A Comprehensive Review: Multi Level Inverters in Renewable Energy Application

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***Abstract*—Multi-level inverters (MLIs) have emerged as a key power electronic interface in renewable energy applications due to their ability to generate high-quality output voltage with reduced harmonic distortion, lower switching stress, and improved efficiency. These inverters are widely employed in photovoltaic systems, wind energy conversion systems, fuel cells, and hybrid renewable energy systems for efficient DC–AC power conversion and grid integration. Compared with conventional two-level inverters, MLIs offer advantages such as modular structure, lower electromagnetic interference, reduced filter requirements, and better scalability for medium- and high-power applications. Common topologies including diode-clamped, flying capacitor, and cascaded H-bridge inverters are extensively used based on system requirements. Recent advancements in modulation techniques, fault-tolerant control, and intelligent switching strategies have further enhanced the performance and reliability of MLIs. This paper presents an overview of multi-level inverter topologies, control methods, benefits, challenges, and their significant role in modern renewable energy systems. The study highlights the importance of MLIs in achieving sustainable, efficient, and reliable energy conversion for future smart grid applications.**

Index Terms*—Multi-Level Inverters (MLIs), Pulse width modulation (PWM), Diode-Clamped Multi-Level Inverter (DCMLI), Neutral Point Clamped (NPC), Cascaded H-Bridge Multi-Level Inverter (CHBMLI), Flying Capacitor Multilevel Inverter (FCMLI).

I. INTRODUCTION

The increasing global demand for clean and sustainable energy has accelerated the integration of renewable energy sources such as solar photovoltaic (PV), wind turbines, fuel cells, and battery energy storage systems into modern power networks. Efficient power conversion technologies are essential for connecting these renewable sources to standalone loads and utility grids. In this context, inverters play a vital role by converting the generated direct current (DC) power into alternating current (AC) power suitable for practical applications. Conventional two-level inverters have been widely used for this purpose; however, they suffer from drawbacks such as high switching losses, increased electromagnetic interference, and poor output waveform quality with higher total harmonic distortion (THD).

Multi-Level Inverters (MLIs) have emerged as an advanced solution to overcome these limitations. By synthesizing the output voltage from multiple DC voltage levels, MLIs produce a staircase waveform that closely approximates a sinusoidal waveform. This results in reduced harmonic distortion, lower voltage stress on switching devices, improved efficiency, and decreased filter size requirements. These features make MLIs highly suitable for medium- and high-power renewable energy applications.

Various MLI topologies, including diode-clamped (neutral-point clamped), flying capacitor, and cascaded H-bridge inverters, have been extensively developed and adopted based on system requirements. Among these, cascaded H-bridge inverters are particularly attractive for photovoltaic and battery-based systems due to their modular structure and independent DC source capability. In addition, advanced pulse width modulation (PWM) techniques and intelligent control strategies have significantly improved the dynamic performance, fault tolerance, and grid synchronization capability of MLIs.

The application of MLIs in renewable energy systems contributes to improved power quality, enhanced reliability, and efficient utilization of distributed energy resources. They are widely used in grid-connected solar systems, wind energy conversion systems, hybrid microgrids, electric vehicle charging stations, and smart grid infrastructures. As the demand for high-performance and eco-friendly energy systems continues to rise, MLIs are expected to play an increasingly important role in future power electronic converters.

This paper presents the concept, topologies, control strategies, advantages, challenges, and renewable energy applications of multi-level inverters, emphasizing their significance in modern sustainable power systems.

II. TOPOLOGIES OF MULTI LEVEL INVERTERS

Multi-Level Inverters (MLIs) are classified into several topologies based on circuit configuration, switching devices, and energy storage components. The primary objective of these topologies is to synthesize a stepped AC output voltage from multiple DC voltage levels with reduced harmonic distortion and improved efficiency. In renewable energy applications, the selection of inverter topology depends on factors such as power rating, modularity, voltage balancing capability, cost, and control complexity. The most widely used MLI topologies are diode-clamped, flying capacitor, cascaded H-bridge, and emerging hybrid structures.

A.Diode-Clamped Multi-Level Inverter (Neutral Point Clamped)

The Diode-Clamped Multi-Level Inverter (DCMLI), also referred to as the Neutral Point Clamped (NPC) inverter, is a widely used topology in medium- and high-power renewable energy conversion systems. It generates multiple voltage levels by dividing the DC-link voltage using series-connected capacitors and employing clamping diodes to restrict the voltage stress across each power switch. This topology provides improved output waveform quality, reduced switching losses, and lower total harmonic distortion (THD) compared with conventional two-level inverters.

In a standard three-level NPC inverter, the DC source is split into two equal voltages by two capacitors connected in series. The midpoint of these capacitors forms the neutral point. Each phase leg consists of four controlled switches and two clamping diodes. By selecting appropriate switching states, the inverter can produce three output voltage levels: +Vdc/2, 0, and –Vdc/2. The stepped waveform obtained at the output is closer to a sinusoidal waveform, thereby reducing the requirement for output filters.

The output voltage is synthesized by controlling the switching states of the power devices. For a single-phase leg, the switching operation is as follows:

- Positive Voltage (+Vdc/2):

The upper switches are turned ON, connecting the output to the positive DC bus.

- Zero Voltage (0):

The middle switches are turned ON, and the clamping diodes ensure the output is connected to the neutral point.

- Negative Voltage (–Vdc/2):

The lower switches are turned ON, connecting the output to the negative DC bus.

The clamping diodes play a crucial role by limiting the voltage stress across each switch to Vdc/2 and ensuring proper voltage sharing among devices.

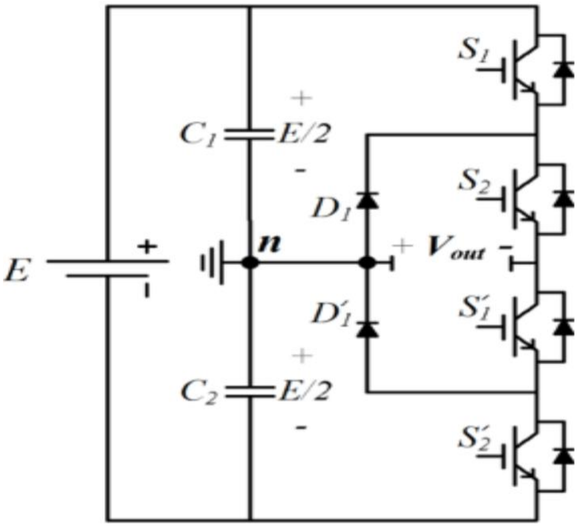

Fig. 1 Three-Level-Diode-Clamped-Inverter

B.Cascaded H-Bridge Multi-Level Inverter

The Cascaded H-Bridge Multi-Level Inverter (CHBMLI) is one of the most suitable inverter topologies for renewable energy applications due to its modular structure, high efficiency, and low harmonic distortion. It consists of multiple H-bridge cells connected in series, where each cell is supplied by an independent DC source such as solar panels, batteries, or fuel cells. By combining the output of each cell, the inverter produces a stepped AC waveform with improved power quality. This topology is widely used in solar photovoltaic systems, wind energy conversion systems, battery storage, and microgrid applications.

A basic CHB inverter consists of multiple single-phase H-bridge cells connected in series at the output side. Each H-bridge contains four switching devices (IGBTs/MOSFETs) and an isolated DC source. By controlling the switching sequence of each bridge, multiple stepped voltage levels are generated at the output.

For an inverter with n H-bridge cells, the number of output voltage levels is given by:

$m=2n+1$ (1)

where:
m = number of output voltage levels
N = number of H-bridge cells

For example, a two-cell CHB inverter produces:

$m=2(2)+1=5$ (2)

Thus, the output voltage levels are: +2Vdc, +Vdc,0, −Vdc, −2Vdc+

Mode 1: Positive Maximum Voltage
When both H-bridges generate positive voltage:

$V_o=V_{dc1}+V_{dc2}$ (3)

Output becomes maximum positive voltage.

Mode 2: Intermediate Positive Voltage
When one bridge produces positive voltage and another remains OFF:

$V_o=+V_{dc}$ (4)

Mode 3: Zero Voltage
When both bridges output zero voltage:

$V_o=0$ (5)

Mode 4: Intermediate Negative Voltage
When one bridge generates negative voltage:

$V_o=-V_{dc}$ (6)

Mode 5: Maximum Negative Voltage
When both bridges generate negative voltage:

$V_o=-(V_{dc1}+V_{dc2})$ (7)

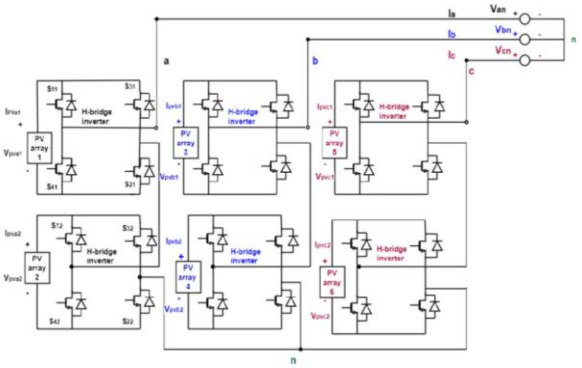

Fig. 2. Cascaded H-Bridge Multi-Level Inverter

C. *Flying Capacitor Multi-Level Inverter*

The Flying Capacitor Multilevel Inverter (FCMLI) is an important multilevel inverter topology widely used in renewable energy applications due to its capability to generate high-quality output voltage with reduced harmonic distortion and improved efficiency. It utilizes capacitors as voltage clamping devices instead of diodes, making it suitable for integrating renewable energy sources such as solar photovoltaic (PV) systems, wind energy systems, fuel cells, and battery storage systems.

A basic flying capacitor inverter consists of multiple switching devices and capacitors connected in series. The capacitors are charged to specific voltage levels and act as intermediate voltage sources. By controlling the switching states, the inverter produces multiple stepped output voltage levels.

For an m-level flying capacitor inverter:
Number of capacitors required:

$C = \frac{(m-1)(m-2)}{2}$ (8)

Number of switches required:

$S = 2(m-1)$ (9)

For example, a 5-level FCMLI produces output voltage levels:

$+V_{dc}, \frac{+V_{dc}}{2}, 0, \frac{-V_{dc}}{2}, -V_{dc}$ (10)

Mode 1: Maximum Positive Output
When upper switches are turned ON, the load receives full DC voltage:

$V_o=+V_{dc}$ (11)

Mode 2: Half Positive Output

The flying capacitor is inserted into the circuit, producing:

$$Vo=\frac{+Vdc}{2} \qquad (12)$$

Mode 3: Zero Output Voltage
Appropriate switches connect the load to neutral potential:

$$Vo=0 \qquad (13)$$

Mode 4: Half Negative Output
The capacitor discharges in reverse direction:

$$Vo=\frac{-Vdc}{2} \qquad (14)$$

Mode 5: Maximum Negative Output
Lower switches conduct and produce:

$$Vo=-Vdc \qquad (15)$$

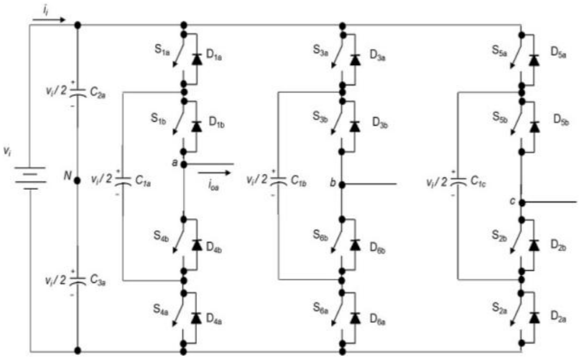

Fig. 3. Three level Flying Capacitor Multi-Level Inverter

III. COMPARISON OF MULTILEVEL INVERTERS FOR RENEWABLE ENERGY APPLICATIONS

The selection of an appropriate multilevel inverter (MLI) topology for renewable energy applications depends on several factors such as output voltage quality, efficiency, component count, control complexity, cost, and suitability for specific renewable sources. The three commonly used topologies—Diode-Clamped Multilevel Inverter (NPC), Flying Capacitor Multilevel Inverter (FCMLI), and Cascaded H-Bridge Multilevel Inverter (CHBMLI)—offer different advantages based on application requirements.

The Diode-Clamped Multilevel Inverter requires fewer capacitors and provides good efficiency in medium-voltage applications. However, it suffers from capacitor voltage balancing issues when the number of voltage levels increases. It is commonly used in grid-connected photovoltaic systems and industrial renewable applications.

The Flying Capacitor Multilevel Inverter offers better voltage balancing flexibility and improved reactive power control. However, it requires a large number of capacitors, increasing system complexity and cost. It is mainly used in high-power renewable systems where voltage quality is critical.

The Cascaded H-Bridge Multilevel Inverter is highly preferred in renewable energy applications because of its modular structure and compatibility with multiple isolated DC sources such as solar panels, fuel cells, and battery storage systems. It provides lower harmonic distortion and easier scalability but requires multiple isolated DC sources.

Parameters	Diode-Clamped (NPC)	Cascaded-H-Bridge	Flying-Capacitor
DC Sources Required	Single	Multiple	Single
Number of Capacitors	Moderate	Low	High
Number of Switching Devices	Moderate	Moderate	High
Harmonic Distortion	Low	Very-Low	Very-Low
Voltage Balancing	Difficult	Simple	Easier
Renewable Energy Suitability	Solar, Wind	Solar, Battery, Fuel-Cell	Large-scale systems
Modularity	Low	High	Low
Efficiency	High	Very-High	High

IV. CONCLUSION

Multilevel inverters have emerged as a highly efficient and reliable solution for renewable energy conversion systems due to their capability to generate high-quality output voltage with reduced harmonic distortion and lower switching losses. The increasing integration of renewable energy sources such as solar photovoltaic systems, wind energy conversion systems, fuel cells, and battery storage units has significantly increased the demand for advanced power electronic converters. Among the various multilevel inverter topologies, Diode-Clamped Multilevel Inverters (NPC) offer simple control and suitability for medium-voltage applications, Flying Capacitor Multilevel Inverters provide improved voltage balancing and reactive power control, while Cascaded H-Bridge Multilevel Inverters offer modularity and easy integration with multiple independent renewable energy sources. Each topology presents unique advantages and limitations depending on system requirements such as voltage level, power rating, cost, and complexity.

With continuous advancements in semiconductor devices, modulation techniques, and intelligent control strategies, multilevel inverters are expected to play a crucial role in future smart grids, electric vehicle charging infrastructure, and sustainable energy systems. Future research can focus on reducing component count, improving voltage balancing techniques, and enhancing overall efficiency for large-scale renewable energy techniques

The future of multilevel inverters (MLIs) in renewable energy applications is highly promising due to the rapid growth of sustainable power generation and smart grid technologies. As renewable energy sources such as solar photovoltaic systems, wind turbines, fuel cells, and battery energy storage systems continue to expand, the demand for efficient and reliable power conversion systems is increasing. Multilevel inverters are expected to play a significant role in improving power quality, reducing harmonic distortion, and enhancing overall system efficiency.

Future research can focus on reducing the number of power electronic components, thereby minimizing system cost, size, and complexity. Advanced semiconductor devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN) switches can be integrated to achieve higher switching frequencies, reduced losses, and improved thermal performance. Intelligent control techniques based on artificial intelligence, machine learning, and adaptive modulation strategies can further optimize inverter performance under varying renewable energy conditions.

Another important research direction is the development of improved capacitor voltage balancing techniques for diode-clamped and flying capacitor multilevel inverters. In addition, modular and fault-tolerant inverter architectures can enhance reliability in large-scale renewable energy plants and microgrid systems. The integration of multilevel inverters with electric vehicle charging stations, energy storage systems, and hybrid renewable energy systems is also expected to grow significantly in the future.

Overall, multilevel inverter technology will continue to evolve as a key component in achieving efficient, stable, and sustainable renewable energy integration in future smart power systems.

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