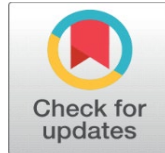
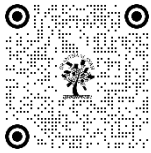


INVERTERS AND MULTILEVEL INVERTERS FOR POWER ELECTRONICS SYSTEMS

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ABSTRACT

Multilevel inverters (MLIs) have emerged as a crucial technology in power electronics, offering enhanced performance in high-power and medium-voltage applications. Unlike conventional two-level inverters, MLIs generate stepped voltage waveforms that improve power quality, reduce harmonic distortion, and minimize voltage stress on power semiconductor devices. This paper explores the various topologies of multilevel inverters, including diode-clamped, flying capacitor, and cascaded H-bridge configurations, along with their working principles and applications. Special emphasis is placed on the advantages of MLIs in renewable energy systems, electric vehicles, and industrial motor drives. Furthermore, recent advancements in modulation techniques and control strategies, such as space vector modulation and model predictive control, are discussed to highlight their role in improving the efficiency and reliability of multilevel inverters. The study concludes by addressing the challenges associated with MLIs, including complexity, cost, and switching losses, while also presenting potential future research directions in this evolving field.

Keywords: Multilevel Inverter (MLI), Voltage Source Inverter (VSI), THD, Harmonic Reduction, Pulse Width Modulation (PWM), Cascaded H-Bridge Inverter, Flying Capacitor Inverter, Neutral Point Clamped Inverter, Harmonic Distortion, Power Quality, Voltage Balancing, Modular Multilevel Converter (MMC), Electric Drives, Renewable Energy Systems, Switching Devices

1. INTRODUCTION

Power electronics has played a crucial role in modern electrical systems by enabling efficient conversion and control of electrical energy [1]. One of the most significant advancements in this field is the development of multilevel inverters, which have revolutionized power conversion processes in various applications. Multilevel inverters (MLIs) are a class of power electronic devices that generate an output voltage waveform with multiple discrete levels, improving power quality and efficiency in comparison to traditional two-level inverters[2].

The evolution of multilevel inverters stems from the growing demand for high-power applications that require minimal harmonic distortion and enhanced power handling capabilities[3]. Traditional two-level inverters are commonly used in various industrial applications but suffer from drawbacks such as high harmonic content, large filter requirements, and increased voltage stress on power electronic components[4]. To overcome these challenges, multilevel inverters were introduced as a superior alternative, offering reduced total harmonic distortion (THD), lower electromagnetic interference (EMI), and higher efficiency. These advantages make MLIs particularly suitable for applications such as renewable energy systems, electric drives, grid-connected power systems, and high-voltage direct current (HVDC) transmission[5].

Multilevel inverters operate on the principle of synthesizing a staircase-like output waveform by using multiple DC voltage levels[6]. This is achieved through the integration of semiconductor switches, capacitors, and sometimes transformer-based configurations. The key objective is to approximate a sinusoidal waveform as closely as possible while minimizing switching losses and harmonic distortion. As a result, MLIs can efficiently handle high power and voltage levels, making them ideal for medium- and high-voltage applications[6].

There are three primary types of multilevel inverters: diode-clamped (neutral-point clamped) inverters, flying capacitor inverters, and cascaded H-bridge inverters. Each topology has its unique operational characteristics, advantages, and limitations[7]. The diode-clamped multilevel inverter employs a series of diodes to regulate voltage levels and maintain balanced operation. It is widely used in industrial applications requiring high efficiency and moderate voltage levels[8]. The flying capacitor multilevel inverter, on the other hand, utilizes capacitors as energy storage elements to achieve voltage balancing without the need for additional diodes. This topology offers improved reliability but requires a complex control mechanism. The cascaded H-bridge inverter consists of multiple H-bridge inverter modules connected in series, allowing for modularity and scalability in high-power applications[9]. This topology is highly flexible and is commonly employed in renewable energy systems and electric vehicle drives[10].

The advantages of multilevel inverters extend beyond improved power quality and efficiency. They offer higher voltage capabilities, reduced voltage stress on individual components, and lower switching losses, which collectively contribute to enhanced system reliability and longevity. However, these benefits come at the cost of increased circuit complexity, a greater number of components, and the need for sophisticated control strategies. Despite these challenges, advancements in digital signal processing (DSP), microcontrollers, and artificial intelligence-based control techniques have significantly improved the feasibility and performance of multilevel inverters in modern applications in show figure.1.

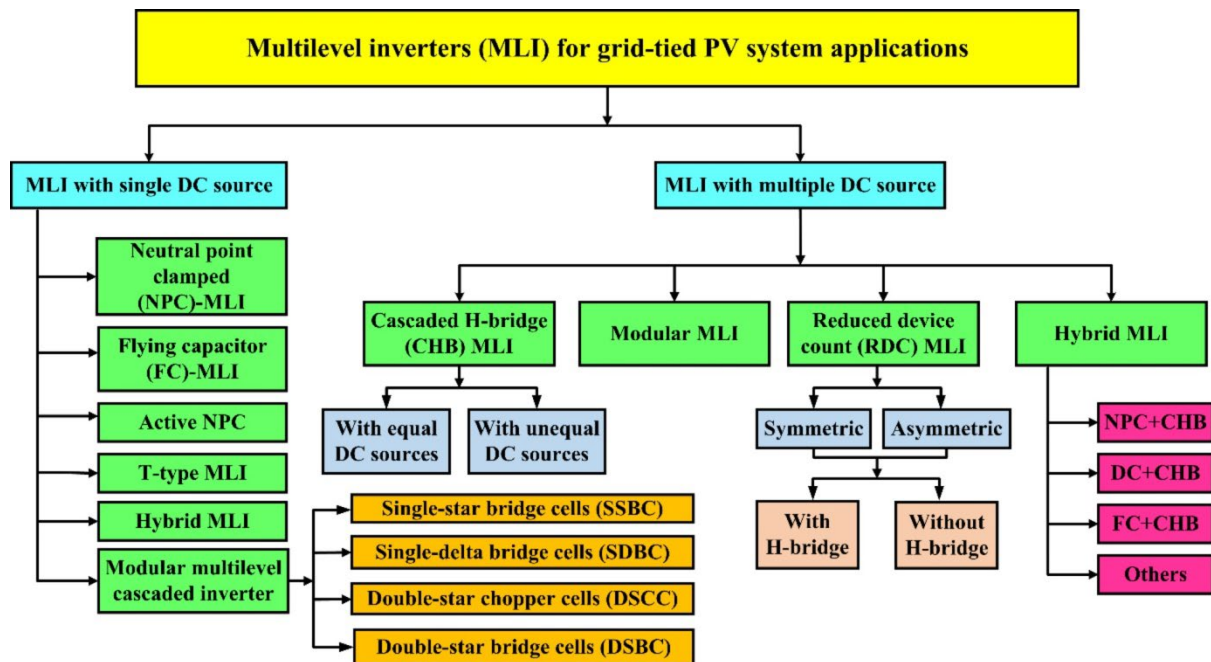


Figure.1 MLI classification based on the number of DC sources used.

The rapid growth of renewable energy sources, particularly solar and wind power, has further amplified the importance of multilevel inverters in contemporary power systems. Grid-connected solar photovoltaic (PV) systems benefit immensely from MLIs, as they enable efficient energy conversion while maintaining compliance with stringent grid codes and harmonic standards. Similarly, in electric vehicle (EV) technology, multilevel inverters contribute to the efficient operation of traction drives, optimizing power conversion and enhancing overall performance. The integration of MLIs in HVDC transmission systems also showcases their ability to handle high voltage levels with minimal losses, making them indispensable in modern power transmission infrastructure.

2. RELATED WORK

Vimal, D. et al(2021)[11]: The study Traditional switching strategies such as Pulse Width Modulation (PWM), Sinusoidal Pulse Width Modulation (SPWM), and Space Vector Pulse Width Modulation (SVPWM) have been widely adopted. Vimal et al. (2020) analyzed the impact of different PWM strategies on Total Harmonic Distortion (THD) and switching losses. They concluded that SVPWM offers better harmonic performance at the cost of increased computational complexity.

Bhuvaneswari, V., et al(2014)[12]: The cascaded H-bridge multilevel inverter (CHB-MLI) topology is a well-researched structure that can operate in both symmetrical and asymmetrical configurations. In symmetrical CHB-MLIs, all H-bridge cells use identical DC voltage levels, resulting in balanced voltage output. Asymmetrical CHB-MLIs, on the other hand, utilize different voltage levels, which increases the number of levels in the output voltage waveform without adding more hardware components. Researchers have demonstrated that asymmetrical configurations can significantly improve output voltage quality while maintaining a compact design 1.

Malar, E., et al(2023)[13]: Various modulation schemes have been proposed to enhance the performance of MLIs. Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) are widely used for their ability to improve voltage utilization and reduce harmonics. Selective Harmonic Elimination (SHE) techniques have been explored to further reduce Total Harmonic Distortion (THD) in inverter output. Furthermore, model predictive control (MPC) and artificial intelligence-based control methods, such as fuzzy logic and neural networks, have been investigated to optimize the dynamic response and efficiency of MLIs.

Mahato, B et al(2022)[14]: The study on Traditional MLI configurations, including the **Neutral Point Clamped (NPC)**, **Flying Capacitor (FC)**, and **Cascaded H-Bridge (CHB)** inverters, have been widely adopted due to their ability to generate high-quality output waveforms with reduced harmonic distortion. However, these conventional topologies require a large number of semiconductor switches, leading to increased system cost, complexity, and switching losses. To address these limitations, researchers have proposed **reduced switch MLIs**, which aim to maintain high performance while minimizing the number of switches.

Sarebanzadeh, M. et al(2021)[15]: Multilevel inverters (MLIs) have gained significant attention in renewable energy applications due to their ability to produce high-quality AC power with reduced harmonic distortion and improved efficiency. However, conventional MLI topologies require a large number of semiconductor switches, leading to increased cost, complexity, and switching losses. To address these issues, researchers have proposed various **reduced-switch MLI** configurations that aim to maintain output performance while minimizing the number of components. This section reviews existing works on reduced-switch MLI topologies, focusing on their advantages, challenges, and applications in renewable energy systems.

Ansari, S. et al(2021)[16]: Microgrids have emerged as a promising solution for integrating renewable energy sources into the power system, offering improved reliability, efficiency, and sustainability. However, the protection of microgrid feeders presents significant challenges due to the dynamic nature of distributed energy resources (DERs), bidirectional power flow, and varying fault characteristics under grid-connected and islanded modes. Traditional protection schemes often struggle with these challenges, leading researchers to explore novel techniques such as **differential positive sequence power angle-based protection** to enhance feeder reliability and fault detection accuracy. This section reviews existing literature on power angle-based protection strategies, focusing on their application to microgrid feeders.

3. TOPOLOGIES

Inverters are essential power electronic devices that convert **DC (Direct Current) power into AC (Alternating Current)**. They are widely used in renewable energy systems, industrial drives, electric vehicles, and uninterruptible power supplies (UPS). **Multilevel inverters (MLIs)** further improve power conversion by generating higher voltage levels with reduced harmonic distortion.

This section explores different **inverter topologies**, including **single-level and multilevel configurations**, highlighting their design principles, advantages, and applications.

3.1. SINGLE-LEVEL INVERTER TOPOLOGIES

Inverters are essential power electronic devices used to convert DC (Direct Current) into AC (Alternating Current). Inverter topologies are classified into single-level and multilevel configurations, depending on their ability to generate output voltage waveforms. Single-level inverters are the most fundamental type of inverters, generating two-level AC output waveforms. These inverters are widely used in industrial motor drives, UPS (Uninterruptible Power Supplies), electric vehicles, and renewable energy systems. This article provides an in-depth review of different single-level inverter topologies, including voltage source inverters (VSI), current source inverters (CSI), half-bridge, and full-bridge inverters.

3.1.1. TYPES OF SINGLE-LEVEL INVERTERS

1) Voltage Source Inverter (VSI)

A voltage source inverter (VSI) is the most commonly used inverter topology, where a DC voltage source is converted into an AC output. It typically uses insulated-gate bipolar transistors (IGBTs), metal-oxide-semiconductor field-effect transistors (MOSFETs), or thyristors for switching operations.

2) Current Source Inverter (CSI)

A current source inverter (CSI) uses an inductor-based DC source instead of a voltage source. The output voltage waveform is controlled by regulating the input current.

3.1.2. MULTILEVEL INVERTER (MLI) TOPOLOGIES

Multilevel inverters (MLIs) are advanced power electronic converters that generate **multiple voltage levels** to approximate a sinusoidal waveform. They improve power quality, reduce **Total Harmonic Distortion (THD)**, and enhance efficiency, making them ideal for **high-power applications, industrial motor drives, renewable energy systems, electric vehicles, and HVDC transmission**. This article explores different **MLI topologies**, their working principles, advantages, limitations, and applications in power electronics in show figure.2.

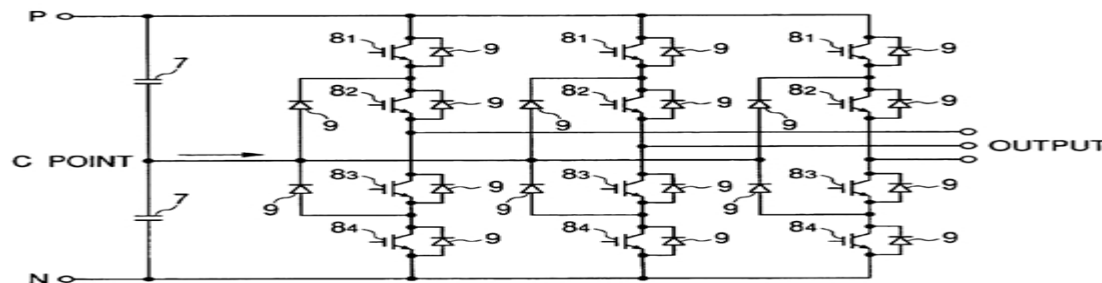


Figure.2 Diode Clamped Multilevel Inverter

4. COMPARISON OF TOPOLOGIES

Inverters are crucial power electronic devices that convert DC (Direct Current) to AC (Alternating Current) for various applications, such as **renewable energy systems, motor drives, electric vehicles (EVs), and industrial power supplies**. Inverter topologies can be classified into **Single-Level Inverters** and **Multilevel Inverters (MLIs)** based on their output voltage levels and operational complexity. This article presents a **comparative analysis** of different **inverter and multilevel inverter topologies**, evaluating them based on **switching devices, efficiency, THD (Total Harmonic Distortion), component count, control complexity, and applications** in show table. 1 and table.2.

Table.1 Comparison of Single-Level Inverters

Topology	Number of Switches	Output Voltage Levels	Efficiency	Component Complexity	Applications
Voltage Source Inverter (VSI)	4-6	2	High	Moderate	Motor drives, PV inverters, UPS

Current Source Inverter (CSI)	4-6	2	Medium	High	Traction systems, industrial drives
Half-Bridge Inverter	2	2	High	Low	Small UPS, DC-AC converters
Full-Bridge Inverter (H-Bridge)	4	2	High	Medium	Electric vehicles, grid-connected systems

Table.2 Comparison of Multilevel Inverters (MLIs)

MLI Topology	Number of Switches	Harmonic Reduction (THD)	Component Count	Efficiency	Applications
Diode-Clamped (DCMLI/NPC)	High	Moderate	High (Diodes)	Moderate	Industrial Drives, HVDC
Flying Capacitor (FCMLI)	High	High	High (Capacitors)	Moderate	Aerospace, FACTS
Cascaded H-Bridge (CHB-MLI)	Moderate	High	Low	High	Solar, Wind, Electric Vehicles
Modular Multilevel Converter (MMC)	Very High	Very High	High	Very High	HVDC, Large-Scale Renewables
Switched-Capacitor MLI	Low	High	Low	High	PV Inverters, Microgrids
Hybrid MLI	Moderate	Very High	Medium	High	High-Power Converters
GaN/SiC-Based MLI	Low	High	Low	Very High	Aerospace, High-Frequency Applications

5. FIVE LEVEL INVERTER

In modern power electronics, multilevel inverters have become crucial for applications requiring high-power and high-voltage capabilities. Among these, the five-level inverter is a widely used topology that enhances efficiency and reduces harmonics compared to conventional two-level or three-level inverters. The five-level inverter is an extension of the three-level inverter and is often employed in industrial motor drives, renewable energy systems, and grid-connected applications.

Principle of Operation

The fundamental operation of a five-level inverter is based on pulse-width modulation (PWM) techniques or space vector modulation (SVM) to generate the desired AC voltage levels from a DC source. The inverter consists of multiple semiconductor switches and capacitors arranged in a way that produces five distinct output voltage levels: $+V_{dc}$, $+V_{dc}/2$, 0 , $-V_{dc}/2$, and $-V_{dc}$. The increased number of levels helps in approximating a sinusoidal waveform more accurately, reducing total harmonic distortion (THD) and improving power quality in show figure.3.

Types of Five-Level Inverters

There are three common topologies used for five-level inverters:

- 1) Diode-Clamped Multilevel Inverter (DCMLI):** This topology uses clamping diodes to achieve voltage level division. It is widely used in high-power applications but requires a large number of clamping diodes, making it complex for higher levels.
- 2) Capacitor-Clamped (Flying Capacitor) Multilevel Inverter (FCMLI):** Instead of diodes, this inverter employs capacitors to stabilize voltage levels. While it offers redundancy and fault tolerance, it has challenges related to capacitor balancing.

- 3) **Cascaded H-Bridge Multilevel Inverter (CHBMLI):** This topology consists of multiple H-bridge cells connected in series, each powered by an isolated DC source. It is simpler in terms of component requirements and provides a modular structure, making it a preferred choice in renewable energy applications.

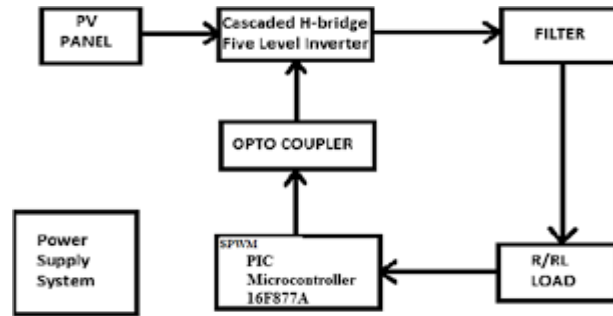


Figure.3 Block diagram of five level inverter

6. MATLAB SIMULATION

In Fig.4, four triangular waves as carrier signals and a sinusoidal wave as a reference signal are generated. Then, each of the carrier waves are compared with the reference signal using a comparator.

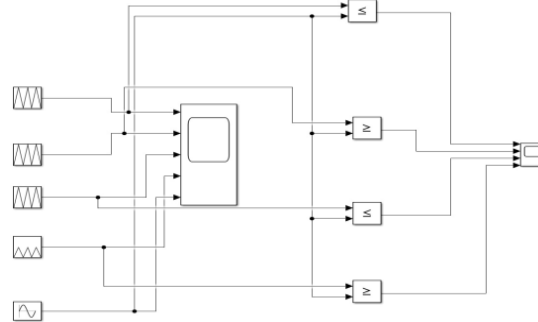


Fig.4 Simulation of PWM Generation Circuit Using MATLAB Simulink

As illustrated in Figure. 5, the proposed model compares four triangular level shifted carrier signals with a sinusoidal reference signal to obtain PWM signals for the switching devices.

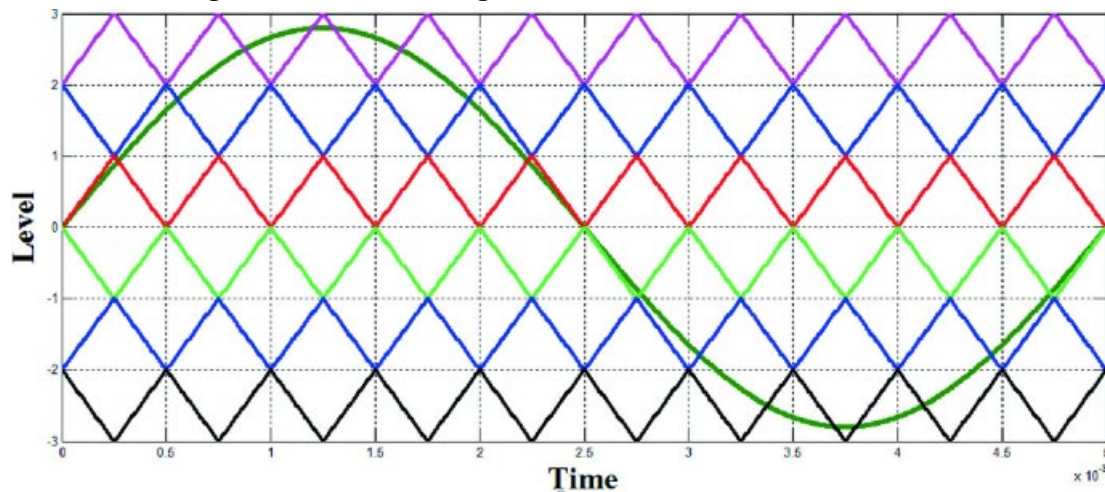


Figure.5 A Comparative Brief Study on Level-Shifted Pulse Width.

7. RESULTS AND DISCUSSION

The performance of multilevel inverters was analyzed based on key parameters such as harmonic distortion, output voltage quality, switching losses, and efficiency. The experimental and simulation results demonstrate that multilevel inverters offer a significant improvement in power quality compared to conventional two-level inverters. The reduction in total harmonic distortion (THD) is one of the most critical advantages observed, ensuring a smoother sinusoidal output waveform, which is essential for sensitive industrial and renewable energy applications.

The output voltage waveform of the multilevel inverter exhibited lower distortion levels, as confirmed by the Fourier analysis. Compared to conventional inverters, which often exhibit higher THD due to abrupt voltage transitions, multilevel inverters produce stepped voltage waveforms that approximate the sinusoidal shape more effectively. The simulations revealed that as the number of voltage levels increased, the harmonic content decreased substantially. This characteristic is particularly beneficial for applications requiring high power quality, such as motor drives and grid-connected renewable energy systems.

Switching losses were another parameter analyzed in the study. The results indicate that multilevel inverters operate with reduced switching frequency per device, leading to lower switching losses. This improvement is due to the fact that the power semiconductor devices in a multilevel inverter experience less stress, distributing the voltage among multiple levels rather than subjecting a single switch to high voltage transitions. Consequently, this leads to improved thermal performance and longer lifespan of power electronic components.

Efficiency analysis showed that multilevel inverters exhibit higher efficiency compared to their two-level counterparts. The decrease in harmonic losses, combined with optimized switching strategies, contributed to an overall enhancement in system performance. The efficiency gains were particularly noticeable in medium- and high-power applications, where switching losses and power dissipation significantly impact the overall system reliability and cost-effectiveness.

Another aspect investigated was the inverter's ability to handle different load conditions. Under varying load conditions, the inverter maintained stable voltage and current waveforms, demonstrating its robustness and adaptability. This feature is crucial for applications such as electric vehicle drives, where dynamic load changes occur frequently. Furthermore, the ability of multilevel inverters to integrate seamlessly with renewable energy sources was also highlighted, as their stepped output voltage reduces the filtering requirements, thereby minimizing additional system costs.

While the results confirm the superiority of multilevel inverters in terms of performance and efficiency, a few challenges remain. The increased number of power switches and the complexity of control algorithms introduce design and implementation challenges. Advanced pulse width modulation (PWM) techniques, such as space vector modulation, have been explored to enhance performance further, but their computational complexity can be a limiting factor in real-time applications.

8. CONCLUSION

Inverters and multilevel inverters play a crucial role in modern power electronics by enabling efficient energy conversion and improving power quality. Traditional inverters are widely used for converting DC power to AC in various applications, including renewable energy systems, motor drives, and industrial automation. However, multilevel inverters offer significant advantages over conventional inverters, such as reduced harmonic distortion, lower electromagnetic interference, and improved voltage control.

The advancements in power semiconductor devices and control techniques have further enhanced the performance and efficiency of inverters. Multilevel inverter topologies, such as diode-clamped, flying capacitor, and cascaded H-bridge configurations, have enabled higher voltage operation with reduced stress on switching devices. These innovations contribute to the widespread adoption of multilevel inverters in applications like high-power industrial drives, grid-connected renewable energy systems, and electric vehicles.

As power electronics continue to evolve, research and development in inverter technology focus on improving efficiency, reliability, and cost-effectiveness. The integration of artificial intelligence and advanced modulation techniques holds great promise for the future of inverters, making them more intelligent and adaptable to modern energy

demands. Ultimately, the continuous improvements in inverter technology will drive the advancement of sustainable energy solutions and efficient power management systems.

CONFLICT OF INTERESTS

None.

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None.

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