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Certificate

This is to certify that the project Report entitled

Design and Implementation of Multilevel Inverters for Electric Vehicles

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ABSTRACT

The efficient and compact design of multilevel inverters (MLI) motivates in various applications such as solar PV and electric vehicles (EV). This paper proposes a 53-Level multilevel inverter topology based on a switched capacitor (SC) approach. The number of levels of MLI is designed based on the cascade connection of the number of SC cells. The SC cells are cascaded for implementing 17 and 33 levels of the output voltage. The proposed structure is straightforward and easy to implement for the higher levels. As the number of active switches is less, the driver circuits are reduced. This reduces the device count, cost, and size of the MLI. The solar panels, along with a perturb and observe (P&O) algorithm, provide a stable DC voltage and is boosted over the DC link voltage using a single input and multi-output converter (SIMO). The proposed inverters are tested experimentally under dynamic load variations with sudden load disturbances. This represents an electric vehicle moving on various road conditions. A detailed comparison is made in terms of switches count, gate driver boards, sources count, the number of diodes and capacitor count, and component count factor. For the 17-level, 33-level, and 53-level MLI, simulation results are verified with experimental results, and total harmonic distortion (THD) is observed to be the same and is lower than 5% which is under IEEE standards. A hardware prototype is implemented in the laboratory and verified experimentally under dynamic load variations, whereas the simulations are done in MATLAB/Simulink.

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The increasing demand for efficient, compact, and cost-effective power electronic systems has driven significant advancements in multilevel inverter (MLI) technology. MLIs are widely recognized for their ability to generate high-quality output voltages with reduced harmonic distortion, making them ideal for applications such as renewable energy systems, electric vehicles (EVs), and industrial motor drives. The core advantage of MLIs lies in their ability to synthesize a staircase-like output voltage waveform, which significantly reduces the total harmonic distortion (THD) and improves the overall power quality compared to traditional two-level inverters.

In recent years, the integration of renewable energy sources, particularly solar photovoltaic (PV) systems, has necessitated the development of advanced inverter topologies that can efficiently handle variable input conditions while maintaining stable output performance. Additionally, the growing popularity of EVs has further emphasized the need for inverters that offer high efficiency, compact size, and reduced complexity to meet stringent performance and cost criteria.

Traditional MLI topologies, such as cascaded H-bridge, diode-clamped, and flying capacitor inverters, often require a large number of active switches, control circuits, and passive components. This not only increases the overall system cost but also adds to the complexity of the design and control strategies. To address these challenges, researchers have proposed various reduced-switch MLI configurations that minimize the component count while maintaining high efficiency and power quality.

In the recent past, various MLI topologies without association with the conventional three types of classification are reported in. Significantly, the sub multilevel converter configurations are proposed in a basic level topology is reported, where multiple dc voltages are required. The coupled inductor-based topologies are documented . These architectures are simple but extending to higher levels is a challenging task. A novel MLI topologies based on switched-capacitor (SC) with boost techniques are presented in where the output voltage levels are limited to 5, 7, and 13, respectively. The MLI topology proposed in can be extended to higher levels. The utilization of several switches and devices increases the cost and size of the system.

Concerning the switched capacitor (SC) technique, a new MLI topology with a multilevel converter and a full bridge is represented . A five-level single phase inverter with a full bridge makes up two diodes, and a single switch is presented in which provides five levels in its output, and its circuitry limits the extension of higher levels. The SC-based MLI topology reported in makes up a frontend SC, and full-bridge backend, the control complexity, and more device count limit the application. As the carrier frequency provides the switching frequency, a high switching loss is irresistible for providing the high-frequency output. A boost MLI with a partial charging technique of SC theoretically can able to extend the number of output voltage levels. The control complexity is high in implementing partial charging . Hence, designing an SC-based MLI with high frequency output, fewer harmonics, and high efficiency is a challenging task . The high-frequency output applies for implementing circuits in electric vehicle (EV) since the weight and size of the system is less.

The photovoltaic power generation comprises solar PV panels, where the output of a solar panel is fed to DC link through a DC-DC converter. The voltage from a DC link is fed to the DC-AC inverter and to load . The output of solar PV is not constant, and it changes according to the solar irradiation and temperature . Therefore, for an efficient operation of PV panels even under various climatic changes, it is essential to extract maximum power from the PV module, admitted to being Maximum power point tracking (MPPT) . Whenever the MPPT exists in a system, a DC-DC converter plays a significant role in handling maximum power as it works with the duty cycle change.

For a PV fed inverter, in producing a stable DC voltage, there is a need for a control technique. A standard PI controller realized in the standalone PV system to select a proper duty cycle of the DC-DC converter by comparing the converter output with reference . It is not desirable to have control over the DC-DC converter with the MPPT technique, and hence various topologies are proposed to solve this issue for the standalone solar system. In the recent past, several advanced techniques like artificial intelligence (AI), practical swarm optimization (PSO), fuzzy and genetic algorithm (GA) to have an auto-control regarding the training data to regulate voltage. The selection of the MPPT technique for a suitable application is an astonishing task where every method has its own merits and demerits. For example, hill climbing (HC), perturb and observing (P&O) and are widely used MPPT methods because of their simple implementation. Under partial shading conditions, the conventional methods like fuzzy, P&O, INC algorithms cannot extract global MPP (GMPP) . Many works of literature have been implemented MLI with DC link with MPPT, where the control of outputs can be done by the load or under steady solar irradiance. MPPT consistently changes the energy of the solar panel to operate at the maximum point of the power, which depends on temperature, load, and solar irradiance. Both solar irradiance and temperature change during day time for climatic conditions and depending on the season. So, it is vital to track all these parameters and get maximum power point.

The Proposed method introduces a novel multilevel inverter topology based on a switched capacitor (SC) approach. The proposed structure leverages the cascade connection of SC cells to achieve higher output voltage levels with fewer active switches and driver circuits. This results in reduced device count, lower cost, and a more compact inverter design, making it particularly suitable for applications in EVs and solar PV systems.

Moreover, the integration of a fuzzy logic controller (FLC) is proposed to enhance the inverter's performance. The FLC provides intelligent control by adjusting the switching patterns based on real-time input conditions, thereby improving the stability and efficiency of the DC voltage supplied by solar panels. The use of a single input, multi-output (SIMO) converter further boosts the DC link voltage, ensuring consistent power delivery to the load.

The proposed work has been implemented, by usig a solar PV system of a 17- level multilevel inverter integrated with a single input, and multiple output DC-DC boost converter is presented. To extract peak energy from the solar panels, P&O powered MPPT technique is implemented. DC voltage from the between the solar panels fed to the single input and multiple output boost converter where the voltage gets boosted to the desired level and provided to the 17-level inverter. The SC units are cascaded to achieve 17, 33 levels of output voltages. Performance of these MLIs based on many such parameters like device count, power losses, efficiency, THD is compared with various MLI topologies and represented. The implemented system is tested in MATLAB/ Simulink, whereas it is tested experimentally with a hardware setup.

1.1 Organisation of thesis :

Chapter 1 Addresses the general introduction of electric vehicle,multi source converters, rules of multi-input converters in electical vehicle and the proposed work has been implemented.

Chapter 2 addresses a complete literature review, Overview of Inverter Technologies in EVs and I-V characteristics and equivalent circuit. It also presents the comparative study and applications along with the selection parameters of multi-input converters for various applications.

Chapter 3 1 addresses the general introduction of electric vehicle and it's types, Equivalent circuit of a solar panel,PV cells and MPPT Controllers, Review of various MPPT algorithms,P&O method modelling of PV and DC-DC boost converter.

Chapter 4 Electrical vehicles with cascade H-bridge for 5 level & 17 level, Generation voltage levels according to Conduction of Switches of 17 MLI and wavefroms for the 5 & 17 level multilevel inverter.

Chapter 5 Comparing 5 level & 17 level multilevel inverters, Reduced Harmonic Distortion,overall difference between 5 level & 17 level and output voltage of Multilevel inverter.

Chapter 6 17 level multilevel inverter, Modes of operation of the proposed 17-Level MLI topology, Simulation results for 17 level MLI, output waveforms for THD.

Chapter 7concludes the thesis by presenting the contribution of research work and further the work to be carried out in future that could be done based on the respective findings.

CHAPTER 2

Literature Review

2.1 Introduction

Electric vehicles (EVs) have become a key focus in the global shift toward sustainable transportation. A major component in EV powertrains is the inverter, which converts DC power from the battery into AC power for the motor. Traditional two-level inverters, although widely used, suffer from limitations such as high total harmonic distortion (THD), significant switching losses, and limited voltage handling capability. To address these issues, multilevel inverters (MLIs) have emerged as an efficient solution, offering superior performance in medium and high-power applications. MLIs can generate stepped output voltages that closely approximate a sinusoidal waveform, reducing harmonics and enabling higher voltage operation with lower voltage-rated devices. The main MLI topologies have been explored extensively in literature: Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB). Among these, CHB inverters are highly suitable for EV applications due to their modular structure and compatibility with battery stacks, where each module can be powered by an individual battery segment. This modularity also enhances fault tolerance and simplifies maintenance. The NPC topology, while efficient in voltage sharing, requires a complex arrangement of clamping diodes and suffers from DC-link capacitor balancing issues at higher levels. Flying Capacitor inverters, though capable of self-voltage balancing, demand numerous capacitors and complicated control methods, making them less favorable for compact EV applications.

Control strategies play a vital role in optimizing the performance of MLIs. Conventional Pulse Width Modulation (PWM) techniques like Sinusoidal PWM and Space Vector PWM have been widely used due to their simplicity and effective harmonic suppression. More advanced strategies such as Selective Harmonic Elimination (SHE) offer precise harmonic control but involve solving complex nonlinear equations. Model Predictive Control (MPC) has also gained attention in recent years for its ability to predict system behavior and optimize switching patterns in real time, although its computational demands require highspeed processors or FPGA implementation. In the context of electric vehicles, MLIs contribute significantly to efficient motor control, especially for Permanent Magnet Synchronous Motors (PMSMs) and Brushless DC Motors (BLDCs). These motors benefit from the high-quality output waveform of MLIs, which reduces torque ripple, enhances speed control, and extends battery life through improved energy efficiency. Furthermore, the use of multilevel inverters supports regenerative braking, enabling energy recovery and boosting overall vehicle range.

Recent research has also focused on integrating MLIs with wide-bandgap semiconductor devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN) transistors. These devices allow for higher switching frequencies, improved thermal performance, and reduced system size and weight—attributes that are highly desirable in EV applications. Moreover, trends in the field show a shift toward reduced switch-count topologies, hybrid inverters, and intelligent control algorithms using artificial intelligence and machine learning to further optimize efficiency and reliability.

The rapid evolution of electric vehicles (EVs) has driven significant advancements in power electronic systems, with the inverter playing a pivotal role in the drivetrain. The inverter is responsible for converting the DC power from the battery into AC power to drive the traction motor. While conventional two-level inverters have been widely used, they exhibit several limitations in high-voltage and high-power applications, such as increased switching losses, high dv/dt stress on motors, and significant total harmonic distortion (THD). These drawbacks can lead to reduced system efficiency, electromagnetic interference (EMI), and torque ripple in the motor. To address these challenges, multilevel inverters (MLIs) have been introduced, offering distinct advantages in terms of improved output voltage quality, lower THD, reduced voltage stress on switching devices, and enhanced power efficiency.

Multilevel inverters synthesize a staircase AC voltage from multiple DC voltage levels, producing waveforms that closely approximate a sinusoidal shape. Among the widely studied topologies are the Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded HBridge (CHB) inverters. The NPC topology utilizes clamping diodes to divide the voltage stress among switches, making it suitable for medium-voltage applications; however, its complexity increases significantly with the number of levels, especially due to capacitor voltage balancing issues. Flying Capacitor inverters use capacitors to generate intermediate voltage levels and offer some self-voltage balancing features, but they require a large number of capacitors, leading to a bulky design and complicated control. On the other hand, the CHB inverter topology has gained widespread attention in EV applications due to its modular structure, scalability, and ease of integration with battery systems. In CHB inverters, each

Hbridge module can be powered by a separate battery unit, which simplifies voltage level generation and enhances redundancy and fault tolerance.

The control of multilevel inverters is a critical aspect of their performance. Traditional Pulse Width Modulation (PWM) techniques such as Sinusoidal PWM (SPWM) are simple and easy to implement but suffer from high switching losses and poor harmonic performance at higher levels. Space Vector Modulation (SVM) offers better utilization of the DC bus and improved harmonic suppression, making it more efficient for three-phase systems. Advanced control strategies like Selective Harmonic Elimination (SHE) have been used to eliminate specific harmonic components, although they require solving complex nonlinear equations. More recently, Model Predictive Control (MPC) and Artificial Intelligence (AI)-based techniques have been explored for real-time control and optimization. MPC predicts the future behavior of the system and selects the switching state that minimizes a cost function, resulting in better dynamic performance and reduced THD. AI-based controllers, using neural networks or fuzzy logic, are being investigated to handle nonlinearities and uncertainties in EV drive systems, showing promise for future smart inverters.

In terms of application in electric vehicles, MLIs are crucial for driving high-efficiency motors such as Permanent Magnet Synchronous Motors (PMSMs), Brushless DC Motors (BLDCs), and Induction Motors (IMs). The improved waveform quality of MLIs leads to smoother torque production, reduced acoustic noise, and better overall energy efficiency. Additionally, multilevel inverters enable bidirectional power flow, which is essential for implementing regenerative braking in EVs—a key feature that recovers kinetic energy during deceleration and stores it back in the battery. The modular nature of CHB inverters is particularly advantageous in EVs, allowing direct integration with battery packs, facilitating dynamic voltage scaling, and improving fault isolation. Recent developments in the field focus on improving the power density and efficiency of MLIs through the use of wide-bandgap semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN). These materials allow for higher switching frequencies, lower conduction losses, and smaller passive components, which contribute to lighter and more compact inverter designs—an important consideration in space-constrained EV environments. Researchers are also working on novel inverter configurations with reduced switch count, hybrid topologies that combine the strengths of multiple inverter types, and integration of the inverter system with battery management and vehicle control units. Another significant trend is the development of fault-tolerant inverter designs that can continue operating under switch or module failures, increasing the reliability and safety of EV systems.

Overall, the literature suggests that multilevel inverters are a vital component in the push for high-performance and energy-efficient electric vehicles. Their ability to deliver high-quality voltage waveforms, improved efficiency, and adaptability to modular battery systems positions them as a preferred choice for next-generation EV powertrains. However, challenges such as increased system complexity, control demands, and cost still need to be addressed through innovative design approaches, advanced control algorithms, and integration of emerging semiconductor technologies.

The increasing demand for electric vehicles (EVs) necessitates advancements in power electronic systems, particularly inverters, which play a critical role in electric drivetrain performance. Multilevel inverters (MLIs) have emerged as a promising solution for highpower applications due to their ability to synthesize high-quality voltage waveforms with reduced harmonic distortion, improved efficiency, and lower electromagnetic interference (EMI). This chapter reviews the existing literature on multilevel inverter topologies, control strategies, and their integration into EV systems. This section introduces the importance of inverters in electric vehicles (EVs) and the limitations of conventional two-level inverters. It establishes the motivation for adopting multilevel inverters (MLIs) in EV powertrains for improved performance and efficiency.

2.2 Overview of Inverter Technologies in EVs

➢ 2.2.1 Role of Inverters in Electric Vehicles

Inverters convert DC power from the battery into AC for motor drive, enabling variable speed and torque control. In electric vehicles (EVs), inverters serve as a fundamental component in the powertrain by converting direct current (DC) from the battery into alternating current (AC) suitable for driving the electric motor. The inverter's role extends beyond simple power conversion; it enables precise control of motor speed, torque, and direction through modulation techniques. This is essential for achieving efficient acceleration, regenerative braking, and smooth driving performance.

Modern EVs typically employ AC motors, such as Permanent Magnet Synchronous Motors (PMSMs) or Induction Motors (IMs), which require a variable-frequency and variablevoltage AC supply. The inverter facilitates this requirement by adjusting the output frequency and amplitude in real time based on inputs from the vehicle control unit (VCU). Moreover, in regenerative braking mode, the inverter operates in reverse, converting AC generated by the motor back into DC to recharge the battery, thereby improving the vehicle's energy efficiency and extending its driving range.

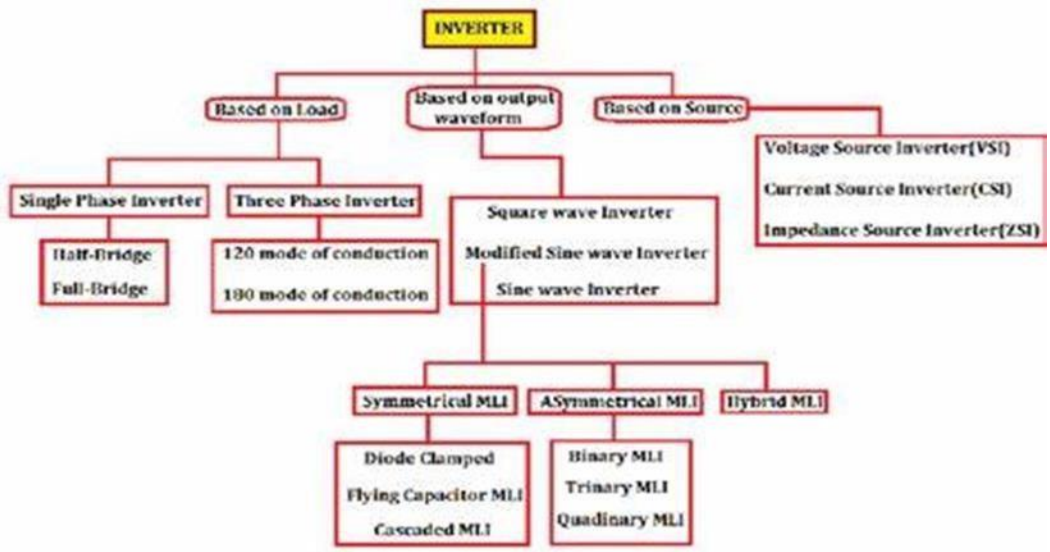

Fig.2.:Types of inverter

In addition to controlling motor operation, inverters play a critical role in energy management and thermal regulation within the EV. Efficient inverter design reduces switching and conduction losses, which not only conserves energy but also minimizes heat generation, leading to more compact and lightweight thermal management systems. In recent years, the integration of intelligent control algorithms and wide-bandgap semiconductor devices in inverters has significantly enhanced their performance, reliability, and compactness key requirements for modern electric mobility solutions.

➢ 2.2.2 Limitations of Inverters in Electric Vehicles

While inverters are essential components in electric vehicles (EVs), enabling DC-to-AC power conversion and motor control, they also present several limitations that can affect the overall performance, efficiency, and reliability of EV systems.

1. **Harmonic Distortion and Torque Ripple**

Inverters, especially conventional two-level types, generate output waveforms that are not perfectly sinusoidal, leading to total harmonic distortion (THD). This can cause torque ripple in electric motors, increased acoustic noise, and heating losses, all of which degrade motor performance and reduce efficiency.

2. High Switching Losses

To improve the quality of the AC output, inverters often operate at high switching frequencies. However, this results in significant switching losses, particularly in silicon-based power electronic devices. These losses lead to heat generation, which demands robust thermal management systems and affects system efficiency.

3. Electromagnetic Interference (EMI)

Rapid switching transients in inverter circuits can cause EMI, which may interfere with sensitive vehicle electronics and communication systems. EMI mitigation requires additional filtering components, which add to the weight and cost of the inverter system.

4. Voltage Stress on Components

Inverters subject power devices and motor windings to high dv/dt and peak voltages. Over time, this can lead to insulation degradation, premature failure of switching devices, and reduced motor lifespan, especially in high-voltage applications.

5. Complexity in Multilevel Inverters

Although multilevel inverters offer improved waveform quality, their design complexity increases with the number of levels. More components (switches, diodes, capacitors) mean a higher probability of faults, more difficult control algorithms, and challenges in balancing voltages across cells or capacitors.

6. Cost and Size Constraints

Advanced inverters using wide-bandgap semiconductors like SiC or GaN offer high performance but are expensive. Additionally, incorporating filters, heat sinks, and control units increases the size and weight of the system, which conflicts with the need for compact and lightweight EV designs.

7. Reliability and Fault Tolerance

Inverters are subject to harsh operating conditions, including thermal cycling, vibrations, and voltage transients. Failure in a power device can lead to system shutdown. Designing inverters with redundancy or fault-tolerant features is complex and costly.

2.3 Two – Level Inverters

A Two-Level Inverter is a basic type of voltage source inverter (VSI) that converts direct current (DC) into alternating current (AC). It is called "two-level" because the output voltage switches between two discrete levels, typically +Vdc/2 and -Vdc/2. The inverter operates using power semiconductor switches, such as IGBTs or MOSFETs, which are controlled to generate a square wave or a pulse width modulated (PWM) waveform that approximates a sine wave. In single-phase configurations, the inverter uses four switches arranged in an Hbridge, while in three-phase systems, it uses six switches, two per phase. The primary goal is to produce a desired AC voltage and frequency suitable for powering loads like motors or supplying energy to the grid in renewable energy systems. Despite its simplicity and ease of implementation, the two-level inverter has limitations such as higher harmonic distortion compared to multilevel inverters. To improve the quality of the output waveform, PWM techniques such as Sinusoidal PWM are employed. These techniques adjust the width of the output pulses to better approximate a sinusoidal output, improving performance and reducing harmonic content.

Two-level inverters are a type of power electronic converter that converts DC into AC with two distinct voltage levels. They have a simple design and relatively low component count, making them easy to implement and cost-effective. Two-level inverters operate at high switching frequencies, leading to higher efficiency and better output waveform quality. They're commonly used in renewable energy systems, motor drives, and power supplies, offering advantages like simplicity and reliability, but may have limitations in terms of output voltage levels and total harmonic distortion.

2.3.1 Advantages of Two- level Inverter

1.Simple to design and control.

2.Low cost and easy to implement.

3.Good for low and medium power applications.

2.3.2limitations of Two-level Inverter

1.High harmonic content in output.

2.Requires filtering to get smooth sinusoidal output.

3. Limited voltage levels lead to less precise waveform synthesis compared to multilevel inverters.

2.4 Multilevel Topologies

Multilevel inverter topologies are advanced inverter designs that generate output voltages with multiple discrete levels, providing a waveform that more closely approximates a sinusoid compared to traditional two-level inverters. These topologies are particularly useful in medium and high-power applications, where they help to reduce harmonic distortion, electromagnetic interference, and stress on power electronic components. The basic idea behind multilevel inverters is to synthesize a staircase-like voltage waveform by combining several voltage levels derived from multiple DC sources or capacitors. The most common multilevel topologies are the Diode-Clamped (Neutral Point Clamped, NPC), Flying Capacitor, and Cascaded H-Bridge inverters. Each of these topologies has unique structural and operational characteristics: the diode-clamped inverter uses clamping diodes to fix voltage levels, the flying capacitor inverter uses capacitors for voltage balancing, and the cascaded H-bridge inverter connects multiple H-bridge units in series, each powered by its own DC source. These inverters offer improved power quality, reduced filter requirements, and better efficiency at higher voltages, but they also come with increased complexity, more components, and challenges in voltage balancing and control. Multilevel inverters are widely used in industrial drives, renewable energy systems, HVDC transmission, and electric vehicles, where performance and power quality are critical.

Electric vehicles (EVs) demand efficient, compact, and reliable power conversion systems to manage energy between the battery and the traction motor. Traditional two-level inverters, while simple, often struggle with issues like high harmonic distortion and voltage stress on switches, leading to reduced efficiency and increased filtering requirements. As a result, multilevel inverter (MLI) topologies have emerged as a promising solution for EV applications due to their ability to produce higher quality output waveforms with lower total harmonic distortion (THD), reduced electromagnetic interference (EMI), and better voltage handling capabilities.

2.4.1 Advantages of Multilevel Inverter Topologies:

- **Improved Output Quality:**

Multilevel inverters produce output waveforms that closely approximate a sinusoidal shape, resulting in lower total harmonic distortion (THD).

- **2.Lower Switching Losses:**

Since switches operate at lower voltage steps and can be turned on/off at lower frequencies, switching losses are reduced compared to traditional inverters.

- **Reduced Electromagnetic Interference (EMI):**

Smoother output voltage with smaller voltage steps helps minimize EMI in sensitive applications.

- **High Voltage Capability:**

By stacking voltage levels, multilevel inverters can handle higher voltages without increasing switch ratings, which is beneficial in medium to high-voltage applications.

- **Modular Design (especially in Cascaded H-Bridge):**

Easier scalability and maintenance, with potential for redundancy and fault tolerance.

- **Reduced Filter Size:**

Because the output waveform is closer to a sine wave, smaller or no output filters are needed to meet power quality standards

2.4.2 Limitations of Multilevel Inverter Topologies:

- **Complex Control Strategy:**

Requires sophisticated modulation techniques (like multicarrier PWM or space vector modulation) to manage multiple switches and voltage levels.

- **Increased Component Count:**

More switches, diodes, and/or capacitors are required, which leads to higher cost, size, and complexity.

- **Balancing Issues:**

Voltage balancing across capacitors (in Flying Capacitor or NPC types) and between Hbridge cells (in Cascaded types) can be difficult and requires active control.

- **Protection and Reliability:**

With more components, the probability of faults increases, and protecting the system becomes more challenging.

- **Bulky Design:** Especially in higher-level systems, the inverter can become large and heavy, which may not be ideal for compact installations.

2.5 SOLAR ENERGY

The steady increase in the level of greenhouse gas emissions and fuel costs are the main motive behind the attempt to use different sources of renewable energy . Among various sustainable sources of energy, the solar energy is a suitable one because it is clean, free from emission and easy to change directly to electricity utilising a photovoltaic (PV) system. The generation of PV power has demonstrated a noteworthy potential in satisfying the demand for energy. Up to the year 2016, the worldwide operation of the sun-oriented power generation capacity has ascended to 302 GWp, which is enough to supply 1.8 per cent of the world energy demand. The solar power generation capacity has increased by nearly 100 GWp in 2017, which is about 31 per cent more from 2017. However, the extensive use of a PV system is not so common because of its high starting cost. Again, there is no assurance that the energy delivered from PV exhibits steady output since it relies completely on the sun-oriented irradiance and the surrounding temperature of the PV modules, cell region, and load. For efficient operation of the PV cell under prevailing climatic conditions, an appropriate mechanism is necessary for achieving maximum power from it, which is considered as a maximum power point tracking (MPPT) in the literature. The MPPT increases the efficiency and lifetime of the PV module .

Researchers around the world create various methodologies to take out as much power as could reasonably be expected from sustainable power sources and particularly, from the PV panels. Until now, a large number of MPPT algorithms are accessible in the literature for both off-grid and grid associated PV systems . The selection of a specific MPPT system from the various existing MPPT methods is a confounding errand since every method has certain focal points and disadvantages. For example, the hill climbing (HC) and perturb and observe (P&O) methods are broadly utilised as MPPT algorithms because of their simple execution and fewer sensor necessities. The incremental conductance (INC) algorithm , which looks at incremental and momentary conductance of PV systems, can track the maximum power point (MPP) of a PV system and exchange high PV power to the load. The research work presented in clarifies the misconception between the widely used P&O and INC algorithms and shows that they are almost highly identical under steady-state and transient conditions. It is shown that they both have similar mathematical expression except that the INC ignores the higher-order term in the discrete differentiation of the power. The sliding control (SC) method, however, complex in equipment usage yet, is more precise than ordinary methods .The classical algorithms, such as P&O, INC, HC, fuzzy logic and neural network, cannot find the global MPP (GMPP) under partial shading condition (PSC). A comparison among various global MPPT (GMPPT) methods based on meta-heuristic algorithms is given . It is concluded that particle swarm optimisation (PSO) and Cuckoo search (CuS) algorithms based trackers ensure the convergence to the GMPP and the tracking performance of the CuS algorithm is better than the PSO. For effectively tracking the MPPT of a PV system, a model-free spline-guided Jaya algorithm is proposed in, which is able to perform efficiently under PSC and also provides faster convergence speed. An MPPT technique based on temperature described in needs a fewer number of sensors than customary strategies. This technique is straightforward in execution and is economical too. The bisection search theorem-based MPPT, detailed in is generally utilised when the PV array shows at least two neighbourhood MPPs under changing climatic conditions, where the utilisation of different methods is a troublesome undertaking.

Until now, the operation of various MPPT methods is presented by various research papers. A lot of research works have also been published to classify these methods. Research works in present a categorisation approach for MPPT methods based on three categories such as off-line, online and hybrid methods. The research work in categorises the MPPT methods as analogue, digital, and hybrid methods and provides a comparison based on only five selection parameters. In the MPPT methods are categorised into five categories based on their tracking techniques and the comparison that is given based on five selection parameters. These available categorisation methods cannot classify all the available methods appropriately and the available comparison among the MPPT methods does not consider all the available selection parameters. An endeavour is made in this study to categorise the discussed 50 MPPT methods into eight categories based on their tracking nature and manipulation techniques for finding the true MPP. The categorised eight groups are conventional methods, methods based on mathematical calculations, constant parameters based methods, measurement and comparison based methods, trial and error based methods, numerical methods, intelligent prediction based methods, and methods based on iterative in nature. To find out the efficient method among others, a tabular comparison is also done in each category based on 11 selection parameters. The considered 11 selection parameters are design complexity, sense parameters, PV array dependency, prior training, periodic tuning, convergence speed, analogue/digital in nature, cost, tracking true MPP, stability, and efficiency of the system. These comparison tables and ways of categorisation will be helpful in future for selecting appropriate MPPT methods for the solar PV system.

2.5.1 Model of PV cell

The model of a solar PV cell is an important part of analysing a PV system. Its modelling is classified into three sections, which are described below.

2.5.2 I-V characteristics and equivalent circuit

PV begins from two separate words – photo, which implies light, and voltaic, which alludes to the production of power. Subsequently, the term PV brings the significance of producing power specifically from the sun. A sun-powered array comprised several combinations of sun-based modules, where every module comprised various solar cells . Solar cells comprise p–n diodes manufactured in a thin layer of semiconductor . They resemble p–n diodes and their attributes are additionally comparative displays the equivalent circuit of a perfect PV cell . This ideal structure is sufficiently precise to comprehend the PV attributes and the reliance of the PV cell on varying climatic conditions. The aggregate output current of the parallel and series connected PV modules is expressed where Ipv is the output current, Vpv is the output voltage, Rs is the series resistance, Rp is the parallel resistance, Np and Ns are the number of PV cells connected in parallel and series for a given PV module, A is the ideality factor of the p–n junction, K is the Boltzmann's constant (1.3806503 x 10^{-23}J/K), T is the temperature in Kelvin, q is the charge of electron (1.6x10^{-19}C) Iph is the produced photocurrent; it depends fundamentally on the radiation and cell's temperature, which is expressed as where Iscc-stc refers to the short-circuit current (SCC) at standard test conditions (STC) in amperes, Tst (25^0C) is the cell temperature at STC, G (in watts per square meters,) is the irradiation on the cell surface, Gstc(1000W/m^2) is the irradiation at STC and is the SCC coefficient, as a rule, given by the cell producer. In addition, the saturation current, , is impacted by the temperature as indicated by the accompanying equation where (Vocv-stc in volt, V) is the open circuit voltage (OCV) at STC, Kv is the OCV coefficient, Vth refers to the thermal voltage of the cell, these values are available on the data sheet provided by module's manufacturer. With Vpv and simplified Ipv, the power produced by the PV module is represented

The I-V and P-V characteristics curve of the solar cell is shown in Fig.2 The curve in this figure indicates that the operating point of the PV does not remain at a stable point; it actually varies from zero to open-circuit voltage. There is only one point, which enables maximum power for a given set of solar insolation and temperature level. That particular point is indicated as MPP and at that point, the current and voltage that are found are presented as Impp and Vmpp.This significant MPP and its numerous tracking methods are the main focal point of this review work.

Chapter 3

PROPOSED SYSTEM

.3.Introduction to Multilevel Inverter

A multilevel inverter is a power electronic device that is capable of providing desired alternating voltage level at the output using multiple lower-level DC voltages as an input.Mostly a two-level inverter is used in order to generate the AC voltage from DC voltage.

Now the question arises what’s the need of using a multilevel inverter when we have a two-level inverter. In order to answer this question, first, we need to look at the concept of the multilevel inverter.

3.1: Multilevel Inverter:

Now a day’s many industrial applications have begun to require high power. Some appliances in the industries, however, require medium or low power for their operation. Using a high power source for all industrial loads may prove beneficial to some motors requiring high power, while it may damage the other loads. Some medium voltage motor drives and utility applications require medium voltage. The multi-level inverter has been introduced since 1975 as an alternative in high power and medium voltage situations. The Multilevel inverter is like an inverter and it is used for industrial applications as an alternative in high power and medium voltage situations.

Fig .3: Multilevel inverter

General DC-AC Inverter Circuit

The need for the multilevel converter is to give high output power from the medium voltage source. Sources like batteries, supercapacitors, the solar panel are medium voltage sources. The multi-level inverter consists of several switches. In the multi-level inverter, the arrangement switches' angles are very important.

3.2: Types of Multilevel Inverter:

Multilevel inverters are three types.

- Diode clamped multilevel inverter
- Flying capacitors multilevel inverter
- Cascaded H- bridge multilevel inverter

3.2.1.Diode clamped multilevel inverter :

The main concept of this inverter is to use diodes and provides the multiple voltage levels through the different phases to the capacitor banks which are in series. A diode transfers a limited amount of voltage, thereby reducing the stress on other electrical devices. The maximum output voltage is half of the input DC voltage. It is the main drawback of the diode clamped multilevel inverter. This problem can be solved by increasing the switches, diodes, capacitors. Due to the capacitor balancing issues, these are limited to the three levels. This type of inverters provides high efficiency because of the fundamental frequency used for all the switching devices and it is a simple method of the back to back power transfer systems.

3.2.2. Flying Capacitors Multilevel Inverter:

A flying capacitor is a type of capacitor that is used in multi-level inverters, common in applications such as electric vehicle (EV) inverters, battery management systems (BMSs), renewable energy systems, and other power electronics. The main function of a flying capacitor is to store and transfer energy between different levels of the inverter, using multiple capacitors connected in series and parallel to produce a desired voltage level.

3.2.3.Cascaded H- bridge multilevel inverter:

The Cascade H-Bridge Multilevel Inverter (CHB-MLI) is another popular multilevel inverter topology used in high-power applications. This type of inverter is known for its modular and flexible structure, which allows it to generate multiple voltage levels in a simpler manner compared to other multilevel inverters. The CHB-MLI uses a combination of **H-bridge inverters** connected in series to produce a higher number of voltage levels, making it particularly useful for applications requiring high-quality power conversion with minimal harmonic distortion.

3.3 PV CELL

The steady increase in the level of greenhouse gas emissions and fuel costs are the main motive behind the attempt to use different sources of renewable energy . Among various sustainable sources of energy, the solar energy is a suitable one because it is clean, free from emission and easy to change directly to electricity utilising a photovoltaic (PV) system. The generation of PV power has demonstrated a noteworthy potential in satisfying the demand for energy. Up to the year 2016, the worldwide operation of the sun-oriented power generation capacity has ascended to 302 GWp, which is enough to supply 1.8 per cent of the world energy demand. The solar power generation capacity has increased by nearly 100 GWp in 2017, which is about 31 per cent more from 2017. However, the extensive use of a PV system is not so common because of its high starting cost. Again, there is no assurance that the energy delivered from PV exhibits steady output since it relies completely on the sun-oriented irradiance and the surrounding temperature of the PV modules, cell region, and load. For efficient operation of the PV cell under prevailing climatic conditions, an appropriate mechanism is necessary for achieving maximum power from it, which is considered as a maximum power point tracking (MPPT) in the literature. The MPPT increases the efficiency and lifetime of the PV module .

Researchers around the world create various methodologies to take out as much power as could reasonably be expected from sustainable power sources and particularly, from the PV panels. Until now, a large number of MPPT algorithms are accessible in the literature for both off-grid and grid associated PV systems . The selection of a specific MPPT system from the various existing MPPT methods is a confounding errand since every method has certain focal points and disadvantages. For example, the hill climbing (HC) and perturb and observe (P&O) methods are broadly utilised as MPPT algorithms because of their simple execution and fewer sensor necessities. The incremental conductance (INC) algorithm , which looks at incremental and momentary conductance of PV systems, can track the maximum power point (MPP) of a PV system and exchange high PV power to the load. The research work presented in clarifies the misconception between the widely used P&O and INC algorithms and shows that they are almost highly identical under steady-state and transient conditions. It is shown that they both have similar mathematical expression except that the INC ignores the higher-order term in the discrete differentiation of the power. The sliding control (SC) method, however, complex in equipment usage yet, is more precise than ordinary methods .The classical algorithms, such as P&O, INC, HC, fuzzy logic and neural network, cannot find the global MPP (GMPP) under partial shading condition (PSC). A comparison among various global MPPT (GMPPT) methods based on meta-heuristic algorithms is given . It is concluded that particle swarm optimisation (PSO) and Cuckoo search (CuS) algorithms based trackers ensure the convergence to the GMPP and the tracking performance of the CuS algorithm is better than the PSO. For effectively tracking the MPPT of a PV system, a model-free spline-guided Jaya algorithm is proposed in, which is able to perform efficiently under PSC and also provides faster convergence speed. An MPPT technique based on temperature described in needs a fewer number of sensors than customary strategies. This technique is straightforward in execution and is economical too. The bisection search theorem-based MPPT, detailed in is generally utilised when the PV array shows at least two neighbourhood MPPs under changing climatic conditions, where the utilisation of different methods is a troublesome undertaking.

Until now, the operation of various MPPT methods is presented by various research papers. A lot of research works have also been published to classify these methods. Research works in present a categorisation approach for MPPT methods based on three categories such as off-line, online and hybrid methods. The research work in categorises the MPPT methods as analogue, digital, and hybrid methods and provides a comparison based on only five selection parameters. In the MPPT methods are categorised into five categories based on their tracking techniques and the comparison that is given based on five selection parameters. These available categorisation methods cannot classify all the available methods appropriately and the available comparison among the MPPT methods does not consider all the available selection parameters. An endeavour is made in this study to categorise the discussed 50 MPPT methods into eight categories based on their tracking nature and manipulation techniques for finding the true MPP. The categorised eight groups are conventional methods, methods based on mathematical calculations, constant parameters based methods, measurement and comparison based methods, trial and error based methods, numerical methods, intelligent prediction based methods, and methods based on iterative in nature. To find out the efficient method among others, a tabular comparison is also done in each category based on 11 selection parameters. The considered 11 selection parameters are design complexity, sense parameters, PV array dependency, prior training, periodic tuning, convergence speed, analogue/digital in nature, cost, tracking true MPP, stability, and efficiency of the system. These comparison tables and ways of categorisation will be helpful in future for selecting appropriate MPPT methods for the solar PV system.

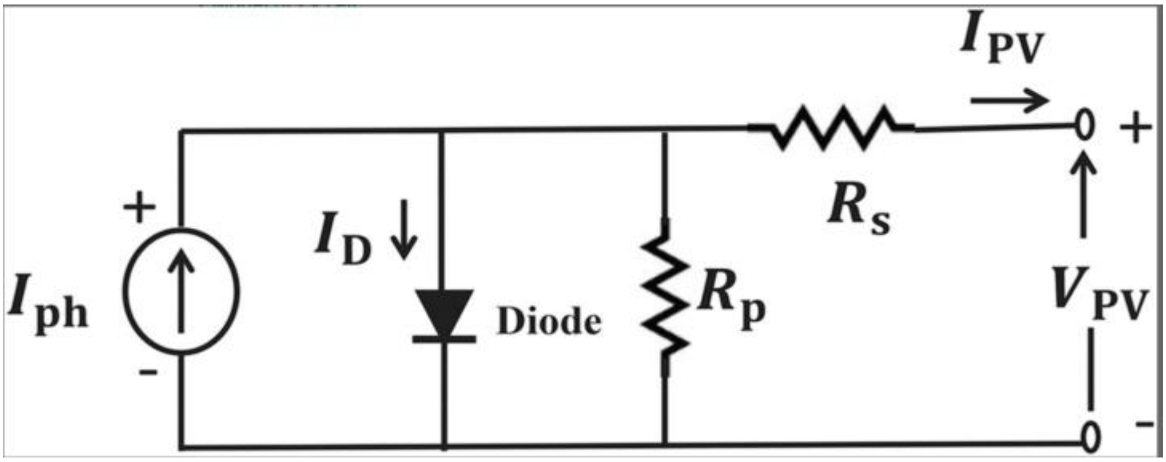

Fig. 3.1 Equivalent circuit of a solar panel

3.4 Model of PV cell

The model of a solar PV cell is an important part of analysing a PV system. Its modelling is classified into three sections, which are described below.

3.4.1:I-V characteristics and equivalent circuit

PV begins from two separate words – photo, which implies light, and voltaic, which alludes to the production of power. Subsequently, the term PV brings the significance of producing power specifically from the sun. A sun-powered array comprised several combinations of sun-based modules, where every module comprised various solar cells . Solar cells comprise p–n diodes manufactured in a thin layer of semiconductor . They resemble p–n diodes and their attributes are additionally comparative this displays the equivalent circuit of a perfect PV cell . This ideal structure is sufficiently precise to comprehend the PV attributes and the reliance of the PV cell on varying climatic conditions.

The aggregate output current of the parallel and series connected PV modules is expressed

$$I_{PV} = N_p \left(I_{ph} - I_o \left[\exp\left(\frac{q(V_{PV} + R_s I_{PV})}{N_s A K T} \right) - 1 \right] - \frac{V_{PV} + R_s I_{PV}}{N_s R_p} \right),$$

where Ipv is the output current, Vpv is the output voltage, Rs is the series resistance, Rp is the parallel resistance, Np and Ns are the number of PV cells connected in parallel and series for a given PV module, A is the ideality factor of the p–n junction, K is the Boltzmann's constant (1.3806503 x 10^{-23}J/K), T is the temperature in Kelvin, q is the charge of electron (1.6x10^{-19}C) , Iph is the produced photocurrent; it depends fundamentally on the radiation and cell's temperature, which is expressed as

$$I_{ph} = [I_{SCC-STC} + K_i(T - T_{STC})]\frac{G}{G_{STC}},$$

where Iscc-stc refers to the short-circuit current (SCC) at standard test conditions (STC) in amperes, Tst (25^0C) is the cell temperature at STC, G (in watts per square meters,) is the irradiation on the cell surface, Gstc(1000W/m^2) is the irradiation at STC and is the SCC coefficient, as a rule, given by the cell producer. In addition, the saturation current, , is impacted by the temperature as indicated by the accompanying equation

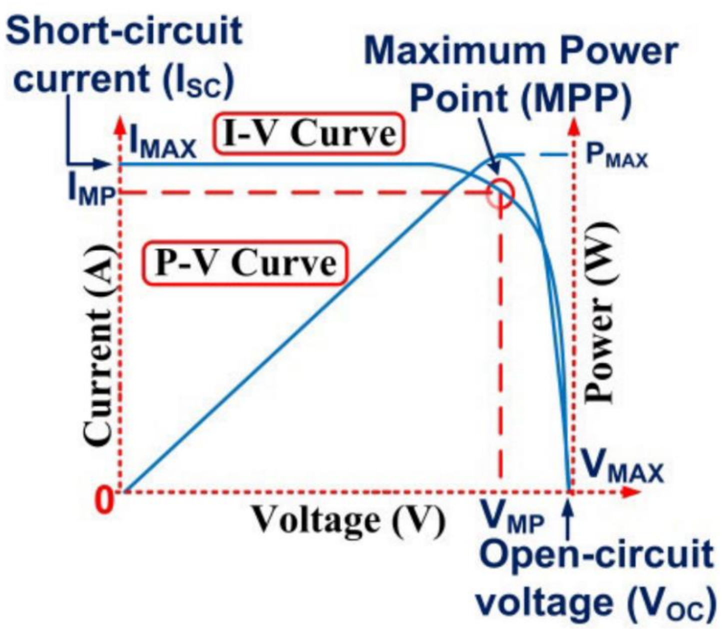

Fig.3.2: I-V and P-V characteristics

where (Vocv-stc in volt, V) is the open circuit voltage (OCV) at STC, Kv is the OCV coefficient, Vth refers to the thermal voltage of the cell, these values are available on the data sheet provided by module's manufacturer. With Vpv and simplified Ipv, the power produced by the PV module is represented

$$P_{PV} = V_{PV} \times N_p\left(I_{ph} - I_o\exp\left(\frac{qV_{PV}}{N_sAKT}\right) - \frac{V_{PV}}{N_s}\right).$$

$$I_o = \frac{I_{SCC-STC} + K_i(T - T_{STC})}{\exp[(V_{OCV-STC} + K_v(T - T_{SCC}) / AV_{th})]},$$

The I-V and P-V characteristics curve of the solar cell is shown in Fig.2 The curve in this figure indicates that the operating point of the PV does not remain at a stable point; it actually varies from zero to open-circuit voltage. There is only one point, which enables maximum power for a given set of solar insolation and temperature level. That particular point is indicated as MPP and at that point, the current and voltage that are found are presented as Impp and Vmpp in Fig. 2. This significant MPP and its numerous tracking methods are the main focal point of this review work.

3.5 .MPPT CONTROLLERS

The system that operates the PV in such a way to extract maximum power is termed as the MPPT controller. If the controller works deliberately at MPP, independent of the climatic condition, the efficiency of the PV system is enhanced. This should be possible by legitimately coordinating PV source with the load for any climate condition to accomplish maximum power production. There are two processes by which maximum power can be extricated from the PV array and they are: mechanical and electrical tracking. In mechanical tracking, the PV panel direction changes according to the changes of months and seasons throughout the year, while in electrical tracking, the curve is used for locating MPP . MPPT is an integral component of modern power systems, which ensures the penetration of maximum power to the load/batteries/motors and the power grid, for off-grid and on-grid applications, respectively. Since the conversion rate of sun energy to electrical energy of PV arrays is still low and the solar irradiance is not always uniform, the MPPT controller finds its widespread application in PV plants. A brief discussion on the necessity of the MPPT controller .

3.5.1 Need for an MPPT controller

Any environmental changes impose imperatives on power production from a sustainable power source. Especially, the impact is more serious in solar and wind energy systems. Additionally, wind and solar systems confront challenges on (i) changing climatic conditions and (ii) grid incorporation. Henceforth, solar PV and wind energy conversion systems embrace MPPT procedures to give upportable power output . For this reason, it is necessary to ensure that there exists an MPP in curve for variable irradiation and temperature. This MPP continuously moves its position when any environmental change happens. Therefore, MPPT controllers are designed to continue the tracking of MPP and they form an indispensable piece of the PV system. The presence of a controller adequately modifies the resistance seen by the panel and consequently, urges the panel to work nearer to MPP . Efficient

MPPT controllers are essential to modify the operating point of the load associated with changing the duty cycle of the converter.

3.5.2 Selection parameters of the MPPT controller

For tracking the true MPP of the PV system, numerous MPPT methods have been presented in numerous research literature. For finding the best one among others, the selection parameters of the MPPT controller play a vital role. The selection parameters provide essential information about which method is better for a particular application. These selection parameters are used only for making comparison among the methods of each categorised MPPT method, not to classify the methods into categories. Eleven selection parameters are considered here for the comparison of different methods in each category.

3.5.3 MPPT controller under PSC

Some well-recognised MPPT methods under uniform irradiance and PSC are depicted in Table. The comparison among the PSC supported MPPT methods . The methods are compared in terms of six selection parameters, such as PV array dependency, convergence speed, periodic tuning, complexity, analogue/digital in nature, and sensitivity it is seen that most of the methods under PSC are digital in nature and highly complex. Moreover, in terms of convergence speed, periodic tuning and PV array dependency, the PSO, genetic algorithm (GA), differential evolution (DE), biological swarm chasing (BSC), PV output senseless (POS), SC, firefly algorithm (FA) and ant colony optimisation (ACO) performs better under PSC than the other classical methods. However, as the characteristics of the PV array under PSC comprises many local MPPs and one global, the classical MPPT algorithms cannot accurately track the GMPP. Therefore, the GMPPT algorithm is needed. In the literature, the GMPPT algorithm is classified into two classes : (a) firmware-based and (b) hardware architecture-based algorithms. The firmware-based GMPPT methods use the hybrid approach by combining two MPPT algorithms. Firstly, the approximate GMPP is located using search algorithms and then, it is accurately tracked using classical MPPT algorithms. The hardware architecture-based algorithms are related to the power converter topology and design of the PV system. Soft computing techniques such as PSO, grey wolf optimisation (GWO), and CuS optimisation can tackle the GMPP of a PV system under the same PSC . However, these techniques suffer from high oscillations around the GMPP and they cannot dynamically track the new GMPP when it changes its position. To solve these problems, a hybrid GWO–fuzzy logic control (FLC) algorithm is proposed in , which is able to track dynamic GMPP. The global perturbed-based extremum seeking (GPESC) scheme is proposed in and the ability of this scheme to track the GMPP is analysed for both static and dynamic PV patterns which shows a high value of tracking accuracy (99.99%).

3.5.4 Review of various MPPT algorithms

Owing to its versatile use, researchers attempted a lot to soak up the maximum amount of power from the panel. Until now, a lot of MPPT methods have been developed. Each technique has its own types of operation processes, advantages, disadvantages, and applications. To classify the available methods there is no proper assessment since one might be useful for a particular application and not for other, again one can be extremely efficient but another is not. In this review work, the discussed 50 methods that are classified into eight groups based on their tracking nature are shown in Fig. **3**.

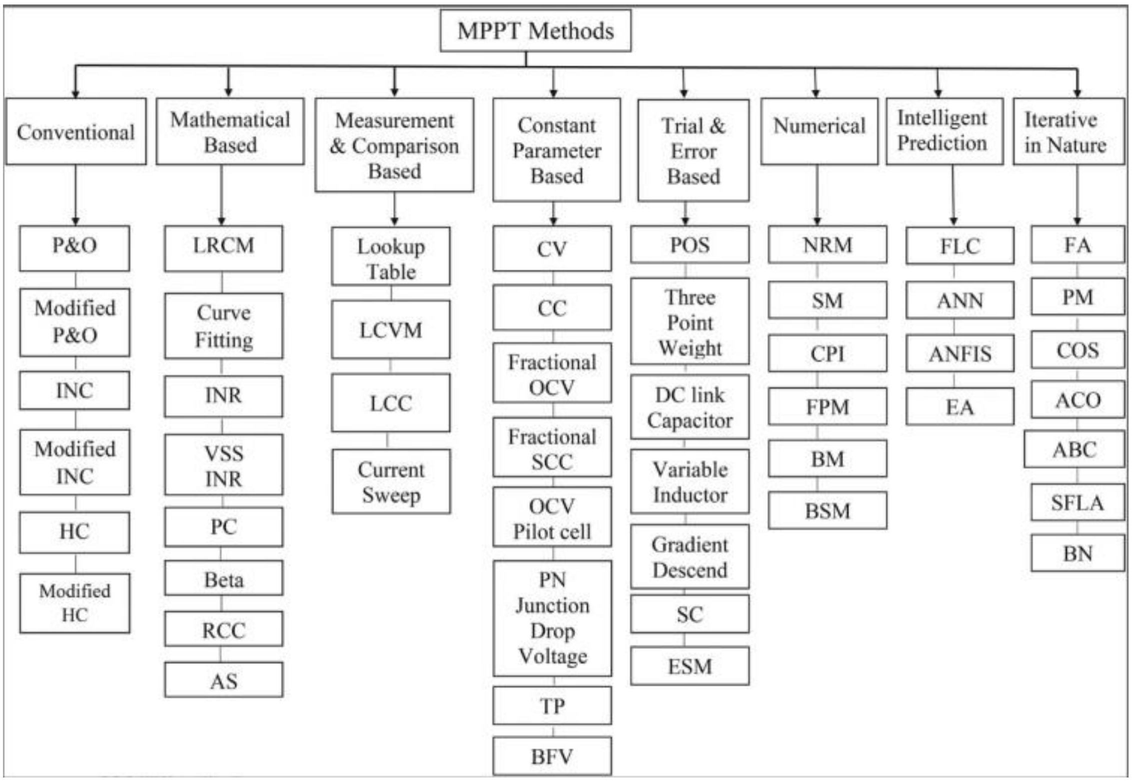

Fig. 3.3: Classification chart of the discussed MPPT methods

3.5.5 Conventional methods

The P&O, INC, and HC methods and their modifications are classified as conventional methodsas these methods have existed for decades. The details of these conventionalmethods are listed in the following sections.

3.6 P&O method

This strategy is one of the least complex strategies, which has been considered by various scientists.In this procedure, the voltage of the PV array is perturbed and the adjustment in its output power is noticed. At each cycle, the voltage and current of the PV are measured by the tracker and derived the real PV power by observing the variations in power . Until reaching the MPP, this situation is recapitulated. The MPP is achieved when the changes of power with respect to changes in voltage being zero (dp/dv=0). The essential flowchart of the P&O calculation is shown in Fig. 3.1. The figure shows that the algorithm starts by obtaining the present value of V and I at V(k) and I(k) and the power at P(k). The algorithm perturbs the operating voltage, V, at every MPPT cycle with respect to the reference voltage Vref. The operating voltage, V, oscillates until the MPP is reached to provide the ideal operating voltage Vmpp. Here, Cp indicates the losses of power due to the step width of the perturbation. The most important focal point of this technique is that the information of the solar cell qualities is not needed and can be connected to any PV system. Notwithstanding, this technique has a few downsides, as detailed in.

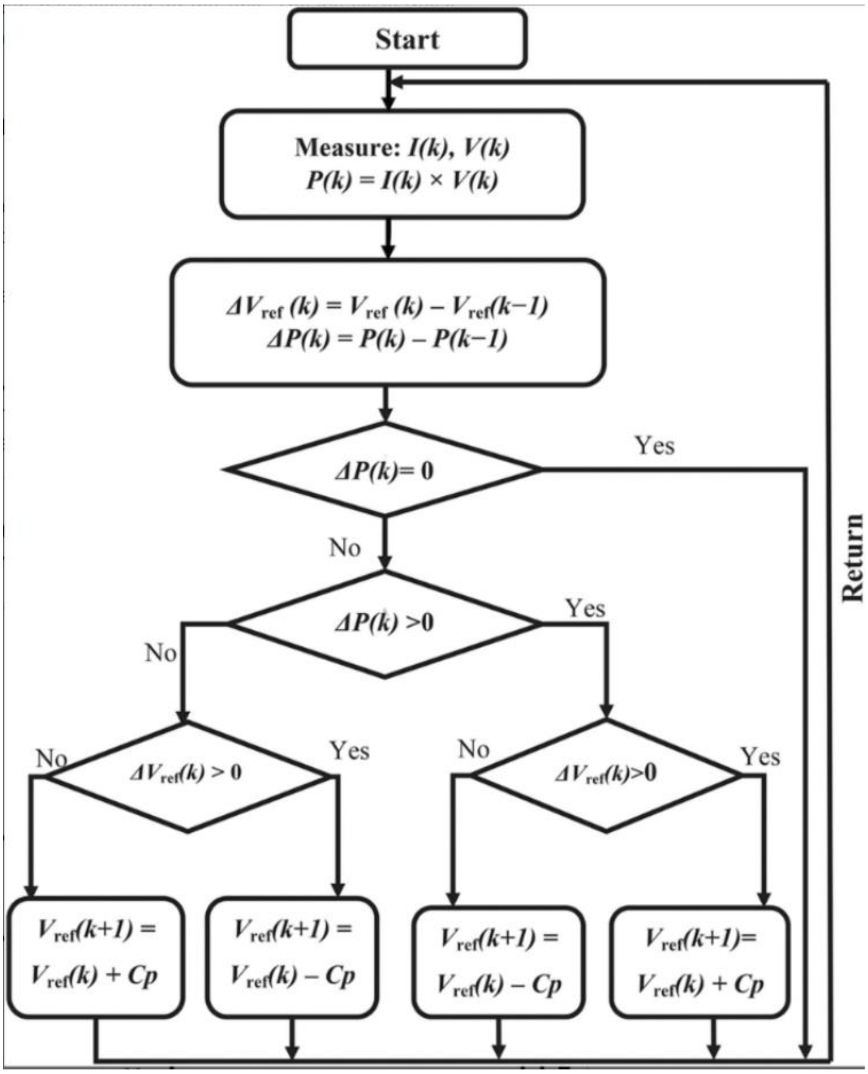

Fig.3.4:Algorithm for P&O method

3.6.1 Intelligent prediction based methods

These methods are mainly soft-computing-based techniques, which are now becoming a powerful toolto accord with MPPT optimisation. Besides, the accessibility of the elite andreasonable micro-controller makes the usage of these calculations conceivableunder practical conditions. The FLC, artificial neural network (ANN),evolutionary algorithm (EA), and hybrid adaptive neuro-fuzzy inference system(ANFIS) methods are listed in this category and they are described below.

3.7 Variable inductor MPPT method

This technique displays a topology of the MPPT controller for solar power applications that satisfy a variable inductance versus current characteristic. This strategy is strong and dependable with the variation of insolation. The utilisation of the variable inductor in the DC–DC converter lessens the overall inductor measure by 75%. In this method, a relationship between the minimum value of the inductor and the PV current is displayed scientifically by utilising the inductor to accomplish the MPPT . The schematic diagram of this method.

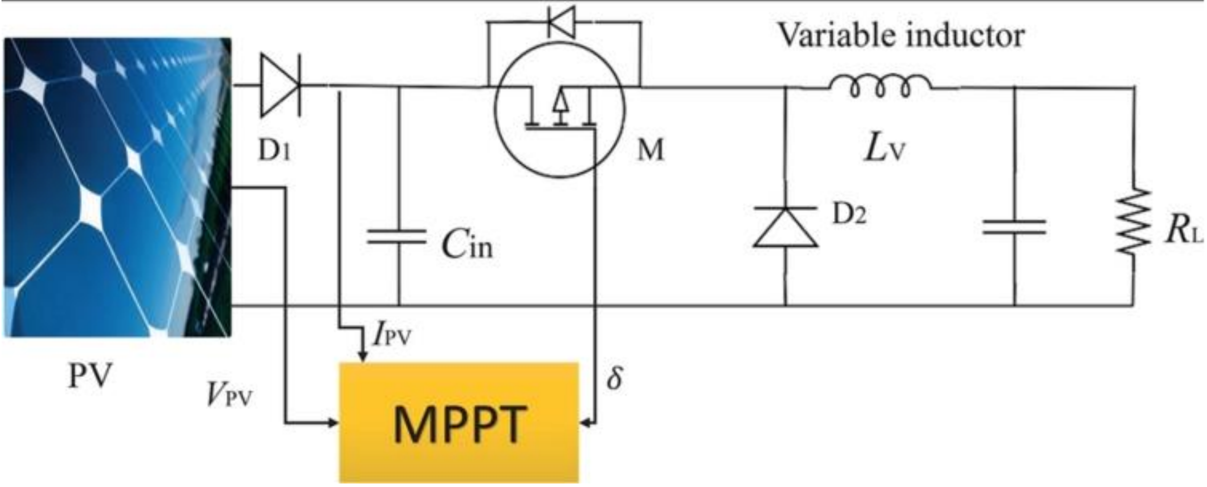

Fig.3.5 Schematic diagram of variable inductor control of MPPT

3.8 MODELLING OF PV AND DC-DC BOOST CONVERTER

3.8.1 MODELLING OF SOLAR PV

The modeling of a solar cell is an important segment of analyzing a solar PV system. The overall proposed circuit comprises solar panels, a three-level DC-DC boost converter fed to 53-level MLI shown in Figure 1. The solar PV can be modeled with three categories such as an equivalent circuit with current-voltage (I-V) and power-voltage (P-V) characteristics, the effect of solar irradiance and temperature, and the partial shading condition is taken into consideration. PV resembles two words photo and voltaic: photo represents the photonic energy and voltaic represents the electrical energy, which implies that the energy conversion from photonic energy into electrical energy [30]. The combination of a solar array is of various types of modules, where each module comprises solar cells. This comprises of p-n semiconductor diodes [31]. The designed solar PV has a behavior of changing its output with the variation of temperature and climatic conditions [32]. Therefore, the factors in modeling a solar PV are represented below:

3.8.2SOLAR CELL: EQUIVALENT CIRCUIT AND I–V CHARACTERISTICS

The solar cell comprises internal resistance RSE and RSH connected to the diode in series and parallel combination, known to be an equivalent circuit shown in FIGURE 2. VPV and IPV are the output voltage and current of a solar cell, respectively. These are got from the series and parallel connection of several PV modules shown in equation (1),

$$I_{PV} = \left\{ I_{Ph} - I_0 \left[exp\left(\frac{q(V_{PV} + R_{SE}I_{PV})}{N_{SE}AKT} \right) - 1 \right] - \frac{(V_{PV} + R_{SE}I_{PV})}{N_{SE}R_{SH}} \right\} \quad (1)$$

Where NSE and NSH are the number of PV cells in series and parallel connection. RSE is the series resistance, and RH is the parallel resistance. A is the ideality factor of a semiconductor device. K is Boltzmann’s constant (1.3806503 × 10−23 J/K), T is ’he temperature. Ip is the current produced and is depends on the irradiation and temperature shown in equation (2)

$$I_P = [I_{SK-STM} + K_i\,(T - T_{STM})] - \left(\frac{G}{G_{STM}} \right) \quad (2)$$

Where ISK−STM is a short-circuited current at standard testing cases (STM), Ki is the SCC coefficient, G (W/m2) is the irradiance on the surface of the cell, GSTM (1000W/m2) is the irradiance at STM, and the cell temperature is TSTM [33].

$$I_O = \left\{ \frac{I_{SK-STM} + K_i\,(T - T_{STM})}{exp\,[(V_{OK-STM} + K_{OV}\,(T - T_{SKC})\,/AV_{Sth})]} \right\} \quad (3)$$

Where VOK−STM is an open-circuited voltage at the standard testing case, KOV represents the open-circuit voltage coefficient, VSth is solar cell thermal voltage.

$$P_{PV} = V_{PV} \times N_{SH}\left(I_{Ph} - I_O exp\left(\frac{qV_{PV}}{N_{SE}AKT}\right) - \left(\frac{V_{PV}}{N_{SE}}\right)\right) \tag{4}$$

I-V/P-V curves represent the characteristics of a solar cell is shown in FIGURE 3 [4]. It is clear from the curve there is instability for the operating point of a PV; it varies continuously from null to open-circuit voltage. In this process, there is a single point that provides peak power for the design of solar PV at various irradiance. Here, the respective voltage and currents are VMPP, IMPP shown in Figure 3.

The values of current and voltage got from the solar PV depend on irradiance, temperature, number of series, and parallel connected strings. So, it is required to choose the solar panel wisely. In this paper, the 1Soltech 1STH-215- P panel is chosen from the list of given solar modules data in MATLAB with 2 series and parallel connected modules per string. The specifications of the selected solar panel are described in table 1 and the readings in the table are given for 1 parallel string and 1 series-connected module with a solar irradiance of 1000 W/m2 and 250oC temperature.

3.8.3.IRRADIANCE AND TEMPERATURE EFFECT

The solar PV output continuously varies with variation in climatic changes [34]. As the solar irradiance confides on the incidence angle of sun rays, this effect forces the I-V/P-V characteristics to change. The output current IPV varies with the variation of sunray incidence, making VPV constant and VPV also shifts its magnitude, making IPV constant [34]. Three factors are influencing the variation in temperature of a solar PV: The heat dissipated on its own during the functioning of PV, for the infrared wavelength started, which is a worn on the cell and the gradual increase in the sunbeam intensity [26]. The VOC and ISC are measured based on the equations (5) and (6) at variable irradiance.

$$V_{OC} = V'_{OC} + a_2\left(T - T'\right) - (I_{SC} - I'_{SC})R_{SE} \qquad (5)$$
$$I_{SC} = I'_{SC}\left(\frac{G}{G'}\right) + a_1\left(T - T'\right) \qquad (6)$$

From the above equations, the temperature coefficients are a1 and a2 of the PV cell, respectively [35]. V 0 OC and I 0 SC are the reference parameters at solar intensity G' and temperature T0 . As the variations of climatic conditions are specific, it affects the output voltage and currents. At any point during the operation of solar PV, the maximum extraction of power can be done. This can be possible with an efficient MPPT technique that tracks the irradiation and temperature and provides a constant voltage at the output.

3.8.4:.PARTIAL SHADING EFFECT

Apart from the temperature and irradiance conditions, a partial shading case is also a challenging task for the MPPT technique in achieving maximum power. This partial shade occurs with mists, consecutive structures, trees, etc. [36]. According to equation (2), the photocurrent Iph gets reduced with low insolation. With series-connected PV modules, the current is the same in all cells. But in this case, the shaded cell goes to a breakdown, and instead of providing the energy, this acts as a load because of the weakening of photocurrent.

3.8.5:MPPT CONTROLLER

The operating of solar PV is to extract the maximum power from the PV module is an MPPT controller. During all the disturbances mentioned above, if the controller can able to operate efficiently in tracking and to provide peak power from the solar panels, the efficiency and life span of the

TABLE 1. Specifications of the 215W PV system.

Maximum power	213.15W
The voltage at maximum power point (V_{MPP})	29V
Open circuit voltage (V_{oc})	36.3V
Current at maximum power point (I_{MPP})	7.35A
Short circuit current (I_{sc})	7.84A
Diode ideality factor	0.98117
Diode saturation current (I_O)	2.9259×10^{-10}A

Solar PV gets increased. This can be achieved by sinking the solar source to the load for various climate conditions to produce maximum power. There are two ways to extracting the maximum power from a solar panel. They are Mechanical and electrical tracking. With mechanical tracking, the solar panels change their direction depends on the climatic variation patterns. This includes seasonal climate changes for several months. With electrical tracking, the I-V curve is forced to locate the point of maximum power in the operation of the PV array [37]. The MPPT controller is an internal part of the system which feeds the maximum power to load (batteries/motors).

For tracking maximum power during the operation of the PV module, a suitable algorithm is to be used. This can be seen in the P-V graph of a solar cell. There are many such methods to track the maximum power such as incremental conductance, perturb and observe, genetic algorithm, fractional open-circuit voltage, etc. In this paper, the perturb and observe algorithm it has many advantages. It is easy to implement using various controllers such as Arduino, microcontroller, etc. The maximum power point determination speed can be controlled by varying the perturbation value. The P&O algorithm is shown in Figure 4. The algorithm for Perturb and Observe Technique is:

a) Ipv and Vpv values are gathered from PV module.

b) Ppv is calculated from Ipv and Vpv.

c) Voltage and power values are stored.

d) The values are recorded for the next consecutive (k + 1)th instant and repeat step ‘a’.

e) The values got at (k + 1)th instant are subtracted from the values got at kth instant.

f) In the PV curve of a solar panel, on the right side, the slope is negative i.e., (dP/dV0). Therefore, the lesser duty cycle occurs on the right side of the curve and the high-duty occurs on the left side of the curve.

g) Based on the polarity of the slope after subtraction, the algorithm decides the change in the duty cycle.

The solar panel is designed with a power of 215W; the respective parameters and their specifications are shown in TABLE 1.

C. DC-DC BOOST CONVERTER

A single input multiple output DC-DC boost converter interfaced in between the solar panels and the proposed inverter .This converter provides three isolated dc sources in the ratio of 4:1:3:9. The converter feeds on a single solar PV to eliminate the unequal voltages along with the variations in the step size based on several climatic conditions.

The magnitude of the inductance can be calculated using the relation:

$$L = \left(\frac{mV_{dc}}{4af_sI_r}\right) \qquad (7)$$

where Vdc is the input dc voltage, m is the modulation index, and fs is the switching frequency, Ir is the ripple current, a is the overloading factor which is usually 1.25. The value of capacitance can be calculated using the relation

$$C = \left(\frac{DI_{dc}}{V_{dc}rf_s \times 0.5}\right) \qquad (8)$$

where Idc is the dc current, fs is the switching frequency, r is the ripple voltage, Vdc is the input dc voltage, D is the duty cycle.

The duty cycle of the converter can be calculated using the following relation :

$$D = \left(\frac{V_O}{V_O + V_{dc}} \right) \quad (9)$$

The simulation and experimental results , respectively. The specifications of the boost converter are represented .

CHAPTER 4:

CASCADE H-BRIDGE WITH 5 LEVEL AND 17 LEVEL MULTILEVEL INVERTER

4.Introduction

The multilevel inverter occupancy rate has increased since the last decade. Multilevel converter is suitable for high power application as a result of their ability to synthesize waveforms with an improved harmonic spectrum and faithful output. In conventional cascade H-bridge is that when the voltage increases, an increase in the number of semiconductor switches and also the source requirement increases. In order to overcome this introduced a new topology of cascaded H-bridge. This new topology gives less order of THD with controlled tension. This paper presents seventeen level inverter with PWM techniques that are used in Hybrid Electric Vehicle for very high efficiency to stabilize as a result of the inverter output voltage. With 5-level and 17-level, we can distinguish that the manner in which THD influence by increasing the levels in both cases, in MATLAB Simulink. Cascade PWM converter is used for the advantage of simple control strategy. PWM (Pulse Width Modulation) method is used to generate the gate drive signal to the controller. However, the proposed topology be expanded with an n-level inverter.

In the context of electric vehicles (EVs), both 5-level and 17-level cascaded H-bridge multilevel inverters offer advantages in terms of power quality, reduced harmonic distortion, and lower voltage stress on switching devices. The 17-level inverter generally provides a more sinusoidal output waveform and lower THD compared to the 5-level inverter.

An EV architecture without cascaded H-bridges, particularly 5-level or 17-level multilevel inverters, typically uses a more conventional two-level inverter with a DC-DC converter to boost the battery voltage, which is then fed into a standard AC motor drive. This simpler approach avoids the complexity and potential cost of cascaded H-bridge topologies, which are more common in applications requiring higher output voltage levels and improved harmonic performance. In essence, the architecture without cascaded H-bridges in EVs prioritizes simplicity, cost-effectiveness, and space efficiency, even though it may come at the cost of slightly lower output voltage and potentially higher harmonic content compared to more advanced topologies like cascaded H-bridges

4.1: 5-Level Inverter

Topology: Can be implemented using Neutral Point Clamped (NPC) or Flying Capacitor (FC) topologies.Advantages: Simpler design, lower component count, and relatively good power quality.Limitations: Higher Total Harmonic Distortion (THD) compared to higher-level inverters.

4.2.1: 17-Level Inverter

Topology: Often implemented using advanced topologies like Modular Multilevel Converters (MMC) or other reduced switch count topologies. Advantages: Excellent power quality, lower THD, and higher efficiency.Limitations: More complex design, higher component count, and increased control complexity.

Benefits for EVs

Improved Efficiency: Reduced energy losses and increased driving range.
Enhanced Performance: Smoother motor operation and faster acceleration. Reduced Emissions: Lower THD and improved power quality contribute to a cleaner and more efficient powertrain.

4.2: Challenges and Future Directions

Complexity and Cost: Higher-level inverters require more complex designs and control strategies, increasing costs.
Scalability and Reliability: Ensuring reliable operation and scalability of multilevel inverters in EV applications.
Examples of Non-Cascaded 5-Level and 17-Level Inverters:

5-Level Switched Capacitor MLI: A recent paper on ResearchGate proposes a 53-level MLI based on SC technology, which can be adapted to a 5-level configuration.
17-Level SC MLI: ResearchGate also explores the use of SC MLIs for 17-level configurations.
Other Reduced-Switch Topologies: Nature describes a 31-level MLI with a reduced number of switching devices for EV applications, which can be adapted to lower levels.

In summary, while cascaded H-bridge inverters are a well-established MLI topology, non-cascaded 5-level and 17-level MLIs using alternative topologies like SC or reduced-switch designs are being actively researched and developed for EV applications. These alternatives aim to improve output waveform quality and efficiency while potentially reducing complexity, cost, and size.

In the context of electric vehicles (EVs), a 5-level and 17-level multilevel inverter (MLI) without a cascaded H-bridge topology can be achieved using alternative structures like switched capacitors (SC) or other reduced-switch topologies. These MLIs aim to improve output waveform quality and reduce harmonics compared to traditional two-level inverters, often used in EVs.

4.3 Cascaded H-Bridge Inverters:

These inverters are a common type of MLI, where multiple H-bridges are connected in series to create multiple output voltage levels. A 5-level inverter can be created with two H-bridges, and a 17-level inverter would require significantly more H-bridges, increasing complexity and potentially size.

Alternative Topologies:To avoid the need for numerous H-bridges, alternative MLI topologies are being explored. These include:

Switched Capacitors (SC) MLIs: These topologies use switched capacitors instead of H-bridges to create voltage levels. They can achieve higher levels with fewer switching devices compared to cascaded H-bridges.

Reduced-Switch Topologies: Some designs aim to minimize the number of switching devices needed to achieve a specific number of voltage levels, potentially by using fewer switches per level or employing a different control strategy.

Benefits of MLIs in EVs:

Improved Output Waveform Quality: MLIs can produce a waveform with fewer harmonics compared to two-level inverters, leading to better motor performance and reduced electromagnetic interference (EMI).

Higher Power and Efficiency: MLIs can handle higher power levels and potentially improve efficiency compared to two-level inverters in EV applications.

Reduced Voltage Stress: MLIs can reduce voltage stress on the switching devices, potentially extending their lifespan.

Challenges:

Control Complexity: MLI control can be more complex than two-level inverters.

Cost and Size: Some MLI topologies can be more expensive and larger than two-level inverters, especially when the number of levels increases.

Voltage Imbalance: In some MLI designs, ensuring equal voltage distribution across the levels can be challenging.

4.4 Ev with cascade bridge 5 level inverter

The concept of this inverter is based on connecting H-bridge inverters in series to get a sinusoidal voltage output. The output voltage is the sum of the voltages that are generated by each cell. The number of output voltage levels are (2n+1), where n is the number of cells. The switching angles can be chosen in such a way that total harmonics distortion is minimized. One of the advantage of this type of multilevel inverter is that it needs less number of components in comparison to the Diode clamped or the flying capacitor, which results in reduction of weight as well as cost .A Operation of Cascaded H-bridge multilevel inverter. The converter topology is based on the series connection of single-phase inverters with separate dc sources. the power circuit for one phase leg of five level cascaded inverter. The resulting phase voltage is synthesized by the addition of the voltages generated by the different cells. In a 3-level cascaded inverter each single-phase full-bridge inverter generates three voltages at the output: +Vdc, 0, -Vdc (zero, positive dc voltage, and negative dc voltage). This is made possible by connecting the capacitors sequentially to the ac side via the power switches. The resulting output ac voltage swings from -Vdc to +Vdc with three levels, -2Vdc to +2Vdc with five-level. The staircase wave form is nearly sinusoidal, even without filtering.

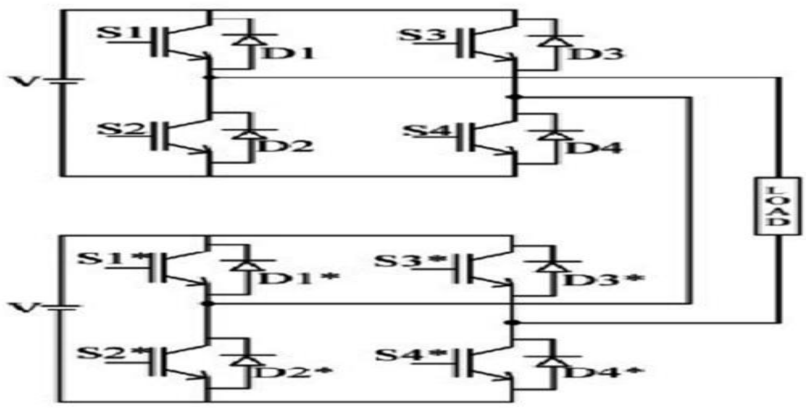

Fig.4: 5 level cascade H-bridge multilevel inverter

Cascaded H-Bridge (CHB) configuration has recently become very popular in high power AC supplies and adjustable-speed drive applications. A cascade multilevel inverter consists of a series of H-bridge (single-phase full bridge) inverter units in each of its three phases. Each H-bridge unit has its own dc source, which for an induction motor would be a battery unit, fuel cell or solar cell. Each SDC (separate D.C. source) is associated with a single phase fullbridge inverter. The ac terminal voltages of different level inverters are connected in series. Through different combinations of the four switches, S1-S4, each converter level can generate three different voltage outputs, +Vdc, -Vdc and zero. The AC outputs of different full bridge converters in the same phase are connected in series such that the synthesized voltage waveform is the sum of the individual converter outputs. Note that the number of outputphase voltage levels is defined in a different way from those of the two converters (i.e. diode Clamped and flying capacitor). In this topology, the number of output-phase voltage levels is defined by m=2N+1, where N is the number of DC sources. A seven-level cascaded converter, for example, consists of three DC sources and three full bridge converters. Minimum harmonic distortion can be obtained by controlling the conducting angles at different converter levels. Each H- bridge unit generates a quasi-square waveform by phase shifting its positive and negative phase legs‟ switching timings. Each switching device always conducts for 180° (or half cycle) regardless of the pulse width of the quasi-square wave. This switching method makes all of the switching devices current stress equal. In the motoring mode, power flows from the batteries through the cascade inverters to the motor. In the charging mode, the cascade converters act as rectifiers, and power flows from the charger (ac source) to the batteries. The cascade converters can also act as rectifiers to help recover the kinetic energy of the vehicle if regenerative braking is used. The cascade inverter can also be used in parallel HEV configurations. This new converter can avoid extra clamping diodes or voltage balancing capacitors. The combination of the 180° conducting method and the pattern-swapping scheme make the cascade inverters voltage and current stresses the same and battery voltage balanced. Identical H-bridge inverter units can be utilized, thus improving modularity and manufacturability and greatly reducing production costs. Battery-fed cascade inverter prototype driving an induction motor at 50% and 80% rated speed both the voltage and current are almost sinusoidal. Electromagnetic interference (EMI) and common mode voltage are also much less than what would result from a PWM inverter because of the inherently low dv/dt and sinusoidal voltage output.

Cascade inverters are ideal for an induction motor that has many separate dc sources (batteries) available for the individual H-bridges, these inverters are not an option for series hybrid induction motors because cascade inverters cannot be easily connected back-to-back. For series-configured induction motors where an onboard combustion engine generates ac power via an alternator or generator, a multilevel back-to-back diode clamped converter drive can best interface with the source of ac power and yet still easily meet the high power and/or high voltage requirements of the induction motor. Induction motors generally have an ac voltage source from an alternator or combustion engine generator. A rectifier converts this ac voltage to dc for the electric energy storage devices on board – batteries or ultra-capacitors. An inverter converts the dc voltage to variable voltage variable frequency ac in order to drive the main induction motor. The multilevel converter can act as an inverter in drive mode when energy is being sent to the motor that drives the wheels and as a rectifier during regenerative braking or during charge mode when the vehicle is plugged into an external ac source. The reduction in dv/dt can prevent motor windings and bearings from failure. The staircase output voltage waveform approaches a sine wave, thus having no common-mode voltage and no voltage surge to the motor windings. A cascaded multilevel inverter is discussed to eliminate the excessively large number of Bulky transformers required by conventional multi pulse inverters, Clamping diodes required by multilevel diode-clamped inverters, and Flying capacitors required by multilevel flying-capacitor inverters.

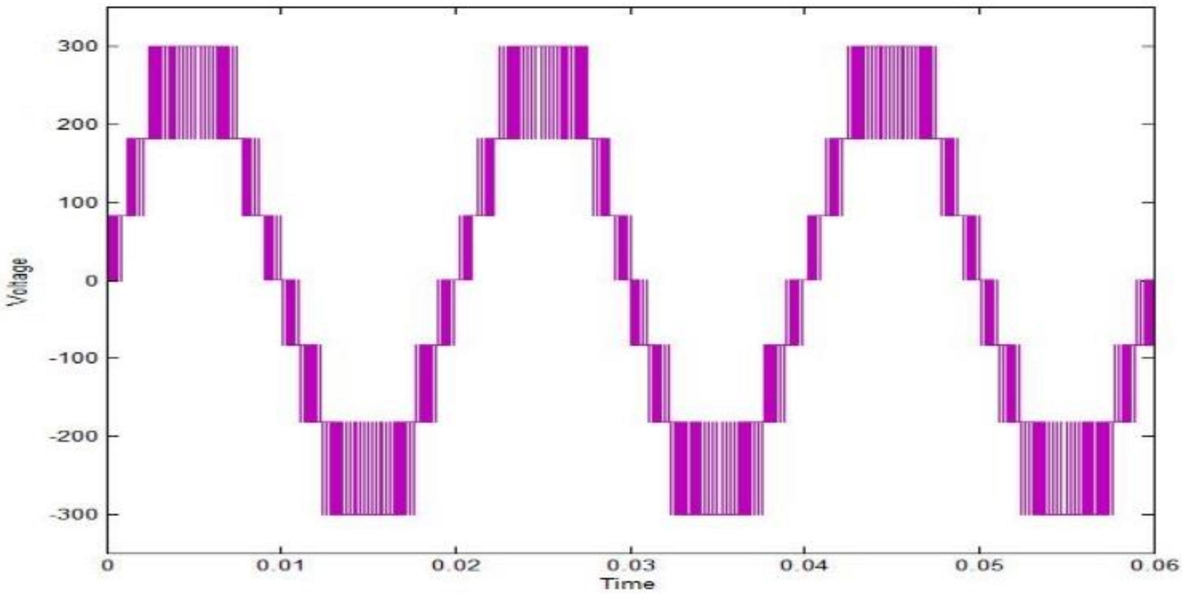

Fig.4.1 : Voltage Waveform of the five level inverter

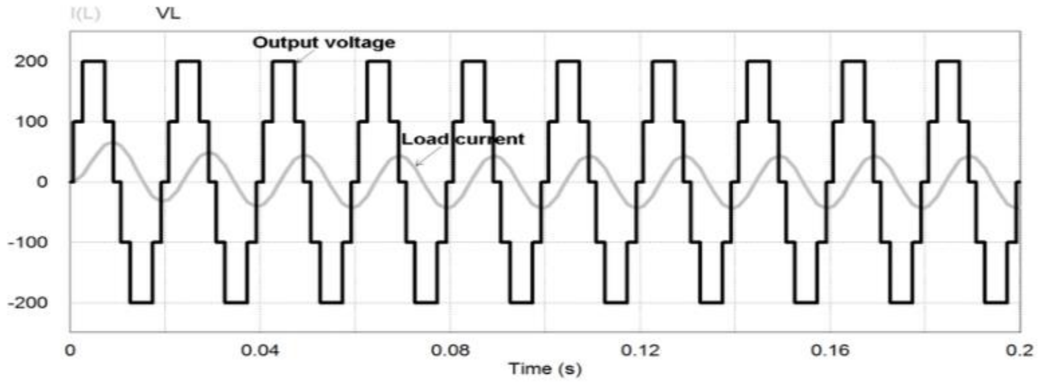

Fig 4.2: Current Waveform of the five level inverter

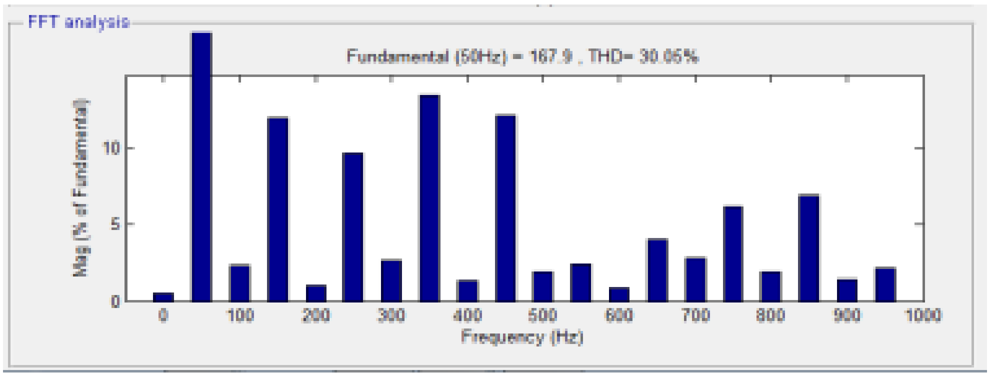

Fig.4.3: Total harmonic distortion (THD)

4.5 Ev with cascade H bridge 17 level inverter

Electric Vehicles (EVs) utilize multilevel inverters to efficiently convert DC power from the battery into AC power for driving electric motors. Among various topologies, the Cascaded H-Bridge Multilevel Inverter (CHB-MLI) is popular due to its modular design, high efficiency, and ability to produce high-quality output voltage with reduced harmonic distortion. A CHB inverter consists of multiple H-bridge cells connected in series, with each cell contributing additional voltage levels to the output. In a 5-level CHB inverter, two H-bridge cells are used per phase, generating five distinct voltage levels: +2Vdc, +Vdc, 0, -Vdc, and -2Vdc. This setup is suitable for low to medium power EVs, offering a good balance between simplicity, cost, and performance. On the other hand, a 17-level CHB inverter uses eight H-bridge cells per phase, producing a near-sinusoidal waveform with seventeen stepped voltage levels. This results in very low total harmonic distortion (THD), improved motor efficiency, and reduced electromagnetic interference, making it ideal for high-power or commercial EV applications. While the 17-level configuration offers superior performance, it also involves higher complexity in control and requires multiple isolated DC sources. Overall, CHB inverters enhance EV performance by delivering smooth motor control, high efficiency, and scalable voltage levels.

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The 17-level Cascaded H-Bridge Multilevel Inverter (CHB-MLI) is an advanced inverter topology used in high-performance and heavy-duty Electric Vehicle (EV) applications. Its main objective is to efficiently convert DC power from the EV battery into high-quality AC power suitable for driving electric motors, with minimal harmonic distortion.

This inverter topology is composed of eight H-bridge cells per phase, each supplied by a separate isolated DC source. These H-bridges are connected in series on the AC side to produce a stepped voltage output waveform. The number of output levels generated by the inverter is given by the formula: $L = 2n + 1$where is the number of H-bridge cells per phase. For , this yields voltage levels.

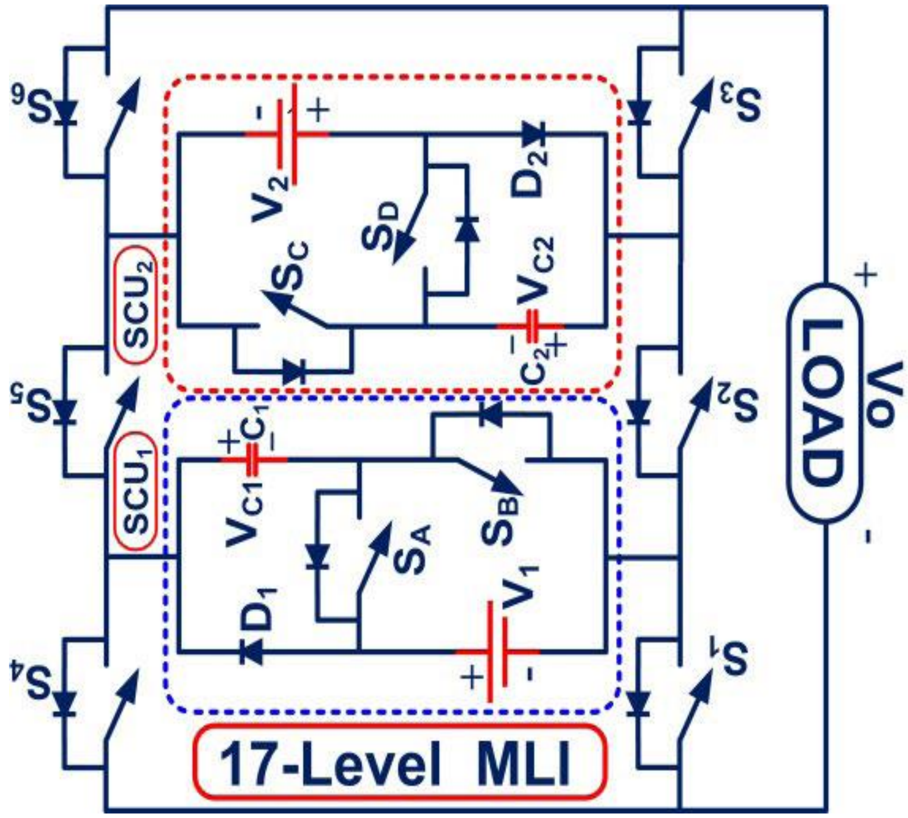

Fig.4.4:Developed structure of 17 Level

The resulting output waveform is a near-sinusoidal staircase pattern, which significantly reduces Total Harmonic Distortion (THD). This improves motor efficiency, reduces

The developed 17-level MLI is operated in various modes of operation shown in TABLE.In mode-1 operation of the circuit, the switches SA, S5, SD, S3, S1 turn on forming a load current path, where V1, VC1, V2, and VC2 sources act in the circuit and produce a voltage of 50V, 150V, 50V, 150V respectively to get a maximum voltage of 400V. The respective switching pulses, switching states, and current paths are represented in Table III. In mode-2 operation, the switches D1, S5, SD, S3, S1 turn on where V1, V2, and VC2 sources act in the circuit and produce a voltage of 50V, 50V, and 150V respectively and get a voltage of 7Vdc which is equal to 350V. In mode-3 operation, the switches SD, S3, S6, S5 turn on forming a load current path where V2, VC2 sources act in the circuit and produce a voltage of 50V and 150V respectively and get a voltage of 6Vdc equal to 300V. In mode-4 operation, the switches SA, S5, D2, S3, S1 turn on with the voltages V1, VC1, and V2 sources act in the circuit and produce a voltage of 50V, 150V, and 50V respectively and get a voltage of 5Vdc which is equal to 250V. In mode5 operation, the switches D1, S5, D2, S3, S1 turn on with the voltages V1 and V2 sources act in the circuit and produces a voltage of 50V and 150V respectively and get a voltage of 4Vdc equal to 200V. In mode-6 operation, the switches D2, S3, S4, S5, turn on with the voltage V2 source act in the circuit and produce a voltage of 50V and get a voltage of 3Vdc which is equal to 150V. In mode-7 operation, the switches SA, S5, S6, S1, turn on with the voltages V1 and VC1 sources act in the circuit and produces a voltage of 50V and 150V respectively and get a voltage of 2Vdc equal to 100V. In mode-8 operation, the switches D1, S5, S6, S1 turn on with the voltages V1 source act in the circuit and produces a voltage of 50V respectively and get a voltage of Vdc which is equal to 50V. In mode-9 operation, the switches S1, S2, S3, turn on with no voltages acts in the circuit and produces a voltage of 0V. Hence the positive cycle is created. The negative cycle is implemented with the negative modes of operation, along with the switching states shown in Table III. Therefore, the 17-level MLI output waveform is achieved with a simulation THD of 4.12%

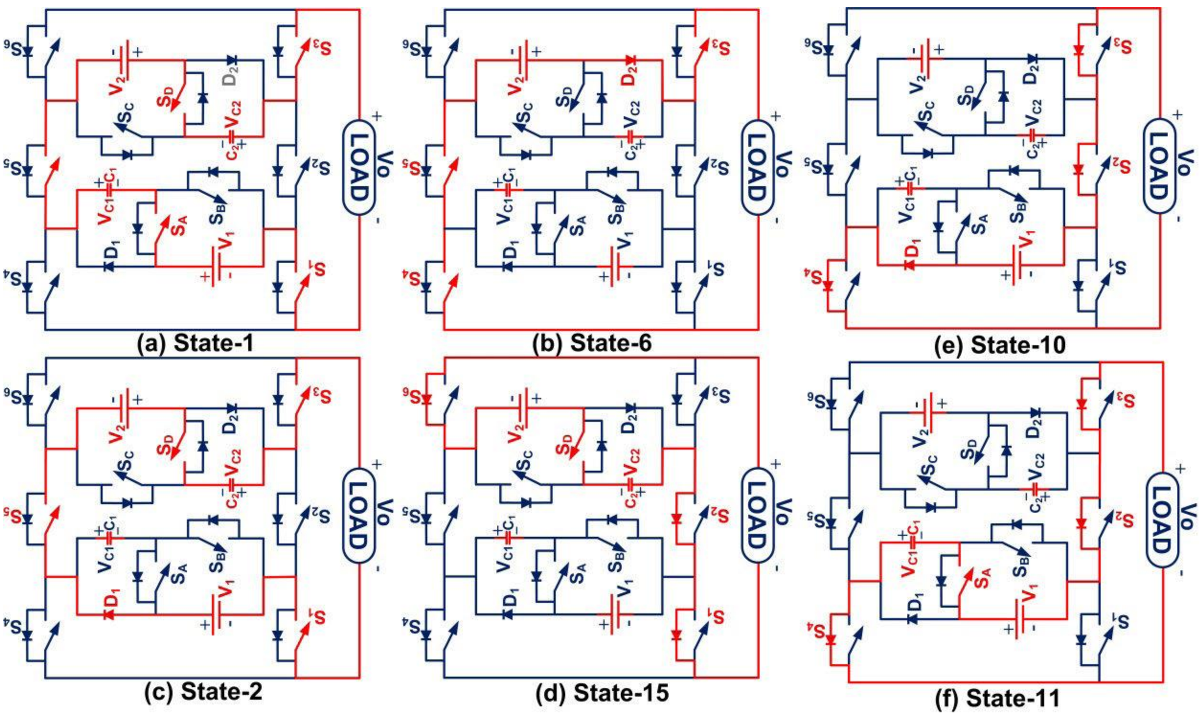

Fig.4.5: Modes of operation of the proposed 17-Level MLI topology

States	Load current path	Output Voltage (V)		
State-1	S_A, S_5, S_D, S_3, S_1	$8V_{dc}$	$V_1+V_{C1}+V_2+V_{C2}$	+400
State-2	D_1, S_5, S_D, S_3, S_1	$7V_{dc}$	$V_1+V_2+V_{C2}$	+350
State-3	S_D, S_3, S_6, S_5	$6V_{dc}$	V_2+V_{C2}	+300
State-4	S_A, S_5, D_2, S_3, S_1	$5V_{dc}$	$V_1+V_{C1}+V_2$	+250
State-5	D_1, S_5, D_2, S_3, S_1	$4V_{dc}$	V_1+V_2	+200
State-6	D_2, S_3, S_4, S_5	$3V_{dc}$	V_2	+150
State-7	S_A, S_5, S_6, S_1	$2V_{dc}$	V_1+V_{C1}	+100
State-8	D_1, S_5, S_6, S_1	V_{dc}	V_1	+50
State-9	S_1, S_2, S_3	0	0	0
State-10	D_1, S_4, S_3, S_2	$-V_{dc}$	$-V_1$	-50
State-11	S_A, S_4, S_1, S_2	$-2V_{dc}$	$-(V_1+V_{C1})$	-100
State-12	D_2, S_2, S_1, S_6	$-3V_{dc}$	$-(V_2)$	-150
State-13	D_2, S_2, D_1, S_4, S_6	$-4V_{dc}$	$-(V_1+V_2)$	-200
State-14	D_2, S_2, S_A, S_4, S_6	$-5V_{dc}$	$-(V_1+V_{C1}+V_2)$	-250
State-15	S_D, S_2, S_1, S_5	$-6V_{dc}$	$-(V_2+V_{C2})$	-300
State-16	S_D, S_2, D_1, S_4, S_6	$-7V_{dc}$	$-(V_1+V_2+V_{C2})$	-350
State-17	S_D, S_2, S_A, S_4, S_6	$-8V_{dc}$	$-(V_1+V_{C1}+V_2+V_{C2})$	-400

Table.2: Generation voltage levels according to Conduction of Switches of 17 MLI

The resulting output waveform is a near-sinusoidal staircase pattern, which significantly reduces Total Harmonic Distortion (THD). This improves motor efficiency, reduces

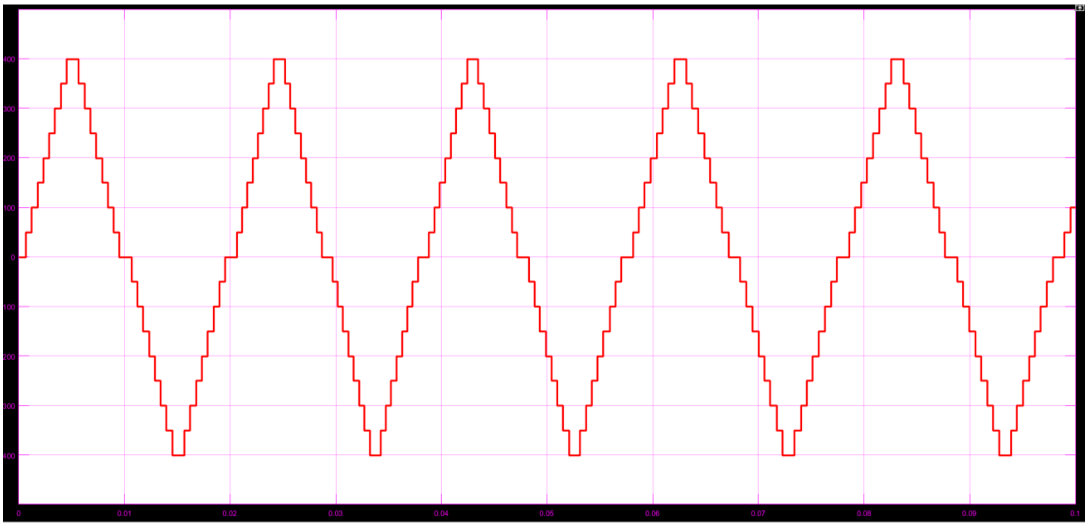

Fig.4.6 : Voltage waveform of the 17 level multilevel inverter

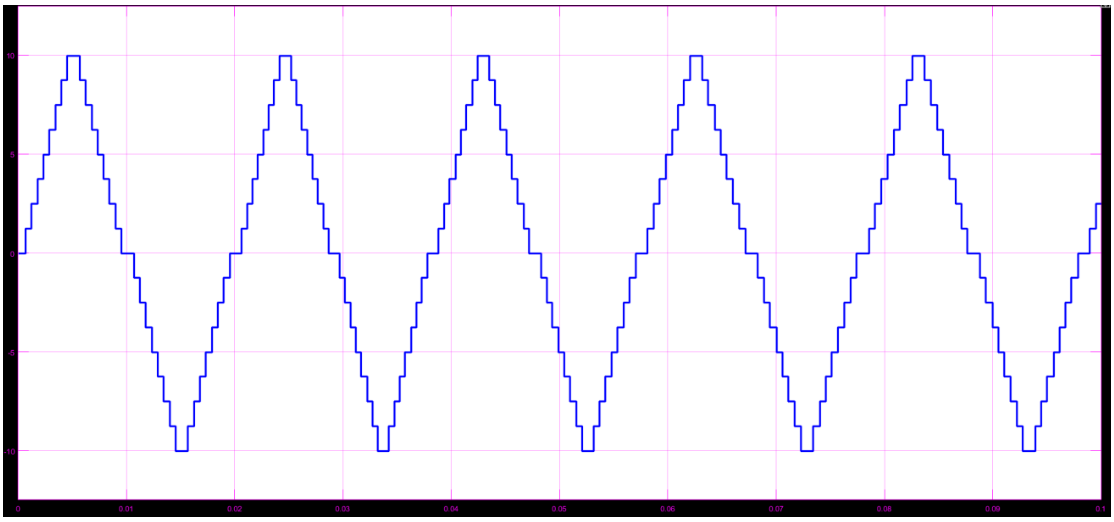

Fig.4.7 : current waveform of the 17 level multilevel inverter

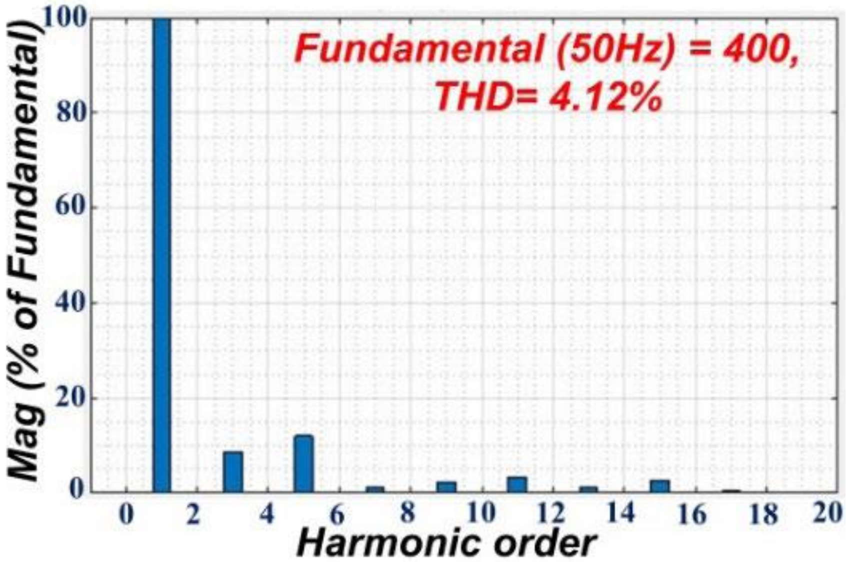

Fig.4.8 : Total harmonic distortion (THD)

CHAPTER 5

Comparison between 5-level and 17-level multilevel inverter in electric vehicles

5. Introduction

Photovoltaic system or PV system is a system that converts sunlight into electricity. Converting the sun's radiation directly into electricity is done by solar cells. These cells are made of semiconducting materials. When sunlight is absorbed by these materials, the solar energy knocks electrons loose from their atoms, allowing the electrons to flow through the material and hence produce electricity . The electricity converted by the cells is in direct current (DC). A grid-connected PV system will require a DC-to-AC inverter. This device will convert the DC electricity produced by the PV array into alternating current. PV system is one of the electricity sources as mentioned above.Topology of 5-level multilevel inverter DC-to-AC converter produces some impacts to distribution network. Harmonic problems occur as the inverters have too high capacitance. When harmonic happens, resonance problems will then occur, leading to high harmonic currents and voltages.

Both 5-level and 17-level multilevel inverters can be used in electric vehicles (EVs) for high power and high efficiency. 17-level inverters offer advantages like reduced harmonic distortion, while 5-level inverters can be simpler and more cost-effective

5.1 : 5-level Multilevel Inverter:

For 5-level inverter, the topology is presented in Figure1. This topology consists of a full-bridge inverter, an auxiliary circuit (comprises of one switching element and four diodes) and two capacitors as voltage divider. The multilevel inverter is connected after the dc power supply. The main point of the auxiliary circuit is to generate half level dc supply voltage. It also reduced the layout complexity compared to other multilevel inverter topology such as flying-capacitor topology, diode-clamped topology and hybrid topology, and these topologies can be studied in various papers The operations of the new topology were presented in literature .The output voltage levels according to the switch on-off conditions were tabulated in Table I. The switch in auxiliary circuit must be properly switched considering the direction of the load current. A 5-level multilevel inverter is used in electric vehicles to improve performance and efficiency compared to traditional two-level inverters. It offers benefits like reduced harmonic distortion, lower switching losses, and a more sinusoidal output voltage, leading to better motor performance and potentially lower maintenance requirements. A multi-level inverter (MLI) is a power converter that synthesizes a desired output voltage from several DC voltage levels. A 5-level inverter means it can produce five different voltage levels at the output, typically:

These extra levels allow for smoother voltage waveforms, reducing stress on the motor and improving efficiency.

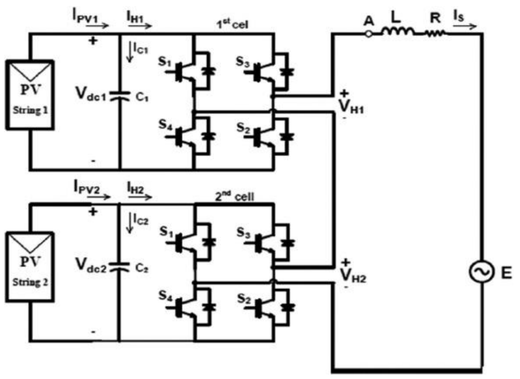

Fig:5-level Multilevel Inverter

Power Factor:

Power factor is the ratio between real power and apparent power in a circuit. The formula for power factor is

Power Factor = active power/apparent power = p/s

where θ is the angle difference (in degrees) between output voltage and output current. Unity power factor is the best. The load with higher power factor will draw less currents, hence decrease the lost in distribution system and therefore wasted energy will be less.

5.1.1 PWM Modulation Technique for 5-level Multilevel Inverter:

The modulation technique used in this inverter topology is sinusoidal pulse width modulation (SPWM) technique. The principle is to generate gate signal by comparing a triangular carrier signal with two reference (sinusoidal) signals, which having same frequency and in phase, but different offset voltages

According to the amplitude of the voltage reference, Vref, the operational interval of each mode varies within a certain period.

The phase depends on the modulation index. The modulation index of the proposed five-level PWM inverte

$$M=Am/2Ac$$

Where AM is the peak value of reference voltage and AC is the peak value of carrier wave. The modulation index recommended in this technique is to be between 0.66 and 1

5.2:Reduced Harmonic Distortion:

Multilevel inverters, including the 5-level type, synthesize the AC voltage from multiple DC voltage levels, resulting in a more sinusoidal output waveform. This reduces harmonic distortion compared to two-level inverters, leading to better motor performance and reduced electromagnetic interference.

5.3: 17-level Multilevel Inverter:

This inverter design utilizes a cascaded switched capacitor (SC) topology to achieve 17 voltage levels. The approach involves cascading SC cells, which can be extended to implement higher voltage levels, such as 33 or 53 levels, depending on the application requirements. The efficient and compact design of multilevel inverters (MLI) motivates in various applications such as solar PV and electric vehicles (EV). This paper proposes a 17-Level multilevel inverter topology based on a switched capacitor (SC) approach. The number of levels of MLI is designed based on the cascade connection of the number of SC cells. The SC cells are cascaded for implementing 33 levels of the output voltage. The proposed structure is straightforward and easy to implement for the higher levels. As the number of active switches is less, the driver circuits are reduced. This reduces the device count, cost, and size of the MLI. The solar panels, along with a perturb and observe (P&O) algorithm, provide a stable DC voltage and is boosted over the DC link voltage using a single input and multi-output converter (SIMO). The proposed inverters are tested experimentally under dynamic load variations with sudden load disturbances. This represents an electric vehicle moving on various road conditions. A detailed comparison is made in terms of switches count, gate driver boards, sources count, the number of diodes and capacitor count, and component count factor. For the 17-level, 33-level, and 53-level MLI, simulation results are verified with experimental results, and total harmonic distortion (THD) is observed to be the same and is lower than 5% which is under IEEE standards.A 17-level multilevel inverter is a type of power electronic converter that generates an AC output voltage waveform with 17 distinct voltage levels. This is achieved by combining multiple DC voltage sources, typically using switched capacitors or cascaded H-bridges. The result is a more sinusoidal output waveform with reduced harmonic distortion compared to a conventional two-level inverter. The proposed 17-level MLI is designed with two developed 9 level units in cascaded without additional circuit components. This topology consists of two unit's 'A' and 'B' having bidirectional and twelve switches with four DC sources and four capacitors.. The power quality issues like THD, fewer switches, dv/dt stress are minimized with this developed multilevel inverter.The multiple voltage levels result in a staircase waveform that closely approximates a sine wave, reducing total harmonic distortion (THD).Lower THD and optimized switching reduce losses, enhancing the overall efficiency of the EV's powertrain.

Compact Design:

The SC topology allows for a more compact inverter design, which is beneficial for space-constrained EV applications.

A 17-level MLI is designed with the two SC units connected in cascade with a smaller number of components. The proposed MLI topology comprises 10 controlled switches with two asymmetric DC sources with the absence of inductors. The two DC sources are of unequal voltage levels formed to be an asymmetrical configuration. Several power quality issues like total standing voltage (TSV), cost factor, and cost per unit with various values of the weight factor, THD, switch count, component count level, voltage stress is minimized with this MLI topology. This topology achieves less TSV and is compared with various topologies. The path of the load current through the switches, along with the states of the operation is represented. Few modes of operation, along with the switching pulses, and the expected output waveform is represented

The proposed switched-capacitor based 53-level MLI topology for electric vehicle applications is designed and implemented for the solar PV energy system with lesser semiconductor devices to reduce the cost and size of the inverter, improving efficiency and reliability. P&O algorithm based MPPT technique is used, the stable output is achieved under all circumstances. The proposed MLI is implemented with various combinations of SC connections. A basic two units are cascaded and obtained a 17-level MLI configuration. The cascade connection of two 17-level MLIs results in the formation of a 33-level MLI, and the proposed 53-level MLI is achieved by cascading three SCunits. All the MLIs are designed and compared with various topologies based on several parameters like devices count, TSV, THD, and cost function per level count. The comparative analysis shows that the proposed MLI is more efficient with fewer power losses. It is noticed that both simulation and experimental THD are 1.41%. TSVpu is 1.15; efficiency is 94.21%, CF/L values for both values of α are 0.7 and 0.73, which clearly shows the cost is significantly less compared with various topologies. The proposed MLI is tested under multiple dynamic load variations. This topology is most suited for renewable energy applications.

5.4:comparison between 5-level and 17-level multi inverter in electric vehicles:

In electric vehicles, 17-level multi-inverters generally offer advantages over 5-level multi-inverters in terms of output voltage and harmonic distortion, while also potentially reducing costs and size. 17-level inverters can achieve higher output voltage with better harmonic evaluation compared to 5-level inverters. This can be achieved by cascading multiple H-bridges or using switched capacitor techniques. While 5-level inverters offer ultra-high efficiency, 17-level inverters can be more suitable for high-power applications due to their ability to generate a wider range of voltage levels.

Parameter	**5-Level Inverter**	**17-Level Inverter**
Voltage Waveform Quality	Moderate	Very High
Total Harmonic Distortion (THD)	10–15%	< 3%
Number of Switches	Moderate (e.g.,8–12 switches)	High (often > 30 switches)
Circuit Complexity	Simple to moderate	High
Control Strategy	Basic PWM or SPWM	Advanced multicarrier or phase-shifted PWM
Switching Losses	Moderate	Low (due to stepped waveform)
Efficiency	90–95%	>96%
Filter Requirement	Medium	Minimal
Thermal Performance	Standard cooling needed	Better distribution of heat
Size and Weight	Compact, lower component count	Larger, due to more components
Cost(Initial+Maintenance)	Lower	Higher
Reliability	High	Can be lower (more points of failure)
Maintenance	Easier	More difficult
Best Use Case in EVs	Passenger cars, low-to-mid power EVs	High-performance or heavy-duty EVs
Control & Implementation	Easier	Complex

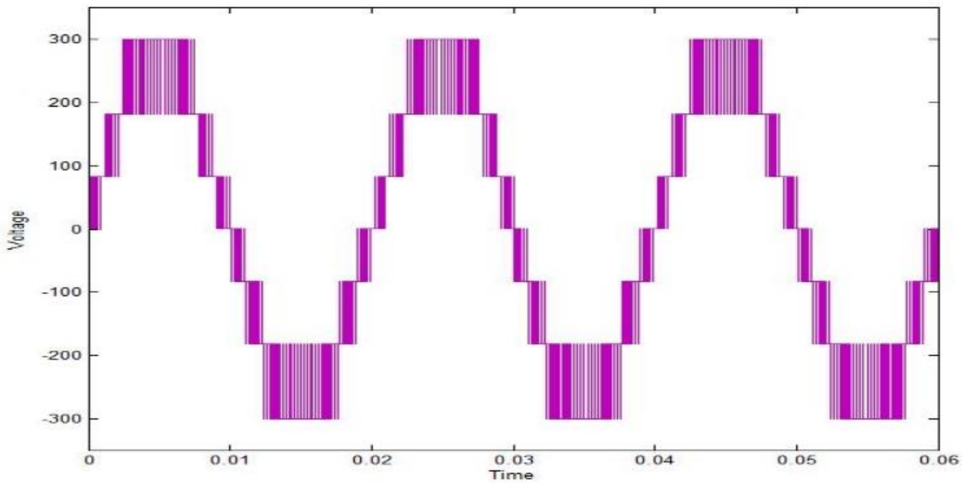

Fig 5.1: Voltage Waveform of the five level inverter

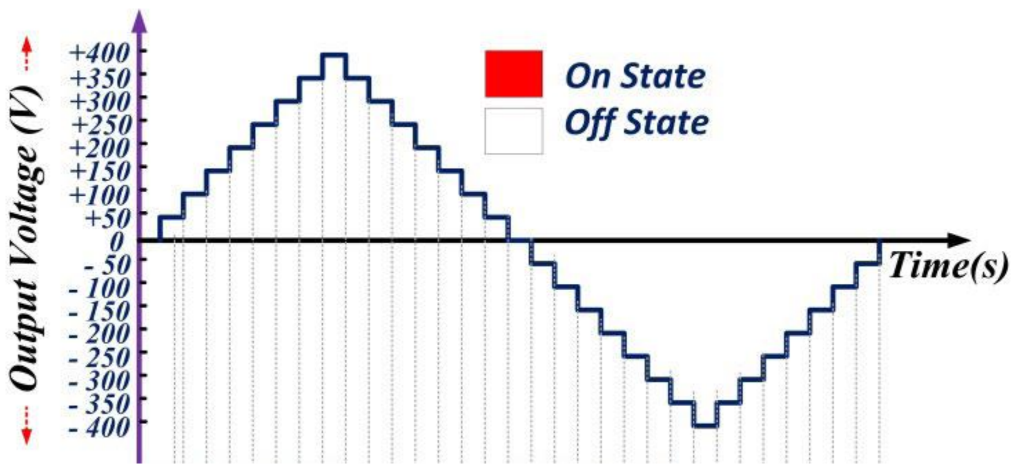

Fig.5.2: Voltage Waveform for 17 level inverter

CHAPTER 6

RESULTS

17-LEVEL MLI

A 17-level MLI is designed with the two SC units connected in cascade with a smaller number of components is shown in FIGURE 9. The proposed MLI topology comprises 10 controlled switches with two asymmetric DC sources with the absence of inductors. The two DC sources are of unequal voltage levels formed to be an asymmetrical configuration. Several power quality issues like total standing voltage (TSV), cost factor, and cost per unit with various values of the weight factor, THD, switch count, component count level, voltage stress is minimized with this MLI topology. This topology achieves less TSV and is compared with various topologies. The path of the load current through the switches, along with the states of the operation is represented in TABLE 2. Few modes of operation, along with the switching pulses, and the expected output waveform is represented in below FIGURE 6.

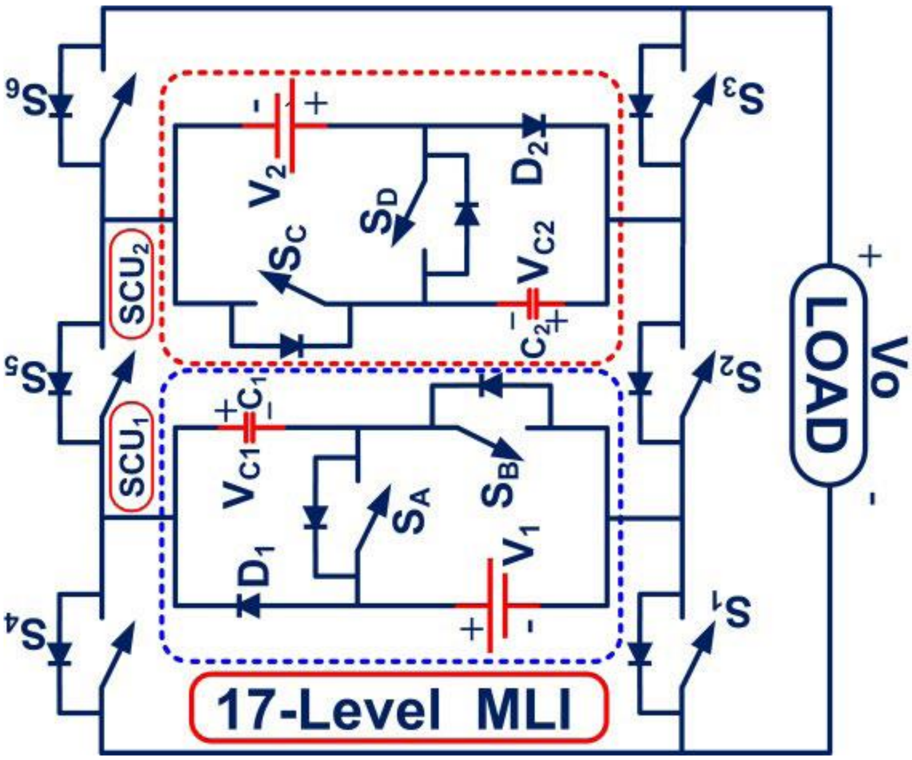

Fig.6: Developed structure of 17 Level

6.1: Modes of operation of the proposed 17-Level MLI topology

The developed 17-level MLI is operated in various modes of operation shown in TABLE III. In mode-1 operation of the circuit, the switches SA, S5, SD, S3, S1 turn on forming a load current path, where V1, VC1, V2, and VC2 sources act in the circuit and produce a voltage of 50V, 150V, 50V, 150V respectively to get a maximum voltage of 400V. The respective switching pulses, switching states, and current paths are represented in Table III. In mode-2 operation, the switches D1, S5, SD, S3, S1 turn on where V1, V2, and VC2 sources act in the circuit and produce a voltage of 50V, 50V, and 150V respectively and get a voltage of 7Vdc which is equal to 350V. In mode-3 operation, the switches SD, S3, S6, S5 turn on forming a load current path where V2, VC2 sources act in the circuit and produce a voltage of 50V and 150V respectively and get a voltage of 6Vdc equal to 300V. In mode-4 operation, the switches SA, S5, D2, S3, S1 turn on with the voltages V1, VC1, and V2 sources act in the circuit and produce a voltage of 50V, 150V, and 50V respectively and get a voltage of 5Vdc which is equal to 250V. In mode5 operation, the switches D1, S5, D2, S3, S1 turn on with the voltages V1 and V2 sources act in the circuit and produces a voltage of 50V and 150V respectively and get a voltage of 4Vdc equal to 200V. In mode-6 operation, the switches D2, S3, S4, S5, turn on with the voltage V2 source act in the circuit and produce a voltage of 50V and get a voltage of 3Vdc which is equal to 150V. In mode-7 operation, the switches SA, S5, S6, S1, turn on with the voltages V1 andVC1

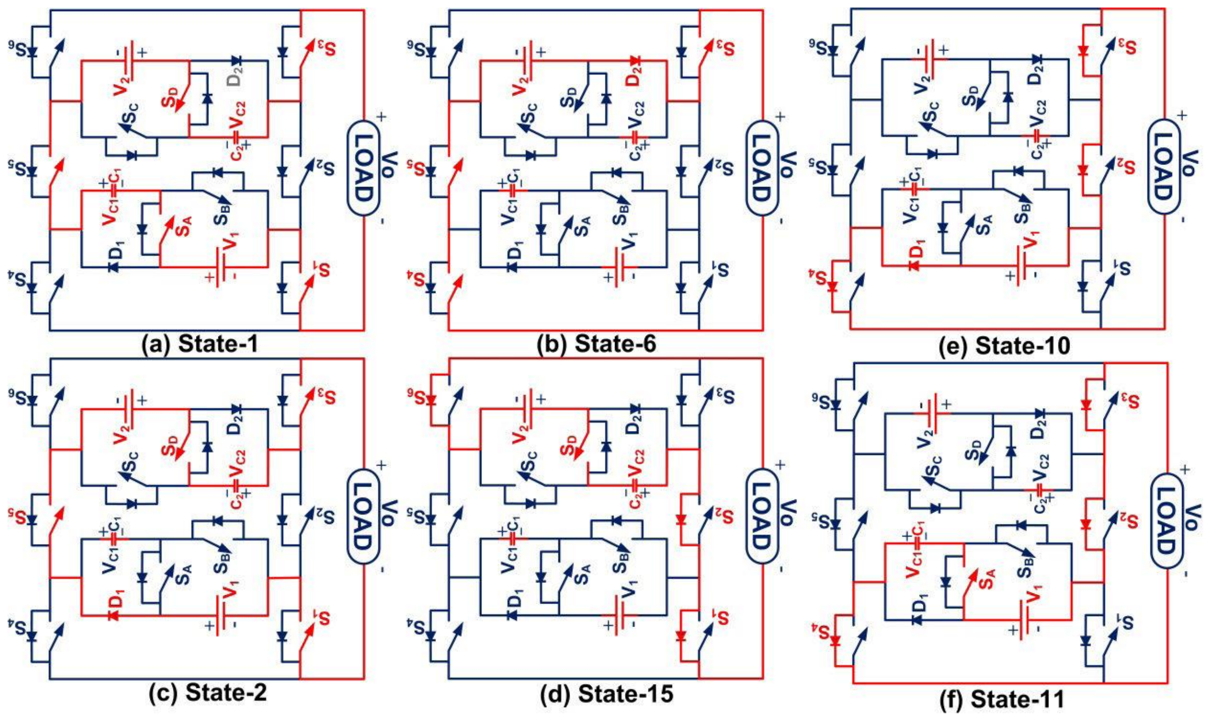

Fig.6.1: Modes of operation of the proposed 17-Level MLI topology

sources act in the circuit and produces a voltage of 50V and 150V respectively and get a voltage of 2Vdc equal to 100V. In mode-8 operation, the switches D1, S5, S6, S1 turn on with the voltages V1 source act in the circuit and produces a voltage of 50V respectively and get a voltage of Vdc which is equal to 50V. In mode-9 operation, the switches S1, S2, S3, turn on with no voltages acts in the circuit and produces a voltage of 0V. Hence the positive cycle is created. The negative cycle is implemented with the negative modes of operation, along with the switching states shown in Table III. Therefore, the 17-level MLI output waveform is achieved with a simulation THD of 4.12%

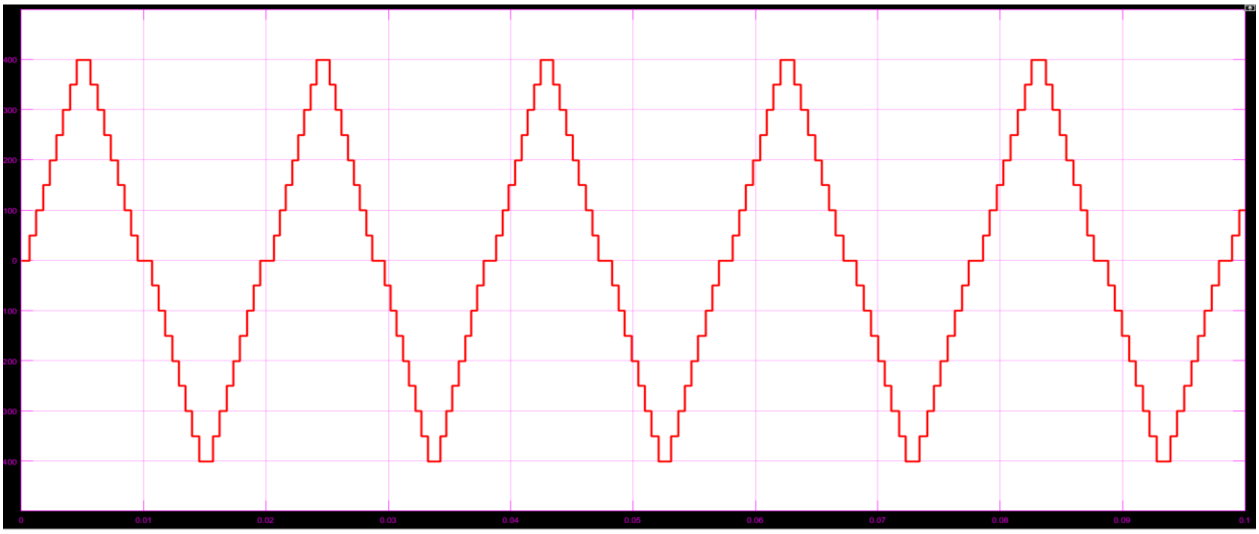

Fig.6.2 : Output Voltage waveform of the 17 level multilevel inverter

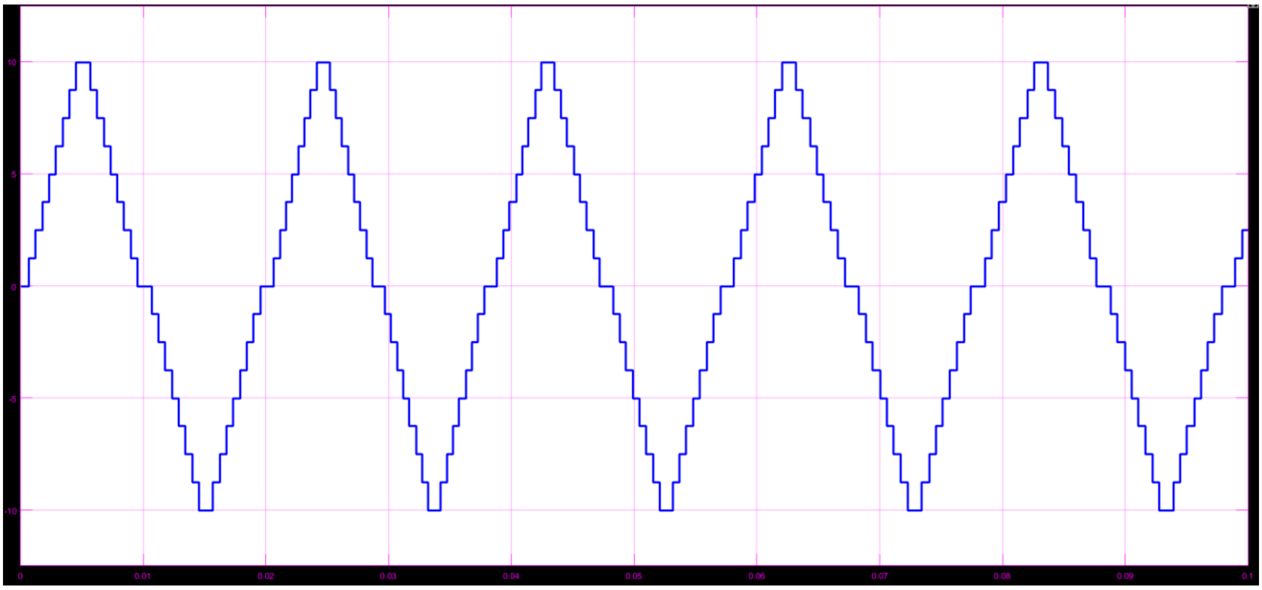

Fig.6.3 : Output Current waveform of the 17 level multilevel inverter

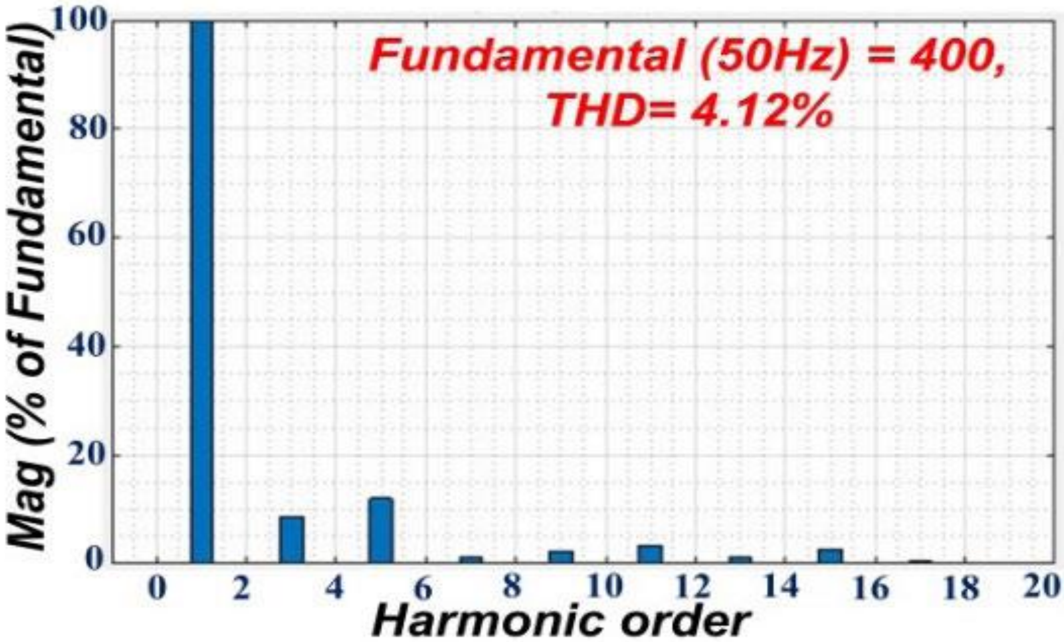

Fig.6.4: Output Total Harmonic Distortion (THD)

A 17-level MLI is designed with the two SC units connected in cascade with a smaller number of components. The proposed MLI topology comprises 10 controlled switches with two asymmetric DC sources with the absence of inductors. The two DC sources are of unequal voltage levels formed to be an asymmetrical configuration. Several power quality issues like total standing voltage (TSV), cost factor, and cost per unit with various values of the weight factor, THD, switch count, component count level, voltage stress is minimized with this MLI topology. This topology achieves less TSV and is compared with various topologies. The path of the load current through the switches, along with the states of the operation is represented in TABLE III. Few modes of operation, along with the switching pulses, is shown in FIGURE 10, and the expected output waveform is represented.

The developed 17-level MLI is operated in various modes of operation shown in TABLE.In mode-1 operation of the circuit, the switches SA, S5, SD, S3, S1 turn on forming a load current path, where V1, VC1, V2, and VC2 sources act in the circuit and produce a voltage of 50V, 150V, 50V, 150V respectively to get a maximum voltage of 400V. The respective switching pulses, switching states, and current paths are represented in Table III. In mode-2 operation, the switches D1, S5, SD, S3, S1 turn on where V1, V2, and VC2 sources act in the circuit and produce a voltage of 50V, 50V, and 150V respectively and get a voltage of 7Vdc which is equal to 350V. In mode-3 operation, the switches SD, S3, S6, S5 turn on forming a load current path where V2, VC2 sources act in the circuit and produce a voltage of 50V and 150V respectively and get a voltage of 6Vdc equal to 300V. In mode-4 operation, the switches SA, S5, D2, S3, S1 turn on with the voltages V1, VC1, and V2 sources act in the circuit and produce a voltage of 50V, 150V, and 50V respectively and get a voltage of 5Vdc which is equal to 250V. In mode5 operation, the switches D1, S5, D2, S3, S1 turn on with the voltages V1 and V2 sources act in the circuit and produces a voltage of 50V and 150V respectively and get a voltage of 4Vdc equal to 200V. In mode-6 operation, the switches D2, S3, S4, S5, turn on with the voltage V2 source act in the circuit and produce a voltage of 50V and get a voltage of 3Vdc which is equal to 150V. In mode-7 operation, the switches SA, S5, S6, S1, turn on with the voltages V1 and VC1 sources act in the circuit and produces a voltage of 50V and 150V respectively and get a voltage of 2Vdc equal to 100V. In mode-8 operation, the switches D1, S5, S6, S1 turn on with the voltages V1 source act in the circuit and produces a voltage of 50V respectively and get a voltage of Vdc which is equal to 50V. In mode-9 operation, the switches S1, S2, S3, turn on with no voltages acts in the circuit and produces a voltage of 0V. Hence the positive cycle is created. The negative cycle is implemented with the negative modes of operation, along with

the switching states shown in Table III. Therefore, the 17-level MLI output waveform is achieved with a simulation THD of 4.12%

CONCLUSION

This paper presents a novel Multilevel Inverter (MLI) topology based on the Switched Capacitor (SC) approach,enhance dynamic performance and voltage stability in renewable energy and electric vehicle applications. The proposed design effectively addresses key challenges associated with traditional MLI topologies, including high component count, complex control strategies, and large system size.The key contributions of this research include:The development of a reduced-switch MLI topology that achieves higher output voltage levels with fewer active switches, thereby reducing system cost, complexity, and size.The integration of an FLC, which provides intelligent control for optimal switching patterns, improving the inverter's dynamic response and voltage regulation under varying load conditions.A comprehensive comparative analysis of the proposed topology with existing reduced-switch MLIs, demonstrating superior performance in terms of efficiency, total harmonic distortion (THD), and component count.Experimental validation of the proposed system under dynamic load variations, confirming the feasibility and reliability of the design.Simulation and experimental results highlight that the proposed MLI topology with FLC control achieves excellent performance in terms of output voltage quality, reduced harmonic distortion, and enhanced efficiency. The system demonstrates robust operation under fluctuating load conditions, making it suitable for real-world applications in solar PV systems and EVs.

This paper presents a novel Multilevel Inverter (MLI) topology based on the Switched Capacitor (SC) approach, integrated with a Fuzzy Logic Controller (FLC) to enhance dynamic performance and voltage stability in renewable energy and electric vehicle applications. The proposed design effectively addresses key challenges associated with traditional MLI topologies, including high component count, complex control strategies, and large system size.

The key contributions of this research include:

The development of a reduced-switch MLI topology that achieves higher output voltage levels with fewer active switches, thereby reducing system cost, complexity, and size.The integration of an FLC, which provides intelligent control for optimal switching patterns, improving the inverter's dynamic response and voltage regulation under varying load conditions.A comprehensive comparative analysis of the proposed topology with existing reduced-switch MLIs, demonstrating superior performance in terms of efficiency, total harmonic distortion

(THD), and component count.Experimental validation of the proposed system under dynamic load variations, confirming the feasibility and reliability of the design.

Simulation and experimental results highlight that the proposed MLI topology with FLC control achieves excellent performance in terms of output voltage quality, reduced harmonic distortion, and enhanced efficiency. The system demonstrates robust operation under fluctuating load conditions, making it suitable for real-world applications in solar PV systems and EVs.

FUTURE SCOPE

While the proposed system has shown promising results, several areas for further research and development remain:

- **Advanced Control Strategies:**

  Integration of advanced control algorithms, such as **Model Predictive Control (MPC)** or **Neural Network-based controllers**, could further improve the dynamic performance and efficiency of the inverter.

  Hybrid control approaches combining FLC with other intelligent control techniques may offer enhanced adaptability under complex operating conditions.

- **Enhanced Topology Optimization:**

  Exploration of new MLI topologies with even fewer components and improved voltage balancing techniques could lead to more cost-effective and compact designs.

  Implementation of **modular multilevel converter (MMC)** structures for high-power applications could be investigated.

- **Real-Time Hardware Implementation:**

  Development of a real-time hardware prototype using advanced microcontrollers or digital signal processors (DSPs) to validate the performance under more dynamic and complex load conditions.

  Integration with **Internet of Things (IoT)** for remote monitoring and control of inverter operations.

- **Energy Storage Integration:**

  Research on incorporating **battery management systems (BMS)** and energy storage devices to improve system reliability and support grid stability, especially in off-grid solar applications.

- **Efficiency Improvement under Extreme Conditions:**

  Investigating the performance of the proposed system under extreme environmental conditions, such as high temperatures, varying irradiance, and fluctuating load demands.

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