MPC-Controlled Hybrid Solar and Battery Storage System with MMCTechnology

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Abstract: *This paper presents a Model Predictive Control (MPC)-based strategy for a Hybrid Modular Multilevel Converter (MMC)-integrated Photovoltaic (PV) and Battery Energy Storage System (BESS). The proposed control approach optimizes power management, ensuring stable grid integration and enhanced dynamic performance. The MMC topology offers superior scalability, reduced harmonics, and improved fault tolerance, making it an ideal choice for renewable energy applications. The MPC strategy enhances voltage balancing, stability and optimally distributes power between PV and BESS, improving overall system efficiency. A detailed MATLAB-based simulation validates the effectiveness of the proposed system, demonstrating improved power quality, transient response, and operational flexibility. The results confirm the feasibility of MPC-controlled hybrid MMC technology for future smart grid applications.*

Keywords: *Model Predictive Control, Modular Multilevel Converter, Photovoltaic System, Battery Energy Storage, Hybrid Renewable System, Power Quality*

I. INTRODUCTION

To fulfill the huge energy requirement and minimize reliance on fossil fuel for electricity production because of its adverse environmental implications, the trend worldwide is to embrace a sustainable energy mix and enhance the share of distributed energy resources (DER). The rapid depletion of fossil fuel reserves, along with their negative impact on the environment in terms of greenhouse gas emissions, air pollution, and global warming, necessitates the transition to renewable energy sources. Solar photovoltaic (PV) and wind energy have emerged as the most promising renewable technologies, offering clean, sustainable, and cost-effective electricity generation.

In 2016, the electricity generated from renewable energy sources accounted for 15.6% of the entire electricity production in the United States.Specifically, solar photovoltaic (PV) energy saw its boost over the last decade, whereby 47% of new installed renewable power capacity worldwide in 2016 was from Solar PV energy. This fast growth of PV energy is mainly being propelled by PV module price reductions, advances in technology, governmental incentives, and growing public awareness regarding renewable energy. Even with the tremendous economic and environmental benefits of this high growth of solar PV penetration, implementation of PV energy is confronted by a number of challenges. Among these issues, intermittency, uncertainty, and performance limits require sophisticated power electronics solutions to optimize the capture of solar energy at any time. The intermittency of solar PV generation causes serious issues in power system stability.

As PV power is solar irradiance dependent, cloud transients and shading can result in significant power output fluctuations.These fluctuations induce voltage flicker, frequency deviations, and other power quality problems, which, if not properly controlled, can cause grid instability. The growing penetration of solar PV

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energy into power grids requires effective energy management techniques to counteract the negative impacts of fluctuating power output.

Among various solutions given in the literature to solve the intermittency issues of PV systems, the integration of battery energy storage systems (BESS) with PV systems has been found to be the most effective solution. BESS can buffer power variations, store energy at times when solar generation is high, and provide power during low or zero sunlight hours. In addition, BESS assists in voltage regulation and load balancing, hence improving the efficiency and reliability of the power grid. It is important that PV and BESS are integrated smoothly for ensuring a stable, robust, and efficient power system. There are various power electronic solutions capable of integrating solar PV systems and BESS. But most traditional topologies consist of several stages of power electronic conversion, which results in higher energy losses, more components, a higher cost, and a lower overall system efficiency. The traditional approaches also need sophisticated control methods and higher maintenance activity, thus rendering them less suitable for large-scale implementation. Thus, a better, more integrated power electronics solution with higher efficiency is needed to regulate and manage PV and BESS simultaneously. One of the best potential solutions to integrating PV and BESS without interruptions in the system is through the use of Modular Multilevel Converters (MMC). MMC has proved to be an emerging power electronic topology with outstanding performance, modularity, scalability, and efficiency. MMC is a newly established converter technology which has found widespread use in high-voltage direct current (HVDC) transmission, medium-voltage motor drives, and grid integration of renewable energy resources as well. Unlike traditional power electronic options for PV arrays, e.g., multi-string and central inverters, the MMC possesses multiple benefits in comparison, e.g., decreased losses of energy, increased tolerance of faults, diminished harmonic distortion, and eradication of huge step-up transformers with reduced cost, leading to the efficiency enhancement of the system in general.

These characteristics have encouraged investigators to investigate and design novel MMC configurations for exclusive use in DER integration, such as PV and BESS. MMC facilitates direct operation at medium- or high-voltage levels, minimizing the number of stages required for conversion and hence enhancing overall power conversion efficiency. Additionally, MMC's modularity by nature provides flexibility in expansion, making it the best fit for utility-scale renewable integration. Individual control of each submodule in the MMC gives better voltage balancing, improved dynamic performance, and better fault-handling properties.

For optimal MMC-based Phototvoltaic and BESS integration, the efficient control approach has to be implemented. Most efficient among those is Model Predictive Control (MPC). MPC is an efficient, robust advanced control approach predicting system dynamic behavior and optimal computation of real-time switching action in order to realize multiple control goals. MPC is particularly well-suited for MMC applications since it has fast dynamic response, lower computational complexity, and better voltage and current regulation. In contrast to traditional control techniques, MPC is able to address multiple constraints at once, allowing for more effective power sharing between BESS and PV, and guaranteeing stable grid integration.

The application of MPC-controlled hybrid MMC-based PV and BESS systems has been widely investigated in recent years with encouraging efficiency, reliability, and operating flexibility outcomes. Simulation studies conducted using MATLAB have proven the viability of the strategy in improving power quality, reducing voltage fluctuation, and maintaining transient response under changing solar conditions.

II. STRUCTURE OF MMC BASED PV

The growing use of solar photovoltaic (PV) systems calls for efficient and dependable power conversion technologies to provide seamless grid connection. Modular Multilevel Converter (MMC) has become a prospective solution for high-power applications based on its modularity, scalability, and improved power quality. MMC is well-suited for the connection of solar PV systems with medium voltage and high-voltage grids, achieving better efficiency and lesser harmonic distortion. In comparison with traditional two-level and three-level converters, MMC provides better voltage waveform quality, minimizing the use of large filters and improving grid compatibility.

One of the major functions of MMC in the grid integration of solar PV is to achieve the process of DC-to-AC conversion. Solar PV installations produce direct current (DC) power, which has to be converted to alternating current (AC) to transmit and distribute.

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MMC helps achieve the conversion while preserving high efficiency with less power loss. In addition, it facilitates matching the voltage levels between the grid and the PV system for smooth power transfer. The MMC can also assist in reactive power compensation, which is important to ensure voltage stability. The benefits of MMC for solar PV are many. It offers high modularity, and it is simple to expand as well as tolerate faults. The distributed submodule design provides improved redundancy and less effect from component failure on system operation as a whole. The second important advantage is improved harmonic performance based on the multilevel voltage synthesis, and this leads to lower total harmonic distortion (THD). Furthermore, MMC-based systems have less switching loss than traditional converters, which means that overall 8 efficiency is improved. Also, the minimized stress on the DC-link voltage eliminates the necessity of large and costly energy storage capacitors, thus compacting and increasing the reliability of the system.

To ensure the efficient operation of MMC in solar PV grid integration, various control strategies are employed. Model Predictive Control (MPC) is one such approach that enhances dynamic performance while optimizing computational efficiency. Moreover, advanced fault detection and protection mechanisms are implemented to safeguard the system against voltage fluctuations and grid disturbances, ensuring stable and uninterrupted operation.

Fig 1 is a Modular Multilevel Converter (MMC)-based PV and Battery Energy Storage System (BESS) integration. The converter leg a is depicted to clearly show the converter details and notation. It is composed of PV submodules (top and bottom) and BESS submodules (middle) in series in the MMC phase arms. The PV submodules produce DC power from sunlight, whereas the BESS submodules store and control energy flow. Inductors (L) and resistors (R) are utilized to control power flow and minimize harmonic distortion. This setup improves grid stability and enhances power quality for hybrid renewable energy systems.Despite its advantages, MMC-based solar PV integration has certain challenges. One of the major issue is the complexity of control algorithms required for managing multiple submodules,requiring advanced monitoring, diagnostic strategies.and maintaining voltage balance.It need for sophisticated fault detection and protection mechanism.The real time computation requirments for large-scale systems can be demanding, necessitating high-performanceprocessors and optimization techniques. Additionally, the initial cost of MMC implementation is relatively higher than traditional inverters, although this is offset by the long-term benefits of improved efficiency and reliability.

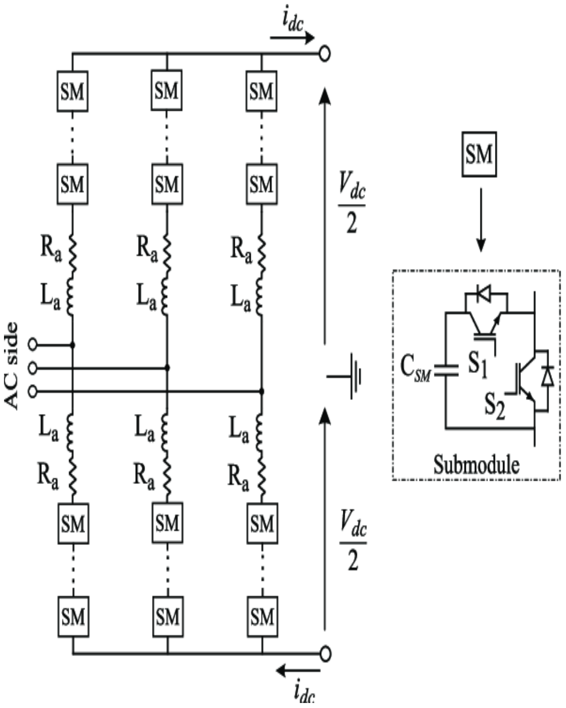

FIGURE1.Strucutre of the MMC-Based PV-BES

III. UTILITYSCALE PV AND BATTERY STORAGESYSTEMS

The combination of utility-scale Photovoltaic (PV) systems with high-capacity Battery Energy Storage Systems (BESS) is a paradigm shift in the generation, management, and utilization of electricity. These large-scale deployments play a crucial role in revolutionizing the energy landscape, allowing for a more resilient, sustainable, and efficient electrical grid. Utility-scale PV installations, with their large land areas and high generating capacity, are engineered to generate electricity on a large scale, directly supplying the high-voltage transmission grid. These facilities comprise large arrays of solar panels, inverters, and related infrastructure, converting sunlight into electrical power. The main goal of such systems is to make a significant contribution to the total supply of electricity and thus decrease the dependence on conventional fossil fuel-powered power plants as well as help curb greenhouse gas emissions. Further, with economies of scale gained in large scale projects, utility-scale PV plants can

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provide a lower levelized cost of electricity, and thus solar energy is becoming more and more competitive compared to traditional sources of energy. Yet, the natural variability of solar electricity generation, which varies according to weather conditions and daily cycles, represents a major challenge for grid managers responsible for ensuring a stable balance between supply and demand for electricity.

This is where the role of Battery Energy Storage Systems becomes essential. Through the integration of BESS with utility-scale PV systems, grid operators have the capability to effectively mitigate the intermittency of solar power and realize a multitude of advantages for the electrical grid. BESS serves as a vital buffer, collecting surplus solar energy when production is high and releasing it when production is low or demand is high, thus evening out the variability of the solar output and providing a more stable and predictable electricity supply. In addition to merely balancing demand and supply, BESS serves a critical function in fortifying grid stability and reliability. Such systems offer critical grid services like frequency regulation, facilitating the instant injection or absorption of power to stabilize the grid frequency, which is critical for ensuring the quality and reliability of electric supply. BESS also offers voltage support, controlling voltage levels within tolerable limits to avoid voltage sags and swells that can ruin electrical equipment and cause operational disruption.

Additionally, in the case of a grid loss of power, BESS is able to deliver black start capability, providing the first power needed to drive the restoration of the electrical system. Aside from these stability services, BESS makes peak shaving and load leveling possible, alleviating peak demand on the grid by releasing stored energy during peak times of electricity use. This lowers the cost of electricity for consumers and reduces the demand for costly and sometimes less efficient peak power facilities that run on a part-time schedule. Inclusion of BESS is also critical in making possible the large scale integration of renewable energy sources such as solar and wind power to provide for higher penetrations of such intermittent resources into the grid through managing to overcome the problems of their variability. BESS further facilitates energy arbitrage, whereby energy can be stored during times of low electricity prices and sold back to the grid at times of high prices, generating potential revenue and maximizing energy market operations. In addition, BESS can help defer infrastructure investment by supplying grid support services, which can delay or even avoid the necessity of expensive upgrades to transmission and distribution infrastructure.

Even with the significant advantages delivered by utility-scale PV and storage systems, however, there continue to be limitations and issues to be overcome. The upfront costs of capital related to these systems can be prohibitive, but these costs are falling rapidly thanks to technological and market development. Large-scale PV systems take big land areas, which can introduce issues around land use, projected environmental effects, and community reception. Connecting these large-scale systems to the current electrical grid can be a complicated process, sometimes involving extensive infrastructure upgrades and meticulous planning to maintain grid stability and reliability. The development and implementation of these systems also rely on the existence of transparent and conducive regulatory frameworks that encourage investment and make grid integration possible. Lastly, BESS performance and economics are directly related to the underlying battery technology, and research and development activities continue to emphasize enhancing battery energy density, cycle life, safety, and overall performance. The prospects for utility-scale PV and storage systems are rosy, with a number of key trends defining their continued development and deployment. Both PV and battery storage costs will continue to move downward.

IV. MODEL PREDICTIVE CONTROL SCHEME FOR MMC

The basic operation of MPC follows three primary steps: prediction, optimization, and implementation. As a first step, the mathematical model of system dynamics of MMC is represented based on state-space equations that express submodule capacitor voltage behavior, arm currents, and circulating currents. Based on these equations, a model of future states of MMC is predicted within a finite horizon based on potential switching actions. A cost function is then established to measure the performance of the system, which can involve goals such as minimizing tracking errors at present, balancing capacitor voltages, minimizing switching losses, and minimizing total harmonic distortion (THD). Lastly, the optimal control action is computed by solving the optimization problem, and the respective gate signals are applied to the MMC.

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Fig 2 demonstrates a Model Predictive Control (MPC) approach to a Modular Multilevel Converter (MMC), focusing on predictive modeling, optimization, and voltage ordering. The block MMC symbolizes the converter in which switching states are regulated on the basis of measured voltage and current. They are inputted into the Predictive Model for the MMC to model the behavior of the system with mathematical representations. The output of the predictive model is then computed in the Cost Function Optimization block, where an optimization algorithm picks the best switching states by optimizing a given cost function (power loss, voltage imbalance, or total harmonic distortion). The optimized number of inserted Submodules (SMs) is calculated and forwarded to the Voltage Sorting Algorithm, where appropriate SMs are selected to be inserted or bypassed in order to maintain suitable voltage balancing. Lastly, the sorted voltage levels and optimized switching states are returned to the MMC,

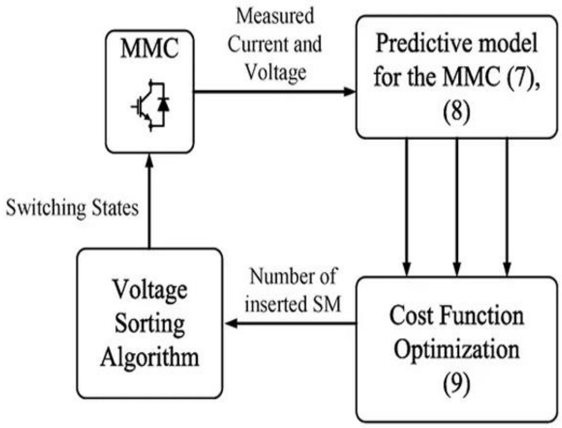

FIGURE 2.model predictive control scheme for MMC.

With the aim to guarantee stable operation with low losses and with better performance. This control loop provides a better efficiency, dynamic response, and power quality of the MMC-based system and is hence a good selection for applications including grid-connected renewable energy integration and high-voltage DC transmission systems.

V . PROPOSED BLOCK DIAGRAM

A Hybrid Modular Multilevel Converter (MMC)-based Photovoltaic (PV) and Battery Energy Storage System (BESS) integrates renewable energy generation with efficient energy storage to ensure a stable and reliable power supply. Figure 4.2 represent the block diagram of simulation.

Fig 3 presents an MPC-based Hybrid Solar Photovoltaic (PV) and Battery Energy Storage System (BESS) that is integrated with a Modular Multilevel Converter (MMC) to achieve optimal grid connection. The PV Array is the major source of renewable energy, utilizing solar radiation and transforming it into DC power. As solar power is intermittent, the Dual Active Bridge (DAB) converter is used to control and regulate the power flow between the PV array and the MMC. This provides a controlled and stable DC voltage supply to the converter. For further system stability and reliability, a Battery Energy Storage System (BESS) is integrated, offering backup power and dampening fluctuations due to changing solar irradiation. The BESS is interfaced directly with the MMC, with bidirectional power flow to enable energy management and grid stability.

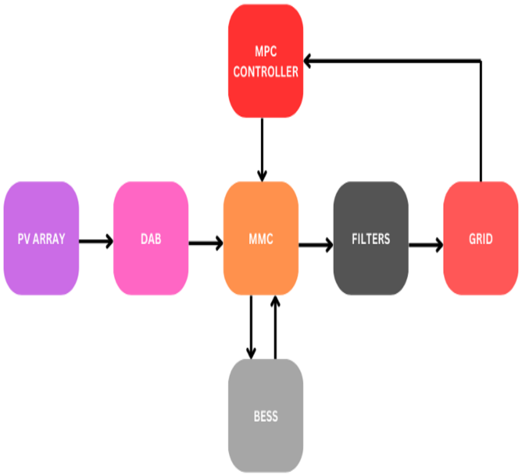

FIGURE 3. Proposed Block diagram

The Modular Multilevel Converter (MMC) is pivotal in the transformation of the DC power from the PV array and the BESS to AC for grid connection. There are various advantages of MMC technology, such as the ability to be modularity scaled, low switching losses, high efficiency, and better power quality. MMC is also capable of high-voltage operation without the use of transformers and is hence a better choice for utility applications. The MPC Controller controls the MMC by forecasting system dynamics and maximizing switching

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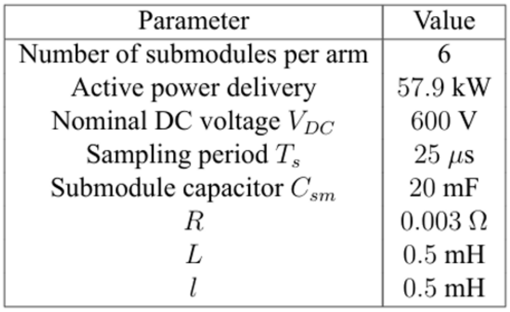
states for better performance, lower power loss, and improved voltage balancing.To provide grid compliance and power quality, filtering stages are inserted prior to providing power to the grid.



Parameter	Value
Number of submodules per arm	6
Active power delivery	57.9 kW
Nominal DC voltage V_{DC}	600 V
Sampling period T_s	25 μs
Submodule capacitor C_{sm}	20 mF
R	0.003 Ω
L	0.5 mH
l	0.5 mH

TABLE 1. Parameters of MMC

VI. SIMULATION

The proposed three-phase Modular Multilevel Converter (MMC) based Photovoltaic and Battery Energy Storage System (PV-BESS) is simulated in the MATLAB/Simulink software environment. The system is tested under various operating conditions to evaluate its performance and demonstrate the effectiveness of the proposed control strategies. The MMC PV-BESS topology consists of six Submodules (SMs) per arm, with each SM directly connected to an individual PV module, enabling distributed power generation and modular scalability.

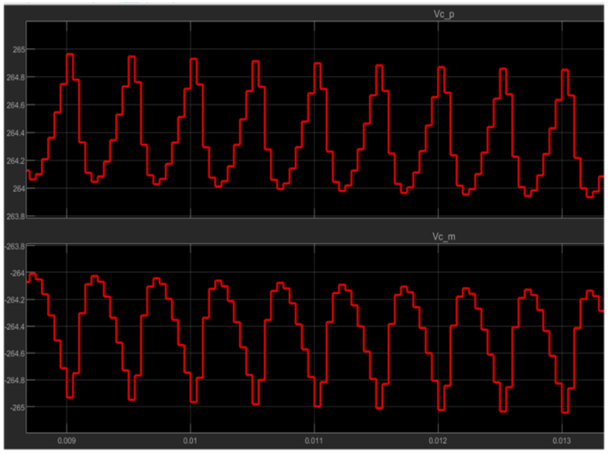


FIGURE 4. MMC output

Figure 4. Represent’s The Modular Multilevel Converter (MMC) output.It is a multi-level power converter that produces an approximate sinusoidal output voltage by synthesizing multiple voltage levels from its submodules (SMs). The MMC output characteristics depend on the number of levels.

FIGURE 5. Grid Voltage

Figure 5 represent the grid output representing the three phases and It is maintained constant using the PV and Battery energy storage system.

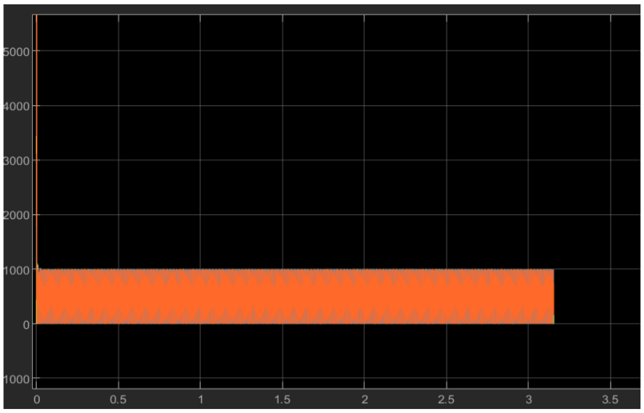


FIGURE 6. DefficientPower supplied to the Grid by PV during Peak load

The figures 6 represents a deficient power supplied by the PV to the Grid during peak load condition. The stable power level and voltage level suggests that the PV system is effectively compensating for increased grid demand.

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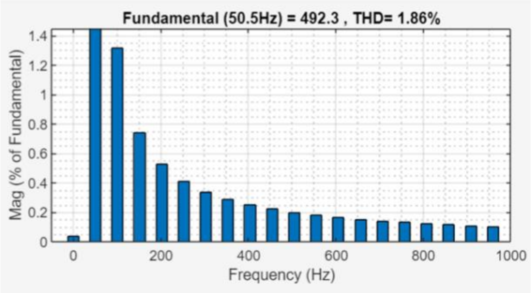

FIGURE 7.FFT Analysis of the proposed model

The graph 4.1 illustrate FFT (fast fourier transform) of MPC controller The Total Harmonic Distortion (THD) value value in a Hybrid MMC-Based Photovoltaic and Battery Energy Storage System (PV-BESS) will decrease to low value as compared to P/PI/PID controllers.The total harmonic distortion(THD) will depend on parameters such as number of submodules,controller used, and grid conditions.

System configuration	Control method	Practical THD value
MMC-PV System(Without MPC)	PI/PID	5% - 10%
HYBRID MMC-PV-BESS	PI/PID	4% - 8%
Hybrid MMC – PV- BESS with MPC	MPC	1% - 3%
IEEE Standard for grid iconnection	-	< 5 %

Table 2 THD values using different stratagies

Table 2 highlights a significant enhancement in power quality achieved through the proposed control method. In the conventional model using P/PI/PID controllers, the Total Harmonic Distortion (THD) is will be upto 10% indicating a high level of harmonic interference in the system. However, by implementing the Model predictive algorithm , the THD is significantly reduced to 1.86 %, resulting in a waveform that is nearly sinusoidal.

VII .CONCLUSION

The Hybrid Modular Multilevel Converter (MMC)-Based Photovoltaic (PV) and Battery Energy Storage System (BESS) is a new technology for the integration of renewable energy sources into the power grid. Utilizing the benefits of MMC topology, this system provides high efficiency, modular scalability, and improved power quality while overcoming the intermittent nature of solar PV generation. The addition of BESS offers energy balancing, peak shaving, and backup power, thus enhancing the stability and dependability of the system in grid-connected operations. The architecture of MMC greatly enhances power conversion through the minimization of harmonic distortion, switching losses, and voltage stress, thus increasing overall system performance. The Model Predictive Control (MPC), further optimize system operation through submodule voltage balancing, and real-time power management. All these features render MMC a better choice compared to conventional converters, particularly in high-voltage and high-power applications.This hybrid system is essential in contemporary power systems, especially in smart grids, microgrids, and renewable energy integration.By facilitating a more efficient and flexible energy system, it leads to better grid stability, better utilization of renewable energy, and less dependence on traditional fossil fuel-based generation.With continued improvement in power electronics, control software, and energy storage devices, Hybrid MMC-based PV-BESS systems will remain a major enabler for a more sustainable and robust power grid in the future.

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