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Smart Inverter Systems for Cyber-Physical Microgrids: A Spotlight on the Evolution, Control Strategies, and Future Directions

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Abstract. Across the globe, the energy landscape is fast changing due to advancements in semiconductor materials, widespread application of artificial intelligence, wireless communication systems, and cybersecurity protocols. These infrastructures have provided leverage for the transition of present microgrid systems to emerging cyber-physical microgrids. It is on these premises that this present work examines AI-driven inverter systems enhanced with a wireless communication system and advanced control strategies. Also, following a careful assessment of the evolutionary trends and inverter topologies, an architecture for an AI-driven inverter system was proposed, which provided a platform for establishing a linkage between cybersecurity concepts and AI-driven inverter systems. Furthermore, premium emphasis was equally placed on the possible mitigating strategies for cyber threats that could result from adopting wireless communication techniques for data transmission in AI-driven inverters to the distributed energy resources in the microgrid systems. Also, the potential impacts and future outlooks towards the development of AI-assisted inverter systems and cyber-physical microgrid systems for sustainable power supply were comprehensively discussed. The potential impacts of emerging cyber-physical microgrid systems and AI-driven inverter systems on sustainable power supply have been extensively discussed, which is one of the key contributions of this work.

Introduction

The global energy landscape is fast changing due to the need to address environmental threats posed by the continual usage of traditional energy sources [1]. The need to build a resilient energy system that will guarantee access to sustainable, affordable, and reliable energy for the modern community is another contributor [1, 2]. Needless to say, this fast change in the energy landscape is characterized by the rising use of microgrid systems, which are often operated either in standalone or grid-connected modes to improve the system's reliability, resilience, and availability [2, 3]. Furthermore, the possibility of a dual mode of operations of microgrid systems permits the evolution of peer–to–peer energy transactions, which foster dynamic energy marketing within the microgrid systems to meet the energy demand response of the global community [4, 5]. In addition, the rising rate of adoption of a microgrid system is indeed a paradigm shift envisaged for the 21st century, where conventional power systems are expected to be transformed into an active power grid. The emerging active power grid should be enhanced with capabilities not only to minimize epileptic energy supply from the grid but also as a pragmatic approach to achieving one of the United Nations Sustainable Development Goals (SDG-7) [6].

A microgrid system is an aggregate of several distributed energy resources (DERs), many of which are characterized by direct current (DC) energy output [3, 4]. They are deployed not only to support rural electrification projects in isolated villages but also to strengthen weak grids in energy-poor communities [7]. However, the DC energy output from the DERs must be converted into alternating current (AC) as most grids around the globe are AC-operated [6, 8]. Also, AC is ranked to be the most compatible form of current used by a large number of consumer appliances around the globe [6, 8]. Furthermore, the energy conversion from DC to AC in the process of interfacing the energy output from the microgrid with the national grid and also with the consumer appliances ranked the inverter system as the heart of the microgrid system [9]. No doubt, it is the medium through which DC-harvested energy from distributed energy resources can be converted directly to alternating current [4, 5]. In a similar vein, the advent of power electronics components and devices has significantly enhanced the traditional roles of inverters from mere DC-AC conversion actions to intelligent devices that can participate in demand response actions such as voltage regulation and frequency control [10]. Also, in recent times, several control strategies such as model predictive control (MPC), fuzzy logic, AI-based algorithms, and droop control, among others, can be embedded with traditional inverters, thereby transforming them into smart inverter systems [10].

These enhancements have reconfigured the operational versatility of inverters to include real-time output monitoring, power quality enhancement, and seamless sharing of energy with the array of energy storage devices and other DERs [10,11]. Also, the inclusion of advanced control strategies with smart inverters can help to improve dynamic control of the flow of real and reactive power under different conditions without compromising their efficiency and reliability [11,12]. Furthermore, recent developments have greatly contributed to the miniaturization of inverter sizes without trading off the expected efficiencies, even at a relatively low cost, thus making them highly compatible with all forms of microgrid configurations; grid-connected, islanded, or hybrid systems [13]. The transitioning of conventional microgrid systems into emerging cyber-physical microgrid systems calls for the evolution of AI-driven inverter systems, which is the major concern addressed in this study. The core objective of this study is to create a roadmap for the birth and adoption of AI-driven inverter systems and cyber-physical microgrid systems. This study makes the following contributions to the existing canon of knowledge:

- An overview of the possible interaction of cybersecurity concepts in the AI-driven smart inverter system as a supporting platform for the birth of cyber-physical microgrid systems has been proposed.
- The potential impacts of emerging cyber-physical microgrid systems and AI-driven smart inverter systems on sustainable power supply have been extensively discussed.
- A smart architecture for the development of AI-driven smart inverter systems has also been extensively discussed.
- Possible future outlooks in the area of material development, cybersecurity protocol for mitigating cybersecurity threats, and malicious attacks on the envisioned cyber-physical microgrid systems have also been proposed.

Evolutionary Trends in the Development of Smart Inverter System Technology

Over time, inverter technologies have transitioned through different phases of evolution with significant enhancements such as increased efficiency, improved reliability, and better real-time output monitoring and control systems [14]. These developmental stages can be grouped into different eras of evolution, which include the Pre-1950s, the 1950s–1970s, the 1980s–1990s, the 2000s-2009, 2010, and 2020 to present. Suffice it to know that each of these periods was marked by significant milestones in the development of inverter technology. A bibliometric analysis of the evolution of technologies in inverter systems with an emphasis on technological improvements in output monitoring, diagnostics, control mechanisms, and peculiarities is summarized in Table 1.

Table 1. Evolutionary trends in smart inverter technologies.

Forms of Inverter	Period of evolution	Technology deployed	Devices employed for monitoring and controlling	Operational efficiency (%)	Peculiarities
Electromechanical inverters	Pre-1950s	Motor-generator (M-G) sets, vibrator-based inverters for DC-to-AC conversion.	i). Analog instruments (voltmeters, ammeters). ii). Uses manual fault detection via physical inspection.	50-60 [15]	i).Relatively Bulky ii).Low efficiency, iii). It is subject to mechanical and wear [15].
Solid-state inverters	1950s–1970s	Transistor and thyristor-based systems enhanced with pulse width modulation	i). Analog circuitry for voltage/current measurement. ii). Uses pulse width modulation for harmonic monitoring	70-80 [16]	i).Limited real-time diagnostics ii). It has only basic monitoring capabilities.
Microprocessor-based inverters	1980s–1990s	It employs the application of a microcontroller that acts as the heart of integration with the grid It employs digital signal processors and Phase-Locked Loops (PLL) to enhance its function as a grid interface inverter.	i). It has capacities for real-time tracking of voltage, current, and frequency. ii). It has digital display capacity. iii). Uses data logging coupled with PLL for synchronization with the grid.	85-90 [17]	It is moderately complex, and it is built with emerging standards compliance.
Advanced digital inverters	2000s	It is designed with DSPs and Field-Programmable Gate Arrays (FPGAs). It is also embedded with RS-485 communication interfaces.	i). It has real-time waveform analysis capability. ii). Endowed with fault prediction and detection capability. iii). It can also perform temperature /harmonic monitoring.	>90 [18]	Cost of advanced processors and integration challenges.
Smart and IoT-Enabled Inverters	2010s	IoT integration with TCP/IP, Wi-Fi, ZigBee; and cloud-based platforms.	i). Provided with remote diagnostics and condition-based monitoring. ii).IGBT degradation detection and high compliance with IEC 61724-1.	95-98 [19]	Liable to network dependency and cybersecurity risks.
AI and predictive inverters	2020s–Present	It is AI and machine learning enabled (e.g., DRL) with grid-forming capabilities and also with SiC/GaN semiconductors	i). It has predictive monitoring with adaptive control. ii). It is endowed with autonomous fault prediction.	>98 [20, 21]	High computational cost and data requirements for AI training.

Furthermore, Table 1 shows the trends of evolutionary progress from the earliest form of inverters, which is the electromechanical type, to the next generation of smart inverters that is expected to be AI-driven**.** It can be seen from Table I that IoT-enabled inverters are evolving for domestic and grid applications, which indeed has expanded the traditional role of inverters appreciably. However, one of the major challenges envisaged is the high level of network dependency and continual possibilities of cybersecurity risks or threats in the face of advanced wireless communication technologies [22]. The next generation of smart inverters is the AI-enabled smart inverters, which are envisaged to combine IoT Infrastructures, cybersecurity facilities, and AI capabilities to boost microgrid resilience and system sustainability.

The Architecture of an AI-Enabled Smart Inverter for Cyber-Physical Microgrids

The next phase of conventional microgrid systems is the cyber-physical smart microgrids equipped with advanced wireless communication facilities. In a bid to foster seamless compatibility of cyber-physical smart microgrids with the inverter system, the next phase of the inverter system is expected to be smart solar inverters [22]. A smart inverter in this context refers to an intelligent-based inverter enhanced with modern wireless communication infrastructures, advanced protection and monitoring schemes such as supervisory control and data acquisition (SCADA), active sensors, and actuators, among others [22]. They are embedded with features that provide real-time output monitoring using a real-time logic controller, thereby promoting a high penetration level of renewable energy resources on the conventional utility grid. This has the propensity to enhance grid sustainability and resilience [22, 23]. Also, advancements in artificial intelligence (AI), wide bandgap (WBG) semiconductors, and 5 G-based IoT communication are setting a new outlook for AI-enabled smart inverters with the possibilities of achieving elevated operational efficiency, high operational reliability, and seamless adaptability to all kinds of applications [23, 24].

The architecture of the envisioned AI-enabled smart inverter for cyber-physical microgrids comprises four primary segments, each contributing to its multifaceted capabilities purposefully to boost the overall performance of the AI-enabled inverters in the prosumer-driven energy markets atmosphere [25, 26]. The essential stages are: the power stage, control unit, communication interface, and protection circuits.

- The power stage is the traditional DC to AC conversion enhanced with WBG semiconductors such as silicon carbide (SiC). The SiC possesses a high switching speed, high power handling capacities, and efficient thermal management compared to the insulated gate bipolar transistors or metal-oxide-semiconductor field-effect transistors (MOS-FET) that are mostly used in recent smart inverters [26-28]. With this semiconductor device as the heart of conversion, a switching efficiency of about 99% at a 30% reduction of switching loss can be achieved for a high-power rating of up to 200kW [28]. Also, with WBG semiconductors, the inverter can still be actively efficient at the ambient temperature of about 65°C. This spells a good improvement in terms of thermal energy management compared to the adoption of insulated gate bipolar transistors (IGBT) or MOS-FET [28].

- The control unit coordinates voltage and frequency regulation alongside maximum power tracking. The control unit is equally used to initiate fault detection and protection through microcontrollers and digital signal processing techniques in most of the IGBT or MOS-FET-based inverters [29, 30]. However, emerging technologies are currently providing a sustainable platform to seamlessly carry out these tasks. For instance, AI-based optimization techniques can be effectively incorporated to predict the maximum point of energy tracking in response to weather variability [29]. Also, rather than using a microcontroller-based device for fault diagnosis, machine-learning approaches can be integrated to achieve fault detection and protection schemes. In addition, the voltage and frequency regulation function can be achieved using supercapacitor modules at the input loop to the inverter, as suggested by the authors in references [31, 32]. Supercapacitor modules are endowed with ultra-fast response time to frequency deviation, and they can also add a DC-uninterruptible power supply to the system [31]. These innovative approaches at the control unit of intelligent-based inverters can grossly reduce downtime and achieve greater operational efficiency.

- The communication interface helps in the wireless transfer of data between the inverter and microgrid management systems. The emerging technologies in the area of wireless communication, such as ZigBee, Bluetooth, Ultra-Wide Band, Wireless fidelity, and Near-field communication, have provided a unique platform to transfer data in real-time using IoT networks based on 5G for low-latency, high-bandwidth communications [33]. The inclusion of any of the wireless communication technologies can enable real-time monitoring with an approximate data accuracy of 99.5%, much needed for large-scale microgrids having multiple DERS [34]. However, the implementation of wireless transmission and monitoring of sensitive data comes with cybersecurity challenges, as the data being transferred is liable to malicious attacks in the form of interception of data that is unencrypted, thereby creating the need for data security to curtail the occurrence of cybercrimes. Data security becomes an essential part of the envisioned AI-driven smart inverter systems to monitor unusual traffic patterns, identify anomalies, and divert potential threats as quickly as possible [34, 35].
- Protection circuits ensure safe and reliable performance in the event of the occurrence of power quality events such as overvoltage, undervoltage, overcurrent, harmonics, interruptions, and spikes [36, 37]. The evolving protection circuit will have to accommodate more advanced features such as AI-based predictive fault detection, where faults are predicted before their occurrence, leading to 15% savings in maintenance costs [36]. Also, the protection circuits can be equipped to cater for high-frequency switching operation, leveraging the utilization of WBG semiconductors. This will help to maintain system integrity under extreme operating conditions [38].

Smart Inverter Topologies and Possible Improvement Strategies

It is essentially necessary to review various existing smart inverter topologies so as to create a roadmap for the possible modifications that can be used to realize the next generation of smart inverter systems for cyber-physical microgrid systems. Also, needless to say, the advancement in artificial intelligence, development of WBG semiconductors, and wireless communication technologies are tools needed to enhance the next generation of smart inverter systems [24, 36]. A concise comparison of different inverter topologies in terms of their operational efficiency, merits, and challenges is presented in Table 2.

Table 2. Comparison of different inverter topologies.

Topologies	Topologies description	Operational Efficiency	Peculiarities	Proposed modifications
String Inverters	i). It is employed to connect multiple PV panels in series to convert the total DC output to AC, ii). It is suitable for small microgrids, commercial microgrids, and residential applications. ii). Typically, the power rating is between 1 to 50 kW iii). The working temperature is typically between 0 to 50°C	95–98%	i).It is cost-effective, simple installation, and is reliable ii). Performance drops with shading or panel mismatch, ii) Liable to limited scalability for complex or large systems.	Integration of AI-based MPPT will improve energy harvesting by 5% under shading.
Microinverters	i). It is usually mounted on individual PV panels for panel-level DC/AC conversion, thus signifying independent operation. ii). Typically, the power range is between 0.2 to 1 kW per unit iii). The working temperature is typically between -40 to +65°C	96–99%	i). It is shade-tolerant and maximizes individual panel output. ii). The upfront cost is high and requires complex maintenance due to multiple units. iii). It is less practical for large-scale systems.	The inclusion of GaN semiconductors will reduce conversion losses by 2% and also increase power density up to 8–12 kW/m^3
Central Inverters	i). It is designed for large-scale utility microgrids. ii). Typically, the power rating is between 100 kW to 5 MW	98%–99%	i). High efficiency and scalable modular designs. ii). Liable to a single point of failure; consequently, the whole system can shut down	AI-driven predictive maintenance for fault diagnosis, and also SiC chips improve thermal performance.
Hybrid Inverters	i). Work effectively with multiple energy systems, both for off and on-grid applications. ii). Typically, the power rating is between 3 to 100 kW	95%–97%	i). It presents compatibility issues with diverse DERs. ii). High maintenance complexity. ii).It requires complex control algorithms	The battery efficiency can be optimized with AI tools.
Grid-Tie Inverters	i). It allows direct power injection of converted DC from solar PV to AC synchronized with the grid ii). The power rating is typically between 3 kW and over 100 kW	95%–99%	i). High efficiency and optimizes energy yield via MPPT, ii). No backup power during outages, grid-dependent, requires strict compliance with standards like IEEE 1547-2018.	Inclusion of IoT-enabled devices for real-time monitoring and control Inclusion of a cybersecurity protocol for data security

Emerging Control Strategies in Intelligent-Based Inverter Systems for Output Monitoring

Smart inverter systems are essentially required in microgrid systems for converting the DC output of DER into AC power output for feeding the consumers' connected loads. Also, recent trends have shown an expanded role of inverter systems from mere DC to AC conversion, thereby needing the incorporation of adequate control strategies for energy management so as to foster grid stability and grid resilience. These control strategies are adopted to manage the stochastic nature of energy output from DERs and also to effectively coordinate the dynamic nature of microgrid loads [39-43]. Some of the prominent versions of these control strategies are explored in this section. Similarly, possible techniques for improving them are suggested for realizing the next generation of AI-driven smart inverter systems.

Model Predictive Control

One of the leading output monitoring control strategies in smart inverter systems is model predictive control (MPC). It employs system models to predict inverter behavior and optimize its output in real time [40]. By forecasting system dynamics, MPC minimizes errors in voltage and frequency regulation, making it highly effective for managing rapid load changes and solar irradiation fluctuations with a response time below 8 milliseconds [41]. The MPC's predictive nature allows it to anticipate disturbances, such as cloud cover or sudden load spikes, and proactively adjust the parameters of the inverter to ensure system stability [41,42]. The development of WBG semiconductor material, such as SiC, can be used to improve the efficiency of smart inverters, as it supports high-frequency operation and is capable of reducing switching losses during DC to AC conversion by 30% [41, 42]. Also, one of the major challenges with the adoption of MPC is the computational complexity involved, which requires significant processing power and increased cost of procurement of smart inverters, usually by 10–15% [41, 43]. Therefore, the next-generation inverter system is expected to leverage the advancement in cloud-based computing techniques and other AI-based optimization techniques to wave off these complexities.

Fuzzy Logic Control

Fuzzy Logic Control (FLC) is a robust strategy for managing uncertainties in distributed energy resources, most especially with solar and wind energy resources [43-45]. With FLC, the parameters of the inverter can be proactively adjusted to dynamically optimize the maximum power point tracking and power dispatch in real time based on linguistic rules and membership functions [44]. Also, the complexity involved in developing membership functions of FLC can be made easy with the use of AI-based techniques. The recent trends for enhancing FLC include the integration of AI-based optimization algorithms and wireless communication devices. This can efficiently enhance its adaptability and improve its dynamic responses to environmental changes with minimal latency. Furthermore, the inclusion of 5 G-based IoT communications and AI-based optimization techniques allows real-time data inputs and can also increase the FLC's responsiveness by 10%.

Droop Control

Also, another viable technique for controlling the output of the inverter system is to adopt the droop control technique. This can seamlessly implement power sharing between inverters and distributed energy resources, thereby ensuring stability and equitable load distribution without any need for extensive communication infrastructures [47]. With the droop control technique, inverters can operate autonomously with reduced latency and enhanced resilience. Similarly, droop control is highly cost-effective and requires minimal computational resources compared to model predictive control and AI-optimization techniques [48]. One of the major shortcomings of droop control is the overreliance on local measurements, which often leads to sub-optimal power sharing in large microgrids. The communication requirement can be improved upon by leveraging the recent trends in wireless communication alongside AI-based optimization techniques to improve real-time data communication between inverters and microgrid systems.

Pulse-Width Modulation

A space vector PWM is an invariant of pulse-width modulation; it is a widely adopted strategy for regulating inverter output and has the capability of ensuring high power quality by minimizing harmonic distortion [49]. Also, the space vector PWM is employed to control the switching of inverter transistors to produce a smooth AC waveform. This can be improved upon by the adoption of wide bandgap semiconductors, such as GaN, which can support high-frequency switching, thereby improving the inverter efficiency and reducing thermal losses [49]. PWM is quite simple and computationally efficient, requiring fewer resources than MPC or AI. Amazingly, the pulse width modulation is suitable for all forms of inverter topologies [48]. However, one of the major challenges with pulse width modulation control is that it is adversely affected by rapid load changes, especially in a dynamic system [50]. Also, quite a number of authors have equally proposed improvements for pulse width modulation by leveraging the possibilities of using AI capabilities [49, 50].

The AI-Based Control Strategies

The next generation of inverters is expected to leverage AI-based control to transform its performance in the area of predictive control and fault detection. Also, a good number of AI-based optimization algorithms, such as neural networks, supervised learning, and deep learning, are excellent models for predicting and diagnosing faults. These AI-based algorithms are capable of forecasting the output of distributed energy resources with enhanced accuracy, thereby optimizing maximum power point tracking [13, 34]. In a similar vein, AI-driven control systems leverage real-time data communication and monitoring from 5G IoT networks to predict solar irradiation, wind speed, ocean tide, and waves, and load variation demand, thereby influencing dynamic adjustment of inverter parameters to maximize efficiency and stable operation [24]. Similarly, the integration of AI alongside wide bandgap semiconductors, like GaN, can support high-frequency switching and enhance control precision [25,26]. However, AI-based control requires skilled personnel for implementation and sometimes may be accompanied by an elevated cost for procuring the device [29, 51]. AI-based control is poised to drive autonomous microgrid operation, supporting global sustainability goals by enhancing system reliability and efficiency [51].

The Nexus Between Cyber-Physical Microgrid Systems and AI-Driven Smart Inverter Systems

The next-generation microgrid systems are expected to be cyber-physical characterized; hence, it is, therefore, necessary that the accompanying inverter systems must be able to dynamically interact with the cyber-physical microgrid systems in a manner that will facilitate enhanced system performance, improve operational resilience, and promote energy sustainability [52]. The envisioned cyber-physical microgrid systems are highly liable to cybersecurity threats and malicious attacks due to the heavy involvement of wireless communication infrastructure deployed for transmitting sensitive network parameter data that is monitored and captured in real-time. Of a necessity, the envisioned AI-driven inverter system must leverage largely on the advanced control strategies and wireless communication infrastructures to be able to realize the implementation of real-time output monitoring, forecasting of energy variabilities from weather, predict unusual traffic that could indicate the presence of cyber-attacks or threats, and activate cyber-physical attacks' detection mechanism to support resilient control systems [53]. Similarly, advancements in artificial intelligence, model predictive control, and wide bandgap semiconductors have created a reliable platform for the birth of AI-driven inverter systems and consequently the birth of a cyber-physical grid.

It is, therefore, necessary to closely examine the nexus between cyber-physical microgrid systems and AI-driven smart inverter systems, bearing in mind some essential cybersecurity-supporting infrastructures, in a prosumer-driven energy market atmosphere. The interaction between cyber-physical microgrid systems and AI-driven smart inverter systems must be able to accommodate the inclusion of a security operation center, security software like SIEM system, data encryption, intrusion detection systems, IT infrastructures, filtering systems, data transportation, and security policies to facilitate the complete transition of conventional microgrid systems into the envisioned cyber-physical microgrid systems. For instance, the security operation center is expected to serve as the nerve center coordinating and monitoring security matters across the DER components, AI-driven inverter systems, and wireless communication protocols in real time. This calls for the integration of wireless sensors with the envisioned AI-driven inverter systems to boost their compatibility with the wireless communication devices linking the cyber-physical microgrid systems and the AI-driven inverter systems.

Furthermore, the security operation center will ensure proper coordination of AI decisions on inverter operations are consistent with grid safety and security requirements by initiating an instant response to cyberattacks targeting inverter control systems or grid stability. The inclusion of security information and event management (SIEM) software in the envisioned cyber-physical microgrid systems and AI-driven inverter systems will assist in real-time data collection from AI-driven inverter controllers, IoT devices, and sensors, alongside the communication channels, and analyze the same to generate a situational awareness report. It will equally help in identifying and detecting unusual patterns in inverter behavior caused by compromised AI models. Similarly, attacks such as false data injection or replay attacks targeting inverter operation or grid balancing can be easily identified, and situation awareness reports of the threats are generated accordingly.

Furthermore, the involvement of wireless communication systems in the envisioned cyber-physical microgrid systems and the AI-driven inverter systems necessitated the need for data encryption. The data encryption stage ensures that appropriate control signals between the AI control layer and smart inverters are not intercepted or altered. Likewise, it will enhance the protection of sensor data streams used by AI algorithms to maintain accurate decision-making. Also, with the inclusion of data encryption, attackers can be easily prevented from eavesdropping or injecting malicious commands into the microgrid control system. Also, the nexus between cyber-physical microgrids and AI-assisted inverter systems calls for the need for an intrusion detection system that will help monitor network traffic and system activity to detect malicious activity or policy violations. This is possible by identifying the abnormal traffic patterns between distributed resources and the central control system. The intrusion detection system will equally facilitate the detection of cyberattacks targeted at influencing AI decision-making in inverter systems. Similarly, the IT infrastructures will equally ensure adequate protection of wireless communication channels used for AI model updates and inverter firmware upgrades accordingly. Also, there is a need for adequate security policy development that will support the requirements for data handling, encryption, and access control.

There is also a need for secure data flow from associated sensors to AI models, from AI to smart inverters, and between cyber-physical microgrid components. This will ensure that AI-driven inverters receive timely, trustworthy data for grid support functions like voltage control or frequency regulation and also secure AI feedback loops that adjust inverter behavior based on grid state. In addition, it will equally prevent man-in-the-middle attacks that could disrupt data-driven control of the microgrid. The summarized interconnectivity between the cyber-physical microgrids and AI-driven smart inverter systems is given in Table 3

Table 3. Nexus Between Cyber-Physical Microgrid Systems and AI-Driven Smart Inverter Systems.

S/N	Evaluation metrics	Nexus
i).	Control dynamics	The utilization of fast decision-making and adaptive learning algorithms will assist the AI-driven inverter systems in improving the control performance of cyber-physical microgrids.
ii).	Communication dependence	The cyber-physical microgrids and AI-driven inverters are both dependent on real-time and secure communication infrastructures.
iii).	Vulnerability exposure	There is a possibility that AI systems used to improve the parameters of inverter systems inadvertently amplify the effects of cyberattacks if they are trained on compromised data or manipulated through adversarial attacks, thereby influencing the performance of cyber-physical microgrid systems.
iv).	Resilience building	The AI-assisted inverter can enhance cybersecurity by detecting intrusions and anomalies, and enabling adaptive responses to attacks on the cyber-physical microgrid systems.
v).	Compliance and protocol integration	AI inverters must operate within cybersecurity frameworks to ensure their actions do not violate grid codes or data privacy norms.

Potential Impacts of Emerging Cyber-Physical Microgrid Systems and AI-Driven Smart Inverter Systems on Sustainable Power Supply

The dynamic response of the system (cyber-physical microgrid systems and AI-driven inverter systems) under system contingencies and cyber threats will have a significant effect on sustainable energy supply. The impacts are as summarized thus;

- Under these emerging technologies, the system power quality will be appreciably enhanced since the system voltage and system frequency will be relatively stable. In addition, the possibilities of adoption of advanced control strategies have a way of reducing total harmonic distortion in a bid to adhere to compliance with grid standards like IEEE 1547-2018 (CNET, 2025; IEEE Standards Association, 2018). These improvements ensure reliable operation for sensitive equipment, enhancing the adoption of microgrids in sectors requiring high power quality, such as healthcare systems.
- The inclusion of wireless communication technologies and advanced control strategies in both the cyber-physical microgrids and AI-assisted inverters will facilitate real-time monitoring and controlling of network parameters, and as such, seamless operation under varying conditions, the grid can be sustained [54]. This will result in improved grid resilience and reliability in the face of a dynamic energy demand and supply structure.
- Environmental sustainability: The cyber-physical microgrids and AI-assisted smart inverters will contribute significantly to environmental sustainability as they encourage widespread participation in renewable energy, and as a consequence, reduce over-reliance on fossil fuels [54, 55]. These environmental benefits position AI-assisted smart inverters as key enablers of global decarbonization efforts, supporting net-zero emissions targets.

- Economic viability: Economically, smart inverters lower operational and maintenance costs, making microgrids more viable for diverse applications. AI-based predictive maintenance reduces maintenance expenses by identifying potential faults before they escalate. Also, the integration of 5 G-based IoT communication enables real-time monitoring, optimizing energy dispatch, and reducing energy waste, which translates to significant cost savings in commercial cyber-physical microgrids [55, 56]. These economic benefits drive the adoption of microgrids, particularly in regions with high energy costs or limited grid access [56].
- Socio-economic developmental impacts: The birth of cyber-physical microgrid systems and AI-assisted inverter systems will have profound social and developmental impacts, particularly in addressing energy poverty in remote communities, powering schools, healthcare facilities, and small businesses [57]. IT-skilled personnel will be engaged, given birth technology know-how transferred between the semi-skilled and unskilled personnel [56, 57].

Progress, Challenges and Future Outlook

The recent progress, particularly in artificial intelligence, wide bandgap semiconductors, and cybersecurity, has transformed smart inverter performance, thus enabling seamless integration into diverse microgrid configurations. It is noteworthy to reiterate that these recent developments focused more on improving component efficiency, scalability, and adaptability to dynamic microgrid environments. The incorporation of AI and machine learning algorithms into smart solar inverters has revolutionized output monitoring and energy management in microgrids. AI-driven inverters leverage predictive analytics to forecast photovoltaic output with reported accuracies of up to 95%, enabling optimized energy dispatch and load balancing. Similarly, deep reinforcement learning models, as explored by authors in reference [57], enhance droop control in microgrids, ensuring stable voltage and frequency regulation under variable solar conditions.

Also, an AI-assisted inverter system can effectively optimize maximum power point tracking and improve energy harvest by adapting to changing irradiance and temperature profiles. AI-driven inverters are strategic to the development of cyber-physical systems, which are believed to have the potential to minimize energy losses and enhance data security from malicious attacks, to enhance grid stability. The recent development in the area of wide bandgap semiconductors, such as silicon carbide, gallium nitride, and diamond, has provided good leverage to improve AI-assisted inverter efficiencies beyond 99% due to effective thermal management and reduced energy loss during DC to AC conversion. Generally, WBG semiconductors offer higher voltage ratings, faster switching speeds, and superior thermal performance, enabling compact designs with lower cooling requirements. These properties, in addition to recent advancements in wireless communication and intrusion detection systems, are particularly advantageous in microgrid applications, where high efficiency and reliability are paramount.

In addition, the evolution of advanced control strategies such as model predictive control, fuzzy logic control, AI-based control, droop control, and pulse-width modulation (PWM), among others, has equally provided a sustainable platform for developing AI-assisted smart solar, which is of great benefit to improving the performance of the current microgrid systems and the envisioned cyber-physical microgrid systems.

Challenges to the Development of AI-Assisted Inverter Systems and Cyber-Physical Microgrid Systems

Some prominent challenges need to be addressed, which include grid synchronization, scalability and coordination, computational complexity, cybersecurity vulnerabilities, and cost and accessibility.

- Grid synchronization is a significant challenge for AI-assisted smart inverters in cyber-physical microgrids, as it often requires the use of precise phase-locked loops to align the output of distributed energy resources with utility grid parameters. However, maintaining stability during dynamic grid events, such as sudden load changes or voltage sags, remains difficult, especially in large microgrids with multiple inverters. There is therefore a need to develop robust grid-forming strategies that leverage 5 G-based IoT communication for real-time grid data, targeting synchronization errors below 1% [57, 58].

- The integration of 5 G-based IoT networks is a good leverage to improve coordination by enabling low-latency communication with 99.5% data accuracy; however, it requires high bandwidth and associated costs limit its scalability in resource-constrained regions [58].
- Computational Complexity: The computational complexity of AI-based control in the envisioned cyber-physical microgrid systems presents a significant barrier to their adoption, as it requires skilled experts rather than mere roadside technicians who are more or less the frontline field men in the renewable energy sector. Integrating both AI-based control modules and wireless communication modules into the conventional inverter system requires real-time optimization and substantial computational resources for training and deployment. Also, the inclusion of AI-driven inverters relies on cloud-based computing to manage processing demands and supply interaction; this alone creates another challenge of latency and dependency on high-speed networks, which may not be available in remote areas.
- Cybersecurity vulnerabilities: Cybersecurity is a growing challenge as AI-driven inverters increasingly depend on 5 G-based IoT networks for real-time communication and control. This exposes smart inverters to cyber threats, such as data breaches or malicious control commands, which could lead to microgrid instability and loss of synchronism. There is therefore a need for additional efforts in developing lightweight encryption and AI-based threat detection systems to reduce cyber risks in the envisioned cyber-physical microgrid systems and AI-driven smart inverter systems.
- Cost and accessibility: The cost remains a critical barrier to the adoption of AI-assisted smart inverter control strategies, as it involves expensive hardware and skilled personnel for implementation. Furthermore, the integration of AI and WBG semiconductors increases inverter costs, which could spell a limitation on its usage, most especially in developing regions where affordability may be a big issue of concern. Hence, the need for trained technicians to deploy and maintain complex control systems further exacerbates accessibility issues, with a shortage of skilled personnel reported in 70% of Sub-Saharan African microgrid projects.

Future Outlooks

The future outlook in the evolution of AI-driven inverters and cyber-physical microgrids can consider the following emerging trends;

- Deployment of blockchain-based encryption techniques for ensuring the security of data transmission to improve the integrity of monitoring data and control commands. Also, a machine learning-based anomaly detection approach can be deployed to identify cyber threats in real-time, such as unauthorized access attempts, or abnormal data patterns can be detected with better accuracy.
- The development of self-learning inverters equipped with advanced AI algorithms will enhance autonomous operation in dynamic microgrid environments. These will help to improve fault prediction accuracy beyond the current 95% benchmark, thus minimizing downtime.
- Exploration of energy-efficient AI frameworks, such as edge-based machine learning, for the implementation of transfer learning techniques aimed at addressing the challenge of limited training data, thus enabling AI deployment in small-scale microgrids with minimal infrastructure. This will further challenge academia and industry to collaboratively focus on developing open-source AI platforms to accelerate adoption and ensure interoperability across inverter types.
- Adversarial learning techniques to detect malicious data in AI training/operation, as smart inverters increasingly rely on IoT-enabled communication for remote monitoring and control, cybersecurity is a critical concern. Vulnerabilities in communication protocols, such as MQTT or HTTP, can expose microgrids to cyber threats, including data breaches and denial-of-

service attacks. There is a need to enhance inverter communication protocols by implementing robust security frameworks, such as zero-trust architectures, which require continuous authentication of devices and users.

- The development of plug-and-play inverter modules that would support seamless integration and 666expansion, reducing installation complexity and costs in the face of wireless communication, intrusion detection systems, and AI-assisted control strategies, is of the essence.
- Policy and Market Incentives: Policies that will showcase the techno-economic models and how they can be used to demonstrate the effect of low-cost AI-assisted inverters in reducing energy access barriers in developing countries should be developed. Also, collaborative initiatives, such as public-private partnerships, can accelerate the commercialization of modular and AI-driven inverters, aligning with global sustainability.

Conclusion

The paper presented a detailed overview of AI-driven inverter systems with emphasis on the evolutionary trends and control strategies for output monitoring of microgrid systems leveraging IoT Infrastructures, cybersecurity, and AI capability. Output monitoring of the inverter system is a pillar of sustainable and reliable energy from the smart microgrid system. It is on these premises that the study carried out a critical assessment of the different control strategies that can be used to enhance the performance of the envisioned AI-driven inverter system, bearing in mind that the generation microgrid systems are cyber-physical microgrid systems. Also, a concise but detailed architecture of an AI-enabled smart inverter for cyber-physical microgrids was equally discussed, which led to examining the nexus between cyber-physical microgrid systems and AI-driven smart inverter systems. Also, the potential impacts of emerging cyber-physical microgrid systems and AI-driven smart inverter systems on sustainable power supply were comprehensively analyzed, and the challenges to the development of AI-assisted inverter systems and cyber-physical microgrid systems were also looked into in this current paper. No doubt, the advancement in wireless communication, intrusion detection systems, development of WBG semiconductors, and evolution of different advanced control strategies are a sustainable platform for the transition of the present grid to the envisioned cyber-physical microgrid systems.

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