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Review article

Next generation power inverter for grid resilience: Technology review

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ABSTRACT

Distributed generation (DG) systems are becoming more popular due to several benefits such as clean energy, decentralization, and cost effectiveness. Because the majority of renewable energy sources provide DC power, power electronic inverters are necessary for their conversion from DC to AC power. To fulfill this demand, the next generation power inverter employs innovative technologies while simultaneously assuring stability and resilience. This paper highlights the limitations of current inverter technology and points the way forward to the next generation of inverters that overcome those limitations. A more efficient, trustworthy, and system-resilient inverter employs new technology such as the internet of things (IoT). However, these new technologies expose the system to cyber-physical threats. This problem is being overcome through the application of artificial intelligence and machine learning. Initially, the present state of the inverter technology with its current challenges against grid resilience has been investigated in this paper. After that, the necessity of smart inverter and their impact on the power system has been reviewed to enhance grid resilience, stability, and adaptability. Finally, a directional pathway to the next generation inverter has been proposed by addressing the features, components requirement integration challenges, and possible solutions in this paper.

1. Introduction

Electricity can be called the pillar of modern civilization that is responsible for enhancing the proliferation of globalization throughout the world [1]. The proper utilization of renewable and non-renewable energy sources as well as human wastage is used to generate electric power in an electric grid that fulfils the incredible demand for electricity throughout the world [2].

As time passes, the consumption of fossil fuels is increasing rapidly making the nonrenewable source of energy more scarce [3]. The statistical data shown in Fig. 1 (last 70 years), is evidence of the rapid increase of fossil fuel consumption as time goes on. This is making us rethink our energy management and forcing us to incorporate other renewable sources of energy into our energy grid [4]. People are looking for new ways of extracting energy from non-conventional sources to meet the ever-increasing demand of the world. Some examples are solar energy, wind energy, tidal energy, etc [5]. However, new challenges are encountered when attempting to incorporate these sources into the existing grid.

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The integration of a variety number of energy sources with the power grid increases the complexity of grid infrastructure that is responsible for to rise in the difficulty of the power management and control structure [6]. The employment of different smart control devices overcomes these problems and spreads the undisturbed power supply to all sectors of areas against different disturbances. The proper management of load forecasting, supply and demand ratio, smart metering infrastructure, information and communication technology (ICT), and smart transmission/distribution system enhance grid stability and reliability [7].

The complex network of the power grid has prescribed operating and managing conditions for efficient power generation and distribution. Any fluctuation in condition can hamper the nominal operation of the power system as well as completely or partially shut down the power grid. An extreme change in the weather that can cause natural disasters (such as tornados, hurricanes, cyclones, floods, and extreme storms) largely affects the power grid, transmission line, and control station. Again, man-made disturbances or cyber-attacks are other crucial factors that can damage the power system to a large extent. The integration of smart devices and control technologies enables the power grid to withstand these extreme events and resume its nominal operation within the minimum time which is termed grid resilience [8].

The enhancement of the grid's structural and operational resiliency largely depends on the proper utilization and placement of the distributed energy sources (DER), control of the energy generation and distribution, management of vegetation, alternative energy sources and dynamics response, as well as planning for defensive and remedial prospects. The rapid evolution of the power system transforms the synchronous generator based traditional power system into a flexible power system dealing with both renewable and non-renewable energy sources. This feature increases the inverter dependency of the grid due to the employment of RES to convert the form generated power [9].

Usually, the dynamic characteristics of the inverter are not fully accounted for while modeling the grid to enhance resilience. However, the nonlinear, lower inertia and multi-time scaling property of the power inverter increase the dynamic complexity of the power grid may be affected by uncertainties or cyber-attacks easily and lose stability. The improper regulation of the response time of the inverter is responsible for system instability that fluctuates the voltage, current and frequency profile of the grid may trip off DER units or shut down the power grid [10–13].

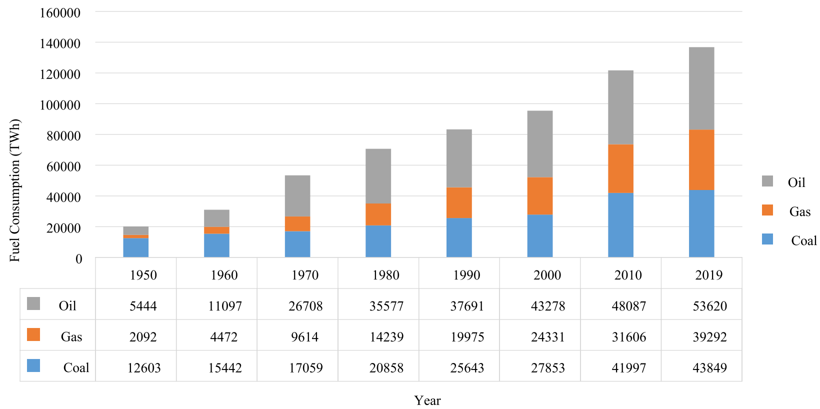
Internet of Things (IoT) has enabled the advancement of smart terminals, wireless link infrastructures, and power generation [14]. It is used to obtain power consumed, monitor, dispatch, and protect transmission and feeder lines, substations, and pylons, manage and regulate equipment, and measure parameters like interoperability between different networks, power consumption, charging and discharging of electric vehicles (EVs), and power demand. It is also used in advanced metering infrastructure (AMI).

Artificial Intelligence (AI) in IoT expands its applicability on the smart grid, making it a major technology for the betterment of both present and future smart grids. Artificial Intelligence of Things (AIoT) creates added value from the huge data extracted from smart grid devices, allowing utility companies to draw precise inferences and improve service delivery, enhance processes, and secure their status as a major competitor in the energy sector. Additionally, AIoT can aid personnel in a specialized department by multitasking with accuracy, and communication with machines will become more natural, moving away from the conventional display operation and to more human-machine interaction [15].

5G network slicing is an occupant-skewed virtual network that provides end-to-end network assurance, service isolation, on-request network function customization, and automation [15]. It allows service providers to flexibly allocate network resources and deliver a network as a service (NaaS). It also provides extra nimble services, stronger security isolation, and a more dynamic business concept for industry clients.

Cognitive Radio (CRT) is a radio that can change its transmitter parameters based on interaction with the environment. It is designed to enable smart communication and decisions within the power grid and requires the use of a cellular spectrum. The next-generation utility network model is a hybrid architecture created through the integration of wireless radio technologies that guarantee dependable, compatible and efficient access to the grid elements [16].

The limitations of the inverters require advanced inverter design and control techniques. The design of the STATCOM inverter has been mentioned in Ref. [17] to increase the performance of PV-based power grids. The benefits of the PV system can be achieved both



	1950	1960	1970	1980	1990	2000	2010	2019
Oil	5444	11097	26708	35577	37691	43278	48087	53620
Gas	2092	4472	9614	14239	19975	24331	31606	39292
Coal	12603	15442	17059	20858	25643	27853	41997	43849

Fig. 1. Global fossil fuel consumption [4].

during the night and daytime as well as it controls the reactive power efficiently. The integration of PV-based power grid with wind farms has been investigated in Ref. [17] that utilizes power sharing.

The prevention of the leakage current by implementing a neutral point clamped (NPC) capacitor has been considered in Ref. [18] that efficiently regulates the common mode voltage (CMV) problems. Lower voltage level and gain are the main limitations of this inverter. The development of H-bridge inverter overcomes these problems by maximizing the voltage level with three-level generation. The requirement of an extra DC- or ac-bypass circuit enhances the CMV issues. A boost inverter having a common AC and DC ground has been proposed in Ref. [19] to enhance voltage gain and reduce common mode voltage (CMV) by achieving DC source current continuously.

An algorithm has been proposed in Ref. [20] that regulates the reactive power injection of converter-connected renewable energy sources (RES) to reduce losses that may undermine the converters' fault-ride-through capacity. This may become vital for the reliable running of the distribution grids, as they may lose precious resources required to maintain grid voltage at key moments. Loss-minimizing algorithms may simultaneously accomplish a substantial decrease in system losses during normal operation and maintain voltage support during malfunctions. A new switched-capacitor-based multilevel inverter (SCMLI) has been proposed in Ref. [21] with decreased capacitance and balanced neutral-point voltage. Without the high-voltage stress of power switches, a topology with voltage-boosting capacity may be created using just a single DC supply. Two charging methods are realizable that successfully restrict voltage ripples and route selection for capacitors.

A novel GFM voltage control technique for a battery-powered system for energy storage has been proposed in Ref. [22] to maintain three-phase balanced output voltages while handling unbalanced loads. Positive- and negative-sequence voltages are controlled using an approach based on a stationary reference frame. The suggested technique exhibits superior dynamic performance when compared to the traditional rotating reference frame-based control strategy.

The construction of a parallel inverter system has been presented in Ref. [23], and a growing number of solar panels have been linked to other energy sources. In order to distribute power from parallel inverters in a micro grid (MG), droop control is used. The intermittency of PV, however, may cause the system to become unstable if the shared load exceeds the PV inverter's maximum power output.

A number of review papers has been focused on the advanced features of the smart inverter. The authors review the smart features of the smart grid (SG) to enhance ancillary services. The functionality of smart inverters with efficient fault, reactive power consumption and harmonic compensation has been investigated in Ref. [24].

The incorporated challenges of smart inverter based PV generation systems have been reviewed in Ref. [25]. The technical and control challenges of PV penetration have been analyzed for smart cities by focusing on environmental impact, smart vehicle charging and big data integration issues to enhance grid resiliency and security. The communication architecture and functionality of the smart inverter for MG have been investigated in Ref. [26]. The advanced features such as self-control and awareness, automatic behavior and cooperativeness of the smart inverter have been analyzed. The way to achieve a long-range free communication protocol has been discussed in this paper.

The security issues of the smart inverter for microgrids (MG) have been focused on in Ref. [27]. The architecture of the inverter for the grid level and its communication protocols have been analyzed in this article. The possible attacks and defensive approaches have been highlighted here. The integration and technical challenges of the smart inverter with their future recommendation have been investigated in this paper.

Different types of inverters by mentioning their features, functionalities, usefulness and limitations have been focused on [28]. It analyzed the integration challenges of the supporting materials to efficiently compensate for the reactive power.

Ancillary services of the smart inverter to mitigate high voltage and tune the voltage, current and frequency profile efficiently have been highlighted in Ref. [29].

The evaluation of the resilience of a smart microgrid based on an IEEE test network and the estimation of the Energy Not Supplied (ENS) index and both faulted and normal operation indices have been analyzed in Ref. [30]. The results suggest that an accurate and practical estimation and selection of energy storage facility, as well as precise modeling of the smart microgrids, can improve the resilience and reliability of the micro-grid in terms of economy and security.

A new model for the deployment of multi-carrier energy hub schemes has been proposed in Ref. [31], which are capable of converting, storing, and transmitting energy carriers from inputs to outputs. It is optimized using a novel metaheuristic solver called Slime Mould Algorithm (SMA), which has demonstrated a stunning performance in terms of accuracy and computation metrics. The results allude to the virtues of the proposed hub scheme in diminishing operation costs and augmenting the reliability and resilience of supply.

The conceptual model and framework of the resilience of power networks, the hypothesis that all the damages caused by natural disasters have their own effect on the network load, and the modeling of the response of the electricity distribution network in several provinces of Iran to several unusual natural phenomena have been discussed in Ref. [32]. Effective suggestions are presented to increase the resilience of the power network and prepare it to face natural disasters.

The analysis of the degree of network resilience against False Data Injection (FDI) attacks by simulating a randomly generated sample FDI attack has been carried out in Ref. [33]. A steady-state AC power flow is used to simulate and predict the power system response after the incidence of an FDI attack, and the ability of this attack to blackout and shut down the transmission network has been investigated. The preliminary results suggest that the targeted electricity grid is resilient against these attacks in terms of the probability of outage and chain blackouts, but transient voltage stability can be affected.

A long-term performance measure for power electronic converters based on reliability has been provided in Ref. [34]. The reliability is shown by continuous lifespan curves generated with Artificial Neural Networks under various operation situations. This nonparametric surrogate model rapidly forecasts converter lifespan, allowing for optimal system-level design for reliability, operation, and maintenance planning in power electronic systems. Numerical case studies assess the efficiency of the suggested reliability modeling technique.

The efficient regulation of grid resiliency requires a detailed infrastructure of the inverter with advanced features that are absent in the aforementioned papers. The lack of smart inverters and the requirement to take this technology to the next step are not focused on in these papers.

The aforementioned papers deal with grid resilience control and management against different natural disasters and cyber-attacks. The efficient regulation of grid resiliency requires a detailed infrastructure of the inverter with advanced features that are absent in the aforementioned papers. The conversion of the smart inverter to the next level to support advanced features and control techniques is the aim of this article. The objectives and contributions of this paper have been listed as,

1. Addressing the power system types and modeling issues on grid resilience has been analyzed to understand the controlling parameters for resilience enhancement.
2. Classifying grid resilience by investigating the factors that affect resilience has been highlighted which will help the researchers to choose a specific research area.
3. Investigating the requirement for inverter design for grid resilience enhancement by addressing the integration and control challenges has been focused.
4. Analyzing the conventional inverters with their functionality and limitations against plant dynamics and cyberattacks has been carried out to understand the requirements of smart inverters.
5. Addressing the advanced features of the smart inverter for self-management, security and adapting to system uncertainties with their control challenges has been focused.
6. Directing a path to construct a next generation inverter for grid resilience enhancement by focusing on the lacking, control and challenging issues of the present inverter technology.
7. Investigating the framework of the next generation inverter and the necessity of implementing AI and blockchain to enhance its strength, reliability, and resiliency has been investigated with future challenges and possible solutions.

The paper orientation is shown in Fig. 2.

2. Power system

To adapt to the changing energy landscape, the power grid must be modernised. Designers and specialists worldwide aim to develop electrical networks using Smart Grid technology rather than replacing and reinforcing the grid. Integrating modern information and communication technologies into the grid creates a communicative environment, allowing varied actors to participate while improving efficiency, economic viability, and safety. Both conventional and unconventional sources of energy can be used to generate power. Any type of source of power can be accepted. The traditional frontier that separates the three sections of the power system (transmission, generation and distribution) is fast receding with the increasing share of generating resources added to the distribution side [35].

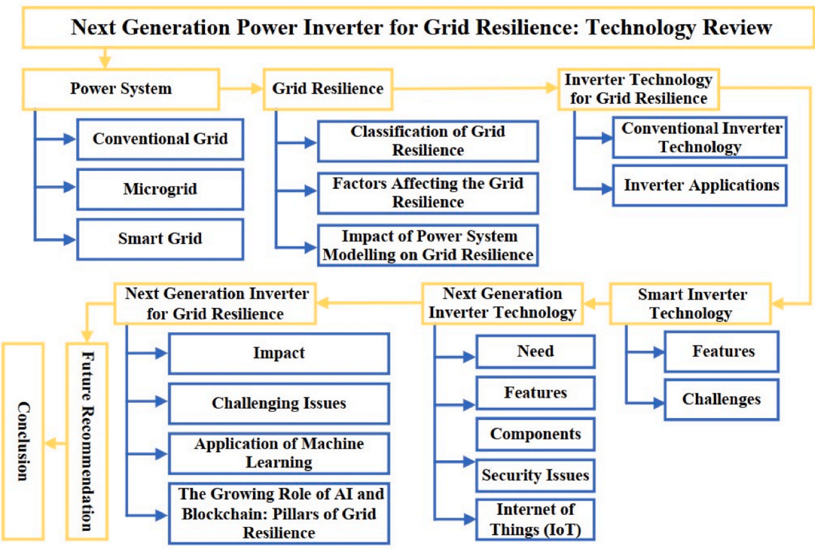


Fig. 2. Paper orientation.

2.1. Conventional Grid

The power grid is the most sophisticated and convenient system in the contemporary period, as well as one of the most magnificent engineering achievements. It distributes the generated energy to various facilities and customers over large distances. The electrical power web is made up of a lattice of generating plants, transformers, transmission lines, distribution lines, substations, and end consumers. Electrical power generation is typically located far from load centers, with the electric grid assisting in connecting them [36]. The conventional Grid is shown in Fig. 3.

2.2. Micro grid

The MG concept is a technique for integrating Distributed Energy Resources, such as the Energy Storage method and controlling the loads, in a dependable manner. The main grid would see MG as a single component reacting to appropriate control signals. micro turbines, fuel cells, solar cells, wind turbines, and other traditional and nonconventional power sources may be used as generators in the MG. MG shows in Fig. 4. While a complete definition of MG is still being debated, it can define a collection of loads, distributed, generation, and energy storage systems operated in synchronization for supplying reliable electric power and linked to the host power system at the consumption level to a single point of connection known as the Point of Common Coupling (PCC). The use of MGs as a model for large number distributed generation integration will aid in the resolution of technical issues that arise in a decentralized approach, which is the first step toward the realization of the Smart grid. An MG could be a commercial shopping mall or a group of community schools. MG could be viewed by the utility as a type of load that can request power at any time, such as at night, as in the case of a solar cell that does not generate power at night or on cloudy days. Because the load may increase or decrease over time, the utility should be prepared. MG is made up of three basic components source controller, energy manager, and protection [36].

2.3. Smart grid

Smart Grid refers to the idea of updating an existing traditional electric power grid with novel automatic control, communications technologies, and information technology such as the internet. Processes, information, energy infrastructure, devices, and markets are all integrated into a cooperative methodology that makes power generation, transmission, distribution, and consumption more cost-effective and efficient. It is an electrical grid that allows for real-time monitoring and bi-directional power control. Smart Grid is shown in Fig. 5. The information flows from the generation point to the consumption point at the end user level are digitally monitored and accessible from anywhere on the planet. As a result, problems and human mistakes are significantly reduced, and faults that do arise are located remotely. A smart grid, according to IEEE, is a huge integrated System of Systems with three layers: (a) the Energy and power layer, (b) the Communication layer, and (c) the Computer layer. The existing generating, transmission, and distribution layers are made smarter by the communication and computing layers [36].

3. Grid resilience

Resilience is a feature of systems that characterizes their capability to recover from adversity and resume normal functioning. Three characteristics—reliability, robustness, and resilience—describe a system's capacity to operate effectively under various operating circumstances. While robustness is the system's capability to withstand changes in running conditions and challenging circumstances without losing proper functionality, reliability is the system's ability to operate as intended under typical or prescribed operating conditions. Contrasted with this, a system's resilience refers to its capacity to quickly and effectively recover from a challenging circumstance—one that has already led to a decline in the performance of the system and a return to regular operation [39]. A summarized classification of grid resilience is shown in Fig. 6.

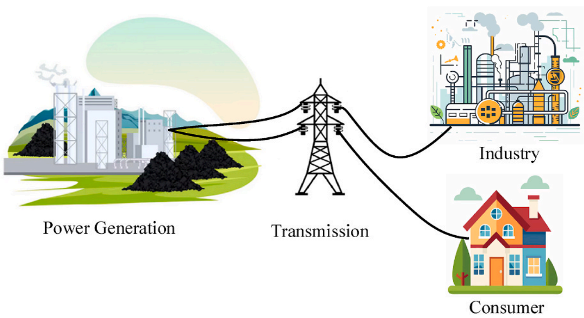


Fig. 3. Modelling of conventional grid [36].

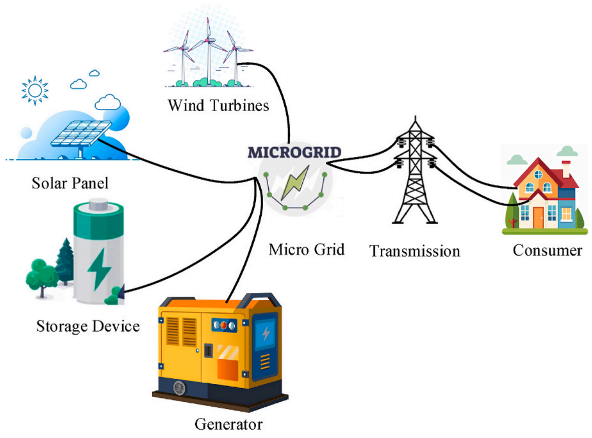


Fig. 4. Modeling of micro grid [37].

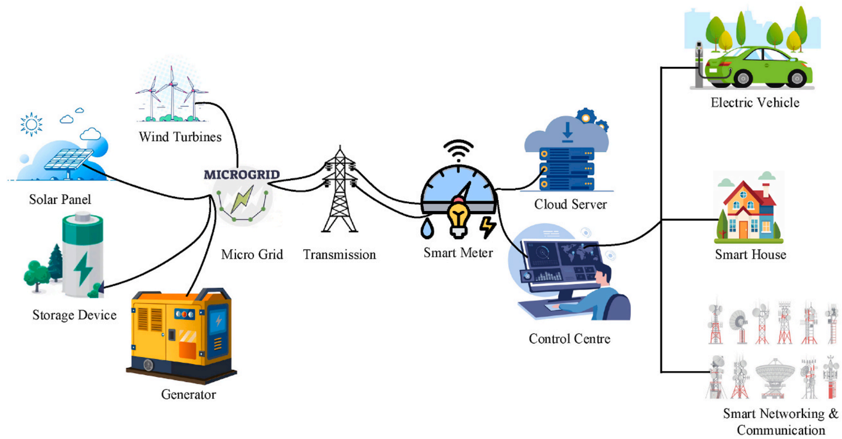


Fig. 5. Modeling of smart grid [38].

3.1. *Classification of grid resilience*

3.1.1. *Passive resilience*

Passive resilience is a factor that provides the Power Distribution System (PDS) resilience by enhancing or isolating inherent characteristics of the system's reaction to events. It may alternatively be characterized as the PDS's intrinsic capacity to decrease failure. A totally subterranean distribution system, for example, has passive resilience to atmospheric conditions (such as cyclones can destroy many over-grade facilities), while a raised substation has passive resistance to flooding disasters. It is also described as infrastructure resilience in certain research studies when resilience is accomplished by enhancing or protecting the PDS infrastructure against catastrophic events. When the effort is deliberate or intended to impart resilience, it is also referred to as designing resilience in certain situations. A costly method of defending the present system against threats is planning resilience, commonly referred to as infrastructure resilience. "Physically changing the infrastructure to make it less susceptible to damage from extreme wind, floods, and other natural catastrophes" is what hardening is defined as. Hardening old infrastructure is more complex and costly than building new infrastructure with lower vulnerability to occurrences. The utmost popular method of hardening is "undergrounding," or burying overhead wires directly or encasing them in concrete. A case study of the Wisconsin public service's system modernization and dependability effort has been provided in Ref. [41], in which overhead wires have been switched to subterranean lines and automation has been added. As was already said, this has been done to make the system more reliable, and there's no reason why taking assets out of danger wouldn't also make the system more reliable. Ref. [42,43] talk about other ways to make infrastructure stronger by raising open-air substation buildings and equipment. Ref. [43] also offers another option for protecting transmission system assets from floods and storms, such as enclosed substations, flood detection, and waterproofing, as well as standards for designing and building such flood- and storm-resistant substations.

3.1.2. *Active resilience*

Active resilience is the process of putting into place means and strategies to create resilience both while the HILF event is happening

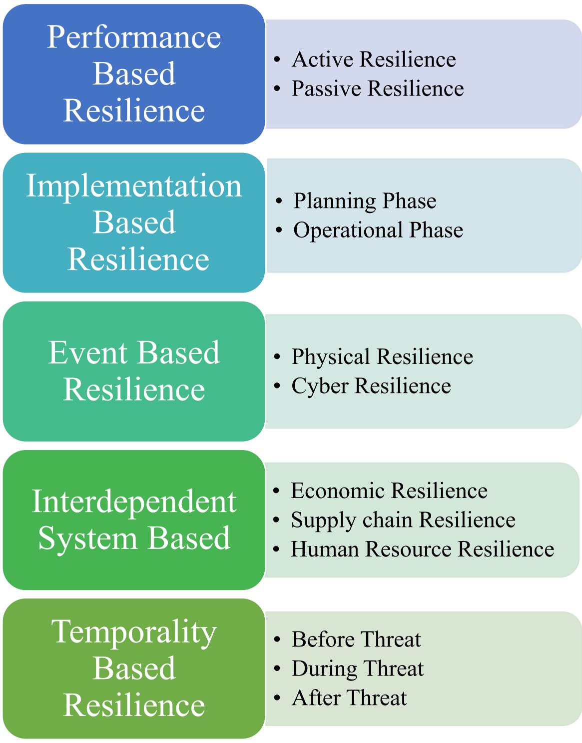


Fig. 6. Classification of grid resilience [40].

and after it has taken place. In certain circles, this concept is also referred to as "operational resilience. " It is important to highlight that many of these strategies, such as the passive resilience measures, have their roots in the effort to improve the dependability of the distribution system. Active resilience is further categorized into proactive and reactive resilience. It is clear that each of these resiliences relies on the same technology to generate resilience. This technology might be described as the construction of a microgrid or islanding. The performance metrics ENS (Energy Not Served) and CLNL (Critical Loads Not Lost), which are generated from the functioning of the system, may be used to quantify active resilience [44].

3.1.3. *Human resource resilience*

The human factors that are part of the PDS have a big effect on its resilience. The technological skills, training, and presence of the crew, as well as the mitigation strategy to the intimidation, are important parts of PDS resilience. Some articles focus on the role that individuals have in assessing and implementing resilience. Ref. [45] uses Mixed Integer Linear Programming (MILP) to solve the repair problem and come up with the best repair sequence for a single crew. This article also talks about the best way to harden something, taking into account the human factor. One of the most important parts of managing after a disaster is getting the crew together. In the restoration process, it can be very important to make sure that crews are routed in the best way and that repair times are kept to a minimum. Ref. [46] uses synthetic MILP to repair and send out crew members in the best way possible. The deployment of maintenance staff and remote power systems, as well as the scheduling of maintenance and MPS output, and load selection and restoration plans, have been co-optimized in Ref. [47]. To determine the most effective approach to repair and restore a PDS, MILP has been utilized in Ref. [48] to synchronize the output of the DG system, location alteration, and repair team dispatch. This article looks at how different utility workers do their jobs by assuming that some workers can only fix certain kinds of equipment and that repair times vary from worker to worker.

3.1.4. *Economic resilience*

The high charge of business interruption losses that are incurred as a result of outages in industrial and commercial revenue centers was the impetus for the early interest that was established in resilience research [49]. The consequence of HILF occurrences that result in the loss of important leads may have both direct and indirect repercussions for one or both of the microeconomies. It is necessary to make use of economic analysis techniques such as input-output modeling as well as computable general equilibrium (CGE) to learn more about the consequences of the disappearance of essential loads. It is necessary to construct metrics for the evaluation of economic costs in order to determine which control and recovery activities may be tailored to provide the greatest economic resilience.

Different types of resilience, their functions and enhancement methods are summarized in Table 1.

Table 1
Resilience functions & their enhancement methods.

Resilience	Functions	Resilience Enhancement Methods	Ref.
Active Resilience	1. Defense islanding 2. Formation of microgrid 3. Response planning 4. Crew training 5. Optimal switch location 6. Recovery of network	Monte-Carlo simulation (MCS)	[50]
Passive Resilience	1. Network redundancy 2. Source redundancy 3. Hardening 4. Vegetation control	A two-stage method based on Mixed-Integral Linear Programming (MILP) through the network topology	[51]
Planning Phase	1. Conductor undergrounding 2. Automation in the distribution phase 3. Crew training 4. Smart sensors and meters 5. implementation	Wide-area supervision based on multi-sensor prediction	[52]
Operational Phase	1. Automation in source transfer 2. Reconfiguration of network and restoration algorithms	Linear programming based optimum positioning and sizing of energy storage system	[53]
Physical Resilience	1. Hardening of pole 2. Seismic equipment 3. Elevation of substations	Voltage control based on Deep Reinforcement Learning (DRL)	[54]
Cyber Resilience	1. Access control 2. Penetration testing, 3. Encryption 4. Redundant communication links 5. Firewall	DRL based data driven multi-agent framework	[55]
Economic Resilience	1. Utility loss minimization during power failure 2. Capital management for HILF events	Hybrid soft-actor-critic (HSAC) method	[56]
Supply Chain Resilience	1. Spares management 2. Diversification of renewable energies 3. Notify threats	Multi-agent soft-actor-critic (SAC) framework	[57]
Human Resource Resilience	1. Response planning 2. Threat assessment 3. Operator training	A deep-Q network and DDPG method-based single-agent centralized automated voltage control framework	[58]
Before threat	1. Algorithm prediction for determining threats 2. Evaluation of threat model 3. Optimum switch placements	A multi-agent system based on centralized training and decentralized execution of deep deterministic policy gradient (DDPG)	[59]
During Threat	1. Diesel generator startup 2. Under generation stress, non-priority loads are shed to serve vital loads	Changing the network's topology, dispersing the generators, and reducing loads based on MILP	[51]
After Threat	1. Recovery and repair 2. Automatic reconfiguration	Crew prepositioning and network reconfiguration methods based on MCS	[50]

3.2. *Factors affecting the grid resilience*

Fig. 7 shows the National Infrastructure Advisory Council (NIAC) in the United States identifies four primary characteristics that define resilience. These characteristics include robustness, resourcefulness, quick recovery, and adaptability. It has been noticed that robustness as well as resourcefulness deal with the crisis as it develops, while rapid bounce-back and adaptability concentrate on rehabilitation after a tragedy as well as long-term planning. For a system to be resilient, it must take into account not just what components it has, but also how those components are arranged and how they interact with one another, as well as its surrounding environment [60].

Even though power system resilience has been linked to HILP occurrences, HILP occurrences are no longer considered low probability [62]. Storms and other natural disasters may have devastating effects on civilization, including a decrease in economic productivity; an increase in the vulnerability of electrical systems; and an increase in the risk of catastrophic damage to infrastructure [63–67]. In addition to natural disasters, man-made calamities like cyber-attacks are also regarded as a significant occurrence [68]. It is impossible to predict the effect of severe events on electricity systems. Power networks are often damaged by natural events including quakes, wind storms, and hurricanes [61,69,70]. According to Ref. [71] cyber-related incidents affect the power system over communication channels and control units. Types of HILP events and their examples are shown in Table 2.

3.2.1. *Climate change/extreme events*

There are a number of things that may go wrong with power generating and transmission systems in big regions when hazardous conditions occur on a regular basis. Climate change is a major factor in this climate change [76]. Climate change is increasing the likelihood of a wide range of severe weather events. Temperatures are rising, heavy rain is occurring more often, and winter storms are becoming more severe. So far, severe weather has been a major factor in the loss of electricity for many individuals. Due to global

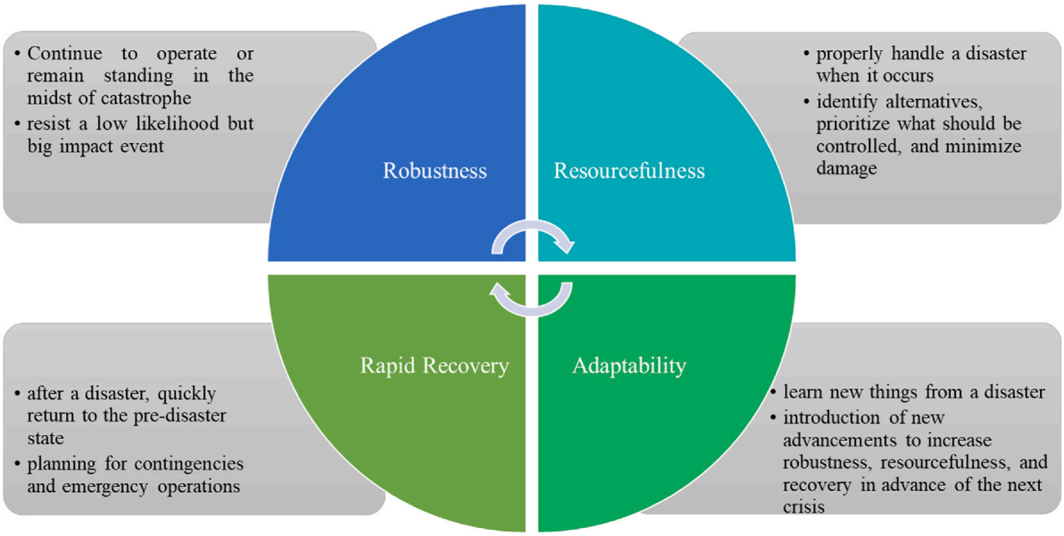


Fig. 7. Features of resilience [60,61].

Table 2
High impact low probability (HILP) events.

Occurrence Types	Examples	Ref.
Natural	Flood, Hurricane, Earthquake, Storms, Tsunami, Cyclone	[72,73]
Man-made	Terrorism, Riots, Vandalism	[74]
Cyber	Bad data injection, Eavesdropping, Modify data packet, Denial of service	[75]

warming, more frequent and severe weather events, as well as increased damage to electrical infrastructure, are anticipated. 100M of individuals will be harmed and the economy will lose billions of dollars every year as a result of this [77]. There is a strong likelihood that a changing climate will continue to increase the frequency and severity of natural catastrophes in the future [78]. Hurricanes, for example, may disrupt electrical networks in ways that have never been witnessed before [72]. Flooding costs power systems more in terms of human misery and damage to components than any other natural calamity [79]. Wildfires have wreaked havoc on electricity grids over the last several years, resulting in many outages and other issues.

Wildfire damage to transmission networks poses a danger to the system's stability and dependability. Over 85,000 people were left without electricity as a result of the 2017 Thomas fire, which shut down the Santa Barbara area's transmission system entirely. The Mendocino Complex Fire continued to ravage Mendocino County in 2018, resulting in the loss of electricity to around 50,000 consumers [80]. Customers in northern California were left without power because of the threat of wildfires, according to a California

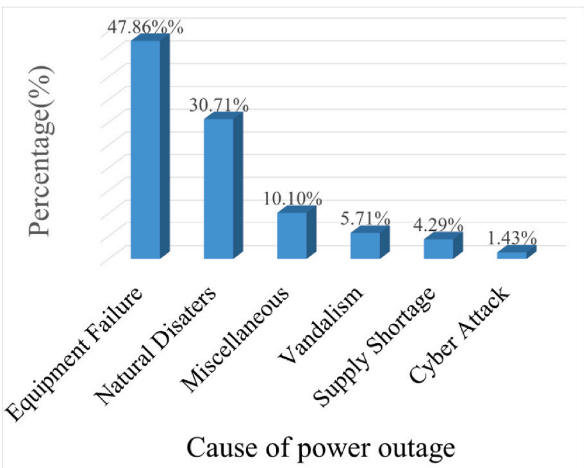


Fig. 8. Percentages of power outage and their causes [86].

utility provider. It was estimated that the ice storm in China would cost more than 2.2 billion dollars in 2008. The earthquake and tsunami that followed in March 2011 in Japan knocked off electricity to 8,5 million people. When Superstorm Sandy struck the United States in October 2012, it knocked out electricity to more than 8 million people across 15 states Hurricane Irene cut electricity to 6.5 million people in 2011 [73]. Over 2 million people lost power as a result of Hurricane Harvey in 2017 [81]. When a powerful storm hit Australia in 2016, 1.7 million people lost power. In 2015 [82], a windstorm knocked off electricity to more than 710,000 Canadians [83]. 570,000 people in Europe were left without electricity due to Cyclone Dagmar, a hefty windstorm [84]. In the Chinese province of Jiangsu in 2016, tornadoes resulted in the loss of power for 135 thousand homes [85].

Percentages of power outages and their causes are shown in Fig. 8.

3.2.2. Lack of awareness

Another difficulty for distribution system operators following catastrophic occurrences is a lack of situational knowledge, which significantly slows down the restoration process and increases consumer expenses. Most of the current distribution systems are "blind" in terms of monitoring and control capabilities outside of the distribution substation, unlike the transmission systems. Data following a natural disaster may be inaccessible or problematic, even with some observability enabled by AMI or DA, because the devices and the underlying communications network may also be damaged. The existing OMS typically relies on customer trouble calls, which are delayed and imprecise, or even unavailable due to damaged telecommunication networks, to determine the defective sections [87].

3.2.3. Cyber attack

Terrorist attacks, contrasted with, are planned and might lead to serious property destruction, in contrast to the unpredictability of natural catastrophes and technical failures [88]. Attacks against the infrastructure of the electrical system might be motivated by a variety of factors, including terrorism, financial gain, and other goals (for example, endangering people's lives by seizing control of their energy supply and other essential supplies) [89]. Modern power systems have developed into sophisticated examples of cyber-physical networks as the technology behind sensors, computers, and communication networks has advanced rapidly. The security of cyber-physical systems has to be evaluated and enhanced before it will be possible to avoid cyberattacks on the future electrical grid [90].

Table 3 lists recent blackouts brought on by extreme occurrences that occurred in different nations in different years.

3.3. Impact of power system Modelling on grid resilience

The existing centralized and extensively synchronized design of the grid puts the nation in danger of cascading failures, even though there are a variety of methods that may be used to increase the physical resistance of the grid to the effects of natural catastrophes. The future grid resilience needs to be considered from the standpoint of the system design. Because there is currently no universally accepted benchmark for the model of robust power systems, the idea of "design for resilience" is very vital to the pursuit of the long-term objective of making the grid more resilient. It is not enough to just advance the architecture of the grid in terms of making the power system more versatile and adaptive to situations that are constantly shifting and changing, regardless of whether these conditions are the result of natural occurrences or cyber assaults. To accommodate new circumstances, the grid must everywhere be intelligent and adaptable. Intelligent power electronics are very important in this field [107].

To attain the maximum degree of grid resilience, it has been suggested that a power electronics-based grid design with innate power supply management, non-cascaded maintenance, and distributed power grid structure with entire controllability be adopted. The new grid infrastructure will be built on design-for-resilience and controllability methodologies. The power electronics-based system continuously decouples production, load, and grid dynamics in contrast to the machine-based grid. This makes frequency control more effective. Important elements include non-propagating fault maintenance, regulated power flow, and asynchronous zonal grid operation [108].

Table 3
Blackout Caused by Extreme Events in case of Lower Resilience.

Extreme Events	Cause	Country	Year	People Affected	Ref.
Cyberattack	Man-made	Pakistan	2021	–	[91]
Wind	Natural	Canada	2018	>35000	[92]
Equipment Failure	Man-made	Brazil	2018	70M	[93]
Bad Weather	Natural	Argentina, Uruguay, Paraguay	2017	50M	[94]
Wind Storm	Man-made	Australia	2016	850,000	[95,96]
Cyberattack	Man-made	Ukraine	2015	230,000	[97,98]
Wind Storm	Natural	USA	2015	>161,000	[99,100]
Typhoon	Natural	Philippine	2014	13M	[101]
Snow	Natural	Poland	2013	100,000	[102]
Equipment Failure	Man-made	India	2012	600M	[103]
Hurricane	Natural	USA	2012	8.1M	[104]
Earthquake	Natural	New Zealand	2011	160,000	[105]
Wind Storm	Natural	China	2008	4.6M	[100,106]

IGBTs and other forms of advanced power switching technology are getting close to the theoretical silicon limit [109]. Materials having a large bandgap, such as silicon carbide (SiC) as well as gallium nitride, have the greatest potential to be used in the progression of the next generation of power devices (GaN). Devices made of SiC and GaN are able to run at higher junction temperatures (over 300 °C) as well as high frequencies (beyond MHz) with a minimal conduction loss, which may significantly boost power density. When it comes to inverters, the particular goals of using such devices are to raise the efficiency of the power conversion while simultaneously lowering the overall cost [110].

4. Inverter technology for grid resilience

When analyzing resilient systems and considering authors who utilize the word resilience in their respective subject fields, the literature employs a variety of meanings. The definition of resilience is "the capability of a body to return to its former shape after shock or deformation" or "the capacity to endure or recover from adversity." Some researchers argue that the largest definition of the resilience concept must be used since the term has grown into one with various meanings [111]. Resilience is an idea that can be applied in various disciplines, covering scientific, social, human, and physical knowledge [112], with various strategies but the same motto in mind: "The ability to face the challenge is resilience" [113].

The most common way of producing electricity involves burning fuel to create steam, which spins a turbine to produce electricity. These generators rotate and generate alternating currents. Similarly, the frequency, or the number of times the sine wave repeats, is dictated by this rotation. The frequency of electricity is an essential indicator of the health of an electrical system. For instance, if there is a high load – too many gadgets requiring energy — more energy is extracted from the grid than can be provided. As a result, the AC frequency will decrease and the turbines will decelerate. Due to their size and mass, the turbines exhibit the same resistance to changes in frequency that other objects do when their velocity is altered. As more solar systems are installed, a record number of inverters are being connected to the grid. Since there is no turbine involved, inverter-based producing may produce energy at any frequency and lack the inertial features of steam-based power. To accomplish the transition to an electrical grid with more inverters, it is necessary to construct intelligent inverters that can react to frequency shifts and other grid disturbances and help stabilize the system against them [114].

4.1. Conventional inverter technology

4.1.1. Single-phase transformerless inverter

By analyzing the configurations and operations of various inverters, it is possible to have a proper understanding of their strengths and drawbacks. There are several inverter topologies, each with specific properties, to address the issues of Common Mode (CM) noise and ground leakage current. The majority of transformerless inverters, including two-switch, three-switch, four-switch, five-switch, six-switch, and multilayer inverters, may be categorized based on the number of required switches [115].

Two-switch inverters: The half-HB architecture consists of a capacitive divider linked to two transistors and a PV module [116] depicted in Fig. 9(a). Connecting the neutral wire of the grid which is the midpoint of a capacitive divider gives a usually steady voltage that prevents module parasitic capacitance from causing leakage current [117]. The half-HB architecture employs just half as many semiconductors as the full-HB system and is thereby easier and cheaper [118]. The disadvantages of the former, however, prevent its widespread usage. For instance, the output waveform has only two levels, individual switches must be capable of withstanding twice as much voltage as the whole HB system, and output current is greatly distorted and produces a large number of electromagnetic interference [117,119]. Therefore, the half HB design necessitates power transistors with a high blocking voltage, which contributes to

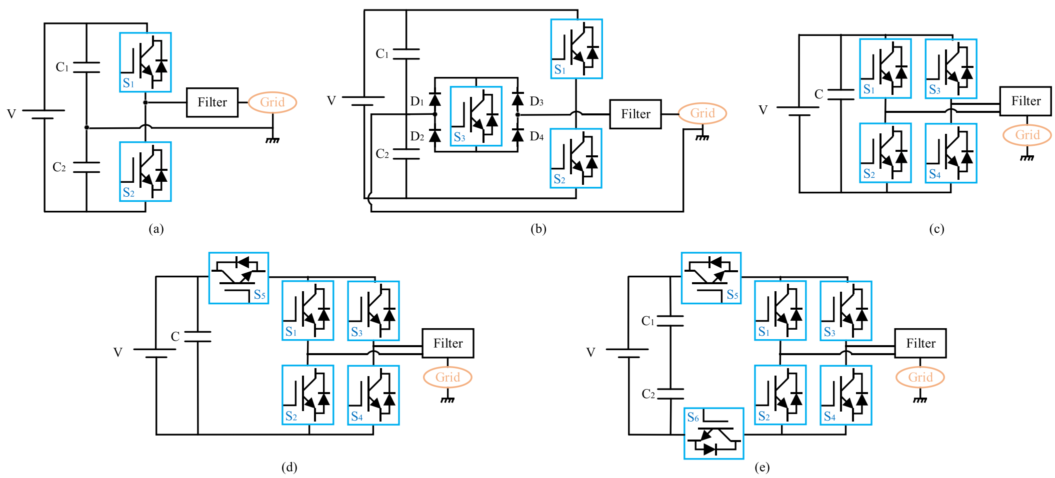


Fig. 9. Structure of (a) two, (b) three, (c) four, (d) five and (e) six switch inverter [116,120,121].

an increase in switching losses.

Power Factor Correction (PFC) converters for single-phase half-bridge Uninterruptible Power Supply (UPS) inverters have been investigated in Ref. [122]. Comparisons are made between two recently released ac-dc/dc-dc boost converters and a conventional half-bridge converter in terms of active switch count, voltage strains on the switches, and the ability to regulate the voltage balance of the DC bus capacitors. Performance variations are evident in terms of input current harmonic distortion and energy efficiency according to analytical and experimental data. A sinusoidally modulated voltage and a sinusoidal current at the inverter's output are used to analytically determine the capacitor currents in the DC-link circuit while operating a pulsed single-phase H-bridge inverter with two and three voltage levels [123]. With the use of spectral analysis, the individual harmonics of output currents that are sinusoidal and those that have harmonics superimposed are computed, and the impact of switching operations on the load is addressed. These real data are contrasted with the theoretically predicted currents in the capacitors.

Three-switch inverters: The Conergy NPC Architecture is shown in Fig. 9(b) [116], where the clamping circuit consists of four diodes and one switch, and the voltage output is pinned to the neutral point by bidirectional switches [124]. Using sw3 and sw4 to clamp the neutral to the output voltage (the center of the DC bus), this design can achieve zero voltage. In the positive half-cycle, SW1 and SW3 commutate at a high frequency, while SW2 and SW4 commutate at a high frequency during the negative half-cycle. Since the common mode (CM) voltage is held at VPV/2 during the whole procedure, the parasitic capacitance leakage current is kept to a minimum [125]. Because of its improved efficiency, this design is suitable for low-power PV applications [126].

A novel single-stage three-port inverter has been introduced that connects PV panels to a single-phase power grid [127]. To handle input and output power changes, a series of active power decoupling circuits using thin-film capacitors are implemented. The suggested inverter uses just three switches and a straightforward control system to decouple the input and output powers, extract the maximum power from PV, and supply a sinusoidal current to the output with a minimal total harmonic distortion. The viability and functionality of the suggested inverter are confirmed by experimental results using a 100-W prototype inverter.

The suggested inverter in Ref. [128] creates a common ground between the input and output terminals, reducing leakage current and boosting voltage gain. It becomes more dependable and has a longer lifespan when film capacitors are used. Using testing data in both grid-tied and off-grid operation modes, the suggested inverter's operation is examined, and its performance is confirmed.

Four-switch inverters: Grid-connected PV inverters, the Full-HB technique is frequently used. This setup involves the interconnection of four transistors as shown in Fig. 9(c). Many commercial inverters use this technique in combination with a low-frequency transformer; thus, it is advantageous to investigate its applicability in transformerless inverters in contrast to bipolar modulation [129], The most common modulation for this design is unipolar pulse width modulation (PWM) due to its huge advantages, such as high efficiency, reduce the emission of electromagnetic interference, and at high frequency lower current ripple.

The innovative single-phase, single-stage switched-boost inverter with four switches has been proposed in Ref. [130]. It has shoot-through immunity, buck/boost voltage with single-stage conversion, and continuous input current. For the proposed inverter, this study discusses operating principles, a pulse-width modulation control approach, suggested parameter designs, and simulation results. Using a 110 V/50 Hz output voltage in both stand-alone and grid-connected modes, an 800-W prototype was created.

A single-phase dual-mode four-switch Buck-Boost transformerless PV inverter with inherent ground leakage current elimination has been proposed in Ref. [131]. During the negative half of the line cycle, there are two operating modes: Buck mode, and for the positive half, Buck-Boost mode. A dual-mode dual-carrier unipolar sinusoidal pulse width-modulation achieves the smooth mode transition (SPWM). It is possible to attain low costs and non-unity power factor capabilities. The principles are validated by simulation results, which also show how well the topology, modulation, and control methods function.

Five-switch inverters: In comparison to the full-bridge (FB) design, the H5 technique needs just one more transistor as given in Fig. 9(d). SMA Solar technology pioneered the H5 technique [132]. In this arrangement, the PV panel is free from the grid in the time of current freewheeling periods in order to avoid switching of frequency ripples in the voltage of PV-panel poles to the ground, hence maintaining constant CM voltage.

An inverter architecture has been proposed in Ref. [133] with the capacity to balance energy between sources to lessen unequal battery charging and can withstand system failures brought on by source and/or switching device failure with the least amount of change.

Six-switch inverters: To eliminate leakage current while retaining a three-level output voltage, the HERIC architecture was developed based on the entire HB inverter [134]. In the architecture shown in Fig. 9(e), a number of parallel branches are introduced to the output filter. Several commercial inverters, like Sunway's converter, have used this architecture [120,135]. Due to high efficiency, low leakage current and unipolar PWM, the HERIC architecture has several benefits. Additionally, the advantages include its unipolar SPWM-generated three-level output voltage and minimal output filter current ripple.

A brand-new hybrid modulation approach for a single-phase, high-efficiency solar inverter has been proposed in Ref. [136]. Inductors and power quality optimization are aided by the feature of a three-level output voltage in the middle point, which is absent in the absence of input split capacitors.

A novel H6-type transformerless inverter for grid-connected PV systems has been investigated in Ref. [137]. This inverter can reduce the risk of leakage current and add reactive power to the utility grid. The suggested design allows for a three-level output voltage that uses unipolar sinusoidal pulse-width modulation. To confirm the theoretical analysis and simulation findings, a universal prototype with a 1 kW rating has been developed and tested. The suggested topological structure and detailed operating principle with reactive power regulation are also studied.

A Comparison table for single-phase transformerless inverter has been highlighted in Table 4.

Fig. 10 shows a generic control block schematic of an inverter architecture. All that has to be changed is the structure described in Fig. 9 of the Inverter Topology Section. It begins at the source, moves through the inverter structure, outputs the voltage to the control

Table 4
Highlights of different types of Single-phase transformerless inverter.

Inverter	Power (KW)	Input Voltage (V)	Switching frequency (KHz)	Grid voltage (v)	Filter inductor (mH)	Filter Capacitor (uF)	Advantages	Disadvantages	Ref.
Two switch	5.5	700	5	230	3	–	1. Low Cost 2. Low conduction loss	1. High DC link voltage stress 2. High device stress	[30]
Three switch	0.225	–	10	–	–	–	1. Improved DC voltage utilization	1. High leakage current	[31]
Four switch	1.7	400	10	240	–	–	1. Very low leakage current	1. High device stress	[34]
Five switch	1	340–700	20	240	4	6.6	1. Low component counts Only one filter and inductor	1. Unbalanced switching High leakage current	[55]
Six switch	1	350	8	230	1.8	2	1. Low leakage current	1. Additional device required	[67]

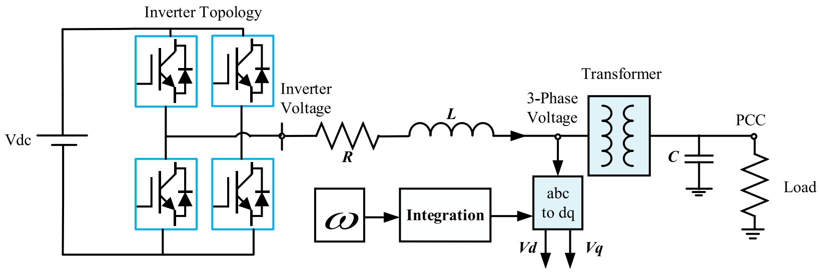


Fig. 10. General control block diagram of inverter topology [138].

region, and finally moves the control output to the load section.

4.1.2. Grid-tied photovoltaic inverter

Central Inverter: The central inverter consists of a large number of the series interconnection of the PV modules enabled in order to increase the voltage rating of the inverter and to avoid further amplification of the system connected to the grid. This series interconnection is commonly referred to as the string. On the other hand, in order to increase the power level a parallel interconnection of these strings is developed by employing the string diodes [139]. PV plants are constructed in parallel or series that are larger than 10 kWp and linked to the inverter, using the central inverter system [140]. There is no need for decoupling since the inverters are generally linked to a three-phase application. The voltage produced by the modules is sufficient to meet the inverter's requirement for input voltage [11]. This inverter has a number of serious limitations, including high power losses due to centralized maximum power point tracking (MPPT), high voltage DC connections between PV panels and inverters due to high input voltage, a stiff structure, string-diode losses, and a high price. Consequently, it is difficult to profit from huge production. In addition, the central inverter's power supply to the grid is of poor quality and contains a great deal of current harmonics. The architecture of the central inverter is illustrated in Fig. 11(a).

String Inverter: The string inverter is the most advanced technology presently available [140]. The string inverter system connects an inverter to a single PV string comprised of serially linked solar panels. Voltage boosting may not be necessary since the string voltage may be enough. For 230 VAC applications, the string inverter's typical working voltage ranges from 340 to 510 VDC. If a DC-to-DC booster or a line frequency transformer has been utilized, the option of employing fewer PV modules linked in series is also possible. The string inverter provides several benefits over the central inverter, including the absence of string diode losses, the ability to apply different MPPTs to each string, a cheaper price owing to mass manufacturing, and improved overall efficiency [142,143]. The string inverter's architecture is depicted in Fig. 11(b).

Also, in this configuration each string is connected independently to the inverter, thus it eliminates the usage of a string diode. An individual MPPT is applied to every string therefore, partial shading and panel mismatching problems are greatly reduced in this configuration. Consequently, the overall system efficiency increases and is 1–3 percent higher as compared to the central inverter

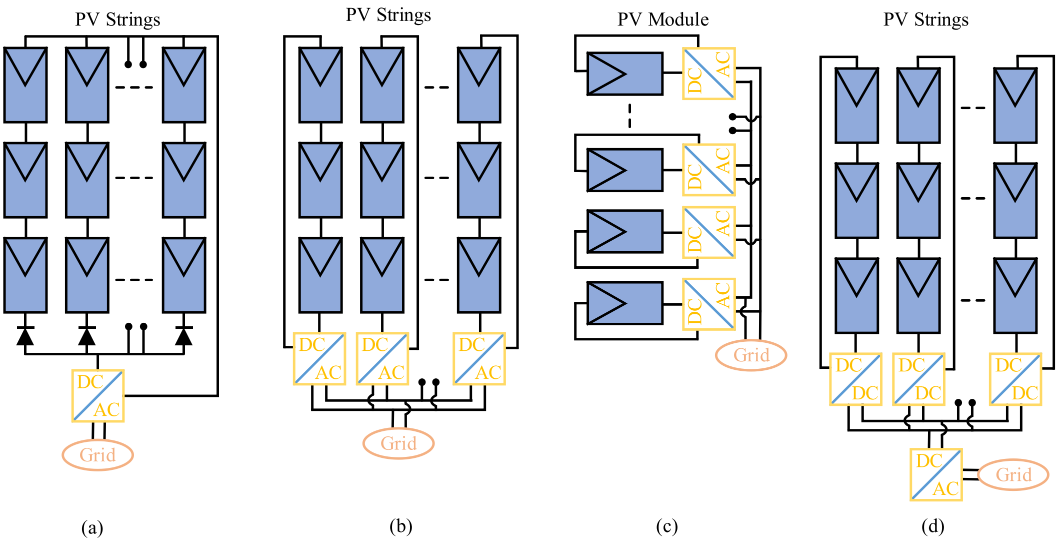


Fig. 11. Structure of (a) central, (b) string, (c) module and (d) multi-string inverter [141].

[144]. The application range of string configuration is up to 5 kW per string. Due to its modular structure, it can be expended to high ratings easily. In this topology, if the string inverter fails to operate it will only affect the operation of its related string rather than the whole PV system like in the central configuration.

Module Integrated Inverter: An AC module presented in Fig. 11(c) has a low power rating, small in size, and is also known as micro-inverter. AC modules are more suitable and preferably used in low-power applications. An AC module constructed from a single solar panel and equipped with an onboard inverter constitutes the module-integrated inverter system. Since the PV modules are all perfectly matched to one another, power loss is kept to a minimum. Since the PV module has its own MPPT and inverter [145], it is also possible to extract the highest possible output from the panel. The modular design has the benefit of simple system expansion. Lower overall efficiency due to greater voltage amplification and higher installation costs is the biggest limitation. Massive production, resulting in cheap production and retail prices, might, however, compensate for this limitation.

Multi-string Inverter: It is a hybrid configuration, as it combines the beneficial and advantageous features of both string and central inverter configurations. This is the evaluation of a multi-string inverter, in which each string of solar panels is connected to its own DC-to-DC converter with a unique MPPT and feeds electricity to a common DC-to-AC inverter. Consequently, any PV power plant with a limited number of modules may function autonomously. Due to the ability to individually control each PV string, the overall efficiency is enhanced. Multistring inverters provide many advantages over single-string inverters, including cheaper overall costs, more flexibility, a smaller DC-link capacitor, and a higher energy yield due to local MPP tracking and improved PV system monitoring [11,146]. This topology can integrate the PV strings of different orientations and different technologies into a grid. It has high structure modularity; therefore, it can be extended easily to high power ratings by connecting a new PV string to an already existing system. The multi-string topologies are expensive as compared to central inverters but are cheap compared to module-integrated inverters. Multi-string configuration system covers a wide range of PV applications up to 50 kW. However, its capability of integrating different ratings of PV strings causes a problem of high voltage variation at the inverter input side [147]. Fig. 11(d) shows the design of the multi-string inverter.

A Comparison table for grid-tied PV inverters has been highlighted in Table 5.

4.1.3. *Multilevel inverter (MLI)*

MLI depends on a combination of one or more DC sources and an array of low-rated power semiconductor switches to create an output voltage with a stepped voltage waveform and, therefore, higher power levels [141,148]. The primary goal of MLI is to synthesize a voltage waveform that is essentially a sine wave with a number of steps utilizing the proper switching signal of the power electronic switches and various direct current voltage sources such supercapacitors, batteries, solar panels, fuel cells, etc. [149]. A greater number of levels in the output waveform may be employed to provide a pure sinusoidal voltage without the usage of bulky transformers and passive filters [149,150]. Depending on how they're built, the most common MLI topologies may be broken down into one of three categories: neutral point clamped (NPC), flying capacitor (FC), or cascaded H-bridge (CHB) [151].

Table 5
Comparison of structural topologies of grid-tied photovoltaic inverters.

Inverter Topology	Solar Connection	Application	Advantages	Limitations
Central inverter	Series or Parallel string	Three phase	1. No decoupling 2. Satisfy the input voltage condition 3. Low maintenance and troubleshooting	1. High power losses due to centralized MPPT 2. High voltage DC cables due to high input voltage 3. Non-flexible design 4. Losses in string diodes 5. Expensive 6. Poor quality due to harmonics
String inverter	Series string	340–510 VDC, 230 VAC	1. No voltage boosting 2. No string diode losses 3. Individual MPPT 4. Lower price 5. Higher efficiency	1. Required special rack for each string 2. Poor flexibility at partial shading 3. Higher per Watt cost than a central inverter
Module integrated inverter	Single solar panel	AC module made	1. No mismatch so power loss is well minimized 2. Obtain maximum power 3. Easy to expand 4. Modular structure	1. Reduced overall efficiency due to higher voltage amplification 2. High installation cost
Multi string inverter	Each string made of several solar panels	Small or medium rooftop PV plants	1. Combination String and Module integrated inverter 2. Each PV string is controlled individually 3. High efficiency is higher 4. Low cost reduction 5. Flexible 6. Small DC-link capacitor 7. High energy reveal due to local MPP	1. More electronic components 2. Difficult to design and manufacture 3. For high altitude areas, it is not suitable

Neutral point clamped multilevel inverter: The NPC inverter is basically a diode-clamped three-level converter designed by Nabae et al. [152] and it is given in Fig. 12(a). This structure offers a low harmonic output voltage for variable frequency driving circuits with excellent efficiency. Neutral point clamped (NPC) multilevel inverters are a suitable solution for a wide range of applications, but capacitor voltage balance is a major issue. The NPC is a mature technology that has become established as a standard topology for a number of applications, with advantages such as lower device voltage rating, reduced harmonic distortion, reduced common mode voltage, enhanced power loss distribution in the converter, and higher efficiency. Different multilevel topologies have been developed, such as the modular multilevel converter, stacked multicell converter, multilevel active-clamped converter, and reduced switch count converters. The limitation of the NPC topology is the requirement to keep the capacitor voltages balanced. This survey provides a review of the solutions proposed in the literature to overcome this specific drawback. The area of application of multilevel converters and, among them, the NPC converters, has expanded over the years. In earlier years, they were intended for high-voltage and high-power applications, but since then, technical evolution has provided enhanced power semiconductor technologies, faster digital processors to implement modulation and control, and thousands of technical papers providing a deeper knowledge about the multilevel converter operation. Therefore, the NPC is at present one of the most implemented multilevel topologies, mainly in DC–AC converters [153].

Flying capacitor multilevel inverter: In comparison to the diode-clamped [155] and series H-bridge [156] inverters, the flying capacitor multilevel inverter architecture [157] is a relatively recent invention. Hence, it is possible to decide how to trade off capacitor voltage stability for power quality. The standard performance of four levels is increased to five, six, seven, and eight levels. With joint redundancy including all phases, the loss in capacitor voltage balancing control is made up for (in effect, adjusting the common mode line to ground voltage). It is shown that whereas applications requiring reactive power compensation may utilize six, seven, or eight-level operations, motor drive applications can employ five-level operations. Although the FC-MLI is similar in construction to the NPC, it was initially modeled by Maynerd and Foch [158] is given in Fig. 12(b). A flying capacitor, like the clamping diode used by NPC, is used to limit the voltage across a device.

Cascaded H-bridge multilevel inverter: The Cascade H-bridge (CHB) multilevel converter has received special attention due to its modularity, reliability and feasibility. It is composed of a cascade connection of H-bridge single-phase converters, whose AC outputs are combined to reproduce a desired output voltage reference. CHB converters have achieved larger output voltage levels (up to 17) in commercial applications, and have shown better efficiency and dynamic performance. A growing interest has been observed in the recent past in the use of this topology in aircraft applications, derived from the More Electric Aircraft (MEA) initiative. The CHB allows the reduction of voltage stress in semiconductors, which enables the use of devices able to switch at higher frequencies [159].

To correctly exploit all the above discussed advantages of the CHB in a given application, both an adequate modulation algorithm and an adequate control strategy must be applied. Controller design depends on a good knowledge of a mathematical model that can accurately describe the system dynamics, and as the number of switching devices increases in multilevel converters, the modeling and control design processes become much more involved. In the case of capacitors, the controller must include an additional balancing scheme to guarantee that each DC capacitor maintains a desired constant level [160]. The modeling and control design processes of a single-phase CHB multilevel converter used as a shunt active filter have been presented in Ref. [161]. The active filter application has been selected as it is more challenging than the rectifier application. The controller has been proposed to compensate for harmonic distortion and reactive power caused by a nonlinear load and includes voltage loops to guarantee regulation and balance of all capacitor's voltages on DC buses. The proposed control scheme can be easily scaled to consider topologies with more levels. Experimental results in a 2 kVA prototype are presented to assess the performance of the proposed controller strategy. A CHB-MLI is created by interconnecting numerous H-Bridge (HB) inverters, depicted in Fig. 12(c) such that the output of each HB adds to outputs of the others to create a staircase waveform [154].

A Comparison table for multilevel inverters has been highlighted in Table 6.

4.1.4. Reduce switch multilevel inverter

MLI has become increasingly popular in industry because it provides effective interaction with renewable energy sources. MLI-

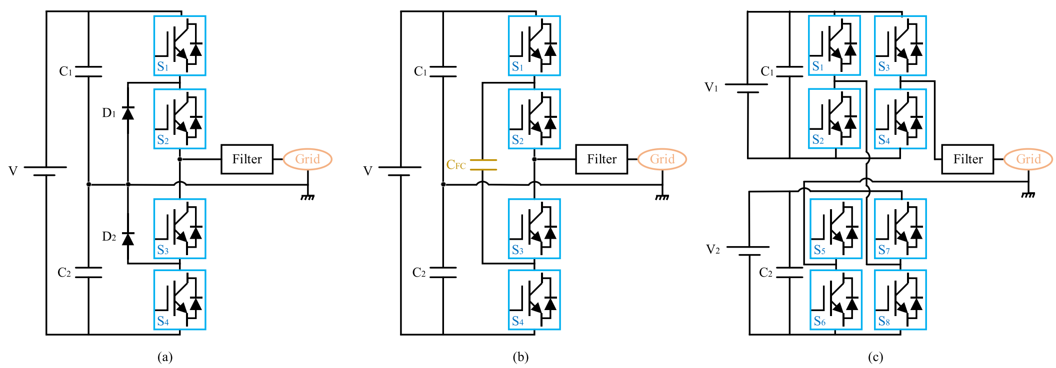


Fig. 12. Structure of (a) NPC, (b) FC and (c) cascaded inverter [154].

Table 6
Analogy of multilevel inverter techniques.

Inverter Topology	Power Switches	Clamping Capacitors	Clamping Diodes	No of DC Source	Requirement of H-bridge	Requirement of total standing voltage	Advantages	Limitations	Ref.
NPC	2 (L-1)	0	(L-1)(L-2)	1	No	2 (L-1)Vdc	1. Simple model 2. Less harmonic and reduce voltage Stress	1. The number of elements increases when the level of output increases 2. More complex when DC-link Capacitor balances the voltage level	[152, 162, 163]
CHP	2 (L-1)	0	0	(L-1)/2	–	2 (L-1)Vdc	1 High Reliability 2. Able to design a high number of levels	1. Each cell has its own DC source 2. Voltage in the inverter's various phases is not balanced	[163, 164]
FC	2 (L-1)	(L-1)(L-2)/2	0	1	No	2 (L-1)Vdc	1. Little amount of total harmonic distortion 2. Small size of Output Filter 3. Similar phase, which makes it simple to balance the output voltage and reduces device stress 4. Decreased amount of component	1. Difficulty arises when design has a high level 2. High installation cost 3. Switching frequency is not efficient 4. Need huge amount of capacitor	[162, 163, 165]

based topologies play an important role in both high or medium voltage and high-power applications. For a variety of applications, reduced switch MLI topologies are developing. These topologies have several benefits, including minimal modularity, high resolution output voltage, fewer components, less space occupied, cost efficiency, and simplicity of operation. To enhance power quality and lessen the need for passive filters, these setups produce higher voltage levels. Reduce switch MLI is classified into three types: symmetric, asymmetric, and hybrid configurations [166].

Symmetrical reduce switch multilevel inverter: The setup is symmetric if the magnitude of all DC supply to the MLIs is equal. Many symmetrical community MLI variants have been presented in the literature throughout the years. The first effort to link two H-bridges in series was made by Mc Murray in Ref. [167], and it was successful in producing a five-level stepped waveform for low-voltage high-frequency applications. Its uses have been broadened to include medium and high voltage equipment after 20 years

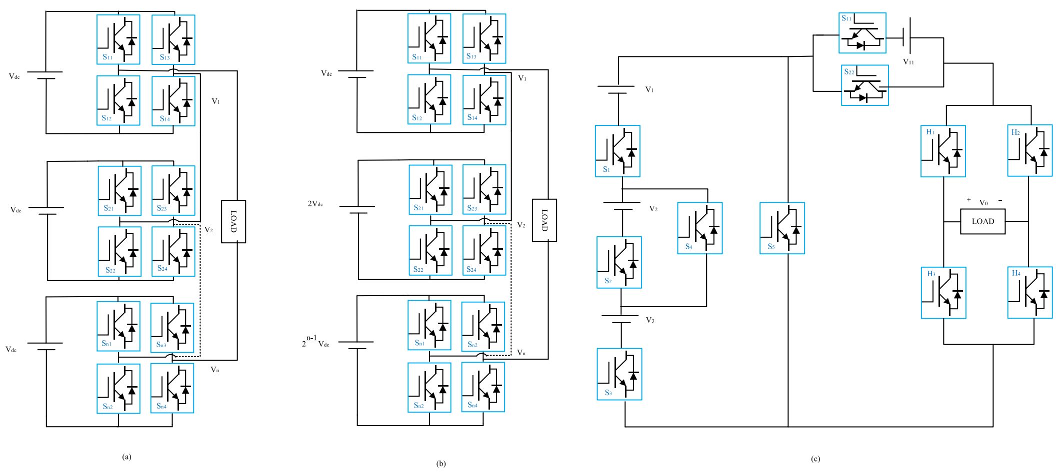


Fig. 13. Structure of (a) symmetrical, (b) asymmetrical and (c) hybrid reduce switch multilevel inverter [166].

[168]. All subsequent symmetrical MLIs use the cascaded H-bridge multilevel inverter (CHB-MLI) as their root structure. It is shown in Fig. 13(a). This structure is made up of cascaded multiple single-phase H-bridge units with equal magnitude input dc sources. Each H-modulation, bridge's control, and protection needs are modular, which lowers the cost of production. Moreover, the following equation relates the number of power cells or DC sources to the effective number of output voltage levels: NL = 2NDC +1. In practice, the cost of the switch compromises the power rating of the semiconductor switches, allowing MLIs to produce a very high output voltage with medium power semiconductor switches. The voltage imbalance in this design is relatively tiny since there are no balancing capacitors. The majority of switching methods may be used with CHB topologies, however, level shifted PWM is not advised.

Asymmetrical reduce switch multilevel inverter: At the phase output, the symmetrical multilevel inverter with 'n' identical DC voltage levels may provide 2n+1. It is best to prevent issues with growing inverter size, cost, installation space, and control complexity since the necessary number of devices relies on the output voltage level. Asymmetrical multilevel inverters, whose DC voltage sources have different magnitudes, are a class of topologies that have been documented in the literature to provide a high number of output voltage levels without increasing the number of bridges.

An asymmetric inverter has been proposed in Ref. [169] that can create the most levels with the fewest IGBTs and gate drive circuits, as illustrated in Fig. 13 (b). As a result, this architecture lowers the expenditure and control complexity while greatly increasing effectiveness and dependability.

Hybrid reduce switch multilevel inverter: The primary driver for research into Hybrid reduce switch multilevel inverter (HMLI) topologies is the search for a synergistic method that integrates several semiconductor switches, topologies, and/or modulation schemes in order to improve the power processing of the whole system. A unique seven level HMLI has been suggested in Ref. [170] employing two different H-bridges linked in cascade with GTO/IGCT and IGBT switches. Nevertheless, each H-bridge is run by a separate DC source with a variable switching frequency, which increases switching complexity and efficiency. There are not many business uses for this. The structure of the hybrid reduce switch multilevel inverter is illustrated in Fig. 13 (c).

4.1.5. Grid following (GFL) and grid forming inverters (GFM)

Inverters that are used by utilities typically use one of two primary control systems. GFL and GFM are their respective names. Through the injection of current at a predetermined phase angle, GFL inverters can manage the production of both real and reactive power. To keep a constant eye on the grid phase angle in real-time, a phase locked loop (PLL) is used. GFL inverter is not capable of providing direct regulation of the system's voltage or frequency. External sources, such as a GFM inverter are responsible for supplying the reference voltage and frequency. If the GFL inverter is unable to detect a frequency or voltage source, it will automatically shut down. GFM inverters and GFL inverters are fundamentally different from one another. An analogous concept to grid-tied synchronous generators is the GFM inverter, which functions as a controlled voltage source behind a coupling reactance. Direct control of both the voltage and the frequency is possible with voltage source inverters that have a droop characteristic. During times of emergency, droop-controlled GFM sources will instantly adjust the amount of power they produce to either increase or decrease to equalize loads and keep the local voltage and frequency from fluctuating. In droop-controlled GFM inverters, the change in output power and frequency occur simultaneously without a discernible lag in time between them. Therefore, the reaction time of the GFM sources to any unexpected events is much quicker than the response time of the GFL sources. It is possible that providing main frequency management from resources based on inverters might be highly beneficial, especially for power systems classified as having "low inertia." When compared to huge synchronous machines, resources based on inverters can modify their output significantly more quickly, therefore arresting the frequency variations of the system before any load shedding is started [171]. In addition, the majority of grid-connected, inverter-based Distributed Energy Resources (DERs) use GFL control at the moment. GFL control typically makes use of a PLL and a current control loop to accomplish the goal of achieving fast control of the inverter's output currents [172]. Using GFL control, an inverter that is created from voltage may be made to behave approximatively like a current source. The capacity to rapidly modify the currents is one of the advantages of employing this control. Nevertheless, grid-following control relies on an external voltage source to provide voltage and frequency references. This is the case since GFL control does not regulate frequency or voltage. GFL inverters are intended to maintain relatively consistent output currents or output power even when the load is perturbed [173]. The structures of the GFM and GFL inverters are depicted in Fig. 14(a) and (b), respectively. A comparison between GFL and GFM is shown in Table 7.

In the proposed control scheme in Ref. [180], the dynamic power set-point and operation mode adjustments of GFL inverters have been used to improve the resiliency of power-electronics-dominated grids (PEDG). A supervisory controller and self-ranking-based coordinated mode selection algorithm maintain the power balance and restore frequency. Case studies validate the autonomous control's feasibility, performance, and robustness.

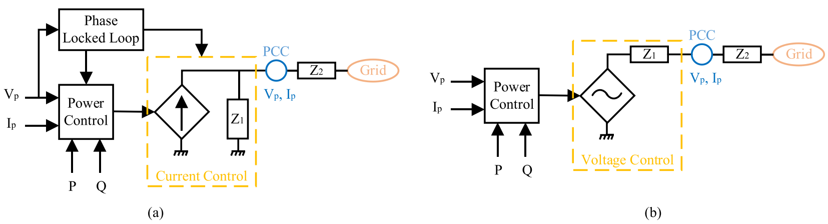


Fig. 14. Structure of grid (a) following and (b) forming inverter [171].

Table 7
Comparison between grid following and grid forming inverter [171,174–177].

Parameter	Grid Following	Grid Forming
Function	Grid following	Grid Supporting
Source type	Current	Voltage
Set grid voltage & frequency	No	Yes
Deliver active & reactive power to load	No	Yes
Inertial response	No	Yes
Response	Fast	Slow
Buffer	No	Yes
Islanding	No	Yes
Variance from the nominal frequency	Lower	Higher
Advantages	• Quick regulation • Simple control structure	• Able to operate in an islanded mode • Provide the regulation of frequency and voltage
Limitations	• Lack regulation of frequency and voltage • Unable to operate in an islanded mode • Instability in weak grids	• Small-signal instability in stiff grids • Easy to suffer from overload

A frequency restoration method to improve PEDG resiliency and transient response has been introduced in Ref. [181] by redefining the role of grid-following inverters (GFLIs) at the grid edge. An artificial intelligence-based power reference correction (AI-PRC) module is developed for GFLIs to adjust power setpoints during transient disturbances. Analytical validation shows control rules in PEDG follow swing-based machines' dynamics, and simulation and experimental case studies show significant improvement in frequency restoration.

GFM inverters are essential for ensuring controllability over non-dispatchable and variable generation, contributing to the practical realization of sustainable energy systems. Classical control methods are inadequate in addressing transient stability circumstances, necessitating the development of current control approaches. A comprehensive examination of GFMs, encompassing fundamental principles, control mechanisms, implementation strategies, operational aspects, and potential avenues for further research has been provided in Ref. [182]. The findings are applicable to various interdisciplinary fields such as power system operation, power electronics, renewable energy integration, advanced control, and smart grids.

Autonomous grid-forming (GFM) inverter testbeds with scalable platforms have gained interest. A self-synchronized universal droop controller (SUDC) was adopted and scaled in a small network and test feeder to operate microgrids without synchronous generators. The GFM inverter control adoption helps understand the dynamic behavior of inverters and their scalability, impacting the distribution system (DS). Steady-state and transient analysis of the GFM power inverter controller, assessing voltage and frequency stabilization and black start capability for photovoltaic microgrids during transient fault conditions has been provided in Ref. [183]. The GFM inverter control shows appropriate response times for synchronization, connection, and disconnection to the grid.

Three control techniques for grid-following inverters (GFLIs) are thoroughly compared. These include the phase-locked loop (PLL)-based vector current control (VCC) and two PLL-less strategies: voltage-modulated direct power control (VMDPC) and linear-parameter-varying power-synchronized control (LPV-PSC). All three controllers are evaluated in the time domain and through frequency domain analysis using an impedance-based stability method based on the generalized Nyquist criterion. This comprehensive analysis not only assesses their time-domain performance but also provides precise predictions of stable and unstable operations for GFLIs equipped with these controllers, validating the time-domain findings [178].

Weak grids present significant challenges due to their wide variation in grid impedance, which can lead to system instability. This variation complicates maintaining the consistent performance and stability of grid-connected inverters, as the system must dynamically adapt to these changes. Additionally, switching harmonics in weak grid conditions can lead to resonance phenomena, amplifying unwanted frequencies and resulting in distorted waveforms and reduced power quality. Various strategies, such as active damping (AD), harmonic resonant control, repetitive control, and grid feedforward, have been proposed to address these issues. Among these methods, feedback-based active damping (AD) control has been demonstrated to perform well across a wide range of grid conditions, making it a robust solution for weak grids. In contrast, resonant and repetitive control methods face constraints and are less effective in these situations. The grid feedforward method, while proposed as a potential solution, introduces an extra positive feedback path, leading to high harmonics or even instability, rendering it unsuitable for weak grids [184].

Unbalanced faults in weak grids can cause unbalanced current injection, posing challenges for inverter control [185,186]. GFLIs have developed various control techniques, including the positive and negative sequence control (PNSC) strategy, to address this issue [187,188]. This strategy allows for the injection of balanced current, active power, or reactive power. However, challenges such as PLL instability in weak grids and unbalanced grid voltages remain unresolved. Despite the success of proposed PLL-less GFLIs in both strong and weak grids, they fail to deliver balanced current when faced with asymmetrical conditions [189]. Additionally, severe unbalanced events can cause inverter instability. Despite the PNSC strategy's stability and performance in strong grids, it remains susceptible to PLL-related instability in weak grids. The PNSC strategy has thus far been exclusively implemented for PLL-based GFLIs.

Recent years have seen increased attention in developing PLL-less control techniques for GFLIs. A double-synchronous-reference-frame-based power-synchronized grid-following inverter (DS-PSGFLI) has been proposed in Ref. [190] for the smooth operation of inverter-based resources (IBRs) during unbalanced grid faults in both strong and weak grid connections. It generates the phase angle required for grid synchronization internally, eliminating the need for a PLL. The proposed control structure allows for independent control of positive and negative sequences, ensuring smooth operation in unbalanced grid conditions. It operates seamlessly in both strong and very weak grids, avoiding PLL-related instability. Power regulation at the PCC, similar to common PCC control strategies, avoids voltage drops and high levels of switching harmonics.

A power-synchronized grid-following inverter (PSGFLI) has been proposed in Ref. [189] to regulate terminal power, enabling reliable operation in strong, weak, and ultra-weak grids without the need for PCC voltage sensing or regulation. Vector current control is used in the inner loop, while the outer power loop extracts grid frequency and generates current references. The controller's dynamic performance is tuned by selecting a desired open-loop transfer function. However, the optimization-based tuning of the outer power loop is complex and dependent on the operating point, making optimal performance reliant on specific conditions. To overcome the limitations of the control design in Ref. [189], a linear parameter-varying control of the power-synchronized grid-following inverter (LPV-PSGFLI) has been proposed in Ref. [191]. The parameters of the outer power controller loop are auto-tuned in real-time based on desired operating points, preserving the benefits of PSGFLI while ensuring effective operation in both stiff and weak grid conditions. However, a significant limitation is the type of controller used in the outer power loop, which generates current references using two PI controllers without integral terms for frequency generation.

An enhanced power-synchronized PLL-less grid-following inverter (ePSGFLI) has been proposed in Ref. [192] to address the constraints of existing control techniques such as PSGFLI and LPV-PSGFLI. Unlike these approaches, ePSGFLI does not require a PCC voltage or a PLL to manage power exchange with the grid, making it suitable for both strong and weak grid grids. The inner current control of ePSGFLI is identical to that of GFLI, but the outside power loop produces the frequency and d-component of the current reference. This article presents a detailed model of power flow equations, focusing on the alignment of injected current with the q-component. It proposes a loop-shaping design approach for a second-order 2-by-2 controller in the outer power loop, ePSGFLI, which can handle high grid frequency fluctuations without affecting inverter output power or causing instability. The controller's settings are adaptively modified in real-time, ensuring constant bandwidth regardless of power reference orders or grid circumstances (strong or weak). A comparison between PLL-based (VCC) and PLL-less (VMDPC, LPV-PSC) grid-following inverters has been highlighted in Table 8.

4.1.6. *Impact of inverter modelling on grid resilience*

Through a range of grid services, grid operators regulate the demand and supply of electricity on the electric grid. Grid services are activities done by grid operators to preserve system-wide balance and enhance the management of electricity transmission. Smart inverters may respond in a variety of ways when the grid deviates from its expected behavior, such as when voltage or frequency fluctuations occur. In general, the standard for small inverters, such as those attached to residential solar systems, is to remain on during or "ride through" small disturbances in voltage or frequency. However, if the disturbance lasts for an extended period of time or is larger than usual, they will disconnect from the grid and shut down. Frequency responsiveness is especially important since a change in frequency is associated with unforeseen generation loss. To re-establish the standard frequency, inverters are configured to adjust their power output in reaction to a change in frequency. Additionally, inverter-based resources may respond to signals from an operator in order to modify their power output in response to varying electrical system supply and demand. The name for this grid function is automated generation control. In order to provide grid services, inverters need regulated sources of power. This may include energy generation, such as a solar panel that is now producing power, or energy storage, such as a battery system that can release previously stored energy. Grid-forming is a supplementary grid function that may be provided by some contemporary inverters. Black start is a process used by grid-formflters to restart a grid in the event of a failure. Traditional "grid-following" inverters need an external signal from the electrical grid in order to forecast when switching will occur in order to inject a sine wave into the power grid. In these setups, the inverter tries to match the grid-supplied signal. Grid-forming inverters with more sophistication may generate their own signal. For instance, a network of small solar panels may designate one of its inverters to operate in grid-formation mode, with the rest following its lead to create a stable grid devoid of turbine-based electricity.

Inverters supply reactive power as one of their most critical grid roles. Voltage, the force that propels electric charge, and current,

Table 8
Comparison summary of the PLL-based (VCC) and PLL-less (VMDPC, LPV-PSC) grid-following inverters operating in different grid conditions [178, 179].

Criteria	Vcc			VMDPC			LPV-PSC		
Grid Type	Strong Grid	Weak Grid	Very Weak Grid	Strong Grid	Weak Grid	Very Weak Grid	Strong Grid	Weak Grid	Very Weak Grid
Full Control of Active Power	α	γ	δ	β	β	γ	β	β	β
Full Control of Reactive Power	α	β	γ	β	γ	β	α	α	α
Stability	α	γ	δ	α	β	γ	α	α	α
Frequency Jump	α	α	β	γ	γ	γ	γ	γ	γ
Phase Jump	α	α	β	γ	γ	δ	γ	β	β
Grid Voltage Sag	β	β	δ	γ	γ	γ	α	α	α
PCC Balanced Fault	β	β	β	γ	γ	γ	α	α	α
Drop based	β	β	β	δ	δ	δ	α	α	α

The performance of the controller is divided into four levels from superior to inferior: α - very well, β - good, γ - marginally accepted, δ - poor (or unstable).

the movement of electric charge, are continually exchanging positions on the grid. When voltage and current are synchronized, electrical power reaches its maximum level. Voltage and current may display delays between their two alternating patterns while a motor is working. A part of the power going through the circuit cannot be absorbed by the connected devices if they are out of sync, resulting in a loss of efficiency. To give the same amount of "real" power, or the power that can be dissipated by the loads, more total power will be necessary. To counteract this, utilities supply reactive power, which synchronizes voltage and current and simplifies the usage of energy. This reactive power is not directly utilized but rather assists the use of other abilities. Modern inverters are capable of both delivering and absorbing reactive power in order to aid networks in balancing this essential resource. Moreover, since it is difficult to transport reactive power over long distances, dispersed energy resources such as rooftop solar are especially important reactive power sources.

4.1.7. Challenging issues

i) **Dynamics and stability Analysis:** When power electronic equipment connects with line impedance or other devices, negative incremental input impedances are known to create oscillations and probable instability. Existing state-space modeling methodologies and commercial software tools become ineffective as a result of their complexity and computing requirements, making the dynamics and stability analysis of multi-inverter systems, which is an immediate development and research requirement for expanding power electronics penetration. Even though there are other impedance-based stability techniques

Table 9
Data extraction for industrial inverter.

Manufacturer	Model No.	Brand	Circuit Topology	Power Source	MPPT Voltage Range	MPPT Current	Efficiency	Specification	Application
Sunpal Power Co. Ltd.	SUN2000-100KTLM1	Huawei	Half-Bridge Type	Solar	200–1000 V	22 A	98.8	1035 × 700 × 365 mm	Industry
Foshan Hanse Industrial Co. Ltd.	NKM- 3kw	HANSE	Full-Bridge Type	Solar	110/ 220VAC	60A	97	2094 × 1038 × 35 mm	Industrial Home Commercial
Hefei Pinergy Solar Technology Co. Ltd.	Sun2000-100ktlM1	Huawei	Half-Bridge Type	Solar	200 V-1000 V	26	98.6	1035 × 700 × 365 mm	Home Solar system
Suzhou Solar Tech Co. Ltd	SPF 2000-5000 TL HVM	Growatt	Full bridge Type	Solar Wind	60 V–200 V DC	80	95	225 × 300 × 550 mm	Industrial Home Commercial
Jinan Deming Power Equipment Co. Ltd	30kw	Deming	Full bridge Type	Solar Wind	220–400 V	272	95	650 × 600 × 1320 mm	Industrial Home Commercial
Hefei Greensun Solar Energy Tech Co. Ltd	MID 20KTLX	Green sun	Push-Pull Type	Solar	140–1000 V	40.2	98.75	525 × 395 × 222 mm	Home
Hefei Remon Technology Co. Ltd.	RMP1000	REMON	Push-Pull Type	Solar	110–220 V	18.3	94	28.6 × 16.5 × 8.7 cm	Industrial Home Commercial
Foshan Sunchees Energy Technology Co. Ltd.	MIC3KW-100w	Sunchees	Full-Bridge Type	Solar Power Wind Hybrid	110–240 V	60	94	720 × 440 × 235 mm	Home Industrial Commerci
Jingjiang Alicosolar New Energy Co. Ltd.	MAX50-100KTL3 LV	Growatt	Full-Bridge Type	Solar	110–380 V AC	80.5A	97.9	970 × 640 × 345 mm	Home
Guangzhou Idealplusing Information Technology Co. Ltd.	IPSHP7200-48	Idealplusing	H Bridge Type	Solar	120 V–450 V	80	94	434 × 283 × 88 mm	Household Office Industrial
Hubei LiBaiChang Technology Co. Ltd.	ECMPPT Inverter	hocqec	H Bridge Type	Solar	150 V–450 V	80	90–93	115 × 300 × 400 mm	Industrial Home Commercial
Anhui Sunpro Solar Energy Co. Ltd.	48 V Input Inverter	yuanda	H Bridge Type	Solar	220 V–240 V	70	93	43 × 25 × 36 mm	Home Industrial Commercial
Puguang Import Export Co. Ltd.	PSI- 100kw	Pugu	Full-Bridge Type	Solar Wind	220 V–380 V	80	90	480 × 840 × 1228 mm	Industrial Home Commercial

that can be implemented, they are still not suitable for large-scale power electronics systems. Ultra-large-scale power electronics based grid analysis, modeling, and simulations need the appropriate tools and techniques [193].

ii) **Hardware overloading capabilities:** Depending on the desired control functions, power inverters may require extra hardware and a larger-than-necessary design size due to their physical hardware limitations. Power semiconductor device development for new generations based on wide bandgap materials has expanded the voltage, frequency, and temperature limitations of power electronics [194]. Nevertheless, compared to traditional iron or copper-based equipment, semiconductor-based power electronics devices are less robust and less efficient at full-power processing settings, or rather brittle under fault circumstances, and have cost and reliability difficulties. For the development and improvement of power electronics for series-connected grid applications, such as solid-state transformers and circuit breakers, the efficiency, power, and overloading or short-circuit interrupting capabilities of power devices are essential performance requirements.

iii) **Energy-buffering capabilities:** The primary objective of power electronics converters is to provide instantaneous input-to-output power balancing. They have low energy buffering capabilities, with the exception of a small amount of energy buffering from DC-Link capacitors. For renewable energy uses, non-dispatchability due to due to irregular energy supply, non-dispatchability for renewable energy uses results in significant operational savings and other difficulties, such as over voltage and reserve ramp rate needs. Utilizing improved prediction techniques, stabilizing measures based on energy savings, and geographical aggregation for smoothing effects are common operational options for tackling this problem. In addition to improved forecasting algorithms and geographic aggregation for smoothing effects at the operational level of the system, hybrid PV energy storage or multi-input and/or multiport converter systems are recommended to address this problem. Compared to traditional machine-based generators, this minimal energy buffering is equal to the absence of mechanical or rotational inertia, which minimizes the primary frequency response capability as in a traditional grid but could be enhanced by inertia simulations in control and the integration of extra energy storage equipment in power inverters [195].

iv) **The challenge of autonomous operation:** The total autonomy of inverters in the next-generation system remains a technical challenge. Voltage and frequency control may be impacted by distributed control strategies. To overcome this issue, collaborative control based on a consensus algorithm and graph theory with nearby communications has been used to control smart inverters for independent MG operation [195].

4.2. Inverter applications

For industries to function, power is a must. A standalone device called an inverter transforms DC voltage into AC voltage. Power supply continuity and interruption are prevented via inverters. It is utilized in many different applications, including UPS, speed controls, and electric motors. There are many different kinds of inverters that are employed in commercial, industrial, and residential settings. Industrial inverters are needed by industries to ensure uninterrupted operation of industry operations. In the manufacturing and production sectors, inverters are essential. Industrial inverters can be customized by inverter manufacturers based on specific industrial needs.

The potential applications for next-generation smart and intelligent power inverters are anticipated to be significant, given their benefits and capabilities, with the ability to completely transform how energy is generated, stored, and distributed. Future uses for these inverters could involve hybrid renewable energy, electric vehicles, energy efficiency, electric aircraft, and grid flexibility, among other things.

Tables 9–11 highlight the industrial and practical uses of inverters.

Table 10
Industry practices.

Application Area	Used Inverter	Advantages	Drawbacks	Ref.
Pumps, Fans, Downhill Conveyors, Elevators, Energy Plants and LNG Plants	Cascaded Multilevel Inverters	• Reduce the switching losses using an optimal modulation technique • High-quality output voltages and input currents and also outstanding availability	• Efficiency improvement needed • Conduction losses	[196]
Electric Aircraft	Flying Capacitor Multilevel Inverter	• Decreases the commutation loop inductance • Allows fast switching with minimal ringing, while also enabling efficient double-sided cooling	• Switching losses • Conduction losses	[197]
Aerospace Applications	Multi-Cell Three-Phase GaN Inverter	• Increase efficiency • Gravimetric power density	• More complexity • Low the system reliability	[198]
Home Appliances	Novel Switched Capacitor Boost Inverter	• Lower losses • Improved current harmonic distortion • Reduced semiconductor requirement • Reduces the torque ripple •	• Increased system's volume and weight • High losses	[199]
Electric Vehicle	Impedance Source Inverter	• Lower design cost • High efficiency • Wide voltage range	• Increase to the cost • Volume of the system	[200]

Table 11
Multi-level inverter used in electric vehicles [201].

Structure	Application	DC Voltage (V)	Switching Devices
Two-level	Buses and Trucks	up to 900 V	MOSFET, or IGBT
Two-level or Multi-level	Trains and Tramways	up to 3000 V	Thyristor, GTO, or IGBT
Two-level or Multi-level	Electric ships	1500 V–15000 V	Thyristor, GTO, or IGBT

5. Smart inverter technology

The ability of a device to operate efficiently and autonomously with minimal operator intervention is defined as "smart." An inverter in a microgrid serves as a bridge between energy generation and consumption points. As a result, its function is not limited to AC DC conversion or vice versa (depending on the type of converter), but also to control power flow, detect faults, and disconnect when necessary, among other things. Because these are the primary factors affecting microgrid control, it can be stated that inverters are the microgrid's thinking and processing components, collecting data and configuring themselves to operate in a safe, controlled, and effective environment [202].

Additionally, any power converter serving as a distributed energy resource (DER) link to the grid must conform to the IEEE 1547 standards series. These guidelines have been put in place and are regularly updated to address issues with things like power and voltage quality, earthing, islanding recognition, etc [11,203].

Table 12 summarises the features, advancements, security issues and solutions for a smart inverter (see Table 13).

5.1. Features

5.1.1. Self-awareness (SA)

SA is becoming more important for decentralized grids to achieve higher levels of autonomy [221]. A network with SA has knowledge about its inner state, which is called private self-awareness. Self-awareness in smart inverters attempts to improve reliability and estimate lifespan, allow safety or restoration measures and successfully avert disastrous accidents in safety-critical systems that use power electronics. Various diagnostic procedures have been developed over the years to fine, segregate, and diagnose faulty power semiconductor devices [222]. Nowadays, the tendency has shifted toward real-time state monitoring of inverter main elements such as capacitors or other parts with the purpose of evaluating component aging and current health level [223]. Smart inverters achieve total prognostics and health management when combined with lifespan prediction. Furthermore, future smart inverters are projected to have a certain level of intelligence, such as understanding their position or relevance within their surroundings and the anticipated consequences of prospective future acts, i.e. meta-cognition and self-expression.

5.1.2. Adaptability

Adaptability is a system's capability to respond quickly and effectively to changing conditions or switches in system components. Smart inverters are designed to make the system adaptable to frequency, impedance and faults. Self-tuning controllers based on adaptive law are used to achieve stability under uncertainties and a broad range of operating situations. For power system applications, a frequency-adaptive phase-locked loop can successfully monitor and synchronize with the system under a variety of non-ideal grid characteristics. Active and reactive power must be successfully decoupled, and this can only be done by grid-connected inverters if they can accurately estimate the grid's impedance and operate accordingly [224].

5.1.3. Autonomy

Autonomy is the system's ability to determine its own operating mode. A distributed system's autonomy is a fundamental attribute. Automation is shifting away from conventional vertical and centralized hierarchies toward CPSbased structures that are more dispersed and parallel. A smart inverter with autonomous operation may be needed as a component of a cyber-physical system in the case of poor or nonexistent connection or if reliability is desired. When many inverters run in parallel, one typical situation is

Table 12
Summary of smart inverter.

Features [204]	Advancements [205]	Cyber-security issues (Area of attack) [206]	Solutions [206]	Challenges [207,208]
1. Self-Awareness 2. Adaptability 3. Autonomy 4. Plug and Play	1. Smart storage and backup system for energy 2. Improvement in power quality Improvement in power supply reliability 3. Stability in power grid 4. Grid Autonomy	1. Alteration of sensor data 2. Change in intended operating Point 3. Unwanted command given to devices 4. Change in forecasting information	1. AI and ML-based protection techniques 2. Implementation of blockchain technology 3. Implementation of message authentication code 4. BlackRidge Transport Access Control (TAC) and Seclab Denelis Modbus Airlock technique	1. Limitations on power electronics systems and equipment 2. Decentralized control 3. Dynamics and transient stability 4. Detection and analysis of threats

autonomous load power sharing employing droop mechanisms [225]. Smart inverters must accomplish features such as dynamic grid feeding and formation, smooth power flow, and power quality improvement in order for an inverter-based microgrid to operate autonomously. The power utility requires further independent functions in Refs. [226,227] for a dispersed generation.

5.1.4. Cooperativeness

Because of the enormity of decentralized energy and automated systems, cooperative controllers must be implemented in each smart inverter. These controllers each take on some responsibility for system stability and quality maintenance, and multiple of them work to achieve a desired collective goal within the system or a nearby subsystem. In contrast to centralized approaches, it is necessary for nearby smart inverters to communicate, and information obtained locally is shared with neighbors. In addition to removing the requirement for a centralized controller, a distributed control and decision architecture may also provide advantages like self-organization and robustness to dynamic uncertainty. Collaboration control can be utilized in microgrids for plug-and-play [228], in smart inverters with components and tools for fault tolerance and scalability, or in active distribution systems for the best voltage management.

5.1.5. Plug-and-Play

Plug-and-play (PnP) refers to the fact that a smart inverter can be added to a system and start working right away without any technical setup. PnP works with or without communication, which gives the system benefits like being scalable, interoperable, resilient, and reliable. Despite its widespread use, the PnP concept was just recently introduced in power systems for usage in computing interfaces and industrial field lines to create intelligence using power electronic components [229]. PnP can also be used in intelligent inverters and modular hardware power converters for distributed frequency/voltage control in MGs and distributed voltage control in SGs. The California Smart Inverter Working Group says that for utility applications, it is best to use IEC 61850-7-420 and -90-7 for data object models, Smart Energy Profile 2.0 (SEP2) as the top utility interprocess communication at the application level, and TCP/IP at the transport level.

5.2. Challenges

For a smart inverter to implement particular features and functionalities, a few significant technological hurdles might be recognized. The first has to do with the way power electronic devices and systems work and their physical limits. A conventional power converter can't store energy on its own, so its output power is limited by the source and how much of it is available. At the discretion of economics, mitigation steps may be implemented by including an extra energy buffer or storage components, simulating mechanical inertia, limiting short-circuit current, and so on. The next problem is related to the decentralized control situation, which makes system stability and global performance difficult to accomplish [207].

6. Next generation inverter technology

6.1. Need

In order to improve the grid system's resilience and deliver a constant and stable supply of electricity from renewable energy sources, new control methods must be created. The next-generation inverter is an essential part of the distributed generation (DG) interface since it raises the utility grid's reliability and efficiency [230]. The next generation of inverters will need to have better qualities. They will need to be self-governing, self-adapting, self-securing, and self-healing. The capacity of inverters to function in grid-following and grid-forming control modes is known as the self-governing feature for grid-interactive inverters. The self-adapting feature is referred to as more flexibility attained by adaptive controllers in regard to stable dynamics of inverters under a variety of grid settings.

6.1.1. Reliability

The percentage of renewable resources that are used by the energy system is expanding at a rate that has never been seen before. Variability and unpredictability are the primary challenges presented by renewable energy sources. It is necessary to perform effective management of the various energy sources to be able to ensure a reliable and cost-effective functioning of the system [231]. The design of solar farms, the topology of inverters, and the primary components of the system, including fuses, capacitors, and semiconductor devices, all have a role in the dependability of the power system. It is generally accepted that centralized architecture is more dependable than distributed design due to the lower total number of parts and the simplified maintenance required. The distributed structure, on the other hand, allows for simple scalability and redundancy, as well as a reduction in the possible consequences that an individual failure may have on the system. The strategy of designing for dependability should be implemented for the next generation of inverters. This should be done using redundant and modular topologies, novel energy buffering mechanisms, and high temperature semiconductor components [232].

6.1.2. High power conversion efficiency

The increasing use of distributed energy resources (DERs) in the direction of generating all of their electricity from renewable sources is driving researchers to develop power electronics that are more functional and efficient. There have been several innovative designs and control systems developed in recent years with the goal of increasing energy transformation process efficiency while simultaneously offering subsidiary services for the grid [233–235].

6.1.3. Power quality

Microgrids are a combination of several types of generators, storage systems, and loads that may be controlled. It has the capacity to conduct in both the islanded mode and the network associated mode. The most important thing is to make sure that there is a steady supply during any sort of problem, whether it be a problem with the voltage or current connected to power quality or any other kind of system disturbing impact. When renewable resources are connected to the grid, it may lead to power quality difficulties such as voltage and current-based power quality problems. A next-generation inverter can assist mitigate these issues, which can be attributed to power quality problems [236].

6.1.4. Adaptability

It is essential for a next generation inverter, to be capable of altering or adapting itself to the many shifts and happenings that occur inside the system in which they function. This involves having the capacity to calculate the parameters, more precisely the impedance of the grid, as well as the capability to self-synchronize in terms of frequency. This is referred to as adaptability, and it is one of the other essential qualities of a next generation inverter [26].

6.2. Features of next generation inverter technology

6.2.1. Resilient stabilizer

A severe incidence of a weak grid might cause the inverter to become unstable, which would result in an abrupt disconnection of the inverter. Weak grids render inverters vulnerable to voltage variations. After the utility power has been cut off, a newly constructed microgrid might experience cascading failure if one inverter in the microgrid suddenly stops providing electricity [237–241]. For better dynamic functions, the current control loop bandwidth, the voltage feedforward route, the phase locked loop (PLL), and the filter controlling parameters can be set up in the right way. As was mentioned previously, the characteristics of the grid have a major effect on the reduction of the normal working area of inverters that are used in weak grids. As a result, the adaptability of smart inverters is increased by adding an adaptive element into the controller [242–244]. An adaptive control theory has been provided in Ref. [242] that depends on the online estimate of grid impedance with the goal of improving the inverter's overall stability. In order to maintain the inverter's position inside the stable area while dealing with increasing values of grid impedance, the PLL bandwidth must be decreased. However, to maintain the stability of the system, the PLL bandwidth had to be significantly reduced. As a result, the system's stability and dynamic performance must now be balanced. An active damper has been assured in Ref. [243] to be added to the system to make the inverter more resistant to changes in grid conditions. This effectively adds an additional resistive term to the inverter circuit that can be changed adaptively. This increases the inverter's resistance to variations in system disturbances. This makes the inverter more resistant to changes in a grid condition. An extra low-power single-phase inverter is used to implement the active damper. This guarantees that the controller is stable without adding any further layers of complexity to it. Nevertheless, it calls for extra circuitry, which contributes to an increase in both size and expense. The gain of the voltage feed-forward route has been adjusted in Ref. [244], in an adaptive manner to raise the system's stability in weak grids. On the other hand, the method described in Ref. [244] needed a grid impedance estimate, which was carried out with the use of a band-pass filter. In conclusion, the control strategy has to be modified to include adaptive components in order to make smart inverters strong enough to withstand weak grids. The most feasible approaches to implementing the adapting functionality for next generation inverters seem to be adaptive feed-forward and virtual impedance techniques. Even though traditional controllers with set parameters are often used, adding these systems seems to be the best way to make the system adaptable.

6.2.2. Use of forecasting data for supervision

A supervisory or tertiary controller, in addition to enabling economic dispatch, may facilitate the connectivity of microgrids to create a grid of microgrids by exchanging synchronization data [13,26,245–249]. Additionally, a supervisory mechanism with accessibility to weather forecasting data might assist to alleviate some of the problems caused by the unpredictable nature of renewable resources. The wind turbine's maximum wind speed may be exceeded on an exceptionally windy day, in which case it will shut down. Similarly, a PV array's output may abruptly decrease when a big cloud passes by. Since renewable energy sources are being used more and more, frequency and voltage oscillations might occur if a wind farm or solar farm fails. Instead, if the weather prediction is known ahead of time, the solar and wind farms might be progressively terminated, while the other sources, notably high inertia synchronized generators, could be gradually brought back up to prevent any under-frequency trips.

6.2.3. Communication and self-defense capabilities

The efficiency of next generation inverters in both grid-forming and grid-following functions can be increased with the availability of external information. However, data packet transfers among intelligent inverters and grid operators through a communication channel can expose inverters to cyberattacks and human error [13,250]. Known message authentication code (MAC) techniques may be used to establish a secure connection and verify that a setpoint originated from the utility and was not changed. However, it is possible to hack the utility computer and send altered set points via secure tags. If a hacker modifies an inverter's set point, the inverter may first assess the new system parameters using the given reference model and then opt not to use them if the expected output is beyond the inverter's secure running range. Different and more advanced ways may be created based on various cyberattacks [251,252]. Low latency, high range, and a sufficient data rate are required in a grid-interactive inverter communication network, together with security and scalability [26]. A communication network may be wireless, such as cellular or Wi-Fi, or wired, such as optical fiber, power line communication (PLC), etc [26,247,248]. Although wired communication methods often have lower EMI sensitivity, they are less scalable than wireless options. Compared to other wired communication techniques, utilizing power lines for data transmission has the lowest data speeds, while being a low-cost option and having a long tale in relay and safety systems. Inverters can potentially lose entry to foreign data when employing power lines for data transfer in island mode. Even if a wireless communication channel with a mesh connection is more fault resistant, the routing procedure has the potential to substantially reduce the real data rate to an undesirable level. In order to minimize complexity and deliver high scalability, sparse communication technology, in which inverters just require to interact with adjacent smart instruments and inverters [253,254].

6.2.4. Features for fault detection and self-healing

A significant aspect of the next generation inverters is the ability to detect and repair impending faults. For the functioning of inverters in island microgrids and grids with significant inverter-based distributed generation (DG) penetration, it becomes even more crucial. In islanded microgrids, the inverters share the system's overall load. As a consequence, if one inverter has a malfunction and is quickly disconnected, it may set off a cascaded occurrence alike to the poor grid situation, which might cause the whole system to collapse. In contrast to the other features taken into account for smart inverters, real-time failure detection and fault-tolerance methodologies for inverters in numerous applications, like motor drives and electric powertrains, can be implemented to grid-tied inverters as long as their execution is not application-specific, according to the [255]. Broadly speaking, there are two types of fault-tolerant inverters: non-redundant and redundant approaches [256]. After detecting an impending problem, nonredundant inverters will transition to a new control strategy to continue operation with less circuitry. For non-redundant approaches, the key components, such as electrical components and dc-bus capacitors, should also be overstated. Even if an inverter is still working after an internal fault has been isolated, non-redundant approaches may result in very asymmetrical grid currents. Two semiconductor devices are needed for an extra leg in redundant methods for two-level inverters. In two-level inverters with an extra leg, the faulty leg must be unplugged and the auxiliary leg must be properly attached to the circuit. In redundant fault-tolerant inverters, each switch has a quick-response overcurrent breaker to segregate the component in the event of a short-circuit incident. When the device is detached, the isolated branch of the circuit acts as if it were an open circuit. Moreover, the location of a defect should be found utilizing effective open-circuit error detection techniques. Depending on the location of the problem, the appropriate connecting switch must be closed before adding a component from the supplementary leg to the circuit. Low-speed semiconductor switches are often employed as connecting switches because they commutate at the fundamental frequency. Despite the fact that two-level inverters are often utilized for grid-connected applications, modular multilevel inverters are naturally more tolerant of internal issues [255,257–262]. They're often seen in medium and high and medium-voltage operations. Multilevel inverters need to be advised if the self-healing functionality is wanted. Ungrounding the inverter neutral point makes the cascaded h-bridge (CHB) inverter one of the most effective topologies for designing failure-tolerant inverters.

6.2.5. Cost effectiveness

In the next generation, inverters utilize advanced architecture and topology, along with cutting-edge power electronic components, software integration, IoT, and machine learning. The advanced architecture and topology with these power components reduce current leakage, enhance power quality, ensure stable output power, and minimize harmonic distortion and switching loss. Software integration with various components facilitates machine-to-machine communication and control, optimizing the inverter's performance. The inclusion of IoT capabilities in next-generation inverters enables remote control and cloud data storage. Moreover, these inverters incorporate machine learning to analyze data from cloud servers, making them intelligent systems capable of self-healing and self-diagnosis. This ensures continuous power supply and a resilient system. while these advancements might seem costly, they are actually more economical compared to current technology, offering better power quality and a more cost-effective solution. An optimal planning model has been proposed in Ref. [263] for improving voltage deviation index and electricity sales revenue in low voltage distribution grids using photovoltaic resources. The model minimizes investment, operation costs, and maximizes sales revenue by determining the optimal smart photovoltaic inverter capacity and fixed capacitor location. The model calculates an annual techno-economic assessment, integrating accurate AC load flow equations and technical constraints. Comparing the model with conventional methods shows significant reduction in investment and energy losses.

6.3. Components

6.3.1. Advance architectures and topologies

Traditionally, centralized inverter systems have been used in solar farms. Today, utility-scale solar farms often use string inverter topologies (single-string or multi-string). The idea of ac modules was first put forth for residential PV systems in the 1990s, and it has lately been revived for use in commercial solar farms to create distributed microinverter architecture, which is intended to increase energy growth with distributed solar power tracking using dc-dc converters linked to each PV panel. The mainframe between totally centralized and wholly distributed systems has been an intermediate option because to cost, reliability, and maintenance issues [232].

6.3.2. Advance power semiconductor components

The theoretical limitations of silicon characteristics are being approached by modern power switching devices, such as Insulated Gate Bipolar Transistors (IGBTs) [264]. The most promising materials for future power devices are those with wide bandgaps, including gallium nitride (GaN) and silicon carbide (SiC). SiC and GaN devices have low conduction loss and can operate at high temperatures and high frequencies, which may considerably increase power density. Improvements in power conversion efficiency and cost reduction are the two main reasons for using these devices with PV inverters [232].

6.3.3. SiC/GaN three-phase variable-speed drive inverter concepts

Wide input and/or output voltage/motor speed ranges, low EMI, and cheap installation costs are all desirable characteristics of variable-speed drive (VSD) systems. They should also not need shielded motor connections. A broad variety of input and/or output voltages and motor speeds are additional desired qualities. The next generation of SiC/GaN PWM inverters should have LC output filters in addition to producing continuous output voltages in light of this. The use of standard low-cost motor technology will be possible as a result of the prevention of conducted and perhaps radiated EMI, reflections on long motor cables, high-frequency motor losses, dv/dt-related motor insulation stresses, and bearing currents [265].

6.3.4. Software integration

A multi-functional smart inverter demands an optimized and flexible control structure to facilitate transition among operation modes or control functions. Research trends are moving towards control modularity [266] and/or universal control architecture [267] driven by software switches or control parameters. Normally an inverter is designed for a dedicated application, such as solar, wind, and energy storage, with specific control requirements and functions. The concept of universal inverters, more like general power amplifiers, has emerged in recent years. These inverters can be customized by software modification to adapt to specific applications; hence, they are referred to as software-defined inverters.

6.4. Security issues

Cyber-physical devices are physical objects that interact with one another through a computer network, such as smart inverters. The performance, effectiveness, and dependability of the system as a whole may be increased by these intelligent cyber-physical devices' capacity to communicate data and accept orders in real-time. As hackers deliberately target device functioning, maintaining security is the key problem in the operation of cyber-physical devices. It should be noted that inverter-based low inertia power grids are more susceptible to sudden changes that may result in voltage sags or surges and cascaded inverter tripping [268]. The degree of information a hacker may get for each device determines the consequences of successful assaults in a significant way.

A trending field of research in recent years is the detection and prevention of cyberattacks. Despite the fact that there are many investigations being conducted in this area, no investigation can guarantee the secure functioning of cyber-physical systems. Security methods may range from sophisticated communication protocols to complex computational procedures, such as machine learning methods. When parameters are known or approximated, some researchers employ a model/knowledge-based method to detect assaults and ensure secure operation. User interface and network security are the fundamental security criteria for every cyber-physical system in order to guarantee data availability, confidentiality, and integrity. When hackers utilize their coding talents to get through security measures, authentication obstacles, user interface firewalls, etc., they may effectively carry out cyberattacks. Existing solutions, such as encryption, certificate-based authentication, and cryptographic algorithms, are mostly focused on data transmission security [269]. The security problem with smart inverters cannot be solved by these measures. Advanced cryptographic methods are required, according to Ref. [269], to provide secure data flow throughout each transaction. Areas of cyber attacks and their Solutions discussed bellow.

6.4.1. Confidentiality attacks and solutions

Confidentiality helps avoid unwanted access to information. Confidentiality attacks aim to steal sensitive information that should only be shared with trusted people. Examples of smart grid attacks include unauthorized device memory reading, payload spoofing, replay assaults, and modifying smart metre control programs. Network coding is used to keep data private. This ensures secrecy in smart grids. Data privacy involves anonymity, unlinkability, unobservability, and undetectability [215,270]. Password attacks undermine confidentiality. Password assaults often involve guessing, sniffing, dictionary attacks, and social engineering. Social engineering is a non-technical approach to system penetration 20. Traffic analysis attacks are known as confidentiality attacks. Sniffing and analysing communications might provide attackers with useful insights into node communication patterns. A side-channel attack attempts to get cryptographic keys. Examples of this type of violence include power analysis, timing, and electromagnetic analysis [213,271]. They compromise passwords, usage data, administrative access, and client privacy. Home appliances and smart meters are susceptible to this attack. Pioneer solutions include detecting saturated channels, optimizing communication bandwidth, and creating distinct infrastructure for power grid device communication. Encryption secures data from cyber-attacks and creates a virtual and private network. To prevent packet sniffing attacks, use a security gateway that transmits IP packets through an encrypted VPN tunnel embedded in the IP network payload. TLS protocol secures VPN tunnel communications, while X.509 certificates verify users and exchange symmetric keys between parties on the smart grid [272].

6.4.2. Data integrity attacks and solutions

These attacks include changing measurements in the communication network. This causes an imbalance in voltage and frequency, preventing synchronization with the grid. Therefore, data must be reliable and accurate in all operational conditions. The most common type of assault on data integrity is false data injection (FDI). These are also known as stealth attacks. Hackers infiltrate the communication layer, leaving system operators unaware of the attack. False data injection attacks occur when incorrect data is put into smart meter readings. The attack targets the smart grid infrastructure [49]. The goal is to compromise measurement and monitoring sub-systems to modify meter and phasor measurements [48]. This affects the state estimation of SCADA systems. By compromising one or more smart meters, attackers can successfully introduce modified data into the SCADA center, bypassing data integrity checks in the state estimation process [204]. To prevent integrity attacks on smart grid networks, authentication and end-to-end encryption are necessary. To conduct a confidentiality or integrity attack, attackers require authenticated access to communication networks and sensitive information [273]. Access control and authentication are critical for protecting the smart grid against integrity attacks.

6.4.3. Availability attacks and solutions

It ensures authorized people have access to the information as needed. This ensures that unauthorized users or devices cannot access the system. In Smart Grids, availability encompasses all cyber systems, including SCADA, DMS, and communication networks with external networks [213]. DoS and DDoS assaults aim to disrupt a system's availability. They try to interrupt data transport in smart grids, causing delays, preventions, and disruptions. This can result in blackouts, brownouts, or loss of data exchange. Power distribution and system issues can lead to loss of control messages or access to data. Availability attacks demand a multilayered security solution with resilient techniques due to their potential to outperform traditional defenses. These attacks target all security objectives, needs, and smart grid components. Analyzing cyber-security needs across network layers can lead to successful security solutions for smart grid applications [274].A classification of cyber attacks in smart grids has been highlighted in Table 13.

6.5. Internet of things (IoT)

Inverters are required in order to link distributed energy resources (DER) devices to utility grids. Specially in photovoltaic (PV) systems that are linked to the grid, the direct current (DC) electricity that is taken from the solar arrays has to be transferred into alternating current (AC) power while maintaining a certain frequency, phase, and voltage. Inverters are the devices that, in essence, execute the conversion and make it possible to quickly and precisely synchronize with the utility grid. Inverters may only be integrated into a system if certain performance conditions are met beforehand. These include efficiency, power capacity, and the minimizing of leakage current. According to Ref. [275], inverter connections must have galvanic separation and anti-islanding detection capabilities in order to meet safety standards and prevent potentially dangerous events from occurring. Inverter applications for photovoltaic systems that are linked to the grid need a high switching frequency in order to decrease the shape of the output filter and the number of harmonics produced. Smart inverters that are enabled by IoT are allowed to be used so that the flow of power can be controlled, and so that the interfaces between DERs and loads may be operated in a self-governing manner. This is a relatively new form of technology that incorporates a number of useful operational characteristics, including wireless communication, fault tolerance, self-awareness, islanding detection, adaptability, decentralized power control, modeflexibility, ramp-rate control, and harmonic current sharing [26,207]. IoT makes it possible for data to be transmitted between distributed energy resources (DERs), loads, and other units automatically and without the intervention of a person. Smart-metering technology is another intelligent gadget that may provide accurate readings of an organization's energy use. It enables data flow in both directions between distributed energy resources (DERs) and loads. Adopting smart inverters and smart meters in power systems may present some tangible challenges, such as the possibility of instability in multi-inverter system dynamics and limited energy-buffering capabilities [195,276,277].

7. Next generation inverter for grid resilience

7.1. Impact

Next generation inverter impacts both the residential sector and the national power grid. They are compatible with intelligent Internet of Things devices and can be accessed from computer and mobile devices. They can provide real-time data, analyze historical data, compare patterns across various dimensions, and export graphs, and so on. They can alert the users via SMS or email for any detection of faults and breakdowns which increases efficiency immensely. The alarms can be game changers for handling certain situations for instance output below simple limits or misfiring of electronics. Unlike traditional inverters which require constant maintenance, Next generation inverters can help fix local issues and thus increase system flexibility Next generation inverters serve multi-functional inverters and exceeds the limited role of conventional inverters thus bringing efficiency and effectiveness to a new height [278].

Fig. 15 illustrates a potential road map for the inverter of the next generation.

Table 13
Classification of cyber attacks in smart grids [209].

Confidentiality	Data Integrity	DC Availability
• Unauthorized Access [210] • Password Pilfering [213] • Traffic Analysis [216] • Man in the Middle [219]	• Data Injection [211] • Data Modification [214] • Data Tempering [217] • Time Synchronization [211]	• DoS/DDoS [212] • Buffer Overflow [215] • Puppet Attack [218] • Jamming Attack [220]

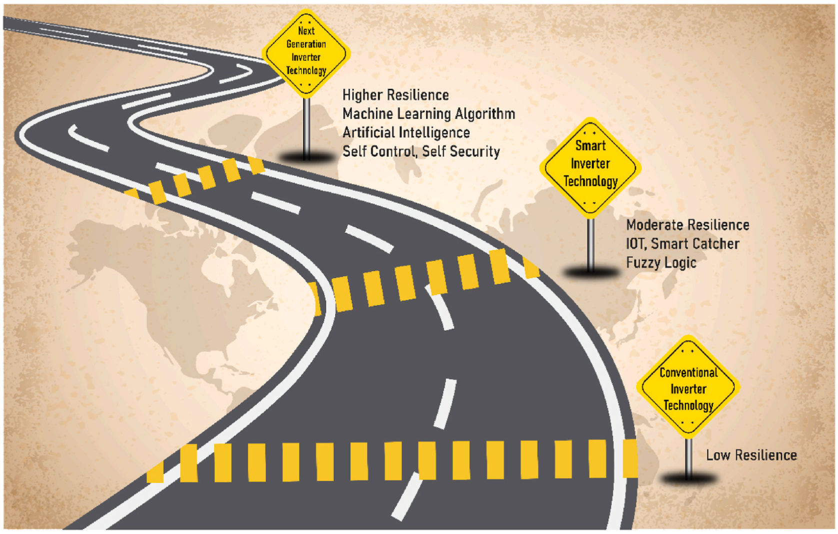


Fig. 15. A road map for the next generation power inverter.

7.2. Challenging issues

A blackout of the power system may happen for a number of reasons, including overloading, voltage violations, cascade failures, cyber-physical issues or even loss of stability. This requires system operators to perform proper counteractive control operations. Fig. 16 indicates many key categories of difficulties and technological problems that need to be solved. The primary difficulties include transient security issues such as voltage stability and compensation during the energization of long-distance transmission lines when there is little or no load, tie-line phase angles of synchronization, switching surge, and so on. Other difficulties include the lack of light or no load. In addition, there are issues with steady-state security, such as active power balancing, reactive power balance, thermal stability, voltage stability, generation selection, line re-routing, and dependability, among other issues. During the process of restoring electricity to the area following the blackout, these difficulties and problems pertaining to power engineering will need to be taken into consideration and controlled. In the event of a limited outage, the process of restoring service may be completed in a short amount of time; but, in the event of a widespread outage, it may present a considerable obstacle [279].

Intelligent inverters increase the number of options available for integrating dispersed resources into the grid. However, the internet-enabled interactions that make it possible for smart inverters to function with the grid also make it possible for something more evil to occur. Cybercriminals are able to take advantage of a variety of components in a smart grid that is based on inverters. EMS,

Fig. 16. Challenges of next generation inverter [280].

solar and wind energy facilities, inverter and power electronic devices, communication and communications devices, WAMPAC applications, Internet of Things devices, DER systems, and so on are some of these components [281].

Concerns regarding cyber-security emerge as inverters become more sophisticated, and the level of risk will continue to escalate as solar power becomes an increasingly significant part of the overall energy mix. This trend will quicken its pace as a result of California's mandate that solar panels be installed on all newly constructed homes by the year 2020. Even smart inverters, like any other internet-connected gadget, are susceptible to being hacked. Using software that is linked to the internet, they interact with the grid in order to execute independently the tasks of voltage control. This implies that intelligent inverters when put to good use, have the ability to control the voltage of the electricity that is sent into the grid in such a manner that there are no detrimental fluctuations. According to Dan Arnold, a research scientist at Berkeley Lab and one of the project's leaders on inverter cyber-security, if hackers take over smart inverters, they might introduce incorrect settings into the software and cause the voltage to spiral out of control, which in extreme cases could lead to brownouts or blackouts [282]. The challenges of the next generation inverter are shown in Fig. 16.

Inverter and DER Controller Related Issues: Maintaining the functionality of the Distributed Energy Resources (DER) system and supplying users and utilities with sufficient instruction concerning their operation typically requires a various set of digital apparatus. In general, this is the case. Nearly every distributed energy resource (DER) system will almost probably incorporate next generation inverters as well as DER controllers; some of these systems may also include battery controllers and sometimes controllers for electric vehicles (EVs). In the event that attackers get access to these systems, they are able to take control of their operations and provide spoofed status information to the owners of DER or utilities. Methods of attack that may directly control smart inverters can be especially dangerous since they have the potential to intelligently fool the operation of the device relying on the situation of the power system, which can lead to the situation of the grid that is not ideal [283].

Energy Management System Related Issues: An Energy Management System (EMS) is a helpful instrument that can control the production of electricity from a variety of sources while simultaneously gaining the economic advantages of doing so [284,285]. The dispatching of power production has often been handled centrally up to this point for the purpose of minimizing operational costs via the use of hierarchical optimization steps like integer planning [286] and technologies based on AI [287]. However, lately, there has been a lot of interest in distributed controllers that have exceptional performance against cyber layer deformities. This is because higher control versatility is required in the face of communication latency and information loss [288]. Attackers often raise the price of power production by infiltrating crucial variables with the intention of lowering the energy conservation of the system, which results in significant financial loss for the grid operator [289]. This is a cybersecurity risk. On the other hand, attackers may also launch assaults on EMS by using covert deception tactics in order to accomplish the same objective [290].

Communication System Related Issues: Remote communication between utilities and DER infrastructures is required in order for the operating point to be controlled, devices' statuses to be managed, and the dependability of the distribution grid to be maintained. Nevertheless, if hacks are successful in disrupting this connection, utilities won't be able to carry out the essential control operations. These attacks may be brought on by the existence of a wide number of vulnerabilities, including unsecured network topologies, the improper handling of cryptographic procedures, or an illegal entrance into utility DER systems. These kinds of assaults have the possibility to supply hackers the opportunity to take control of a large number of DER, which would have a huge effect on the grid [283].

IoT Related Issues: Because those infrastructural facilities may lack a strong security position and can provide attackers with web access to DER components, the potential interconnection of Distributed Energy Resources (DERs) and other platforms and networks, such as IoT nodes and third-party cloud system services, can increase the likelihood of cyberattacks. Through these connections, attackers might get access to the DER system and then manufacture bogus orders and messages to transmit to the system from outside sources. This would have a substantial influence on the operational parameters of the DER-using electricity grid [291,292].

Scalability Issue: The scalability of next-generation inverters within the present grid infrastructure is a major area of research for the growth of contemporary energy systems. Next-generation inverters, with greater management capabilities and increased efficiency, are designed to smoothly incorporate renewable energy sources like solar and wind power. Their large-scale implementation presents substantial problems and potential issues with the present grid infrastructure. While the scalability of next-generation inverters within the present grid infrastructure presents various obstacles, it is critical for achieving a sustainable and resilient energy future. To realize the full potential of renewable energy integration, addressing these difficulties needs a multidisciplinary strategy that includes technology developments, infrastructural enhancements, and supporting regulatory regulations. A Scalable Optimal Inverter Dispatch algorithm (SOID) using a linear approximation has been proposed in Ref. [293] to address Optimal Power Flow problems, including active and reactive power setpoints for PV inverters.

Interoperability Issue: The interoperability of next-generation inverters with the present grid infrastructure is critical to upgrading and improving the dependability of electricity systems. Next-generation inverters, which are distinguished by additional functionality and increased efficiency, are essential for the integration of distributed energy resources (DERs) such as solar PV and wind turbines. To ensure that these inverters work smoothly with the existing grid infrastructure, a number of technical, regulatory, and standardization difficulties must be addressed. One of the most pressing challenges is the standardization of communication protocols and interfaces. To ensure efficient data sharing and synchronization, inverters from various manufacturers must follow similar standards. Interoperability is facilitated by standards like IEEE 1547 and IEC 61850, which define inverter performance, operating, and communication criteria. Compliance with these standards guarantees that inverters may function in tandem with current grid management systems and other distributed energy resources. Furthermore, the use of next-generation inverters needs improvements in grid management software and control systems. These systems must be able to analyze real-time data from many inverters and distributed energy resources (DERs), allowing for dynamic modifications to ensure grid stability and dependability. Interoperable inverters contribute to sophisticated capabilities like demand response, voltage and frequency management, and a smooth transition from grid-connected to islanded modes. An interoperable controller, enabled by Distributed Network Protocol 3 (DNP3) communications protocols, has been proposed for a grid-connected PV inverter in Ref. [294], and the communication capability of the controller has been validated by means of a controller-hardware-in-the-loop experimental setup.

Compatibility Issue: The compatibility of next-generation inverters with present grid infrastructure is an important factor in power system modernization, especially when incorporating renewable energy sources. Technical concerns emerging from various technologies and standards provide substantial obstacles that must be solved to ensure smooth integration and peak performance. A key issue is the absence of uniform standards between areas and manufacturers. While standards like IEEE 1547 and IEC 61850 provide frameworks for inverter-grid interactions, differences in implementation might cause compatibility concerns. For example, variations in communication protocols and data formats might impede the seamless integration of inverters from various manufacturers. To ensure compatibility, organizations must work together continuously to harmonize technology implementations, in addition to adhering to these standards [295].

Regulatory and Policy Related Issues: Next-generation inverters for renewable energy systems face several problems. Different locations have different grid requirements, which makes it difficult for manufacturers to satisfy them everywhere. Testing for these standards can be expensive and time-consuming. Cybersecurity is a major concern as inverters get smarter and more connected. They require excellent cyber-security measures and must adhere to data privacy rules. Performance and reliability standards are constantly evolving, necessitating regular upgrades and certification. Renewable energy incentives and subsidies impact the inverter industry. Changes in these policies can disrupt investments. Inverters must also be compatible with smart grid technology and energy storage systems, which require certain restrictions. Environmental regulations require manufacturers to utilize sustainable techniques and manage electronic trash responsibly. Tariffs and local content regulations are examples of international trade policies that have an influence on global supply chains. Financial rules impact investment risks and insurance, affecting inverter adoption. Government financing and collaboration are critical for research and development, but the future is uncertain. Finally, consumer protection and education regulations are required to promote transparency and confidence in renewable technology. Addressing these difficulties is critical to the development of next-generation inverters [296–298].

7.3. Application of machine learning

The future of analytics includes machine learning, which utilizes algorithms based on previous data to forecast how to get the greatest outcomes. By enhancing data science's scalability and using computational skills to create predictive systems and address challenging analytics challenges, machine learning may be utilized to enhance data digitalization and big data [299]. Due to the difficulty of adjusting energy production and consumption in real-time, predicting demand, and blueprint for future energy system needs, machine learning and methods like Artificial Neural Network (ANN) have a huge role to play in the energy sector [300,301]. As new technologies like smart meters, smart appliances, next generation power inverters, and control systems increase both the quantity of data that can be gathered and evaluated and the ability to do so, and the use of renewable energy sources makes grid management more difficult because things like changing weather, system noise, line losses, and behind-the-meter loads as well generation, ANN algorithms are starting to offer researchers possible solutions that can be used to support intelligent energy management. Although it may be challenging to mine and discover the value in enormous data sets, big data technologies made available by machine learning are already assisting academics and businesses at the forefront of their industries in finding speedy solutions to these issues [302]. A machine learning-based big data forecasting approach is suggested in Ref. [303] that trains the power dispatch and operation system to more accurately estimate supply and demand with a 99 percent success rate. Geospatial modeling and comparable machine learning techniques, Assouline et al. [304]. Considering shading impacts, solar radiation, roof slopes and aspects, and accessible roof surface area, were able to calculate the peak penetration level potential of solar PV. Google is attempting to develop its own big data and machine learning capabilities as the quantity of data saved, exchanged, and uploaded to the internet continues to increase at an exponential pace. DeepMind, a division of Google's artificial intelligence division, is researching trends in Google's data center operations to improve their energy efficiency [305].

Smart inverters are increasingly being used in the distribution grid due to the increasing penetration of intermittent solar photovoltaic systems. These inverters require accurate information about distribution network topology and line parameters for traditional model-based Volt-VAR control (VVC) methods. A reinforcement learning-based two-time-scale VVC algorithm has been proposed in Ref. [306] to jointly control conventional voltage regulating devices and smart inverters. This algorithm minimizes voltage violation costs and system operation costs using historical operational data. The algorithm uses two hierarchically organized agents for both slow-timescale and fast-timescale problems, learning control policies concurrently.

7.4. The growing role of AI and blockchain: pillars of grid resilience

One of the most hotly debated topics in the area of computer science today, artificial intelligence is the subject of hundreds of papers and fresh ideas that are published every day from all around the world. Artificial intelligence (AI) will inevitably be employed in the energy industry due to its potential and future uses. Deep learning methods, in particular, are traditionally used a lot in artificial intelligence for prediction and forecasting. Future event forecasting is a powerful component of power system management because it enables grid operators to anticipate potential outcomes and better plan for them. Deep learning could be employed to detect and recognize cyber anomalies based on the training of past data sets, as shown in previous sections. In general, compared to other model-based techniques, AI's capacity to identify sophisticated cyberattacks is still constrained in terms of efficiency. However, given the field's ongoing growth, artificial intelligence offers a lot of promise for power system cybersecurity, necessitating more study and the use of increasingly sophisticated AI algorithms to improve the power system's capacity to identify hostile assaults [181,307]. AI-based controllers are a promising solution for optimizing and controlling power converter-based systems. These controllers, including online/offline supervised, unsupervised, and reinforcement-trained models, can be used to create surrogates for inner control loops, complete power converter controllers, and external supervisory or energy management control. The benefits of AI-based controllers include reduced computational complexity, near-optimal real-time operation, increased efficiency, reliability, and scalability. By utilizing physics-informed methods, a deeper understanding of underlying physical processes can be achieved, and data-driven methods can analyze the behavior of the surrounding system, forming the basis for adaptive control. However, AI also has potential disruptive impacts on various power converter-based systems [308].

Communication systems in smart grid control applications require real-time, efficient systems that can function in severe propagation conditions. IEEE C37.118 and IEC 61850 have been implemented for synchronization communication, but they face significant propagation and packet delays due to synchronization precision issues. This leads to inaccurate measurement and monitoring of smart grid applications. Existing communication systems use GPS timestamps as reference clock stamps, which can lead to imprecise measurements. To address this issue, a new algorithm is needed that considers alternative reference timestamps. Artificial Intelligence (AI) can significantly improve engineering solutions, and this article proposes an AI-based Synchronization scheme to mitigate smart grid timing issues. The backpropagation neural network is used as the AI method, employing timing estimations and error corrections for precise performance. The novel AIFS scheme connects the external timing server and performs better than the existing system using a MATLAB-based simulation approach [309].

Blockchain is one of the trendiest themes in today's culture, along with the advancement of AI. Blockchain is very safe and might be a great solution for both the energy sector's operational issues as well as its cybersecurity problem. By providing an independent transaction life cycle, blockchain technology simplifies the whole wealth management and payment process. The internet of things and blockchain combined with AI have the potential to create a more robust system [310,311].

8. Future recommendation

As we look to the future of power inverter technology, several critical areas require targeted research and development to guarantee that these devices satisfy the changing needs of contemporary energy systems. The key recommendation is to improve efficiency and performance. Future inverters must attain better levels of efficiency to reduce energy losses and enhance overall system performance. This may be accomplished by utilizing modern materials such as wide bandgap semiconductors, such as silicon carbide and gallium nitride, which have better electrical characteristics than typical silicon-based devices. However, the difficulty is balancing efficiency gains with cost concerns, as these sophisticated materials frequently have greater production costs. Innovative production processes and economies of scale will be critical for making these technologies economically viable [312].

Improving reliability and lifespan is another major priority area. Next-generation power inverters should be built to resist catastrophic working conditions and have a longer lifespan. This may be accomplished through strong design principles, innovative heat management technologies, and the use of predictive maintenance algorithms. Realtime monitoring and diagnostic skills are critical for predicting future faults and maintaining continuous operation. Developing accurate and cost-effective predictive maintenance systems demands substantial investment in sensor technology and data analytics, offering a hurdle to attaining widespread acceptance [313].

Future power converters must be designed to integrate seamlessly with renewable energy sources. As the use of renewable energy grows, inverters must be capable of handling varied input conditions and grid variations. They should also be compatible with energy storage devices to offer a consistent and dependable power source. The intermittent nature of renewable energy sources such as solar and wind poses problems to electricity stability and quality. Advanced control techniques and algorithms are required to successfully handle these oscillations while keeping the grid stable and reliable [314,315].

Power inverters are becoming more interconnected with smart grids and IoT devices, making cybersecurity an increasingly critical factor. Future inverters must include strong security capabilities to defend against cyber attacks and preserve the reliability of the electric grid. Implementing comprehensive cybersecurity safeguards may be difficult and costly, and keeping up with emerging cyber threats necessitates ongoing developments in security standards [316].

Scalability and modularity are also required for the next generation of power inverters. These devices should be easily scalable and adaptive to varying power requirements, ranging from modest home systems to big industrial installations. Developing a modular design that retains high efficiency and reliability at several sizes is difficult, but it is critical for widespread acceptance and flexibility in a variety of applications [317].

Cost reduction and affordability are key to the widespread adoption of next-generation power inverters. Innovations in manufacturing methods, material science, and design are critical for lowering production costs. Achieving considerable cost savings while retaining excellent performance and dependability necessitates a fine balance, highlighting the need for cost-effective solutions without sacrificing quality [318].

Finally, complying with environmental requirements and reducing the ecological imprint of power inverters are critical. Future inverters should be made from recyclable materials, consume less energy during manufacture, and meet worldwide standards. Navigating the complicated environment of international norms and standards can be difficult, but it is essential for ensuring compliance while retaining competitive performance and pricing [319].

To summarise, upgrading inverter technology is crucial for the future of energy systems. By tackling these issues and focusing on the indicated areas, researchers and developers may create innovations that result in more efficient, dependable, and sustainable power solutions. Collaboration among business, academia, and regulatory authorities will be critical to meeting these objectives and paving the way for the next generation of power inverters.

9. Conclusion

As the world continues to move towards cleaner energy sources, the need for more efficient, decentralized and reliable electrical systems has become increasingly important. In this context, next-generation inverters have emerged as a critical component for improving the resilience and sustainability of the electricity grid. Next-generation inverters provide greater efficiency, reliability, and grid-supportive functions than their predecessors. The integration of advanced semiconductor devices, artificial intelligence, machine learning, the internet of things and cybersecurity features has enabled these devices to predict future grid conditions and diagnose and correct faults in real-time. As research in this field continues to evolve, these advancements will help unlock the full potential of renewable energy and facilitate the transition to a cleaner, more sustainable energy future. This paper can be summarized as follows:

1. The detailed classification of grid resilience has been analyzed in this paper to find out the factors that affect resilience and discuss the method to enhance grid resilience.
2. An analysis of traditional inverters has been carried out, looking at their usefulness as well as their limitations when it comes to protecting against plant dynamics and cyberattacks.
3. The investigation of the next-generation inverter and the necessity of implementing AI and blockchain to enhance its strength, reliability, and resiliency has been analyzed.
4. A pathway has been developed to design a next-generation inverter for improving grid resilience by focusing on the lack of control and challenging issues of current inverter technology. The focus has been on the sophisticated capabilities of smart inverters for self-management, security, and adjusting to system uncertainties with their control challenges.

CRediT authorship contribution statement

Md Tonmoy Hossain: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Md Zunaid Hossen:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Faisal R. Badal:** Writing – original draft, Supervision, Resources, Methodology, Conceptualization. **Md. R. Islam:** Visualization, Supervision. **Md. Mehedi Hasan:** Formal analysis, Conceptualization. **Md.F. Ali:** Visualization, Supervision, Investigation. **Md.H. Ahamed:** Visualization, Investigation, Conceptualization. **S.H. Abhi:** Validation, Investigation. **Md. Manirul Islam:** Visualization, Formal analysis. **Subrata K. Sarker:** Investigation, Formal analysis. **Sajal K. Das:** Supervision, Formal analysis. **Prangon Das:** Visualization, Formal analysis. **Z. Tasneem:** Supervision, Formal analysis.

Data availability statement

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