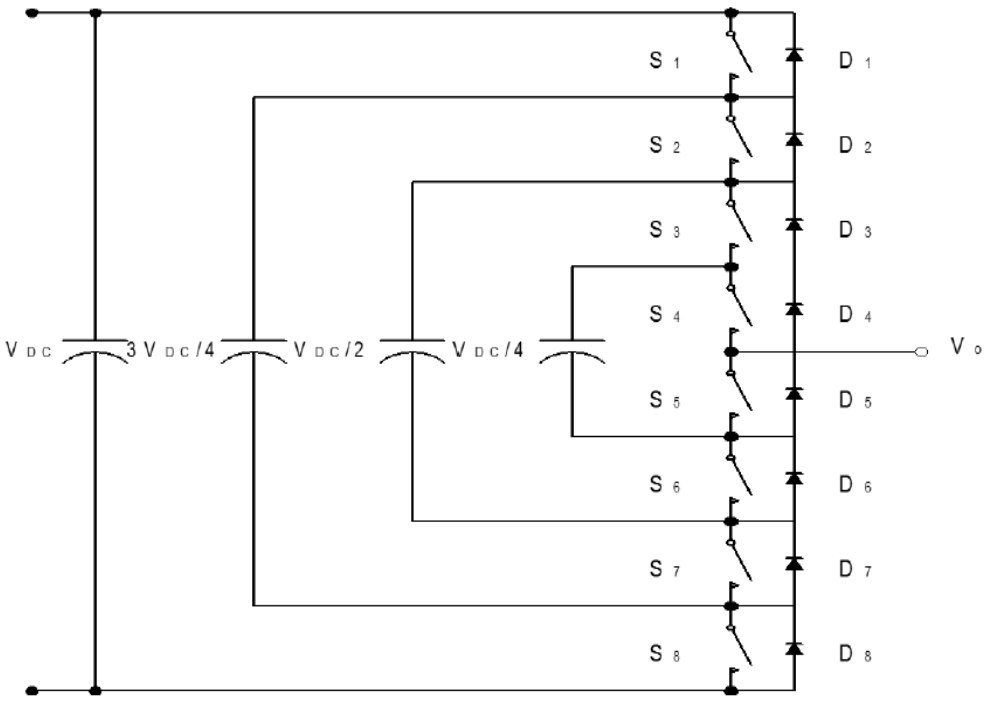


Figure 1.2 Single Phase Five-Level Flying Capacitor Inverter

A single-phase five-level Flying Capacitor Converter (FCC) or Capacitor Clamped Converter is shown in Figure 1.2. Each voltage level is produced using conduction of four switches as in case of diode clamped inverter. Multiple combinations are possible to produce one particular output level, these are called phase redundancies, which makes this configuration more flexible than diode clamped inverter. The redundancies help in charging and discharging of capacitors for control of voltage levels. But only one possible combination for different switching states is shown in Table 1.4. However, the switches are not required to be turned ON in a sequential manner.

Table 1.4 Switching States of Five-Level Flying Capacitor Inverter

V_0	S_8	S_7	S_6	S_5	S_4	S_3	S_2	S_1
$-V_{dc}/2$	1	1	1	1	0	0	0	0
$-V_{dc}/4$	1	1	1	0	1	0	0	0
0	1	1	0	0	1	1	0	0
$V_{dc}/4$	1	0	0	0	1	1	1	0
$V_{dc}/2$	0	0	0	0	1	1	1	1

Advantages and Disadvantages of Flying Capacitor Multilevel Inverters are summarized as below:

ADVANTAGES

- Redundant switching configurations allow balancing of the voltage levels of DC-Link capacitors.
- This structure allows decent control over active and reactive power flow.
- This configuration does not require any transformer.
- More number of capacitors enable the inverter to ride through deep voltage sags and short duration outages.
- Higher levels of flying capacitor inverter yields lower THD.

DISADVANTAGES

- Increased number of capacitors increases the cost and size of inverter, as well as complexity of control.
- The method of charging the clamping capacitors at the required voltage levels is difficult.
- It has poor switching operation and low efficiency in short duration outages.
- Voltage transition between adjacent levels is achieved by changing the on/off state of many switching devices. This increases the number of commutations and thus switching losses.

1.4.3. Cascaded H-Bridge Multilevel Inverter

A relatively new configuration, using H-bridge structure of power switches, was proposed in 1975. A single H-bridge is capable of producing three levels at output ($+V_{dc}$, 0, and $-V_{dc}$) as produced by single-phase full bridge inverter. Cascaded H-bridge (CHB) inverter uses a series of such H-bridges connected to Separate DC Sources (SDCSs) to produce desired waveform. Each bridge is capable of adding two levels in the output. This structure requires minimum number of components, as only few switches and no clamping devices are used by the configuration. Such inverter is capable of producing almost sinusoidal waveform using several DC sources which may be obtained from batteries and different renewable sources.

A single phase Cascaded H-bridge Five-level inverter employs two H-bridges connected to separate DC sources, as shown Figure 1.3. Zero level is produced when all the switches are either off/on. Basically, an n-level cascaded H-bridge inverter requires (n-1)/2 H-bridges with four switches per phase to generate n-level of output voltage. Due to the ability of producing near sinusoidal waveform using minimum components, it is suitable for high voltage and high power applications. Each voltage level of phase output voltage is produced using conduction of four switches and the possible switching states are shown in Table 1.5.

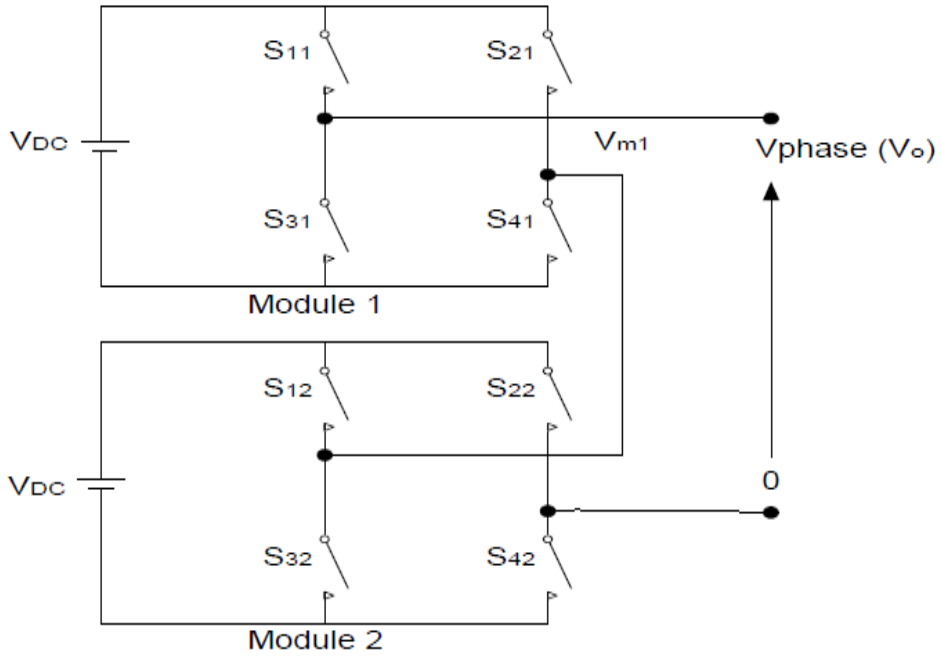


Figure 1.3 Single-Phase Five- Level Cascaded H-Bridge Inverter

Table 1.5 Switching States of Five-Level Cascaded H-Bridge Inverter

V_0	S_{11}	S_{21}	S_{31}	S_{41}	S_{12}	S_{22}	S_{32}	S_{42}
$-2V_{dc}$	0	0	1	1	0	0	1	1
$-V_{dc}$	0	1	0	1	1	0	0	1
0	0	1	0	1	1	0	1	0
V_{dc}	1	0	0	1	0	1	0	1
$2V_{dc}$	1	1	0	0	1	1	0	0

Advantages and Disadvantages of Cascaded H-Bridge Multilevel Inverters are summarized as:

ADVANTAGES

- The structure doesn't require any clamping diodes or voltage balancing capacitors. Therefore, least number of components is required to achieve same number of voltage levels.
- It has modular structure and thus control becomes simple.
- The phase output voltage is sum of the individual outputs generated by each H-bridge of cascaded multilevel inverter. Therefore, redundancy of switching states for inner voltage levels is possible.

DISADVANTAGES

- This topology requires separate DC sources for each H-bridge.
- The circuit is not used for low power applications.

Different configurations of multilevel inverters are studied and a comparison is made to conclude that Cascaded H-bridge MLIs outperform among other topologies of multilevel converters [16], [17], [24], [25]. The Cascaded H-Bridge Multilevel Inverters are most suitable due to high degree of modularity, possibility of connecting directly to medium voltage, high power quality, high availability, and simplicity of control [26]–[28]. For same level of voltage output, the components required by Cascaded H-bridge inverter are least out of different topologies of multilevel inverter. The output voltage produced by Cascaded H-bridge inverter has minimum harmonics and resembles to sinusoidal shape better than other configurations of multilevel

inverter. Also, the harmonics content improves with increase in the level of inverter. Now, the important factor in design of a proficient multilevel inverter is to make sure that the THD of output waveform should comply with IEEE 519-2014 harmonic guidelines.

1.5. RESEARCH OBJECTIVES

In the light of the above motivational issues, the significant goal of the recommended work is to improve the performance of multilevel inverters using an optimal control technique employing efficient optimization algorithm. The specific objectives set for the proposed work are as follows:

a) To perform Literature review and find the information on Multilevel Inverters, nonlinear loads characteristics, current waveform distortion, and total harmonic distortion in current scenario and IEEE standards related harmonics.

b) To compare various existing Pulse Width Modulation (PWM) control techniques as applied to multilevel inverters.

c) To simulate multilevel inverter that works efficiently for all operating conditions of inverter.

d) To develop new control techniques for multilevel inverters for power quality improvement.

e) To analyse the impact of hybrid multilevel modulation strategy on harmonic content of input current and output voltage.

f) To develop an optimal modulation strategy using artificial intelligence methods for multilevel inverters.

g) To develop a generalized formula for selective harmonic elimination PWM control for cascaded multilevel inverters.

h) To analyze Power Quality using proposed modulation strategy in Multilevel Inverters.

i) To design a multilevel inverter model for power quality improvement using new modulation technique.

1.6. ACCOMPLISHMENTS

During the work, following accomplishments were made for the specified objectives:

a) Various configurations of MLIs and control techniques applied to improve power quality of multilevel inverter are explored to reach to the complications associated with them.

b) The most effective PWM methods are investigated, and the difficulties, like high switching frequency, high thermal losses, high switching loss and poor converter efficiency, faced by these methods are marked. Afterwards, a comparative analysis is performed and implemented using MATLAB/Simulink to draw better conclusion.

c) Using the concepts and limitations from the literature survey, a new objective function is proposed using Cuckoo Search algorithm to improve the power quality of multilevel inverter. The proposed function outperforms all other existing functions.

d) The performance of some common algorithms Gravitational Search (GS) Algorithm, Particle Swarm Optimization (PSO), Harmony Search (HS) Algorithm, Simulated Annealing (SA), Teaching Learning Based Optimization (TLBO) and Cuckoo Search (CS) Algorithm are studied and compared to get optimize results and THD value. Cuckoo Search algorithm is found efficient in every perspective for the required objective.

e) A detailed analysis for power quality assessment in proposed scheme is conducted. It is observed that the reactive power drawn by the load circuit and power losses have reduced significantly. The value of power factor has increased from 0.91 to 0.98 and efficiency is improved from 62.3% to 83.3%.

Experimental validation of simulation results is done using a hardware prototype of three-phase Five Level Cascaded H-Bridge Multilevel Inverter equipped with FPGA controller. The voltage waveform and THD analysis results are found similar to the simulation results. The outcomes confirm that significant reduction in THD in output line voltage of MLI is attained with lower order harmonics within specified limits.

1.7. ORGANIZATION OF THESIS

The thesis is organized into various chapters:

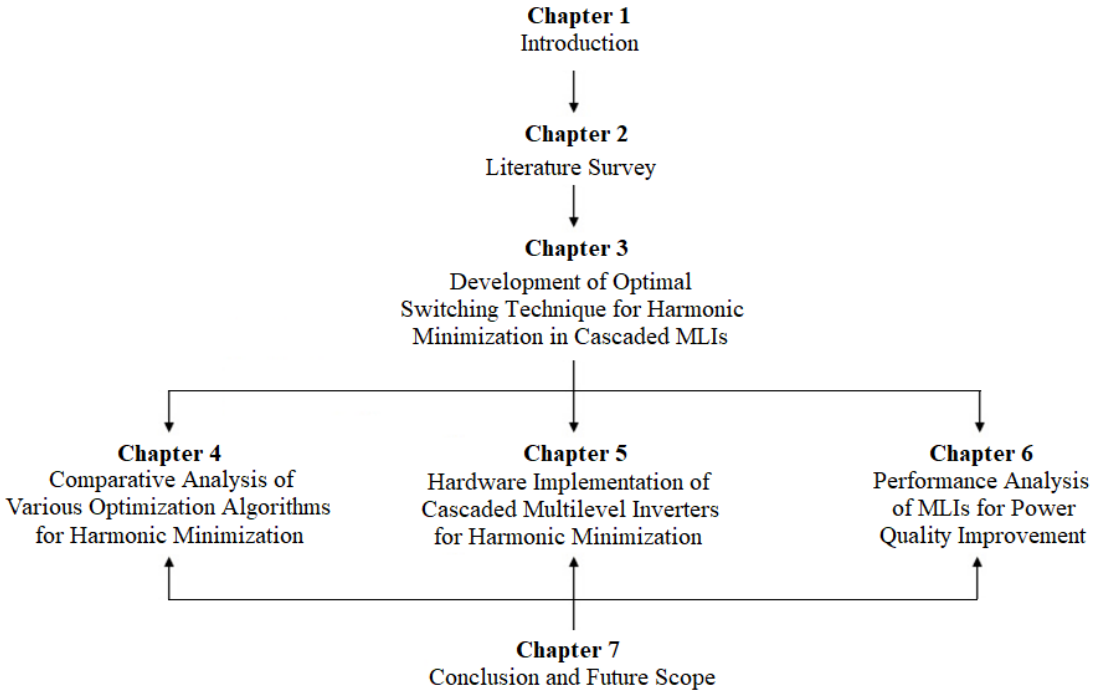


Figure 1.4 Organization of the Thesis

Chapter 1 The first chapter describes the introduction about the various power quality issues faced by the power electronic sector. It discusses the motivation behind the research, objectives of the proposed work, overview of the proposed methodology, and organization of the thesis. It also highlights the need for power quality improvement of multilevel inverters.

Chapter 2 In this chapter, existing related work that solves the power quality problem of technical world is discussed. Based on the literature survey on each topic, the problems and challenges identified from existing modulation techniques are discussed in brief, providing the basis for the research to be carried out. Literature work also identifies major challenges and the limitations of the existing optimization algorithms.

Chapter 3 This chapter discusses various modulation techniques for multilevel inverters. It aims to analyze and compare the different existing PWM techniques. The fundamental PWM methods and most recent modified PWM methods are discussed along with their advantages and disadvantages. It further investigates various efforts made for harmonic minimization or mitigation or Selective Harmonic Elimination

(SHE) that have been proposed in the literature. Finally, a new improved objective function based switching technique is proposed.

Chapter 4 The chapter covers the detailed discussion for commonly available optimization algorithms. It also discusses the heuristics methods that are being adopted in almost every field of engineering. Keeping in mind the harmonic optimization function, some of modest and commonly implemented algorithms that can resolve the problem better are chosen for the comparative analysis. This chapter also describes the performance comparison of various selected algorithms Gravitational Search Algorithm, Particle Swarm Optimization, Harmony Search Algorithm, Simulated Annealing, Teaching Learning Based Optimization and Cuckoo Search Algorithm on the basis of parameters such as harmonic content in output voltage, computational time of algorithm, computational efficiency and number of iterations required to get optimize results and THD value.

Chapter 5 The chapter presents simulation results of new objective function based switching technique as applied to Single Phase MLIs. The detailed procedure to use this method for cascaded multilevel inverters has been presented using MATLAB/Simulink. This chapter also covers the experimental validation of these results with the hardware prototype.

Chapter 6 This chapter provides the discussion of various power quality parameters like THD, Root Mean Square value of Voltage (V_{RMS}), Lower Order Harmonics (LOH), Reactive power (Q), Power factor (PF), Distortion Factor (DF), Form Factor, and Efficiency (η) related to multilevel inverters. The work in this chapter implements the proposed algorithm to perform the analysis of power quality improvement in multilevel inverters.

Chapter 7 In this chapter, the work is concluded with the description of potential future work in the area of power quality improvement methods for multilevel inverters.

CHAPTER II

LITERATURE SURVEY

Literature Review is basically a survey of existing work in order to understand the present state of art. The aim is to identify the problems with the existing methodologies being used for the control of multilevel inverter. So, for the purpose, a detailed study of existing control techniques, their advantages and disadvantages, area of application, is done. There are a variety of methods regarding the area which have been proposed by various other researchers, but, the details of the most common methods are discussed in the chapter. However, description and limitations of different techniques, whether basic or modified, are highlighted to draw the proposal for a new or better control strategy.

2.1. INTRODUCTION

Inverters are known to convert available DC power to required form of AC power by means of a simple power electronic circuit. Initially, they are introduced as two-level, but with the introduction of multilevel inverters, they have gained importance in almost all sectors of industries. With this revolution in the field of power electronic sector, Cascaded H-Bridge Inverters have emerged as a useful and popular choice for controlled power in grid connected Photo-voltaic systems [29]–[32]. Though, increase in the level of inverters increases the number of switches being used to produce more levels. These switches cause the harmonic content in the output voltage waveform to increase beyond acceptance level. Different standards define different limits for harmonics, like recommended harmonic voltage limits of IEEE 519-2014 are given in Table 2.1. Harmonics can be removed by using filters between load and inverter, but the size of filters depends on harmonics and harmonics are inversely proportional to frequency. This would mean that the odd orders of harmonics (like 3, 5, 7, ….) are the most significant harmonics in three-phase systems. In three-phase four-wire systems, the triplen harmonics out of these odd order harmonics are neglected. The filter size or the filter components required to attenuate these lower order harmonics is much more than required for higher order harmonics. Therefore, it is appropriate to use some other control methods for lower order harmonics whereas higher order harmonics can be eliminated by the use of filters.

Table 2.1 Voltage Distortion Limit as per IEEE 519-2014

Bus Voltage V at PCC	Individual harmonic (%)	Total Harmonic Distortion THD (%)
V ≤ 1 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Modulation Strategies are the methods that control the output voltage waveform of inverter to have only allowable harmonic content. Different modulation strategies with different characteristics have been developed by the researchers for the control of multilevel inverter such as Sinusoidal Pulse Width Modulation (SPWM), Space Vector Modulation (SVM), Selective Harmonic Elimination and many more. Some techniques are proposed according to some specific applications [24], [33]. A wide literature review is carried out with the aim of understanding the different control schemes, their advantages and disadvantages. Furthermore, the main concern in the design of multilevel inverter is to develop an efficient strategy in order to eliminate lower order harmonics from the output voltage waveform as specified in IEEE 519-2014 standard.

2.2. REVIEW OF EXISTING WORK

Extensive literature has been reviewed to get acquainted with the growing concern for power quality, and Multilevel Inverters as power quality improvement. Various modulation and control methods used to minimize the harmonics and improve power quality in Multilevel Inverters are explored, so that relevant information can be drawn. For this purpose, many websites, and research papers (more than 100) were referred to. The survey identifies the limitations of the existing modulation techniques used for obtaining quality output of MLI. An outline of literature survey is presented concisely in Table 2.2. It summarizes the contribution made by an author/authors and the limitation of their work.

Table 2.2 Review of the Literature

Author name & Year of Publication	Description about the paper	Limitation
Patel, H.S. & Hoft, R.G. (1974) [34]	Described the harmonic elimination technique that can be regarded as the conventional method which reduces the predominant low-order harmonics and maximizes the fundamental wave of the output phase voltage.	The drawback of the conventional method is that in order to determine the switching instants, iterative methods need to be used which can be time demanding, and may include errors since they depend on iterations. Also, a large computational effort is required.
Buja, G.S. (1980) [35]	In VSIs, this approach uses the distortion in the current as a figure of merit and attempted to minimize this as a function	The method demands much more difficult procedures because the current waveform is not known in advance without current sensors or without the knowledge of the load.
Boys, et.al. (1990) [36]	A SVPWM scheme has been introduced where the switching time for the inverter legs is directly determined from	This technique reduces the computation time considerably more

	sampled phase voltage amplitudes.	than the conventional SVPWM techniques, but it involves region identification based on modulation indices. The method is limited to three-level PWM generation, because the region identification becomes more complicated for higher levels.
Holtz, et.al. (1993) [37]	For two-level inverters, a SVPWM scheme is proposed extending the modulation range into the over modulation range.	The approach requires extensive offline computations and look up tables to determine the modified reference vector, in the over modulation range. This is even possible by adding a common mode voltage of suitable magnitude to the sinusoidal reference phase voltage.

Li Li, et.al. (2000) [38]	Selective harmonic elimination Pulse Width modulation (SHEPWM) method is systematically applied for the first time to multilevel series-connected voltage-source PWM inverters. The method is implemented based on optimization techniques.	The SPWM schemes are more flexible and simpler to implement, but the maximum peak of the fundamental component in the output voltage is limited to 50% of the DC link voltage
Celanovic, et.al. (2001) [39]	A carrier based PWM scheme has been presented, where sinusoidal references are added with a proper offset voltage before being compared with carriers, to achieve the performance of a SVPWM. The offset voltage computation is based on a modulus function depending on the DC link voltage, number of levels and the phase voltage amplitudes.	The implementation details and the operation of the proposed method in the over modulation region remain unaddressed.
Keliang Zhou and Danwei Wang (2002) [40]	Generic algorithms have been used to optimize the harmonic content for power inverters under the SVM. The relationship between three-phase carrier based PWM and SVM has been analyzed.	The technique gets complicated with increase in level of outputs.

Subrata, et.al. (2003) [41]	The paper proposes an overmodulation strategy of space vector PWM of a three-level inverter with linear transfer characteristic that easily extends from the undermodulation strategy previously developed by the authors for neural network implementation.	Conventional SVPWM requires sector identification and look up tables to determine the timings for various switching vectors. This makes the implementation of the SVPWM scheme quite complicated.
A. Mehrizi-Sani and S. Filizadeh (2009) [42]	Uses generic algorithms for optimization of SVM with an aim to minimize the filtering requirement by lowering most significant harmonics while conforming to the available standards for voltage waveform quality.	The SVM in three-leg inverters topology cannot handle the neutral current
Mohan, N., Undeland, T.M. & Robbins, W.P. (2003) [43]	Suggested that to have voltage with less THDthe carrier frequency must be very high. This means an average switching frequency f_s must be greater than 1 kHz.	As switching frequency is between 2 to 20 kHz for having small THD, it leads to higher switching losses.
Keith A. Corzine, Mike W. Wielebski, Fang Z. Peng, Jin Wang (2004)[44]	Introduces a seven-level inverter MLI created by cascading two three-phase three-level inverters using the load connection, with only one dc voltage source. Two types of control were developed, one	Both controls suffer from the problem of capacitor voltage balancing.

	relies on controlling the two three-level inverters jointly and the other uses separate controls.	
Mauricio Angulo, et.al. (2007) [45]	Proposed a modified PD-PWM technique that combines the benefits of level shifted modulation, achieving good output voltage and input current quality.	Level shifted PWM technique is not recommended as it undergoes the risk to attain voltage level which give rise to more redundancy despite the fact it had failed to generate all output voltage levels.
M.Malinowski, K. Gopakumar, J.Rodriguez, M. A.Pérez (2010) [27]	Presents a review of the most commonly used modulation techniques and control strategies in cascaded multilevel inverters. They mainly focus on reducing switching frequency and thus switching losses.	The first issue that needs attention is the efficiency improvement. The conduction losses are far more critical than switching losses due to the series connection of several semiconductors and high output currents. To reach higher voltage levels is a challenge for semiconductor technology, increasing the blocking voltage and

		other related technologies like gate drivers and sensors.
Yang Ke-hu, et.al.(2015) [46]	Presents a method to solve the selective harmonic elimination problem with Groebner bases theory	The main disadvantage of programmed PWM techniques lies in their practical implementation, as complex algorithms need large computational power to solve transcendental equations
A. K. Al-Othman, and Tamer H. Abdelhamid (2008) [47]	Uses PSO technique for selective harmonic elimination of multilevel inverters and results in a dramatic decrease in both the computational times and the output voltage %THD.	The main drawback of PSO algorithm is its poor local search ability.
R.N. Ray, D. Chatterjee, S.K. Goswami (2009) [48]	A particle swarm optimization (PSO) based technique is suggested to minimize the overall THD of the output voltage of a multilevel inverter.	The work focuses on overall THD reduction, and overlooks lower order harmonics which are also an important parameter of concern.

N. Prashanth, B. Kumar, J. Yadagiri, A.Dasgupta (2011) [49]	Derives an equation for the computation of THD for elimination of possible lower order harmonics. PSO algorithm is proposed to deal with inequality constraints which will help in accelerating the optimization process.	It gives lower THD but lower order harmonics are ignored.
Suman Debnath, Dr. Rup Narayan Ray, Tapajit Ghosh (2012) [50]	Compares three commonly used Artificial intelligence algorithms GA, PSO and HS as applied to THD minimization in Seven Level Cascaded H-Bridge Multilevel Inverter.	Every algorithm has its own pros and cons.
A. Salami, B. Bayat (2013) [51]	Proposes a general genetic algorithm (GA) approach by which the switching angles can be calculated in the context of step modulation for multilevel inverters.	The major issue with GA is fine tuning of its parameters, like mutation rate, crossover parameters, selection parameters, etc, which is often chosen by hit and trial method.
S.Assly Steffy, B.Mangaiyarkarasi, S.Sherin Jasper, K.Priyanka, K.Soorya (2014) [52]	A multicarrier PWM control is presented that serves as a replacement for the conventional method which has high switching losses and eliminates the use of transformer.	The drawback of this work is that it focuses on THD reduction, whereas lower order harmonics are also an important parameter of concern.

Priyal Mandil and Dr. Anuprita Mishra (2014) [53]	Weight Improved Particle Swarm Optimization (WIPSO) is suggested by incorporating Inertia weight 'w' in the classical version of PSO to achieve the balance between exploration and exploitation process.	The optimal values achieved in different experiments have no particular trend. The values do not always converge to global optima.
Ranjhitha.G, Padmanaban.K (2014) [54]	Suggested GA to produce all possible solution sets without much computational burden	GA takes more computational time, and gets complex with more number of solutions required
Ali Ajami, Behrouz Mohammadzadeh and Mohammad Reza Jannati Oskuee (2014) [55]	SHE is an efficient method to achieve desired fundamental voltage and eliminate selective harmonics. The work adopts Cuckoo evolutionary optimization for SHE.	There is requirement to make modifications in objective function, as it targets only a few lower order harmonics.
M.Mythili, N.Kayalvizhi (2014) [56]	SHEPWM equations are solved using GA and PSO algorithm and a comparison of GA and PSO algorithms is done using MATLAB software	Fifth and seventh harmonic obtained violates the IEEE standard of individual harmonic distortion which must be less than 3%.
S.Gokul Priya, R.Sasikala, R.Meenakumari (2014) [57]	Bee Algorithm is chosen to optimize the switching angles in order to reduce the lower order harmonics and improve	Lack of use of secondary information requires new fitness tests on

	the PQ performance.	new algorithm parameters. Higher number of parameters to be optimized slow down the algorithm speed when in sequential processing.
Mohammad Mardaneha & Faranak Golestaneh (2014) [58]	Enhance TLBO is presented with an aim to reduce the Total Harmonic Distortion (THD) in multilevelconverter.	The proposed method takes more computational time. Also performance is poor than original TLBO
Banaei MR, Jannati Oskuee MR, Khounjahan H. (2014) [59]	A new topology is proposed based on the connections of several cell units in an appropriate scheme with the help of six power switches.	Placement of DC source is crucial for generating the desired output voltage level. Improper placement may cause failure in voltage level.
Babaei E, Sheermohammadzadeh Gowgani S, Sabahi M. (2015) [60]	DC voltage sources are arranged in series and parallel, and the values of the DC voltage sources are determined using an algorithm.	The structure uses a less number of dc input sources, but requires more power switches. Hence the circuit becomes more complex, and increases the cost of the inverter.

Barzegarkhoo R, Kojabadi H, Zamiry E, Vosoughi N, Chang L (2015) [61]	Switched-capacitor converter (SCC) is suggested to boost the input dc power supply voltage without transformer by switching the capacitors in series and in parallel.	The balancing of capacitor is a difficult task to create the output voltage.
Babaei E, Laali S, Bayat Z. (2015) [62]	A new configuration with reduced number of power switches is described	The creating of switching states for the proposed topology is complex
Parul Gaur and Preeti Singh (2015) [63]	Discuss different optimization techniques and suggests a species based PSO (SPSO) method, which includes the suitable adjustment of niche radius for calculation of the optimum firing angles of MLIs, has been proposed	The algorithm is quite sensitive to value of niche radius. Small values cause particles to get trapped in local optima and too large values prevent the algorithm from locating nearby optima.
Jackson Lago, M.L. Heldwein (2016) [64]	Solves the problem of optimizing the modulation pattern of multilevel inverters in a single optimization problem at a given modulation index.	The matrix involving different parameters is hard to optimize. Optimization complexity and initial guess angle sensitivity contribute to long runs and inaccuracies.

Jeyabharath Rajaiah, Velmurugan Ramar, Veena Parasunath (2016) [65]	The proposed work uses two evolutionary algorithms, GA and PSO algorithm. They are used to generate the switching angles by satisfying the nonlinear transcendental equations that govern the low order harmonic components.	The proposed method uses filter for lower order harmonic elimination, increasing the cost. GA takes more computational time and requires many parameters. The low order harmonics acquired from PSO is more prominent than 3% that abusing IEEE standard.
Shruti Garg, Ashok Kumar Sharma and Priyanka Yadav (2016) [66]	Considers the expression of THD as objective function that aims to controls the individual selective harmonics within the allowable limits by incorporating the constraints in PSO algorithm.	The harmonic values obtained and THD does not comply with IEEE-519 Harmonic standard.
Syed Saad Azhar Alia, Ramani Kannana, M.Suresh Kumarb (2016) [67]	PSO is implemented to solve SHE transcendental equations such that harmonics are minimized.	PSO suffers from the problem of getting struck at local optima.
Janardhan Kavali, Arvind Mittal (2016) [33]	A flowchart for THD minimization is presented to calculate the switching angles of a cascaded multilevel inverter based on the equation of THD for multilevel	In case more switching angles are needed, the more for loops must be nested and the program can spent a lot of time

	inverters.	running.
N.Vinoth kumar, et.al. (2017) [68]	Simulated Annealing based optimization is offered for harmonic elimination in MLIs.	Despite of the advantage of SA to avoid becoming trapped at local minima, it took much computational time to converge.

The literature survey done in this thesis essentially surveys the most widely used methods: Sinusoidal Pulse Width Modulation [33], [69]–[71], Space Vector modulation [42], [72]–[77], Optimized Harmonic Stepped Waveform (OHSW) [78], Optimal Minimization of Total Harmonic Distortion (OMTHD) [79], [80], and Selective Harmonic Elimination [68], [81]–[88]. The survey of existing work can be summarized as:

a) SPWM, modified SPWM [89] and multicarrier PWM [90]–[93] techniques are effective for controlling the inverter output voltage but they employ high switching frequency which is not preferable due to associated high thermal losses, high switching loss and poor converter efficiency. Low switching frequency means low switching losses but it requires large filter size as lower order harmonics are introduced in the spectrum.

b) OMTHD method uses the conventional formula for THD that gives same weightage to all harmonics, results in minimum THD but certain lower order harmonics are not within permissible range.

c) Selective Harmonic Elimination technique is benefited from its low switching frequency and high output power quality, by using harmonic equations derived by applying Fourier Series Expansion.

d) Several other switching techniques combine the conventional THD with SHE techniques to minimize THD as well as eliminate low-order

harmonics [94]–[97]. Though, such functions cannot guarantee elimination of specific harmonic orders for all modulation indices.

e) Most of the reviewed research discusses the application of optimization algorithms like Genetic Algorithm (GA) [51], [54], [98], [99], Differential Evolution (DE), Particle Swarming Optimization [49], [52], [66], [67], [100], [101], and numerous other algorithms [102]–[104]. These algorithms based optimization techniques were likewise proposed for computing switching angles of multilevel inverter.

2.3. LIMITATIONS OF EXISTING WORK

The following limitations were identified while looking over the above mentioned approaches:

- SPWM methods are not able to efficiently utilize the DC-link supply voltage. In some cases, maximum peak of fundamental component in the output voltage is limited to 50%.
- SVM gets complicated with increase in level of outputs.
- Application of some techniques is limited to three-level inverters only.
- High switching frequency techniques (involving frequencies between 2 to 20 kHz) lead to higher switching losses.
- THD Minimization techniques give lower THD but lower order harmonics are ignored.
- SHE targets only a few lower order harmonics.
- Determination of switching instants using SHE requires a large computational effort and time.
- SHE using GA has the major issue of fine tuning of parameters, like mutation rate, crossover parameters, selection parameters, etc, which increases the computational time. And complexity increases with high level of inverter.

- The main drawback of SA and PSO algorithm is its poor local search ability. So, the results obtained using PSO do not always converge to global optima.

These challenges have served as the motivating factors to propose an appropriate objective function for control of multilevel inverter. The details of the modification designing are available in Chapter 3 of this thesis. The selection of efficient algorithm for optimization of modified SHE function has been done in Chapter 4 of this thesis. Further implementation outcomes and validation of power quality parameters are provided in Chapters 5 and 6 of this thesis.

2.4. DEFINING THE SCOPE OF THE PROBLEM

The mission to be accomplished in this work was to present an efficient and optimized control of multilevel inverter for power quality improvement. Now, as for power quality improvement, it is desirable to keep the fundamental component of output voltage of multilevel inverter at acceptable value, and equally important is to keep the harmonic components in the output voltage within stated harmonic limits. This led to the need for improved harmonic minimization function that optimizes the switching angles to generate the switching scheme for different inverter modules of Cascaded H-Bridge Multilevel Inverter. To understand the problem better, different methods for control of multilevel inverter are discussed. As the main issue is power quality improvement of multilevel inverter, there are various parameters that define the power quality in multilevel inverters. These are shortlisted as:

- Total Harmonic Distortion (THD)
- Root Mean Square Value of Voltage (V_{RMS})
- Lower Order Harmonics (LOH)
- Reactive Power (Q)
- Power Factor (PF)
- Distortion Factor (DF)
- Form Factor (FF)
- Efficiency (H)

So, initially the work concentrates on modification of minimization function by analyzing already existing functions proposed by different researchers. Now, choosing the appropriate optimization search algorithm is equally important as framing a well-defined problem. Every algorithm has its own pros and cons and applicability. Thus, different optimization algorithms are required to be explored to find the best suitable algorithm for optimizing the proposed harmonic minimization function. The comparison helped to conclude that simplicity and efficiency of Cuckoo Search algorithm is the best to be used for optimization of switching angles for control of multilevel inverter. All this work led to an efficient control of multilevel inverter using an optimal modulation technique for harmonic minimization using Cuckoo Search Optimization.

2.5. MODULATION STRATEGIES

The process of switching/altering the state of a semiconductor device of a converter is known as modulation. The goal of a modulation method is to deliver a staircase waveform, with desired fundamental part and minimum harmonics. Other important requirements that a modulation strategy should possess are:

- Simplicity and Modularity of Design
- Good Output Quality
- Low Switching and Conduction Losses
- Better Efficiency
- Minimum Harmonic Distortion
- High Power Factor
- Low Ripple Current
- Easy Implementation and Low Cost

Generally, modulation strategies are categorized as shown in Figure 2.1, on the basis of switching frequency employed into High switching frequency methods and Low or Fundamental switching frequency methods [16].

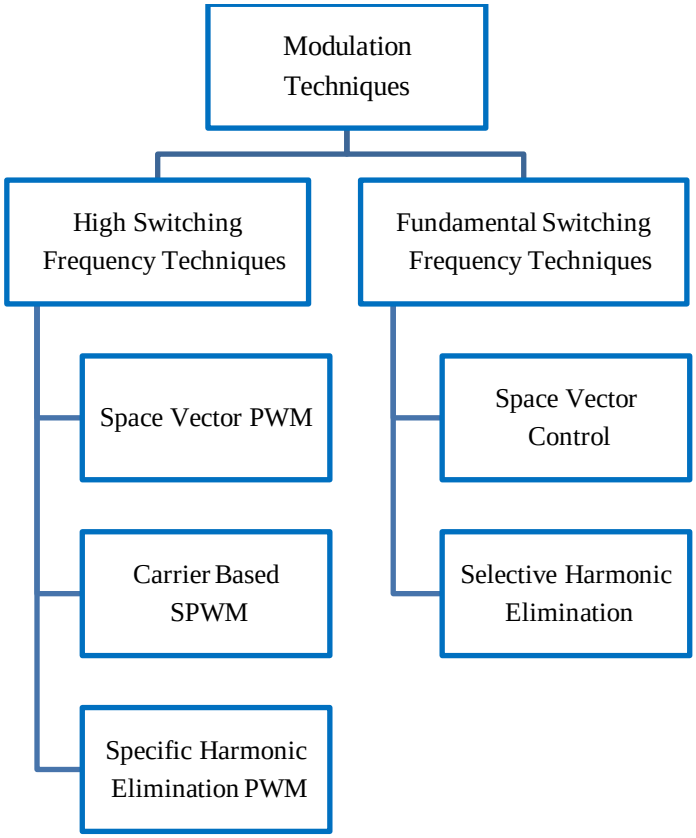


Figure 2.1 Classification of Modulation Techniques on the Basis of Switching Frequency

Techniques using high switching frequency mean high switching losses, due to switches being turned on/off many times in one fundamental period. Different types of high switching frequency methods are classified in Figure 2.2. SPWM techniques are the traditional method of PWM employing sinusoidal modulating signal. They employ high switching frequencies of the order of several kHz, and low order harmonics at high frequencies are prominent. This leads to the requirement of high size filters. However, these high frequency switching techniques are further explored and classified in various categories due to widespread use of PWM methods. Space Vector PWM (SVPWM) provides an alternative to SPWM and is also among widely used methods. The selection of switching method or modulation technique mainly depends upon the application. In some cases, it is not possible to deal with the size of filters required due to high low order harmonics and high switching losses.

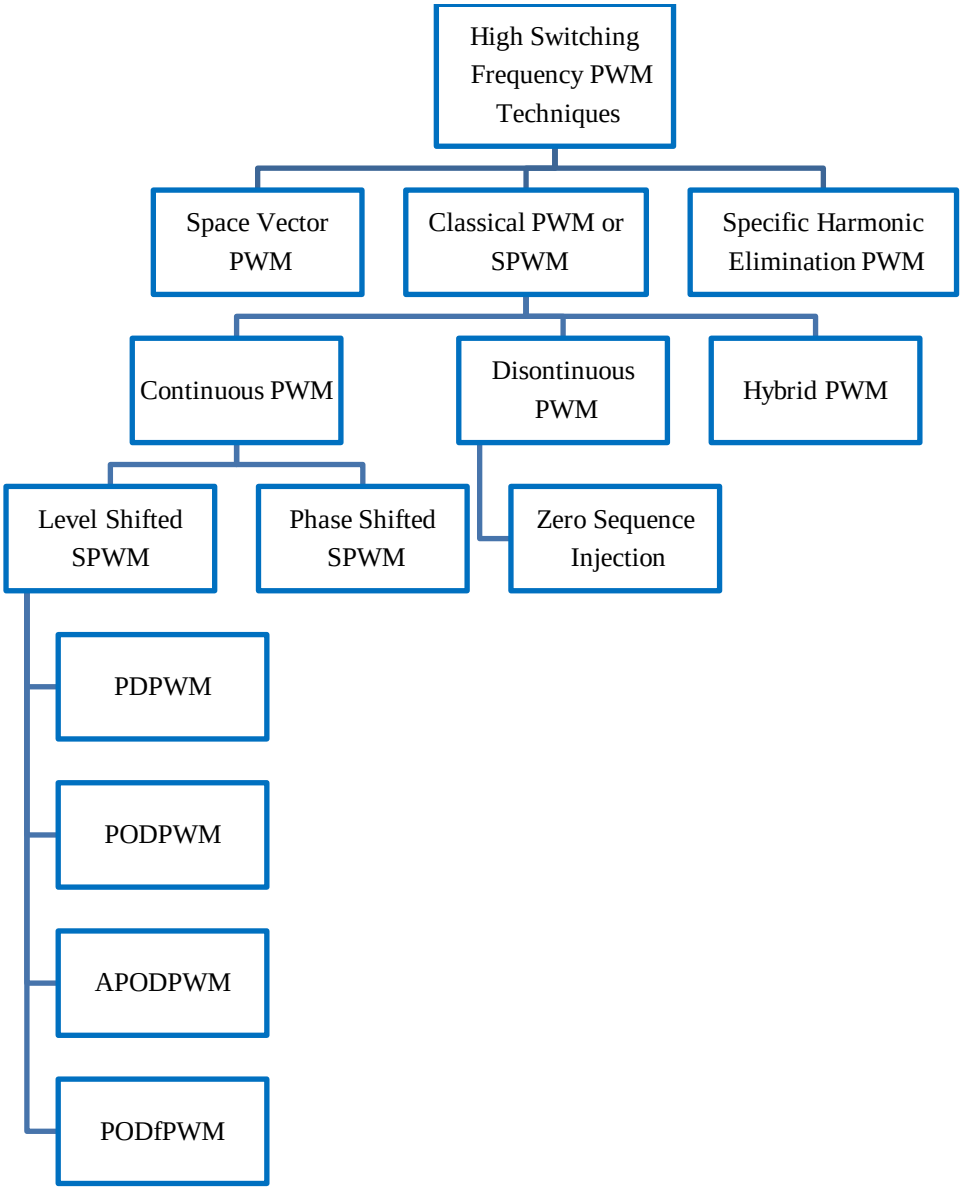


Figure 2.2 Classification of High Switching Frequency Methods

The techniques that use fundamental switching frequency are also termed as Multilevel Fundamental Switching Schemes. They perform only one or two commutations in one fundamental cycle. SHE and SVC fall under fundamental switching frequency operation. Low frequency automatically minimizes the switching losses to a great extent, leading to better efficiency. Also, low order harmonics are suppressed in case of low switching frequency and high order harmonics are dealt with low size filters. An extensive review is carried out in order to understand the existing modulation strategies, their advantages, and disadvantages. Appropriate switching frequency for modulation method and proper arrangement of switching states are the factors responsible for producing the desired quality of voltage output.

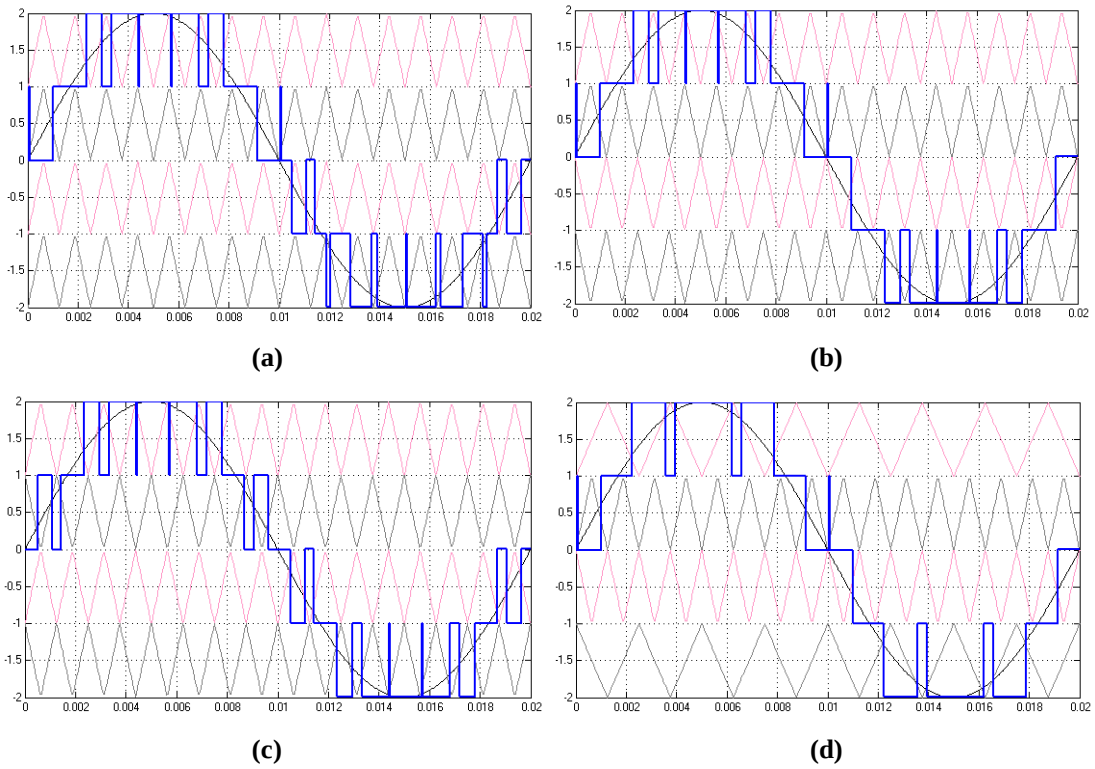
2.5.1. Sinusoidal PWM

Sinusoidal PWM (SPWM) is one of the most popular and widely used methods in industrial applications. This technique utilizes a sinusoidal reference signal as modulating signal and multiple carriers to synthesize the desired output. The carrier waveform is essentially a high frequency triangular wave. Different names are given to the technique by different researchers. Sometimes, SPWM is also termed as Multilevel Modulation as it uses (m-1) carriers to generate m-level output [105]. Also, it is carrier based modulation, so it can be termed as Carrier Based PWM (CB-PWM) [71], [106]. Basically, a sinusoidal modulating signal is compared with different carrier signals to generate a switching pulse, whenever the modulating signal exceeds carrier wave. The switching pulse then generates the on/off pattern for the switches of multilevel inverter. The number of carrier waves decides the number of levels in output and frequency of carrier waves decides the switching frequency of inverter.

SPWM techniques are further classified as level-shifted and phase-shifted techniques depending on whether the carriers are shifted according to different levels or phase amongst each other. In level-shifted PWM, many different arrangements of carriers are possible, according to the phase displacement of carriers at different levels. They are Phase Disposition PWM (PDPWM), Phase Opposition Disposition PWM (PODPWM), Alternate Phase Opposition Disposition PWM (APODPWM), and Phase Opposition Disposition with variable Frequency PWM (PODfPWM). Figure 2.3 illustrates all these methods for Five-level PWM methods. In the first three methods, frequency of all the carriers is same, but in the last method, the frequency of the carriers in the outer band is less as compared to the frequency of the carriers in inner band, which is same as switching frequency. However, amplitude of the carrier wave is dependent of the level of inverter, i.e. for m-level inverter, amplitude of the carrier wave is the ratio of magnitude of modulating signal/number of carriers.

In PDPWM, all the carriers above and below are placed in same phase, whereas in PODPWM, the carriers above and below are 180˚ out of phase with each other. In APODPWM, all the carriers are 180˚ out of phase alternately. All these arrangements are suggested and experimented in order to find best output for different topologies of multilevel inverters. All the methods are similar to each other, but, mostly PDPWM gives the better results. The phase-shifted PWM, all the (m-1) carriers are of the same

amplitude as modulating signal, but they are 90˚ phase displaced from each other. Numerous research reports the advantages and applications of different SPWM methods. Various comparisons have also being done in order to suggest the best modulation technique for different topologies of multilevel inverter. Nevertheless, SPWM methods suffer from a major disadvantage of not being able to completely eliminate low order harmonics, which cause high filter requirements.



(a) **(b)**

(c) **(d)**

Figure 2.3 (a) Phase Disposition PWM, (b) Phase Opposition Disposition PWM, (c) Alternate Phase Opposition Disposition PWM, and (d) Phase Opposition Disposition with variable Frequency PWM

2.5.2. Hybrid SPWM

As, SPWM is the conventional method of modulation, it has been deeply explored. Various modifications have been proposed, like combining two different SPWM methods, two modulating signals with 180˚ phase difference for levels above and below the reference, etc. Many a times, the carrier is modified without changing the peak-to-peak magnitude and frequency of the carrier wave as presented in Figure 2.4. Various researchers changed the triangular carriers in the outermost band by rectified sine waves of the same frequency [107]. These techniques changed the harmonic profile of the output waveform because the shape and frequency of the carrier signal effects the harmonics in the multilevel output waveform.

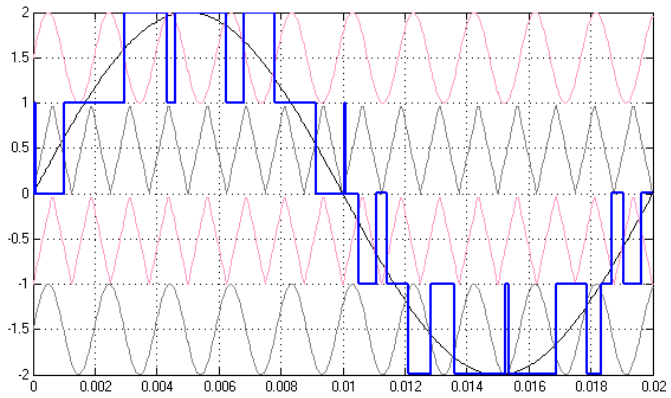


Figure 2.4 An example of Hybrid SPWM

2.5.3. Space Vector PWM or Space Vector Modulation

Space Vector Modulation is an alternative method to SPWM for deciding the switching pattern for MLIs, and most commonly used for the control of three-phase AC motors [108]. In SPWM, the switching times/duty cycles are derived through comparison of modulating and carrier signal, whereas in SVM or SVPWM, these times are calculated using some dedicated equations. The basic concept of SVPWM is to produce an average output equal to the desired/reference voltage vector, during the PWM period given in Figure 2.5.

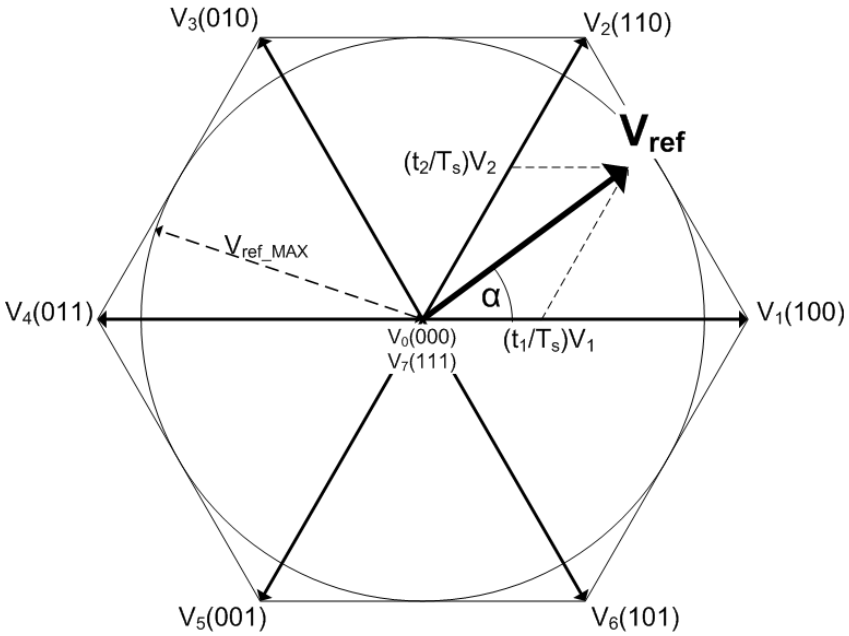


Figure 2.5 Space Vector Diagram

The process is divided in three steps, namely, region determination, selection of switching states, and calculation of switching times. Firstly, the d-q plane is divided

into six equal sectors and the reference voltage is synthesized as the weighted average of nearest three vectors called NTV approach. This step is known as determination of region or three voltage vectors adjacent to reference voltage. The reference vector can move in counterclockwise direction with magnitude and angle according to the desired/reference voltage output. The idea of reference vector in d-q plane is similar to the rotating field of motor.

At any particular time, the reference belongs to a particular sector, which can be represented by four switching states generally called as state vectors. For three-level inverter, there exist eight switching states/state vectors, out of which six are called active vectors and two are zero vectors. Different strategies have been employed for selection of three state vectors and calculation of switching times, so that the output produced approximates the desired output waveform, in any switching period. The selection of switching states and calculation of switching time affects the harmonics produced in the output and thus efficiency.

Space-Vector PWM offers several advantages:

- enables efficient use of the DC-link supply voltage
- provides flexible and easy online control
- relatively good performance
- low current ripple and maximum transfer ratio
- reduced harmonic distortion and improved power factor

These advantages make it suitable to use it for high voltage applications, though it has certain disadvantages also.

- not able to eliminate the low order harmonics completely.
- cannot be applied for unbalanced DC voltages.
- with increase in the number of levels, the complexity of selecting switching states increases significantly.

2.5.4. Discontinuous PWM or Zero Sequence Injection

Cascaded H-Bridge Inverters suffer from an inherent problem of unbalancing of DC-link capacitor voltage, which affects the efficiency and overall rating of multilevel

inverter. Commonly, Carrier Based PWM or Space Vector PWM methods are used for the control of multilevel inverters. CB-PWM methods use a pure sinusoidal signal as reference modulating signal to achieve the desired output voltage. However, it has been observed that modification of this modulating signal can help to solve the problem of unbalancing of DC link capacitor voltage. The idea is taken from the concept of third harmonic injection for harmonic minimization [109]. The method of addition of zero sequence component will make the sinusoidal modulating signal discontinuous, so the method is called Discontinuous PWM. The injection of zero sequence to all three phases will not change the magnitude of output, but will balance the neutral point or lead to proper utilization of DC-link voltage, if properly chosen. The technique, termed as zero sequence modulation by some researchers, became widely popular and a variety of algorithms or methods of calculating zero sequence voltage have been suggested [110]. The zero sequence injection is calculated so as to balance the unbalanced component in the system and can be achieved by altering the magnitude or phase angle of reference modulating signal. Various researchers suggested instantaneous power theory, weighted maximum/minimum or averages, multiples of one-sixth or third harmonic, for calculation of zero sequence component. One of the examples is shown in Figure 2.6.

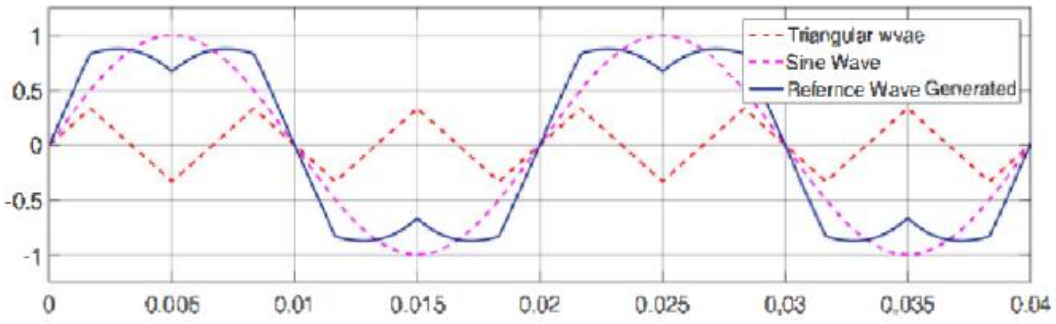


Figure 2.6 An example of Carrier Based Harmonic Injection

Discontinuous PWM offers several advantages over conventional Continuous PWM or CB-PWM methods.

- helps in achieving voltage-balancing between DC-link capacitors
- decrease the switching losses
- extends the linear-modulation range of the converter.
- mitigates the low frequency voltage oscillations of the neutral point.
- allows sharing of power among different legs of inverter.

2.5.5. Space Vector Control or Space Vector at Fundamental Frequency Modulation

SVPWM has been extended to be used at low switching frequencies or fundamental frequency for multilevel inverters, termed as Space Vector at Fundamental Frequency Modulation (SVFFM) or simply Space Vector Control (SVC) [111], [112]. An illustration of Space Vector Control of Five-Level Inverter is given in Figure 2.7.

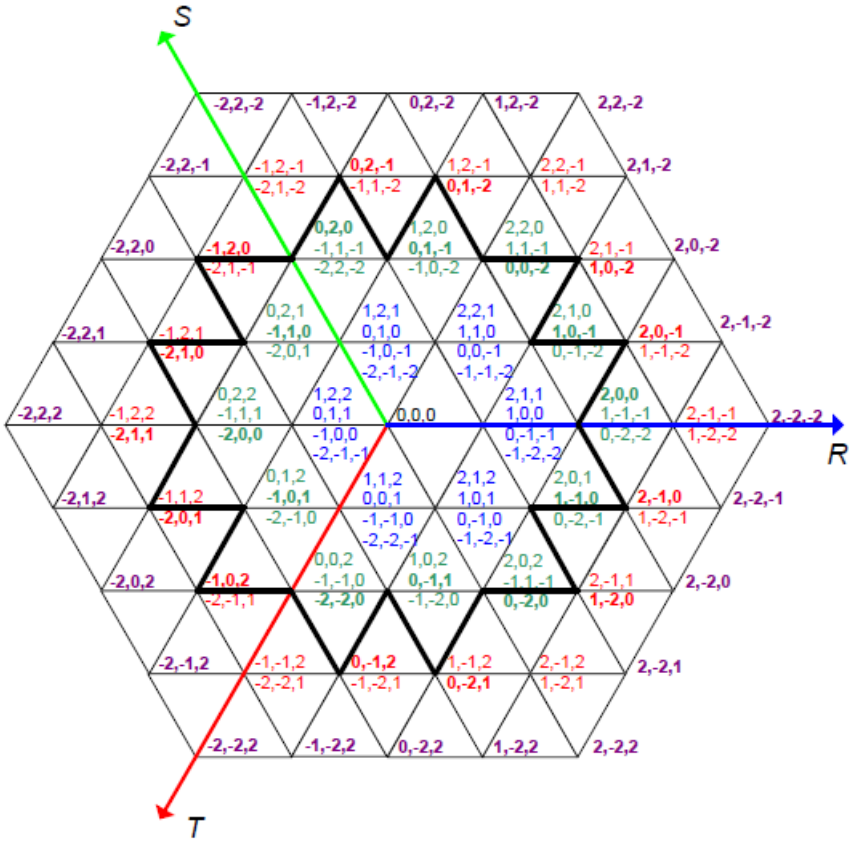


Figure 2.7 Space Vector Control of Five-Level Inverter

The concept of Space Vector Control has been derived from SVPWM, but it doesn't aim to produce the average of the desired output using the nearest three vectors (NTV) approach. Rather, it aims to generate an output voltage such that the space error or distance between generated and desired output is minimum. So, identification of adjacent three vectors is not required, but selection of switching sequence is done using some algorithms, like routing algorithm. Sequence selection can be simplified using two concentric hexagons and following the zig-zag pattern between them. This ensures that each level of the output voltage is traced only once in a fundamental period. Calculation of switching time is necessary; however, it remains constant throughout the period. Therefore, SVC can be easily extended to higher levels.

SVC is an approximate method, and thus, fundamental voltage component is somewhat different from the desired reference voltage and only certain harmonics are eliminated. It also exhibits similar advantages as SVPWM. But, as it doesn't carry out the process of sector identification and uses constant switching time, the technique is useful with higher levels. The major disadvantage is that it can be applied only to three phase inverters.

2.5.6. Selective Harmonic Elimination

The Selective Harmonic Elimination or SHE method is one of the most popular techniques of control in multilevel inverters as it mainly focuses on low order harmonics which are of major importance when power quality is concerned. SHE is proposed by Patel and Hoft (1974) using the harmonic elimination theory [34]. It can work with low/fundamental switching frequency as well as high/PWM switching frequency. However, the technique is commonly used with fundamental frequency, where the most significant low order harmonics are eliminated using the SHE theory and high order harmonics are removed by the use of filters. The control at fundamental frequency reduces the switching losses and increases the efficiency of multilevel inverter. Also, it is useful in suppressing the unavoidable harmonics between grid and non-linear loads.

The technique is based on the fact that the output of multilevel inverter can be represented by Fourier series expansion, given as a sum of fundamental and harmonic components. Now, the aim is to achieve the desired amplitude of fundamental component and minimize the harmonics. So, for m-level inverter, we need (m-1) levels of output voltage or (m-1)/2 switching angles to operate the inverter at fundamental frequency. Thus, a set of equations is chosen with one equation to obtain desired fundamental value and other (m-3)/2 equations representing low order harmonics to eliminate. These equations are non-linear in nature and involve (m-1)/2 switching angles, which needs to be calculated such that above conditions are met.

Thus, SHE involves a set of transcendental equations which are required to be solved in order to obtain the switching angles for getting desired waveform with reduce harmonics. Here, the number of harmonics which can be eliminated at a time is proportional to the level of inverter. To eliminate more harmonics than specified by the condition, switching frequency will increase. These equations contain nonlinear

trigonometric terms which can be solved with the use of iterative and numerical methods. Various methods have been tried and proposed for the calculation of best set of switching angles, such as elimination theory, theory of resultants of polynomials [113], theory of symmetric polynomials, Newton-Raphson method [114]–[116], etc. The task of computing switching angles gets complex with the increase in the level of inverter. As the method is offline, it is suitable only for a low number of levels.

Now, a contrast about both categories of switching frequency techniques can be drawn in Table 2.3 after having the understanding of modulation techniques. And the comparison leads to a conclusion that fundamental switching frequency techniques are far better than low switching frequency techniques in terms of every parameters.

Table 2.3 Comparison between High and Fundamental Switching Frequency Techniques

PARAMETERS	**High Frequency PWM Switching Scheme**	**Fundamental Frequency Switching Scheme**
THD	Harmonic content is low	Harmonic content is low
Even Order Harmonics	Present	Negligible
Switching Loss	High	Low
Control Circuit Complexity	Complex	Simple
Modularity of Circuit	Not possible	Possible
Generalization	Difficult	Easy

CHAPTER III

DEVELOPMENT OF OPTIMAL SWITCHING TECHNIQUE FOR HARMONIC MINIMIZATION IN CASCADED MLIs

Primarily, this chapter discusses the basics of Selective Harmonic Elimination method. Then, the problems associated with the conventional selective harmonic elimination method are highlighted. The existing methods are investigated to find their shortcomings and accordingly modifications are proposed to present a modified SHE function. Finally, the proposed function is considered and compared with existing methods by realizing it in MATLAB.

3.1. METHODS OF HARMONIC MINIMIZATION/MITIGATION

Multilevel inverters are generally used for medium-voltage and high power applications. The modulation technique used for controlling the output of inverter generally aims at either minimizing/eliminating the individual or total harmonic distortion. A number of approaches for harmonic minimization or mitigation have been proposed in the literature. These approaches can be broadly categorized as:

3.1.1. Harmonic Minimization Methods

Harmonic Minimization methods aim for minimization or reduction of harmonics and formulate the problem as minimization of harmonics rather than their complete elimination [100], [101], [103]. These methods generally employ different carrier based SPWM methods to reduce harmonics. SPWM methods use higher switching frequency which shifts the lower order harmonics to higher frequencies and reduce the required size of filter but this method increases switching losses. Though low switching frequency means low switching losses yet in that case, it requires large size of filter making the system bulky and costly. Also, the fundamental frequency component needs to be controlled at desired amplitude. Moreover, the real time implementation of harmonic minimization methods becomes easier as convergence to a local optimum can be achieved within a reasonable time step, but at the expense of

low-order harmonics, and thus making it impractical for certain applications [123]–[126].

3.1.2. THD Minimization Methods

More researchers contemplate towards minimizing Total Harmonic Distortion in voltage by approximating this value in order to have a fast calculation of the switching angles. These methods aim at minimization of voltage THD rather than elimination of individual harmonics, often termed as Optimal Minimization of THD methods [79], [80]. The derived formula for the computation of THD of the output voltage of the multilevel inverter is used as the objective function. The number of harmonics to be considered in THD calculation is not limited by the number of switching angles in the waveform, but can be chosen according to the application. This approach enables a global minimum THD while low order harmonics may or may not lie within the harmonic limits.

3.1.3. Harmonic Elimination Methods

It seems difficult to achieve the minimization of THD directly because the numerator generally has many terms. So, it is convenient to consider only a finite number of harmonics in numerator, but only a few lower order harmonics will be eliminated in that way and will contribute to more THD. In Harmonic Elimination methods, the fundamental frequency component is the only component that needs to be accurately controlled to the required level whereas all individual harmonics are within acceptable range. This approach facilitates convergence to solutions and higher continuity of solutions at the expense of low-order harmonics in the spectra. Selective Harmonic Elimination or SHE refers to a special case of harmonic elimination that aims at eliminating specific lower order harmonics, whereas all other harmonic components can be removed by filtering.

3.2. BASICS OF SELECTIVE HARMONIC ELIMINATION

The performance of multilevel inverters mostly depends on the modulation strategy used for their control and switching frequency used for control. Low switching frequency operation leads to low switching losses and improved efficiency, so it is preferred over high switching frequency operation. Among various low switching

frequency control methods, Selective Harmonics Elimination at fundamental frequency is the most widely used because of its ability to obtain the desired output with better power quality. It has gained importance in many applications such as motor drives and renewable energy conditioning converters. It is a promising approach for future advanced power conversion systems, and there is a wide range of research opportunities across different aspects that should be investigated to improve its features and practicality.

Selective Harmonic Elimination method was initially introduced as SHEPWM (i.e. SHE at high or pulse width modulated frequency) by Husmukh and Richard in 1973 [34]. The basic idea is to obtain a staircase waveform with chopped square waves at every level and reduced harmonic content. Multilevel Inverters have multiple levels of voltage; and for every level of voltage, there can be a number of switching angles to get multiple square waves at the same level as shown in Figure 3.1. The number of switching angles is related to the number of harmonics being eliminated and decides the switching frequency of the inverter. Using many switching angles at the same level makes the method complex and increases the switching frequency. Thus, it is highly recommended to use one switching angle per level; the method is called fundamental switching frequency control as illustrated in Figure 3.2. Also, most of the literature explored suggested the use of SHE at fundamental frequency more than at high frequency (SHEPWM) [121], [122].

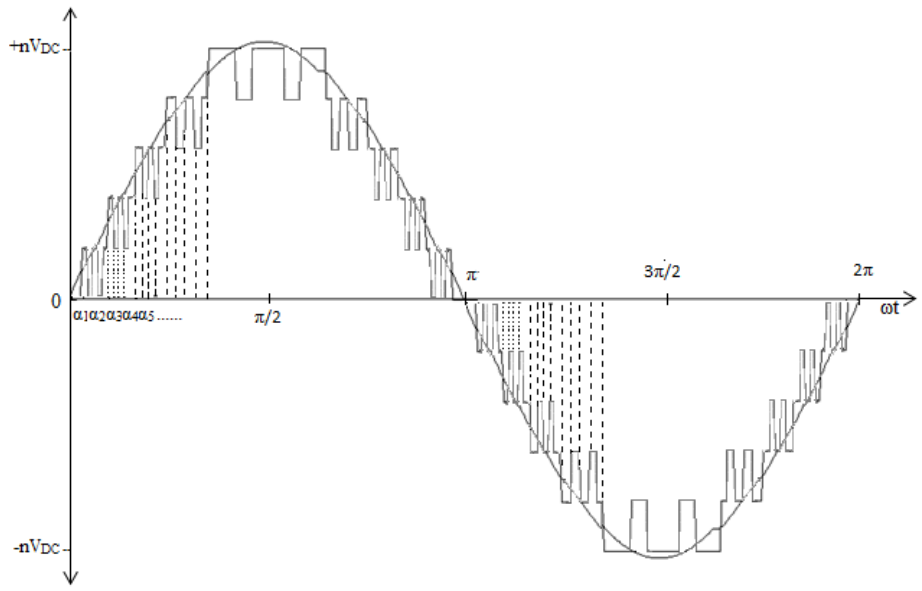


Figure 3.1 Multilevel Output with Multiple Switching at One Level, i.e. High or PWM Switching Frequency

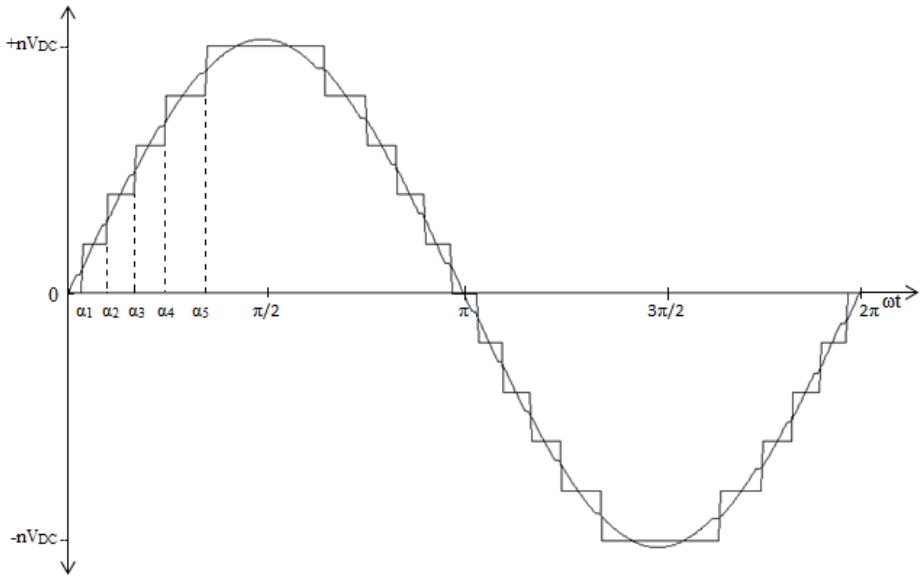


Figure 3.2 Multilevel Output with Single Switching at One Level, i.e. Fundamental Switching Frequency

SHE is a pre-programmed technique, to restrict the amount of harmonics in the output of multilevel inverter by proper selection of switching angles. The use of fundamental frequency operation shifts the low order harmonics to higher frequencies, where they can be filtered by small size filters. It also reduces the ripple in the DC link current and increases the utilization of DC-link voltage.

Now, the staircase waveform of the phase output voltage of multilevel inverter can be synthesized by the use of Fourier series expansion. The Fourier series contains a number of trigonometric terms and can be represented as:

$$\mathrm{v(t)} = a_0 + \sum_{\mathrm{n=1}}^{\infty} (\mathrm{a_n}\cos(\omega nt) + \mathrm{b_n}\sin(\omega nt)) \tag{3.1}$$

where $\omega=2\pi f_0$ and f_0 is the fundamental frequency, n is the number of other frequency components known as harmonics and a_0, a_n and b_n are called Fourier coefficients which can be obtained by the following integration equations

$$a_0 = \frac{1}{2\pi}\int V_{dc}\, d\omega t$$

$$a_n = \frac{1}{2\pi}\int V_{dc}\cos(n\omega t)\, d\omega t$$

$$b_n = \frac{1}{2\pi}\int V_{dc}\sin(n\omega t)\, d\omega t \tag{3.2}$$

As the output voltage of multilevel inverter exhibits half wave symmetry and is a periodic function, it is said to have quarter wave symmetry. And for such waveforms, the Fourier coefficients in equation (3.2) are reduced to

$$a_0 = 0$$

$$a_n = 0 \text{ for all n}$$

$$b_n = 0 \text{ for even values of n}$$

$$b_n = \frac{4}{\pi}\int_0^{\pi/2} V_{dc} \sin(n\omega t)\, d\omega t \quad \text{for odd values of n} \tag{3.3}$$

After integration, the value will become,

$$b_n = \frac{4V_{dc}}{n\pi}\sum_i^N (-1)^{i+1} \cos(n\alpha_i) \tag{3.4}$$

Substituting values of equation (3.4) in equation (3.1) and expanding,

$$\mathrm{V}(\omega t) = \frac{4V_{dc}}{\pi}\left\{\begin{array}{c} (\cos\alpha_1 + \cos\alpha_2 + \cdots)\dfrac{\sin\omega t}{1} \\ +(\cos 3\alpha_1 + \cos 3\alpha_2 + \cdots)\dfrac{\sin 3\omega t}{3} \\ +(\cos 5\alpha_1 + \cos 5\alpha_2 + \cdots)\dfrac{\sin 5\omega t}{5} + \cdots \end{array}\right\} \tag{3.5}$$

Further, triplen harmonics are not considered as they are absent in thecase of three-phase systems. For any level of inverter, the method of SHE uses one equation to get desired value of fundamental component and other equations for eliminating selected harmonics. Basically, an m-level of inverter has (m-1)/2 levels in positive phase, thus required minimum (m-1)/2 switching angles for fundamental frequency operation. For high switching frequency, switching angles depend upon the employed frequency. So, we require minimum (m-1)/2 equations for finding these switching angles. As one equation is dedicated to meet the requirement of fundamental component, the other (m-1)/3 equations focus on eliminating (m-1)/3 harmonics which include odd terms excluding triplen orders. If (m-1)/2=N, an m-level inverter need N equations and (N-1) harmonics can be eliminated. For SHEPWM, more switching angles are required, say 2 per level or 3 per level, and according to that equations will be incorporated to solve for the switching instants. So, the number of harmonics eliminated is dependent on the switching angles or switching frequency, but independent of the number of output voltage levels.

$$\frac{4V_{dc}}{\pi}(\cos\alpha_1 + \cos\alpha_2 + \cos\alpha_3 \ldots\ldots + \cos\alpha_N) = V_f$$

$$\cos 5\alpha_1 + \cos 5\alpha_2 + \cos 5\alpha_3 \ldots\ldots + \cos 5\alpha_N = 0$$

$$\cos 7\alpha_1 + \cos 7\alpha_2 + \cos 7\alpha_3 \ldots\ldots + \cos 7\alpha_N = 0 \text{ and N equations} \quad (3.6)$$

The switching angles α_1, α_2... α_N can be obtained by solving these nonlinear transcendental equations. Numeric mathematical or iterative techniques such as the Newton–Raphson method, Resultant theory and theory of polynomials, etc were employed for solving these equations.

The strategy behind both methods (SHE at fundamental or higher frequency) is the same, except for the number of switching angles to be calculated. However, the complexity involved in the solution of switching angles motivates the use of fundamental frequency operation. Accurate calculation of switching instants will produce the required output waveform with desired fundamental component and eliminate low order harmonics. Off-line calculation of switching angles is done in advance and the information about the harmonic content in output waveform will be available prior to the actual operation. This feature made SHE controlled MLIs useful in many industrial applications.

3.3. UNDERSTANDING PROBLEMS IN EXISTING MODULATION TECHNIQUES

One of the most prevalent techniques in control of multilevel inverters is Selective Harmonic Elimination. It can be implemented at high as well as low switching frequency. The frequency of operation can be as low as fundamental frequency, i.e. 50Hz. The operation at fundamental switching frequency helps in the reduction of switching losses of multilevel inverter. Elimination of lower order harmonics improves the quality of output voltage and current, and therefore, ripple in the DC link current is also small. Selective Harmonic Elimination technique offers many benefits, but there are certain limitations. In SHE, the number of switching angles to be optimized increases with the number of levels in output voltage, which complicate the problem. Also, the method can't eliminate the number of harmonics more than the number of levels in the output voltage. Thus, there's a need to modify the method so

that it can include more harmonic terms, and enable easy computation and implementation with increased accuracy.

Modification alone is not sufficient; there is a bigger challenge of solving highly non-linear transcendental equations to obtain the perfect set of switching angles which gives the desired staircase voltage output. Various numerical methods and algorithms have been suggested for this purpose. Proper selection of an optimization algorithm with proper design variables, constraints and bounds can solve the problem. All the mentioned problems are solved initially by looking for modification of objective function. For modifications, firstly, we need to go in the depth of the problem in existing functions. So, a number of functions, proposed by different researchers in literature, have been considered.

3.4. FORMULATION OF OBJECTIVE FUNCTION FOR HARMONIC MINIMIZATION

THD is one of the most important parameters to estimate the harmonic content of any waveform. So, initially the formula for THD is considered as objective function, that aim to minimize odd harmonic terms while triplen harmonics may or may not be considered depending on whether we are working on single phase or three phase systems.

$$\text{Voltage THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} * 100 \tag{3.7}$$

But Conventional THD minimization technique does not intend to eliminate any specific harmonic order, particularly because THD is an approximate term. So, there is a need for the calculation of exact THD of the line voltage of a three phase multilevel inverter. An analytical algebraic method based on formulating the line-voltage THD of multilevel inverters with unequal dc sources is presented by Farokhnia [123]. However, much simple expressions are introduced for calculating the exact THD of MLIs [124]. This formula is applicable to all types of MLIs utilizing any switching techniques for harmonics elimination or reduction, provided the switching angles of the phase voltage are known. And it is especially suitable to be applied with the Mixed Integer Linear Programming optimization model.

Several other switching techniques have been proposed by combining the conventional THD with SHE techniques to minimize THD as well as eliminate low-order harmonics [125]. These techniques involve the weighted combination of some low-order harmonics and THD formula to form the objective function, which is to be minimized by considering its constraints. However, such functions cannot guarantee elimination of specific harmonic orders for all modulation indices. Moreover, a nonlinear equality constraint is also required to be considered for regulation of the fundamental component at the desired value.

The performance of many objective functions proposed by previous research has been studied and discussed. Those functions found relevant are considered here for designing modifications.

i) The formula for THD can be used as an objective function.

ii) The fitness function can be taken as the sum of total harmonic distortion of the output staircase voltage and difference between V_1 and $V_{1(ref)}$ (reference value of the fundamental component of the output voltage).

iii) Some researchers have focussed on eliminating only a few terms or harmonic components thus reducing THD.

iv) Another function was proposed with the purpose of elimination of some low order harmonics and to maintain the fundamental component at the desired value.

Various functions presented by researchers have been investigated, whereas some of the functions are discussed and executed in detail to formulate a new objective function so as to meet the requirements. These functions are executed and analyzed for Single phase 11-level cascaded H-Bridge inverter in MATLAB/Simulink environment.

1. A very common term that is used to describe voltage or current distortion is THD or Total Harmonic Distortion. So, the formula for THD can be used as an objective function for three-phase systems. The function[52] given below aims to minimize 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics by considering 'n=49' number of individual distortion terms.

$$OF_1 = \sqrt{\left(\frac{V_3}{V_1}\right)^2 + \left(\frac{V_5}{V_1}\right)^2 + \left(\frac{V_7}{V_1}\right)^2 + \cdots \left(\frac{V_{49}}{V_1}\right)^2} \tag{3.8}$$

The optimized values of Switching Angles using equation (3.8) for the Single-Phase Eleven-level CHB Inverter are α_1=5.48˚, α_2=16.83˚, α_3=28.98˚, α_4=40.13˚, and α_5=65.71˚. The graph of obtaining these values with iterations is shown in Figure 3.3. These values are then used to simulate the Single-Phase Eleven-level CHB Inverter model, and the FFT (Fast Fourier Transform) analysis of output voltage waveform is presented in Figure 3.4.

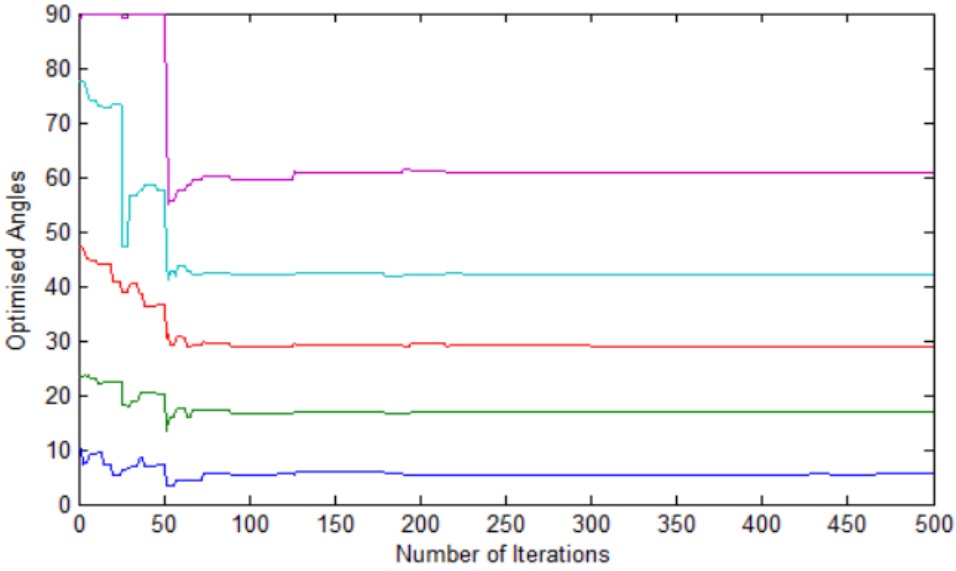


Figure 3.3 Optimized values of Switching Angles using Objective Function 1

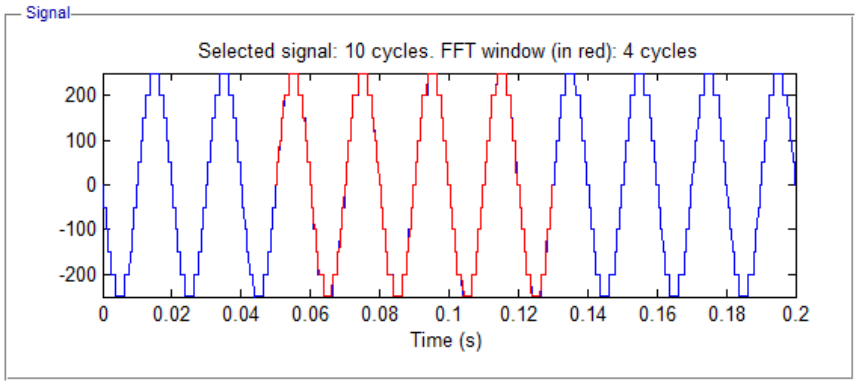


Figure 3.4 a) Output Voltage obtained from Objective Function 1

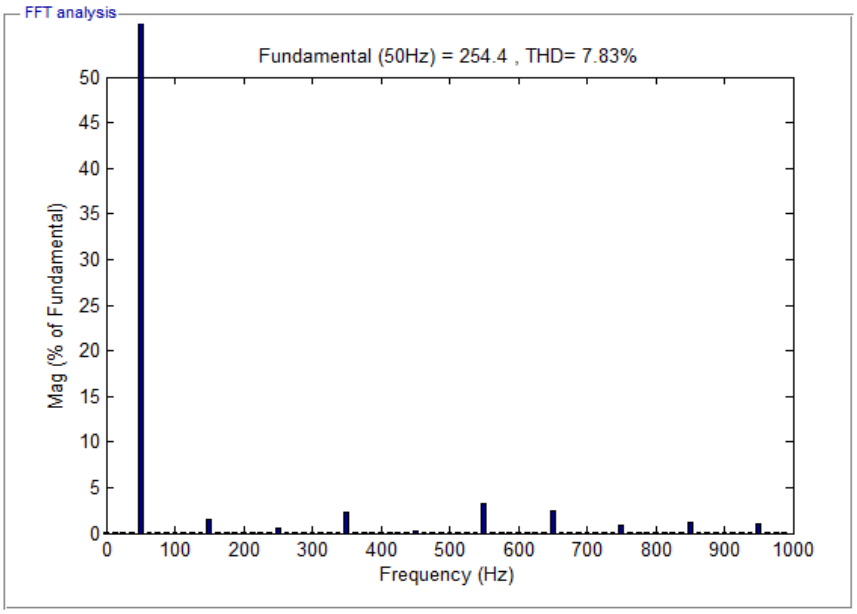


Figure 3.4 b) FFT Analysis of Output Voltage obtained from Objective Function 1

2. Several objective functions have been proposed by combining the conventional THD with SHE techniques to minimize THD as well as eliminate low-order harmonics. The fitness function [94] for THD optimisation problem can be taken as the sum of total harmonic distortion of the output staircase voltage and difference between V_1 and $V_{1(ref)}$ (reference value of the fundamental component of the output voltage). To have exact value of fundamental component in the output of the multilevel inverter the error of the reference value and real value is multiplied with 5. The value of multiplication factor changes with different theories.

$$OF_2 = 5 * \left(V_{1(ref)} - V_1\right) + \sqrt{\frac{\sum_{n=3,5,7,\ldots}^{49} V_n^2}{{V_1}^2}} \tag{3.9}$$

The optimized values of Switching Angles using equation (3.9) are α_1=1.81˚, α_2=4.78˚, α_3=8.44˚, α_4=11.42˚, and α_5=15.27˚. The graph of obtaining these values with iterations is shown in Figure 3.5. These values are then used to simulate the Single-Phase Eleven-level CHB Inverter model, and the FFT analysis of output voltage waveform is presented in Figure 3.6.

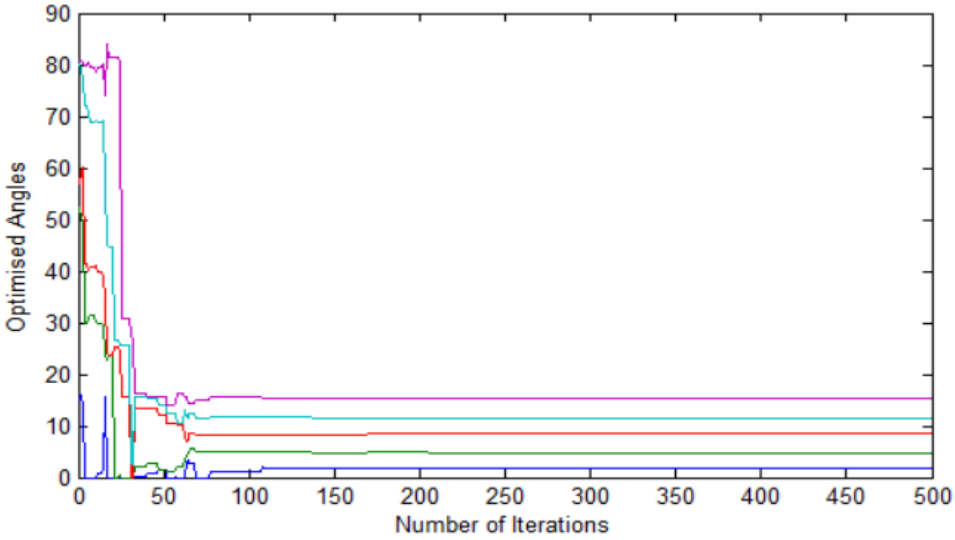


Figure 3.5 Optimized values of Switching Angles using Objective Function 2

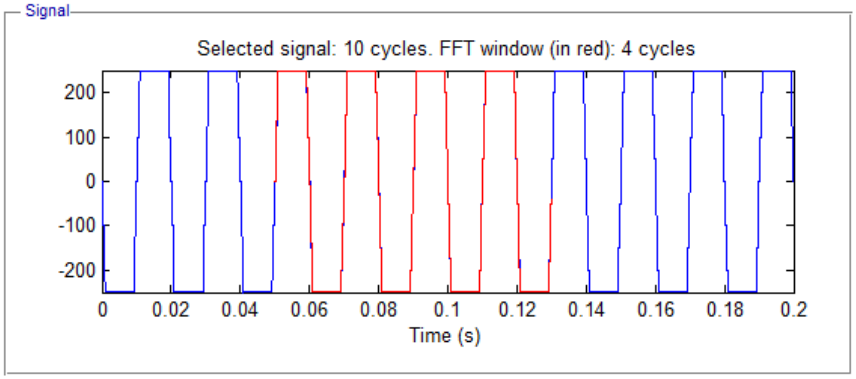


Figure 3.6 a) Output Voltage obtained from Objective Function 2

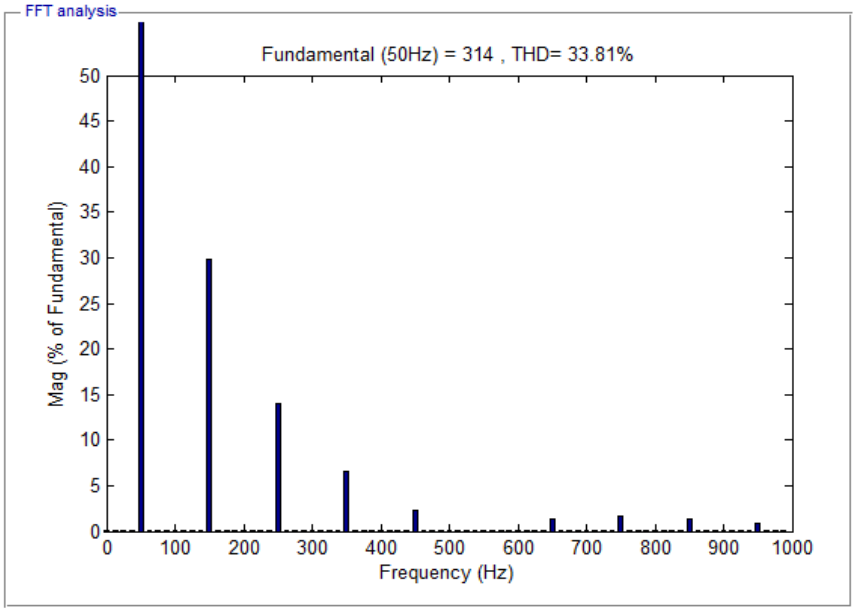


Figure 3.6 b) FFT Analysis of Output Voltage obtained from Objective Function 2

3. Minimization of THD is a bit complex task while considering many terms in numerator. Thus, some researchers have focussed on eliminating only a few terms or harmonic components thus reducing THD. The objective function [84] OF_3 considers weighted combination of fundamental deviation and some low-order harmonics as the objective function. But, considering limited number of harmonics like in SHE, cannot guarantee low THD or best optimal results.

$$OF_3 = 100 * \left| m - \frac{V_1}{V_{1(ref)}} \right| + \left| \frac{V_5 + V_7 + V_{11} + V_{13}}{V_{1(ref)}} \right| \tag{3.10}$$

The optimized values of Switching Angles using equation (3.10) are α_1=5.51˚, α_2=21.87˚, α_3=42.73˚, α_4=49.05˚, and α_5=52.14˚ shown in Figure 3.7. These values then simulate the Single-Phase Eleven-level CHB Inverter model, and the FFT analysis of output voltage waveform is presented in Figure 3.8.

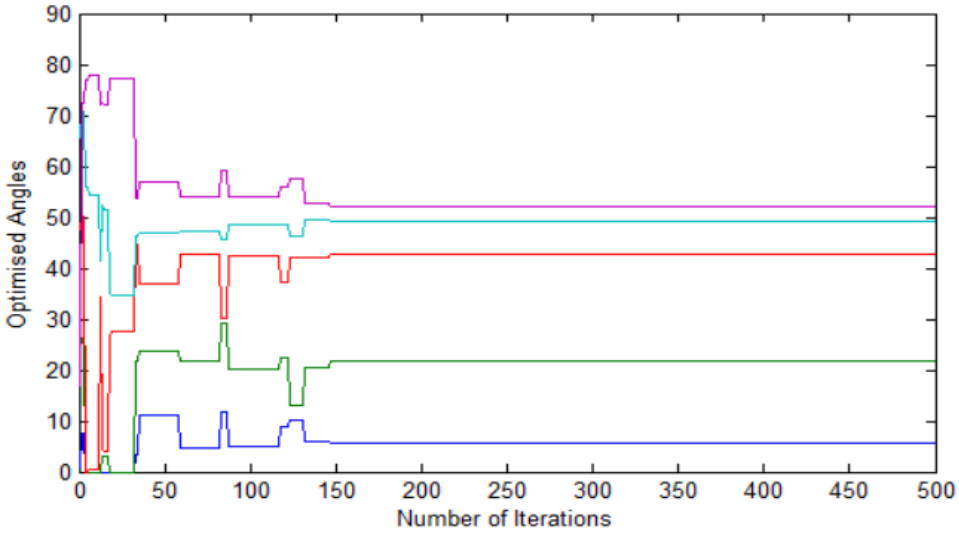


Figure 3.7 Optimized values of Switching Angles using Objective Function 3

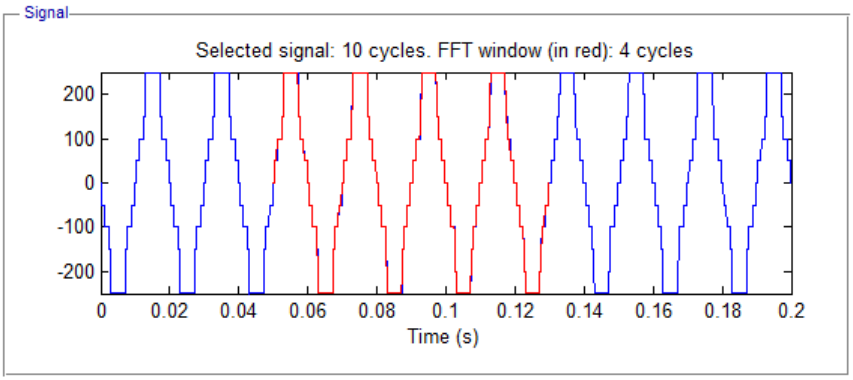


Figure 3.8 a) Output Voltage obtained from Objective Function 3

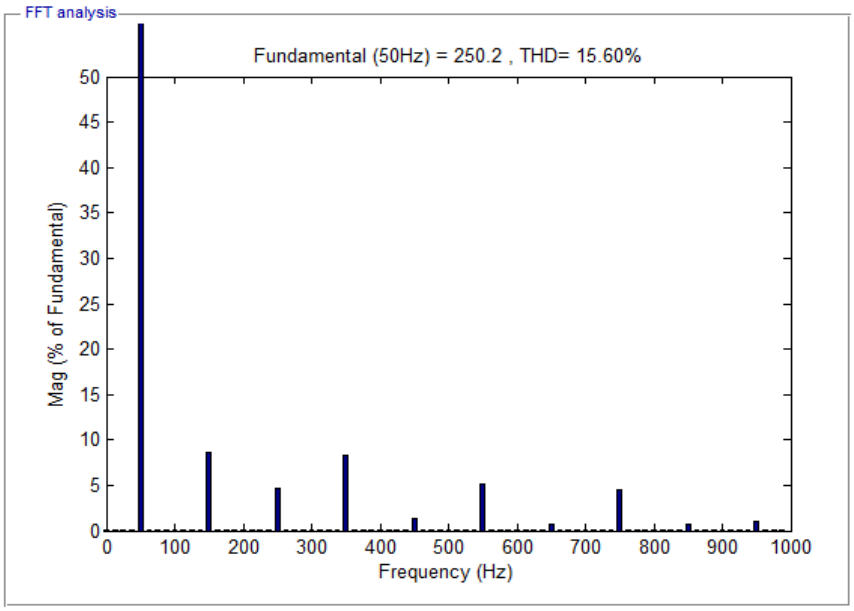


Figure 3.8 b) FFT Analysis of Output Voltage obtained from Objective Function 3

4. Another function [126] was proposed with the purpose of elimination of some low order harmonics and to maintain the fundamental component at the desired value. The optimized values of Switching Angles using equation (3.11) are α_1=7.84˚, α_2=19.36˚, α_3=29.63˚, α_4=47.65˚, and α_5=63.19˚ shown in Figure 3.9.

$$OF_4 = 100 * \left(\frac{V_{1(ref)} - V_1}{V_{1(ref)}}\right)^4 + \sum_{i=5,7,11,15,17} \frac{1}{h}\left(50 * \frac{V_i}{V_1}\right) \tag{3.11}$$

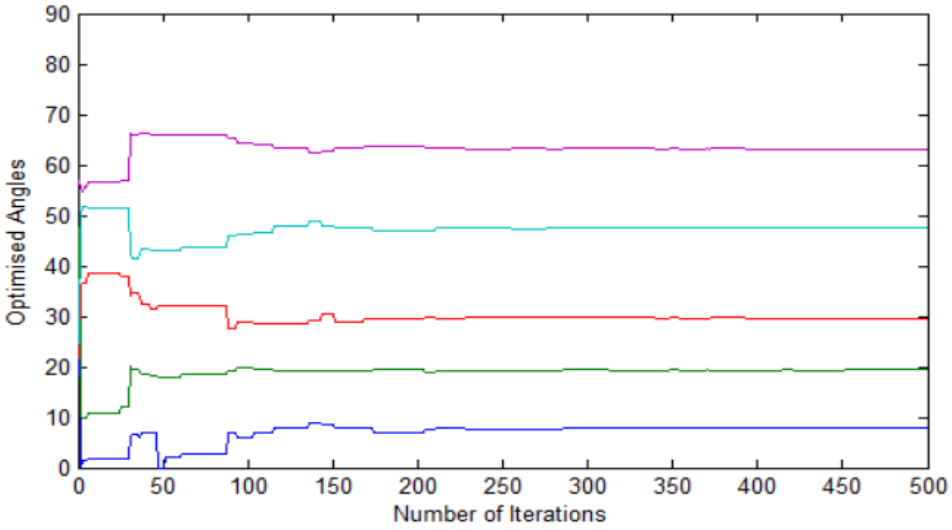


Figure 3.9 Optimized values of Switching Angles using Objective Function 4

These switching angles are then used to simulate the Single-Phase Eleven-level CHB Inverter model, and the FFT analysis of output voltage waveform is presented in Figure 3.10.

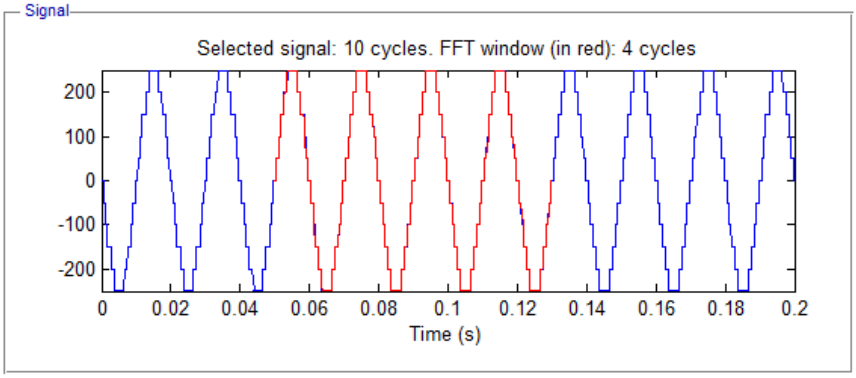


Figure 3.10 a) Output Voltage obtained from Objective Function 4

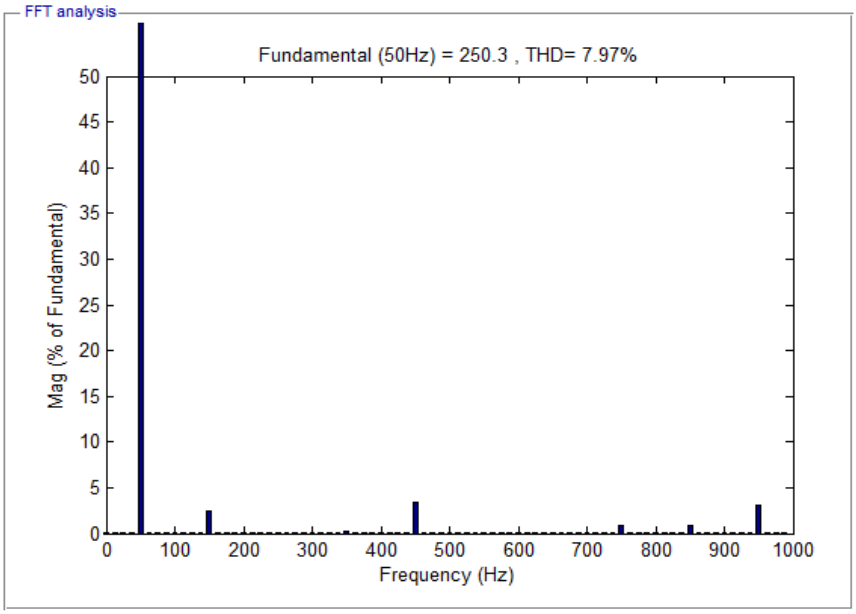


Figure 3.10 b) FFT Analysis of Output Voltage obtained from Objective Function 4

3.5. PROBLEM FORMULATION

Finally, the analysis of above objective functions has given the idea that it is important to control the fundamental voltage component as well as harmonics. But, considering limited number of harmonics like in SHE, using equations equal to number of switching angles doesn't promise desired results. Keeping all the aspects in above stated objective functions in view, a modified objective function has been framed with the following concerns:

- Equation 3.8 indicates that THD is better when voltage distortion factors upto 49th harmonic $\sum_{i=3,5,7,\ldots}^{49}\left(\frac{V_i}{V_{1(ref)}}\right)$ are considered.
- Now, equally important is to keep the fundamental component of voltage at reference value, such conditions are framed as least squares problem. Equation 3.11 has used the similar component; the voltage deviation should be minimum. Thus, considering fundamental voltage deviation as least square problem $\left(1-\frac{V_1}{V_{1(ref)}}\right)^2$ helps to get the better results.
- The least fourth powers method allows fitting a geometric figure to a set of points in such a way, that the maximal value of displacement between the fitted figure and the points is smaller than in the least squares method. This property can be very useful in some engineering tasks,
- Thus, combining the two perspectives together, the optimization function as a weighted sum of two functions with one using least fourth powers and other using least square powers, can be framed as:

$$OF_5 = W_1 * \left(1-\frac{V_1}{V_{1(ref)}}\right)^4 + W_2 * \sum_{i=3,5,7,\ldots}^{49}\left(\frac{V_i}{V_{1(ref)}}\right)^2 \quad (3.12a)$$

In weighted sum method, each objective is given a weight to differentiate their relative importance during the aggregation of the overall objective function. The weights W_1 and W_2 are such that their sum is unity. To determine the optimum weights W_1 and W_2, the two functions are calculated for different combinations of weights, represented in Figure 3.11. That set of weights is chosen where the value of objective function, as sum of two functions, is found to be minimum. Therefore, equation 3.12a can be rewritten as

$$OF_5 = 0.1 * \left(1-\frac{V_1}{V_{1(ref)}}\right)^4 + 0.9 * \left(\sum_{i=3,5,7,\ldots}^{49}\frac{V_i}{V_{1(ref)}}\right)^2 \quad (3.12b)$$

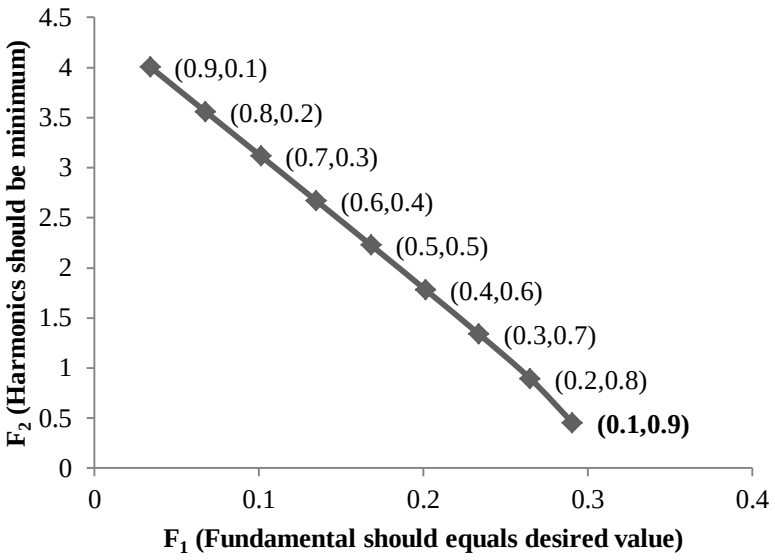


Figure 3.11 Geometrical Representation of two functions

The optimized values of Switching Angles using equation (3.12) for the Single-Phase Eleven-level CHB Inverter are α_1=5.52˚, α_2=16.91˚, α_3=29.13˚, α_4=42.39˚, and α_5=61.21˚. The graph of obtaining these values with iterations is shown in Figure 3.12. These values are then used to simulate the Single-Phase Eleven-level CHB Inverter model, and the FFT analysis of output voltage waveform is presented in Figure 3.13.

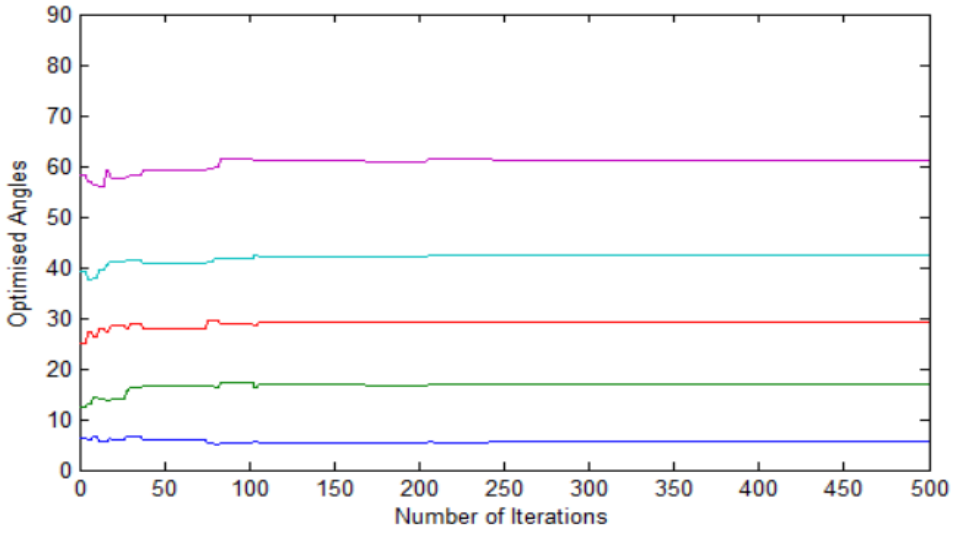


Figure 3.12 Optimized values of Switching Angles using Objective Function 5

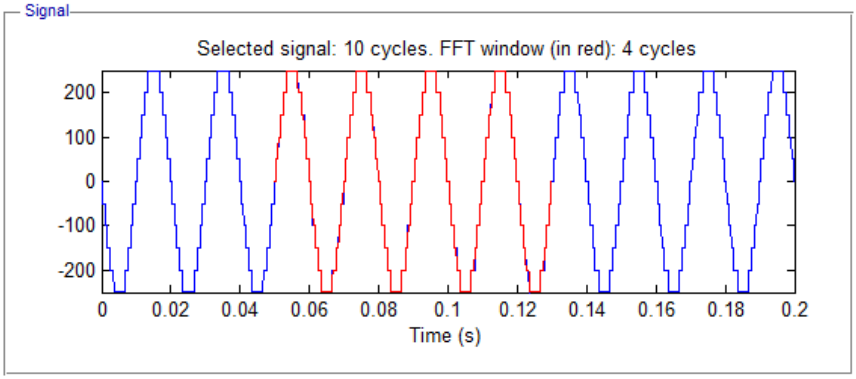


Figure 3.13 a) Output Voltage obtained from Objective Function 5

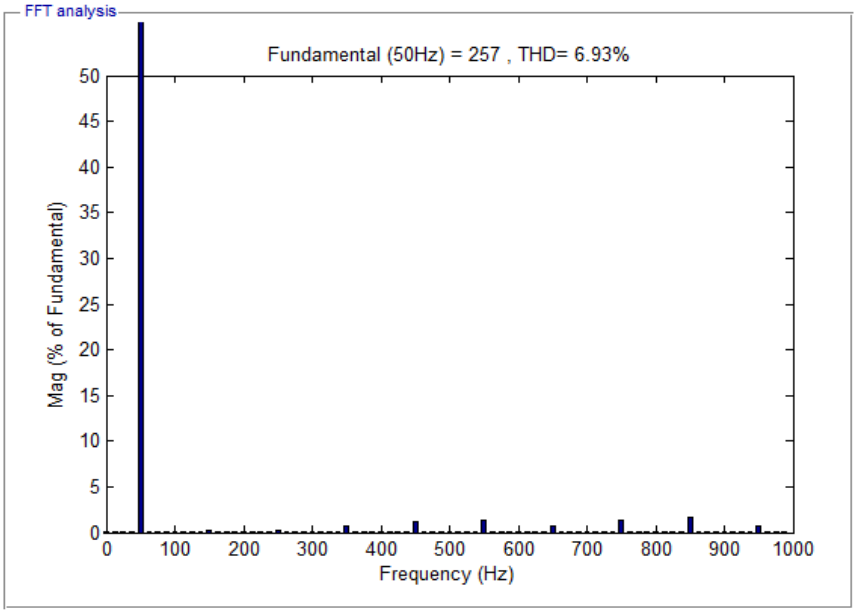


Figure 3.13 b) FFT Analysis of Output Voltage obtained from Objective Function 5

The comparison of values of switching angles optimized using objective functions and respective THD obtained from the simulation results has been shown in Table 3.1. Furthermore, detailed harmonic analysis is presented in Table 3.2. It is very much clear from the tabulated results that the suggested objective function gives best results.

Table 3.1 Comparison of Switching Angles Using Different Objective Functions and Respective THD

Objective Function	α_1 (degree)	α_2 (degree)	α_3 (degree)	α_4 (degree)	α_5 (degree)	Phase THD (%)
OF_1	5.48	16.83	28.98	40.13	65.71	7.84
OF_2	1.81	4.78	8.44	11.42	15.27	33.81
OF_3	5.51	21.87	42.73	49.05	52.14	15.60
OF_4	7.84	19.36	29.63	47.65	63.19	7.97
OF_5	5.52	16.91	29.13	42.39	61.21	6.93

Table 3.2 Detailed Harmonic Analysis of Different Objective Functions

Parameters	OF_1	OF_2	OF_3	OF_4	OF_5
THD (%)	7.83	33.81	15.60	7.97	6.93
3th Harmonic	1.56	29.78	8.55	2.39	0.22
5th Harmonic	0.48	14.00	4.65	0.12	0.28
7th Harmonic	2.26	6.51	8.37	0.16	0.78
9th Harmonic	0.17	2.26	1.27	3.36	1.15
11th Harmonic	3.17	0.14	5.14	0.08	1.42
13th Harmonic	2.52	1.30	0.78	0.13	0.77
15th Harmonic	0.94	1.62	4.45	0.80	1.37
17th Harmonic	1.23	1.41	0.71	0.85	1.71
19th Harmonic	1.08	0.94	1.07	3.16	0.76

Further study is done to extend the operating range of multilevel inverter and different values of modulation index are considered. The optimal values of switching angles are obtained using proposed objective function with different values of modulation index are shown in Figure 3.14. Also THD obtained in FFT analysis using switching angles at different values of modulation index are summarized in Table 3.3.

Observations conclude that the inverter can be efficiently used within modulation index range from 0.7 to 1.0 with the same value of switching angles.

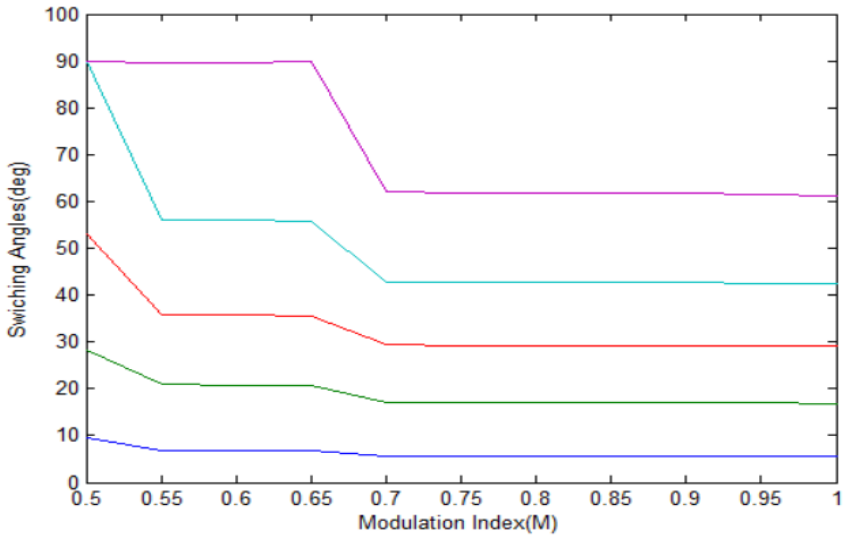


Figure 3.14 Switching Angles using Proposed Function at Different Values of Modulation Index

Table 3.3 Comparison of THD using Switching Angles at Different Values of Modulation Index

Modulation Index (M)	Voltage THD (%)	V(rms value) (V)
0.5	12.65	112.1
0.55	8.96	148.7
0.6	8.94	148.7
0.65	8.87	148.7
0.7	6.98	181.5
0.75	6.98	181.6
0.8	6.91	181.6
0.85	6.91	181.6
0.9	6.99	181.6
0.95	6.98	181.6
1.0	6.93	181.7

3.6. CONCLUSION

Different methods of Harmonic Minimization based on THD minimization, harmonic elimination and Selective Harmonic Elimination (SHE) based methods previously proposed in literature are discussed. Their benefits and shortcomings have been

addressed after analyzing the various objective functions proposed in previous research papers. Then finally, an improved form of objective function is framed and compared with previously proposed objective function on the basis of output voltage and the harmonic content present in output waveform of multilevel inverter.

But, framing a problem alone doesn't promise the solution. The comparison or modification alone may not help to reach to the optimized values of switching angles; it requires an efficient method of optimization of modified SHE function. So, the next important step is choosing an optimization algorithm. Classical Optimization Techniques like Linear programming, Mixed integer programming, Nonlinear programming, and Constraint programming, etc, require an ample amount of time and are mostly inefficient. They have limited scope in practical applications. So, advanced optimization algorithms are discussed in the next chapter.

CHAPTER IV

COMPARATIVE ANALYSIS OF VARIOUS OPTIMIZATION ALGORITHMS FOR HARMONIC MINIMIZATION

4.1. NEED OF OPTIMIZATION

Framing an objective function or optimization problem doesn't always guarantee the best solution. However, it will take you to the half way towards your goal. So, these days, optimization algorithms are being adopted to unravel the problem, in almost every field of engineering. The classical optimization techniques like Newton-Raphson, Walsh functions, and Block-pulse functions are some of the direct or gradient search techniques which require an ample amount of time, and thus inefficient for realizing true value of non-homogeneous differential problems. Linear programming, Mixed integer programming, Nonlinear programming, and Constraint programming are based on the mathematical methods and are all numerical optimization methods.

Over the years, several advanced optimization techniques have been introduced by the various researchers like Genetic Algorithm(1960), Simulated Annealing(1983), Particle Swarm Optimization(1995), and many more. But, an engineer generally chooses to explore the firstly proposed most complicated algorithm (i.e. Genetic Algorithm) to reach to the solution without much trouble. On the contrary, a number of design parameters are associated with GA, and it is very important to choose the values of these parameters carefully, in order to achieve best results. Moreover, it performs many operations like crossover, mutation, etc. in every iteration and hence takes more time for optimization. It means this commonly known algorithm can be computationally more expensive and one of the longest technique. Therefore, choosing the appropriate optimization search algorithm is equally important as framing a well-defined problem.

So, basically there are two main difficulties that an engineer faces in the process of optimization. The selection of an optimization algorithm and its design parameters is the first barrier and afterwards; to meet the need of generalization for large-scale studies is another parameter of concern. The process of selection of algorithm/design

parameters is done by the use of hit and trial method or case studies. The time required in selection or tuning of algorithm parameters also adds to the setup cost. So, some algorithms may not be efficient when extended for higher-order optimizations. With the advancement of technology, different nature-inspired algorithms have also been suggested, with every algorithm having its own benefits and limitations. Also, every optimization problem is different depending on the nature of design variables, type of constraints, type of search space, and nature of the equations involved. So, it is essential to make the choice of algorithm according to the type of optimization problem.

4.2. CLASSICAL OPTIMIZATION METHODS

The Classical Optimization methods are advantageous for optimization of single variable functions, multivariable functions with no constraints, and multivariable functions with both equality and inequality constraints. These methods are analytical and based on the principles of differential calculus. They have led to the development of some numerical methods that have evolved into advanced techniques more suitable to today's practical problems. So, classical optimization techniques that are incorporated in electric engineering problems can be broadly categorized as:

i) Direct Search methods

ii) Gradient Search methods

iii) Numerical Methods

4.2.1. Direct Search Methods

Direct Search technique can be defined as a continuous act of searching for a set of possible solutions around current solution with fitness value better than current value, till an optimal criterion is met. They are commonly termed as unconstrained optimization methods that do not rely on the use of derivatives. These methods can be used for non-differentiable or even discontinuous functions. Some of the common direct search methods are random search method, golden-section search or Interval halving method, Exhaustive search method, Bounding phase method, Region-elimination method, and Quadratic interpolation method.

Random search repeatedly generates a set of points of independent variables and calculates the value of function at every point to find the best solution. With adequate number of points, optimal solution can be obtained for multi-dimensional problem. Interval halving method or golden-section search begins with lower and upper bound values as two initial points. A new point is selected within this interval according to the golden ratio and the interval (upper or lower bound) is updated according to the function value at that point. This method can be used for one-dimensional problems only. But these methods do not ensure the global optimum solution. Interpolation methods (Quadratic or Cubic Interpolation) provide a better way to find global optimum rather than local optimum solution. In this technique, the function's critical value is bracketed, and quadratic/cubic polynomial is fitted to the arc which interpolates the function at some points in the interval. It keep determining new intervals, where the minimum of polynomial exists, and forgets the information about already evaluated points, which is the main drawback of this method.

4.2.2. Gradient Search Methods

Gradient-based methods, also termed as stochastic approximation methods, are one of the oldest methods for solving an optimization problem. They make use of gradient of the objective function to find the optimal solution, and thus, are applicable to the functions which are continuous and differentiable in nature, limiting the scope in practical applications. At every step, the value of decision variable is adjusted so as to obtain reduced value of objective function. As the methods involve change in decision variable in proportion to the change in value of objective function, these methods tend to get stuck in local maxima or minima. However, these methods works better with functions having one clear optimum solution.

Some of the common Gradient Search methods are Steepest Descent Method, Conjugate Gradient method, Newton method, Modified Newton method, Quasi-Newton method, Newton-Raphson method, Bisection method, Secant method and Cubic search method. The steepest descent method utilizes the gradient vector at each point as the search direction. Newton's method uses a second-order Taylor series expansion of the function about the current design point, i.e. a quadratic model. These methods are slow methods and may take an infinite number of iterations to converge

to a global optimum solution. They can work for any number of dimensions, even in infinite-dimensional ones.

4.2.3. Numerical Methods of Optimization

Various optimization methods have been evolved using the theories of numerical methods like Linear Programming methods, Nonlinear Programming methods, Mixed Integer Programming methods, and Constraint Programming methods. Linear Programming methods are useful for a wide range of problems if objective function and constraints are linear functions of design variables. They include Simplex method, Revised Simplex method, and Interior Point techniques. Nonlinear programming methods are used for optimization of nonlinear objective function having linear or nonlinear constraints. Commonly known NLP methods are Sequential Quadratic Programming method, Augmented Lagrangian method, Generalized Reduced Gradient method, Projected Augmented Lagrangian method, Successive Linear Programming method and Interior Point method. Here, Sequential quadratic programming is a method of optimization used for nonlinear constrained problems. Generalized Reduced Gradient method deals with linearizing the non-linear objective and constraints using Taylor expansion.

4.2.4. Limitations of Classical Optimization Methods

Conventional or Classical Methods of Optimization are generally random search techniques or techniques based on well-established theories of calculus. They perform satisfactorily for the particular problems they are meant to optimize. But there are certain restrictions to these methods due to algorithm complexity, long execution time, danger of convergence and possibility of getting trapped in local optima. Another biggest problem with classical methods is that they need complete information of the objective function. Direct Search methods are comparatively easy to implement and attractive as they do not require solving for gradient information. On the contrary, Gradient Search methods completely rely on the gradient of function. Also, their convergence to an optimal solution depends on the chosen optimal solution. For example, the steepest descent method starts its search from a single point and reaches an optimal solution, which may or may not be global optimum.

The real optimization problems involve many complexities like mismatched objectives, nature of variables (continuous, discrete, or mixed), types of constraints/irregularities, type of search space, etc. Solution to such problems may not be achieved using these conventional methods of optimization. Researchers have explored and introduced various advanced optimization methods which can provide a more sophisticated way of search because they use the information gathered at previously solved points.

4.3. ADVANCED OPTIMIZATION METHODS

In the real world, almost every engineering problem directly or indirectly depends on the solution of an optimization problem. Such problems generally have certain conflicting objectives and constraints which makes it difficult to be solved by classical optimization methods. Increased complexity of real-world engineering problems has led to a greater need and application of advanced programming techniques. So, advanced techniques of soft computing are employed to investigate a better optimal solution with a high probability of convergence.

The word 'Heuristic' means to discover or learn something. Heuristic methods facilitate to discover an approximate solution for complex optimization problems. These methods are best suited when classic methods are too slow, or fail to find any exact solution. It is based on making tradeoffs between different factors like optimality, completeness, accuracy, or precision for speed, in order to achieve desirable outcomes. Numerous heuristic methods including evolutionary computation, simulated annealing, particle swarm and many more have been evolved to solve various types of optimization problems.

Soft computing techniques, in contrast to traditional techniques, deal with approximate models of complex real-life problems. Soft computing utilizes chaotic, but flexible neural models of computing. As no single method can compute like people, soft computing uses combination of different methods like Fuzzy Logic, Evolutionary Computation, Machine Learning, and Probabilistic Reasoning.

Researchers have observed that firstly, generating a population (set of initial solutions) and afterwards, updating it iteratively will increase the possibility of converging on best optimal solution. Evolutionary Computation methods refer to a

family of population based nature inspired algorithms developed for global optimization. Figure 4.1 illustrates various advanced optimization techniques or evolutionary computation techniques under Soft Computing methods.

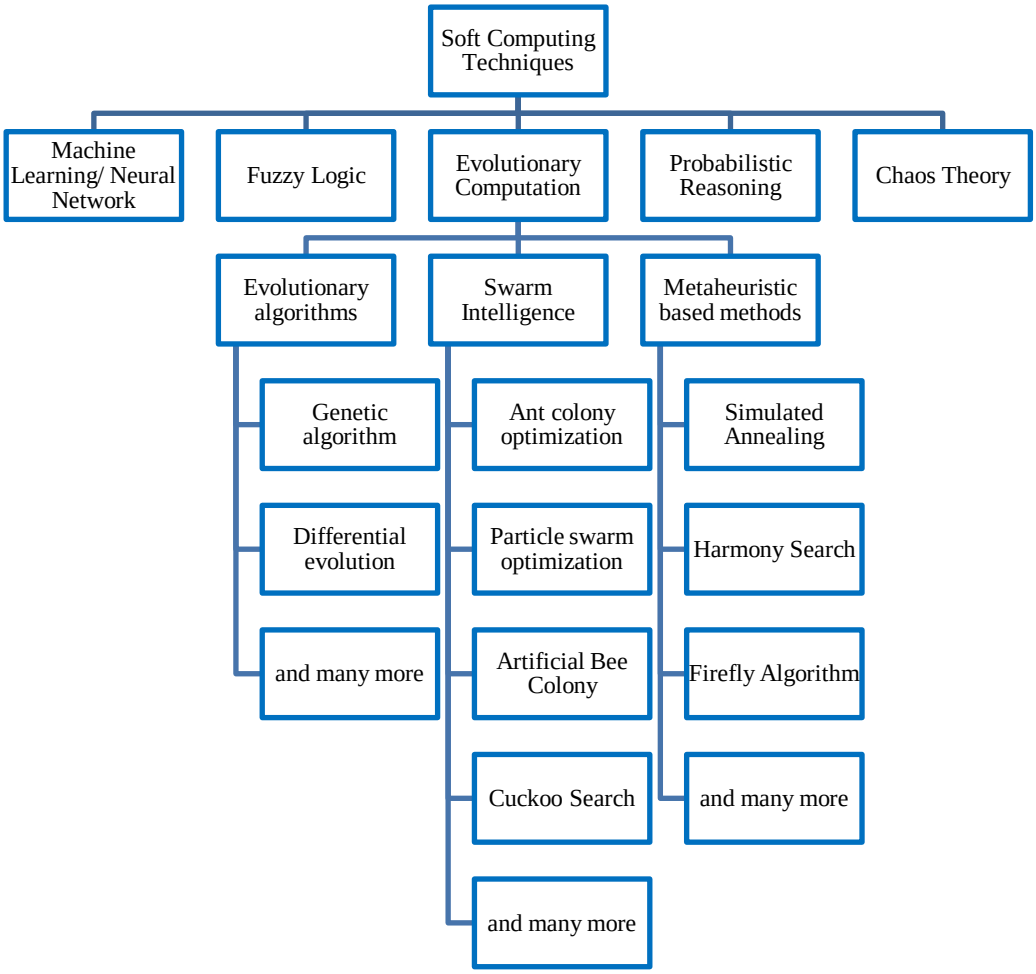


Figure 4.1 Hierarchy of Soft Computing Techniques

4.3.1. Evolutionary Algorithms (EAs)

Evolutionary Algorithms are robust in nature and enables to find the solution of large scale problems having multiple local optima. In evolutionary algorithms, initial population gradually evolves to yield highly optimum solution, by means of mechanisms inspired by biological evolution, such as reproduction, mutation, crossover, and selection. The process of evolution takes place after repeated application of these mechanisms, which means high computation times, and thus they have poor convergence. As they utilize stochastic search mechanism and thus can avoid premature entrapment in local optima. Therefore, EAs have been recognized as important mathematical tools for solving continuous and multi-objective optimization

problems. However, evolutionary algorithms are extremely slow. Genetic algorithms and evolutionary programming are the two most widely used evolutionary algorithms.

❖ **Genetic Algorithm**

Genetic Algorithm is a local search technique well suited for determining approximate solutions to optimization and search problems. Genetic algorithms are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology such as inheritance, mutation, crossover (also called recombination), and selection. John Holland introduced genetic algorithms in 1960 based on the concept of Darwin's Theory of Evolution; afterwards, his student David E. Goldberg extended GA in 1989. The algorithm proceeds with a population of randomly generated individuals refer to as solutions and then progressively improve it by the application of the mutation, crossover, inversion and selection operators. Genetic algorithms are difficult to set up because the user must choose how to represent and encode elements of a solution in the initial population. Additionally, they are difficult to fine tune because they may require modifying the set of decision variables, finding alternate solution encodings, and changing crossover and mutation implementations. Thus, achieving an optimal solution using GA requires expensive evaluations.

❖ **Differential Evolution**

Differential Evolution is a stochastic, population-based optimization algorithm, introduced by Storn and Price in 1996, for solving nonlinear optimization problems. The algorithm initializes randomly generated solutions as population and performs mutation, recombination, replacement and evaluation to obtain desired quality of solution. The new solution is selected on the basis of best fitness. The algorithm doesn't guarantee to find global minima of an optimization problem.

4.3.2. Swarm Intelligence Based Algorithms

Swarm Intelligence Algorithms are inspired by the 'collective intelligence' of biological systems. Collective Intelligence emerges when a large number of homogeneous agents present in the environment interact locally with one another and environment. Although there is no centralized control specifying how these agents should behave in the environment. The information is either stored throughout the

participating homogeneous agents, or transferred in the environment itself. Examples of swarm intelligence in natural systems include ant colonies, bird flocking, hawks hunting, animal herding, bacterial growth, fish schooling and microbial intelligence. Like evolutionary algorithms, swarm intelligence algorithms are considered as adaptive techniques and are typically applied to search and optimization domains.

❖ Ant Colony Optimization (ACO)

This is a probabilistic method inspired by the behaviour of ants. ACO is introduced by Dorigo and found useful in problems that deal with finding better paths through graphs. In this algorithm, a population of initial solutions (artificial ants) is allowed to change their position by moving through a parameter space representing all possible solutions in search of better solution (food). Each solution keeps track of its previous position, like ants lay a pheromone trail. The solutions do not keep moving to a random solution if one of the solutions has achieved the global optimum (minimum fitness), instead they follow the best solution, like ants track the trail laid by earlier ants. However, the pheromone trail tends to evaporate over time, thus reducing its attractive strength. This feature helps to avoid the convergence to a locally optimal solution. If there were no evaporation, the best position of initial solution (shortest path where an ant from the colony locates food) is likely to be followed by all other solutions. Thereby, exploration of the parameter space would be limited. The ant colony algorithm can run continuously and adapt to changes in real time. So these algorithms are useful for achieving the near-optimal solutions to problems similar to traveling salesman problem, like optimization problems in the areas of network routing and urban transportation systems.

❖ Particle Swarm Optimization

Particle Swarm Optimization, proposed by Dr. Eberhart and Dr. Kennedy in 1995, is inspired by the social behavior of bird flocking or fish schooling. PSO is a very popular algorithm amongst the class of numerical and qualitative problems. This algorithm employs a population of randomly generated particles (which are basically potential solution to the optimization problem) that moves stochastically in the search space. These particles are evaluated at each time step, so that particles with weak fitness are accelerated towards the better fitness attained by other particles. Each particle keeps track of its Personal Best Solution known as P_{best} and Global Best

Solution, known as G_{best} and modifies its position accordingly. This algorithm has proven to be fast and effective for a diverse set of optimization problem and can be easily implemented in most programming languages.

❖ **Artificial Bee Colony Algorithm**

Artificial bee colony algorithm, commonly known as ABC algorithm, was introduced by Karaboga in 2005, taking motivation from the foraging behaviour of honey bees. The ABC algorithm has three phases: employed bee, onlooker bee and scout bee. In the first two phases, exploitation, i.e. search locally in the neighborhood for best possible solutions, takes place. The exploitation is based on deterministic selection in employed bee phase, and probabilistic selection in onlooker bee phase. The last phase or the scout bee phase deals with exploration, I.e. abandons the weak solutions (like abandoning exhausted food sources in the foraging process) and explore new solutions from the search space. When the parameters of ABC algorithm are perfectly tuned, it presents a well-balanced exploration and exploitation ability.

❖ **Bat Algorithm**

Bat Algorithm is also a swarm-intelligence-based algorithm, inspired by the echolocation behavior of microbats. It uses a frequency-tuning and spontaneous balance of exploration and exploitation by adjusting loudness and pulse emission rates.

4.3.3. Metaheuristic Based Methods

Heuristic-based methods are very robust and tend to optimize in relatively much less time than other traditional methods. These methods maintain a balance between exploration and exploitation. The exploitation capabilities not only help in identification of local minima, but also increase the probability of discovering global optima. However, discovery of global optimum solution requires fine tuning of algorithm parameters. These classes of algorithms are not mutually exclusive and many algorithms combine ideas from different classes, commonly termed as hybrid algorithms. So, many a times, a heuristic method is combined with some traditional method such as statistical analysis, or two different heuristics are combined to yield better performance than the individual algorithms. It is done with the intention to

improve or enhance overall search efficiency. Though, the process takes more time as parameters which require fine tuning increase in number.

Metaheuristic is a higher-level problem independent framework that provides a set of guidelines or strategies to find sufficiently good solution to an optimization problem, especially with incomplete or imperfect information or limited computation capacity. In practice many researchers and practitioners use the terms heuristics and metaheuristics interchangeably. Compared to other algorithms and iterative methods, a metaheuristic method does not always guarantee a global optimal solution, but near global optimum solution. These methods implement some stochastic optimization technique on a set of randomly generated variables and search over a large set of feasible solutions to find good solutions with less computational effort. Various algorithms based on metaheuristic approach are Simulated Annealing, Ant Colony Optimization, Particle Swarm Optimization, Tabu Search, Harmony Search, Firefly Algorithm, Cuckoo Search and many more.

❖ Simulated Annealing

Simulated annealing is based on the physical process of annealing, i.e. cooling down of metal from molten state to solid state, by lowering its energy/temperature. This is similar to the phenomenon of dropping some bouncing balls on the ground, and they keep losing their energy and settles at some local minima and finally lowest position, known as global minima. SA uses acceptance probability which decides whether or not objective function has reach its global minima. The algorithm has an impressive feature of avoid getting trapped at local optima and thus can be used to find solution for problems with nonlinearity, boundary conditions, and constraints.

❖ Tabu Search

Tabu Search, developed by Fred Glover in the 1970s, is one of the most successful and widely used metaheuristic based algorithm. The principle of this algorithm is basically a gradient descent search method that uses memory and search history to optimize a problem. The memory used in Tabu Search stores search history in form of tabu list, which saves a significant amount of computational time. Length of list and area around the list are termed as critical design parameters. Further, Aspiration and

Diversification allows the solution to converge. The algorithm is useful for hill-climbing problems.

- **Harmony Search**

Harmony search, proposed by Geem in 2001, is a relatively new heuristic optimization algorithm inspired by spontaneous act of music improvisation. Basically, it is a metaheuristic way to cope with numerous challenging tasks during the past decade. The act of transforming the beauty and harmony of music into an optimization procedure through search for a perfect harmony is named as Harmony Search Optimization. The process of optimization is however similar to Genetic Algorithm. Where on the one hand, the generation of offspring in GA is done using only single mutation or two crossovers of existing chromosomes, the modification of any arrangement in HS algorithm is done using all the existing members of Harmony Search memory.

- **Firefly Algorithm**

The Firefly Algorithm (FA) was proposed by Xin-She Yang (Yang 2008) and is based on the unique flashing pattern of fireflies. It belongs to the class of nature inspired, swarm intelligent and metaheuristic algorithm. The algorithm is extremely effective for multi objective optimization, as it uses real random numbers and based on the global communication among the set of particles (fireflies). The underlying principle of this method is that fireflies are attracted to other flies, with intensity proportional to brightness/flash of other firefly. The light or attractiveness decreases with increasing distance between two fireflies. The fitness value of an objective function determines the brightness. The major advantage of Firefly Algorithms is that their speed of convergence is very high. In spite of the high speed, it has a few disadvantages of being trapped in local optimum and slow convergence in the global searching.

4.3.4. Hybrid Algorithms

Hybrid Algorithms are developed by combining two or more algorithms to improve or enhance overall search efficiency. Researchers frequently try to apply hit and trial method to combine the advantages of two particular algorithms to develop new algorithm with an intention to improve search efficiency. Whereas, practically whether a hybrid can really achieve better performance is a matter of concern. So, it

becomes necessary to consider time and space related issues a priori before combining two algorithms.

Often GA is used to create the random initial population with any other search algorithm. Various combinations have been tried, however the results came out to be nearly similar but the computations required and thus the time taken is increased. Thus, hybridization of two algorithms is not considered in this work.

4.4. PERFORMANCE OF ALGORITHM

The selection of best algorithm depends upon its performance, which can be obtained in terms of efficiency, reliability, and quality of solution, displayed in Figure 4.2.

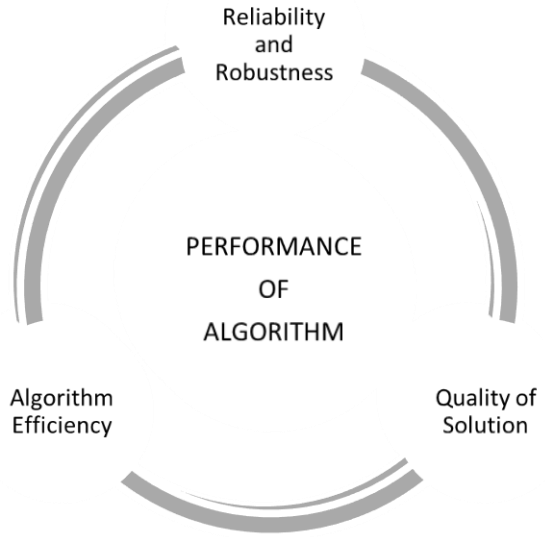


Figure 4.2 Performance of Algorithm

4.4.1. Algorithm Efficiency

In common language, efficiency means the ability to produce desired output with minimum efforts. In context with optimization, it can be defined as the minimum computational effort required achieving best optimal results. So, efficiency can be measured in terms of total number of iterations required to obtain optimal solution, computational time, or memory usage. An algorithm has to perform a certain number of evaluations in every iteration and more number of iterations means more evaluations and thus, more computational time. Therefore, these parameters are required to be maintained under minimum limits.

4.4.2. Reliability and Robustness

Some algorithms have a tendency of getting trapped at local optimum rather than global optimum. In that case, multiple executions of same algorithm are performed and the best case is selected. Reliability is the degree of consistency or the extent to which an algorithm can produce same results in repeated trials. Success Rate (i.e. ratio of the number of times an algorithm has successfully solved a problem to the maximum number of executions) is the most common parameter to measure reliability. Mean and Variance can also be considered according to the precision requirements of a problem. Further, an algorithm must be capable of optimizing a problem under all conditions like different initial conditions, higher dimensions, etc. Robustness is the ability of an algorithm to withstand different circumstances. Selecting the initial population for a search procedure is known as exploration of an algorithm and plays an important role in optimization. As initial population decides the search path, so it may change the result of a search procedure. Also, the number of variables in a problem can be increased for a higher order problem, so the algorithm should be able to achieve the optimum results for increased dimension of problem.

4.4.3. Quality of Solution

The quality of the solution produced by the algorithm is also an important parameter of concern while comparing different algorithms. The criterion of termination for an algorithm is generally some tolerance value or accuracy required. But if the algorithm fails to reach desired accuracy then it should have an alternate criterion for termination like maximum iterations. If an algorithm terminates without achieving desired accuracy of solution, then the quality of solution is definitely not good. Further, the time taken by the algorithm to reach desired accuracy also measures the quality of algorithm.

4.5. SELECTION OF OPTIMIZATION ALGORITHM FOR MINIMIZATION OF HARMONICS

Over the years, several advanced optimization techniques have been introduced by the various researchers like Genetic Algorithm(1960), Simulated Annealing(1983), Particle Swarm Optimization(1995), and many more. Regardless of the available

broad range of optimization methods, the selection of appropriate method will lead to realization of the true value of optimization problem (deciding switching instants for cascaded MLIs. The knowledge of certain factors like type of problem (single objective/multi-objective), nature of the equations involved, type of constraints, nature and range of design variables, and type of design space can narrow the exhaustive list of optimization techniques. Furthermore, selecting an optimization algorithm and then tuning its parameters is normally a hit and trial process and thus consumes time. Also, some algorithms take several hours to reach best solution, and thus not efficient enough to be used for large-scale optimization studies.

Table 4.1 Introduction of Various Algorithms with Proposed Year

Year	Algorithm	Proposed By
1960	Genetic Algorithm	(John Holland)
1983	Simulated Annealing	(Kirkpatrick, Gelatt and Vecchi)
1992	Ant Colony Optimization	(Dorigo)
1992	Real Coded Genetic Algorithm	(Michalewicz)
1995	Particle Swarming Optimization	(Eberhart and Kennedy)
1997	Differential Evolution Algorithm	(Storn and Price)
2001	Harmony Search Algorithm	(Geem, Kim and Loganathan)
2002	Fish-swarm Algorithm	(Li, Shao and Qian)
2005	Bee Colony Optimization	(Teodorovic and Dell'Orco)
2006	Shuffled Frog Leaping Algorithm	(Eusuff, Lansey and Pasha)
2007	Artificial Bee Colony	(Karaboga and Basturk)
2007	Bacterial Swarming Algorithm	(Tang, Wu and Saunders)
2009	Cuckoo Search Algorithm	(X. Yang and Suash Deb)
2009	Firefly Algorithm	(Yang)
2009	Gravitational Search Algorithm	(Rashedi, Nezamabadi-pour and Saryazdi)
2010	BAT Algorithm	(Yang)
2011	Teaching Learning Based Optimization	(R.V. Rao)
2014	Grey Wolf Optimization	(Mirjalili and Lewis)
2014	Hyper-spherical search algorithm	(Karami, Sanjari and Gharehpetian)
2016	Whale Optimization Algorithm	(Mirjalili and Lewis)

While designing the control of multilevel inverters, it is required to optimize the switching instants at which the power cells of MLI are fired with the intention of having minimum harmonics in the output voltage waveform of MLI. A clear knowledge of optimization problem and a decent background of optimization techniques will assist in the selection of proper optimization technique. Keeping in mind the minimization function for harmonic elimination, the shortlisted algorithms that can resolve the problem better are:

1. Simulated Annealing
2. Particle Swarm Optimization
3. Gravitational Search
4. Harmony Search
5. Teaching Learning Based Optimization
6. Cuckoo Search

4.5.1. Simulated Annealing (SA)

Annealing refers to a way in which metal slowly cool from molten state to solid state. Simulated annealing (SA) is a probabilistic based search technique, based on the concept of lowering of temperature to reach a lowest energy state. SA was developed in 1983 [127] for finding an approximate global optimum in presence of large number of precise local optimum. The process of optimization begins with randomly generated solution (current state) having high energy (temperature) and higher probability of acceptance of new solutions moving in a wide region of the search space, to reach a new solution (new state with lower energy). Selection of new points with lower energy prevents the algorithm from being trapped in local minima. Acceptance Probability depends upon the temperature which controls the evolution of state (selecting a new state from current state). SA controls the rate of cooling of the temperature, by which it reaches the global optimum. The major advantage of Simulated Annealing over other methods is its ability to avoid becoming trapped in local minima, though this process generally takes longer time.

The algorithm is explained below:

Step 1. Initialize the parameters of algorithm: Maximum iterations (itermax), Maximum Temp (very high) and Coolest Temperature.

Step 2. Generate a random initial solution by considering the upper and lower limits and current temperature as maximum temperature.

Step 3. Evaluate the fitness value 'Fi' at each position.

Step 4. Generate a random new solution, and calculate its fitness 'Fj'.

Step 5. Find the change in score, and depending on that accept or reject the new solution. The probability of acceptance depends on the current temperature.

Step 6. Update current temperature by lowering it towards coolest temperature.

Step 7. Repeat the iterations till current temperature equals coolest temperature or best solution is achieved.

4.5.2. Particle Swarm Optimization (PSO)

Particle Swarm Optimization, introduced by Russell Eberhart and James Kennedy in 1995 , is a computational method that optimizes a problem iteratively. PSO is inspired by the social behavior of bird flocking in search of food, and applied successfully to a wide variety of search and optimization problems. The algorithm utilizes a population of randomly generated particles (possible solution) that moves stochastically in the search space according to simple mathematical formulae. As optimization is achieved through searching and subsequent updating particles for next generation, each particle keeps track of its movement (P_{best}), which moves toward the other optimum solutions in the search-space, and updated as better solutions (G_{best}). The basic idea of PSO algorithm is to modify the velocity of each particle towards its 'P_{best}' and 'G_{best}' points at every time step. In contrast to GA, PSO doesn't use any evolution operators like crossover and mutation. Though, it suffers from partial optimism, which causes the less exact at the regulation of its speed and the direction.

The algorithm is widely used for its easy implementation and few particles are required to be tuned. The PSO algorithm is implemented using the following steps:

Step 1. Initialize the parameters of algorithm: Population Size (n), Maximum iterations (itermax), Inertia Weight, and Acceleration Factors.

Step 2. Generate the initial population of randomly generated particles (x_i for i=1, 2, 3, …, n) by considering the upper and lower limits.

Step 3. Initialize the velocity, personal best 'P_{best}', global best 'G_{best}' and iteration count.

Step 4. Evaluate the fitness value 'F_i' at each position.

Step 5. Update the velocities based on the P_{best}, G_{best} position for each particle.

Step 6. Update the particle position using the equation.

Step 7. Check for any violation of constraints and repeat the iterations till 'G_{best}' best solution is achieved.

4.5.3. Gravitational Search (GS)

Gravitational Search [128], proposed by Rashedi, is a stochastic search algorithm based on the law of gravity and mass interactions. In this algorithm, possible solutions of the problem are referred to as objects, characterized by position, inertial mass, active gravitational mass, and passive gravitational mass. The position of each object represents a solution, and inertial and gravitational masses are determined by a fitness function. GSA is a memory-less algorithm. All these objects interact with each other according to the force of gravity and the laws of motion. Based on the Newtonian force, the objects with heavier mass (represented as good solutions) move more slowly than the objects with lighter mass (represented as bad solutions), this represents the exploitation of the algorithm. At each step, the object changes its position, according to the values of fitness function, velocity and acceleration. Updating these parameters requires too many computations with every iteration as compared to other evolutionary algorithms, which is the major drawback of this algorithm. Thus, it is obvious that GSA takes more computational time.

The steps of GSA are outlined as follows:

Step 1. Initialize the parameters of algorithm: Population Size (n), Gravitational Constant (G), Maximum iterations (itermax), and Accuracy.

Step 2. Generate the initial population of randomly generated objects (x_i for i=1, 2, 3, …, n) by considering the upper and lower limits.

Step 3. Evaluate the fitness value 'F_i' of each object.

Step 4. Update the values of gravitational constant G, good solution (object with heavier mass), bad solution (object with lighter mass), and inertia mass of each iteration. The active gravitational mass M_a, passive gravitational mass M_p, and inertial mass of mass M_i, are computed using fitness evaluation.

Step 5. Compute Total Force ($Force_i$) on i^{th} object due to all other objects.

Step 6. Update the position of each object.

Step 7. Update the particle position using the equation.

Step 8. Check for any violation of constraints and repeat the iterations till iter= itermax or best solution is found.

4.5.4. Harmony Search (HS)

Harmony Search is a metaheuristic way to deal with various optimization problems. Basically, the metaheuristic approach avoids getting caught in local optimum solutions and aims at obtaining the global optimum solution. The HS method is presented by Geem in 2001, and is inspired by spontaneous act of music improvisation. It is an act of transforming the beauty and harmony of music into an optimization procedure through search for a perfect harmony, and thus named as Harmony Search Optimization. The perfect condition of concordance in music is similar to best optimal solution of a problem. HS algorithm employs a Harmonic Search Memory (HSM) of a specific size termed as Harmonic memory size (HS), and two probabilities namely, Harmonic Memory Considering Rate (HMCR) and Pitch Adjustment Rate (PAR), keeps revising the solution till ideal solution/requirement is met. Harmony Memory Considering Rate is the probability of selecting a component from the HSM. Pitching Adjust Rate is the probability of a candidate from the HSM

to be mutated. The spontaneous act of result optimization in Harmony Search is analogous to Genetic Algorithm. Where on the one hand, the generation of offspring in GA is done using only single mutation or two crossovers of existing chromosomes, the modification of any arrangement in HS algorithm is done using all the existing HSM members. Thus, it has strong ability of exploring the regions of solution space in a reasonable time. However, it has lower exploitation ability in later period.

The Harmony Search Algorithm is given by the steps below:

Step 1. Initialize the parameters of algorithm: Population Size (n), Maximum iterations (itermax), Harmony memory size (HS), Harmony Memory Considering Rate (HMCR), Pitch Adjustment Rate (PAR).

Step 2. Create an initial HSM having randomly generated particles (x_i for i=1, 2, 3, …, n) by taking into the account the upper and lower limits.

Step 3. Initialize Worst solution as the solution with maximum fitness value.

Step 4. Start the iteration for computing switching angles.

Step 5. Improvise new solution from HSM using HMCR and PAR.

Step 6. Solve the fitness function and get the value of $F(\alpha)$.

Step 7. If new solution is better than previous one, update HSM, else discard the solution.

Step 8. Check for any violation of constraints and repeat the iterations till best solution is achieved.

4.5.5. Teaching Learning Based Optimization (TLBO)

Inspired by process of teaching and learning in classroom, Teaching-Learning-Based Optimization is introduced as a novel metaheuristic search algorithm by Rao et al. in 2011. TLBO algorithm does not require any algorithm-specific parameters, but only common controlling parameters like population size and number of generations. Due to this fact, it has caught great attention and used extensively to optimize many scientific and engineering applications in recent years. TLBO uses two phases of teaching learning process, ‘Teacher phase’ and ‘Learner phase’. The randomly

generated solutions in entire population are considered as learners and the best solution among them is considered as the teacher. The dimension of the optimization problem is treated as the number of subjects taught to learners and their result is the fitness value. In 'Teacher Phase', the learners gain the knowledge from the teacher with same probability. And in 'Learner Phase', learning takes place through interaction amongst them.

The algorithm can be explained more clearly in the following steps:

Step 1. Initialize the parameters of algorithm: Population Size as number of students in class (n), Number of generations (G), Number of subjects offered as dimension of problem (G).

Step 2. Produce a random population according to population size (n) and dimension.

Step 3. Evaluate the average grade of each subject offered in the class, i.e. fitness value.

Step 4. Choose the best learner from the population as teacher based on the grade point (fitness value).

Step 5. Teacher Phase: Modify each learner (each dimension of population).

Step 6. Compute the fitness value of updated solution (population) and replace the solution, if better than the previous one.

Step 7. Learner Phase: Randomly select a solution from the population and update it using other solutions (learners).

Step 8. Compute the fitness value and update the solution, if better than the previous one.

4.5.6. Cuckoo Search (CS)

Cuckoo Search is a heuristic approach, proposed in 2009 by Xin-She Yang and Suash Deb, used for solving optimization problems in different fields of engineering. The algorithm is inspired by the behavior of cuckoo bird, also known as brood parasites, that it never builds its own nest and lays their eggs in the nests of other host birds (of different species). The eggs in a nest represent solutions, whereas egg of cuckoo bird is a new solution. Normally, each cuckoo lays one egg at a time in a randomly chosen

nest. Numbers of host nests are fixed. So, each nest has one egg of cuckoo bird and rest of the eggs of the host bird. Sometimes host birds get involved in direct conflict with the intruding cuckoos. If the host bird recognizes the eggs as someone else's egg, they either throw them or move to build a new nest. The probability of cuckoo's egg being recognized is ρ_a, and is generally fixed at 25%. However, if cuckoo's egg matures, it moves to the next generations. The ability of algorithm to maintain balance between local and global random walks using switching parameter makes it suitable for global optimization problems.

The algorithm used for optimizing a problem using Cuckoo Search is given as:

Step 1. Initialize the parameters of algorithm: Population Size (n), Probability of cuckoo's egg being recognized (ρ_a), Maximum iterations (itermax) .

Step 2. Generate the initial population of randomly generated particles (xi for i=1, 2, 3, …, n) by considering the upper and lower limits.

Step 3. Obtain a cuckoo randomly and get its location using Lévy flights.

Step 4. Evaluate the fitness value 'F_i' at each position and find the best nest corresponding to minimum fitness value (best fitness).

Step 5. A random nest is selected among n (say j), and fitness value 'F_j' is evaluated for x_j.

Step 6. Update the best fitness if $F_j < F_i$ and best nest as xj.

Step 7. A fraction (ρ_a) of worse nests is destroyed.

Step 8. The process is repeated till the best solution is obtained.

4.6. COMPARATIVE STUDY

In this context, a comparison among the optimization algorithms is performed in order to select the best algorithm suitable for the objective of harmonic minimization in multilevel inverters. But the process of optimization depends on several factors such as initial population of solution, population size, dimension of search space, numbers of iterations, and tolerance. Thus, the values of these factors are considered same for all the algorithms. Now, to investigate the optimization performance, it is required to compare the algorithm efficiency, reliability, robustness and quality of solution

achieved by every algorithm. The two different case studies with Five-level (two variables) and Eleven-Level (five variables) CHB Inverters are considered to check the robustness of an algorithm. The optimal switching angles are obtained by optimizing harmonic minimization function using different optimization algorithms and further performance analysis is done. Simulink models of Three-phase Five Level and Eleven Level CHB Inverter are developed in MATLAB software to investigate the performance of various optimization algorithms as applied to minimization of harmonics in Cascaded MLIs.

4.6.1. Performance Comparison for Three-Phase Five Level CHB Inverter

Primarily, it is essential to choose the common parameters for all the algorithms. So, maximum iterations, population size, search space, tolerance and number of executions (runs) are same for each algorithm with randomized starting points. The effectiveness or efficiency of an algorithm can be compared on the basis of fitness value achieved, computational time and minimum iterations required for optimization. Table 4.2 compares the efficiency of various optimization algorithms executed for 100 iterations.

Table 4.2 Comparison of Algorithm Efficiency for Five-Level CHB Inverter in 100 iterations

Algorithm	Optimized Switching Angles		Number of Iterations	Fitness Value	Computational Time (s)
	α_1	α_2			
GS	5.35	21.93	100	0.25e-02	0.24
PSO	7.63	24.53	100	6.2339e-04	0.28
HS	7.22	32.22	100	8.2634e-04	0.04
SA	9.22	24.10	100	6.2979e-04	0.56
TLBO	7.63	24.53	100	6.2339e-04	0.71
CS	7.63	24.53	100	6.2339e-04	0.31

The validation of the quality of solution (optimized switching angles) is done by simulation and verifying the whether the objective function is optimized, i.e. fundamental voltage deviation should be minimum and harmonics should be according to IEEE 519-2014 standard. Table 4.3 summarizes the detailed fundamental voltage deviation and harmonic limit comparison for all algorithms. It is clear from

Table 4.2 and 4.3 that Particle Swarm Optimization is the most efficient algorithm, whereas, Gravitational Search and Simulated Annealing fail in achieving the quality of solution pertaining to the time taken in getting accurate results. Figure 4.3 shows the graphical plot for values of fundamental voltage deviation and total harmonic distortion in percentage obtained after simulation for various algorithms.

Table 4.3 Comparison of Simulation Results of Fundamental Voltage and Voltage Harmonics in Five-Level CHB Inverter

Algorithm	Fundamental Voltage		THD (less than 8%)	Individual Voltage Harmonics (less than 5%)								
	$V_{(peak)}$ 220.63 V max	Deviation (%)		3rd	5th	7th	9th	11th	13th	15th	17th	19th
GS	211.9	3.96	7.16	0.07	5.7	0.65	0.26	0.34	2.69	0.27	3.16	0.97
PSO	209.55	5.02	5.65	0.26	2.68	3.06	0.2	0.5	0.26	0.15	0.44	2.99
HS	202.8	8.08	8.53	0.17	1.6	0.71	0.46	5.59	1.74	0.08	5	3.19
SA	209.7	4.95	5.88	0.15	1.96	4.16	0.38	1.39	0.77	0.16	0.82	3.16
TLBO	209.55	5.02	5.65	0.26	2.68	3.06	0.2	0.5	0.26	0.15	0.44	2.99
CS	209.55	5.02	5.65	0.26	2.68	3.06	0.2	0.5	0.26	0.15	0.44	2.99

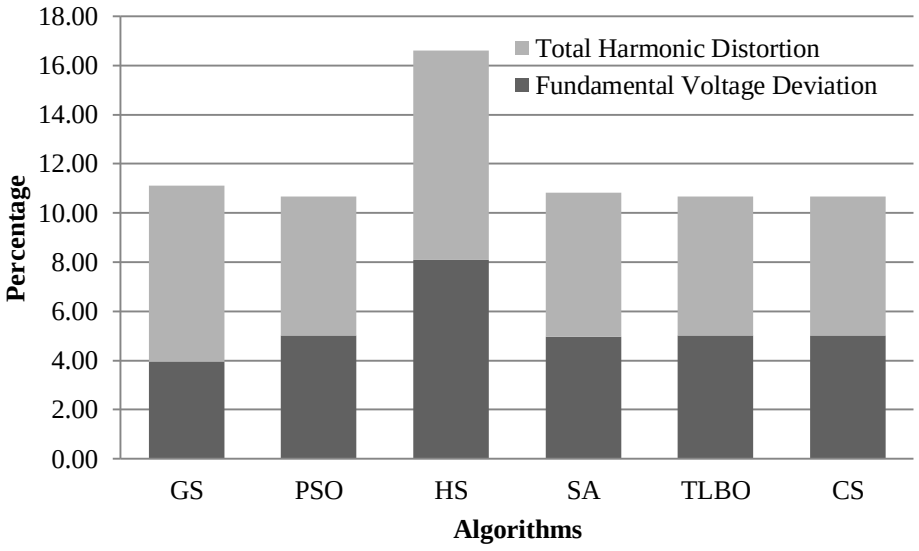


Figure 4.3 Simulation values of Fundamental voltage deviation and Total Harmonic Distortion for various algorithms

Further, the behavior of an algorithm to reach the minimum fitness value and obtain optimal solution with number of iterations and computational time is studied as given in Figure 4.4 and 4.5, respectively. It can be seen easily that only PSO, TLBO and CS reach to the near best solution but with different time or speed. For reliability of an algorithm, all the algorithms are executed 10 times and success rate is computed as given in Table 4.4. Success Rate is calculated as percentage of correct solutions to the total times the algorithm is executed to get optimized values.

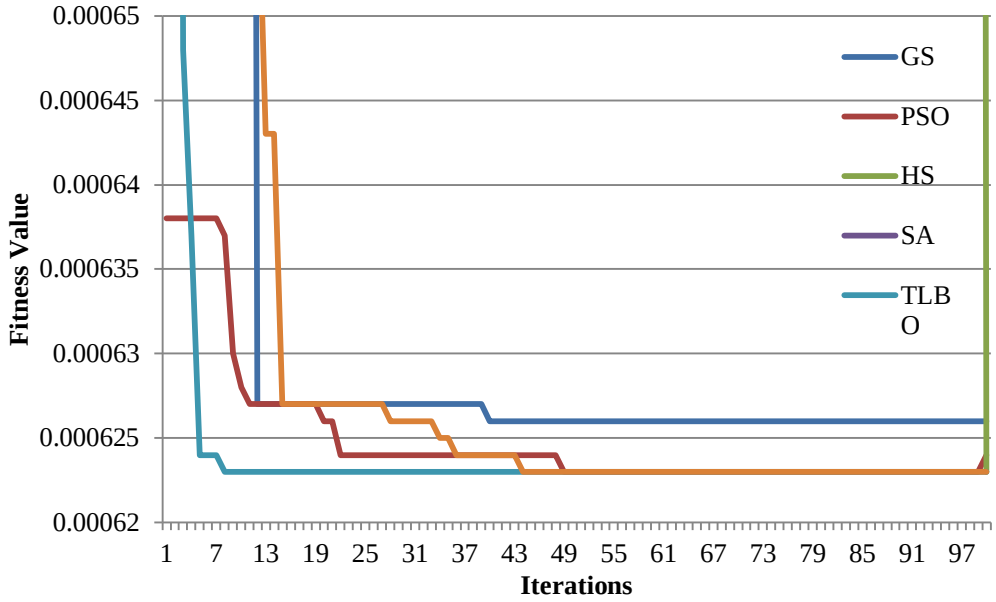


Figure 4.4 Fitness value w.r.t. Iterations for Various Algorithms

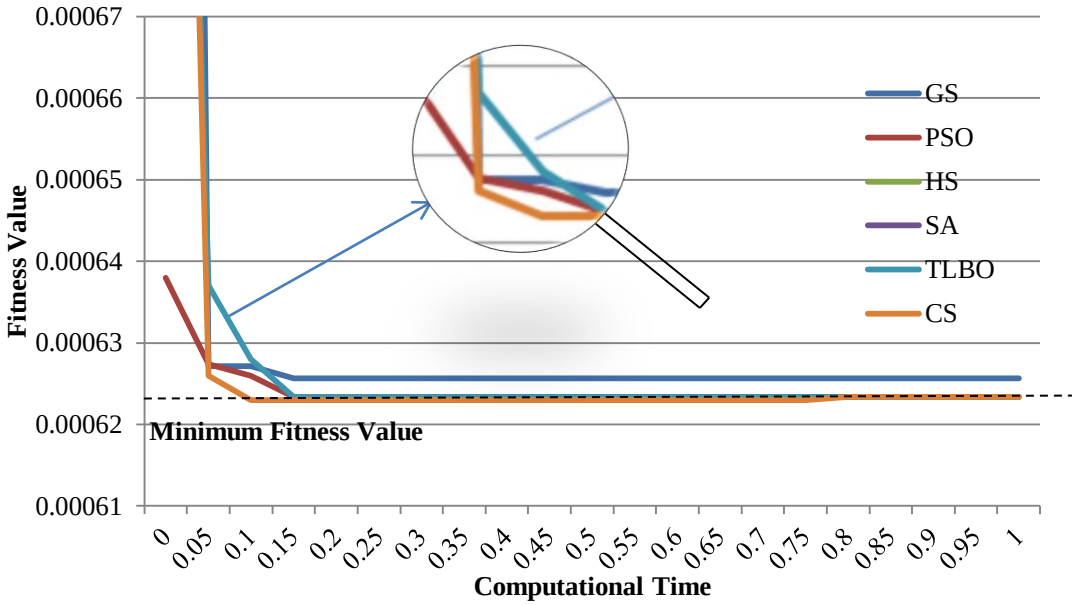


Figure 4.5 Fitness value w.r.t. Computational Time for Various Algorithms

Table 4.4 Comparison of Reliability of Algorithms on the basis of Success Rate

Algorithm	Number of Iterations	Time (s) taken for 10 runs	Success Rate (%)
GS	100	2.31	10%
PSO	100	2.44	90%
HS	100	0.48	10%
SA	100	1.36	40%
TLBO	100	7.00	100%
CS	100	2.81	100%

The results determine that GS, HS, and SA do not comply with the harmonic requirements of the proposed fitness function, and also their reliability is very low in discovering best results. However, they may reach to optimal solution after more iteration, but that means more computational time. The three algorithms PSO, TLBO and CS find good optimum results. But, CS and TLBO are 100% reliable, so only single execution is enough to get the optimal results. The magnified view in Figure 4.5 indicates that the CS algorithm reaches best solution for the first time at 0.05s only, while other TLBO took longer time than CS. However, the results of PSO are somewhat similar to CS, but for generalized comparison, the study is extended to increased dimension of problem.

4.6.2. Performance Comparison for Three-Phase Eleven Level CHB Inverter

As far as robustness of an algorithm is concerned, it is required to check the feasibility of the algorithm with higher dimensions. So, the study is extended to Eleven Level Inverter where five variables are required to be optimized. Firstly, Table 4.5 compares the efficiency of various optimization algorithms executed for 500 iterations, specifying that TLBO and CS achieve minimum fitness value but Cuckoo Search took much lesser time than TLBO. Table 4.6 summarizes the simulation results of Eleven Level CHB inverter in reference to the fundamental component and harmonic content present in output voltage waveform of inverter using switching angles obtained using different algorithms.

Table 4.5 Comparison of Algorithm Efficiency for Eleven-Level CHB Inverter in 500 iterations

Algorithm	Optimized Switching Angles					Number of Iterations	Fitness Value	Computational Time (s)
	α_1	α_2	α_3	α_4	α_5			
GS	3.17	9.48	20.73	27.05	43.75	500	0.00013859	2.10
PSO	0.00	10.12	16.09	26.89	38.36	500	0.0001359	1.60
HS	14.77	24.66	25.59	36.14	68.84	500	0.0029	0.10
SA	9.27	23.22	39.15	48.56	64.41	500	0.0035	0.11
TLBO	3.21	9.64	16.04	27.02	38.12	500	0.00007423	7.02
CS	3.21	9.64	16.04	27.01	38.12	500	0.00007423	1.76

Table 4.6 Comparison of Simulation Results of Fundamental Voltage and Voltage Harmonics in Eleven-Level CHB Inverter

Algorithm	Fundamental Voltage		THD (less than 8%)	Individual Voltage Harmonics (less than 5%)								
	$V_{(peak)}$ 220.63 V max	Deviation (%)		3rd	5th	7th	9th	11th	13th	15th	17th	19th
GS	499.4	9.46	2.26	0.2	0.47	0.28	0.2	0.16	0.65	0.02	1.76	1.09
PSO	510.2	7.50	2.84	0.22	0.5	0.21	0.13	1.04	0.45	0.15	0.35	0.82
HS	434.4	21.25	12.06	0.11	4.56	10.9	0.21	2	1.26	0.18	0.3	0.7
SA	416.7	24.45	7.51	0.18	2.08	1.79	0.07	0.26	2.6	0.17	2.02	2.35
TLBO	509.4	7.65	1.51	0.03	0.44	0.32	0.3	1.11	0.77	0.1	0.23	0.2
CS	509.4	7.65	1.51	0.03	0.44	0.32	0.3	1.11	0.77	0.1	0.23	0.2

Figure 4.6 represents the comparison of fundamental voltage deviation and total harmonic distortion in various algorithms. The simulation data indicates that Cuckoo Search accomplishes the harmonic requirements as well as gives the optimized value of switching angle in least time. Reliability of all the algorithms is illustrated by executing the same algorithm 10 times and is shown in Table 4.7.

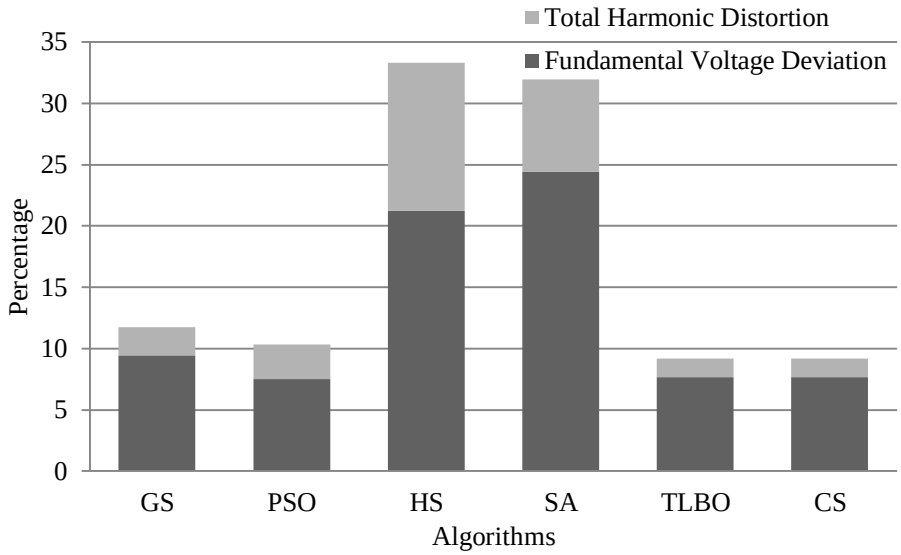


Figure 4.6 Simulation values of Fundamental Voltage Deviation and Total Harmonic Distortion for various Algorithms

Table 4.7 Comparison of Reliability of all Algorithms on the basis of Success Rate

Algorithm		**GS**	**PSO**	**HS**	**SA**	**TLBO**	**CS**
Fitness value	**1st run**	0.000139	0.0000742	0.001085	0.001523	0.0000742	0.0000742
	2nd run	0.000139	0.000136	0.000467	0.000249	0.0000742	0.0000742
	3rd run	0.000139	0.000603	0.000345	0.001326	0.000172	0.0000742
	4th run	0.000139	0.0000742	0.001503	0.000951	0.0000742	0.0000742
	5th run	0.000139	0.000136	0.007135	0.000673	0.0000742	0.0000742
	6th run	0.000139	0.0000742	0.000123	0.002605	0.000586	0.0000742
	7th run	0.000139	0.000603	0.000255	0.00214	0.0001038	0.0000742
	8th run	0.000139	0.000136	0.000161	0.001561	0.0000742	0.0000742
	9th run	0.000139	0.000136	0.001124	0.000285	0.0000742	0.0000742
	10th run	0.000139	0.000136	0.011783	0.00065	0.0000742	0.0000742
Success Rate		**NA**	**30%**	**NA**	**NA**	**70%**	**70%**

The results signify that GS, HS, and SA are not able to successfully optimize the function and not reliable for discovering best results. PSO and TLBO both tends to fail with increased dimension of problem by getting trapped into local optima when dealing with higher levels, which means less reliability. Thus, it can be concluded that CS has the best performance with minimum iterations required, less time and 100% efficiency.

4.6.3. Experimental Results of Three-Phase Five Level CHB Inverter

An experimental setup including a single phase autotransformer connected to six separate isolation transformers and rectifiers and finally to hardware prototype of FPGA controller based Three-phase Five-level Cascaded H-bridge inverter has been made as shown in Figure 4.7. A star-connected load with 300Ω, 40mH in each phase is connected to the inverter. Xilinx Spartan-6 FPGA Controller is programmed to drive the gates of H-bridges using optimized switching angles as obtained from either algorithm. The performance of multilevel inverter can be estimated using harmonic spectrum, measure of THD, and other important parameters like R.M.S. and peak value of voltage. The same results have been summarized in Table 4.8.

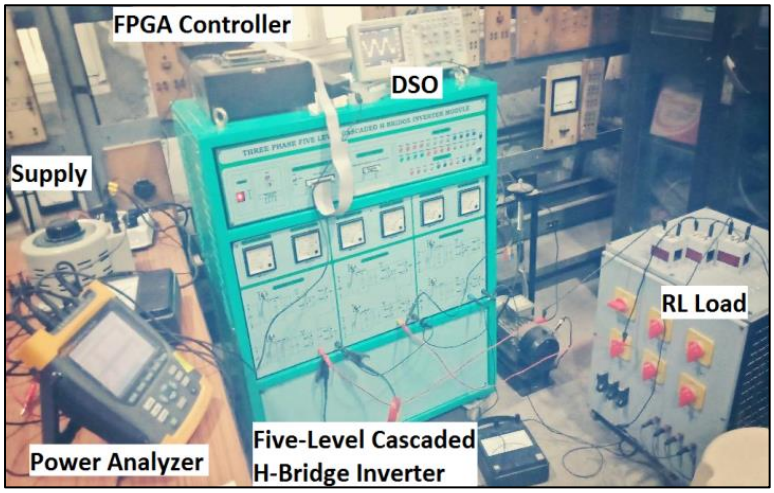


Figure 4.7 Hardware prototype of FPGA Controlled Three-phase Five-level Cascaded H-Bridge Inverter

Table 4.8 Comparison of Experimental Results of Fundamental Voltage and Voltage Harmonics in Five-Level CHB Inverter

Algorithm	THD	Fundamental Voltage	3rd	5th	7th	9th	11th	13th	15th	17th	19th
GSA	11.2	213.7	6	4.1	3.1	1.1	0.6	2.4	0.2	3.4	1.2
PSO	7.9	211.1	0.4	1.5	3.5	0	1.1	2.8	0	0.9	3.7
HS	13.7	221.7	1.4	2.4	1.4	0.9	7.2	2	0.9	6.7	4.3
SA	8.2	219.5	0.8	2.1	7.2	0.1	2.3	1.2	0	1.4	5.1
TLBO	7.9	211.1	0.4	1.5	3.5	0	1.1	2.8	0	0.9	3.7
CS	7.9	211.1	0.4	1.5	3.5	0	1.1	2.8	0	0.9	3.7

The output voltage waveform and harmonic spectrum for different sets of optimized angles obtained using DSO and power analyzer are shown in Figure 4.8.

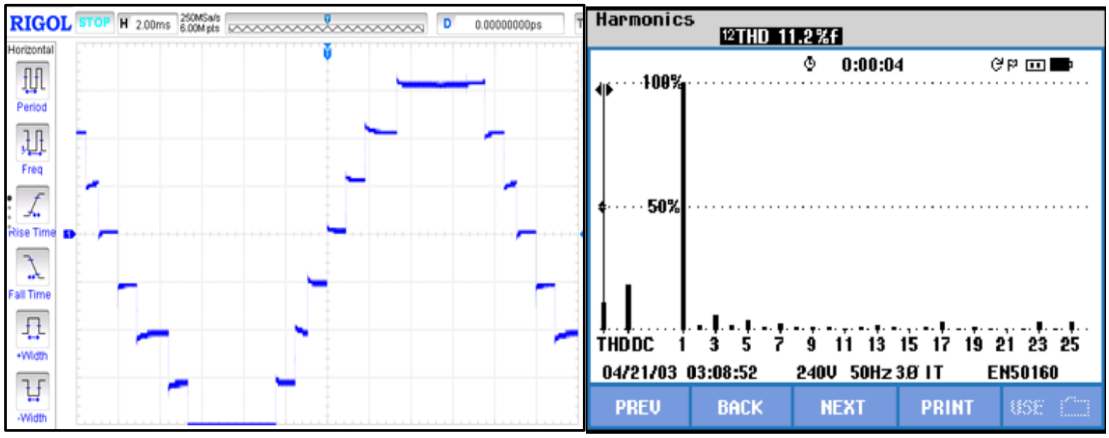


Figure 4.8 a) Output Voltage and Harmonics using GS (Switching angles: α_1 =5.35˚, α_2 =21.93˚)

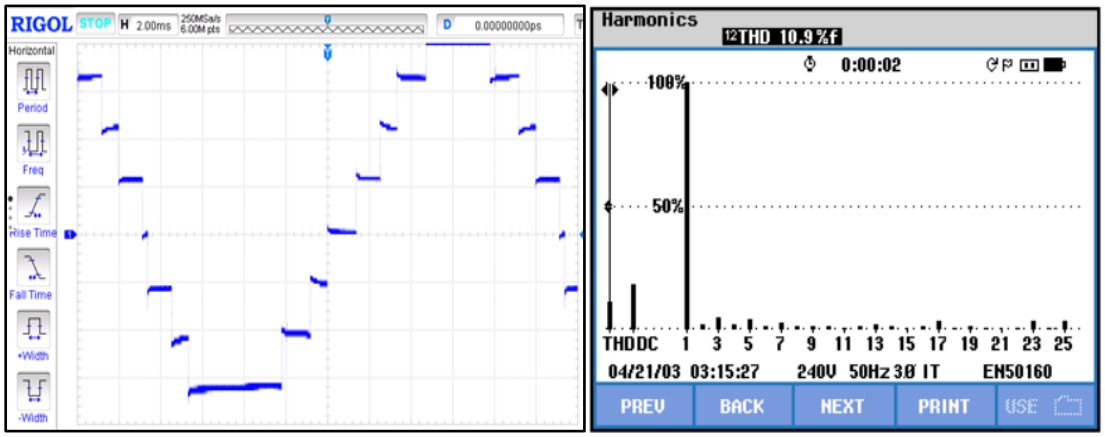


Figure 4.8 b) Output Voltage and Harmonics using HS (Switching angles: α_1 =7.22˚, α_2 =32.22˚)

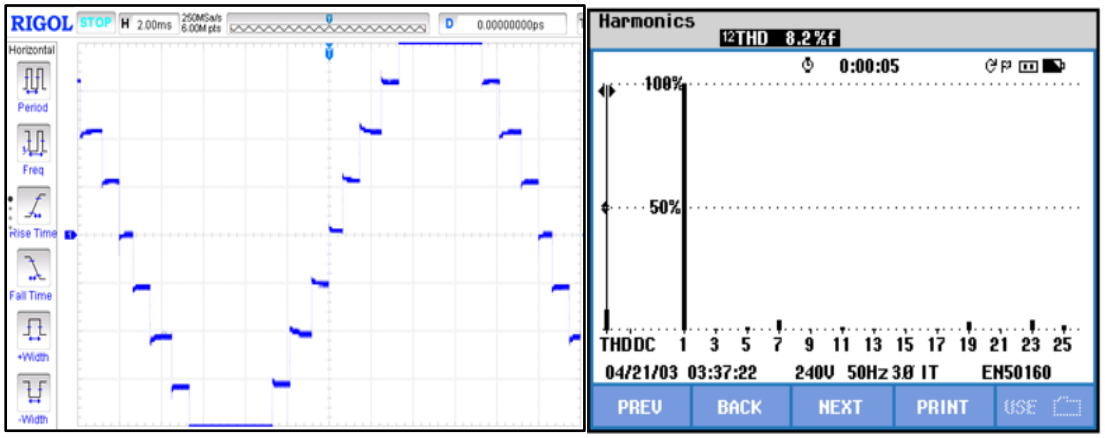


Figure 4.8 c) Output Voltage and Harmonics using HS (Switching angles: α_1 =9.22˚, α_2 =24.10˚)

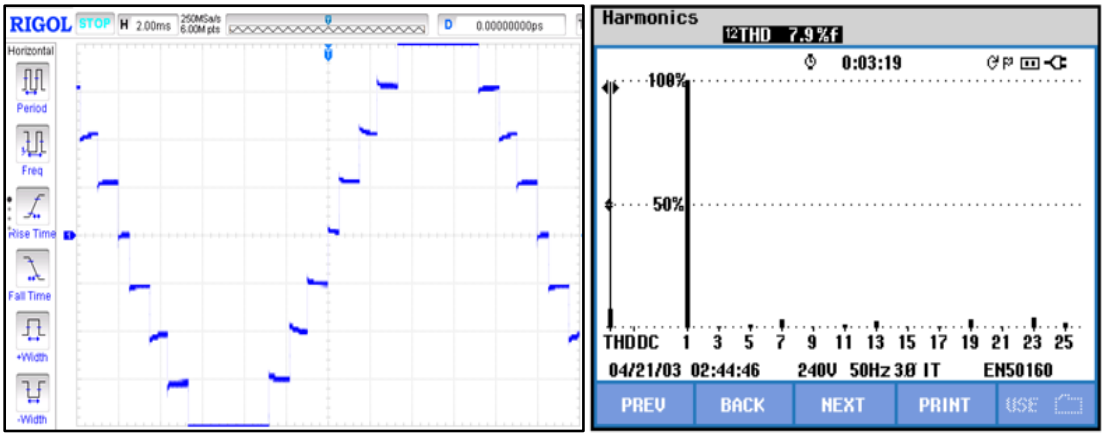


Figure 4.8 d) Output Voltage and Harmonics using PSO, TLBO and CS (Switching angles: α_1 =7.63˚, α_2 =24.53˚)

The tabulated results show that the Five-Level CHB Inverter has better quality voltage output and minimum THD, i.e. 7.9%, when fired using switching angles optimized by CS Algorithm. Moreover, the low order harmonics have improved and are within IEEE 519-1992 specified limits. Thus, it is obvious that Cuckoo Search method is efficient in optimizing the switching angles required for control of multilevel inverter.

4.7. CONCLUSION

In this chapter, different optimization algorithms are explored and compared on the basis of quality of solution, efficiency, reliability and robustness. An objective function is presented to maintain harmonic content in the output voltage waveform of MLI within limits and algorithm is used for the optimization of switching angles. The result of optimization algorithms shows that almost every algorithm has tendency to produce best optimized results in more or less time with their own speed. The detailed comparison indicates that CS algorithm reaches best solution in minimum time and thus produces quality result. In terms of reliability, GS, HS, and SA fail, because they require more iteration to find optimal solution means more computational time. Furthermore, PSO and TLBO both tend to fail with increased dimension of problem by getting trapped into local optima when dealing with higher levels. Thus, the efficiency of Cuckoo Search Algorithm has proved to be being reliable and robust in determining the optimum switching angles. The CS Algorithm is also easy to implement, because the value of only single parameter ρ_a is required to be tuned, apart from the population size. Further, simulations of Five and Eleven Level CHB Inverter are done using different switching angles optimized by GS, HS, PSO, SA, TLBO, and

CS. The analysis confirms that the fundamental voltage component deviation and harmonics, obtained using CS optimization, are controlled within allowable limits and comply with IEEE 519-2014 harmonic guidelines. The experimental results of the hardware prototype ensure the quality and efficiency of Cuckoo Search algorithm for optimizing switching angles required for control of CHB Inverters. So, the optimal switching angle control of CHB Inverters can be seen as Figure 4.9.

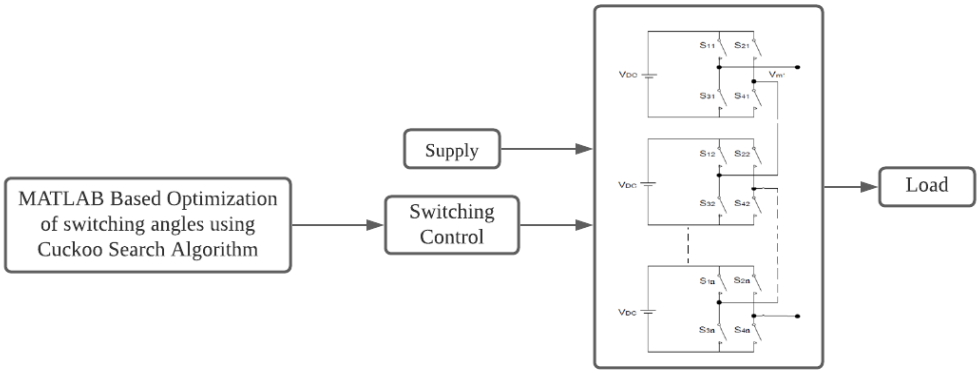


Figure 4.9 Optimal Switching Control of Multilevel Inverters

CHAPTER V

HARDWARE IMPLEMENTATION OF CASCADED MULTILEVEL INVERTERS FOR HARMONIC MINIMIZATION

5.1. INTRODUCTION

Considering the simplicity and efficiency of the Cuckoo Search algorithm [129]–[132] for solving highly non-linear optimization problems in real-world engineering applications, this research study utilized Cuckoo Search optimization for control of multilevel inverter. The algorithm is used to obtain the switching angles by optimizing the proposed objective function for harmonic minimization. The algorithm is coded in MATLAB and the switching instants where the switches of multilevel inverter should be fired are obtained. Further the algorithm for pulse generation are coded for each switch of H-bridge and verified. For simulation purpose, these pulses are then given to multilevel inverter in Simulink and the results for staircase output voltage are obtained. Harmonic analysis of the output of multilevel inverter is done using FFT Analysis Toolbox in Simulink. To make the understanding of control scheme even better, the technique is applied to different levels of single phase Cascaded H-Bridge inverter in this chapter as given in Figure 5.1. Analysis of Three-phase Cascaded H-Bridge inverter is considered in next chapter of this thesis.

MATLAB is a high-level language for the expression of engineering and scientific ideas, and it is the computational engine that motivates discovery and innovation [133]. It serves as an interactive environment to solve many technical problems, particularly those involving matrix and vector formulations in a fraction of time. It incorporates the feature of integrating computation, modeling, and programming in a user-friendly environment. SimPower System Toolbox offers component libraries and analysis tools for modeling and simulating electrical power systems [134]. It contains models of electrical power components, including machines, electric drives, and other components, etc. Harmonic analysis, calculation of THD, load flow, and other key electrical power system analyses are automated, helping you investigate the performance of your design. It also aid in modeling of control systems and study the behaviour of system.

Advancement in the field of power electronic and digital world has made possible to implement the control of multilevel inverter with the help of different controllers like FPGA controller. To validate the ability of Cuckoo Search Optimized Switching scheme in minimization of harmonics and simulation results obtained from Simulink, a hardware prototype of Cascaded H-Bridge Multilevel Inverter equipped with a FPGA controller is setup. This chapter presents the experimental results obtained by implementation of a CS Optimized Switching technique for Single-Phase Cascaded H-Bridge Multilevel inverters. Experimental results of a CS Optimized Switching technique are further compared with results obtained using most prevalent SPWM Switching technique scheme as applied to Single-Phase Cascaded H-Bridge Multilevel Inverters.

5.2. HARDWARE SETUP AND SPECIFICATIONS

The hardware setup for Cascaded H-Bridge Inverter consists of mainly four parts, namely

- Power Inverter Unit,
- Controller Unit,
- Load and
- Measurement Unit.

The Power Inverter Unit further comprises input supply circuit and converter circuit designed using switches. The control scheme has been implemented using Xilinx Spartan-6 XC6SLX9 FPGA processor. The program for generating the switching pulses for inverter switches is coded in XILINX ISE 14.3 DESIGN SUIT software. The output is then fed to FPGA controller which provides control signals to switches of inverter to produce desired output.

A single phase RL load with 500Ω, 120mH is connected to the output of inverter. The measurement unit may include several current sensors, ammeters, voltmeters, wattmeters, and multimeters which are essential for the assessment of power quality. The system also requires Digital Signal Oscilloscope (DSO) for display and analysis of different waveforms, and Harmonic Analyzer or Power Analyzer for measurement of harmonics and THD.

5.2.1. Power Inverter Unit

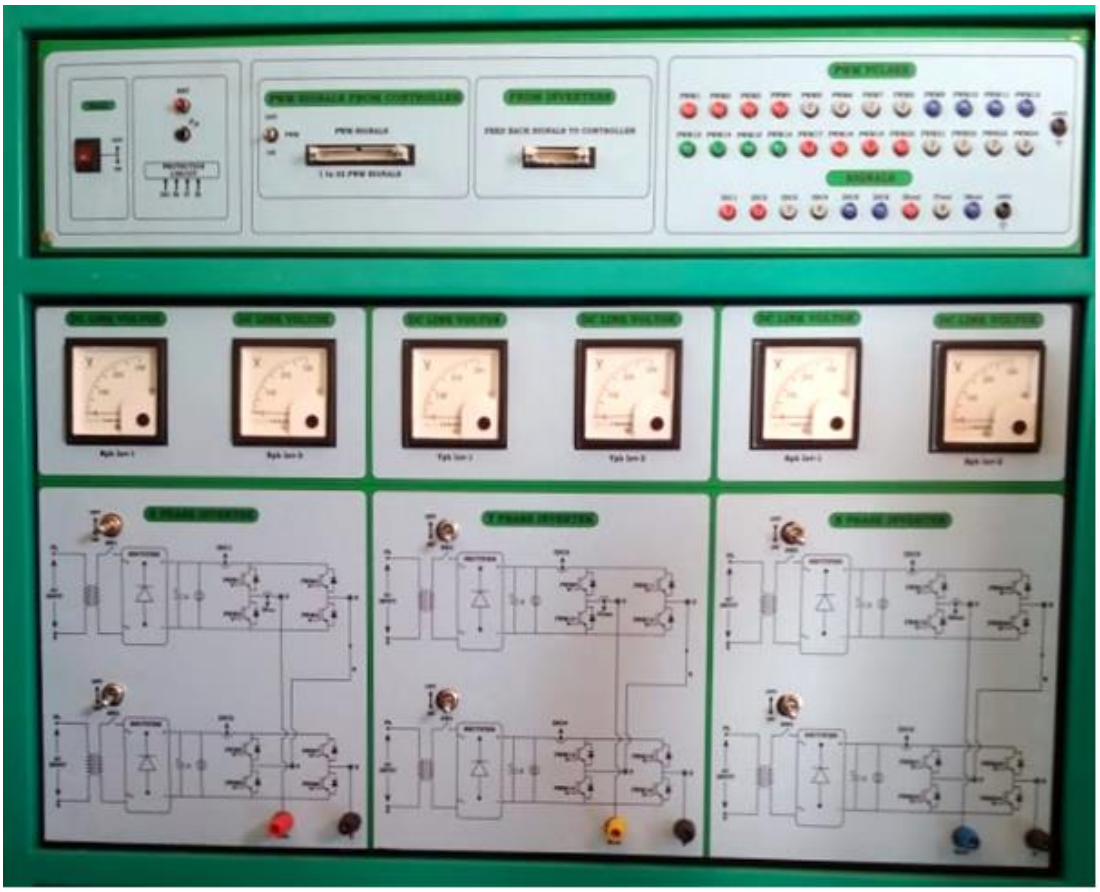


Figure 5.1 Cascaded H-Bridge Inverter Module

Cascaded H-bridge inverter power module as shown in Figure 5.1 consists of several components, mainly input supply, switches to form H-bridge, their driver circuits and protection circuits. The components are listed with specifications given below:

6 Single-Phase Isolation Transformers	-	1kVA
6 Diode Bridge Rectifiers	-	35A
6 Isolated Regulated Power Supply	-	+15V/0.5A
DC Link Input Voltage at each H-Bridge	-	150V DC max
24 IGBTs	-	1200V, 10A
AC Output Voltage at each H-Bridge	-	0 – 100 V(rms)
AC Output Current at each H-Bridge	-	2A max

The power unit is connected to a single-phase autotransformer to provide the supply, which is then connected to six separate single phase isolation transformers and bridge

rectifiers to provide six isolated DC supply for each H-bridge inverter. Then, the inverter unit consists of six H-bridges formed by combining 24 IGBTs with anti-parallel diodes, mounted with proper heat sink and snubber capacitor for dv/dt protection. Driver circuits for each H-bridge are used to isolate and drive IGBT PWM signals and necessary interfacing connectors are provided for PWM input from FPGA controller. Six current sensors are used to sense the dc link current of each H-bridge inverters. Current Transformers (CTs) are also used to sense the load currents. All the Sensor outputs are terminated in front panel for measurement purpose.

5.2.2. Controller Unit

The control algorithm is developed in the system generator environment and corresponding code for FPGA processor is generated. The code is then downloaded into the digital processor Xilinx Spartan-6 XC6SLX9, which then provides the output switching pulses. By the use of interfacing connectors, PWM input signals from FPGA controller are provided to H-bridges of multilevel inverter.

SPARTAN6 Development Board

Spartan-6 is an easy to use FPGA Development board featuring Xilinx Spartan-6 FPGA, block diagram is shown in Figure 5.2. It is specially designed for experimenting and research system design with FPGAs. This development board features Xilinx XC6SLX9 FPGA with maximum 100 user input/outputs.

On-Board Features:

- Processor speed 20 MHZ
- 100 output lines/inputs lines are in 3.3/5V level
- Isolated serial communication interface through USB connector
- 4MB PROM for code execution memory.
- External JTAG header for programming
- 20x4 (or 16x2) LCD interface header.
- 8 user LEDs/4 position user DIP switch
- 2 up & down input push switch
- Up to 100 Individually Programmable GPIO Pins

- ADC
    - No of ADC input : 4 Channels
    - Resolution : 12 bit
    - Sampling rate : 1MSPS
    - Analog input range : 0 – 3.3 v
    - Buffer section for voltage protection

FPGA

FPGA board featuring Xilinx Spartan-6 FPGA is specially designed for research, experimenting and learning system design with FPGAs. Spartan®-6 devices are the most cost-optimized FPGAs, offering industry leading connectivity features such as high logic-to-pin ratios, small form-factor packaging, and a diverse number of supported I/O protocols. Built on 45nm technology, the devices are ideally suited for a range of advanced bridging applications found in automotive infotainment, consumer, and industrial automation.

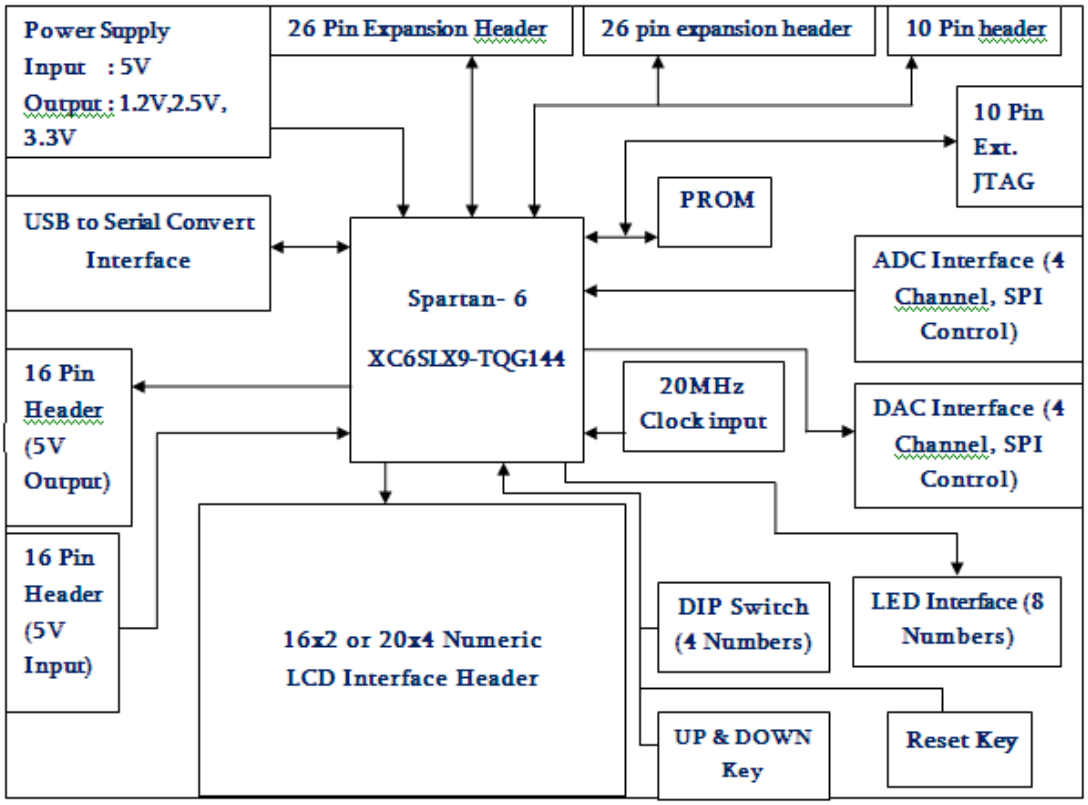


Figure 5.2 Block Diagram of Spartan-6 XC6SLX9 FPGA Controller

Board Features:

1. **FPGA: Spartan-6 XC6SLX9 in TQG144 package**

2. **Programming & Memory section**
    - Processor speed 20 MHZ.
    - 40 Individually Programmable GPIO Pins.
    - 4MB On board PROM for standalone program execution memory.
3. **Interfaces**
    - 8 output and 8 input lines with 5V Level.
    - Isolated serial communication interface through USB connector.
    - 4 position user DIP switch.
    - 8 user LEDs.
    - 2 no of input push switches.
    - 20x4 (or 16x2) LCD interface header.
    - External JTAG header for programming
4. **ADC**
    - No of ADC input : 4 Channels
    - Resolution : 12 bit
    - Sampling rate : 1MSPS
    - Analog input range : 5V(unipolar)
    - Over voltage protection
5. **DAC**
    - No of DAC output : 4 Channels
    - Resolution : 12 bit
    - Settling time : 6µs
    - Analog output range : 0 to +5V
6. **Headers**
    - 16 pin header for ADC input, 5V level Output and 5V level Input.
    - 2 no's of 26 pin and 1 no's of 10 pin headers for GPIO line termination
    - 10 pin External JTAG header for Programming
    - 4 pin DAC output connector.
    - 5 pin Unicon connector for power supply (+5V, GND).
    - 20 pin header used to interface 20x4 LCD or 16x2 LCD.

Further, the board layout and detailed description of Spartan-6 FPGA is provided in Appendix A. To implement the proposed control scheme, firstly the objective function is optimized using Cuckoo Search algorithm coded in MATLAB. Using the

optimized switching angles, the program for generation of switching pulses is coded using VHDL language in XILINX ISE 14.3 Design Suit software. Different case studies are performed to substantiate the effectiveness of the Cuckoo Search Algorithm for the power quality improvement of CHMLIs. The simulation and experimental results of the proposed control algorithm are discussed in the next section.

5.3. SINGLE-PHASE FIVE-LEVEL CASCADED H-BRIDGE INVERTER

A Single-Phase Five-Level H-bridge inverter comprises two H-bridge inverters connected in series to obtain phase output voltage with five levels ($+2V_{DC}$, $+V_{DC}$, 0, $-V_{DC}$, $-2V_{DC}$). Each H-bridge is provided with separate DC-link voltage. Figure 5.3 shows the structure of a Single-Phase Five-Level H-bridge Inverter. The same has been modeled in Simulink as well as in hardware setup by cascading two H-bridges. A single phase RL load of 500ohm, 120mH is connected across the output terminals of H-bridge inverter. The output voltage of multilevel inverter obtained using Cuckoo Search Optimized Switching technique is compared against the output voltage obtained using SPWM Switching technique.

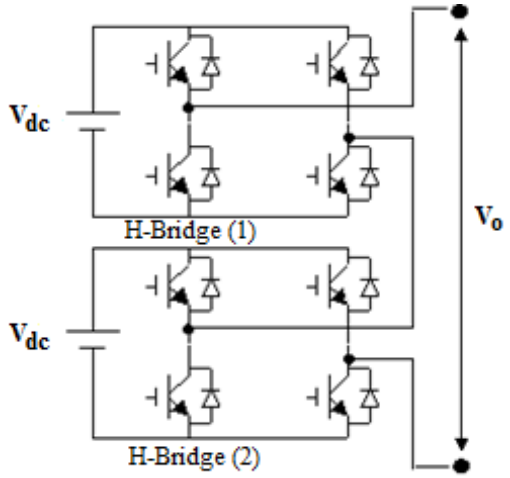


Figure 5.3 Structure of Single-phase Five-level Cascaded H-bridge Inverter

Ideally, THD is reducing while we are increasing switching frequency but higher switching frequencies mean higher switching losses. The more the carrier frequency is increased, the less will be the THD, if there is a filter connected to the output. So the optimum value for switching frequency is the maximum your system can handle if your only aim is to reduce THD. However, the adverse effect is that the switching loss will be very high. Another important consideration is the temperature of the

semiconductors switches also. So, the proposed Cuckoo Search Optimized Switching technique utilizes optimized switching angles and generates a pulse pattern with 50Hz as switching frequency, resulting in minimum harmonics, THD and losses. The SPWM Switching technique is only taken as a reference to compare the results obtained using proposed method. Generally, SPWM utilizes carrier frequency in the range 1kHz-15kHz. Here, in this chapter the frequency for SPWM is considered as 1kHz.

5.3.1. Determining Switching Angles Using CS Optimized Switching Function

The objective function in case of Single-Phase Five-Level Inverter for optimizing switching angles with the aim of having minimum fundamental voltage deviation and minimum harmonics can be presented as:

$$Fxn\_single\_phase\_5\_level = 0.1 * \left(1 - \frac{V_1}{V_{1(ref)}}\right)^4 + 0.9 * \sum_{k=3,5,7,\ldots}^{49} \left(\frac{V_k}{V_{1(ref)}}\right)^2 \quad (5.1)$$

where,

$$V_{1(ref)} = {}^{4 * m * 2V_{DC}}/_{pi}$$

$$\mathrm{V_k} = \frac{4 * \mathrm{V_{DC}}}{\mathrm{k} * \mathrm{pi}} (\cos k\alpha_1 + \cos k\alpha_2)$$

The Cuckoo Search Optimized Firing Scheme is implemented by initially optimizing the objective function to find switching angles using Cuckoo search algorithm code in MATLAB. Since the results of Cuckoo Search Optimization algorithm are same on every run, only a single run is considered for further study. The program is executed for different modulation indexes, and the optimum values of switching angles for single-phase five-level inverter are obtained and plotted in Figure 5.4. In addition, the function value with respect to the modulation index is shown in Figure 5.5. The step size here is taken as 0.05.

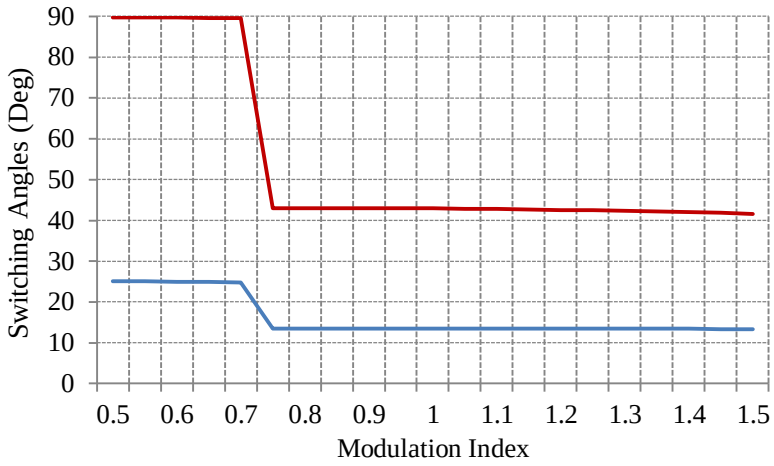


Figure 5.4 CS Optimized values of Switching Angles at different value of Modulation Index

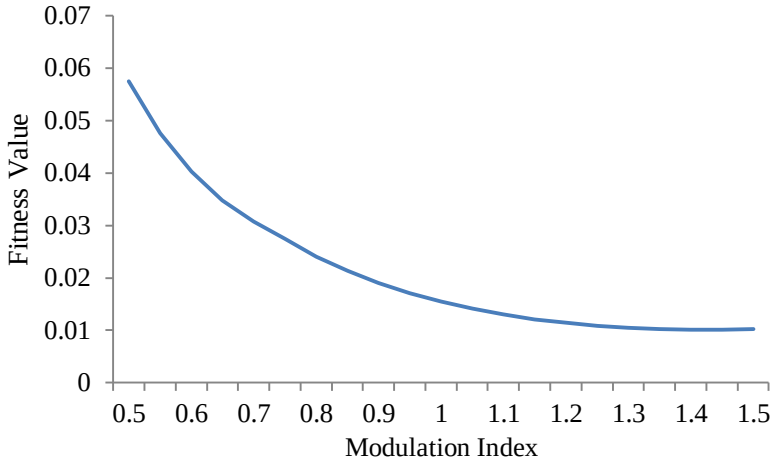


Figure 5.5 Optimized Function Value at different value of Modulation Index

From this Figure, it can be seen that the function value at every modulation index lies within tolerance. And the values for optimized switching angles are nearly 13.50˚ and 42.90˚ for modulation index ranges from 0.7 to 1.5.

5.3.2. Simulation Results using SPWM Firing Scheme and Cuckoo Search Optimized Firing Scheme

The MATLAB/Simulink model of a Single-phase Five-level H-Bridge Inverter is shown in Figure 5.6a. It consists of a control system for generating gating pulses, H-Bridge inverter and load connected in series. Detailed block for H-Bridge inverter is further shown in Figure 5.6b. Each switch of inverter is provided with the switchinhg pulses from the control system.

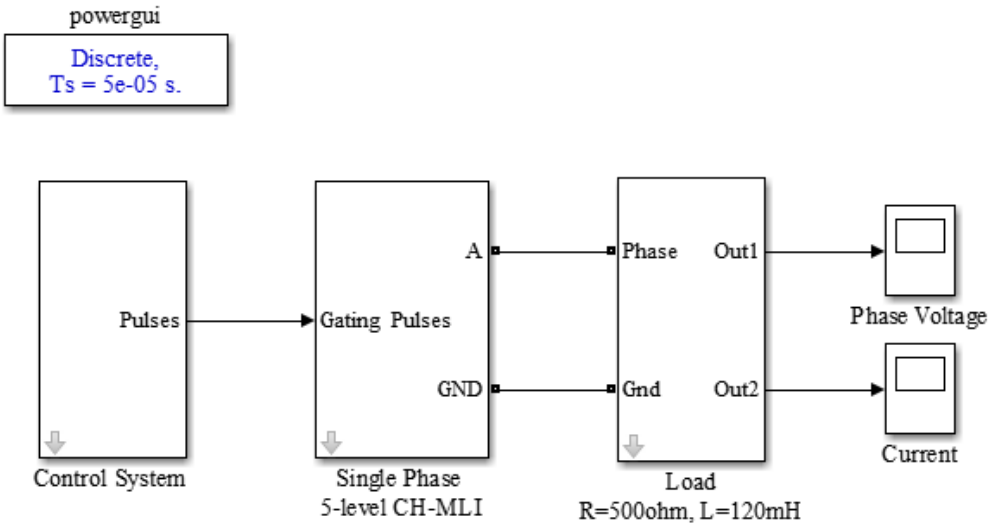


Figure 5.6 a) MATLAB/Simulink model of a Single-phase Five-level H-Bridge Inverter

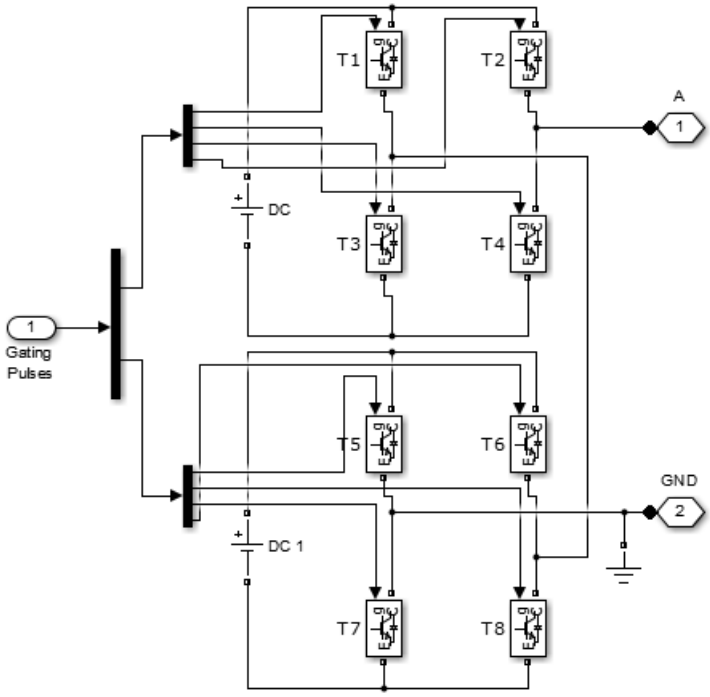


Figure 5.6 b) Detailed block for H-Bridge inverter

Optimized Switching angles are obtained by using Cuckoo Search algorithm with 500 iterations for m=1. The value of Optimized Switching angles and Fitness Value with respect to number of iterations are shown in Figure 5.7 and 5.8. Now, the switching patterns for m=1 are generated by the use of optimized switching angles (13.51˚, 42.91˚). The program for generation of switching pulses is coded in Simulink using MATLAB function and output pulses are then fed to the power switches of H-bridge inverter and finally, the output voltage is obtained.

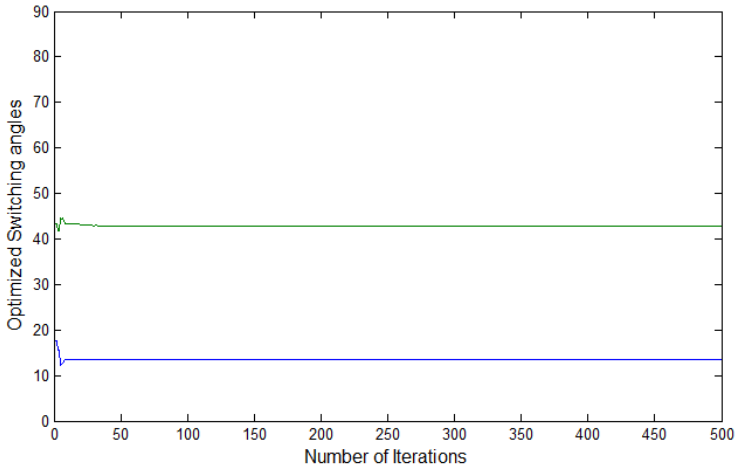


Figure 5.7 CS Optimized Switching angles for Single-Phase Five-Level Inverter

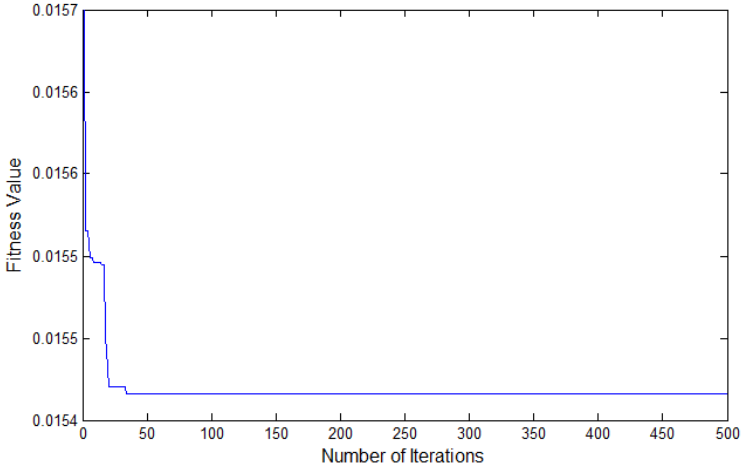


Figure 5.8 Fitness Value for Single-Phase Five-Level Inverter

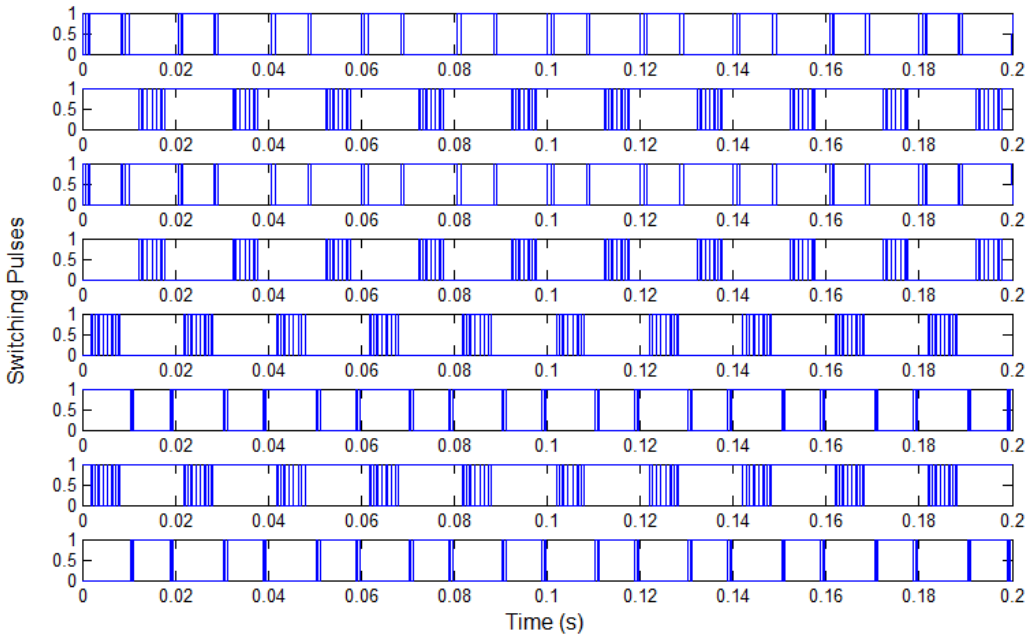


Figure 5.9 a) Switching Pattern using SPWM Switching Technique at m=1 and F_c=1kHz

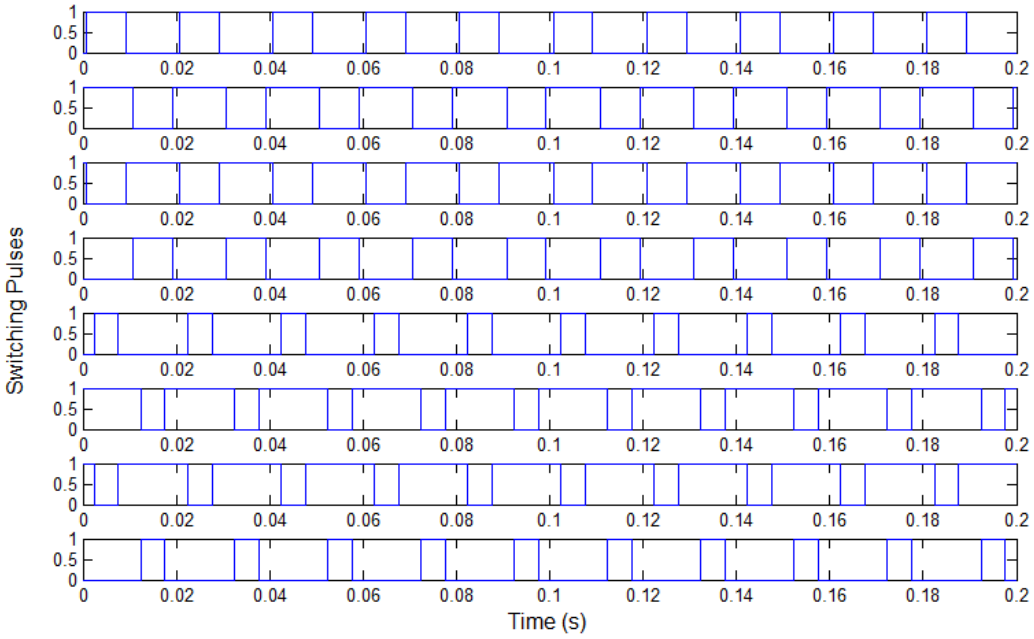


Figure 5.9 b) Switching Pattern using Cuckoo Search Optimized Switching Technique

The switching pattern for the power switches of each H-bridge using SPWM Switching Technique and Cuckoo Search Optimized Switching Technique is represented above in Figure 5.9. The corresponding output voltage across the load terminals are captured with the help of scope in Simulink as shown in Figure 5.10.

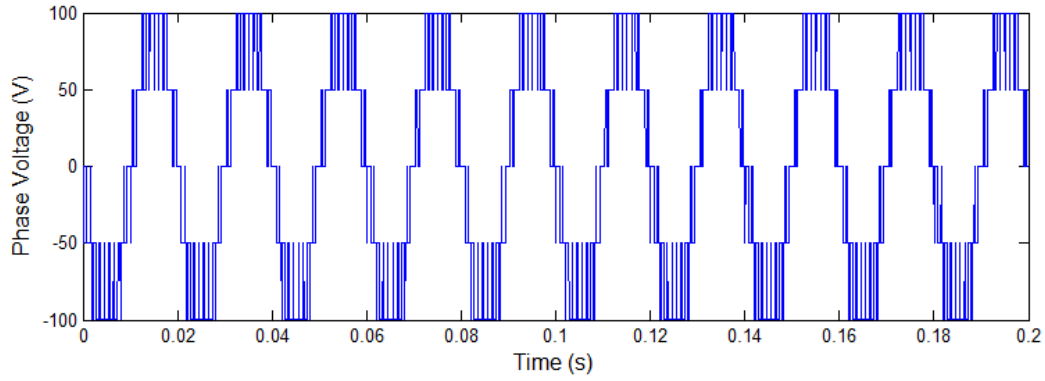


Figure 5.10 a) Single-Phase Five-level Output Voltage using SPWM Switching Technique at m=1 and F_c=1kHz

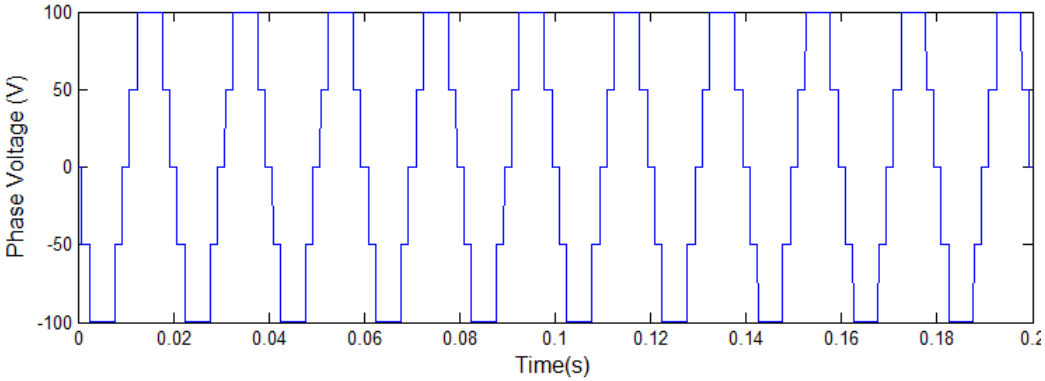


Figure 5.10 Single-Phase Five-level Output Voltage using Cuckoo Search Optimized Switching Technique

FFT analysis of Single-phase Five-level H-bridge inverter simulated at m=1 using both the schemes is presented in Figure 5.11. It can be clearly seen that THD is minimized from 26.75% with SPWM Firing Scheme and 16.19% with Cuckoo Search Optimized Firing Scheme. Also, the even-order and other inadequate harmonics are minimized.

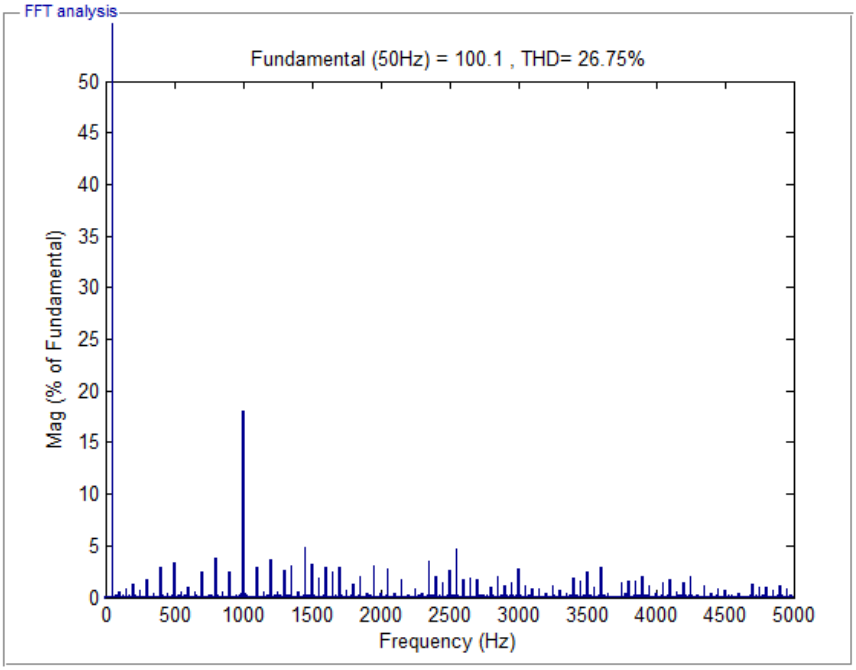


Figure 5.11 a) FFT Analysis of Single-Phase Five-Level Inverter using SPWM Firing Scheme

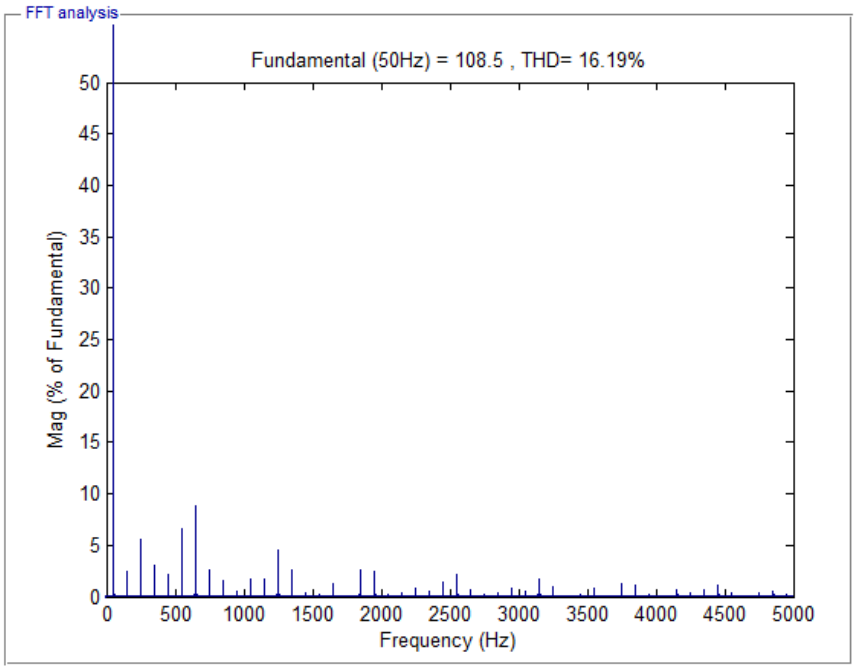


Figure 5.11 b) FFT Analysis of Single-Phase Five-Level Inverter using Cuckoo Search Optimized Firing Scheme

As the main focus of objective function is to minimize harmonics, THD and maintain fundamental voltage at desired value, so these parameters are observed for different values of modulation index. A comparison between Cuckoo Search optimized firing scheme and SPWM firing scheme is made based on these parameters. Graphical representations shown in Figure 5.12 summarizes the comparison and verify the effectiveness of Cuckoo Search as THD is minimized and the fundamental voltage component is enhanced near the desired value for modulation index between 0.7 to 1.5. Thus, the algorithm is efficient in optimizing the switching angles for minimum harmonics for a wide range of modulation index.

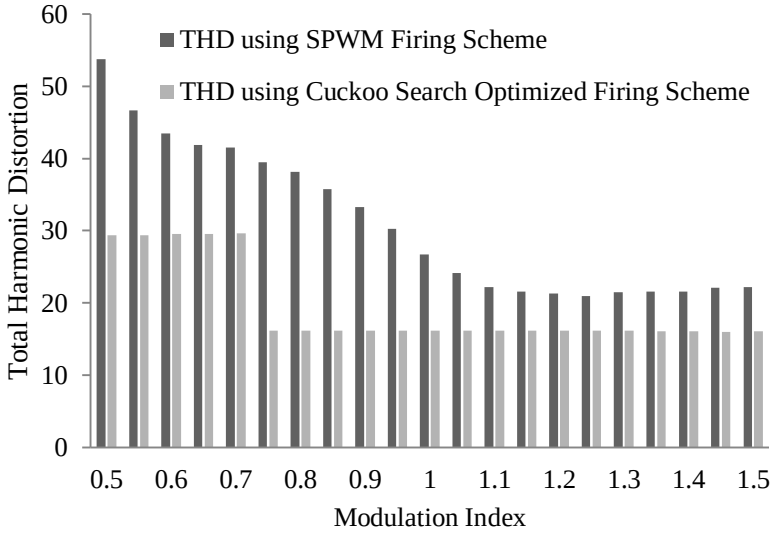


Figure 5.12 a) Phase Voltage THD of Single Phase Five-Level H-Bridge Inverter at different values of Modulation Index

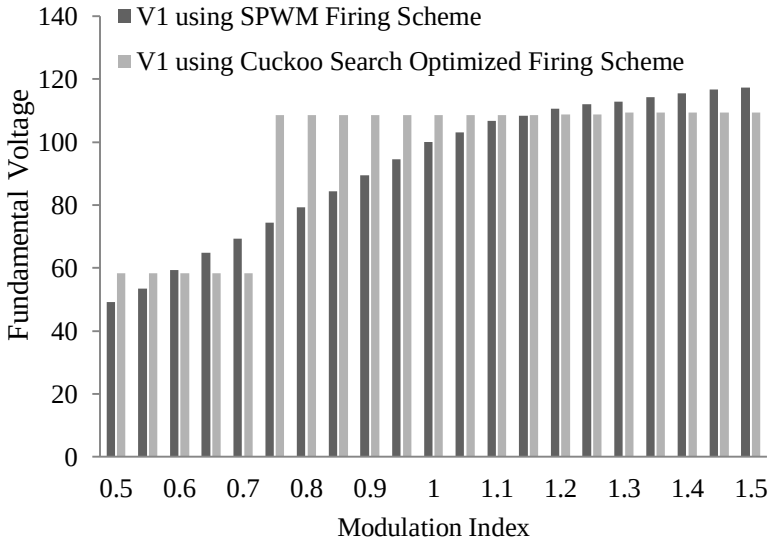


Figure 5.12 b) Fundamental Voltage of Single Phase Five-Level H-Bridge Inverter at different values of Modulation Index

5.3.3. Experimental Results using SPWM Firing Scheme and Cuckoo Search Optimized Firing Scheme

A hardware setup firstly requires two H-bridges to be connected in series to form Single-phase Five-level H-bridge inverter and other necessary measurement devices should be connected accordingly. Using the optimized switching angles, the program for generation of switching pulses is coded in XILINX ISE 14.3 Design Suit software. The pulse pattern is then given to inverter unit using interfacing connector, from where each switch is provided with their corresponding gating signal. The inverter generates the phase output waveform by following the switching pulse pattern, which can be observed on DSO screen as shown here in Figure 5.13. Harmonic analysis of the output waveform is obtained with the help of Power Analyzer as shown below in Figure 5.14.

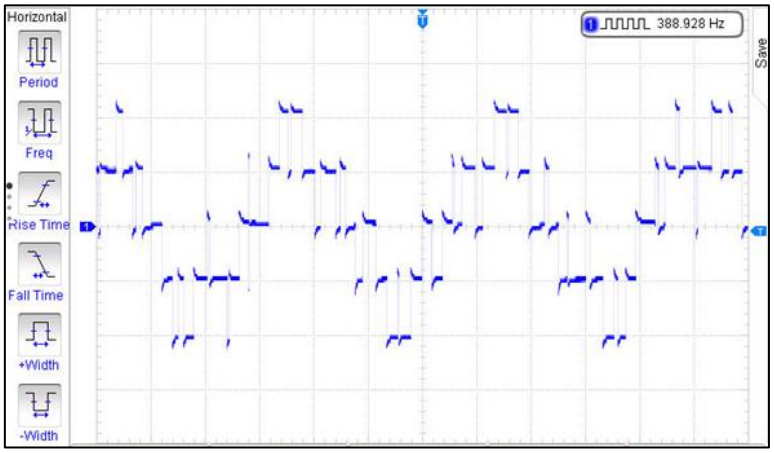


Figure 5.13 a) Single-Phase Five-Level Output Voltage using SPWM Switching Scheme from DSO

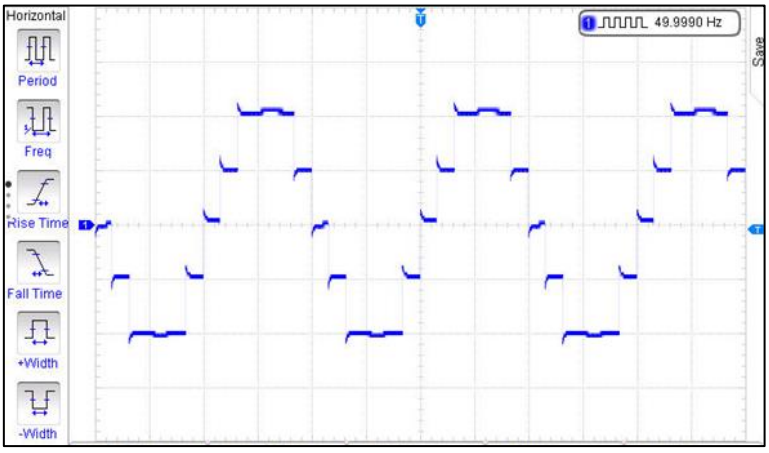
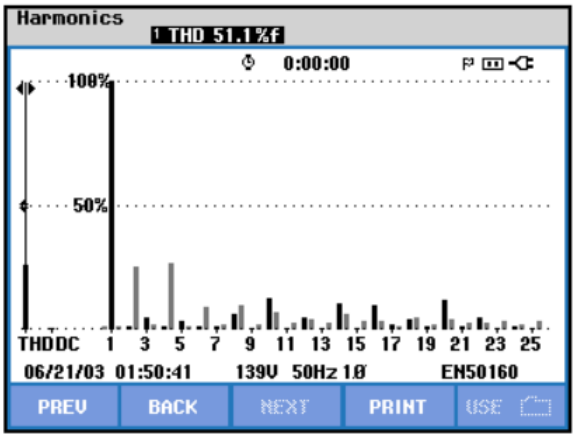
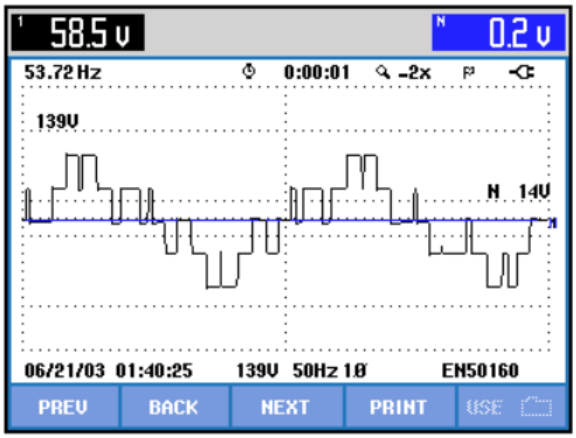


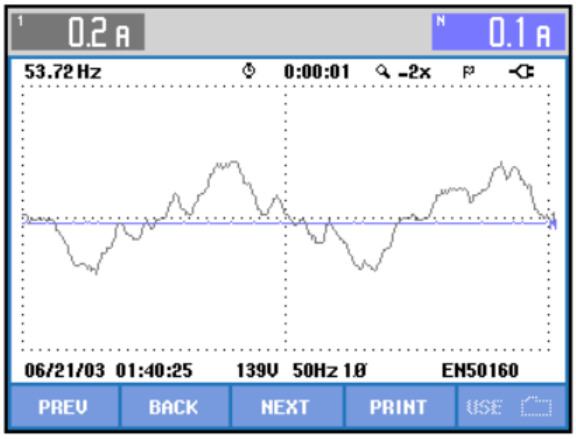
Figure 5.13 b) Single-Phase Five-Level Output Voltage using Cuckoo Search Optimized Switching Scheme from DSO



(a)



(b)



(c)

Figure 5.14 Single-Phase Five-Level a) Harmonics, b) Output Voltage and c) Current using Power Analyzer obtained by SPWM Switching Scheme

The detailed comparison among Cuckoo search Optimized scheme and SPWM Firing scheme is presented using simulation and hardware results in Table 5.1. The values for phase output voltage, current, and harmonic content are considered for comparison. Observations clearly confirm the simulation results and indicate the reduction in THD using CS Optimized Switching technique. Even order harmonics

which dominates in SPWM Switching technique vanishes with the proposed scheme. And also the harmonic content is improved to 15.5%.

Table 5.1 Comparison of Simulation and Hardware results of Single-Phase Five-Level using SPWM Firing scheme and Cuckoo Search Optimized scheme

Parameters		SPWM Firing Scheme		Cuckoo Search Optimized scheme	
		Simulation Results	Hardware Results	Simulation Results	Hardware Results
Phase Current	Peak value	0.1994	0.4	0.2165	0.5
	R.M.S. value	0.141	0.2	0.1531	0.3
	THD	12.45	12.19	11.18	8.8
Phase Voltage	Peak value	100.1	105.4	108.5	105
	R.M.S. value	70.76	57.6	76.75	80.3
	DC Component	0.02766	0.1	0.0022	0.1
	THD	26.75	51.1	16.19	15.5
Distortion Factor or Harmonics	2^{nd} Harmonic	0.58	1.5	0.03	0
	3^{rd} Harmonic	0.88	4.6	2.50	1.6
	4^{th} Harmonic	1.25	1.7	0.03	0
	5^{th} Harmonic	0.7	3.6	5.63	5.8
	6^{th} Harmonic	1.73	1.6	0.01	0
	7^{th} Harmonic	0.32	1.6	3.04	3.6
	8^{th} Harmonic	2.88	6	0.02	0
	9^{th} Harmonic	0.40	1	2.17	2.6
	10^{th} Harmonic	3.34	12.7	0.04	0
	11^{th} Harmonic	0.58	0.7	6.59	6.7
	12^{th} Harmonic	0.90	4.8	0.02	0
	13^{th} Harmonic	0.48	0.8	8.84	8.9
	14^{th} Harmonic	2.46	10.5	0.02	0
	15^{th} Harmonic	0.18	1	2.67	2.6
	16^{th} Harmonic	3.73	9.7	0.03	0
	17^{th} Harmonic	0.58	2	1.50	1.3
	18^{th} Harmonic	2.51	4.5	0.01	0
	19^{th} Harmonic	0.26	1.3	0.45	1

Similarly, higher levels can be modeled and studied for the better understanding. The switching pattern is required to be programmed again using new set of optimized switching angles for higher levels. The output waveforms for higher level will have better THD and resembles the sinusoidal shape properly.

5.4. SINGLE-PHASE NINE-LEVEL CASCADED H-BRIDGE INVERTER

A Single-phase Nine-level H-bridge inverter comprises of four H-bridge inverters connected in series to obtain phase output voltage with nine levels ((+4V_{DC}, +3V_{DC}, +2V_{DC}, +V_{DC}, 0, -V_{DC}, -2V_{DC}, -3V_{DC}, -4V_{DC}). Each H-bridge is provided with separate DC-link voltage as shown in Figure 5.15. The same has been modeled in Simulink as well as in hardware setup by cascading four H-bridges. A single phase RL load of 500ohm, 120mH is connected across the output terminals of H-bridge inverter. The output voltage of multilevel inverter obtained using Cuckoo Search optimized control is compared against the output voltage obtained using SPWM control.

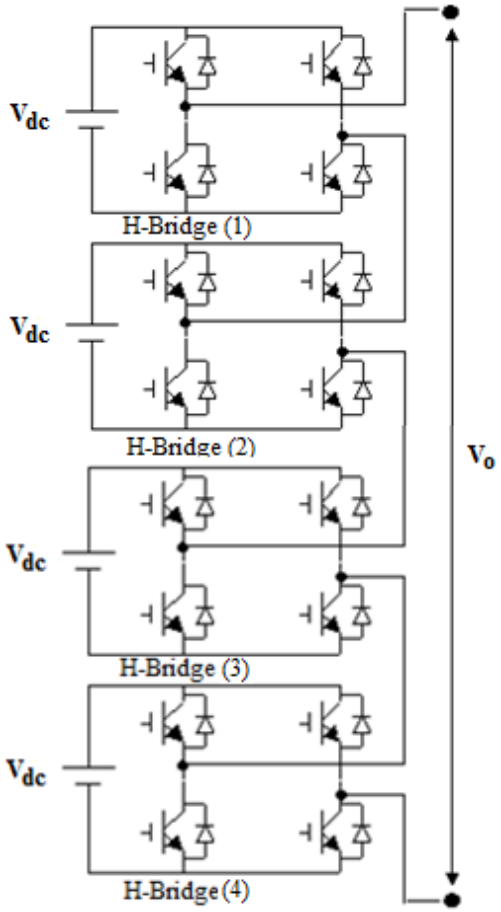


Figure 5.15 Structure of Single-phase Nine-level Cascaded H-bridge Inverter

5.4.1. Determining Switching Angles Using CS Optimized Switching Function

The Objective function in case of Single-phase Five-Level Inverter for optimizing switching angles to have minimum fundamental voltage deviation and minimum harmonics can be presented as:

$$Fxn\_single\_phase\_9\_level = 0.1 * \left(1 - \frac{V_1}{V_{1(ref)}}\right)^4 + 0.9 * \sum_{k=3,5,7,\ldots}^{49} \left(\frac{V_k}{V_{1(ref)}}\right)^2 \quad (5.2)$$

where,

$$V_{1(ref)} = {}^{4 * m * 2V_{DC}}/_{pi}$$

$$\mathrm{V_k} = \frac{4 * \mathrm{V_{DC}}}{\mathrm{k} * \mathrm{pi}} (\cos k\alpha_1 + \cos k\alpha_2 + \cos k\alpha_3 + \cos k\alpha_4)$$

Similarly, the coding for optimization of above function is done in m file in MATLAB and the optimized switching angles are obtained by using Cuckoo Search algorithm with 500 iterations as 6.8834˚, 20.8495˚, 35.6943˚,and 56.0736˚ for m=1. The value of Optimized Switching angles and Fitness Value with respect to number of iterations are shown in Figure 5.16 and 5.17.

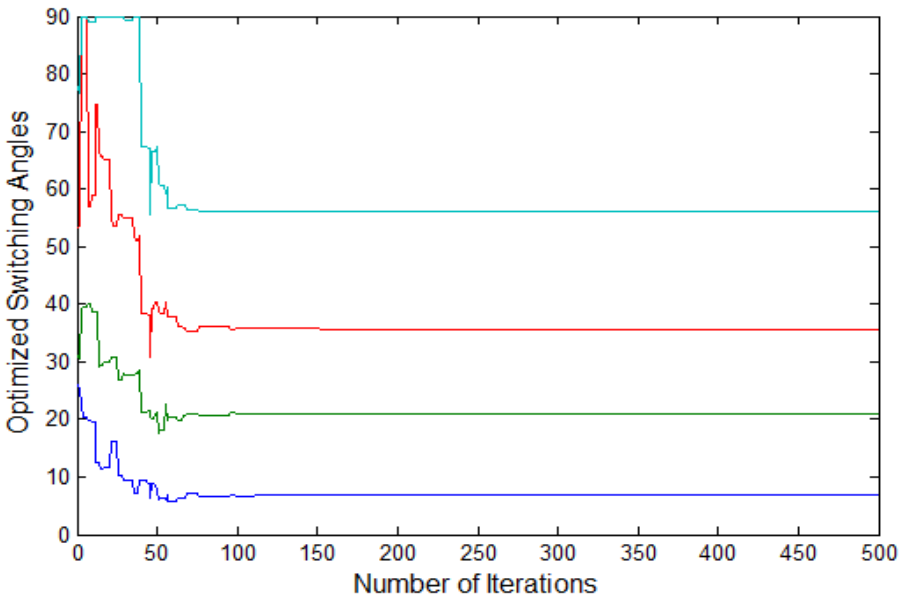


Figure 5.16 CS Optimized Switching angles for Single-Phase Nine-Level Inverter

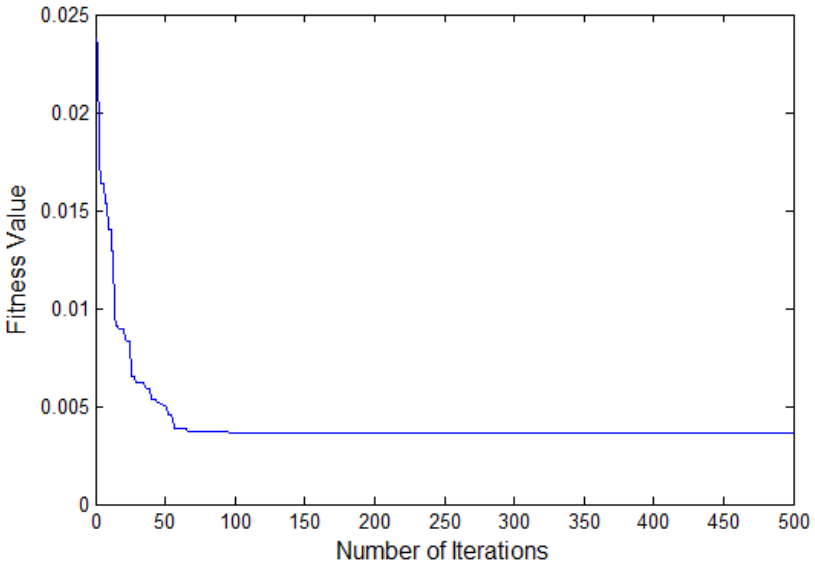


Figure 5.17 Fitness Value for Single-Phase Nine-Level Inverter

5.4.2. Simulation Results using SPWM Firing Scheme and Cuckoo Search Optimized Firing Scheme

Similar to previous model, the MATLAB/Simulink model of a Single-phase Nine-level H-Bridge Inverter is shown in Figure 5.18. It consists of four H-bridges where each switch of H-bridge is provided with the switching pulses from the control system.

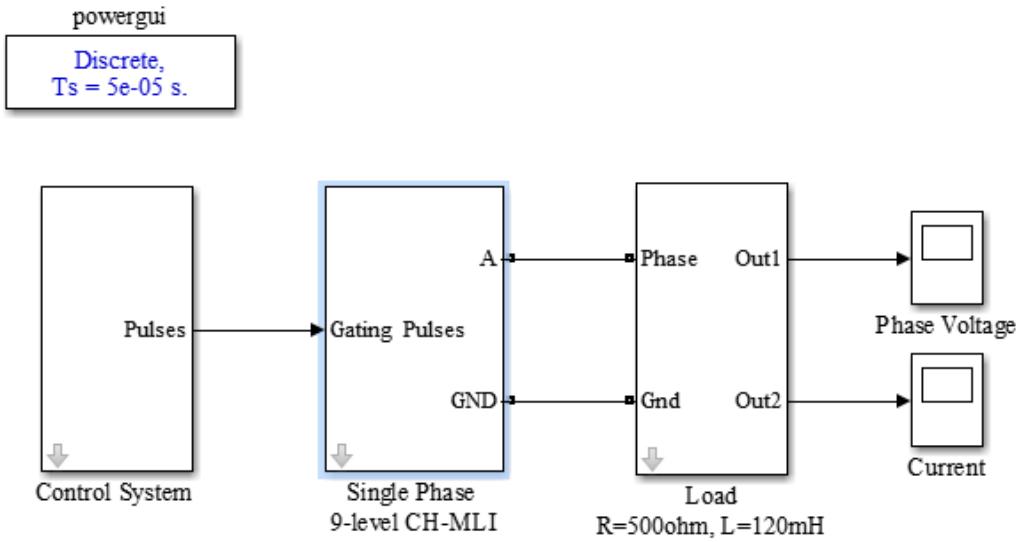


Figure 5.18 MATLAB/Simulink model of a Single-phase Nine-level H-Bridge Inverter

The program for generation of switching pulses is coded in Simulink using MATLAB function and output pulses are then fed to the power switches of H-bridge inverter and the output voltage across the load terminals is obtained as shown in Figure 5.19.

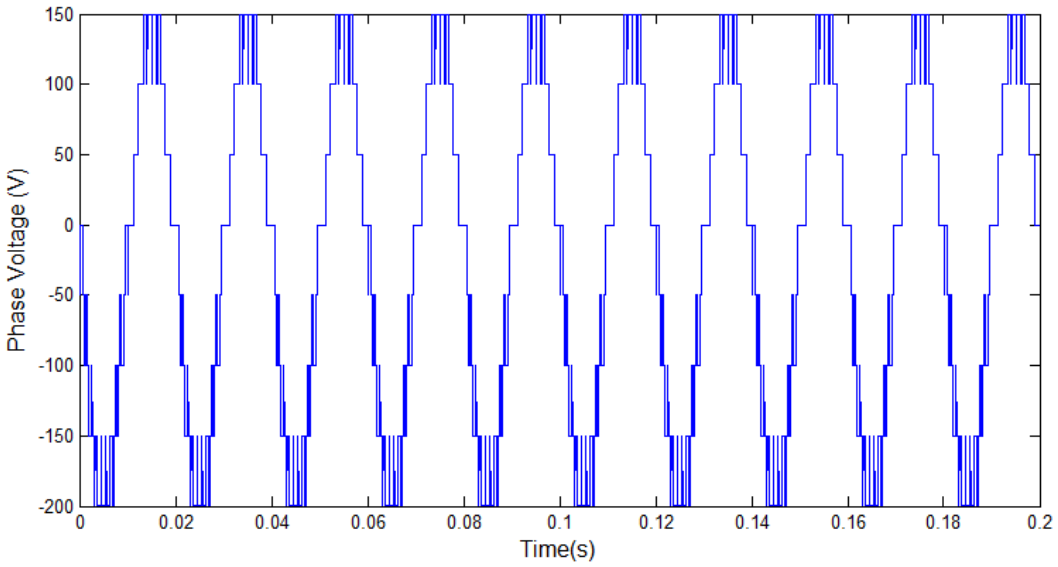


Figure 5.19 a) Single-Phase Nine-level Output Voltage using Cuckoo Search Optimized Switching Technique

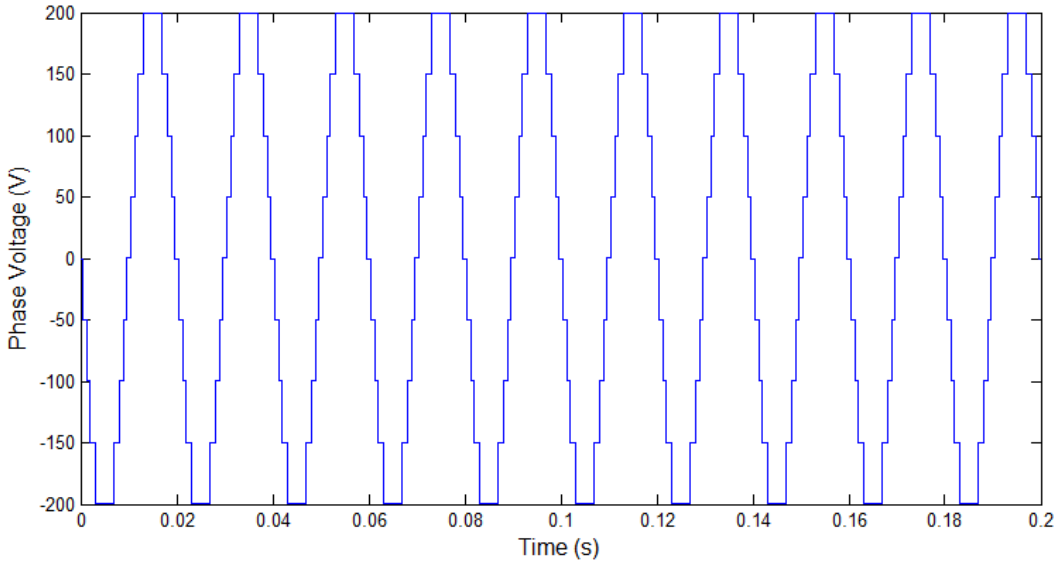


Figure 5.19 b) Single-Phase Nine-level Output Voltage Cuckoo Search Optimized Switching Technique

FFT analysis of Single-phase Nine-level H-bridge inverter simulated at m=1 using both the schemes is presented in Figure 5.20. It can be clearly seen that THD is minimized from 18.90% with SPWM Switching Scheme and 8.59% with Cuckoo Search Optimized Switching Scheme. Here also, the even-order and other inadequate harmonics are minimized.

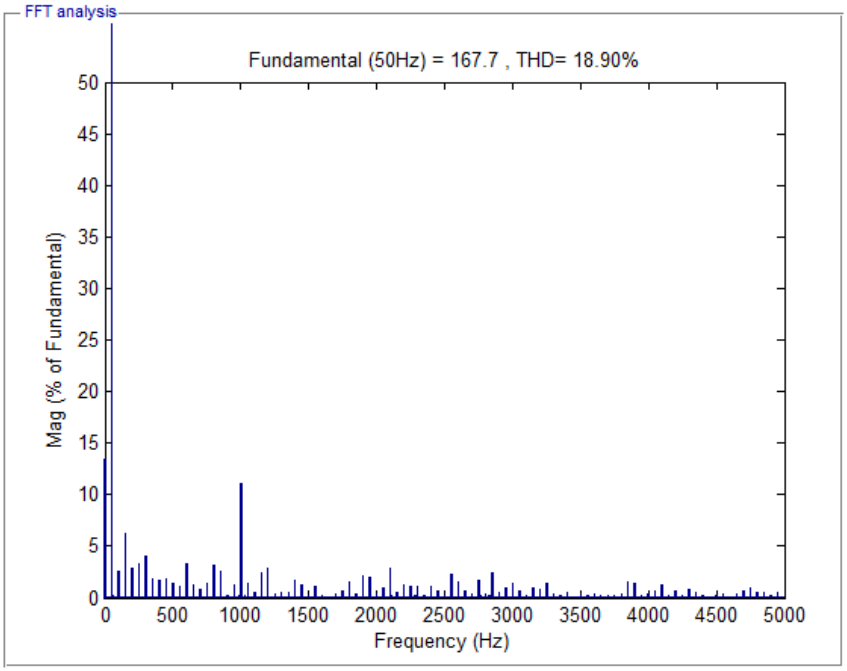


Figure 5.20 a) FFT Analysis of Single-Phase Nine-Level Inverter using SPWM Firing Scheme

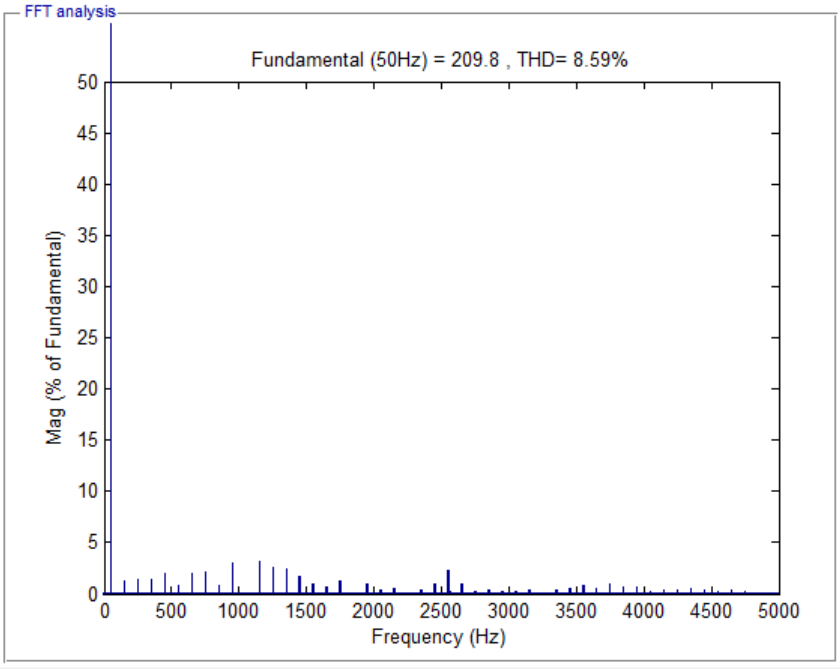


Figure 5.20 b) FFT Analysis of Single-Phase Nine-Level Inverter using Cuckoo Search Optimized Firing Scheme

5.4.3. Experimental Results using SPWM Firing Scheme and Cuckoo Search Optimized Firing Scheme

Single-phase Nine-level H-bridge inverter is formed by connecting four H-bridges in series and necessary measurement devices are connected accordingly. Using the

optimized switching angles, the program for generation of switching pulses is coded using VHDL language in XILINX ISE 14.3 Design Suit software. The pulse pattern is then given to inverter unit using interfacing connector, from where each switch is provided with their corresponding gating signal. The inverter generates the phase output waveform by following the switching pulse pattern, which can be observed on DSO screen as shown here in Figure 5.21. Harmonic analysis of the output waveform is obtained with the help of Power Analyser and shown below in Figure 5.22.

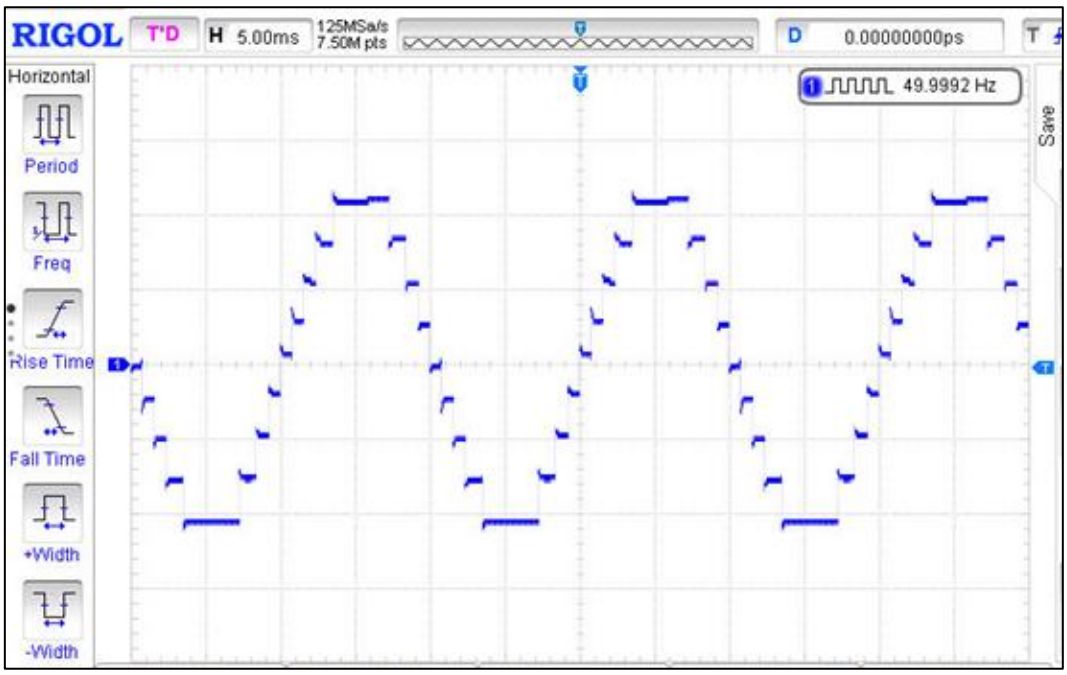
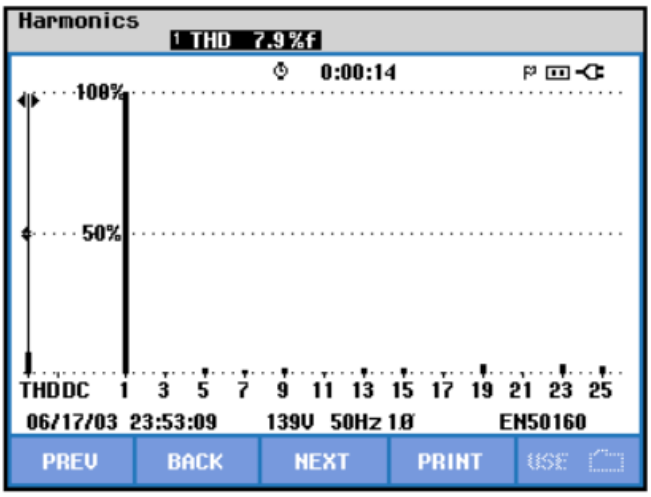
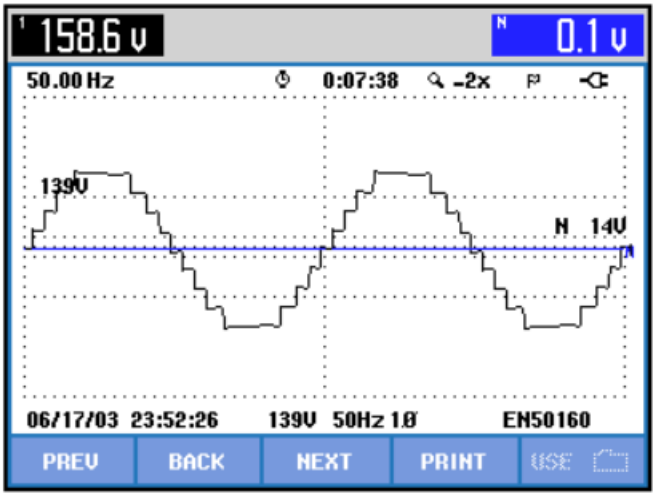


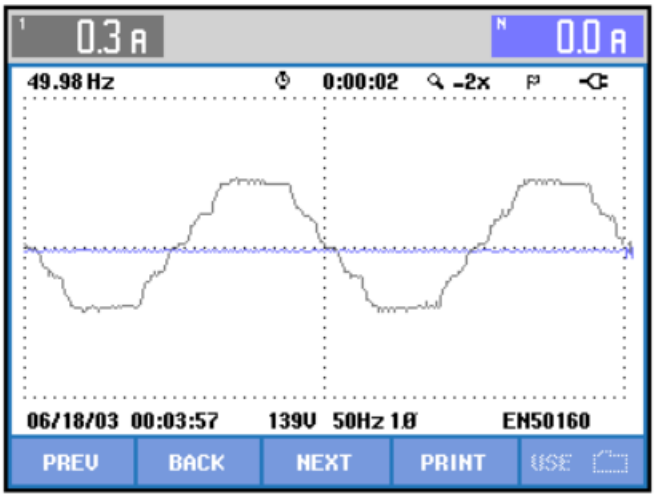
Figure 5.21 Single-Phase Nine-Level Output Voltage using Cuckoo Search Optimized Switching Scheme from DSO



(a)



(b)



(c)

Figure 5.22 Single-Phase Nine-Level a) Harmonics, b) Output Voltage and c) Current using Power Analyzer obtained by Cuckoo Search Optimized Switching Scheme

The detailed comparison among Cuckoo search Optimized Switching scheme and SPWM Switching scheme is presented using simulation and hardware results in Table 5.2. The values for phase output voltage, current, and harmonic content are considered for comparison. Observations clearly confirm the simulation results and indicate the reduction in THD using CS Optimized Switching technique. Even order harmonics which dominates in SPWM Switching technique vanishes with the proposed scheme. And also the harmonic content is improved to 7.9% along with zero DC component and improved fundamental component.

Table 5.2 Comparison of Simulation and Hardware results of Single-Phase Nine-Level using SPWM Firing scheme and Cuckoo Search Optimized scheme

Parameters		SPWM Firing Scheme		Cuckoo Search Optimized scheme	
		Simulation Results	Hardware Results	Simulation Results	Hardware Results
Phase Current	Peak value	0.3345	0.75	0.4183	.9
	R.M.S. value	0.2365	0.53	0.2958	0.6
	THD	12.00	11.2	4.64	3.633
Phase Voltage	Peak value	167.7	196.45	209.8	225.4
	R.M.S. value	118.5	138.93	148.4	161.4
	DC Component	22.53	5.7	0.006934	0
	THD	18.90	22.35	8.59	7.9
Distortion Factor or Harmonics	2^{nd} Harmonic	2.59	0.8	0.03	0
	3^{rd} Harmonic	6.24	2.1	1.26	.8
	4^{th} Harmonic	2.81	1	0.02	0
	5^{th} Harmonic	3.31	1.2	1.41	1.9
	6^{th} Harmonic	3.99	1.9	0.01	0
	7^{th} Harmonic	1.76	0.9	1.34	1.4
	8^{th} Harmonic	1.75	2.3	0.01	0
	9^{th} Harmonic	1.82	0.3	1.91	2.1
	10^{th} Harmonic	1.39	2.6	0.01	0
	11^{th} Harmonic	1.09	0	0.82	07
	12^{th} Harmonic	3.24	3.5	0	0
	13^{th} Harmonic	1.23	0.1	1.99	2
	14^{th} Harmonic	0.77	4.8	0	0
	15^{th} Harmonic	1.44	0.3	2.11	2.2
	16^{th} Harmonic	3.20	3.2	0	0
	17^{th} Harmonic	2.50	1.3	0.75	0.7
	18^{th} Harmonic	0.20	2.9	0.01	0
	19^{th} Harmonic	1.27	0.6	2.93	3.2

Further, Thirteen-level Cascaded H-Bridge Inverter is also modeled and examined using SPWM Switching scheme and CS Optimized Switching scheme in Simulink and hardware setup.

5.5. SINGLE-PHASE THIRTEEN-LEVEL CASCADED H-BRIDGE INVERTER

Similar to above, a Single-phase Thirteen-level H-bridge inverter comprising six H-bridge inverters has been modeled in Simulink as well as in hardware setup. A single phase RL load of 500ohm, 120mH is connected across the output terminals.

5.5.1. Determining Switching Angles Using CS Optimized Switching Function

The Objective function in case of Single-phase Five-Level Inverter for optimizing switching angles can be presented as:

$$Fxn\_single\_phase\_13\_level = 0.1 * \left(1 - \frac{V_1}{V_{1(ref)}}\right)^4 + 0.9 * \sum_{k=3,5,7,\ldots}^{49} \left(\frac{V_k}{V_{1(ref)}}\right)^2 \quad (5.3)$$

where,

$$V_{1(ref)} = {}^{4 * m * 2V_{DC}}/_{pi}$$

$$\mathrm{V_k} = \frac{4 * \mathrm{V_{DC}}}{\mathrm{k} * \mathrm{pi}} (\cos k\alpha_1 + \cos k\alpha_2 + \cos k\alpha_3 + \cos k\alpha_4 + \cos k\alpha_5 + \cos k\alpha_6)$$

The optimized switching angles can be obtained by using Cuckoo Search algorithm with 500 iterations as 5.3238˚, 13.9016˚, 23.5937˚, 34.8588˚, 47.345˚, and 62.9878˚ for m=1. The value of Optimized Switching angles and Fitness Value with respect to number of iterations are shown in Figure 5.23 and 5.24.

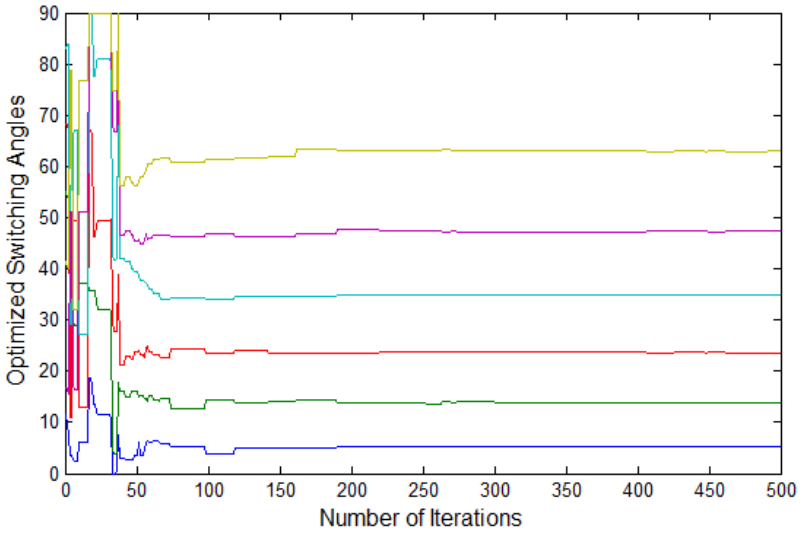


Figure 5.23 CS Optimized Switching angles for Single-Phase Thirteen-Level Inverter

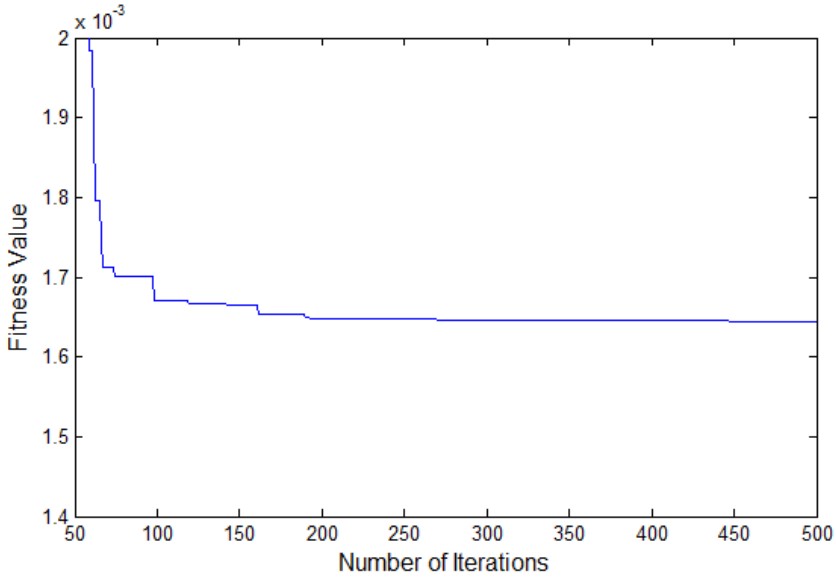


Figure 5.24 Fitness Value for Single-Phase Thirteen-Level Inverter

5.5.2. Simulation Results using SPWM Firing Scheme and Cuckoo Search Optimized Firing Scheme

Similar to previous models, the MATLAB/Simulink model of a Single-phase Thirteen-level H-Bridge Inverter is shown in Figure 5.25.

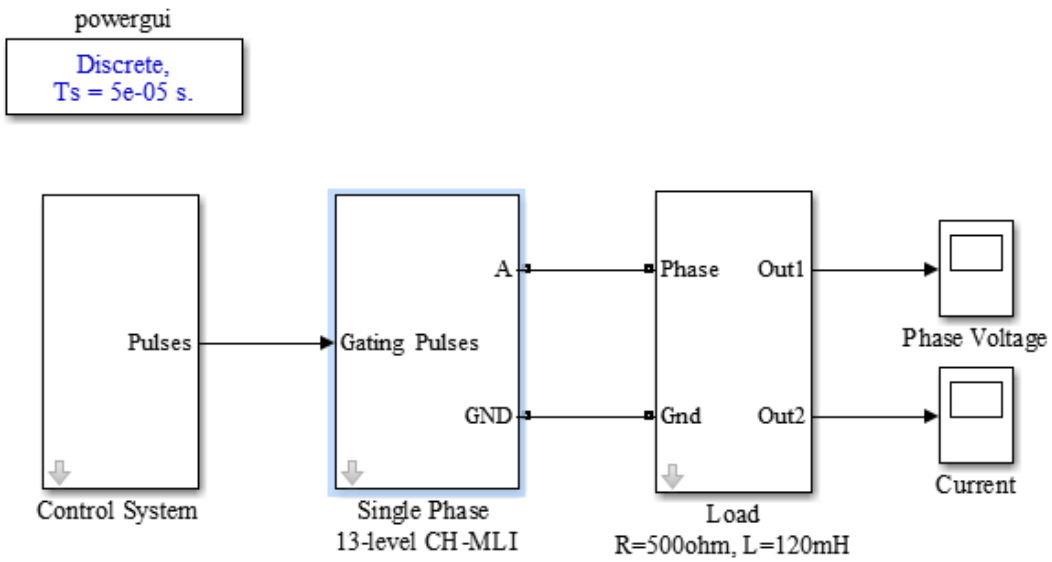


Figure 5.25 MATLAB/Simulink model of a Single-phase Thirteen-level H-Bridge Inverter

The program for generation of switching pulses is coded in Simulink using MATLAB function and output pulses are then fed to the power switches of H-bridge inverter and the output voltage across the load terminals is obtained as shown in Figure 5.26.

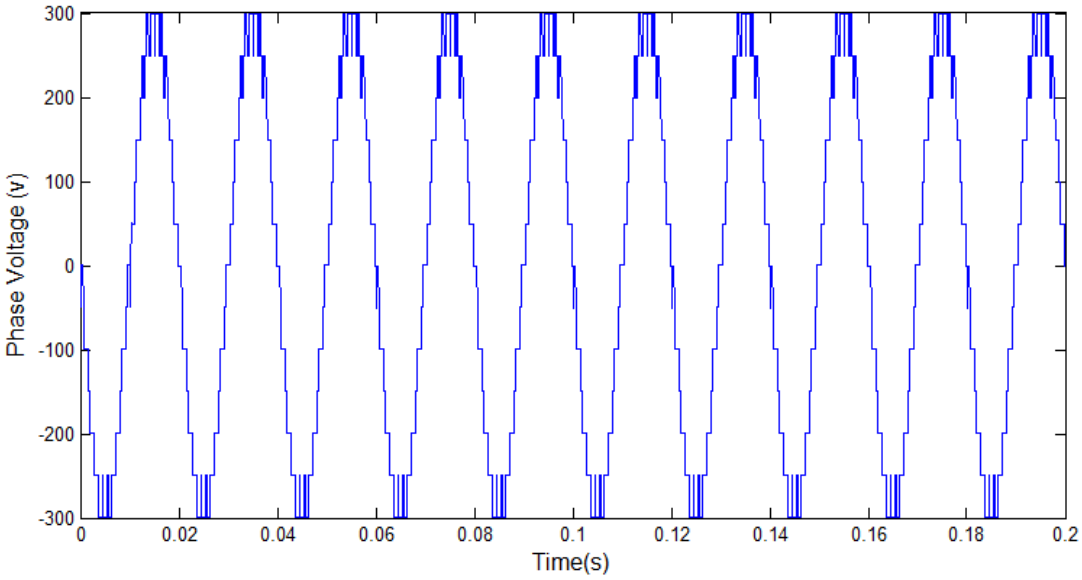


Figure 5.26 a) Single-Phase Thirteen-level Output Voltage using SPWM Switching Technique at m=1 and F_c=1kHz

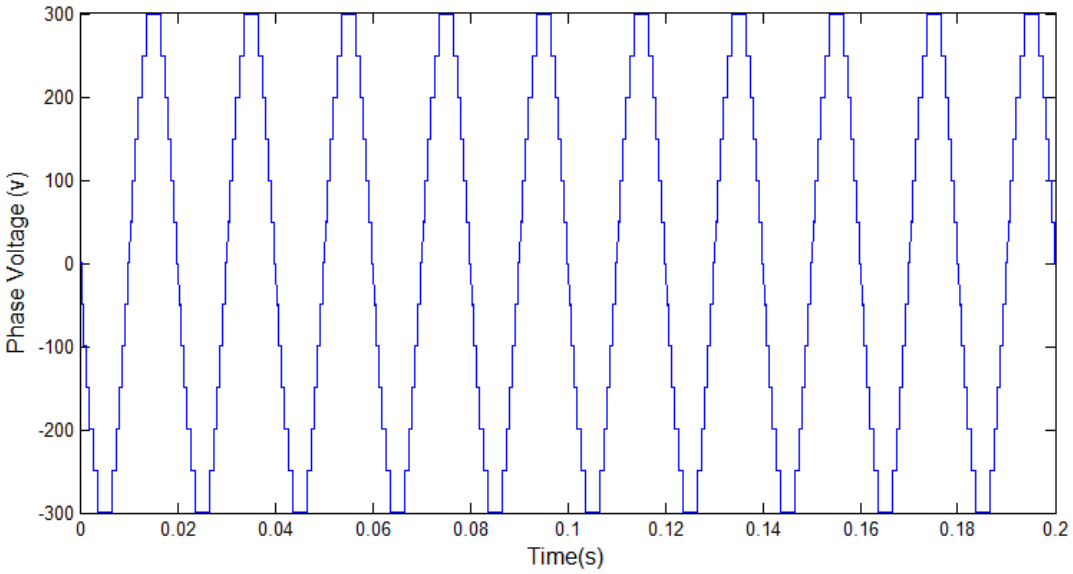


Figure 5.26 b) Single-Phase Thirteen-level Output Voltage using Cuckoo Search Optimized Switching Technique

FFT analysis of Single-phase Thirteen-level H-bridge inverter simulated at m=1 using both the schemes is presented in Figure.5.27. It can be clearly seen that THD is minimized from 9.23% with SPWM Switching Scheme and 5.76% with Cuckoo Search Optimized Switching Scheme. Also, the even-order and other inadequate harmonics are minimized.

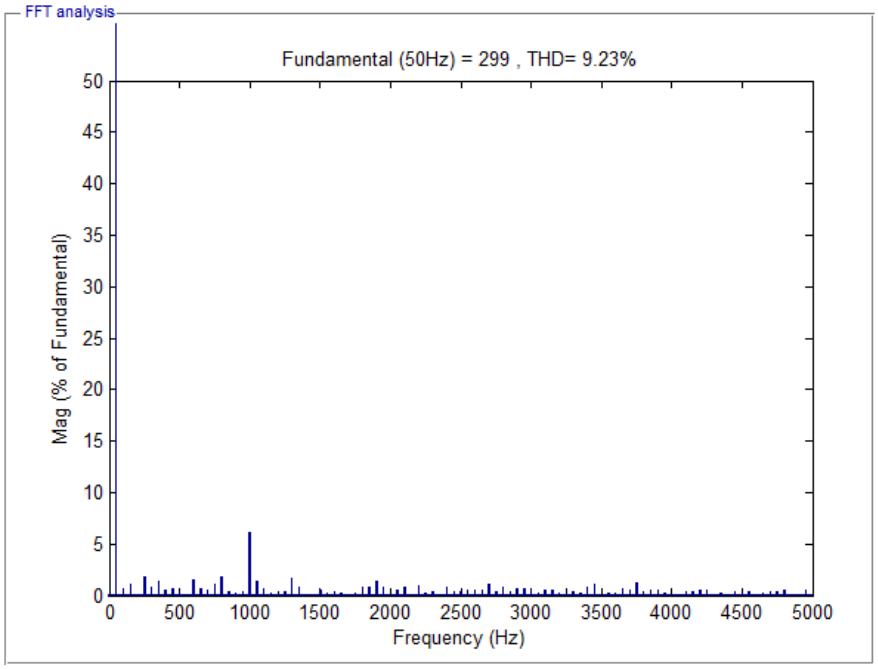


Figure 5.27 a) FFT Analysis of Single-Phase Thirteen-Level Inverter using SPWM Firing Scheme

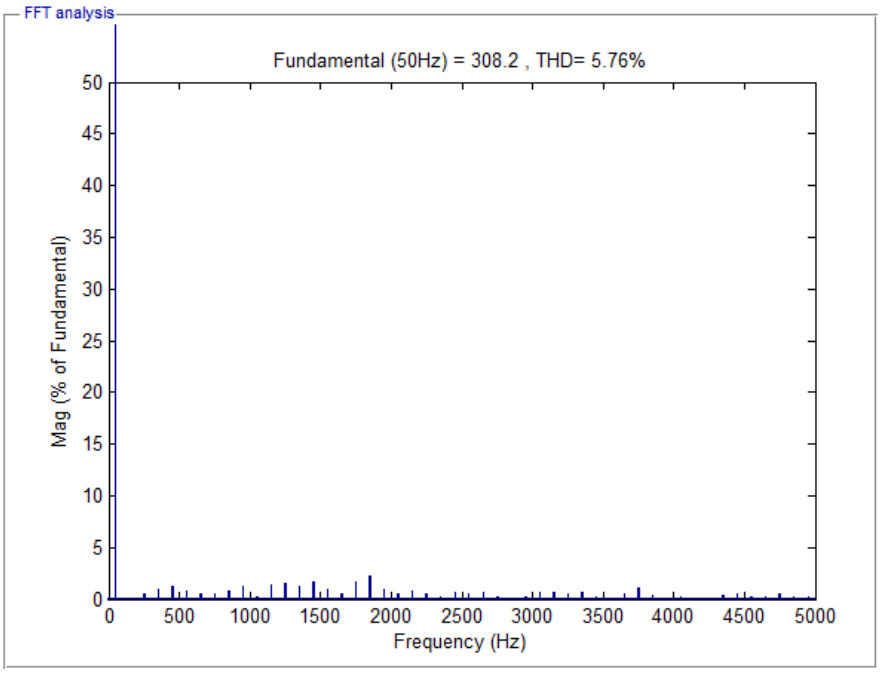


Figure 5.27 b) FFT Analysis of Single-Phase Thirteen-Level Inverter using Cuckoo Search Optimized Firing Scheme

5.5.3. Experimental Results using SPWM Firing Scheme and Cuckoo Search Optimized Firing Scheme

Single-phase Thirteen-level H-bridge inverter is formed by connecting six H-bridges in series and necessary measurement devices are connected accordingly. The procedure followed in above cases is repeated and the phase output waveform

observed on DSO screen and Harmonic analysis of the output waveform is displayed here in Figure 5.28 and 5.29, respectively.

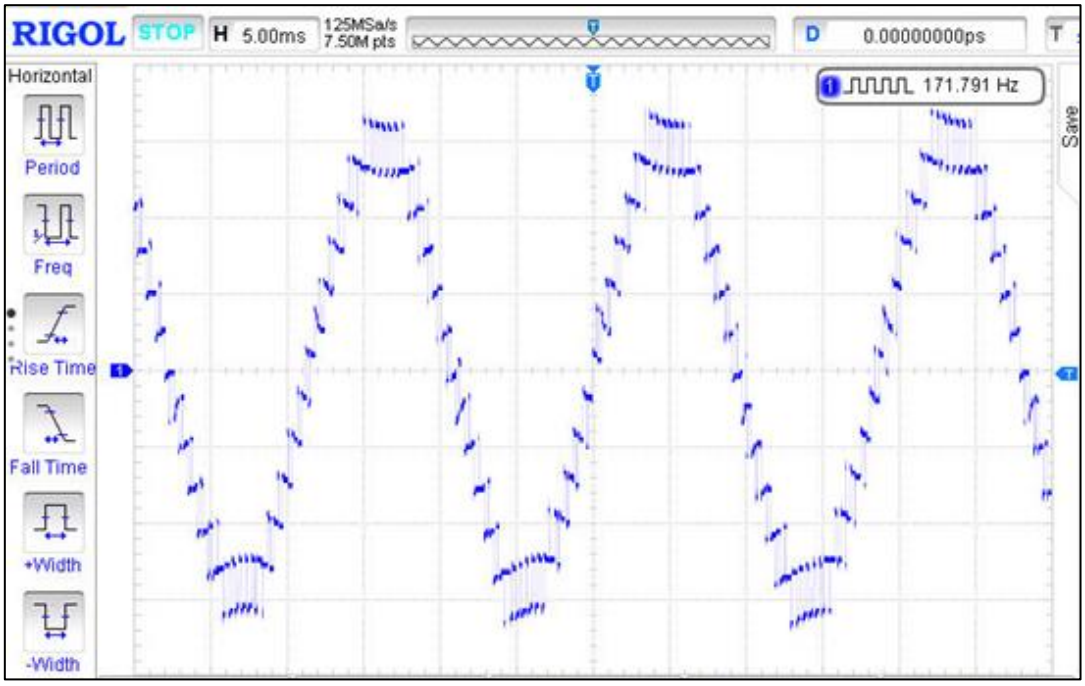


Figure 5.28 a) Single-Phase Thirteen-Level Output Voltage using SPWM Switching Scheme from DSO

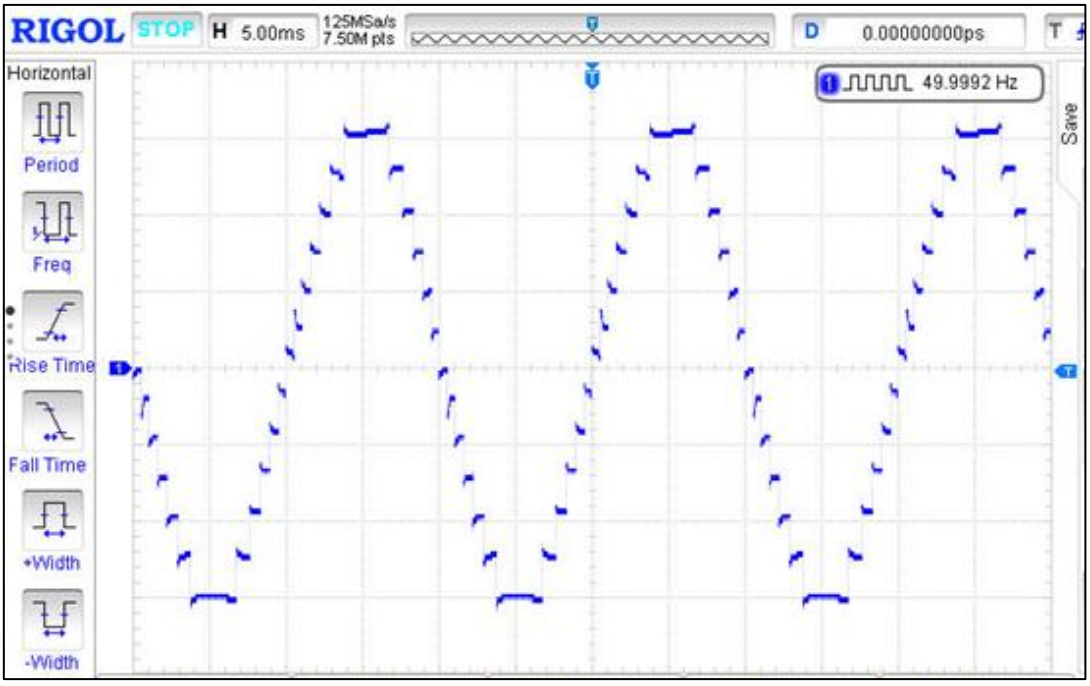
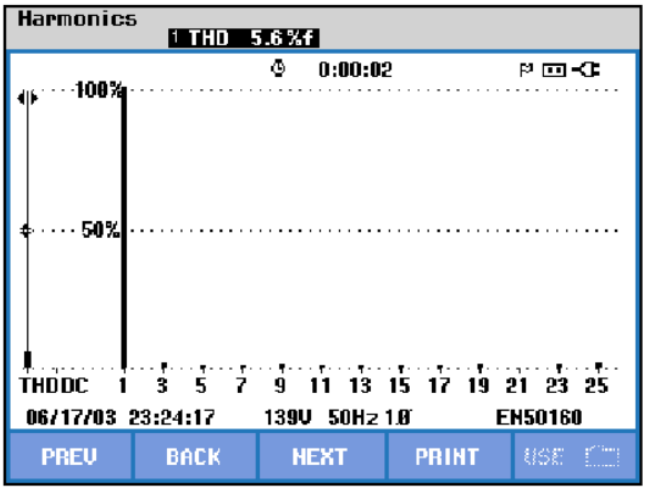
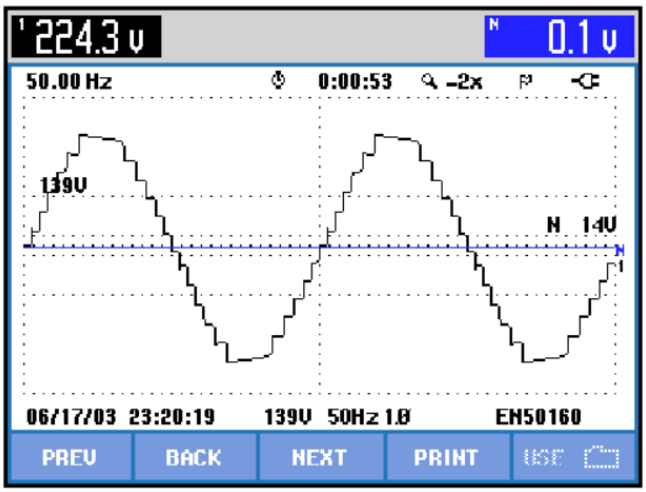


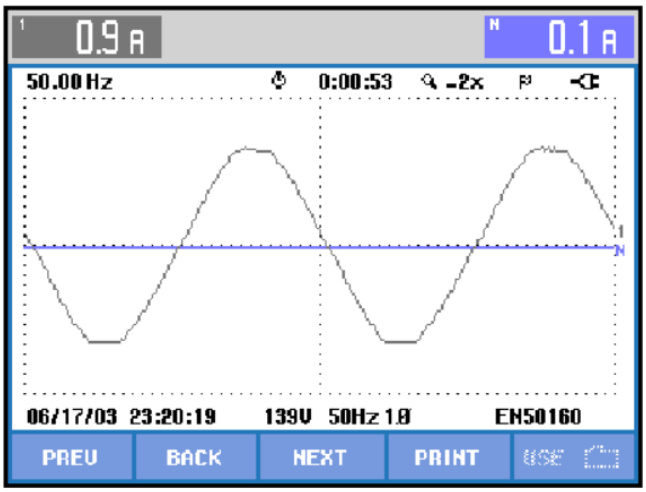
Figure 5.28 b) Single-Phase Thirteen-Level Output Voltage Cuckoo Search Optimized Switching Scheme from DSO



(a)



(b)



(c)

Figure 5.29 Single-Phase Thirteen-Level a) Harmonics, b) Output Voltage and c) Current using Power Analyzer obtained by Cuckoo Search Optimized Switching Scheme

The detailed comparison among Cuckoo search Optimized scheme and SPWM Firing scheme is presented in Table 5.3 using simulation and hardware results.

Table 5.3 Comparison of Simulation and Hardware results of Single-Phase Thirteen-Level using SPWM Firing scheme and Cuckoo Search Optimized scheme

Parameters		SPWM Firing Scheme		Cuckoo Search Optimized scheme	
		Simulation Results	Hardware Results	Simulation Results	Hardware Results
Phase Current	Peak value	0.5963	1.2	0.615	1.2
	R.M.S. value	0.4217	0.8	0.4349	0.8
	THD	4.89	2.8	2.54	2.6
Phase Voltage	Peak value	299	330.5	308.2	308
	R.M.S. value	211.4	211.5	217.9	218.2
	DC Component	0.3546	0.3	0.0060	0.2
	THD	9.23	5.8	5.76	5.6
Distortion Factor or Harmonics	2^{nd} Harmonic	0.58	0.4	0.03	0.1
	3^{rd} Harmonic	1.10	1.8	0.05	2.1
	4^{th} Harmonic	0.13	0.2	0.01	0
	5^{th} Harmonic	1.74	0.8	0.44	0.8
	6^{th} Harmonic	0.78	0.1	0.01	0
	7^{th} Harmonic	1.41	0.6	0.92	0.7
	8^{th} Harmonic	0.53	0.1	0.01	0
	9^{th} Harmonic	0.58	0.5	1.24	1.6
	10^{th} Harmonic	0.41	0.1	0	0
	11^{th} Harmonic	0.12	0.3	0.72	0.6
	12^{th} Harmonic	4.45	0.1	0.01	0
	13^{th} Harmonic	0.68	0.3	0.49	0.9
	14^{th} Harmonic	0.44	0.1	0	0
	15^{th} Harmonic	1.04	0.3	0.51	0.6
	16^{th} Harmonic	1.78	0.1	0	0
	17^{th} Harmonic	0.37	0.2	0.78	1.0
	18^{th} Harmonic	0.26	0.1	0.01	0
	19^{th} Harmonic	0.43	0.2	1.24	1.2

Once again, the observations confirm the simulation results and prove the efficiency of CS Optimized Switching scheme. And also the harmonic content is improved to 5.6%. Similarly, any levels can be modeled by connecting H-bridges in series.

5.6. CONCLUSION

The modified objective function is implemented for various configurations of Single Phase CHB Inverter in MATLAB/Simulink and Hardware. The simulation and experimental results proves the effectiveness of Cuckoo Search optimized switching control scheme for Single Phase CHB Inverters. The simulation and experimental results of each configuration has been compared amongst SPWM firing scheme and Cuckoo Search optimized switching scheme. The observations confirm that lower order odd harmonics and THD is reduced to an acceptable value and the even harmonics have disappeared completely. Further, Three-phase five-level cascaded H-bridge inverter is modeled and studied for the power quality parameters.

CHAPTER VI

PERFORMANCE ANALYSIS OF MLIs FOR POWER QUALITY IMPROVEMENT

6.1. PERFORMANCE PARAMETERS IN MULTILEVEL INVERTERS

As for power quality improvement, firstly it is desirable to keep the fundamental component of output voltage of multilevel inverter at preferred value, and equally important is to keep the harmonic components in the output voltage within stated harmonic limits. Now, as far as metric study of power quality is concerned, there are various parameters related to voltage and harmonics that define the power quality in multilevel inverters. So, parameters listed below are considered in this chapter and compared for analysis.

- Total Harmonic Distortion (THD)
- Root Mean Square value of Voltage (V_{RMS})
- Crest Factor (CF)
- Lower Order Harmonics (LOH) or Distortion Factor (DF)
- Reactive Power (Q)
- Power Factor (PF)
- Power Losses
- Efficiency (η)

For the stated purpose, three-phase five-level CHB inverter is modeled in Simulink. Afterwards, simulation results obtained are validated experimentally with hardware setup equipped with a FPGA controller.

6.2. IMPLEMENTATION OF CS OPTIMIZED SWITCHING TECHNIQUE IN THREE-PHASE FIVE-LEVEL H-BRIDGE INVERTER

The objective function is developed for optimization of switching angles with the aim of having minimum fundamental voltage deviation and minimum harmonics. Primarily, the proposed harmonic minimization function in case of three-phase five-level inverter can be presented as:

$$Fxn\_three\_phase\_5\_level = 0.1 * \left(1 - \frac{V_1}{V_{1(ref)}}\right)^4 + 0.9 * 0.9 * \sum_{k=5,7,\ldots}^{49} \left(\frac{V_k}{V_{1(ref)}}\right)^2 \quad (6.1)$$

where,

$$V_{1(ref)} = \frac{4 * m * 2V_{DC}}{pi}$$

$$V_k = \frac{4 * V_{DC}}{k * pi}(\cos k\alpha_1 + \cos k\alpha_2)$$

Subsequently, Cuckoo Search Algorithm is employed for the optimization of switching angles to obtain minimum harmonics and better power quality. The proposed technique is implemented by developing code in the MATLAB programming environment. The parameters for the population size, maximum iterations and number of runs are taken as 25, 100 and 10. The value of minimization function and the optimized switching angles of five-level inverter are plotted with different numbers of iterations in Figure 6.1 and 6.2, respectively. The angles are found to be same, i.e. α_1=7.63 and α_2=24.52 in every run at modulation index, m=1. The function value during each run is same as shown in Figure 6.3, therefore, the effectiveness of this algorithm is confirmed. The computational time taken by the algorithm to determine results, i.e. the switching angles is approximately 0.3s for 100 iterations in one run.

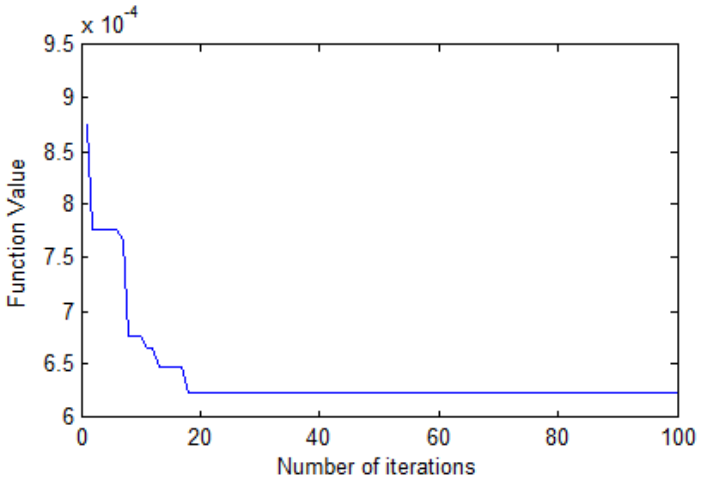


Figure 6.1 Fitness Value of CS Optimized Switching Technique for Three-phase Five-Level Inverter

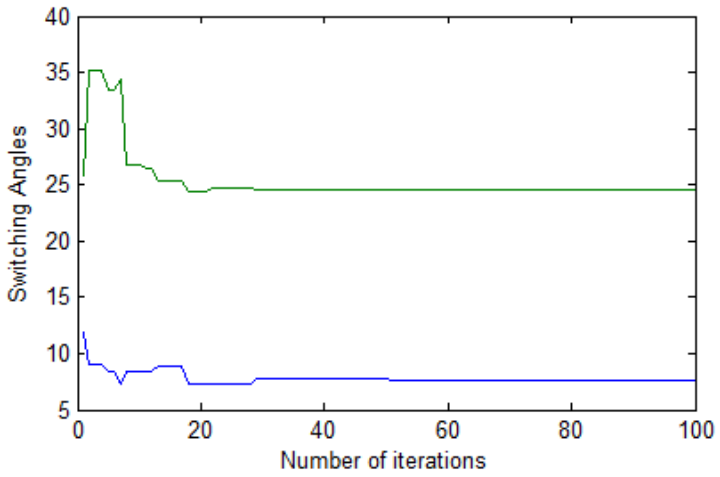


Figure 6.2 Optimized Value of the Switching Angles for Three-phase Five-Level Inverter

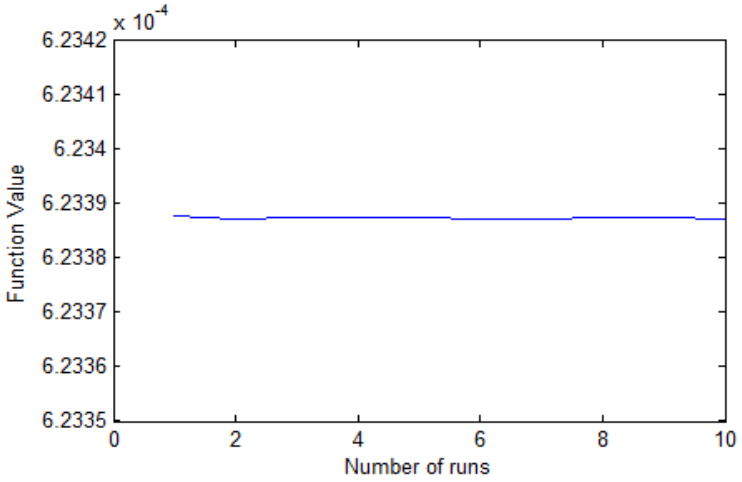


Figure 6.3 Optimized Function value CSOS Technique at different runs

Since the results of Cuckoo Search Optimization algorithm are same on every run, only a single run is considered for further study. The program is executed for different values of modulation index, and the optimum values of switching angles are obtained and plotted in Figure 6.4. In addition, the function value with respect to the modulation index is shown in Figure 6.5. The step size here is taken as 0.05. From this figure, it can be seen that the function value at every modulation index lies within 10^{-3} to 10^{-4}. Thus, it is evident that the algorithm is efficient in optimizing the switching angles for minimum harmonics.

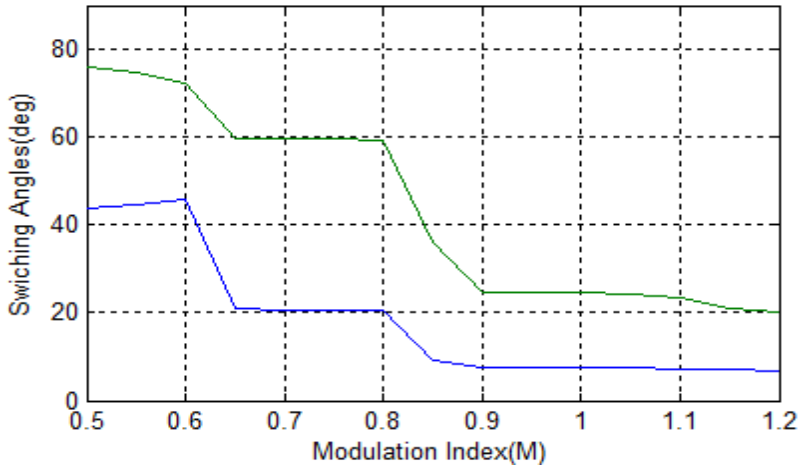


Figure 6.4 CS Optimized Switching Angles at different values of the modulation index

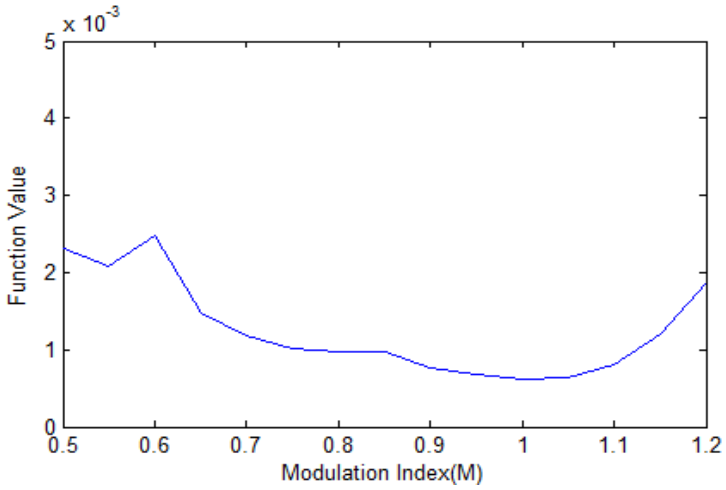


Figure 6.5 Optimized Function Value at different values of Modulation Index

6.3. SIMULATION AND ANALYSIS OF THREE-PHASE FIVE-LEVEL CASCADED H-BRIDGE INVERTER USING CS OPTIMIZED SWITCHING TECHNIQUE

A model of Three-phase Five-Level CHMLI is developed in MATLAB/Simulink software and the optimized switching angles are used to produce the switching pattern for switching the H-bridges of Inverter. The output voltage generated is used to observe various power quality related parameters and FFT analysis. Here, power quality related parameters such as THD and fundamental voltage values are observed for different values of modulation index. A comparison between Cuckoo Search Optimized Switching scheme and SPWM Switching scheme is made based on these parameters. As switching losses are more when the switching frequency is high, and

the major focus of this research is on power quality improvement, so the switching frequency for SPWM Switching scheme is taken as 200Hz. Graphical representations shown in Figure 6.6 and 6.7 summarize the comparison and verify the effectiveness of Cuckoo Search as THD is minimized and the fundamental voltage component is enhanced near the desired value for all of the values of modulation index.

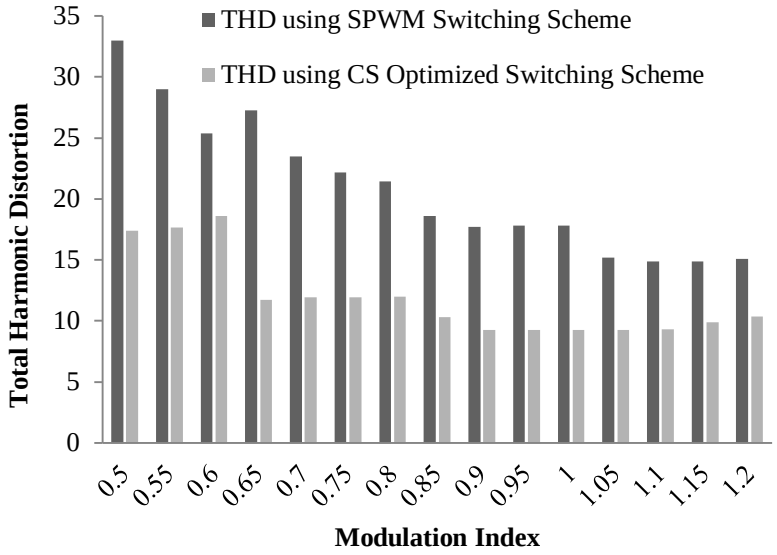


Figure 6.6 Comparison of Line Voltage THD at different values of Modulation Index

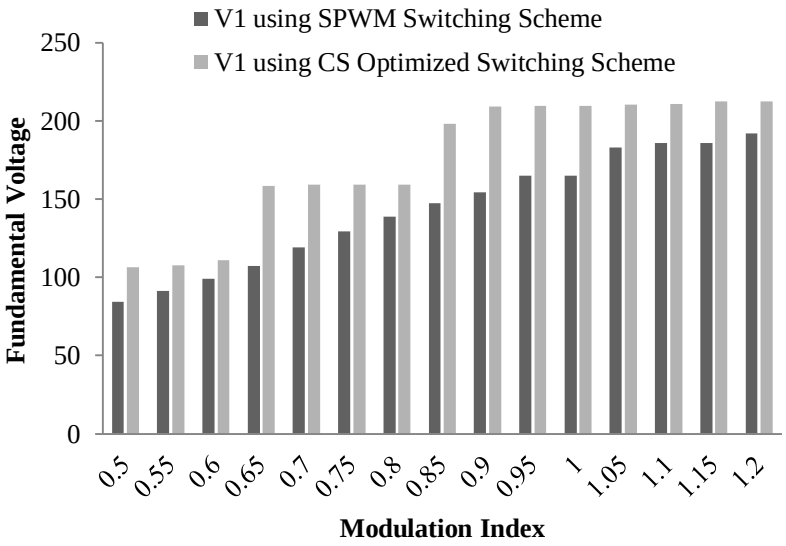
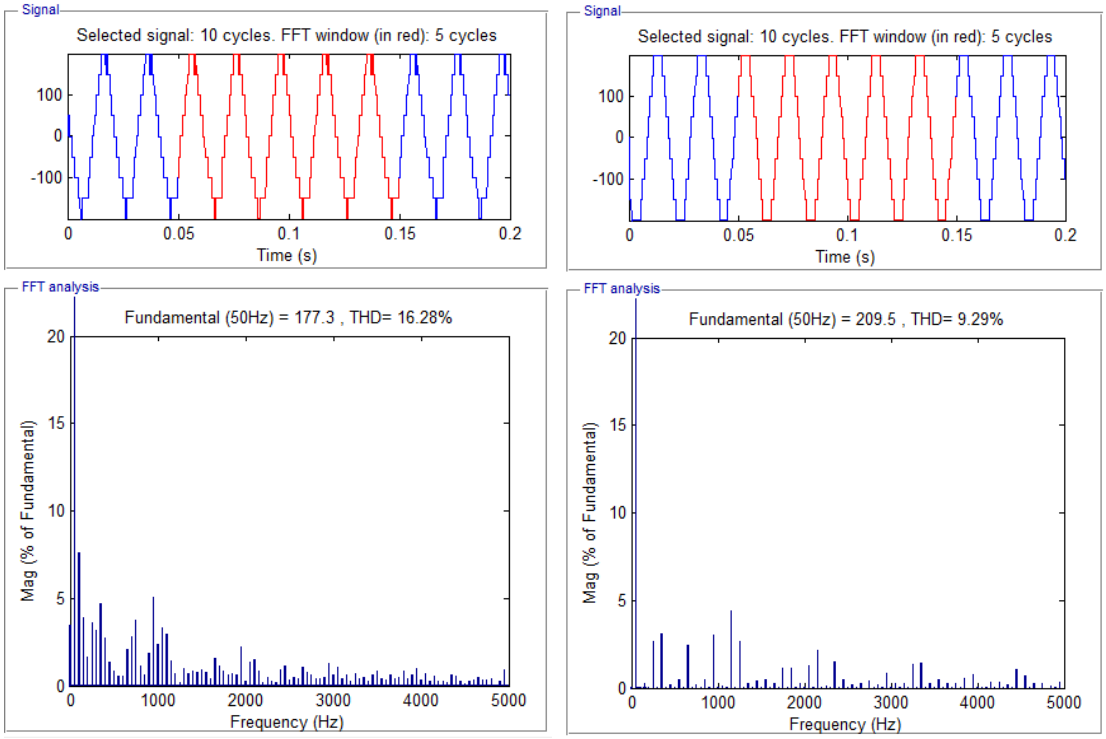


Figure 6.7 Comparison of Fundamental Voltage at different values of Modulation Index

The output waveform of Three-phase Five-level Inverter is then analyzed at m=1 using both schemes and is presented in Figure 6.8. It can be clearly seen from the FFT analysis that THD is minimized from 16.28% with SPWM Switching Scheme and

9.29% with Cuckoo Search Optimized Switching Scheme. Also, the even-order and other inadequate harmonics are minimized.



(a) **(b)**

Figure 6.8 FFT Analysis of Three-Phase Five-Level Inverter using a) SPWM Switching Scheme and b) CS Optimized Switching Scheme

6.4. EXPERIMENTAL VALIDATION OF FPGA CONTROLLED FIVE-LEVEL CASCADED H-BRIDGE INVERTER USING CS OPTIMIZED SWITCHING TECHNIQUE

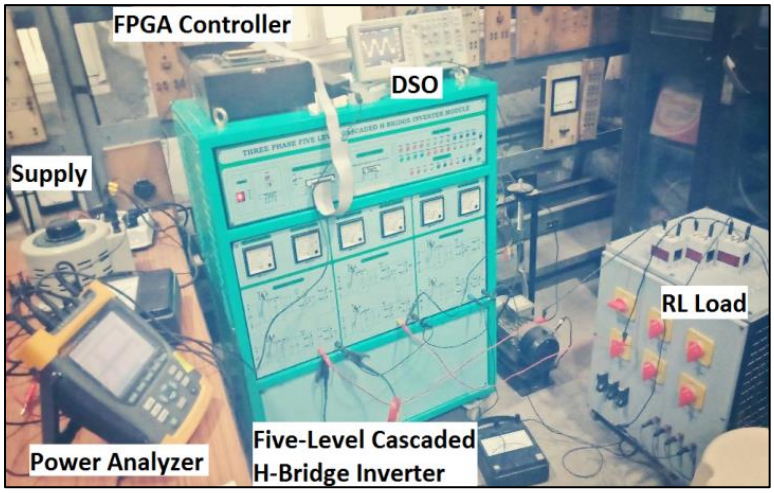
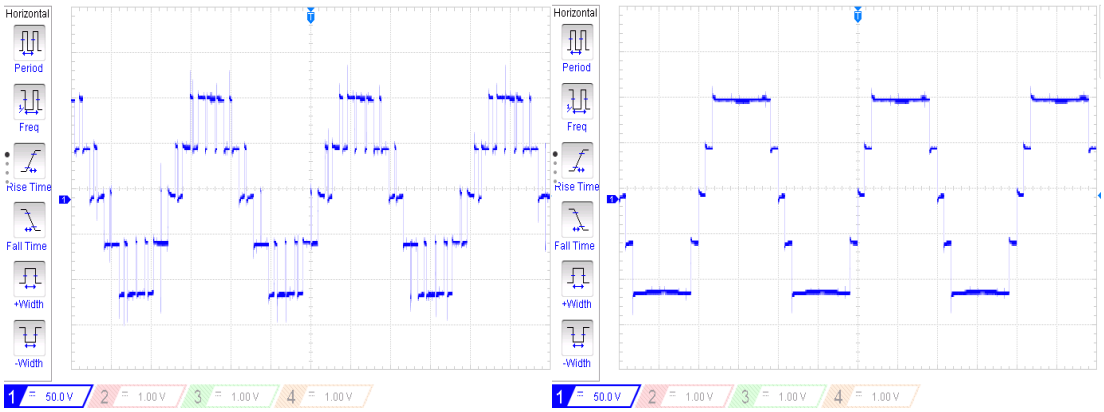


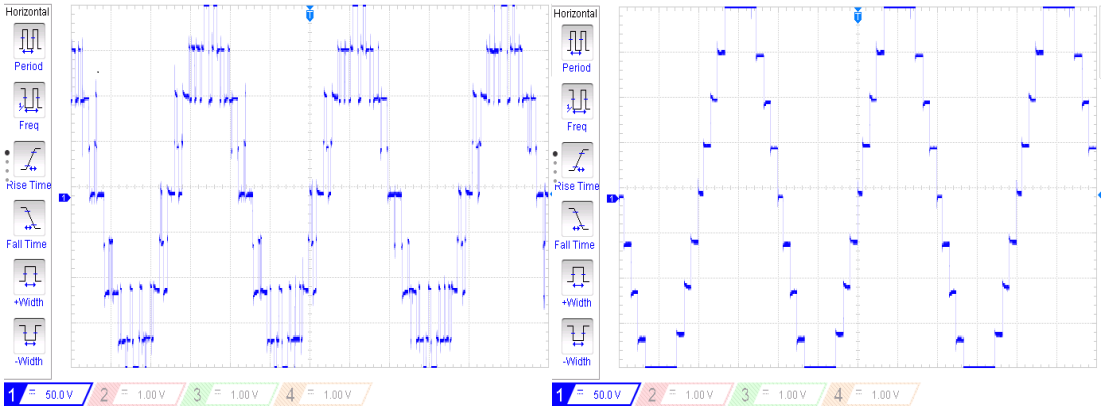
Figure 6.9 Hardware prototype of FPGA Controlled Three-phase Five-level Cascaded H-Bridge Inverter

For the validation of simulation results, a hardware prototype of FPGA controller based Three-phase Five-level Cascaded H-bridge Inverter has been setup as shown in Figure 6.9. A single-phase autotransformer is connected to six separate isolation transformers and rectifiers to generate six isolated DC supply for six H-bridges. Three-phases of inverter are formed by connecting two H-bridges in series for each of the phase and connecting their neutral point together. A Xilinx Spartan-6 FPGA controller is programmed to drive the gates of H-bridges using switching pattern obtained from both of the Switching schemes. A star-connected load with 300Ω, 40mH in each phase is connected to the inverter. Once the measurement devices are ready, supply is switched on and results are observed. Experimental results of the output phase and line voltages for SPWM Switching scheme and Cuckoo Search Optimized Switching scheme obtained from DSO are presented in Figure 6.10 and 6.11, respectively.



(a) **(b)**

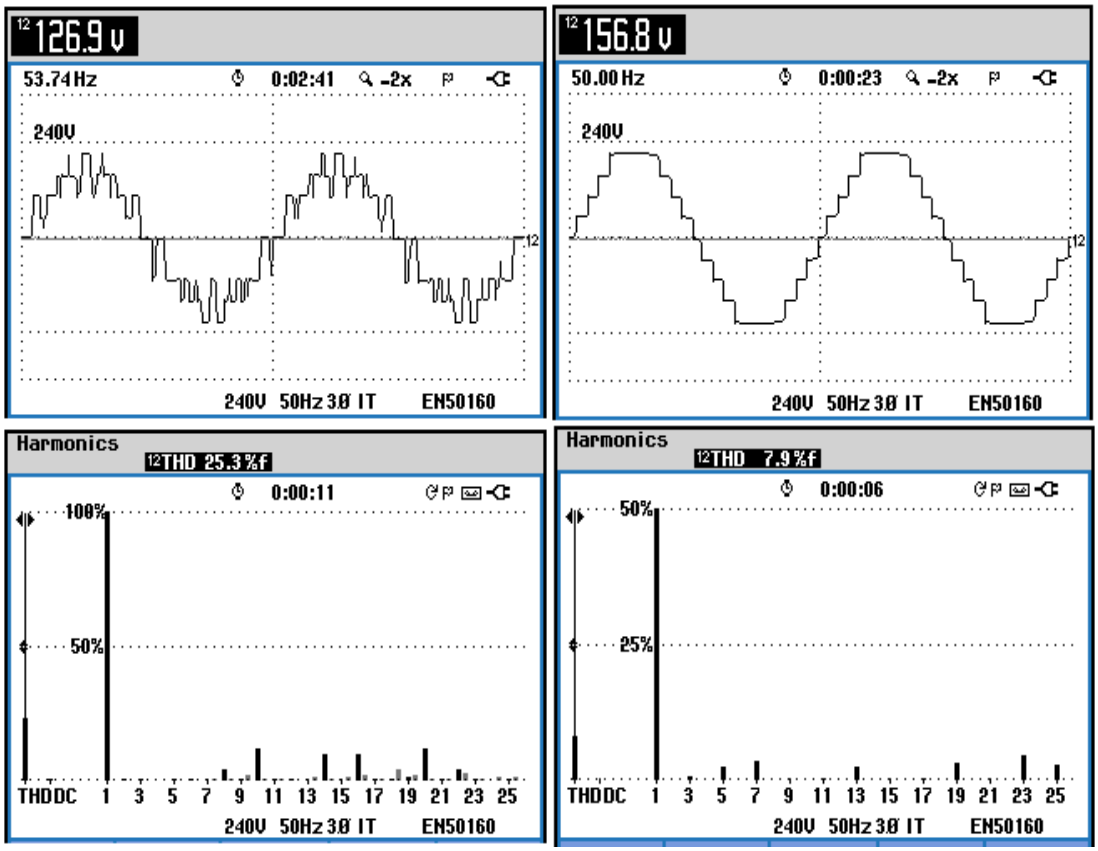
Figure 6.10 Output Phase Voltage of Three-Phase Five-Level Inverter from DSO Screen using a) SPWM Switching Scheme and b) CS Optimized Switching Scheme



(a) **(b)**

Figure 6.11 Output Line Voltage of Three-Phase Five-Level Inverter from DSO Screen using a) SPWM Switching Scheme and b) CS Optimized Switching Scheme

It can be clearly seen from these figures that the waveforms obtained using Cuckoo Search Optimized Switching scheme are much better than those obtained with SPWM Switching scheme. A THD analysis is done using power analyzer, line voltage waveforms and Harmonic graphs for both the Switching schemes are shown in Figure 6.12. The obtained experimental results support the simulation since they are found to be comparable to the simulated results shown in Figure 6.8. From the Harmonic results, it can be seen that THD of the line voltage is measured as 7.9% using CS Optimized Switching scheme whereas it is 25.3% using SPWM Switching scheme.



(a) **(b)**

Figure 6.12 Voltage and Harmonic graphs of Three-Phase Five-Level Inverter from Power Analyzer using a) SPWM Switching Scheme and b) CS Optimized Switching Scheme

6.5. PERFORMANCE ANALYSIS OF THREE-PHASE FIVE-LEVEL MLI

To provide a clear vision of the power quality, a detailed analysis and comparison of the power quality assessment of SPWM and proposed CS Optimized Switching scheme is done. Observations made using ammeter, voltmeter and wattmeter connected to the hardware setup are shown in Table 6.1. These values are further used

to calculate active power, apparent power, reactive power, power factor, power loss, and efficiency.

Table 6.1 Voltage, Current And Power Values At Input And Output

	Input Side Meter Readings			Output Side Meter Readings (per phase)		
	V_{RMS} (V)	I_{RMS} (A)	P_{IN} (W)	V_{RMS} (V)	I_{RMS} (A)	P_{OUT} (W)
SPWM Scheme	85	1.2	65	74	0.2	13.5
Proposed Scheme	85	1.6	90	85	0.3	25

A detailed analysis for power quality assessment to provide a clear vision for power quality is carried out and presented below:

1. **Total Harmonic Distortion (THD)**

   Harmonics are the result of nonlinear loads that convert AC line voltage to DC. Harmonics flow into the electrical system because of nonlinear electronic switching devices, such as variable frequency drives (VFDs), computer power supplies and energy-efficient lighting. So, fundamental switching scheme is used in case of multilevel inverters in order to have low THD. Further, controlled switching pulses are used to minimize the THD present in the output voltage (V_{out}) of multilevel inverter. THD is a measure of closeness of the output voltage waveform to its fundamental component. Mathematically, it can be defined as the ratio of RMS value of its total harmonic component of the output voltage and the RMS value of the fundamental component.

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

   Figure 6.12 represents the Voltage and Harmonic graph obtained from Hardware using SPWM and Cuckoo Search Optimized Switching scheme measured using Fluke Power Analyzer. And clearly shows THD of Line Voltage is measured as 7.9% using CS Optimized Switching scheme whereas it is 25.3% using SPWM Switching scheme.

2. **Root Mean Square value of Voltage (V_{RMS})**

The RMS value is referred to the effective value based on the magnitude of any waveform. As, the harmonics are reduced from the output waveform, the magnitude of output voltage, hence, the RMS value is increased. Here, RMS value of the Fundamental component of output voltage is considered, the value is 123V with SPWM Switching scheme whereas it is 156V with the CS Optimized Switching scheme with the hardware setup.

3. **Crest Factor**

Crest factor is considered as the essential parameter in case of low frequency signals. It is the ratio of V_P value to the V_{RMS} value of a signal. V_P represents the peak value of the output voltage waveform and V_{RMS} indicates the RMS value of the output voltage waveform. It is also called peak to RMS ratio. The reason for CF calculation is to quickly identify how much impact has occurred in the waveform. For a perfect sine waveform, crest factor is square root of '2' (i.e. 1.414). Improvement in RMS value of Voltage causes Crest factor to improve.

$$Crest\ Factor\ = \frac{V_P}{V_{RMS}}$$

Here, in hardware results, C.F.(SPWM Switching Scheme)= 210/123 =1.70, and, C.F.(CS Optimized Switching Scheme)= 214/156 =1.37~1.4.

4. **Lower Order Harmonics (LOH) and Harmonic Factor**

The harmonic factor is a measure of the individual harmonic contribution in the output voltage of an inverter. It is defined as the ratio of the RMS voltage of a particular harmonic component to the RMS value of fundamental component.

$$Harmonic\ Factor_n = \frac{V_n}{V_1}$$

It is very much clear from the tabulated results and harmonic chart that lower order harmonics and thus harmonic factor are reduced to a great extent using proposed Switching scheme.

Table 6.2 Comparison of Power Quality Parameters

	SPWM Scheme	Proposed Scheme
Input P_{IN} (W)	65	90
Total Output P_{OUT} (W)	40.5	75
Apparent Power (VA)	44.4	76.5
Reactive Power (VAR)	6.06	5.07
Power Factor (p.f.)	0.91	0.98
Power Loss (W)	24.5	15
Efficiency (%)	62.3	83.3

5. **Reactive Power**

The most significant difference between the active and reactive power is that the active power is the actual power which is dissipated in the circuit. Whereas, the reactive power is the useless power which only flow between source and load. Thus, Reactive Power drawn by the load should be minimized. As, harmonic currents are reactive in nature, so higher the harmonics, higher is the reactive power and vice-versa. Therefore, minimization of harmonics results in less reactive power flow in the line.

$$Reactive\ Power = I_R * X$$

The observations made using Ammeter, Voltmeter and Wattmeter connected in hardware setup are used to calculate active power, apparent power, reactive power, power factor, power loss, and efficiency. It can be observed from the tabulated results given in Table 6.2 that the reactive power drawn by the load circuit has reduced in case of proposed scheme.

6. **Power Factor**

Power factor is ratio of actual electrical power dissipated by an AC circuit to the product of RMS value of current and voltage. Power factor at fundamental

frequency is given by the ratio of actual power by the apparent power in the circuit.

$$P.F. = \frac{Actual\ Power\ or\ True\ Power}{Apparent\ Power}$$

Due to reduction in reactive power, losses are reduced, and the power factor is improved. The value of power factor has increased from 0.91 to 0.98 using the proposed CS optimized Switching scheme.

7. **Power Loss**

Primarily, there are four types of power losses that occur during the operation of multilevel inverters. These are: (1) Conduction losses; (2) Switching losses; (3) OFF-state losses, and (4) Gate losses. Practically, the Off-state and Gate losses are very small and normally neglected. So, only Conduction losses and Switching losses are considered for the Loss estimation of multilevel inverters. Switching losses occur due to the number of times a device is turned ON and OFF, whereas Conduction losses depends upon T_{ON} and T_{OFF} . As, we are performing the switching of inverter devices at fundamental frequency, switching losses are low. And, reactive power is reduced due to minimization of harmonics, which minimizes the total current drawn by the circuit, so power losses are reduced. Here, the losses in a circuit are calculated by subtracting the output power from input power and it is observed to be reduced from 24.5W to 15W.

8. **Efficiency**

Conceptually, efficiency is the percentage of the total energy input to the system that is consumed for useful work. It determined by the ratio of output to input in mathematical terms. In this system, input power is the power delivered from DC supply, while the output power is the load side power. Reduction in power losses, results in enhancement of efficiency. The efficiency of proposed scheme is improved from 62.3% to 83.3%.

For better understanding, a comparison of experimental results and simulation results obtained using SPWM Switching Scheme and CS Optimized Switching Scheme is presented in Table 6.3.

Table 6.3 Comparison of Simulation and Hardware Results Obtained Using SPWM and CS Optimized Switching Scheme

Factors for Assessment of Power Quality	Measured Parameters	SPWM Switching Scheme	CS Optimized Switching Scheme
THD	Phase Voltage THD	27.5%	23.1%
	Current THD	22.1%	21.7%
	Line Voltage THD	25.3%	7.9%
RMS Value	RMS Value of Fundamental	123.2 V	156.0 V
Peak Value	Peak value of Line Voltage	210.1 V	214 V
Crest Factor	CF	1.70	1.37
Even Order Harmonics	2^{nd} Harmonic	0.6%	0
	4^{th} Harmonic	0.3%	0
	6^{th} Harmonic	0.3%	0
	8^{th} Harmonic	0.4%	0
	10^{th} Harmonic	0.6%	0
	12^{th} Harmonic	0.5%	0
	14^{th} Harmonic	0.3%	0
	16^{th} Harmonic	0.7%	0
	18^{th} Harmonic	0.5%	0
Lower Order Harmonics Or Distortion Factor	3^{rd} Harmonic	0.5%	0.6
	5^{th} Harmonic	0.5%	2.1
	7^{th} Harmonic	3.9%	3.4
	9^{th} Harmonic	12.1%	0
	11^{th} Harmonic	0.3%	0.4
	13^{th} Harmonic	9.7%	2.4
	15^{th} Harmonic	9.8%	0
	17^{th} Harmonic	0.5%	0.3
	19^{th} Harmonic	1.3%	3.1
Reactive Power	Q (VAR)	6.06	5.07
Power Factor	PF	0.91	0.98
Power Loss	Input-Output (W)	24.5	15
Efficiency	η (%)	62.3	83.3

6.6. CONCLUSION

This chapter presents the detailed study and analysis of power quality parameters of Three-phase Five-level CHB Inverter. Cuckoo Search optimization based firing scheme is used to generate the switching pattern for firing the H-bridges of five-level cascaded H-bridge inverter. The simulations have been carried out in MATLAB/Simulink and a comparison on the basis of different performance parameters has been done. At all values of modulation index, THD and fundamental voltage component are observed better with CS optimized firing scheme. The FFT analysis confirms that the even order harmonics are zero and other lower order harmonics are controlled within allowable limits and comply with IEEE 519-1992 harmonic guidelines. The computational time required for determining switching angles is 0.7~ 0.9s only. The algorithm can be easily implemented for any level of inverter. The experimental results of the hardware prototype are presented for the validation of simulation results. The two firing schemes are implemented experimentally and the voltage waveform and THD analysis results are found similar to the simulation results in both the cases. The power factor has increased from 0.91 to 0.98 and efficiency has improved by 20%. Hence, it is confirmed that CS optimized switching scheme provide better switching pattern to have minimum THD and better quality voltage output.

CHAPTER VII

CONCLUSION & FUTURE SCOPE

7.1. CONCLUSION

To provide a clear This chapter presents the detailed study and analysis of power quality parameters of Three-phase This chapter presents the detailed study and analysis of power quality parameters of Three-phase The idea of producing multilevel output with low THD by Multilevel Inverters, that approximates sinusoidal AC voltage waveform, has gained popularity since many years. Perhaps the modulation technique to control the harmonics of output waveform is still the most popular field of research. The literature has proposed numerous control schemes having their own advantages and disadvantages. But, the desire to find the best topology or optimal strategy for power quality improvement of multilevel inverters will continue to remain the area of interest. The work carried out in this thesis is an effort in this direction.

The research in this thesis presents a comparative study of various existing control techniques as applied to multilevel inverters. The major focus is on the development of an efficient and effective control technique for multilevel inverters for power quality improvement. An objective function with the intention of achieving minimum harmonics and desired value of fundamental voltage output is proposed to evaluate the optimized value of switching angles for generating the switching pattern for firing H-bridges of multilevel inverter. The work not only develops a new objective function to improve output of MLI, but also concentrates on optimization of developed objective function. Several Artificial Intelligence methods are explored and compared for the effective optimization of switching angles to obtain minimum harmonics at the output of MLI. Simulations are carried out in MATLAB/Simulink and a comparison of optimization algorithms on the basis of different performance parameters (efficiency, reliability and quality of solution) has been presented. Cuckoo Search (CS) algorithm employs only a single parameter ρ_a, apart from the population size, hence, easy to implement. Also, it converges in the minimum time with much better accuracy than any other algorithms considered. FFT analysis of the output voltage produced using Cuckoo Search Optimized firing scheme confirms that the even order

harmonics are zero and that the other lower order harmonics are controlled within allowable limits to comply with IEEE 519-2014 harmonic guidelines. At all values of modulation index, THD and fundamental voltage component observed are better with CS optimized firing scheme. The observed results verify the success of Cuckoo Search based optimization in determining the optimum switching angles.

A hardware prototype of multilevel inverter is presented for validation of simulation results and assessment of power quality improvement using proposed control technique. The two firing schemes, SPWM firing scheme and proposed firing scheme, are implemented experimentally for comparison. Different structures of multilevel inverter including Single-phase 5- level, 9- level, and 13- level and Three-phase Five-level CHB Inverters are investigated and the obtained voltage waveform and THD analysis results are found to be similar to the simulation results in all the cases. Hence, the proposed control technique can be easily implemented for both single-phase and three-phase inverter with any number of levels. Furthermore, for analyzing the performance of Multilevel Inverters, a number of performance parameters like reactive power, power factor, power loss, efficiency, etc. are measured and found to have improved values with CS optimized firing control. Consequently, the proposed Cuckoo Search optimized firing scheme is recommended as an efficient way of controlling the power quality of multilevel inverter.

7.2. SCOPE FOR FUTURE WORK

The work can be further extended by the researchers in following areas:

i) Implementation of the proposed control method in all other topologies of the multilevel inverter, like reduced switch topologies, modular multilevel converter, etc.
ii) Optimized programming of proposed control scheme using an online digital micro-processor based system can be considered.
iii) The control method can be presented for the implementation of multilevel inverter in various applications such as drives, etc.
iv) Integration of multilevel inverters with Grid is an important area to be explored for advancements in renewable energy applications.
v) The control of multilevel inverter can also be studied for demand side management in Smart Grid.

7.3. RESEARCH HIGHLIGHTS

In the different phases of this research, following accomplishments have been made:

- Comparative study of various existing PWM control techniques as applied to multilevel inverters is done.
- In this work, a modified SHE function is presented as an objective function to minimize THD and maintain lower order harmonic content within limits.
- Several Artificial Intelligence methods are explored and compared for the effective optimization of switching angles to obtain minimum harmonics at the output of MLI. Cuckoo Search Algorithm is found to be effective in determining the optimum switching angles.
- Cuckoo Search optimized switching control scheme is successfully applied to Single Phase and Three Phase CHB Inverters multilevel inverter and it works efficiently for all configurations when implemented in MATLAB/Simulink.
- The optimal switching control is implemented experimentally using a hardware prototype of multilevel inverter for Single phase (Five-Level, Nine-Level, and Thirteen –Level) and Three-Phase Five-Level Inverter and validates the simulation results.
- Three-phase Five-level CHB Inverter is analyzed for different power quality parameters using optimal switching control and all the parameters have found to be improved to a great extent.

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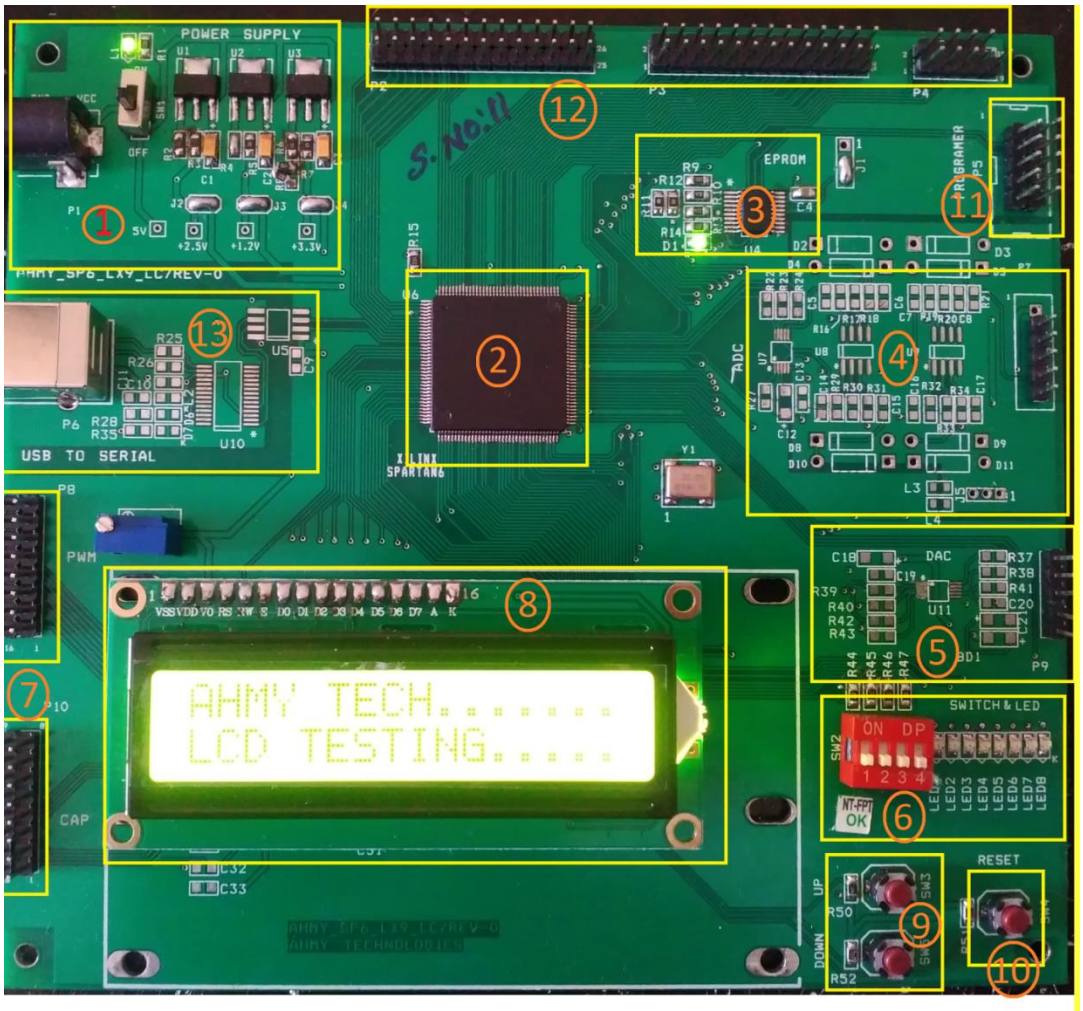
APPENDIX A



Parts of Board Layout

1. Power Supply Section
2. Spartan-6 XC6SLX9-TQG144
3. PROM & Clock
4. ADC Section
5. DAC Section
6. Switch & LED
7. 5V Input & Output Connector
8. LCD Interface Section
9. UP & DOWN Switch

10. RESET Key

11. External JTAG Programming Header

12. GPIO Expansion Header

13. USB to Serial Converter

1. Power Supply Section

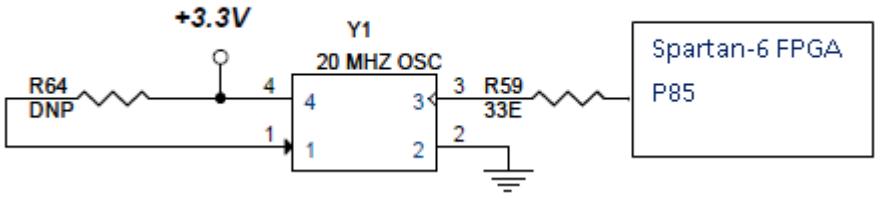
The SP6_LX9_LC operates from a single +5V external power supply connected to the main power input (P1) Connector. Internally, the +5V input is converted into +1.2V, +3.3V, +2.5V using multiple voltage regulators. J2, J3, J4 Jumper is used to test the output (+3.3V, +2.5V, +1.2V) Volts.

2. Spartan-6 XC6SLX9-TQG144

Spartan®-6 devices are the most cost-optimized FPGAs, offering industry leading connectivity features such as high logic-to-pin ratios, small form-factor packaging, and a diverse number of supported I/O protocols. This board is having 144 Pin Spartan-6 FPGA IC. Spartan-6 IC Number of Logic Elements/Cells having 9152, Total RAM Bits is 589824.

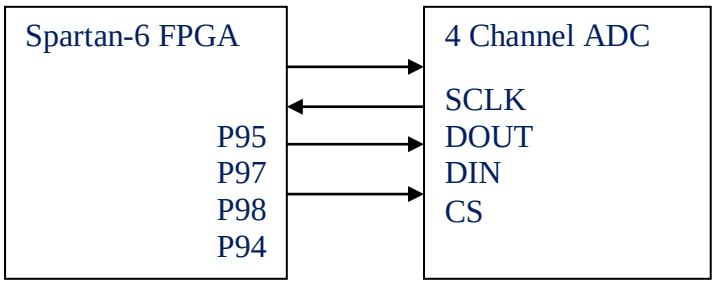
3. PROM & Clock

AHMY_SP6_LX9_LC board having 4MB On board PROM ic for standalone program execution purpose. D1 LED is used to indicate the program successfully downloaded into FPGA. 20MHz Clock input used in this board and Connected pin is

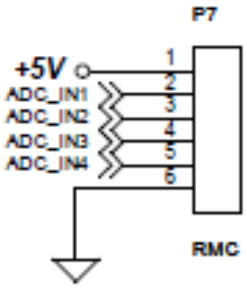


4. ADC Section

This board having 4 channels 12 bit SPI Protocol ADC and Maximum sampling is Rate 1MSPS. ADC operating voltage selected by using J5 Jumper (+5V or +3.3V).

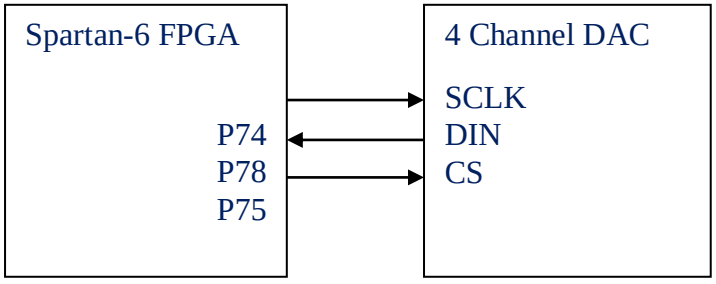


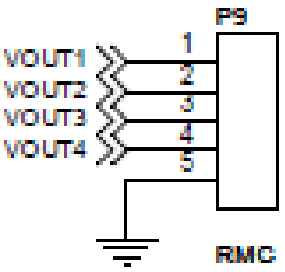
The entire analog inputs are having buffered and over voltage production done by buffer IC. Analog input connection Header details given below.



5. DAC Section

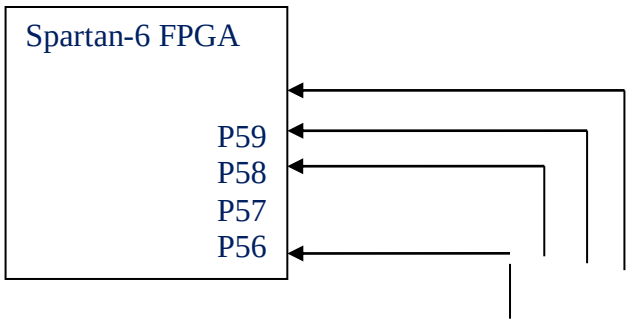
This board having 4 channels 12 bit SPI Protocol DAC and Maximum settling time is 6µs. Analog Output voltage selected by using J5 Jumper (+5V or +3.3V). Interface and DAC connector details given below

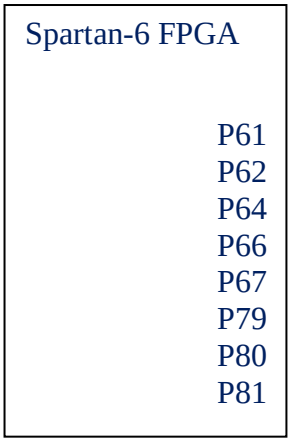


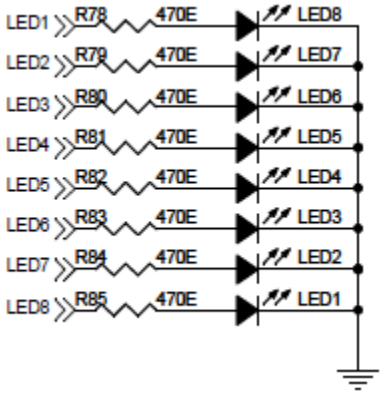


6. Switch & LED

4 Position user DIP switch and 8 User LED's are placed in bottom of the board.

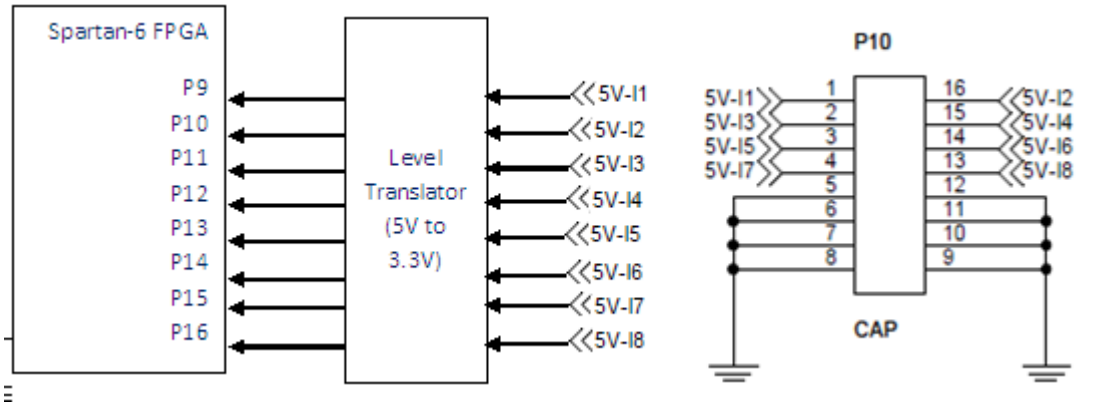


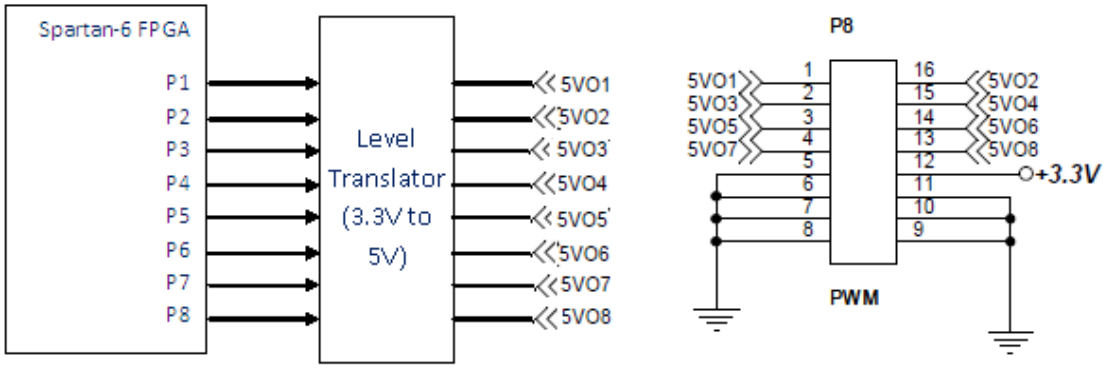




7. 5V Input & Output Connector

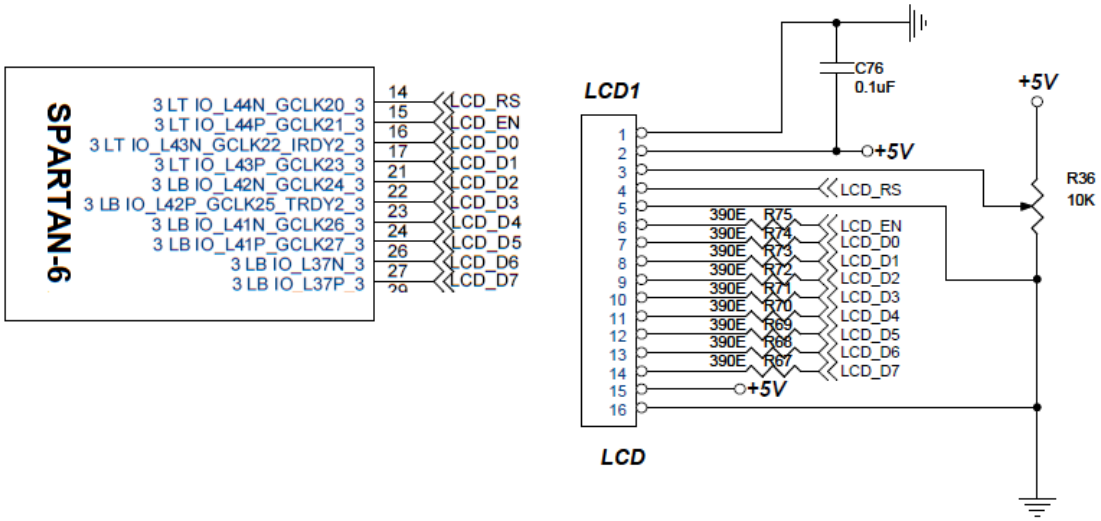
5V input Signal is given through P10 connector. Here level translator is converting the 5V input into 3.3V level and it's given to FPGA.





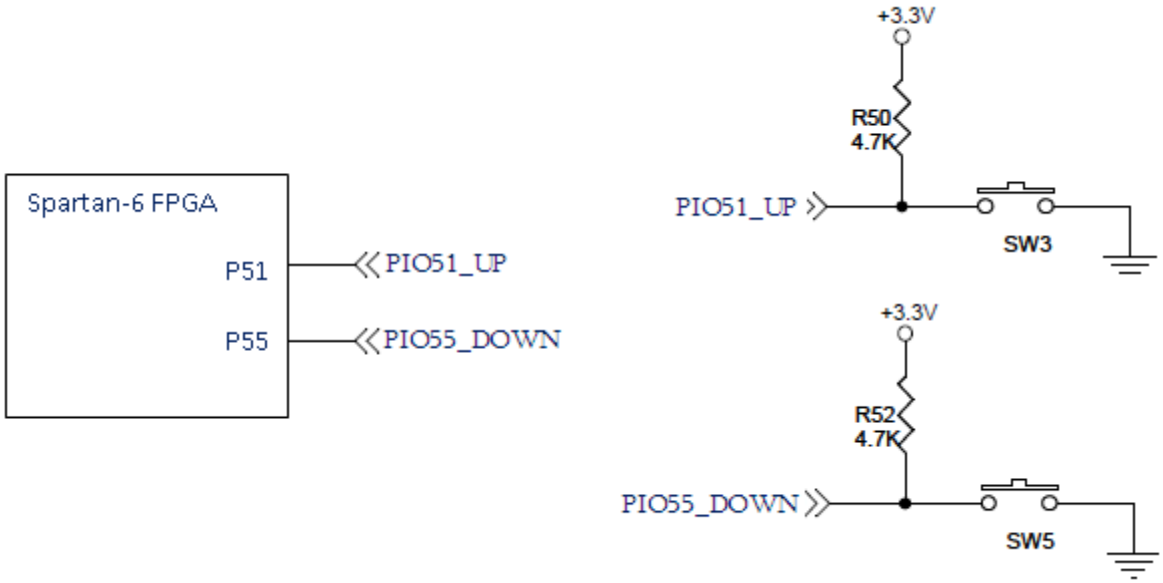
8. LCD Interface Section

20x4 or 16x 2 Numeric LCD interface Header provided in this Board and brightness adjustable trim pot placed top of the LCD (R36-10K) . LCD Data Lines and FPGA interface details given below



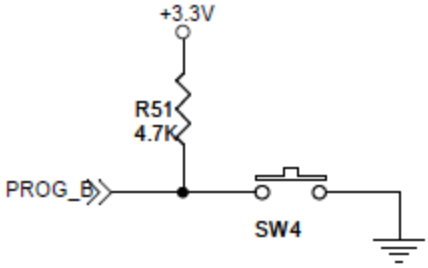
9. UP & DOWN Key

UP and DOWN Push button used as input lines. It will give 3.3V default input, when user presses the button it changed '0'.



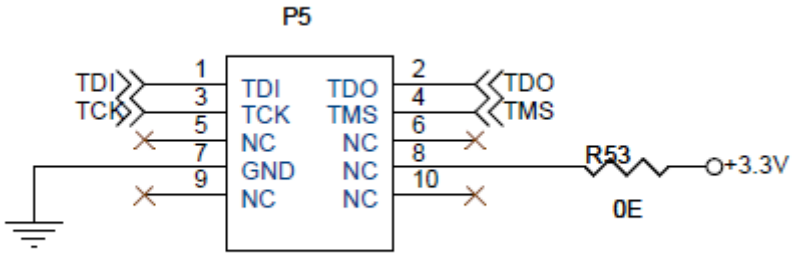
10. Reset Key

Reset Key used to reset the FPGA.



11. External Programming Header

The Spartan-6 FPGA LX9 AHMY has one device in the JTAG chain, the Spartan-6 FPGA LX9 FPGA. Configuring the Spartan-6 FPGA on the S6LX9 AHMY can be performed via Boundary Scan with a JTAG download cable. The 10 pin Header details given below



12. GPIO Expansion Header

FPGA GPIO Expansion header shown below

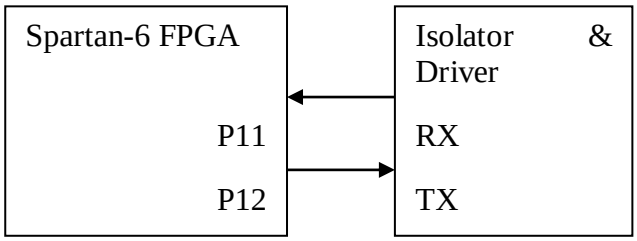
P2 Connector			
Connector Pin No	FPGA PIN No	Connector Pin No	FPGA PIN No
1	P10	14	P99
2	P9	15	P88
3	P8	16	P92
4	P7	17	P84
5	P6	18	P87
6	P5	19	P82
7	P2	20	P83
8	P1	21	P69
9	P144	22	P60
10	P143	23	Gnd
11	P142	24	Gnd
12	P100	25	Gnd
13	P93	26	Gnd
P3 Connector			

Connector Pin No	FPGA PIN No	Connector Pin No	FPGA PIN No
1	P141	14	P121
2	P140	15	P120
3	P139	16	P119
4	P138	17	P118
5	P137	18	P117
6	P134	19	P116
7	P133	20	P115
8	P132	21	P114
9	P131	22	P112
10	P127	23	Gnd
11	P126	24	+5V
12	P124	25	Gnd
13	P123	26	+5V

P4 Connector			
Connector Pin No	FPGA PIN No	Connector Pin No	FPGA PIN No
1	P101	6	+5V
2	P101	7	Gnd
3	P104	8	+5V
4	P105	9	Gnd
5	P111	10	+5V

13. USB to Serial Converter

AHMY_SP6_LX9_LC board have Isolated serial communication interface through USB connector. The USB-to-UART bridge interface connects to the Spartan-6 FPGA through the following pins:



BRIEF PROFILE OF THE RESEARCH SCHOLAR

Deepshikha Singla has received her Degree of Bachelor of Engineering in Electronics and Instrumentation Engineering in 2007. and her Master of Technology in Electrical Engineering (Power System and Drives) from the YMCA University of Science and Technology (YMCAUST), Faridabad, India, in 2011, where she is presently working towards her Ph.D. degree. She has five years of teaching experience at the Manav Rachna International University (MRIU), Faridabad, India. She has published around twelve research papers in various international journals and conferences. Her current research interests include Multilevel Inverters, Optimization Algorithms, and Power Quality Improvements in Multilevel Inverters.

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LIST OF PUBLICATIONS OUT OF THESIS

List of Publications in International Journal

S.No	Title of the paper	Publisher	Impact factor	Whether Referred or Non Referred	Whether you paid any money or not for publication	Remarks
1.	Implementation of Cuckoo Search optimized firing scheme in 5-Level Cascaded H-Bridge Multilevel Inverter for Power Quality Improvement	Journal of Power Electronics (JPE), Vol.19 Issue 6, pp 1458-1466, November 2019. ISSN: 2093-4718	0.901	Refereed ISSN: 2093-4718	No	SCIE and SCOPUS Indexed Journal
2.	Power Loss Investigation in 11-Level Cascaded H-Bridge Inverter using Cuckoo Search Optimized Switching Scheme	International Journal of Engineering and Advanced Technology (IJEAT), Vol. 8 Issue 6, August 2019. ISSN: 2249-8958	5.97	Refereed ISSN: 2249-8958	No	SCOPUS Indexed Journal
3.	Optimal Minimization of THD and Loss Analysis in Multilevel Inverter using Cuckoo Search Algorithm	Journal of Emerging Technologies and Innovative Research (JETIR), Vol. 5, Issue 8, August 2018, ISSN: 2349-5162.	5.87	Refereed ISSN: 2349-5162	Yes (2100)	UGC Approved Journal
4	Performance Analysis Of Harmonic Elimination In Cascaded H-Bridge Multilevel Inverters Using Constrained PSO Algorithm	International Journal Series in Engineering Science (IJSES), Vol. 3, pp 1-14, November 2017, ISSN: 2455-3328.		Refereed ISSN: 2455-3328	No (Open access fee-3000)	It is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License. The title is under evaluation by SCOPUS.
5	Power Quality Improvement Using Multilevel Inverters – A Review	Int. J. of Engg. Sci. & Mgmt.(IJESM), pp 64-76, December 2011, ISSN: 2277-5528.	5.085	Refereed ISSN: 2277-5528	No	Indexed in IIJIF and Thomson Reuters

List of Publications in International Conferences

S.No	Title of the paper	Publisher	Impact factor	Whether Referred or Non Referred	Whether you paid any money or not for publication	Remarks
1.	Harmony Search Algorithm based Power Quality Improvement in Multilevel Inverter	IEEE International conference on power Electronics, Intelligent Control and Energy Systems (ICPEICES-2018)	-	Yes, 22-24 Oct. 2018, DOI:10.1109/ICPEICES.2018.8897495	Yes (Registration Fee)	SCOPUS Indexed Conference, IEEE Explore
2	Power Loss Analysis in Multilevel Inverters using Multi-objective Optimization	IEEE International conference on power Electronics, Intelligent Control and Energy Systems (ICPEICES-2018)	-	Yes, 22-24 Oct. 2018, DOI: 10.1109/ICPEICES.2018.8897435	Yes (Registration Fee)	SCOPUS Indexed Conference, IEEE Explore
3.	Comparative Analysis of Harmonic Reduction in Multilevel Inverter	IEEE Fifth Power India Conference	-	Yes pp. 1-5, 19-22 Dec. 2012, DOI: 10.1109/PowerI.2012.6479521	Yes (Registration Fee)	SCOPUS Indexed Conference, IEEE Explore
4.	SMC based Shunt Active Harmonic Filter for Power Quality Enhancement	IEEE International Conference on Energy, Automation, and Signal (ICEAS)	-	Yes pp. 1-7, 28-30 Dec. 2011, DOI: 10.1109/ICEAS.2011.6147116	Yes (Registration Fee)	SCOPUS Indexed Conference, IEEE Explore

List of Communicated Papers

S.No	Title of the paper	Name of Journal	Year
1	Minimization of Harmonics using Various Optimization Algorithms in Cascaded Multilevel Inverters	Sadhana Indian Academy of Sciences	2020
2	Optimal Switching Technique for Cascaded Multilevel Inverters Using Meta-Heuristic Approach	Computers & Electrical Engineering	2020