Modelling and Analysis of a selective harmonic elimination technique in 5 level packed U cell inverter

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Under the Guidance
Of

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July 2022

CANDIDATE'S DECLARATION

I hereby declare that the thesis entitled **"Modelling And Analysis Of A Selective Harmonic Elimination Technique In 5 Level Packed U Cell Inverter"** submitted in partial fulfillment for the award of the degree of Master of Technology in 'Electrical Engineering' completed under the supervision of **Dr. Mohammad Asim, Assistant Professor and Dr. Faizan Arif Khan, Assistant Professor, Electrical Engineering Department,** Integral University, Lucknow is an authentic work to the best of my knowledge.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

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Abstract

The multilevel inverter consists of many advantages over a two-level inverter in terms of THD, low electromagnetic interferences, low switching stress and high-quality voltage waveform. Due to these reasons, the demand of multilevel inverter is increasing day by day. Although conventional multilevel inverter topologies like Neutral Point Clamped (NPC), flying capacitor and cascade H-bridge are generally employed in industry but have some limitations. Balancing of DC-link capacitor voltage and higher number of components is required for the generation of higher voltage levels. Consequently cost and complexity of the inverter increases. Switched capacitor multilevel inverter topology can overcome these drawback. The higher number of voltage levels can be achieved using just a single voltage source, capacitors and diode. This can be done by charging the capacitors (when connected in parallel to the voltage source) and discharging them through the load by connecting the capacitors in series with the voltage source.

This thesis concentrate on the five level multilevel inverter with new and emerging method called Packed U Cell (PUC) with different loading condition, total harmonics distortion (THD), a fast Fourier transform (FFT) analysis, and different input output waveforms. Different modulation techniques like PUC, selective harmonic elimination and nearest level control modulation schemes are discussed in detail. A detailed description of basic unit is discussed it consist of one voltage source, one diode, two capacitors and six semiconductor switches. By using nearest level control modulation scheme five level waveform has been obtained. Elimination of 5th harmonics with low THD, output current and voltage waveform is also discussed. The gradient based algorithm is also used to find α1 and α2 value to eliminate 5th harmonics. The genetic algorithm optimization technique is also employed for obtaining optimized switching angle. At these optimum angles minimum THD is achieved in grid current. All the models are simulated in MATLAB®/Simulink 2016a.

CHAPTER-1

INTRODUCTION

This chapter includes a brief introduction about multilevel inverter. It also reveals the significant properties of multilevel inverter followed by the advantage and disadvantages with their basic topology.

1.0 Introduction of Multilevel Inverter (MLI) :

Electrical energy is the most efficient and popular form of energy, it has become 4th essential element after food, shelter and clothing. The modern society is heavily dependent on the electric supply, the life cannot be imagined without the supply of electricity. At the same time the quality and continuity of the electric power supplied is also very important for the efficient functioning of the end user equipment. Most of the commercial and industrial loads demand high quality uninterrupted power [1]. Thus maintaining the qualitative power is of utmost importance. The quality of the power is affected if any deviation occurs in the voltage and frequency at which the power is being supplied. This affects the performance and life time of the end user equipment. Whereas, the continuity of the power supplied is affected by the faults which occur in the power system. So to maintain the continuity of the power being supplied, the faults should be cleared at a faster rate and for this the power system switchgear should be designed to operate without any time lag [2].

The most obvious power defects are complete interruption of power supply (which may last from a few seconds to several hours) and voltage dips or sags (where the voltage drops to a lower value for short duration). Naturally long power interruptions are a problem for all users, but many operations are very sensitive to even for very short interruptions. These problems are also responsible in deteriorating the consumer appliances [3]. In order to enhance the behavior of the power system, these problems should be eliminated.

1.1 Multilevel inverter Concept:

Multilevel inverters are power-conversion systems composed of a group of power semiconductors and capacitive voltage sources that, when properly connected and controlled, can generate a multiple-step voltage waveform with variable and controllable frequency, phase, and amplitude [4]. The stepped waveform is obtained across the load by connecting it to the suitable capacitive voltage sources with the help of proper switching of the power semiconductors switches. The number of levels of an inverter can be defined as the number of steps or constant voltage values that can be generated by the converter between the output terminal and any arbitrary internal reference node within the inverter. To be called a multilevel converter, each phase of the converter has to generate at least three different voltage levels. This differentiates the classic two-level voltage source converter (2L-VSC) from the multilevel family. Two-level converters can generate a variable frequency and amplitude voltage waveform by adjusting a time average of their two voltage levels. This is usually performed with pulse-width modulation (PWM) techniques. On the other side, multilevel converters add a new degree of freedom, allowing the use of the voltage levels as an additional control element and giving more alternatives to generate the output waveform. For this reason, multilevel inverters have intrinsically improved power quality, characterized by lower voltage distortion (more sinusoidal waveforms), reduced dv/dt, and lower common-mode voltages, which reduce or even eliminate the need of output filters. It is worth mention that, generally, the different voltage levels are equidistant from each other in multiples of Vdc [5]-[6].

1.1.1 Advantage of Multilevel inverter:

- Multilevel inverter exhibits a better harmonic profile.
- Filter requirement is greatly reduced
- The voltage stress on the semiconductor switches is less, therefore, a smaller rating of switches are suitable for generating high voltage levels [7]–[11].
- It can easily be interfaced with renewable energy resources such as solar photovoltaic wind and fuel cells.

1.1.2 Disadvantage multilevel inverter:

- It requires a large number of switches
- Each switch requires it’s on gate drive circuit which increases the complexity and the cost of the overall system.

1.2 Basic Multilevel topology:

Over a few decades, researchers have taken more interest in the development of new multilevel topology. As a result, Baker and Banister developed cascaded H Bridge inverter in the middle of 1970. Cascaded H bridge multilevel converters formed by the series connection of two or more single-phase H-bridge inverters, hence the name. When two or more H-bridges are connected in series, their output voltages can be combined to form different output levels, increasing the total inverter output voltage and also its rated power. In general terms, when connecting k H-bridges in series, 2k+1 different voltage levels are obtained (two per H-bridge and the zero, common to all), and a maximum output voltage of kVdc is possible. Isolated DC voltage source is required for each H bridge module. It generates multilevel output waveform by adding or subtracting different dc voltage sources.

Also it does not require any clamping diode and flying capacitor. This topology is modular in nature and simple in structure [12]. Baker was first introduced 3 and 5 level NPC or diode clamped in 1980. This topology produces multilevel voltage from a single DC voltage source with an extra diode connected to the neutral point. In the year of 1990, Nabae implemented PWM scheme on NPC. The NPC topology can be extended to higher power rates and more output voltage levels by adding additional power switches and clamping diodes to be able to block higher voltages. Here the name diode clamped (DC) makes more sense since there are more voltage-level clamping nodes than only the neutral N. Note that the number of clamping diodes needed to share the voltage increases dramatically. This fact, together with the increasing difficulty to control the dc-link capacitor unbalance, has kept the industrial acceptance of the NPC topology up to three levels only. Fixed capacitor topology was first introduced by Maynard and fork in 1990. This topology uses capacitors to clamp the switch voltages instead of clamping diodes. The main and most important difference with the NPC topology is that the FC has a modular structure and can be more easily extended to achieve more voltage levels and higher power rates. But requires a complex control mechanism to ensure that the voltage across the capacitor is maintained constant [13]. This control becomes more challenging when the number of capacitor increases exponentially with a higher output voltage level generation. Figure 1.1 shows the basic multilevel topologies.

Although the above topologies are very popular in the industry as well as in literature [14], [15].These are particularly used based on applications and cost consideration. Apart from these classical topologies researchers are still developing new application-oriented topologies. T-type Inverter, Switched Series/Parallel Sources (SSPS) based MLI and Packed-U Cell (PUC)

Topology are the examples of recent multilevel inverter topology. Each multilevel inverter is assessed by some factors. These are discussed in the following subsection.

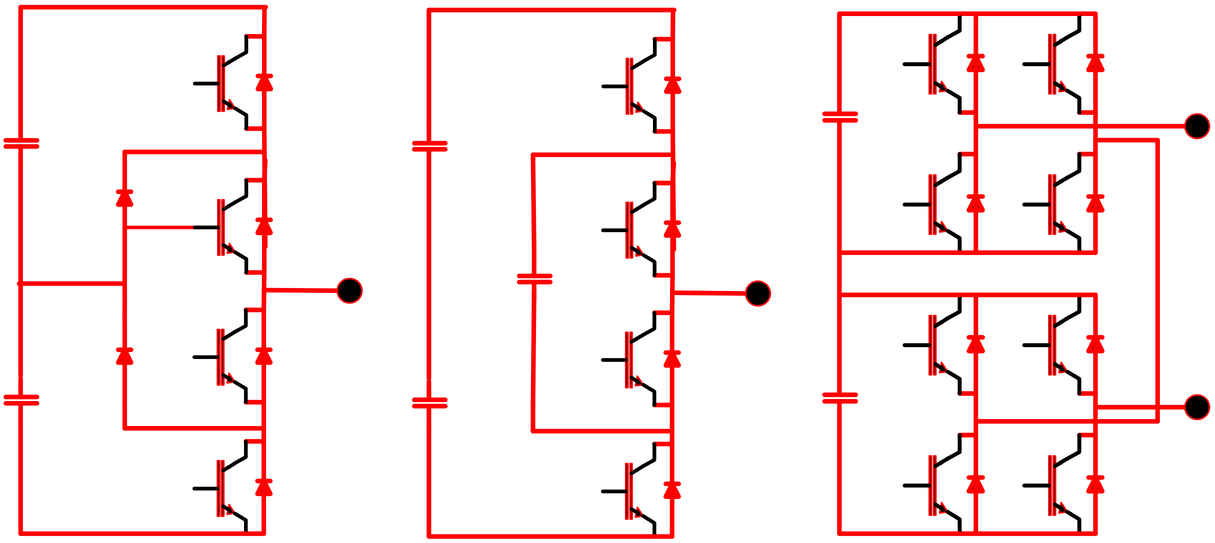


Figure. 1.1 Multilevel inverter topologies (a) NPC (b) FC (c) Cascaded H-bridge

1.3 Background and Motivation:

As the advancement in technologies become greater in the market, the need for greener and cleaner energy is increasing day by day. Renewable energy systems are attaining much more consideration in present times and most of the nations are attempting to put themselves out of the dependency on conventional energy recourses. Wind and solar power plants are making their place in the electric power generation network as much and technologies required for making renewable energy sources reliable are also updating rapidly and great advancements about it are going on to maximize the generation of electric energy by the renewable power plants [16].

The power conversion between DC and AC in different areas like generation, transmission, distribution, and utilization of electrical energy finds one of the way to meet the continuously increasing demand for electrical energy. DC-AC converters (i.e. inverters) play an important role in various areas like renewable energy systems. HVDC transmission, electric vehicles, electric drives, etc.

Based on the output waveform, inverters are classified as two-level or square wave inverters, quasi-square wave inverters, two-level PWM inverters, and multilevel inverters (MLI). The major issue related to two-level square wave and PWM inverters is that for a medium and high power inverter, they require components of high power rating which is not available, and hence for this reason numerous components need to be arranged in series/parallel to get the specified voltage/current capacity. Another problem is the power quality is not so good yield and hence filter circuits are required to supply the load [17].

The MLI structure is presented as an elective for such high power conversion. MLI employs different arrangements of few DC sources along with several lower rating semiconductor switches and sometimes capacitors to get a staircase output voltage waveform for attaining large voltage. Semiconductor switches employed in MLI are controlled using algorithms to add all these multiple DC sources voltage to achieve high output voltage and make the output voltage waveform similar to a stepped waveform. The energy sources for MLI can be DC voltage/current source capacitors, fuel cells, solar PV panels, etc. Various benefits of using MLIs in terms of lesser switch stress as large no. of switches required, improved power quality, reduction in filter size as output voltage is of staircase waveform, no. of components, etc. as compared to two-level square wave and PWM inverters have made the MLIs the premier choice for DC-AC power conversion.

The conventional topologies of MLI are cascade H-bridge (CHB), diode clamped (DC), and flying capacitor (FC). These conventional topologies have their respective advantages and disadvantages. CHB has the advantage of good modularity but it requires a large number of components. DC has equal static and dynamic voltage share but requires additional clamping diodes. FC requires additional capacitors which require separate pre charging circuits. New topologies are also being proposed to provide better performance [18].

MLI can be classified as symmetrical and asymmetrical. The symmetrical MLI has the dc sources of equal magnitude whereas asymmetrical MLI which has the dc sources are of different magnitude. The symmetrical topologies have lesser complexity, more no. of redundant states, and lessor no, of output voltage levels. Whereas asymmetrical topologies have less number of components for the same number of output voltage levels which reduce complexity of the MLI. Many symmetrical and asymmetrical MLI topologies have been presented after conventional topologies to provide the better designs and operation of MLI in respect of different parameters such as number of DC voltage sources, output voltage levels, component counts, driver circuits for operation of the switches, total standing voltage (TSV), etc.

The contribution of renewable energy sources to the electrical grid is extensively required to make the world independent of conventional energy sources [19]. Most of the countries have taken concrete steps to implement solar energy technologies to meet the local energy demands. Despite plenty of multilevel inverter topologies that have been invented, special efforts has been devoted to searching for new promising topologies.

1.4 Organization of Thesis:

The thesis is organized as follows:

Chapter 1: Introduces the study and work. This chapter mainly discusses the motivation & objectives of this thesis work.

Chapter 2: This chapter contains the thorough study of Packed U Cell (PUC) with all switching's states and its role in the multilevel inverter.

Chapter 3: This chapter discusses the Gradient based optimization technique to solve equation for the switching angles.

Chapter 4: This chapter discusses the PUC topology description and SHE technique applied on the PUC inverter to get five level waveform with THD and FFT analysis. It also includes the Simulink model and simulation results for investigation of SHE technique on the PUC inverter in the multilevel inverter application.

Chapter 5: Summarizes the main conclusions of this dissertation and provides some suggestions for future work.

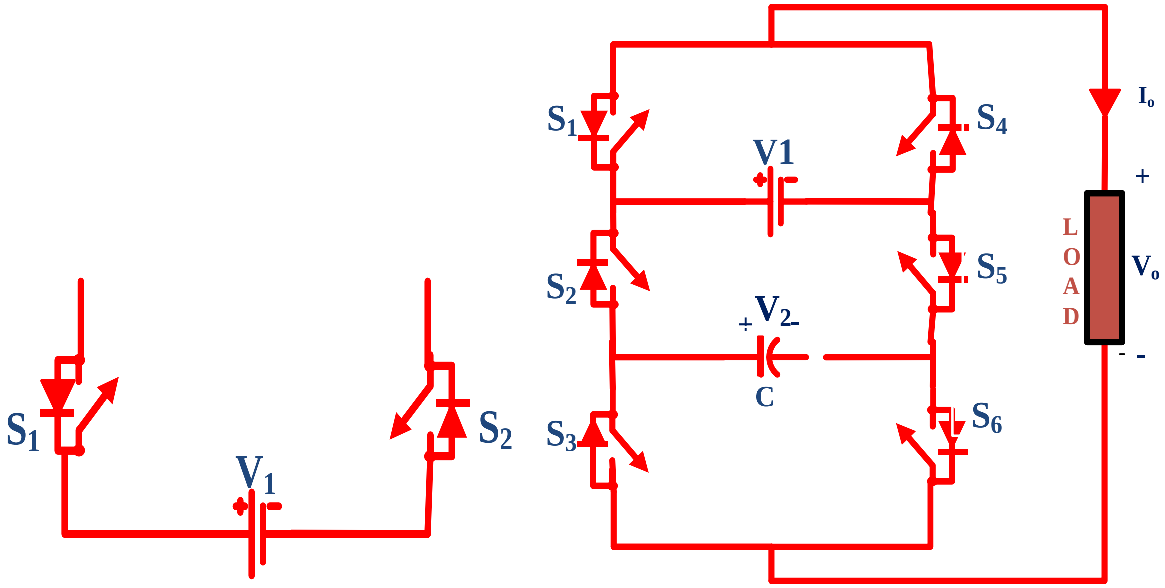
CHAPTER-2

LITERATURE REVIEW

The thorough study of Packed U Cell (PUC) with all switching's states and its role in the multilevel inverter during the course of the present work are discussed in this chapter.

2.1 Packed U Cell:

Packed U cell contains up a single-phase packed U-cell (PUC) multilevel inverter topology. Packed U cells inverter was invented in 2008 as modification of CHB inverter, with two lower switches eliminated and adding two U cells connected directly by changing the upper two switches. For specific output levels, the PUC inverter has the fewest device counts of all multilevel inverters. It is the multilevel inverters that have recently been designed with less capacitors and energy devices. The main difference between the two is that the CHB uses more DC power sources then PUC [20]. As shown in figure 1, there are two power switches and one capacitor in every U cell. Lower voltage levels are automatically generated by switching operation in capacitors in the PUC inverter, which has one high voltage DC source. In comparison to the FC topology, the suggested PUC inverter topology has the same number of voltage levels and uses half the power supply and one-third the capacitors. It provides better efficiency and lower cost, it has a number of significant disadvantages, including a high switching frequency, asymmetric output voltage cycles and levels, a complex controller with many feedback sensors, and the use of a large capacitor to regulate voltage in variable situations.



(a) *(b)*

Figure 2.1 (a) Single U cell, (b) Single Phase Five Level Packed U Cell

Table 2.1 Switching states switching table for five level PUC cell

States	S1	S2	S3	Output Voltage	V1	Effect on Auxiliary Capacitor
1.	1	0	0	V_1	+2E	No Effect
2.	1	0	1	V_1-V_2	+E	Charging
3.	1	1	0	V_2	+E	Discharging
4.	1	1	1	0	0	No Effect
5.	0	0	0	0	-0	No Effect
6.	0	0	1	-V_2	-E	Discharging
7.	0	1	0	V_2-V_1	-E	Charging
8.	0	1	1	-V_1	-2E	No Effect

Table 2.2 Capacitor Magnitude for different Level

No. of output levels	Capacitor Voltage
Three levels	Equal to main DC- link voltage
Five Levels	Half of Main DC-link voltage
Seven Levels	One third of Main DC – link voltage

Table 2.3 Number of voltage levels surplus according to the number of capacitor

NC	N of Classic cascaded H-Bridge	N of PUC converter
1	3	3
2	5	7
3	7	15
N	2n+1	2^{n+1}-1

Table 2.4 Comparison Table For Single Phase Five Level Inverters

Inverter Type	DC Sources	Capacitor	Clamped Diode	Active Switch	Total Parts Count
Cascaded-H bridge	t-1/2	0	0	2(t-1)	5(t-1)/2
NPC without Voltage Control	t-2	0	2(t-2)	2(t-1)	5n-7
Flying Capacitor	1	t-2	0	2(t-1)	3(m-1)
PUC 5	1	$\sqrt{t-1}$ -1	0	$2\sqrt{t-1}$ +2	$3\sqrt{t-1}$+2

After that another PUC topology has been developed with a self –voltage balancing operate as 5-level inverter by assuming V1=2V2=2E, therefore the output 5-level voltage waveform includes the levels 0, ±E, ±2E. In this case, the capacitor voltage (V2) is kept constant at half of the DC source (V1) amplitude. In this configuration six switching states are available to produce three levels [21].

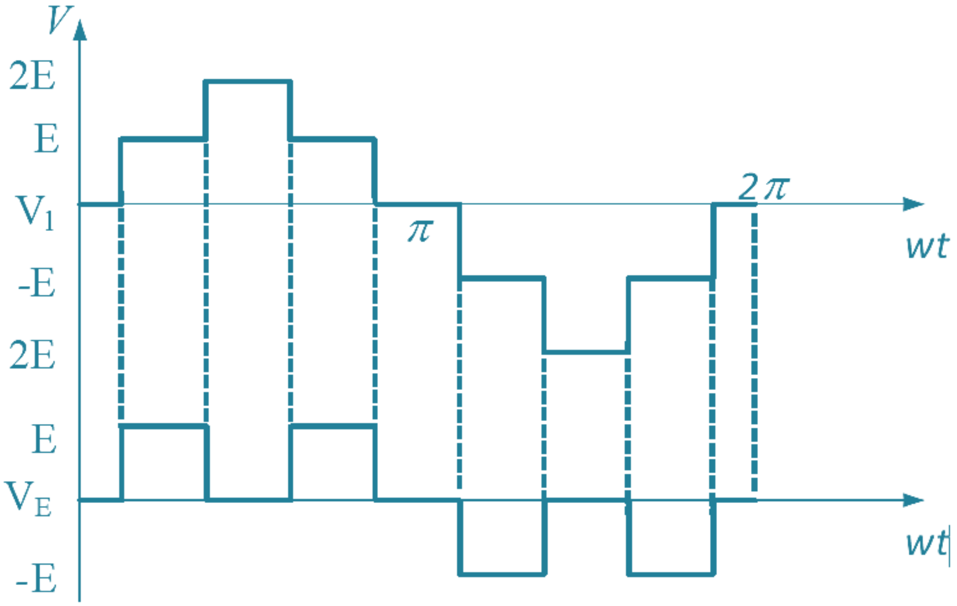
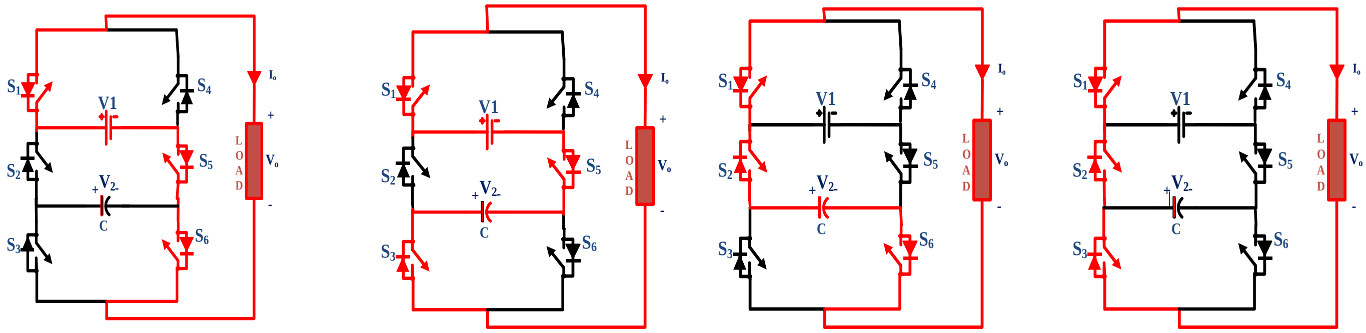
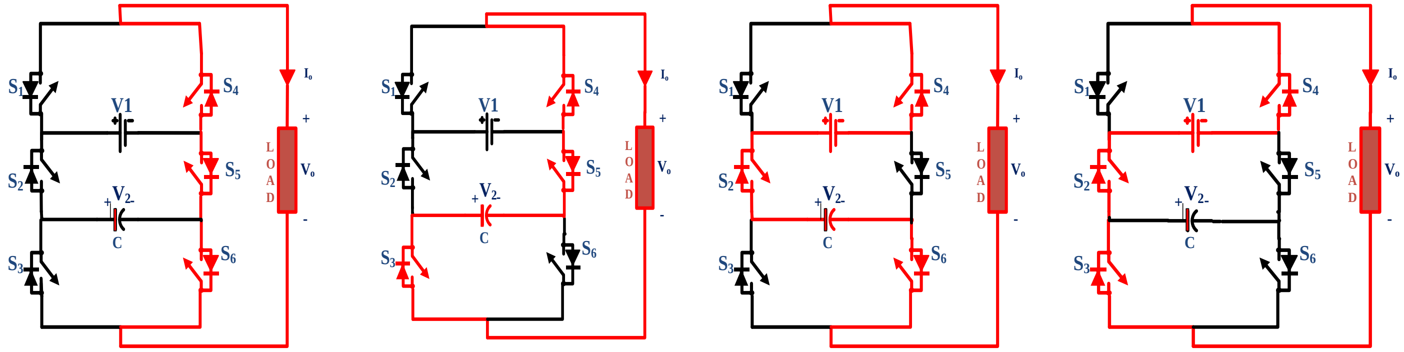


Figure 2.3 Output voltage wave for five level PUC



State 1: V_1=+2E **State 2: V_1–V_2=+E** **State 3: V_2=+E** **State 4: 0**



State 5: 0 **State 6: -V_2=-E** **State 7: V_2-V_1=-E** **State 8: -V_1=-2E**

Figure 2.4 switching states and conducting paths of PUC5 inverter.

Including –E, 0 and +E that means there are some redundant switching states which may help to find different paths for flowing current through the load. The redundant switching states can deal with charging and discharging the capacitor in order to balance the voltage at the half of the DC source voltage. It is clear that in states when the DC source and capacitor are connected in series with the load, the capacitor is charged (states 2 & 7). On the other hand, on some paths that the capacitor feeds the load alone, it is discharging (states 3 & 6). Eventually, for rest of the states, the capacitor voltage is remained unchanged because it is neither connected to DC source nor to the load. As shown in figure 1, every U cell consists of two power switches and one capacitor. Figure 2.1 illustrate the single-phase PUC inverter topology. The complete associate switching states are listed in table 2.1 [22].

2.2 Advantage of Packed U Cell:

The Packed U-Cells (PUC) inverter is a new single-DC-source MLI architecture that makes it easier to use current controllers in a variety of applications. It is a competitive topology that combines multiple features of other MLI topologies, such as:

1. Low impact on the power grid;
2. Flexibility in expanding to higher output levels without DC bus extension
3. Ability to offer a wider range of control actions and improve filter bandwidth through switching state redundancy.
4. Because there are fewer active components, there is greater reliability and lower cost.
5. Better ride-through capabilities using existing storage capacitors [23].

2.3 Voltage Balancing Techniques for PUC5 Inverter:

The PUC5 design uses a DC capacitor, voltage management is required, just like it is in any other MLI structure. Recent research has focused on the precise estimate of capacitor voltages for various PUC5 designs, motivated by the significance of having proper information of capacitor voltages in control design. The suggested sensor-less voltage method simplifies the control system, making the PUC5 inverter suitable for industrial use.

For the PUC5 inverter, a sensor-less voltage control approach based on redundant switching states was developed. The suggested method maintains the dc capacitor voltage at half that of the dc source, resulting in a 5-level output voltage waveform with reduced harmonic distortion. Only a sensor-less controller included into the modulation method regulates the PUC auxiliary dc bus. As analyze in Table 2.2, states 2 and 6 are used in PUC5 inverter in order to balance the capacitor voltage at the desired level [24].

2.4 Modulation techniques:

The output voltage of a multilevel inverter is controlled through adjustable gate pulses to the power electronics switches. Easy control of gate pulses produces undesirable different frequency components in addition to desirable fundamental frequency component which creates the problem of distortion of voltage and current waveform. This distortion results in the faulty operation of protective relays, unsatisfactory operation of electric machines and electromagnetic interference with a communication line [25]. This distortion can be minimized by filtering the output voltage by the LC filter. But for this purpose the size of the filter becomes bulky. The harmonics distortion can also be minimized by the application of modulation techniques which results in the reduction of the filter size and it is the advantageous property of modulation techniques. A classification of the most common modulation methods for multilevel inverters is presented in Figure 2.5.

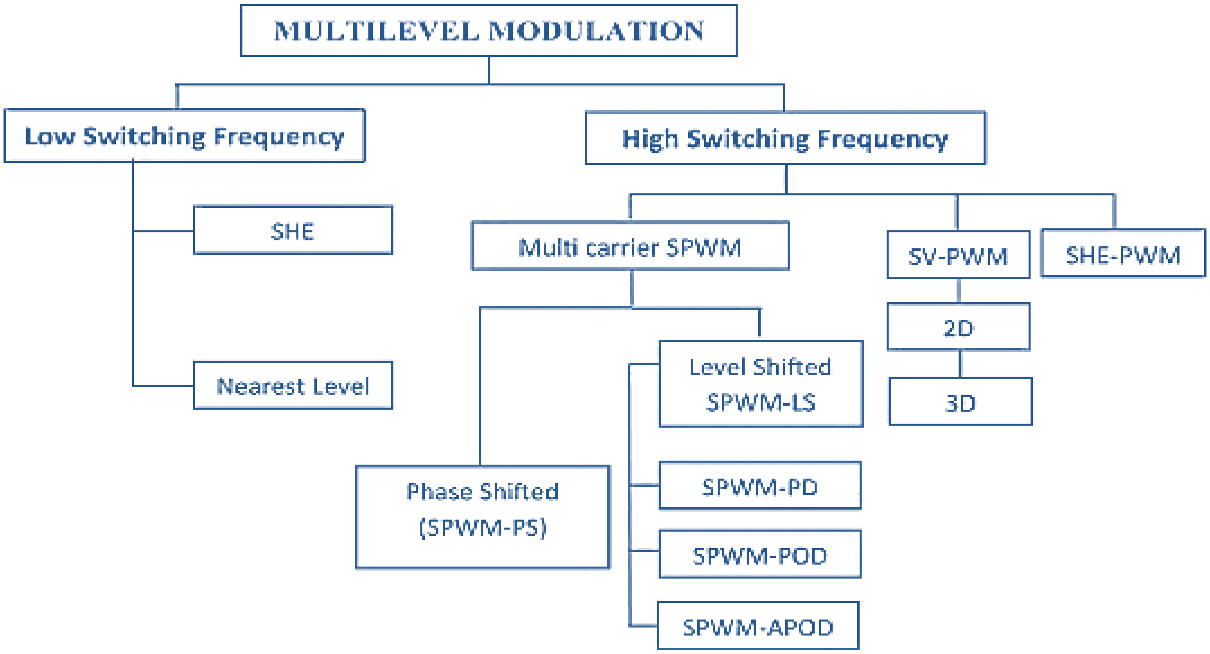


Figure 2.5 Classification of modulation techniques

IGBT, MOSFET, GTO, IGCT, and other power electronics devices of such type have been extensively employed for low to high power applications. These devices are selected based on the performance of devices and applications in which these are used. IGBTs are preferred in high power low switching applications. MOSFETs are preferred in low power high switching applications due to low values of current handling capability, reverse blocking voltage and switching losses. The total harmonic distortion is an important index to measure both modulation technique and multilevel inverter, which can be calculated based on the number of harmonics presented in the output waveform of both voltage and current [26]. Some researchers focused on the development of new topologies and others focused on the development of modulation techniques to fully exploit the available topologies. But every development in multilevel inverter,

2.3 Selective harmonic elimination (SHE):

SHE technique has been an extensive research substitute for the traditionally PWM Scheme. By the application of SHE particular low order harmonics are eliminated from output voltage and current which provides a superior harmonic profile with less switching losses. In addition to minimum THD and switching losses it has the ability to leave 3rd and its multiple harmonics uncontrolled to take advantage of circuit topology in the three-phase system. These desirable properties of SHE technique have made it as an opted technique for high power electric drives and HVDC transmission etc. The SHE technique can be applied for unbalanced DC voltages. SHE technique has employed various mathematical non-linear trigonometric equations in terms of switching angles to eliminate particular harmonics such as 3rd, 5th, 7th, 11th, 13th, etc. To obtain optimized switching angles these mathematical equations are solved using any numerical method [28].

SHM has been introduced based on the optimized selective harmonic elimination (SHE) method as an improvement to control more harmonic orders. SHM-PWM has proven to involve all harmonic orders below 49th; those are taken into power quality evaluation, in order to overcome SHE disadvantage of leaving non-eliminated orders uncontrolled [29]. Hence, an objective function (OF) has been defined to turn SHM equations into an optimization technique. The OF is adjusted to allocate appropriate coefficients to SHM equations in order to mitigate low-order harmonics amplitudes and control non-eliminated ones. However, the number of mitigated amplitudes is equal to the number of angles in the equations.

According to the SHM-PWAM principle, both dc voltage magnitudes of inverter and switching angles are considered as variable in traditional SHM equations [30]. Thus, there is a possibility of mitigating more harmonic orders proportional to the number of dc sources added into equations as variables. Afterward, SHM-PWAM was simplified into the pulse amplitude modulation (PAM) technique in [31] through generalizing a formulation that the fundamental output voltage component can be directly controlled via dc input voltage. Several modifications have also been conducted to improve SHM-PAM in order to deal with more harmonic orders with the same number of variables. In [32], the SHM-PAM technique was applied on strictest power quality requirements and proposed to be used in back-to-back converter applications as active front end rectifiers. Another critical challenge is in single-phase inverters where both triplen and non-triplen harmonics must be considered in the equations due to the fact that triplen harmonics exist in single phase systems inherently. Then, there would be more undesired low harmonic orders in single-phase equations compared to the three-phase one, which should be controlled. Furthermore, triplen harmonic orders have severer standard amplitude limitation than the non-tiplen ones, which weakens the SHM flexibility. The standard limitations for triplen orders higher than 15th are below 0.2%. In fact, SHM should have the ability of eliminating triplen harmonic orders in a single-phase inverter.

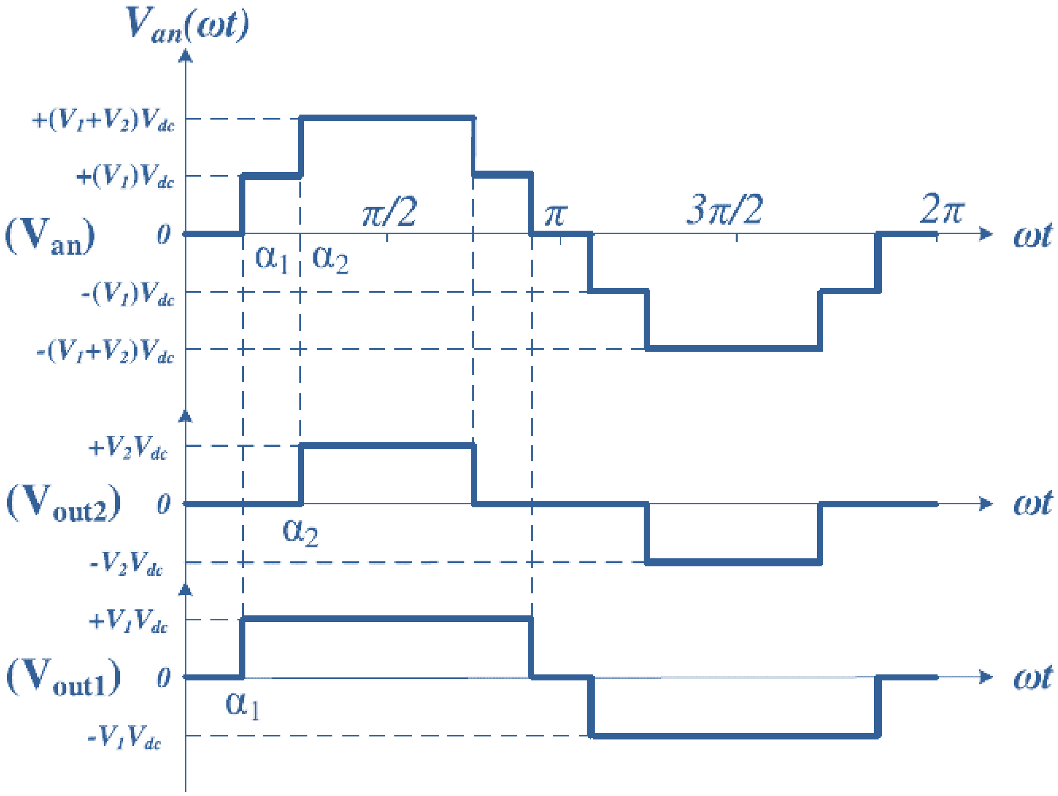


Figure 2.6 Five-level low switching frequency voltage waveform.

2.4 Nearest level control (NLC):

Fundamental switching frequency schemes such as SHE, Space vector control and nearest level control are preferred for high power applications. The Nearest control techniques are divided into two parts: (1) Nearest space vector control (Rodriguez et al. 2002) and (2) Nearest level control (Perez et al. 2007). The main drawback of SHE is to solve the system of non-linear trigonometric transcendental equations which consume more computational time. Hence SHE technique is not concerned with closed-loop real-time applications such as dynamic response systems. This drawback of SHE can be eliminated by the nearest control techniques. Nearest space vector control is complex and needs more time for numerical computation. The level control technique is simpler and normalized value is evaluated using the round-off method. Nearest level control is also classified on the basis of step size (integer type) as: (1) conventional (2) modified (3) optimized. The operation of MLI can be divided into two categories depending on the modulation strategies as (1) fundamental frequency and (2) high switching frequency modulation. Operation at higher switching frequency results in considerable switching losses in the inverter. Therefore, in high power applications, fundamental or low switching frequency (<1kHz) modulation scheme is preferred to avoid the significant switching losses. The nearest level control & nearest space-vector control-technique work at the fundamental frequency. NLC scheme is efficient and fast in terms of implementation procedures. Selective harmonic elimination is a low switching frequency technique and is limited to 1kHz operation. Lower order harmonics which are required to be removed in the SHE method are done so by solving the nonlinear transcendental equation to find the value of the predefined switching angle per quarter of fundamental frequency. Solving the equations can be done by employing any of the soft computing techniques like population-based Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony. The Newton-Raphson method can also be employed for fast convergence [33]. The metaheuristic techniques take more computational time for closed-loop applications; thus, they require fast computational processors. Finding the nearest vector is complicated in the vector control method and requires more computational time as compared to the NLC. Due to reduced lower order harmonics and lesser switching losses, the NLC technique is preferred over the other two techniques [34]. NLC is quite a simple and efficient method of voltage control.

CHAPTER-3

GRADIENT BASED OPTIMIZATION TECHNIQUES

This chapter focuses on the algorithm used for the elimination of the 5th harmonics.

3.1 Introduction of Gradient Based Optimization (GBO):

In this study, a novel metaheuristic optimization algorithm, gradient-based optimizer (GBO) is proposed. The GBO, inspired by the gradient-based Newton's method, uses two main operators: gradient search rule (GSR) and local escaping operator (LEO) and a set of vectors to explore the search space. The GSR employs the gradient-based method to enhance the exploration tendency and accelerate the convergence rate to achieve better positions in the search space. The LEO enables the proposed GBO to escape from local optima. Many real-world applications in various science and engineering fields can be converted to optimization problems. However, the related problems are often highly non-convex, nonlinear, and multimodal. Although a variety of optimization algorithms have been developed, they frequently fail to provide satisfactory results for such challenging problems, which emphasizes the need for new optimization methods. The metaheuristic algorithms (MAs) [35], which are known as global optimization techniques, have been successfully used to solve various complex and real optimization problems [36, 37]. The metaheuristic methods use some principles of physics, swarm intelligence, and biology. In the last decades, different MAs have been developed and used. For example, the genetic algorithm (GA) was derived from the Darwin's theory of evolution [38]. The differential evolution (DE) algorithm employs the same operators (i.e., mutation and crossover) as those in the GA but with a different approach [39]. The DE algorithm uses the difference between two randomly selected vectors to generate a new vector. Particle swarm optimization (PSO) was inspired by the social behaviors of birds and fish for catching food [40].

The aforementioned methods are categorized as population-based algorithms, which involve a set of solutions in the optimization process. The search engines of such optimization methods are based on different phenomena as described above. Many studies have demonstrated successful applications of these methods for a broad variety of real-world problems [36, 41, 42]. Generally, the population-based optimizers share common information despite their natures [41]. In these algorithms, the search engine implements two steps: exploration and exploitation [42]. Exploration involves exploring new positions far from the current position in the entire search area, while exploitation aims to explore the near-optimal positions. The utilization of exploration alone may lead to new positions with low accuracy. In contrast, the employment of exploitation alone increases the chance to get stuck in local optimal positions. Many studies emphasized the importance to balance the exploration and exploitation search processes in the metaheuristic algorithms [43]. Hence, creating a suitable balance between these two processes is crucial [44].

Most of the metaheuristic algorithms are managed to create a proper trade-off between exploration and exploitation. To do this, some studies have been conducted to enhance the efficiency of basic algorithms by using suitable setting of the control parameters or hybridization of optimization algorithms [45-46]. However, to date, creating a suitable balance between exploration and exploitation in the metaheuristic methods is a challenging and unsolved issue. On the other hand, based on the rule of No Free Lunch (NFL) [47], no metaheuristic algorithm can solve all problems, indicating that a specific algorithm may provide very good results for a set of problems, but the same method may have low efficiencies for a different set of problems. NFL also implies that this field of research is highly dynamic, which leads to the development of many new metaheuristic optimization algorithms over years [48]. This study attempts to fill the research gap by proposing a new metaheuristic algorithm with population-based characteristics.

Thus, the main objective of this study is to get as low THD as possible for the output of voltage and output current by using gradient-based metaheuristic algorithm, namely gradient-based optimizer (GBO). The most popular gradient-based search methods include the Newton's method [49], Quasi-Newton method [50], Levenberg Marquardt (LM) algorithm [51], and the conjugate direction method [52]. These methods have been applied in many studies to solve different types of optimization problems.

3.2 Theoretical background:

Generally, the optimization methods can be categorized into two groups: gradient-based (GB) methods such as the LM algorithm [48], gradient descent (GD) [52], and Newton's method [53], and modern non-gradient-based methods (i.e., metaheuristic algorithms (MAs)) such as genetic algorithms (GAs) [54], simulated annealing (SA) [55], water evaporation optimization (WEO) [56], teaching learning based optimization (TLBO), self-defense mechanism of plants (SDMP) algorithm, henry gas solubility optimization (HGSO) [57], and Harris hawks optimization (HHO) [58]. The gradient-based methods have been broadly employed to solve optimization problems. To determine an optimal solution using the gradient-based methods, an extreme point, at which the gradient is equal to zero, must be identified. The gradient methods such as the conjugate direction [59] and Newton’s method are based on this concept. In the gradient methods and most of other optimization methods, a search direction is selected and the searching process moves along this direction towards the optimal solution. Exploring the search directions in these methods needs to determine the derivatives of the objective function together with the constraints. The two main disadvantages of this type of optimization are: (1) the convergence speed is very slow and (2) there is no guarantee to achieve the optimal solution.

In the second category, some initial points (i.e., initial population) are randomly generated. Each point has a search direction, which is determined by the information acquired from previous results. The optimization process is continued by updating the search directions until the convergence criterion is met. Such optimization techniques (i.e., MAs) have been widely utilized to optimize different engineering problems. The MAs provide great robustness to find the global optima, while the gradient-based methods tend to converge into local optima. However, the non-gradient-based methods require higher computational capacities, especially for the problems with high-dimensional search spaces. Hence, it will be very worthwhile to develop an optimization method that uses a gradient method to skip the unfeasible points and move towards the feasible area and also takes advantage of the capabilities of the population-based optimization methods. Thus, one of the unique features of this study is to combine the concept of the gradient-based methods with the population-based methods for creating a powerful and efficient algorithm to overcome the drawbacks of previous methods.

3.2 Newton’s method

The Newton’s method is a powerful method to numerically solve equations [44]. This method is a root-finding algorithm that employs the initial terms of the Taylor series. This method starts with a single point (y_0) and then uses the Taylor series assessed at point y_0 for estimating another point that is nearby to the solution. This procedure continues until the final solution is obtained. The Taylor series of function $f(y)$ can be expressed as:

$$f(y) = f(y_0) + f'(y_0)(y - y_0) + \frac{f''(y_0)(y - y_0)^2}{2!} + \frac{f^3(y_0)(y - y_0)^3}{3!} + \ldots \ldots \ldots \ldots \ldots (1)$$

where f'(y), f''(y), and $^{(3)}$(y) respectively are the first-, second-, and third-order derivatives of f(y) with respect to x. Assuming that the initial point is very close to the actual root, $(y - y_0)$ is small and the higher-order terms in the Taylor series will approach to zero. Therefore, truncating the series (Eq. 1) attains a linear approximation of f(y) as follows:

$$f(y) \cong f(y_0) + f'(y_0)(y - y_0) \tag{2}$$

To determine the root for $f(y)$, let f(y) be zero and solve for y:

$$\mathrm{y} = y_0 + \frac{f(y_0)}{f'(y_0)} \tag{3}$$

Accordingly, given yn, next approximation yn + 1 can be expressed as:

$$y_{n+1} = y_n - \frac{f(y_n)}{f'(y_n)}\,, \tag{4}$$

The Newton's method implements an iterative process to eventually obtain the final solution.

3.3 Modification of Newton's method

In this study, a new variant of the Newton's method introduced by Weerakoon and Fernando is used to formulate the proposed algorithm, which is defined as:

$$y_{n+1} = y_n - \frac{f(y_n)}{[f'(y_{n+1})_1 + f'(y_n)]/2} \tag{5}$$

where $f'(y_{n+1})$ is the first-order derivative of f(y) with respect to y_{n+1}.

According to Özban [60], Eq. (5) can be expressed as

$$y_{n+1} = y_n - \frac{f(y_n)}{f'\left(\frac{z_{n+1}+y_n\,]}{2}\right)}\,' \tag{6}$$

where

$$z_{n+1} = y_n - \frac{f(y_n)}{f'(y_n)} \qquad (6-1)$$

So, the new variant of the Newton's method can be achieved by using the arithmetic mean of z_{n+1} and y_n.

In the proposed GBO that combines the gradient and population-based methods, the search direction is specified by the Newton's method to explore the search domain utilizing a set of vectors and two main operators (i.e., gradient search rule and local escaping operators). Minimization of the objective function is considered in the optimization problems.

3.3.1 Initialization

An optimization problem involves a set of decision variables, constraints, and an objective function. The control parameters of the GBO include a parameter for transition from the exploration to exploitation (α) and a probability rate. The number of iterations and the population size are determined, depending on the problem complexity. In the proposed algorithm, each member of the population is called "vector". Accordingly, the GBO includes N vectors in a D-dimensional search space. Thus, a vector can be expressed as:

$$Y_{n,d} = [Y_{n,1}, Y_{n,2}, \ldots\ldots\ldots Y_{n,D}], \quad n = 1,2,\ldots\ldots\ldots,N, \qquad d = 1,2,\ldots\ldots\ldots,D \tag{7}$$

Usually, the initial vectors of the GBO are randomly generated in the D-dimensional search domain, which can be defined as:

$$Yn = Ymin + rand(0,1) \times (Ymax - Ymin) \tag{8}$$

where and $Ymin$ $Ymax$ are the bounds of decision variable X, and $rand(0,1)$ is a random number in [0, 1].

3.3.2 Gradient search rule (GSR):

In the gradient search rule, the movement of vectors is controlled to better search in the feasible domain and achieve better positions. With the aim of enhancing the exploration tendency and accelerating the convergence of the GBO, the GSR is proposed based on the concept of the GB method. However, this rule is extracted from the Newton's gradient-based method [43]. Given the fact that many optimization problems are not differentiable, a numerical gradient approach is employed as a substitute for the direct derivation of the function. Generally, the GB method begins a guessed initial solution and moves toward the next position along a gradient-specified direction. To derive the GSR based on Eq. (4), the first-order derivative must be calculated by utilizing the Taylor series. The Taylor series for functions $f(\mathrm{y} + \Delta \mathrm{y})$ and $f(\mathrm{y} - \Delta \mathrm{y})$ can be respectively expressed as:

$$f(y+\Delta y) = f(y_0) + f'(y_0)\Delta y + \frac{f''(y_0)\Delta y^2}{2!} + \frac{f^3(y_0)\Delta y^3}{3!} + \ldots\ldots\ldots \tag{9}$$

$$f(y-\Delta y) = f(y_0) - f'(y_0)\Delta y + \frac{f''(y_0)\Delta y^2}{2!} - \frac{f^3(y_0)\Delta y^3}{3!} + \ldots\ldots\ldots \tag{10}$$

From the truncated Eqs. (9) and (10), the first-order derivative is given by the following central differencing formula [41]:

$$f'(y) = \frac{f(y+\Delta y) - f(y-\Delta y)}{2\Delta y} \tag{11}$$

Based on Eqs. (4) and (11), the new position (y_{n+1}) is then defined as:

$$f_{n+1} = f_n - \frac{2\Delta y + f(y_n)}{2\Delta y} \tag{12}$$

Since the GSR is considered as the main core of the proposed algorithm, some modifications are essential to handle the population-based search. Regarding Eq. (12), the neighboring positions of yn are $yn + \Delta \mathrm{y}$ and $yn - \Delta \mathrm{y}$, which are depicted in Fig. 1. In the GBO algorithm, these neighboring positions are replaced with two other positions (vectors) in the population. Since $f(\mathrm{y})$ is a minimization problem, as shown in Fig. 1, position $yn + \Delta \mathrm{y}$ has a worse fitness than yn, while yn — Δy is better than yn. Accordingly, the GBO algorithm substitutes position yn — Δy with y_{best}, which has a better position in the neighborhood of position yn, while yn + Δy is replaced with y_{worst}, which is a worse position in the neighborhood of yn. In addition, the proposed algorithm employs the position (yn), instead of its fitness ((yn)) because the use of fitness of a position is more time-consuming in the computation. The proposed GSR is then formulated as follows:

$$GSR = rand \times \frac{2\Delta y + f(y_n)}{(y_{wrost} - y_{best} + \varepsilon)} \qquad (13)$$

where $randn$ is a normally distributed random number, and ε is a small number within the range of [0, 0.1]. y_{best} and y_{worst} are the best and worst solutions obtained during the optimization process. Eq. (13) can assist the current solution to update its position. To improve the search capability of the proposed GBO and balance exploration (global) and exploitation (local), the GSR is modified by introducing a random parameter $\rho 1$ in Eq. 13, as detailed below.

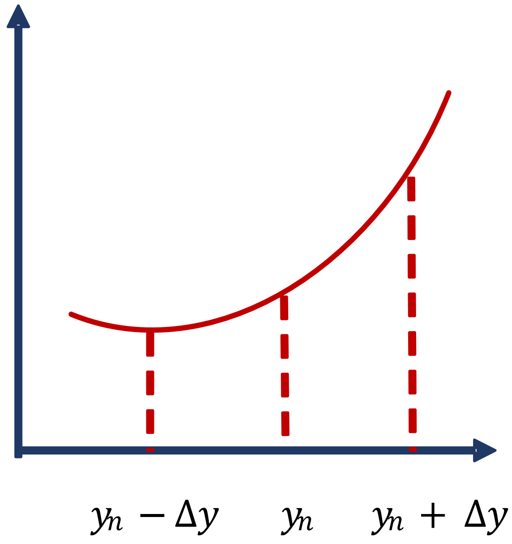


Figure. 3.1 Gradient estimation using yn and its neighboring positions

Generally, an optimization algorithm should be capable of balancing the global exploration and local exploitation to explore the promising areas in the search domain and eventually converge to the global optimal solution. To achieve this goal, the GSR can be changed by utilizing an adaptive coefficient. In this study, $\rho 1$ is introduced as the most significant parameter in the GBO to balance the exploration and exploitation searching processes, and it can be expressed as:

$$\rho_1 = 2 \times rand \times \alpha - \alpha \tag{14}$$

$$\alpha = \left| \beta \times \sin\left(\frac{3\pi}{2} + \sin\left(\beta \times \frac{3\pi}{2}\right)\right) \right| \tag{15}$$

$$\beta = \beta_{\min} + (\beta_{max} - \beta_{min}) \times (1 - (\frac{m}{M})^3)^2 \tag{16}$$

where βmin and βmax are 0.2 and 1.2, respectively, m is the number of iterations, and M is the total number of iterations. To balance the exploration and exploitation processes, parameter $\rho 1$ changes based on the sine function α. Fig. 2 depicts how the parameter α changes with the iteration number. The maximum iteration number is 1000. This parameter can be changed at each iteration. It has a large value at the early iterations to enhance the population diversity and then its value decreases as the iteration number increases to accelerate the convergence. The generated solutions should be capable of exploring the search space around their corresponding best solutions. In this regard, the parameter value increases for the iteration numbers ranging from 550 to 750, which assists the proposed algorithm to escape from any local optima because it can increase the diversity of population to search around the best solution ever obtained. Thus, Eq. (13) can be rewritten as:

$$GSR = rand \times \alpha_1 \times \frac{2\Delta y + (y_n)}{(y_{wrost} - y_{best} + \varepsilon)} \tag{15}$$

The proposed GSR helps the GBO to account for the random behavior during the optimization process, promoting exploration and escaping local optima. In Eq. (15), Δy is determined based on the difference between the best solution ($xbest$) and a randomly selected position (ym) (see Eqs. 16, 16-1, and 16-2). To ensure that changes at each iteration, $r1$ Δy parameter δ is defined by Eq. (16-2). Additionally, to improve exploration, a random number ($rand$) is added to Eq. (16-2).

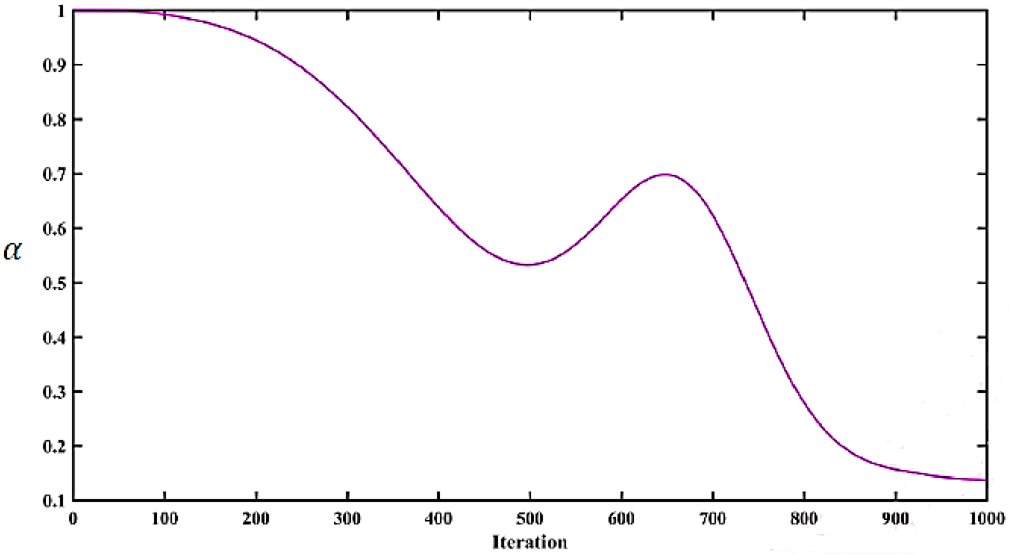


Figure. 3.2 Variation of α parameter over course of iterations

$$\Delta y = rand(1{:}N) \times |step| \tag{16}$$

$$step = \frac{(y_{best} \ - \ x_{r1}^{m}) + \delta}{2} \tag{16 – 1}$$

$$\delta = 2 \times rand \ \times \left(\left| \frac{y_{r1}^{m} + y_{r2}^{m} + y_{r3}^{m} + y_{r4}^{m}}{4} - y_{r}^{m} \right| \right) \tag{16 – 2}$$

where $rand(1{:}N)$ is a random number with N dimensions, $r1$, $r2$, $r3$, and $r4$ ($r1 \neq r2 \neq r3 \neq r4 \neq n$) are different integers randomly chosen from [1, N], $step$ is a step size, which is determined by $ybest$ and ym. Based on the proposed GSR, Eq. (12) can be rewritten $r1$ as:

$$y_{n+1} = y_n - GSR \tag{17}$$

The direction of movement (DM) is also added to better exploit the nearby area of yn. This term uses the best vector and moves the current vector (yn) in the direction of ($ybest — yn$). Therefore, this process creates a suitable local search tendency to promote the convergence speed of the GBO algorithm. The proposed DM is formulated as follows:

$$DM = rand \ \times \rho_1 \times (y_{best} \ - y_n) \tag{18}$$

where $rand$ is a random number in $rand$ [0, 1], and $\rho 2$ is a random parameter, which assists each vector to have a different step size. In addition, this can be another component of the GBO that supports the exploration process. $\rho 2$ is given by:

$$\rho_2 = 2 \times rand \ \times \alpha - \alpha \tag{19}$$

Finally, based on the terms of the GSR and DM, Eqs. (20) and (21) can be used to update the position of current vector (y_n^m).

$$Y1_n^m = y_n^m - GSR + DM \tag{20}$$

$$Y1_n^m = y_n^m - rand \times \rho_1 \times \frac{2\Delta y \ \times y_n^m}{(y_{wrost} \ - \ y_{best} + \varepsilon)} + rand \times \rho_2 \times (y_{best} \ - y_n^m) \tag{21}$$

where $Y1_n^m$is the new vector generated by updating y_n^m. Fig. 3 displays how the current position $Y1_n^m$is updated. As shown in Fig. 3, the position $Y1_n^m$ is created at a random point which is specified by the GSR and DM in the search space.

In this study, the Newton’s method introduced by Özban (Eq. (6)) is used to improve the GSR. Based on Eqs. (6) and (11), the GSR can also be expressed as:

$$y_{n+1} = y_n - \frac{2\Delta y + f(y_n)}{f(x_n + \Delta y) - f(x_n - \Delta y)} \qquad (22)$$

Where,

$$x_n = \frac{[Q_{n+1} + y_n]}{2} \qquad (22-1)$$

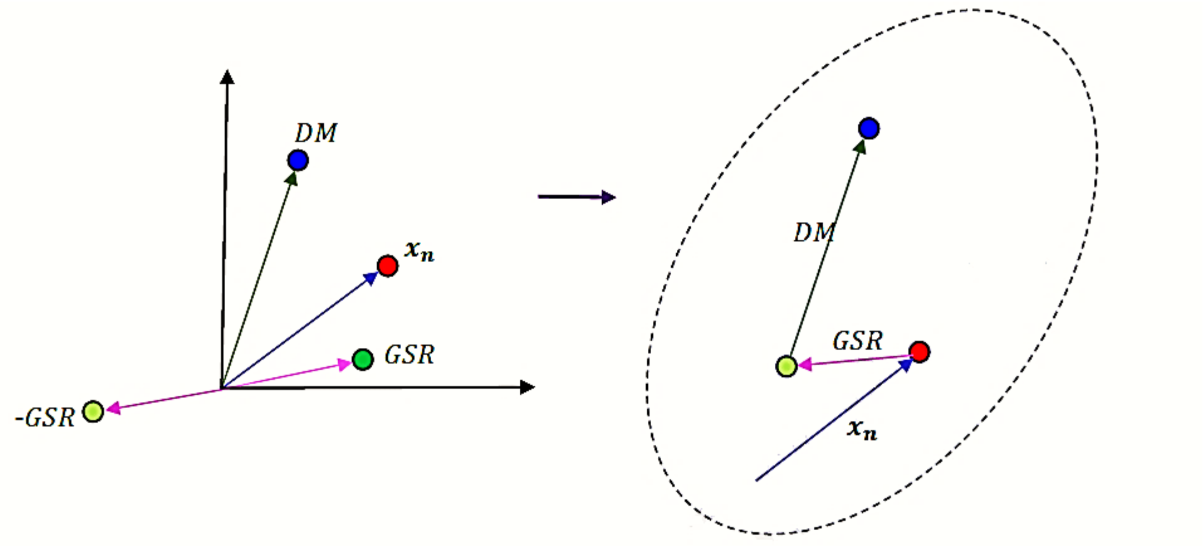


Figure. 3.3 Updating the current position xn

In this study, the Newton's method introduced by Özban (Eq. (6)) is used to improve the GSR. Based on Eqs. (6) and (11), the GSR can also be expressed as:

$$y_{n+1} = y_n - \frac{2\Delta y + f(y_n)}{f(x_n + \Delta y) - f(x_n - \Delta y)} \qquad (22)$$

Where,

$$x_n = \frac{[Q_{n+1} + y_n]}{2} \qquad (22-1)$$

Eq. 22 is employed to update the position of the current solution with a formula different from Eq. 12. This equation uses the average of two vectors Qn + 1 and yn, instead of yn only. This new formula can assist the optimization algorithm by improving the search process in the solution space.

Similar to Eq. (15), to convert Eq. (22) to a population-based search method, zn + 1 is first formulated as:

$$Q_{n+1} = y_n - \frac{2\Delta y \times f(y_n)}{f(y_n + \Delta y) - f(y_n - \Delta y)} \qquad (22-2)$$

Then, to change to a population-based algorithm, Eq. (22-2) can be rewritten as:

$$Q_{n+1} = y_n - rand \times \frac{2\Delta y \times y_n}{(y_{worst} - y_{best} + \varepsilon)} \qquad (22-3)$$

xn + Δy and xn — Δy in Eq. (22) are respectively given by:

$$x_n + \Delta y = \frac{[Q_{n+1} + y_n]}{2} + \Delta x \qquad (22-4)$$

$$y_n - \Delta x = \frac{[Q_{n+1} + x_n]}{2} - \Delta x \qquad (22-5)$$

In this research, to enhance the diversity and exploration and to create a robust population-based search method, Eqs. 22-4 and 22-5 are revised as (note that xn + Δy and xn — Δy are simplified as xpn and xqn):

$$xP_n = rand \times \left(\frac{[Q_{n+1} + y_n]}{2} + rand \times \Delta y \right) \qquad (22-6)$$

$$xq_n = rand \times \left(\frac{[Q_{n+1} + y_n]}{2} - rand \times \Delta y \right) \qquad (22-7)$$

where xpn and xqn are two positions created in regard to Qn + 1 and yn, respectively.

Using the above equations, the GSR can be expressed as:

$$GSR = randn \times \rho_1 \times \frac{2\Delta y \times y_n}{(xp_n - xq_n + \varepsilon)} \qquad (23)$$

With respect to the GSR and DM, Eqs. (24) and (25) are used to produce the position of $Y1_n^m$.

$$Y1_n^m = y_n^m - GSR - DM \qquad (24)$$

$$Y1_n^m = y_n^m - rand \times \rho_1 \times \frac{2\Delta y \times y_n^m}{(xp_n^m - xq_n^m + \varepsilon)} + rand \times \rho_2 \times (y_{best} - y_n^m) \qquad (25)$$

By replacing the position of the best vector (y_{best}) with the current vector (y_n^m) in Eq. $x$best xm n (25), the new vector ($Y2_n^m$) can be generated as follows:

$$Y2_n^m = y_{best} - rand \times \rho_1 \times \frac{2\Delta y \times y_n^m}{(xp_n^m - xq_n^m + \varepsilon)} + rand \times \rho_2 \times (x_{n1}^m - x_{n2}^m) \qquad (26)$$

This search direction method emphasizes the exploitation process. The search method expressed by Eq. (26) is good for local search but is limited for global search, while the search method introduced in Eq. (25) is good for global search but is limited for local search. Therefore, the GBO takes advantage of both search methods (Eqs. (25) and (26)) to enhance both exploration and exploitation. Accordingly, based on the positions$Y1_n^m, Y2_n^m$, and the current Y_n^mposition, the new solution at the next iteration (y_{n1}^{m+1}) can be defined as:

$$y_{n1}^{m+1} = r_a \times (r_b \times Y1_n^m + (1 - r_b) \times Y2_n^m) + (1 - r_b) \times Y3_n^m \qquad (27)$$

$$Y3_n^m = Y_n^m - \rho_1 \times (Y2_n^m - Y1_n^m) \qquad (27 - 1)$$

where r_a and r_b are two random numbers in [0, 1].

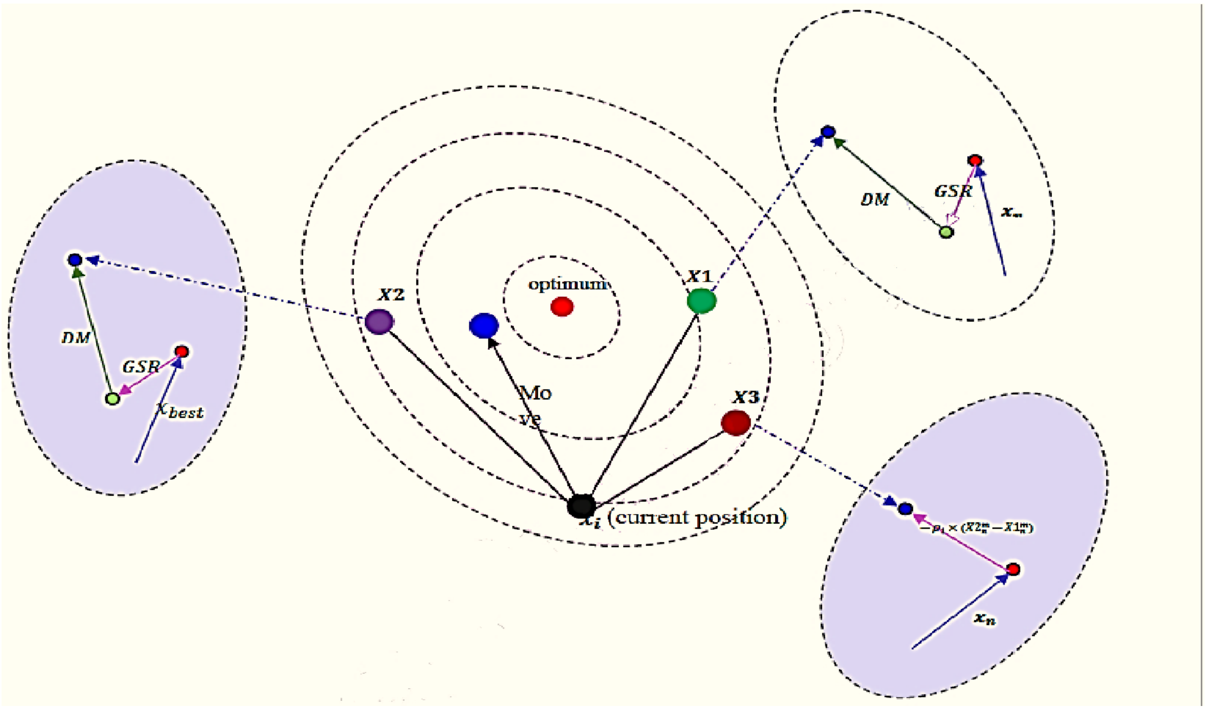


Figure. 3.4 Sketch map of the GBO algorithm

Fig. 4 depicts how a vector updates its position with regard to $Y1_n^m$, $Y2_n^m$ and $Y3_n^m$ in a 2D search space. According to Fig. 4 and Eq. (30), the position y_{n1}^{m+1} would be at a random place determined by the positions $Y1_n^m, Y2_n^m\ and\ Y3_n^m$ and in the search space. Indeed, these three positions specify the positiony_{n1}^{m+1} , and other vectors change their positions randomly aroundy_{n1}^{m+1} .

CHAPTER-4

PACKED U CELL MULTILEVEL INVERTER

This chapter summarizes the conclusions drawn from the results obtained and the literature along with the ideas regarding the future work to imply in the electrical engineering field.

4.1 Introduction:

This chapter presents the waveforms obtained from the simulation performed in MATLAB®/Simulink. The nearest level control scheme is implemented on packed U cell 5 level multilevel inverter. Simulation of selective harmonics elimination of 5th harmonics has also been done with packed U cell multilevel inverter.

Switching pulses, output voltage, output current, ripple voltage across the capacitor and FFT analysis is obtained .this is to be presented one by one in a different section of this chapter.

4.2 Simulation of PUC5 Multilevel Inverter:

4.2.1 Simulink Model:

Fig 4.1 shows the Simulink model of 31 level with modified H bridge modules, all the capacitors are different rating, and it is calculated based on the longest discharging time.

PUC inverter prototype can self-balance for both linear and non-linear loads to validate the planned PUC5. As well as simulating and presenting the proposed topology (Linear and Non-Linear Load), hardware findings were also provided. The simulation was performed on MATLAB/Simulink 2018a platform.

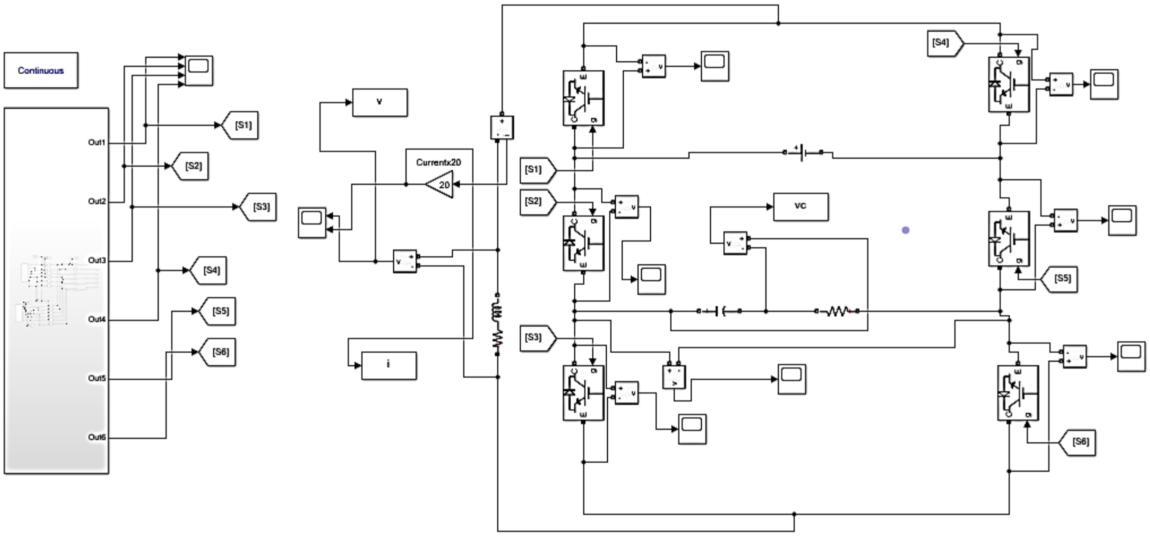


Figure. 4.1 Simulink model of 5 level PUC model multilevel inverter.

4.3 Simulation result:

In figure 4.1, at instant 2.5 seconds the resistance is doubled so that the current reduces to half but in figure 4.2 the current is doubled and resistance is half at 2.5 seconds. Figure 4.3 show the five-level waveform of the output voltage and current and waveform of voltage capacitor is varied between 50.5 to 50.8 volts in resistive load conditions. The inductor has been connected with resistance for the RL load conditions as shown in figure 4.4, the waveform of voltage is the same as in resistive load which is five-level, but the waveform of the current is sinusoidal in nature which shows that it has smooth repetitive oscillation. The voltage capacitor waveform shows variations from 49.8 to 50.3. By adding rectifier to supply circuit, figure 4.5 shows non-linear load conditions with the five-level waveform of output voltage and have symmetric well-balanced current waveform. The voltage capacitor waveform shows variations from 49.9 to 50.4

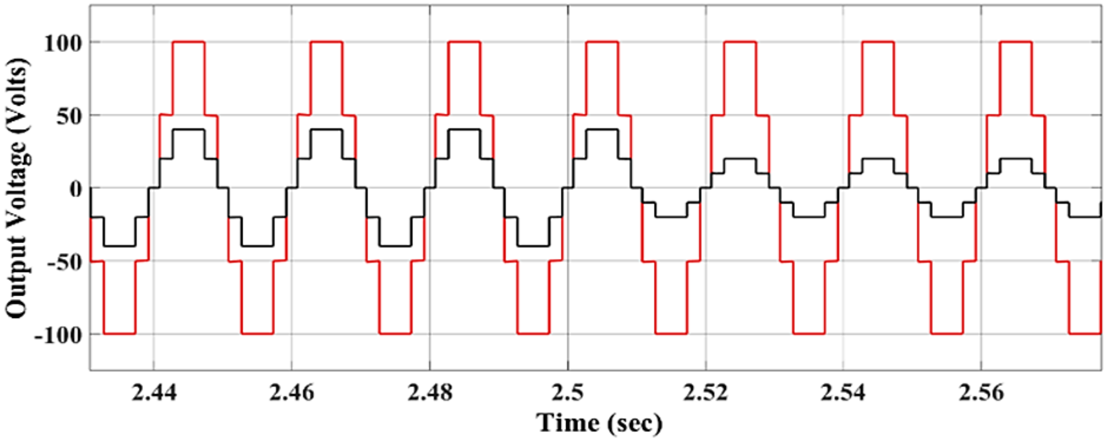


Figure 4.2 Output waveform of Voltage and Current for Change in Loadx`(R Load Increase).

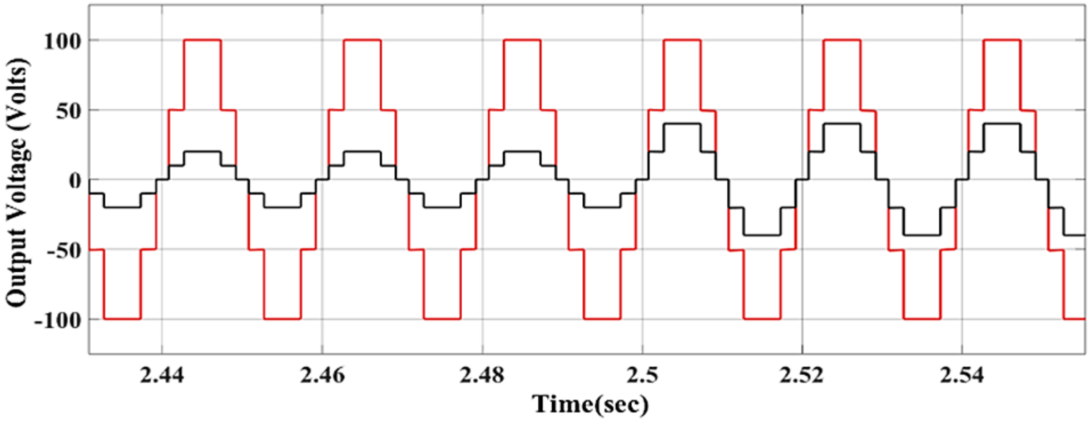


Figure.4.3 Output waveform of Voltage and Current for Change in Load (RL Load Decrease).

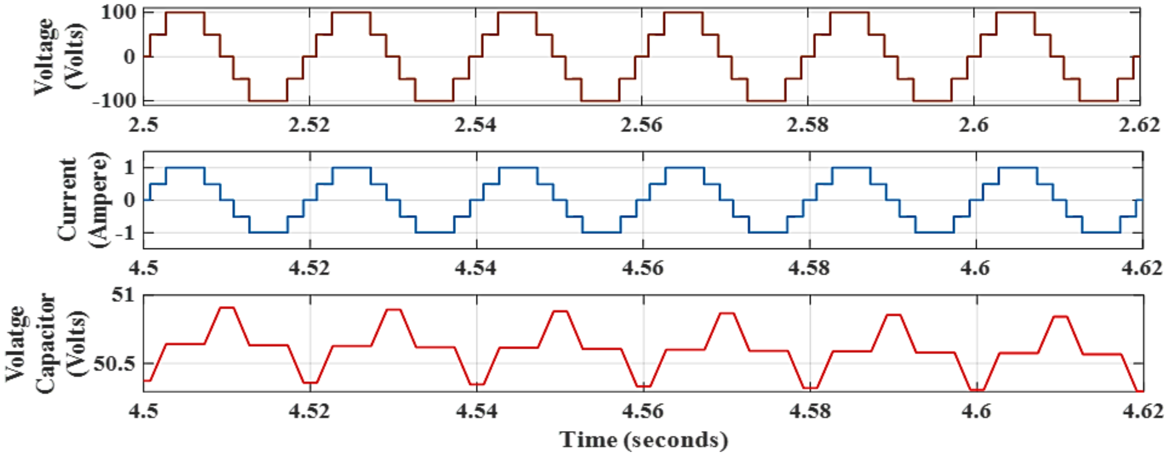


Figure 4.4 Waveform of R Load

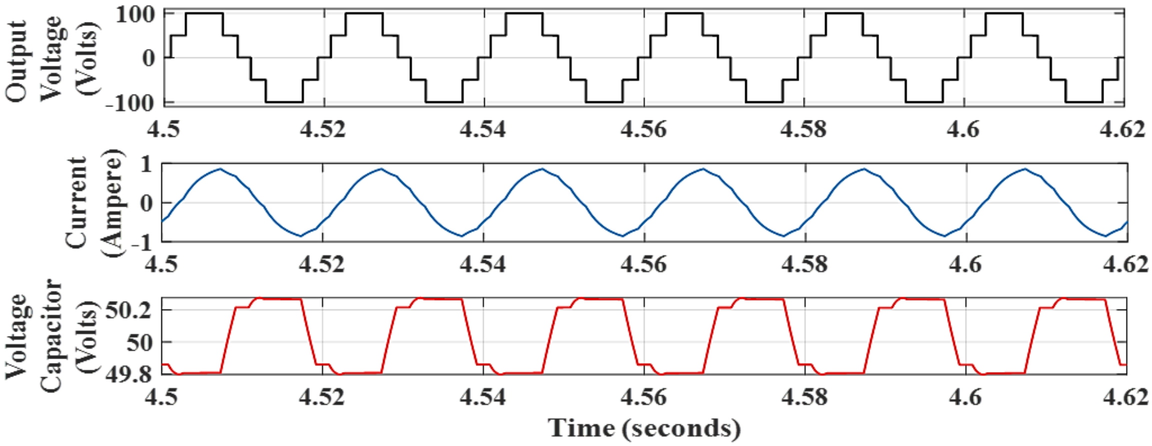


Figure 4.5 Waveform of RL Load

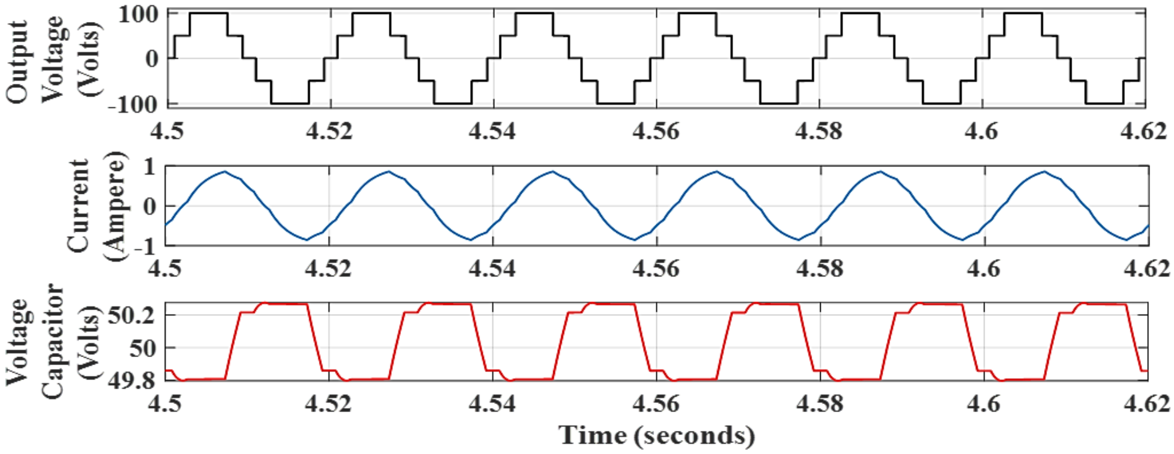


Figure 4.6 Waveform Non Linear Load

Simulation of Selective Harmonic Elimination of 5th Harmonics:

4.3.1 Simulink Model:

Fig 4.7 represents the Simulink model of the proposed scheme. This simulation is carried out after achieving optimized angle for minimum SHE current and voltage THD.

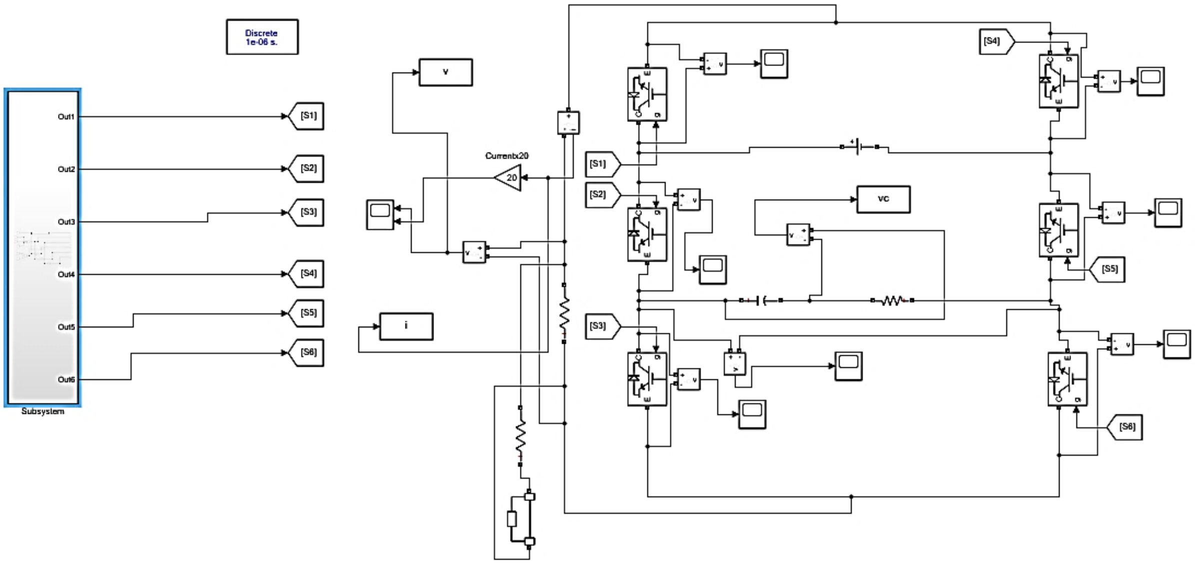


Figure 4.7 Simulink model of SHE connected PUC

4.3.2 Simulation result:

The FFT analysis of output current is shown in Fig.4.7. Fig 4.8 shows Output waveform of current in R Load, Fig 4.9 Output waveform of Voltage in R Load, Fig 4.10 The FFT analysis of RL Load, Fig 4.11 Output waveform of Voltage and current in RL Load, Fig 4.12 The FFT analysis of R Load and Fig 4.13 Output waveform of Voltage current in R Load.

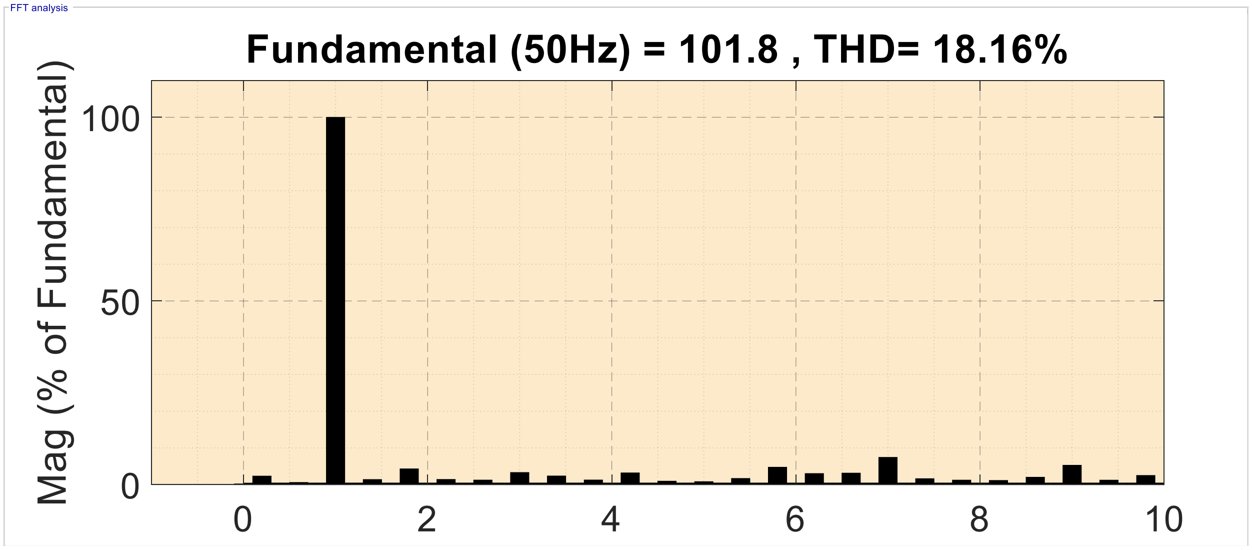


Figure 4.8 The FFT analysis of output Voltage

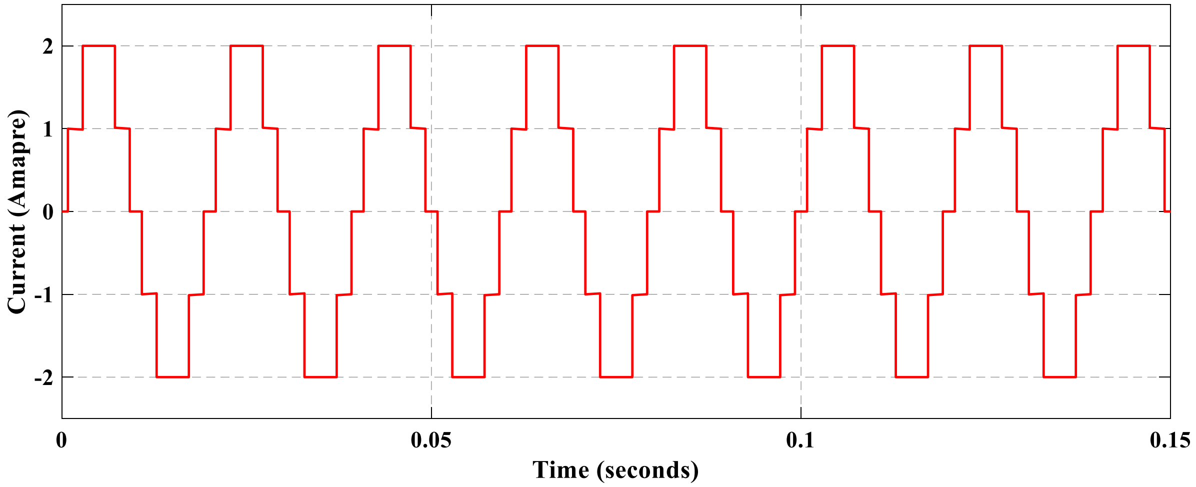


Figure 4.9 Output waveform of current in R Load

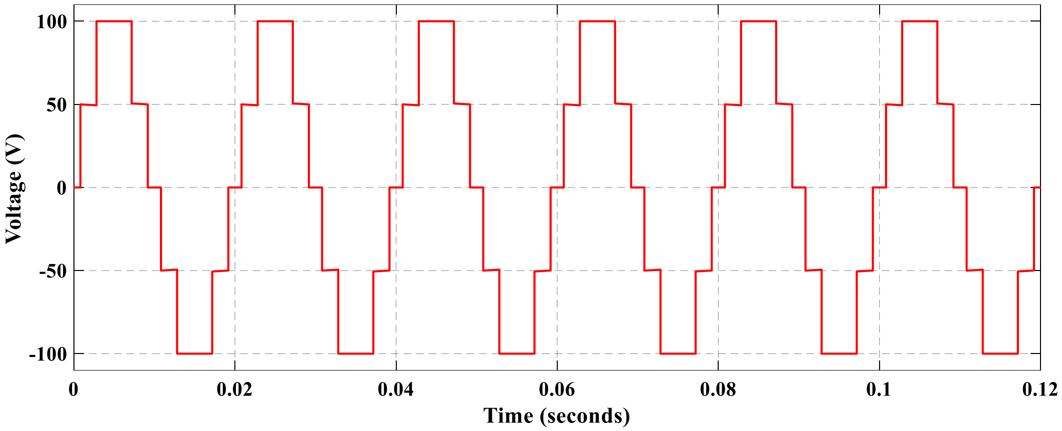


Figure 4.10 Output waveform of Voltage in R Load

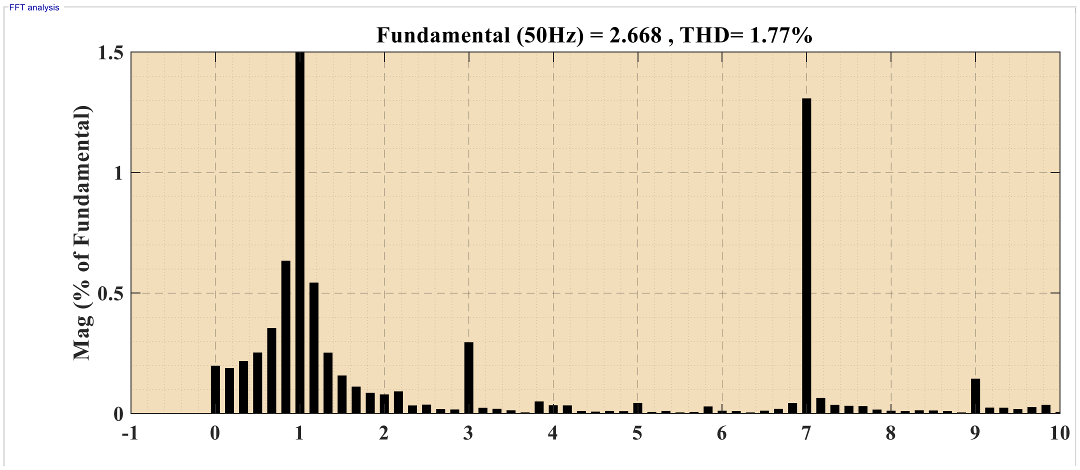


Figure 4.11 The FFT analysis of RL Load

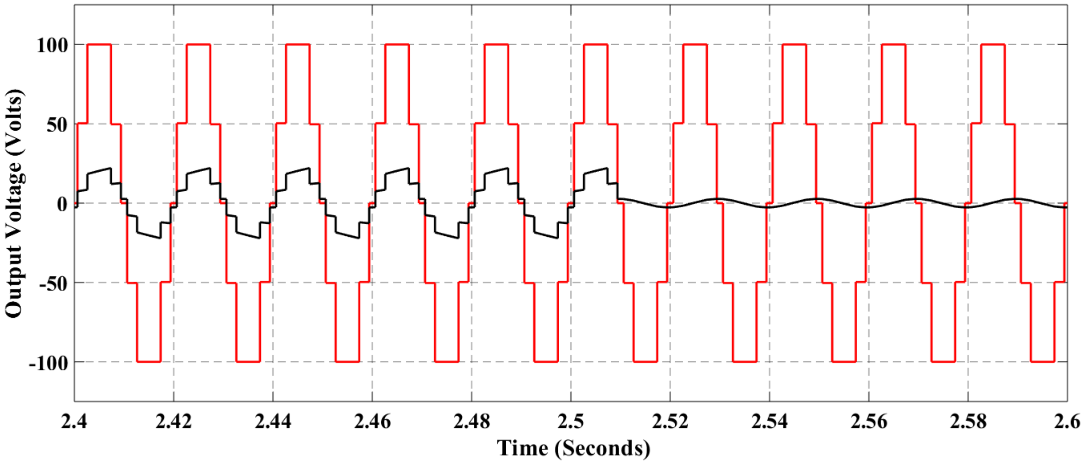


Figure 4.12 Output waveform of Voltage and current in RL Load

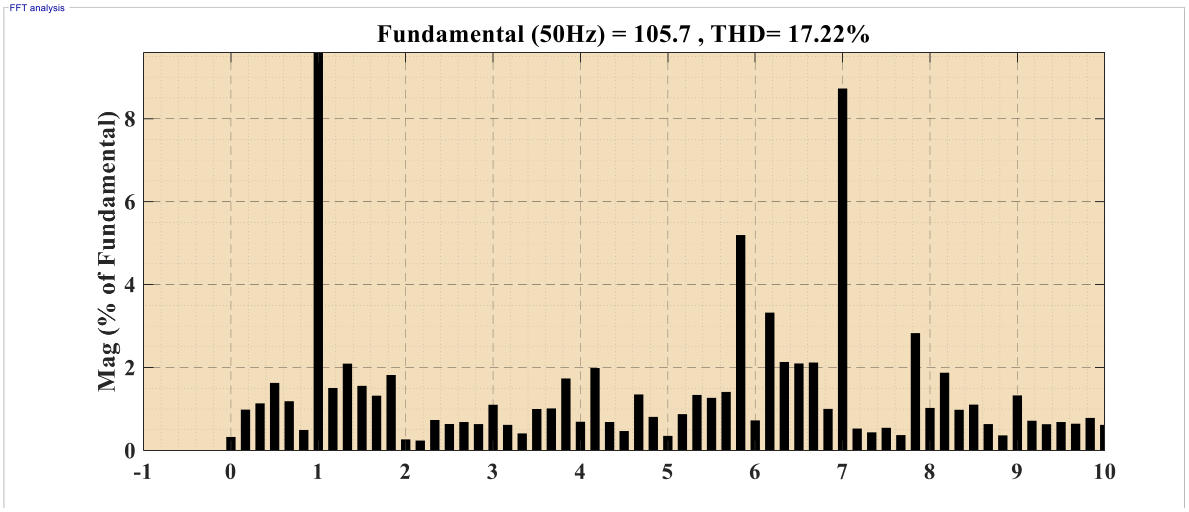


Figure 4.13 The FFT analysis of R Load

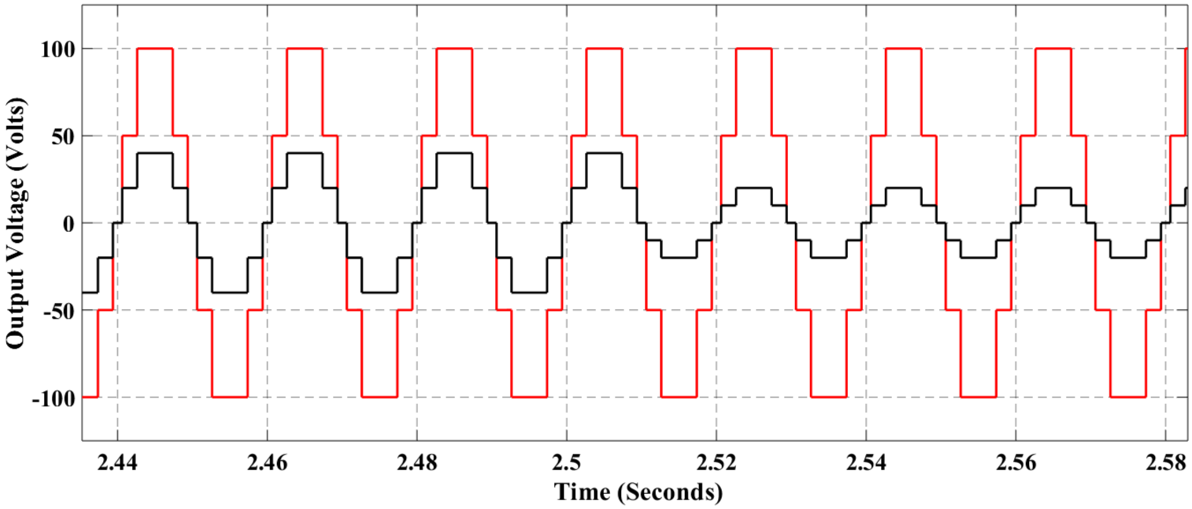


Figure 4.14 Output waveform of Voltage current in R Load

CHAPTER-5

CONCLUSION AND FUTURE SCOOPE

This chapter summarizes the conclusions drawn from the results obtained and the literature along with the ideas regarding the future work to imply in the electrical engineering field.

5.1 Conclusion:

The increase in requirement for electrical energy and the depletion of conventional resources makes the whole world's attention towards the resources which are abundant in nature and also efficient. So the researchers are focused on how to optimize and make the appliances, equipment, and converting devices energy-efficient to achieve the present requirement of energy.

The packed U cell inverter was able to provide varied output levels by adjusting the capacitor voltage. There is a necessity of a single DC-link voltage, which is the key features of this inverter. In this thesis, the performance of the PUC5 MLI has been tested at different current levels and voltage levels. Using redundant switching states and simple voltage balancing, the PUC5 inverter could provide stable performance and straightforward implementation due to integration into general modulation techniques. The five level packed U cell inverter was compared to some commonly used topologies to demonstrate the promising features of that arrangement. Due to its redundant switching states, the PUC5 inverter does not require an external voltage regulator or auxiliary capacitor. The simulation of 5-level PUC topology is performed in MATLAB®/Simulink 2018 using NLC as a modulation scheme. The simulation results that are included are output voltage, load current and THD in output voltage. The elimination of 5th harmonics is also done with low THD and FFT analysis to get the output waveforms of current and voltages. The results has been taken with different loading conditions such as R load RL load.

5.2 Future Work:

Future work may include the hardware implementation of model predictive control of PUC based inverter. It may also include that with Digital storage oscilloscope (DSO) equipment, the THD of current and voltage can be formed. The waveform of change in output voltage and current with different loading conditions can also be formed. There are several topologies methods available for the anticipation and diagnosis THD. As Model Predictive Control for number of power converters are available in the literature, this approach can be further extended to the diagnosis and mitigation of eliminations of further harmonics with different loading conditions.

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Publication

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