Multilevel Inverter-Based Smart Grid IoT Integration: Enhancing Power Quality and Energy Efficiency

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Abstract: This research paper explores the integration of multilevel inverters into smart grid systems intending to enhance power quality and energy efficiency. The increasing deployment of Internet of Things (IoT) technologies in smart grids provides an opportunity to optimise energy management and improve overall system performance. The proposed multilevel inverter system leverages its advanced voltage control capabilities to address power quality issues, such as harmonics and voltage sags, commonly encountered in traditional power distribution networks. Through the integration of IoT in the smart grid, real-time monitoring, control, and communication capabilities are harnessed to enable intelligent decision-making. This paper investigates the synergy between multilevel inverters and IoT technologies, highlighting the benefits of their combined implementation. The research delves into the adaptive control strategies enabled by the IoT, facilitating dynamic adjustments in response to grid conditions and demands. Furthermore, the study assesses the impact of this integrated system on energy efficiency, examining the potential for optimised power flow and reduced losses. The results presented in this paper contribute valuable insights into the practical implementation of multilevel inverter-based smart grid IoT integration, offering a comprehensive understanding of its implications for power quality enhancement and energy efficiency improvement in modern electrical networks.

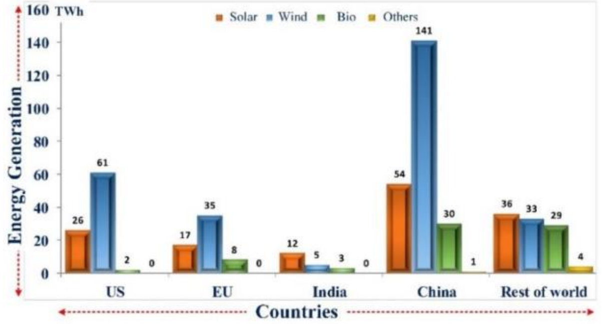
Keywords- Multilevel Inverter, Smart Grid, IoT Integration, Power Quality, Energy Efficiency

INTRODUCTION

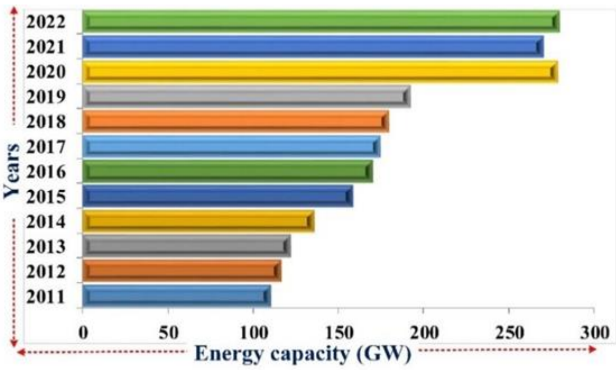
Modern electric grids are composed of numerous node power plants that use various power-producing units such as coal-fired, gas-fired, hydroelectric, and so on [1]. It is also worth noting that most of the traditional power grid's equipment and wires have been in place for a long time. Because they are significant investments, supplying them may take years. As a result, many grid components are obsolete and must be regularly repaired and monitored to keep power flowing [2, 3]. This device has two purposes: it generates electricity and maintains synchronism for dependable operation. Power grids have developed from small, localised grids to massive, spatial grids that sometimes cover many nations or even whole planets. The energy sector has adopted digital technology more slowly than other industries due to its size and need for increasing system availability, despite its importance to modern civilisation. This is also demonstrated by interpreting and enforcing the classification of electricity grids as infrastructural facilities. Due to the drive for increased efficiency, the computer revolution is becoming more widely used. New energy grid technologies heavily rely on high-frequency monitoring cycles and system bottleneck adaptation. The growth of sustainable power strengthens this trend. However, to be long-term sustainable, grids must have long-term goals such as efficient and dependable connectivity across diverse grid networks [4, 5]. As a result, dependable connectivity between power units and loads has emerged as a new idea that provides strategic management for advanced electric power systems. The provision of communication between devices is the primary necessity of the IoT. This is because IoT network users are gadgets. Therefore, achieving smooth end-to-end D2D communication is essential for the IoT's success. In the Internet of Things (IoT) ecosystem, devices will predominate, and people will use them as they use them. Devices will cooperate in a multicast network to collect, share, and forward information while interacting autonomously and without centralised supervision.

The building of an intelligent environment and the capability of real-time data collection, which is crucial for maximising the value of the IoT, will make this possible. A typical electric grid comprises many power plants that use various power-generating units, such as coal-based units, gas-based units, hydro units, etc. Most of the infrastructure and wires that make up the conventional electricity grid have existed for a long time, so it should be mentioned. They require significant investments, so providing them could take years. As a result, many grid components are outmoded and must be maintained and monitored regularly to keep power flowing. The smart grid (SG) system is sophisticated, making integrating green technology and environmental considerations easier. SGcyber–physical system was implemented thanks to the advancement of conventional power systems and communication technologies. The Internet of Things (IoT) and essential devices are present in the complicated architecture of the SG systems. The traditional electric grids are transformed into smart and efficient grids known as "Smart grids". The IoT smart grid allows for two-way communications among connected devices and technology that can recognise and respond to human needs. The cost and reliability of a smart grid are superior to that of conventional power infrastructure. Through use and data maintenance, smart grid technology will assist in reducing energy use and costs. One of the primary contributions to grids is the integration of IoT with producing facilities using sustainable energy at various levels. To enhance the smart grid for bidirectional information exchange, improve power quality, and increase reliability, Internet of Things (IoT) devices are becoming an important part of the smart electric grid. IOT Infrastructure (IOTI) provides a flexible, efficient, and secure platform with strategic management for monitoring and controlling different operations under different working conditions. This paper discusses cyber security on IOT-based infrastructure for electric power systems. A comprehensive study includes the type of IOTs, the architecture used for smart grid, and future challenges.

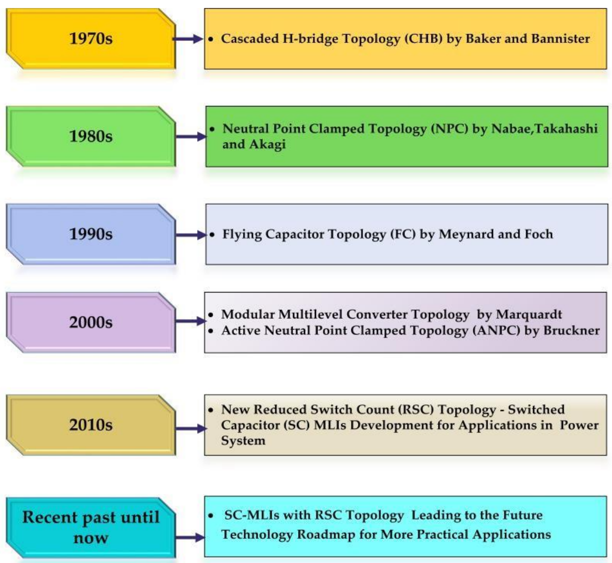
It is an electrical network of hardware, software, and infrastructure elements that allow effective power generation and transmission throughout the supply chain and two-way communication among all system parts and consumers. Through use and data maintenance, smart grid technology will assist in reducing energy use and costs. One of the primary contributions to grids is the integration of IoT with producing facilities using sustainable energy at various levels. At different grid nodes, this will cause varied voltage swings. The Internet of Things (IoT) fuels these advancements to address the flow of electricity by providing real-time data and information. Smart city technologies will enable intelligent lighting to track usage across numerous places. Modern fast monitoring systems are required to achieve the above-stated sustainable goal, so the term IOT exists [6]. The smart grid IoT technologies aid in the provision of dependable and efficient. The IoT smart grid enables two-way communication between linked devices and hardware that recognises and responds to human requirements. A smart grid is more reliable and less costly than traditional electricity infrastructure [7, 8]. Smart grid technology will help to reduce energy consumption and expenditures via use and data upkeep. integrating IoT with producing facilities using sustainable energy at various levels is one of the main contributions to grids. This will result in various voltage fluctuations at various grid nodes. By supplying real-time data and information, the IoT drives these improvements to address the flow of electricity. Intelligent lighting will be able to monitor usage in multiple locations thanks to smart city technologies. Quickly adapt to changing circumstances such as rain or fog. Change the output depending on the time of day or traffic conditions. Identify and resolve lighting issues immediately [9, 10]. The IoT smart grid enables two-way connectivity between linked technology and devices, recognising and responding to human requirements. A smart grid is less expensive and more sturdy than the current power network. Smart grid solutions are more carbon-efficient and less taxing on batteries. They are made to lessen the peak demand for feeders for distribution. The smart grid is regarded as one of the best computer intelligence applications demonstrating networking capability. The IoT refers to using advanced smart electronic communication devices to gather large real-time information for wide area monitoring and control [11, 12]. An electrical infrastructure, software, and hardware network allows for efficient power generation and distribution throughout the supply chain and two-way communication between all system components and users [13, 14]. A self-sufficient distributed system is widely used to characterise a smart grid. Energy storage and renewable energy sources are just two of the possible energy sources it could use. As a result of the implementation of this system, suppliers and customers now have access to new tiers of administration and control [15], [16]. Modern energy systems disperse energy generation throughout the system, which increases the complexity of several system components like stability, dependability, and security. When it comes to MGs, most energy production depends on them. In order to better describe the controllability of DGs in a distributed system, additional indices are offered [17]. The smart grid is gaining popularity as existing power networks evolve towards a more efficient and sustainable energy system. It uses cutting-edge information and communication technologies to offer a reliable and reasonable atmosphere for the command organisation [18, 19] and because it uses technologies for managing data to analyse and store metering and control data [20]. This is because the capabilities and locations of DGs within an integrated system impact the thresholds of system variables. Energy sources must be examined from various angles, including their stochastic character, controllability, and emission awareness, as they are the fundamental components of every energy system. It has been predicted that renewable energy will contribute 29% of worldwide power output in 2020, up from 27% in 2019, that renewable energy generation will increase by more than 8% to 8300 TWh by 2021, and that solar PV and wind will account for two-thirds of the growth in renewable energy. The increase in renewable energy alone in China in 2021 was about half of what was predicted, followed by the United States, the European Union, and India, as shown in Figure 1a. China has continued to be the largest PV market, although there is growth in the United States due to continuous federal and state legislative support. New solar PV capacity additions in India have recovered quickly from COVID-19-related delays in 2021. According to the IEA's 2021 Renewable Energy Market Update, by 2020, renewable energy was the only type of energy whose consumption increased despite the pandemic. The renewable energy sector has looked at new additions to increase worldwide renewable power in 2021 and 2022. In addition, 270 GW went online in 2021, and 280 GW went online in 2022, continuing the remarkable level of anticipated renewable energy additions. This expansion has exceeded the yearly capacity rise record set in 2017–2019 by more than 50%, indicating that renewables have been responsible for 90% of the increase in global capacity in 2021 and 2022, as shown in Figure 1b.



(a)



(b)



(c)

Figure 1. (a) Worldwide renewable power generation in 2020–2021; (b) net renewable capacity additions by renewable energy market update 2021—IEA; (c) an outlook on the development of various MLI topologies.

Flexible alternating current transmission systems (FACTSs), customised power devices (CPDs), variable-speed drives (VSDs), active front-end converters (AFCs), and renewable energy sources for power generation are just a few of the many uses for MLIs [2–5]. MLIs can be classified as classical if they use the most common topologies, such as the diode-clamped multilevel inverter (DCMLI), flying capacitor multilevel inverter (FCMLI), and cascaded H-bridge (CHB) multilevel inverter, mentioned in Figure 1c. There has been a lot of interest in these topologies, but the application, the designed system, and the costs highly impact their practical implementation. The fundamental disadvantage of a DCMLI is its asymmetrical loss distribution. This, in turn, results in an irregular distribution of junction temperature, which, in turn, results in constraints on the inverter's power, current, and switching frequency at maximum junction temperature [6, 7].

The complex architecture of the SG systems includes the Internet of Things (IoT) and necessary devices. The traditional electric networks have been replaced with the "Smart grid", a smart and effective grid. The IoT smart grid enables two-way communication between linked gadgets and machinery that can recognise and react to human requirements. A smart grid is more affordable and reliable than traditional electrical infrastructure. Smart grid technology will aid in lowering energy use and expenses through utilisation and data upkeep. Integrating IoT with generating facilities using sustainable energy at various levels contributes to grids. To improve the smart grid for the unidirectional exchange of information, enhance energy quality, and raise dependability, Internet of Things (IoT) devices have become an important aspect of the smart electric grid. IOT Infrastructure (IOTI) offers a secure, versatile platform for tactical management that allows for monitoring and managing various operations in various working environments. With benefits for demand response and reduction, smart grids are anticipated to provide new incentives for SMEs to help reduce carbon emissions.

Type of IOT layer used in electric grid

The Internet of Things (IoT) is a computing concept that uses sensors and other wireless technologies to link many physical things to the Internet. This concept can be used in smart grids to improve their functionality and coordination with intelligent loads, EVs, and renewable energy sources (RES). This section deals with the type of IOT used for smart grid infrastructure.

The architecture of advanced IOTI

The IOTI aims to assist the traditional grid by providing large flexibility regarding automation interaction [28]. The monitoring layer is used for better power management. The control centre and the operator must be able to monitor the system continuously. This layer helps the operator with real-time operations and decisions. Data Collection layer can be easily understood that for proper planning,

LITERATURE REVIEW

Integrating multilevel inverters with Internet of Things (IoT) technologies in smart grid systems has emerged as a promising approach to enhance power quality and energy efficiency. In recent literature, researchers have extensively explored various multilevel inverter topologies and control strategies to address power quality issues such as voltage sags and harmonics. [1-5]. Advanced modulation techniques and control algorithms have been proposed to optimise energy conversion processes and minimise losses, thereby improving overall system efficiency. Furthermore, IoT-enabled monitoring and control systems have been developed to provide real-time insights into grid operations and enable proactive maintenance, fault detection, and demand response. Despite significant progress, challenges such as interoperability, cybersecurity, and standardisation remain to be addressed. Future research directions include investigating novel IoT-enabled sensing technologies, developing robust communication protocols, and exploring advanced control strategies to enhance further the integration of multilevel inverters with smart grid IoT systems.[6-10].

Discussion and Findings

Integrating multilevel inverters with Internet of Things (IoT) technologies has emerged as a promising approach to enhancing power quality and energy efficiency in smart grids. This literature review delves into recent advancements, challenges, and future directions.

Smart Grid and IoT Integration

The literature reveals a growing body of research on integrating IoT technologies with smart grid infrastructure. Through real-time monitoring, demand-side management, and distributed energy resource optimisation, IoT-enabled smart grids offer enhanced operational efficiency and reliability.

Multilevel Inverters

Multilevel inverters are crucial in smart grid applications because they provide high-quality power conversion with reduced harmonic distortion. Topologies and control strategies have been extensively studied to improve power quality and efficiency, including cascaded H-bridge, neutral-point-clamped, and flying capacitor inverters.

Power Quality Improvement

Studies demonstrate the effectiveness of multilevel inverters in mitigating voltage sags, harmonics, and other power quality issues. Advanced modulation techniques and control algorithms enhance power factor correction and maintain stable grid operation.

Energy Efficiency Enhancement

Research highlights the impact of multilevel inverters on energy efficiency improvement in smart grids. Optimal control strategies and energy management algorithms minimise losses and maximise energy conversion efficiency, reducing operational costs and environmental impact.

IoT-enabled Control and Monitoring

Integrating IoT technologies enables real-time control and monitoring of multilevel inverter-based smart grid systems. Communication protocols, sensor networks, and data analytics facilitate predictive maintenance, fault detection, and adaptive control strategies for optimal system performance.

Case Studies and Applications

Case studies and practical implementations demonstrate the feasibility and effectiveness of multilevel inverter-based smart grid IoT integration in diverse applications. Successful deployments showcase improved power quality, energy efficiency, and grid stability, albeit with certain interoperability, cyber security, and scalability challenges.

Challenges and Future Directions

Despite significant progress, challenges remain in realising the full potential of multilevel inverter-based smart grid IoT integration. Addressing interoperability issues, ensuring cyber security, and developing standardised protocols are critical for widespread adoption. Future research directions include exploring advanced control strategies, optimising energy management algorithms, and investigating novel IoT-enabled sensing and communication technologies.

CONCLUSION

IOT-based smart grid solves problems associated with traditional electrical grids, such as unidirectional information flow, security, reliability, consumer interaction, and many more. It enhances the smart grid by providing a common platform for different devices, such as remote terminal units, actuators, and sensors, for interaction, monitoring, analysis and control for different operations and conditions. There is a growing demand for IoT in smart grids to combat energy loss in every known sector, and there is immense potential for enhancing power quality and energy efficiency in smart grid systems. Through extensive research and development efforts, various multilevel inverter topologies and control strategies have been explored to mitigate power quality issues such as voltage sags and harmonics while optimising energy conversion processes. IoT-enabled monitoring and control systems offer real-time insights into grid operations, enabling proactive maintenance, fault detection, and demand response mechanisms. Despite significant progress, several challenges, such as interoperability, cybersecurity, and standardisation, must be addressed to facilitate the widespread adoption of multilevel inverter-based smart grid IoT integration.

Moreover, future research directions should explore novel sensing technologies, develop robust communication protocols, and implement advanced control strategies to enhance system performance and reliability. Integrating multilevel inverters with IoT technologies represents a transformative approach towards building intelligent and sustainable energy systems. By leveraging the synergies between these technologies, researchers and practitioners can pave the way for a more resilient, efficient, and environmentally friendly smart grid infrastructure that meets the evolving demands of modern society.

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