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Evolution and Prospects of Multilevel Inverter Technologies: A Survey of Topologies, Control, and Applications from Fundamentals to Future Trends

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ABSTRACT

In modern power electronics, multilevel inverters have emerged as a transformative solution compared to conventional inverters in both high-voltage and high-power applications. They offer superior electromagnetic compatibility performance, large DC-link voltage capacity, reduced total harmonic distortion, and increased reliability & efficiency. This review comprehensively analysis the types of multilevel inverter topologies along with their control strategies and modulation techniques. Even though traditional multilevel inverters have their own importance, advancement in power electronics has paved the way to newer configurations of MLIs. It highlights that applications of multilevel inverters have expanded across a broad spectrum in the power system, renewable sector, especially solar and wind energy, smart grids, and intelligent industrial automation. Also discuss the limitations of compact design, fault tolerance, and control technologies. The study highlights the area of innovation and provides a bridge for engineers and researchers to optimize the performance of MLI in the evolving power electronic world.

Keywords: *Multilevel inverter, Control strategies, Algorithm, Harmonic distortion, power electronics*

1. INTRODUCTION

In today's modern power electronic boundary, multilevel inverters have emerged as a cornerstone for converting and delivering electricity in a controlled manner. The society's need is increasing day by day, leading to the demand for more efficient and reliable power systems. Therefore, the MLI inverter continues to shine in the following applications, such as industries, households, transportation systems, and renewable energy integration. The advantages of MLI [1] are less EMI, switching loss, and THD, leading to increased system efficiency. The lifespan of the devices is prolonged, and the system's overall reliability is worth a penny increase. Even required multiple voltage levels that approximate a sine wave can be established by combining a capacitor network or a DC source.

In the 1970s, the multilevel inverter was being explored and implemented till today due to motivation received from both engineering and industrial constraints to produce robust and quality power systems with cost-effectiveness and preserving the environmental sustainable goal. At the early stage of multilevel inverter development, Neutral Point Clamped (NPC) topology was first introduced. Next the Flying Capacitor, Cascaded H-bridge, was developed one by one and is still ruling the industrial world. Each classification of MLI is not only based on topology design, but it also depends on source arrangement, control, and modulation strategy. Everyone has their own constrains and satisfies their specific needs.

The basic three types of MLI topologies form the bedrock for most of the modern topologies that exist today. The evolution represents complex hybrid architecture, such as a packed U cell, a switched capacitor, and a modular multilevel inverter. This design helps to focus on fault tolerance, intelligent control, and modular integration beyond the electrical performances. Hybrid architecture made possible by combining multiple multilevel inverter topologies and offering optimization in design [2], [3]. Next, modulation technique such as sinusoidal pulse width modulation, due to their simplicity and easy adaptation is widely used. To overcome the hurdles present in SPWM, Space vector PWM, selective harmonic elimination, and multicarrier modulation schemes are used. These methods show high performance in suppressing harmonics, reducing switching stress, and improving voltage utilization to provide their application in smart grids and electric vehicles.

In this review, a detailed report about various types of multilevel inverters, along with advantages and disadvantages, is provided in Section 1. Section 2 explores the control strategies used in a multilevel inverter. Section 3 discusses the applications across five different sectors. Section 4 lists the challenges present in topologies and discusses the solution.

2. TYPES OF MULTILEVEL INVERTER

Multilevel inverters are advanced converters that produce a stepped AC output voltage, approximately a sinusoidal signal with multiple voltage levels. These inverters overcome the disadvantages of conventional two-level inverters, such as THD, EMI, and bulky filters. The topologies of MLI, as shown in **Fig.1**, are discussed below along with their complexity, advantages, and disadvantages.

1. Cascaded H-Bridge:

In 1970, a complete cascade H-Bridge multilevel inverter was developed. It is nothing but combining the single-phase inverter with a separate DC source. Levels that are required can be formed using the formula m=2k+1, where m is the level, k is the number of H-bridge inverters needed.

Advantages: a) Flexibility and modular structure. b) Provide fault tolerance and reactive power capability for higher-level output.

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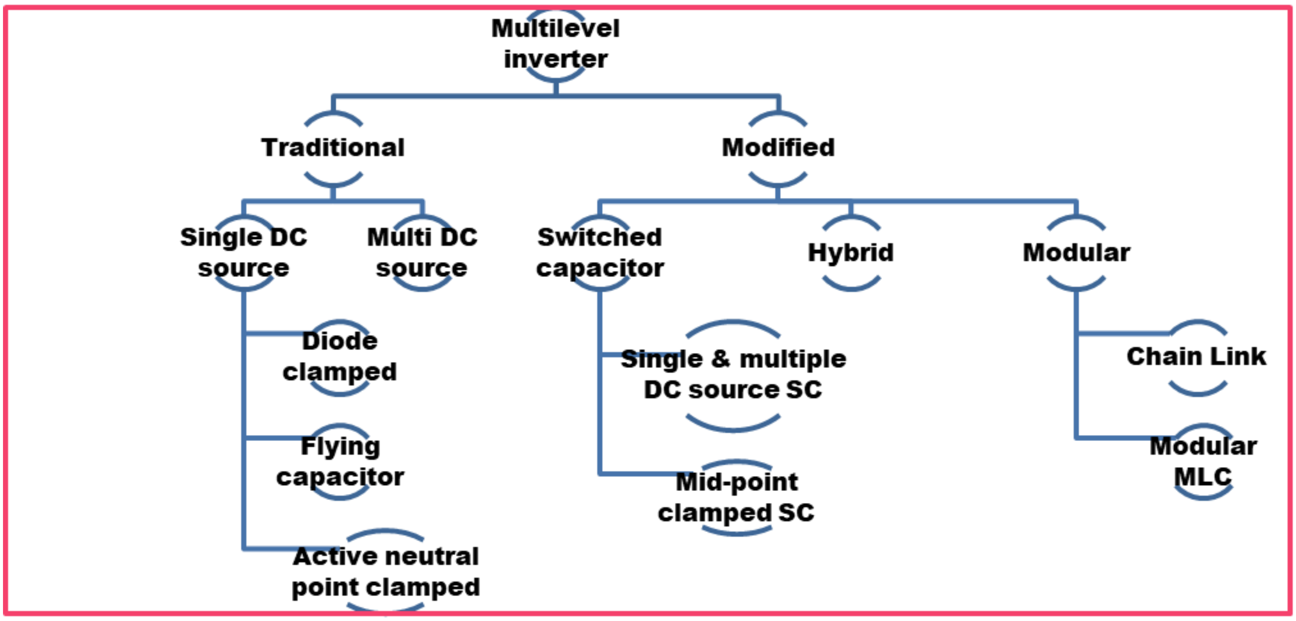

Fig.1: a) Shows the types of multilevel inverters

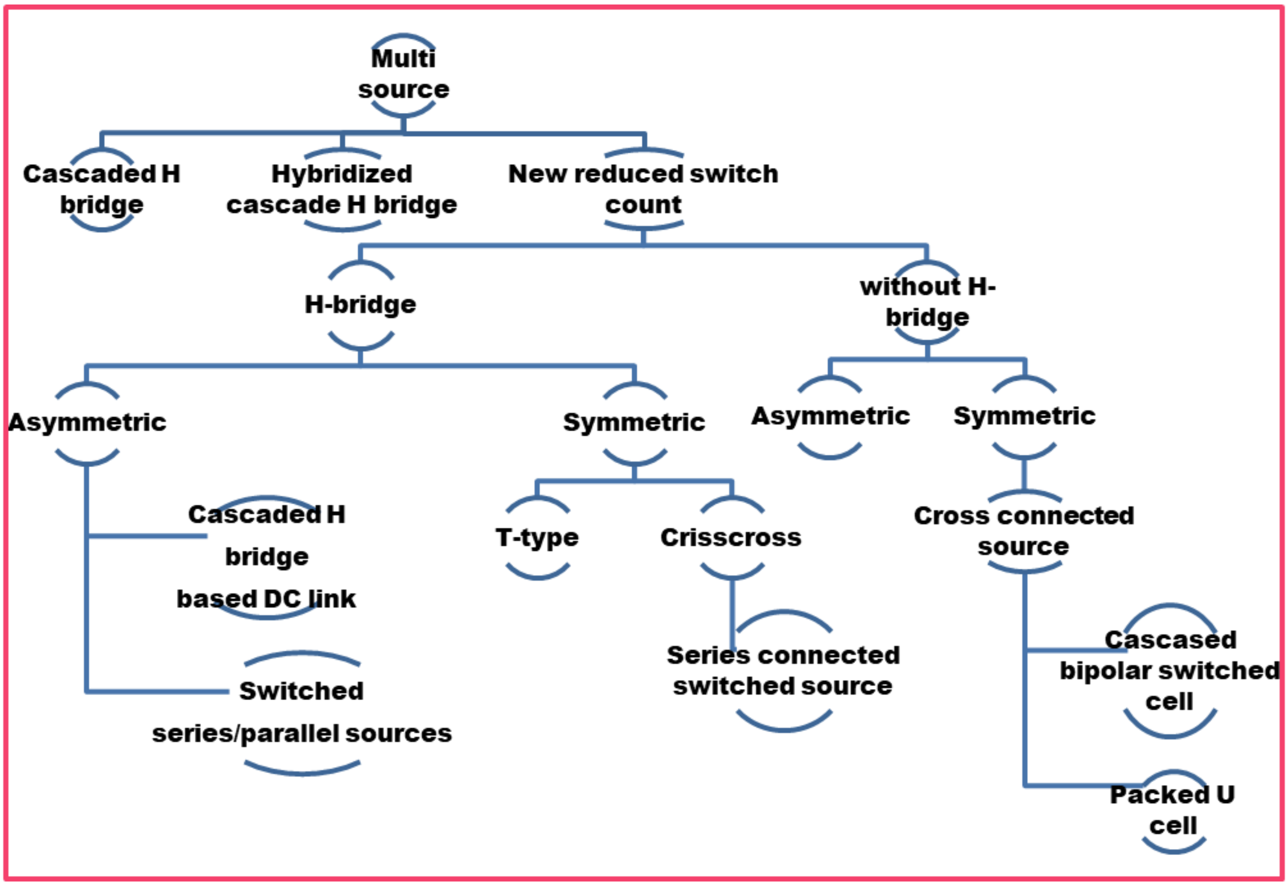

Fig.1: b) Shows the types of Multiple DC source MLI

Disadvantages: a) A separate DC source is required as the voltage level increases. b) The controller for DC line voltage is needed.

2. Diode-clamped MLI inverter:

In 1980, the inverter derived from a cascaded H-bridge was named the diode clamped inverter. Also known as a neutral point clamped inverter. As the name indicates, multilevel output is obtained by clamping the DC bus voltage with the help of a diode.

The output voltage waveform can be made into a sinusoidal waveform by increasing the voltage level.

Advantages: a) As level increases, diodes and switching devices also increase and lead to complexity.

b) Reverse blocking voltage of the clamping diode is quite challenging.

Disadvantages: a) Fluctuations take place at the neutral point due to deviations in the switching pattern. b) Overvoltage and capacitor voltage imbalance issues.

3. Flying Capacitor MLI:

In 1992, the Flying Capacitor MLI was introduced. The difference between the flying capacitor and the diode-clamped MLI is the replacement of the capacitor with a diode. Therefore, it is called a capacitor-clamped multilevel inverter. The step voltage level is decided by the capacitor's leg.

Advantages: a) Redundancy of switching improves the stability of FC MLI. b) More flexibility and capability to control reactive power.

Disadvantage: a) As the level increases, charging and discharging of the capacitor become a problem. b) High switching frequency leads to switch losses.

4. Active Neutral Point Clamped MLI:

Active NPC MLI is an advanced version of the neutral point clamped inverter. Here, losses take place between the inner and outer surfaces. It is overcome by replacing clamping diodes with power switches. This inverter is suitable for medium to high power applications such as energy storage and motor drives.

Advantages: a) Better voltage control and switching losses b) Also better in handling faults and provides protection

5. DC switched series/parallel source MLI:

Later, the SSPS topology is developed with an H-bridge. This topology consists of two units: the polarity and the level generation unit. The level generation unit generates staircase output voltage with a positive sign, and the polarity unit converts it into an AC output voltage.

Advantages: a) Two or more sources can be either connected in series or parallel. b) A flexible configuration is obtained by the limited number of switches

6. T-type MLI:

T-type MLI inverter operates at a switching frequency of 6-30KHz. The reason behind this topology is to reduce the power component by 40%. The reduction in conducting and switching losses shows little increase in efficiency. The midpoint connection with the help of a bidirectional switch device between the series capacitors point is created to clamp the output voltage to the neutral point during both positive and negative cycle.

Advantages: a) No clamping diodes are needed for clamping action. b) A medium switching frequency range is required to achieve efficiency higher than NPC.

Disadvantage: Failure to render the correct switching state.

7. Crisscross cascades MLI inverter:

This topology consists of two basic units similar to a DC switched series/parallel source MLI (SSPS). Here, the difference is that the level generation unit uses unidirectional switches, while the polarity generation unit uses bidirectional switches along with blocking switches.

Advantage: Lower cost due to reduction in semiconductor switches

Disadvantage: Usage of an isolated DC source is limited.

8. Series-connected switch series MLI:

A series-connected switch series MLI consists of many DC sources connected in opposite polarity, along with switching devices. The polarity changing does not require an additional section, like a 2-level full bridge.

Advantages: a) Fewer switching devices compared to CHB MLI. b) Complexity in the triggering circuit is minimized.

Disadvantages: a) Semiconductors used must have the same power rating. b) Various configurations are required for load sharing.

9. Asymmetric MLI:

Asymmetric MLI can be operated in separate DC sources by using different values of DC voltage ratio. Here, the value of the DC voltage ratio can be increased by a power of two or three. An increment in power two is called binary asymmetric topology, where an increase in power three is called trinary asymmetric topology. Asymmetric topology can also operate in symmetric mode.

Advantages: a) Higher voltage level obtained using switching devices than conventional CHB MLI.

10. Packed U-Cell MLI:

A Packed U-Cell multilevel inverter consists of only one DC source. A single DC source is capable of increasing output levels for higher values. The inverter uses storage capacitors to compensate for the high voltage ride-through (HVRT). Also, this technology reduces the stress in switches during the voltage level changing process.

Advantages: a) Reduction of active components cuts off the extra costs. b) Reliability is high

Disadvantage: To regulate the capacitor voltage, an additional balancing circuit is required.

11. Hybridized Cascaded H-bridge MLI:

The design that Hybridized Cascaded H-bridge MLI stands out from Cascaded H-bridge topology is that a) An auxiliary switch is attached to the H-bridge to improve THD. b) The requirement of components is less for the same output.

Disadvantage: Not suitable for high-voltage applications.

12. Hybrid Multilevel Inverter:

As the name indicates, a Hybrid Multilevel Inverter is a combination of 2 or more. In order to obtain a particular result, a combination of balanced and unbalanced MLI topologies takes place. A balanced MLI comprises a capacitor-switching MLI and a capacitor-clamped MLI unit.

Advantages: a) Reduction of power loss. b) Improve the efficiency.

Disadvantage: Not suitable for high voltage applications.

13. Modular Multilevel Inverter:

In 2000, the Modular Multilevel Inverter was most promising for medium to high voltage and power applications. It is applicable to a wide range of applications with the help of balanced sub-modules. Sub-modules may be half-bridge, full-bridge, self-balancing, clamp-single sub-modules, and so on. MMC and CLC are types of modular multilevel inverters.

Advantages: a) To have a balance between all the sub-modules, a unique design for capacitor control is used. b) Reduce the circulating current in the circuit.

14. Switched capacitor MLI:

Here, SC MLI, with the help of multiple capacitors and a switching device, produces many output levels. At the same time, it requires only a few symmetric or asymmetric DC sources. This altogether makes a building block of the SC unit. The three types of SC-MLI topologies are,

1. Single DC-Source SC-unit-based MLI: Here, SC units comprise many sub-sets. The subsets of SC units are SPSU, SC voltage double, SC half mode, SC bipolar, and SC voltage triple unit. A subset is nothing but a combination of components formed according to the required purpose. SPSU provides output at two discrete voltage levels. SC voltage doubling produces a double output compared to the original output. SC bipolar generates a bipolar output voltage level. SC voltage triple provides three times the output voltage.

2. Mid-point clamped MLI: As the name indicates, a neutral/midpoint reference is created by splitting the DC-link. This method increases the output voltage and makes them suitable for grid application. Here, due to a single DC voltage, the leakage current is reduced.

3. Hybrid SCMLI: This hybrid multilevel inverter is a combination of two or more SC-MLI. It comprises an H-bridge, a bidirectional switch MLI, and a switched capacitor unit. Since a bidirectional switch is used, the power flow takes place in either direction.

Advantage: Overcome the high-frequency variable common-mode voltage problem due to various uses of HB legs.

15. Modular Multilevel Converter:

A Modular Multilevel Converter consists of series or parallel sub-modules(SM). A combination of sub-modules is used according to the application needed. The sub-modules are connected in series with the inductor to form an arm. The two sets of arms form a phase. The sub-modules are HB commutation cell, FB commutation cell, NPC commutation cell, and T-type commutation cell. These cells are building blocks for the MMC configuration. The sub-topologies are the Alternate Arm Converter (AAC) and the Flying Capacitor-MMC.

1. Alternate Arm Converter: The Arm consists of a series of SM with a high voltage switch, and this arm can be activated or deactivated to provide better performance in terms of circulating current, voltage ripple, and power loss when compared to the standard MMC.

2. Flying Capacitor-MMC: Here, the capacitor connects the upper arm and lower arm in each phase. The advantages of this configuration are reduced voltage ripple and balanced power between the arms. If FC is replaced by a series of sub-modules, then the configuration becomes an active cross-connected MMC.

Advantage: Reduced voltage ripple across the capacitor can be achieved by controlling the circulating current.

Disadvantage: Large number of sub-modules.

16. Chain Link Converter:

CLC configuration is simple and a repeated circuit configuration. The cells connected in series may be a half bridge, a full bridge, or a chopper converter. Therefore, any fault in one cell can be easily replaced by the other cell. The sub-topologies of CLC are single-star/delta-bridge cell (SSBC/SDBC), double-star/delta-bridge cell (DSBC/DDBC), and triple-star bridge cell (TSBC).

1. SSBC/SSDC: Both topologies consist of three strings. Each string contains multiple HB converters in cascaded form. In SSBC, this string is connected in star form, whereas in SSDC, it is connected in delta form. It requires only a minimum number of cells.

2. DSCC: These topologies are the same as SSBC/SSDC, which contains a series of multiple HB converter sets of 2 connected in either star or delta. The difference is that there will be two sets of star/delta combination and an additional DC voltage.

3. TSBC: This configuration consists of 3 sets of SSBC. Each SSBC is a combination of 3 clusters. A cluster is nothing but multiple single-phase FB converters connected in cascade form. This topology is also called a Modular matrix converter.

Advantages: a) Fewer components compared with the diode-clamped and capacitor-clamped converter, and reactive power control is provided. b) Continuous supply to loads in a fault situation by bypassing the faulty module.

Disadvantages: a) Implementing the DC voltage regulation loop is complex. b) No common DC link leads to affecting the output power by the frequency due to oscillation.

3. CONTROL STRATEGIES

Modulation control techniques, as shown in **Fig.2**, are important in increasing efficiency, and reducing the total harmonic distortion and switching losses. To provide a balanced output, these modulation techniques generate control signals. There are two switching frequency techniques, such as fundamental switching frequency and high switching frequency techniques. Fundamental switching frequency technique operates at a low frequency and has fewer losses. The high switching frequency technique operates at high frequency and has many commutations. Each type is discussed below,

1. Sine property:

The sine property is the mathematical foundation for generating the output. In short, the sine property indicates using a sine reference waveform in Sinusoidal pulse width modulation. The purpose of a sinusoidal reference waveform is to control the switching instance of power semiconductor devices.

2. Sinusoidal Pulse Width Modulation:

The fundamental and most widely used modulation technique is SPWM. The operation takes place by comparing high-frequency triangular carrier signals with a reference sinusoidal signal. In MLI, each level has a switching threshold defined by stacking the multiple carriers vertically. Switching

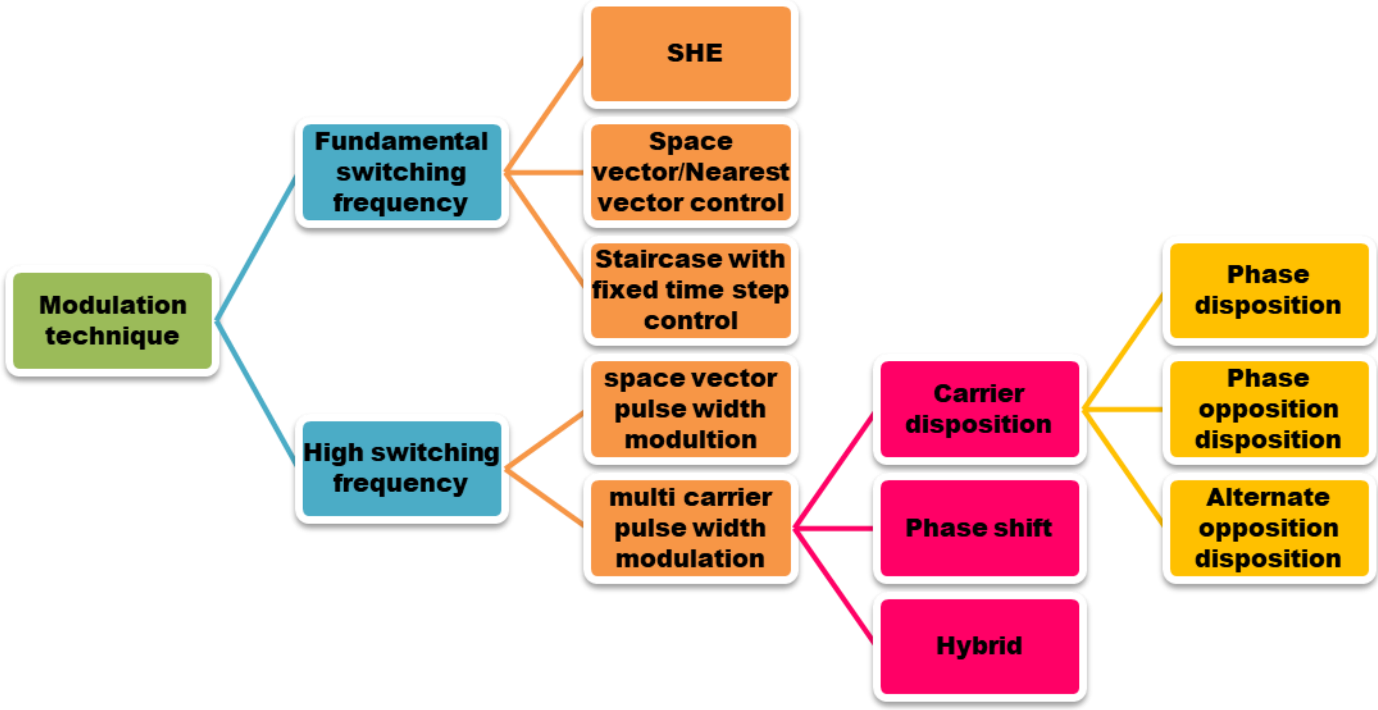

Fig.2: Shows the types of modulation techniques

instant is determined by the intersection point of the carrier signals and the reference signal. This method seems to be simple and moderate harmonic control. Switching complexity arises when levels increase with multiple carriers.

3. Selective Harmonic Elimination:

In 1964, the harmonic elimination method was developed. Later, it was developed into selective harmonic elimination. The SHE method removes the lower harmonics and improves the inverter output waveform. The SHE method calculates the correct switching angle to reduce the particular harmonic order. SHE is suitable for high switching frequency operation. However, it requires many passive filters to limit the lower-order harmonics. The calculated switching angles are saved in a loop-up table; otherwise, the optimization algorithm generates the switching angles in real time. SHE is used in a cascade H-bridge, where a single H-bridge needs separate control. Even though THD is reduced with minimal switches, as the level increases, complexity increases. To make this method more effective, it makes use of optimization algorithms [4], and commonly used algorithms are Genetic Algorithm, Newton Raphson, Particle Swarm Optimization, Cuckoo Search Algorithm, and Hybrid Optimization.

a) Genetic Algorithm:

The principle behind the GA is natural evolution. This work presents a possible solution that evolves over generations by using terms such as mutation, crossover, and selection. In SHE, this algorithm helps in finding the switching angles with minimal THD. The advantage of this method is that it finds solutions in a wide space and avoids local minima, making it suitable for complex problems. However, convergence takes place slowly when compared to other available methods.

b) Newton Raphson:

The NR method is a classical technique for finding roots in nonlinear equations. In the SHE application, switching angles are defined by the transcendental equation. So, this equation is solved using the NR method. The advantages of the method are fast and efficient. If the initial value is close to the actual solution, it converges; otherwise, it leads to divergence. So, it is suited for the equations that have a well-behaved and known range of solutions.

c) Particle Swarm Optimization:

This algorithm is inspired by the behaviour of flocking birds. The particle means a potential solution found by adjusting the position in the space based on its own experience. The PSO algorithm is easy to implement and simple to find the optimal switching angles in SHE. Even though it converges quickly, it can enter into the local optima by not tuning properly. It also provides a better balance between exploration and exploitation in real-time applications.

d) Cuckoo Search Algorithm:

The optimization technique CSA is inspired by the behaviour of the cuckoo species. This algorithm expands its capability in both local and global searches by combining it with the Levy flight strategy. This algorithm is used in SHE to eliminate the lower harmonics with the required output. The advantages are solving the nonlinear transcendental equations and being efficient in finding the solution.

e) Hybrid Optimization:

A combination of two or more algorithms for utilizing their individual advantage is a hybrid. For example, fine turning by NR and global search by GA are combined to find the switching angle in SHE. This improves the convergence speed, deals with nonlinear equations, and provides better accuracy. Even though it has its own difficulties in implementation, it offers superior performance in the given scenarios. Hybrid approaches are more often used by researchers now-a-days in MLI for lower THD and better output.

4. Space Vector Control:

Space vector is also called nearest vector control. SVC works great under high voltage applications for low switching frequency inverters. The modulation tragedy SVC treats the output voltage of the 3-phase inverter as a rotation vector in the complex plane. This method produces the desired output by choosing a switching state that indicates a discrete vector of voltage. These vectors are usually combined over the switching period to fix the reference vector and avoid modulation for each phase separately. The space vector control method minimizes the spatial errors by identifying the vector nearest to the reference value. Here, vector density is used to reduce the probability of error in correcting the THD. In MLI, the vector count increases exponentially to produce a finer output.

5. Staircase Modulation with fixed time step control:

As the name indicates, the output voltage is a series of discrete steps combined to form a voltage level of the inverter. Hence, switching instants are spaced equally, and each time step changes the voltage level to form a sine waveform. With the help of designed control, this method is implemented more easily. Even though it can’t control harmonics entirely like SHE/SVPWM, it is a simple and strong method to generate an output waveform and a predictable switching pattern.

6. Space Vector Pulse Width Modulation:

This method is an advanced method of SVC and uses digital modulation to generate a PWM signal. SVPWM gives better results in eliminating harmonics and fundamental voltage ratio when compared to the triangular carrier-based modulation method. It operates at high frequencies and separates the switching period into segments. In this method, multiple vector states are applied to the modulation of reference signals to produce the required output. In short, by optimizing the position and timing of switching states, the DC voltage is used at maximum value, and THD is reduced. However, finding switching intervals and a lookup table is difficult. It can be comprised of digital signal processing and a microprocessor.

7. Multicarrier PWM technique:

In this technique, multiple triangular carrier signals are compared with a reference sinusoidal signal to determine the switching instants. This method is widely to produce high-quality output. There are three types of Multicarrier PWM techniques.

a) Carrier Disposition:

Carrier disposition indicates the arrangement of multiple triangular carrier signals. This arrangement decides how they are going to interact with the reference sinusoidal signal to generate the switching instants. There are three types of carrier disposition.

1. **Phase Disposition:** Here, all the triangular signals are in phase and stacked vertically. All the carriers are simultaneously compared with reference signal, and switching signals are generated when each carrier is intersected by the reference signal.
2. **Phase opposition Disposition:** The carriers present above and below the zero reference are 180 out of phase. This method cancels even harmonics and provides a symmetry output, but it is a bit complex.
3. **Alternate Phase Opposition Disposition (APOD):** To produce a more balanced switching pattern, carrier signals are arranged in phase shifted by 180 alternately. This reduces the switching stress and provides uniform thermal distribution. Ultimately, it requires a complex gate driver.

b) Phase-shifted PWM (PSPWM): Here, carrier signals are phase-shifted by an equal angle. The phase shift for the converter is 360/n-1, where n is the level of the inverter. This method reduces peak current and voltage stress by equal distribution of switching signals. However, modules need control to maintain the waveform integrity.

c) Hybrid PWM: The hybrid PWM is a combination of two techniques, such as phase-shifted and level-shifted techniques. It can also be integrated with SHE or SVM to enhance the control. This method is suitable for Asymmetric MLI.

Table 1presents various modulation techniques and their suitable MLIs, along with corresponding THD values. To make it more suitable for real-time adaptability and for optimizing the performance, intelligent control method such as fuzzy logic controller and adaptive neural network are used. This integration of an intelligent controller adds a new dimension to the inverter operation.

Table 1: Shows various modulation techniques, their applicable MLIs and its THD value

S.NO	Modulation Techniques	Commonly used in MLIs	THD Values
1	Sinusoidal Pulse Width Modulation	Diode-Clamped (NPC)	18-22%
		Flying Capacitor (FC)	20-24%
		Cascaded H-Bridge (CHB)	15-18%
2	Selective Harmonic Elimination	CHB	7-10%
		FC	10-12%
3	Space Vector Control	NPC	10-14%
		FC	12-16%
4	Staircase	CHB	8-11%

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	Modulation with fixed time step control		
5	Space Vector Pulse Width Modulation	NPC	9-12%
		FC	10-13%
6	Phase Disposition	NPC	Voltage-9.3%, Current-9.6%.
		FC	10-12%
7	Phase Opposition Disposition	NPC	Voltage-18.06% Current-15.67%
		FC	16-18%
8	Alternate Phase Opposition Disposition	NPC	Voltage-18.27%, Current-15.67%
		FC	17-19%
9	Phase Shifted PWM	CHB	10-13%
10	Hybrid PWM	CHB	20-24%
		NPC	25.57%
		FC	22-26%

4. APPLICATIONS OF MLIs

A multilevel inverter has its own technical and operational constraints that extend its application across various sectors, as discussed in **Table 2**. In terms of the renewable energy sector, especially solar and wind plants [5]–[7], multilevel inverters play a crucial role. They help in converting DC into AC power according to compliance with the grid, along with reduced harmonic distortion and increased efficiency. To achieve these, a multilevel inverter supports in implementing auxillary services such as maximum power point tracking, reactive power control, voltage control, and an anti-islanding protection scheme. In the sector electric vehicle [8], [9], the role of MLI is to enhance the performance of the machine by controlling speed/ torque, regenerative braking, and battery management. This pay way to reduces stress on the components, THD, and improves the lifespan durability of the e-vehicle. In the industrial sector, motors receive high voltage, high-quality supply with the help of MLI. So, reduced vibration, heating effect, and mechanism stress are the following benefits offered from MLI. Another impressive application of MLI is the HVDC transmission system and the FACTS device. They are used to control power flow, both active and reactive power, balance the voltage level, and clean the faulty section for grid stability. MLI usage does not stop here; it extends in uninterrupted power supplying UPS and smart appliances to increase energy efficiency. Choosing the correct topologies of MLI with control techniques according to the needs of appliances leads to achieving greater results.

Table 2: Various applications of MLIs

S.No	Applications	Recommended MLI	Role	Why MLIs needed
Power System and Grid				
1	Solar PV system connected to the grid	Cascaded H-Bridge (CHB), Diode clamped (NPC) & Flying Capacitor (FC) for medium voltage.	To convert the DC power from PV panels to AC power	MLI provides voltage conversion to match the grid compliance with reduced THD.
2	FACTS device	NPC/Modular Multilevel converter(MMC)	To provide the desired output voltage by reactive power support	MLIs offer control to regulate the unbalanced voltage with improved response time, THD, and flicker compensation.
3	HVDC transmission	MMC	To convert the power from DC to AC & from AC to DC for transferring over long distances	MLIs allow bidirectional flow of power with improved quality and reduce the usage of filters.
4	Reactive power compensation	NPC, MMC	To maintain the voltage stability and improve the power factor	MLIs enhance compensation during dynamic response.

5	voltage regulation in a substation	NPC, MMC	To make the distribution system receive the required voltage level without losses	MLIs support control over multi-level voltage.
6	Distributed generation	CHB, FC	To provide rural electrification with the help of hybrid sources (solar and wind)	MLIs offer a modular architecture for the integration of renewable energy.
7	Frequency control	NPC, MMC	To maintain the frequency of the system within a limit, irrespective of load changes	MLIs support in regulating the frequency in real time.
8	Synchronization with the grid	CHB, Single-stage MLI	To synchronize the output with the grid voltage, frequency, and phase	MLIs offer smooth synchronization with the grid.
9	Islanding service	CHB	To support the connection and disconnection of the device.	MLIs detect abnormal conditions and offer protection.
Renewable Energy System				
10	Solar inverter for Rooftops	CHB, Reduced switch MLI	To support the individual's home electricity needs	MLIs improve power quality by reducing THD using soft switching.
11	Wind turbine	NPC, MMC	To convert the variable AC voltage into grid voltage	MLIs support changes in the speed of wind and smoothing out fluctuation
12	Solar - Wind hybrid system	CHB	To combine the multiple DC inputs and convert them into an AC output	MLIs offer control for smooth hybrid operation.
13	Fuel cell	CHB, Diode clamp-3L (DC)	To offer both boosting and converting DC/AC	MLIs offer energy conversion with reduced switching stress.
14	Net-metering	Two-level MLI	To enable power flow in a bidirectional direction	MLIs offer accuracy and transparency of the system.
15	Forecasting for a renewable system	NPC, MMC	To stabilize the system by forecasting the power generation	MLIs help in predictive energy dispatch and stabilize output.
16	Green building	CHB, ANPC	To manage the integration of smart buildings with renewable energy	MLIs provide smart control and balancing in real-time.
17	Solar-irrigation	Single-source MLI	To control the irrigation pumps for farming	MLIs provide control over speed and protect the motor.
18	Smart home integrated with renewable	CHB	To have seamless operation between solar power and battery	MLIs provide compatibility between solar and battery.
19	Telecom tower-	5L CHB, ANPC	To provide the required	MLIs reduce maintenance and

	Renewable		voltage for the communication gear in telecom towers	enhance reliability.
E-vehicle and transportation				
20	EV motor	Reduced switch CHB, NPC, T-Type	To supply AC voltage for traction motors	MLIs offer speed and torque control.
21	Regenerative braking	Bidirectional CHB, Dual active full bridge MLI	To provide the bidirectional power for the recovery of braking energy	MLIs offer dynamic braking for a range of speed.
22	Battery management system	Single source MLI, CHB	To offer control for charging and discharging of the battery.	MLIs provide multi-pack configuration and offer better thermal performance.
23	Wireless EV charging	H-bridge MLI, Multilevel resonant inverter	To provide power for charging without cables	MLIs offer precise control over switching frequency.
24	EV buses	MMC	To handle the heavy powered vehicles	MLIs offer acceleration and regenerative braking.
25	Railway traction	MMC	To drive the AC traction motors	MLIs offer a robust design even in harsh rail surroundings.
26	Metro propulsion	NPC	To provide control over urban transit	MLIs offer a compact design to fit in metro compartments.
27	Aircraft propulsion	Hybrid MLI	To drive the engine	MLIs provide lightweight and ensure fault tolerance.
28	Marine propulsion	MMC	To handle the ship and submarines with high power	MLIs design improves the fuel efficiency and withstands the marine conditions.
29	Hybrid vehicle converters	NPC/CHB	To manage the combination of the engine and battery system	MLIs provide energy optimization and seamless switching support.
30	V2G system	Bidirectional CHB, MMC	To enable the power exchange between the vehicle and the grid	MLIs support fast energy dispatch and provide intelligent control.
31	Drone propulsion	FC/NPC	To provide flight control for the drone motor	MLIs provides compact design and thrust modulation.
32	Electric ship	MMC	To control the propulsion and drive the marine vessel	MLIs control propulsion and protect sensitive navigation system.
33	Mining vehicle	NPC	To offer high power for traction equipment	MLIs handle the high power requirements.
Industrial Applications				
34	Variable frequency drives	NPC	To provide variable frequency control for the motor	MLIs provide lower switching losses and control the speed.

35	Conveyor motor	CHB	To drive the acceleration and deceleration of industrial conveyors	MLIs save energy and support the long conveyor lines.
36	Automation in Industries	FC,CHB	To handle the automatic robotic system	MLIs provide flexible support for voltage support and reduce EMI.
37	Robotic motor	FC,CHB	To provide control for robotic arms and joints' motion in multi-axis.	MLIs lower the THD and enhance the movement.
38	CNC machine	NPC ,CHB	To ensure high power to precision tools like rollers and cutters	MLIs control accurate precision with less noise and vibration.
39	Textile machine	NPC	To provide torque control to manage looms and spindles	MLIs help in reducing the mechanical stress during the cycles.
40	steel plant	MMC	To provide high power for rollers and furnaces	MLIs suppress the harmonic and support during heavy loads in rolling and casting.
41	Oil and gas drilling	MMC, NPC	To adjust the speed for drilling depth	MLIs provide reliability during extreme temperatures and vibration.
42	Chemical process	NPC, Flying Capacitor	To regulate the reactors and the mixer	MLIs offer control over motor torque.
43	Food automation	CHB, NPC	To provide vibration-free motor control for packing and sorting	MLIs offer a compact design for motion control.
44	Water treatment	Single source MLI, CHB	To control the pumps and aerators of the filtration system	MLIs offer control over flow and pressure.
45	Compressors in industries	NPC, CHB	To optimize the motor for the driving air system	MLIs reduce start-up current and adjust the dynamic loads.
Commercial Applications				
46	UPS	3L CHB, NPC	To offer backup power	MLIs provide double conversion and minimize the filtering.
47	Air conditioning	NPC, CHB	To provide the required temperature by controlling the voltage of the compressor	MLIs reduce inrush current and support soft-start.
48	Washing machine	CHB, Flying Capacitor	To control the speed of driving for different wash cycles	MLIs offer energy-efficient operation and reduce the torque ripple.
49	Retail energy management	CHB, NPC	To control the energy usage across the retail infrastructure by segmenting loads	MLIs offer integration with IoT devices and optimize the power flow.

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50	ATM system	CHB	To provide a smooth transaction and uninterrupted service	MLIs reduce the voltage fluctuation for efficient operation.

Just as selecting the right type of multilevel inverter for an application is crucial for achieving optimal system performance, choosing the appropriate modulation technique for specific applications is also equally important. **Table 3** illustrates the connection between various applications and the modulation methods best suited for them, emphasizing how both factors contribute to efficient and reliable power electronics design.

Table 3: Suitable modulation techniques for required applications

S.NO	Applications	Modulation Techniques
1	Medium voltage level application, UPS system, Motor drives, Solar inverter	SPWM
2	THD control, Grid-connected solar inverter	Selective Harmonic Elimination
3	EV traction system, Motor control, Robotics	Space Vector Control
4	Renewable energy integrated with the grid in medium voltage	Staircase Modulation with fixed time step control
5	High voltage and high power applications, Automotive electronics, Aerospace, Motor control	SVPWM
6	Symmetrical switching application	Phase Disposition
7	Harmonic reduction	Phase Opposition Disposition
8	Power quality improvement, Distributed generation	Alternate Phase Opposition Disposition
9	Battery system, Large PV solar inverters	Phase-Shifted PWM
10	Custom modulation strategy, EV traction inverter	Hybrid PWM

5. CHALLENGES IN SWITCHING SEMICONDUCTORS OF MLIS

A multilevel inverter generates a high-quality output and reduces stress on the components. But semiconductor switches often experience various failures. This is due to thermal, electrical, and environmental stresses on the switches. Each failure factor is discussed below including its impact on the operation of the MLI inverter. At the same time, it should be addressed, and implementation of the protection techniques is required.

1. **Overvoltage stress:**

During a switching or transient event, the voltage across the switching device exceeds its rated value, leading to overvoltage stress. Advancements in multilevel inverter topologies lead to a complex structure. This way leads to unequal voltage distribution across the available switches, resulting in a voltage spike. This voltage spike is capable of puncturing the insulation layers. Sometimes an avalanche breakdown takes place.

2. **Overcurrent:**

Same concept as overvoltage, if the current flowing through the semiconductor devices increases beyond their operation limit, it leads to an overcurrent condition. The effect of overcurrent results from control errors, short circuits, and load changes. In the worst case, overcurrent leads to thermal runaway, internal melting junction, or wire damage. For example, in a cascading inverter, a fault in one stage can propagate and cause stress in switches.

3. **Thermal overload:**

Degradation of the switch leads to thermal overload. Thermal overload is nothing but the temperature of semiconductor devices increasing beyond their limit. This increase is due to high switching frequency, power heat dissipation, and an improper cooling system. The repeated thermal overload gives way to mechanical stress, delamination, and micro cracking. If this continues, the lifespan and reliability of switches are reduced.

4. **Chip-related malfunction:**

There are two types of failure: extrinsic failure due to thermal and mechanical stress, and intrinsic failure are due to electrical overstress. Due to this, chip-related failures such as dielectric breakdown, latch-up, and electron migration occur. Dielectric breakdown is caused by extreme thermal or electrical stress, and latch-up is caused by a parasitic thyristor or transistor present in the circuit that affects the gate control and damages the device.

5. **Electromagnetic interference:**

Electromagnetic interference can radiate and conduct noise into the neighbour circuit. High-frequency switching operation and rapid switching on and off lead to EMI. This causes control signal corruption, displacement in driving time, and false triggering of semiconductor switches. EMI management is necessary in MLI, where many switches operate in close proximity to have stable operation.

6. **Component aging:**

Continuous exposure to electrical and thermal stress degrades the semiconductor switches. This aging leads to a

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reduction in switching speed, an increase in leakage current, and insulation failure. In MLI, aging has a huge impact on the circuit. Therefore, maintenance and modeling of the strategies are required to overcome the unequal performance and increased fault circumstances.

7. **Capacitance voltage imbalance:**

Voltage balance in a capacitor is important in topologies like FC, NPC MLI, etc. If this capacitor becomes unbalanced by not dividing the voltage level correctly, voltage stress on the semiconductor switches takes place and leads to parameter failure. The reason behind this imbalance is improper charging and discharging of components. To overcome this, active balancing techniques are required.

8. **Control system fault:**

The control system manages the switching function of the inverter. Even if a sensor failure, a software bug, or communication errors take place, it affects the switching timing and sequences. So, this leads to shoot-through, distortion in output, or damage to the switch. Therefore, real-time monitoring and fault-tolerance control are essential.

9. **Environmental factor:**

Conditions like dust, humidity, temperature, and vibration can impact semiconductor devices. For instance, dust leads to short circuits, vibration lowers the connection and damages the soldering, and moisture leads to corrosion and affects the insulation. Therefore, protection enclosures and environmental hardening are required.

Even though a multilevel inverter has numerous benefits, the design and control implementation must undergo ongoing extensive research, it is essential due to the above reasons. The research area also includes reducing the component count, balancing the capacitor voltage, managing faults, and decreasing circuit complexity and precisely synchronizing and periodic scheme during voltage level increases. For example, the voltage drift of a capacitor can cause a dip in output quality and the lifespan of the components. So, each area requires its unique ongoing research to develop and upgrade according to the needs of the real- time world. Next, switches that are designed in MLI for high power applications must be supervised carefully to avoid system faults happening due to cascade of short circuit misfiring and overheating. Another important problem is electromagnetic interference; careful PCB design, layout, shielding, and strategic filtering are needed to overcome this. At last, seem-less communication is required for grid-connected inverters in order to maintain the scalability and synchronization between the grids. This avoids instability in the system and power quality issues. Overall, the implementation will be fulfilled by thermal management [10]. Therefore, cooling techniques can increase the longevity of IGBTs, and each method has its own performance, cost, and complexity. Research found solutions to these problems by using fault-withstand topologies, real-time autonomous systems, diagnosis in an unpredictable environment, and redundant switching paths innovatively is discussed in **Table 4.**

Table 4: Presents the advanced techniques to prevent the faults

Fault Type	Advanced Technique	Diagnostic approach
Over voltage Stress	Harmonic analysis using FFT	Real-time Fast Fourier Transform (FFT) spot transient spikes and harmonics caused by grid fluctuations or switching events, and isolate the abnormal voltage to avoid overvoltage stress.
Over current	ANN-based fault classification	ANN can detect the multi-class fault with high accuracy using the previous real-time data.
	Digital Twin-Based Fault	As the name indicates, the virtual replica of the inverter is created and operated in parallel with the physical device, and predicts the fault before it occurs in the real system.
	Wavelet Packet Transform prediction	The Wavelet Packet transform decomposes signals into many frequency bands and extracts the fault portion.
Thermal Overload	Embedded thermal sensors with feedback	Embedded the sensor in the power modules to monitor the temperature and enable the cooling system.
Chip Mal-function	LabVIEW-based fault simulation	Using LabVIEW along with time fault signatures helps to train the algorithm without destroying hardware.
EMI	DWT-based EMI isolation	Use the discrete wavelet transform to separate and suppress high-frequency interferences and improve signal clarity.
Component Aging	AI-based predictive maintenance	With the help of an AI model trained with aging data, predict the early signs of failure and remaining useful time (RUL)
Control System Fault	ANN + DWT hybrid fault model	The Hybrid model helps in improving the robustness over a single technique by combining the benefits of machine learning and frequency analysis.
Environ-mental Factors	Real-time environmental feedback loop	Based on feedback obtained from the sensor that senses the humidity, temperature, and dust conditions, it adjusts the system parameters.

6. PILOT PROJECTS:

1. GE Verona has introduced a high-efficiency solar application with a capacity of 2000V DC. This system is well-suited for grid integration, thermal management, real-time operation, and fault rectification.

2. The Flex Inverter has introduced an inverter integrated with a battery. These pilot systems are undergoing tests focused on control algorithms, energy dispatch capabilities, and operational flexibility.

3. RWTH Aachen University has developed both half-bridge and full-bridge MMC inverters, integrated with OPAL-RT and HYPERSIM real-time simulation platforms. Their performance is designed to support control and protection functions for HVDC systems.

4. Hoher Powertrain and ETH Zurich GaN have collaborated to develop a high-frequency GaN-based three-level (3L) multilevel inverter. This prototype is aimed at delivering high efficiency and supporting next-generation electric vehicles (EVs).

5. Predictive and model-based balancing techniques are employed alongside real-time systems to forecast imbalance trends and dynamically adjust control parameters.

7. CONCLUSION:

In the future, MLI can undergo many converging trends. Among them, one promising direction is reducing the complexity of the topology by minimizing the components like switches and capacitors, to develop lightweight inverter modules without compromising the high-quality output voltage. So, it aims not only to reduce the cost and complexity of the circuit but also for easy maintenance and reliability. In the field of decentralized power systems and smart grid scalability, an important development called Pley and Play architecture has been integrated. To facilitate the smart control techniques, tying up with AI and deep learning helps in dealing with real-time optimization, prediction, analysis, and recovering from the fault on its own. This feature helps the inverter retain its reliability in situations where unexpected things happen. The choice of a material plays a key role in producing higher switching speed, thermal performances, and minimizing the system loss. Gallium nitride (GaN) and silicon carbide (SiC) can both be used perfectly in place of silicon. This improves the performance of MLI and enhances its suitability for integrating into fields like EV, renewable energy, and aerospace.

REFERENCES

[1] J. Rodríguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls, and applications," IEEE Trans. Ind. Electron., vol. 49, no. 4, pp. 724–738, 2002, doi: 10.1109/TIE.2002.801052.

[2] R. A. Rana, S. A. Patel, A. Muthusamy, C. W. Lee, and H. J. Kim, Review of multilevel voltage source inverter topologies and analysis of harmonics distortions in FC-MLI, vol. 8, no. 11. 2019. doi: 10.3390/electronics8111329.

[3] S. Choudhury, M. Bajaj, T. Dash, S. Kamel, and F. Jurado, "Multilevel inverter: A survey on classical and advanced topologies, control schemes, applications to power system and future prospects," Energies, vol. 14, no. 18, 2021, doi: 10.3390/en14185773.

[4] A. Singh, V. Jately, P. Kala, R. Singhal, and Y. Yang, "Selective harmonic Elimination using Dwarf mongoose optimization in Single-Phase Seven-Level switched capacitor inverter with reduced components," AEU - Int. J. Electron. Commun., vol. 195, no. March, p. 155768, 2025, doi: 10.1016/j.aeue.2025.155768.

[5] L. Hassaine, E. OLias, J. Quintero, and V. Salas, "Overview of power inverter topologies and control structures for grid connected photovoltaic systems," Renew. Sustain. Energy Rev., vol. 30, pp. 796–807, 2014, doi: https://doi.org/10.1016/j.rser.2013.11.005.

[6] A. Hafeez and S. Singh, "Study of Total Harmonic Distortion (THD) Reduction by Filter in Renewable Energy Inverter," Test Eng. Manag., no. August, pp. 15019–15023, 2021.

[7] P. Horrillo-Quintero, P. García-Triviño, R. Sarrias-Mena, C. A. García-Vázquez, and L. M. Fernández-Ramírez, "Fault-tolerant control for a microgrid with PV systems and energy storage systems integrated into quasi-Z-source cascaded H-bridge multilevel inverter," Electr. Power Syst. Res., vol. 226, p. 109938, 2024, doi: https://doi.org/10.1016/j.epsr.2023.109938.

[8] R. P. Narasipuram and S. Mopidevi, "A technological overview & design considerations for developing electric vehicle charging stations," J. Energy Storage, vol. 43, p. 103225, 2021, doi: https://doi.org/10.1016/j.est.2021.103225.

[9] S. Jaglan, "Testing and Investigation of GaN-Based High Voltage Inverters for Electric Drives," no. March, 2024.

[10] C. Qian et al., "Thermal Management on IGBT Power Electronic Devices and Modules," IEEE Access, vol. 6, pp. 12868–12884, 2018, doi: 10.1109/ACCESS.2018.2793300.

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