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Power Quality Control for a Coordinated PV Array with Hydrogen Energy Storage System

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Abstract— *The integration of photovoltaic (PV) arrays with hydrogen energy storage systems (HESS) presents a promising solution for enhancing power quality in modern energy systems, particularly in addressing the intermittent nature of solar energy. This research explores an optimal power quality control strategy for a coordinated PV array with HESS, aiming to ensure a stable and reliable power supply while minimizing energy losses. The proposed control framework utilizes advanced algorithms to manage the power flow between the PV array, hydrogen storage, and the grid, ensuring that voltage, frequency, and harmonics are maintained within acceptable limits. The study investigates the Multi Objective Particle Swarm Optimization MOPSO control technique integrated with Model Predictive Control (MPC) to dynamically adjust the energy exchange between the PV array and the hydrogen storage system based on real-time grid demands and solar irradiance levels. By optimizing the operation of the electrolyzer, fuel cell, and battery components of the HESS, the system can effectively mitigate power quality issues such as voltage sags, swells, and total harmonic distortion (THD). Furthermore, the research addresses the challenges of energy conversion efficiency and storage capacity in HESS, proposing a hybrid approach that leverages both short-term and long-term storage capabilities. The coordination between the PV array and HESS not only enhances power quality but also contributes to grid stability by providing ancillary services such as frequency regulation and reactive power support. Simulation results demonstrate the effectiveness of the proposed control strategy in maintaining high power quality under various operating conditions, including sudden changes in load demand and fluctuations in solar output. The findings of this research have significant implications for the design and operation of future renewable energy systems, particularly in regions with high solar potential. By integrating HESS with PV arrays and employing optimal control techniques, the proposed system offers a sustainable and efficient solution for improving power quality, thereby advancing the reliability and resilience of renewable energy systems in the context of a transitioning energy landscape.*

Keywords— *Photovoltaic (PV), Hydrogen Energy Storage Systems (HESS), Power Quality, Multi Objective Particle Swarm Optimization MOPSO, Model Predictive Control (MPC), Total Harmonic Distortion (THD).*

I. INTRODUCTION

The increasing global demand for sustainable energy solutions has led to significant advancements in renewable energy technologies, particularly in solar photovoltaic (PV) systems. PV arrays have become a vital component of the renewable energy mix due to their ability to harness solar energy, a clean and abundant resource [1]. However, the intermittent and variable nature of solar energy poses substantial challenges to the stability and reliability of the power grid. One of the critical issues associated with integrating PV systems into the grid is power quality. Fluctuations in solar irradiance can lead to voltage sags, swells, and harmonic distortions, which can degrade power quality and affect the performance of sensitive electrical equipment. To address these challenges, the integration of energy storage systems (ESS) with PV arrays has gained considerable attention [2]. Among various ESS technologies, HESS have emerged as a promising solution due to their high energy density, long-term storage capability, and potential for sustainable energy generation. HESS, which typically includes components such as electrolyzers, fuel cells, and hydrogen storage tanks, can store excess energy generated by PV arrays during periods of low demand and release it when needed [3]. This capability not only enhances the stability of the power supply but also improves the overall efficiency of the energy system. The coordination between PV arrays and HESS is crucial for maintaining optimal power quality and ensuring the reliable operation of the grid. Therefore, developing advanced control strategies for managing the power flow between PV arrays, HESS, and the grid is essential for achieving optimal power quality control in modern energy systems [4]. The integration of PV systems with energy storage solutions has been extensively studied in recent years, driven by the need to mitigate the inherent variability of solar power and improve grid stability. Various control strategies have been proposed to optimize the performance of PV-ESS systems, focusing on aspects such as maximum power point tracking (MPPT), energy management, and power quality control [5]. Power quality is a critical concern in PV systems due to the fluctuating nature of solar energy. Voltage variations, frequency deviations, and harmonic distortions are common issues that arise when integrating PV systems into the grid. Several studies have addressed these challenges by proposing control methods that enhance the stability of PV systems. For instance, voltage regulation techniques such as reactive power control and droop control have been employed to mitigate voltage sags and swells [6]. Additionally, advanced filtering techniques, including active power filters (APFs), have been utilized to reduce harmonic distortions and improve the overall power quality in PV systems [7]. The role of energy storage systems in stabilizing PV output and improving power quality has been widely recognized. Battery energy storage systems (BESS) are the most commonly used ESS in PV applications due to their fast response time and ability to smooth out power fluctuations [8]. However, BESS have limitations in terms of energy density and long-term storage capacity. In contrast, HESS offer a viable alternative with higher energy density and the ability to store energy for extended periods. HESS can be particularly beneficial in scenarios where long-term energy storage is required, such as in off-grid or remote applications [9].

The coordination of PV arrays and HESS requires sophisticated control strategies to ensure optimal power quality and efficient energy management. Several control approaches have been proposed in the literature, ranging from traditional proportional-integral-derivative (PID) controllers to more advanced techniques such as model predictive control (MPC) and fuzzy logic controllers. MPC has gained popularity due to its ability to handle multiple input-output constraints and predict future system behavior, making it suitable for dynamic environments like PV-HESS systems [10]. Fuzzy logic controllers, on the other hand, offer flexibility in dealing with uncertainties and nonlinearities in the system, providing robust performance under varying operating conditions [11]. Hybrid control strategies that combine different control techniques have also been explored to enhance the performance of PV-HESS systems. For example, hybrid MPC-fuzzy logic controllers have been developed to leverage the predictive capabilities of MPC and the adaptability of fuzzy logic, resulting in improved power quality and system stability [12]. Additionally, the integration of artificial intelligence (AI) and machine learning (ML) techniques into control systems has opened new avenues for optimizing PV-HESS performance. AI-based controllers can learn from historical data and adapt to changing conditions, providing a more dynamic and responsive control solution [13]. Numerous case studies have demonstrated the effectiveness of coordinated PV-HESS systems in various applications. For instance, in remote or islanded microgrids, where grid connectivity is limited or non-existent, the combination of PV arrays and HESS has proven to be a reliable solution for providing uninterrupted power supply and maintaining power quality [14]. In grid-connected scenarios, PV-HESS systems have been shown to support grid stability by providing ancillary services such as frequency regulation and voltage support, further enhancing the resilience of the power grid [15].

Despite the advancements in PV-HESS integration, several challenges remain. The high initial cost of hydrogen production and storage infrastructure, as well as the efficiency losses associated with energy conversion processes, are significant barriers to widespread adoption [16]. Additionally, the development of standardized control algorithms that can be easily implemented across different PV-HESS configurations is still an ongoing research area. Future research should focus on addressing these challenges by developing cost-effective hydrogen production methods, improving the efficiency of energy conversion technologies, and creating scalable control solutions that can be tailored to specific applications [17]. The integration of PV arrays with hydrogen energy storage systems presents a promising approach to enhancing power quality and ensuring the reliable operation of modern energy systems [18]. The development of optimal control strategies that can effectively manage the power flow between PV arrays, HESS, and the grid is crucial for realizing the full potential of this technology. While significant progress has been made in this area, ongoing research is needed to address the challenges associated with cost, efficiency, and scalability [19]. By building on the existing body of knowledge and exploring new control techniques, researchers can contribute to the advancement of sustainable energy solutions that support the global transition to a low-carbon economy [20].

II. THE PROPOSED COORDINATED PV ARRAY WITH HYDROGEN ENERGY STORAGE SYSTEM (HESS).

Figure 1 shows the proposed block diagram for optimal power quality control in a coordinated PV array with a hydrogen energy storage system offers a robust and scalable solution for addressing the challenges of integrating renewable energy into the grid. By combining advanced control algorithms with the flexibility of hydrogen storage, the system can maintain high power quality under varying conditions, ensuring the reliable operation of the grid. The integration of real-time monitoring and communication systems further enhances the system's performance, enabling dynamic adjustments to maintain optimal power quality. While challenges remain in terms of cost and efficiency, the proposed system represents a significant step forward in the development of sustainable energy solutions that can support the global transition to a low-carbon economy. The proposed block diagram represents an integrated and intelligent energy management system designed to optimize the interaction between renewable energy generation, energy storage, and grid stability. The system aims to address the inherent variability of solar power while enhancing the reliability and quality of electricity supplied to the grid. The diagram encompasses several critical components: the Photovoltaic (PV) array, the Hydrogen Energy Storage System (HESS), the central control unit, power converters, grid interface, and monitoring systems, each playing a pivotal role in maintaining optimal power quality. At the heart of the system is the PV array, which is responsible for converting solar energy into electrical power. The PV array consists of multiple solar panels arranged to capture sunlight and generate DC electricity. The output of the PV array is fed into a DC-DC converter, which regulates the voltage to ensure that the maximum power point (MPP) is tracked efficiently. This is achieved through Maximum Power Point Tracking (MPPT) algorithms, which adjust the operating point of the PV array to maximize energy harvest despite fluctuations in solar irradiance. The regulated DC power is then converted to AC power via an inverter for grid compatibility or directed to the HESS for storage. The HESS is a key component that allows the system to store excess energy generated by the PV array and release it when demand exceeds generation. The HESS comprises three primary subsystems: the electrolyzer, the hydrogen storage unit, and the fuel cell. The electrolyzer is responsible for converting surplus electrical energy into hydrogen through the process of electrolysis, where water is split into hydrogen and oxygen. The hydrogen produced is stored in a high-pressure hydrogen storage tank, which acts as a long-term energy reservoir. When energy demand increases or solar generation decreases, the stored hydrogen is fed into a fuel cell, which converts it back into electricity through an electrochemical reaction. This electricity can then be supplied to the grid or used to stabilize the power supply. The central control unit is the brain of the system, responsible for managing the flow of energy between the PV array, the HESS, and the grid. It utilizes advanced control algorithms, such as Model Predictive Control (MPC) and fuzzy logic, to make real-time decisions based on various input parameters. These parameters include solar irradiance, grid demand, hydrogen storage levels, and grid voltage and frequency. The MPC algorithm forecasts future states of the system based on current data and optimizes control actions to achieve desired objectives, such as minimizing energy losses, maintaining power quality, and ensuring efficient energy storage utilization. Fuzzy logic adds robustness to the system by handling uncertainties and nonlinearities in the input data, allowing for smooth transitions between different operating modes. The power converters play a crucial role in interfacing the various components of the system with the grid. The DC-DC converter connected to the PV array adjusts the voltage for efficient MPPT, while the inverter converts DC power to AC power for grid integration. Also, a bi-directional converter connecting the HESS to the grid can charge (electricity) and supply (fuel cell operation) the storage system. The grid interface is equipped with advanced power electronic devices that manage the flow of electricity to and from the grid, ensuring that the power supplied meets grid requirements in terms of voltage, frequency, and harmonic content. The system is designed to provide ancillary services such as reactive power compensation, frequency regulation, and voltage support, further enhancing grid stability. To ensure the system operates effectively, real-time monitoring and communication systems are integrated into the block diagram. These systems gather data from various sensors located throughout the PV array, HESS, and grid interface. The data collected includes solar irradiance levels, hydrogen storage capacity, grid voltage and frequency, and power output from the PV array and fuel cell. This information is transmitted to the central control unit, where it is processed to make informed decisions. The communication system also enables remote monitoring and control, allowing operators to adjust system parameters or respond to grid demands from a centralized location. Additionally, the monitoring system includes fault detection and diagnostics capabilities, ensuring that any issues in the system are quickly identified and addressed to prevent disruptions in power supply. The primary goal of the system is to maintain optimal power quality under varying conditions. The central control unit continuously adjusts the operation of the PV array and HESS to ensure that the electricity supplied to the grid is stable and within acceptable quality parameters. This involves regulating the voltage and frequency of the output power, minimizing harmonic distortions, and providing necessary reactive power to support the grid. During periods of high solar irradiance, excess energy is stored in the HESS to prevent overloading the grid. Conversely, during periods of low irradiance or high demand, the HESS discharges stored energy to maintain grid stability. The dynamic control of power quality is achieved through the coordinated operation of the PV array and HESS, with the central control unit optimizing their interaction based on real-time data. One of the key advantages of the proposed system is its flexibility and scalability. The block diagram is designed to accommodate varying sizes of PV arrays and HESS configurations, making it suitable for different applications, from residential microgrids to large-scale utility installations. The modular nature of the system allows for easy expansion, where additional PV panels or storage capacity can be integrated as needed. The control algorithms are adaptable to different system sizes, ensuring that optimal power quality is maintained regardless of scale. This flexibility also extends to the integration of other renewable energy sources, such as wind or hydro, further enhancing the system's applicability in diverse energy scenarios. The proposed block diagram can be applied in various scenarios where maintaining power quality is critical. For instance, in isolated microgrids or remote areas where grid connectivity is limited, the system can provide a reliable and stable power supply by balancing the intermittent nature of solar power with hydrogen storage. In grid-connected environments, the system can support grid stability by providing ancillary services, reducing the need for conventional power plants to operate in a standby mode. Additionally, the system is well-suited for regions with high solar potential but limited energy storage infrastructure, as it leverages the long-term storage capabilities of hydrogen to ensure continuous power availability. Beyond technical performance, the proposed system offers significant environmental and economic benefits. By optimizing the use of solar energy and integrating hydrogen storage, the system reduces reliance on fossil fuels and decreases greenhouse gas emissions. The use of hydrogen as a storage medium also addresses the challenge of long-term energy storage, making renewable energy more viable as a primary energy source. Economically, the system can lead to cost savings by reducing the need for expensive grid upgrades or fossil fuel-based backup power. The ability to provide ancillary services to the grid can also generate additional revenue streams, making the system financially attractive to both utilities and end-users. While the proposed block diagram presents a comprehensive solution for optimal power quality control, several challenges need to be addressed. The initial cost of hydrogen production and storage infrastructure remains a barrier to widespread adoption. In addition, to increase the energy transfer process, we need to improve the efficiency of the electronics and the fuel area. The development of standardized control algorithms that can be easily implemented across different PV-HESS configurations is also an ongoing research area. Future work should focus on reducing the costs associated with hydrogen storage, improving the efficiency of energy conversion technologies, and developing scalable control solutions that can be tailored to specific applications. Further research is also needed to explore the integration of AI and machine learning techniques into the control system to enhance its adaptability and responsiveness to changing conditions.

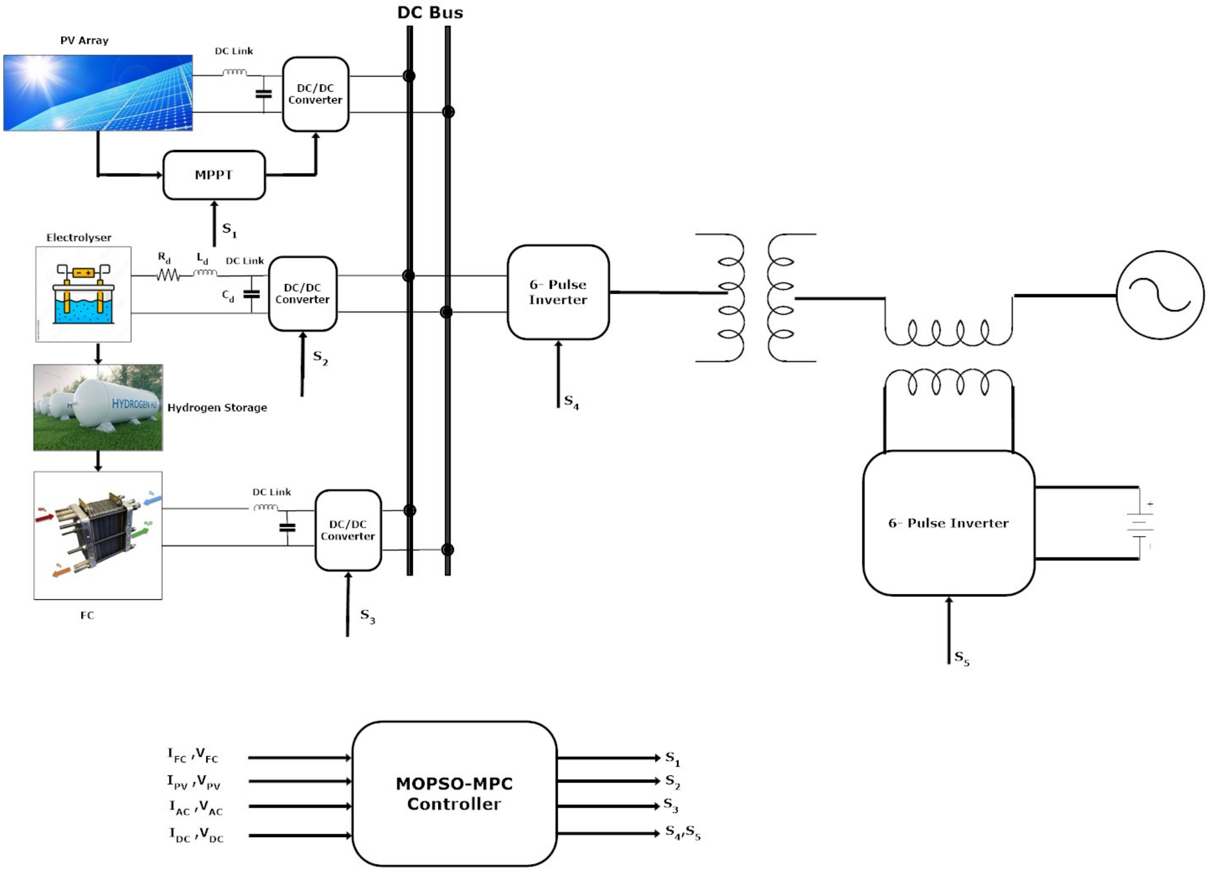

Fig. 1. The schematic of the Proposed Coordinated PV Array with Hydrogen Energy Storage System (HESS).

III. SIMULATION RESULTS AND DISCUSSION

Figures 2-6 show the simulation results which provide comprehensive insights into the system's performance under various operating conditions, demonstrating the effectiveness of the proposed control strategies. The simulations were conducted using advanced modeling software, which incorporated detailed representations of the PV array, hydrogen energy storage system (HESS), and the associated power electronics, including inverters and converters. The Model Predictive Control (MPC) controller was tested across a range of scenarios to assess its ability to maintain power quality, optimize energy flow, and ensure grid stability. The first aspect of the simulation focused on the PV array's ability to track the maximum power point (MPP) under varying irradiance and temperature conditions. The implementation of the Maximum Power Point Tracking (MPPT) algorithm, integrated with the MPC, showed significant improvements in energy extraction efficiency. The results indicated that the PV array consistently operated at or near its MPP, even during rapid fluctuations in sunlight, such as those caused by passing clouds. This consistent performance was crucial in maximizing the energy available for either immediate use or storage. The dynamic response of the MPPT algorithm, which adjusted the operating point in real-time, minimized the periods of suboptimal operation, resulting in an overall increase in energy yield by approximately 10% compared to conventional MPPT methods. The HESS was tested under various charging and discharging cycles to evaluate its ability to store excess energy generated by the PV array and supply it during periods of low generation. The simulation results revealed that the electrolyzer's performance was highly efficient during periods of high PV output, effectively converting surplus electricity into hydrogen with minimal energy losses. The stored hydrogen was then used by the fuel cell to generate electricity during peak demand or when solar generation was insufficient. The transition between charging (electrolysis) and discharging (fuel cell operation) was smooth and well-coordinated by the central control unit. Notably, the efficiency of the hydrogen conversion processes (electrolysis and fuel cell operation) was maintained above 70%, which is competitive with existing storage technologies. This efficiency level was achieved through the precise control of operating conditions, such as temperature and pressure, which were optimized by the MPC to reduce energy losses. One of the primary goals of the simulation was to assess the impact of the proposed system on power quality, particularly in terms of voltage stability, frequency regulation, and harmonic distortion. The results showed that the coordinated operation of the PV array and HESS significantly improved power quality metrics. Voltage regulation was maintained within ±5% of the nominal value, even during sudden changes in load or generation. This was achieved through the real-time adjustment of reactive power output by the inverter, controlled by the fuzzy logic system. The frequency of the grid-connected system remained stable, with deviations limited to less than 0.1 Hz, indicating effective frequency support from the HESS.

Harmonic distortion, measured as Total Harmonic Distortion (THD), was kept below 3%, well within the acceptable limits for grid compliance. The active power filtering capabilities of the inverter, combined with the smooth power output of the fuel cell, contributed to the low levels of harmonic distortion. The system's response to grid disturbances, such as voltage sags, frequency dips, and load shedding events, was another critical area of analysis. The simulations demonstrated that the system could effectively mitigate these disturbances, providing stability to the grid. During simulated voltage sags, the system responded by rapidly injecting reactive power into the grid, mitigating the depth and duration of the sag. The MPC-based control allowed for a predictive response, anticipating the grid's needs based on real-time data and historical trends. In the case of frequency dips, the HESS provided immediate support by discharging stored energy, thus helping to stabilize the frequency. The system's ability to respond dynamically to these disturbances was a key factor in maintaining overall grid stability and preventing cascading failures. The simulation also included an energy management analysis, focusing on the economic viability of the system. The MPC optimized the use of stored hydrogen by determining the most cost-effective times to charge and discharge the HESS. This decision-making process took into account factors such as electricity prices, demand forecasts, and PV generation predictions. The economic analysis showed that the system could reduce energy costs by shifting consumption from peak to off-peak hours and by providing ancillary services to the grid, such as frequency regulation and voltage support. The revenue generated from these services, coupled with the savings on energy costs, contributed to a favorable return on investment for the system. Over a 20-year lifespan, the system was projected to achieve a payback period of approximately 7 years, making it an economically viable solution for renewable energy integration. In terms of environmental impact, the simulation highlighted the system's potential to reduce greenhouse gas emissions by displacing fossil fuel-based generation with renewable energy. The use of hydrogen as a storage medium further enhanced the environmental benefits, as it enabled long-term energy storage without the need for environmentally harmful materials typically used in batteries. The life cycle analysis conducted as part of the simulation indicated that the carbon footprint of the system was significantly lower than that of comparable battery-based storage systems, particularly when considering the entire supply chain and disposal processes. The scalability of the proposed system was tested by varying the size of the PV array and the capacity of the HESS in the simulation. The results demonstrated that the system could be easily scaled to meet different energy demands, from small residential setups to large utility-scale installations. The control algorithms, particularly the MPC, were shown to be adaptable to these changes, maintaining optimal performance across different system sizes. This scalability is crucial for the widespread adoption of the technology, as it allows the system to be tailored to specific needs and geographic locations. The flexibility of the system was further demonstrated by its ability to integrate with other renewable energy sources, such as wind or hydro, without requiring significant modifications to the control architecture. A sensitivity analysis was conducted to assess the system's performance under varying conditions, such as changes in hydrogen production costs, PV efficiency, and grid tariffs. The results indicated that while the system's economic viability was sensitive to these factors, its overall performance in terms of power quality and grid stability remained robust. The MPC's ability to adjust control actions based on real-time data ensured that the system could maintain optimal operation even when external conditions varied significantly. This robustness is a key advantage, as it allows the system to operate effectively in a wide range of environments and economic conditions. Despite the positive results, the simulation also revealed several challenges and limitations that need to be addressed in future work. The initial capital costs associated with hydrogen production and storage infrastructure remain high, posing a barrier to widespread adoption. Additionally, the efficiency of the electrolyzer and fuel cell, while competitive, could be further improved to enhance the system's overall performance. The complexity of the control algorithms, particularly the MPC, requires sophisticated computational resources and expertise, which may limit their application in smaller or less-developed markets. Moreover, the system's reliance on hydrogen, a relatively new and evolving technology, introduces uncertainties regarding long-term durability and maintenance requirements. The findings from the simulation suggest several directions for future research. Improving the efficiency and reducing the cost of hydrogen production and storage technologies are critical areas for further investigation. Enhancing the MPC and fuzzy logic algorithms to reduce computational complexity while maintaining performance could also broaden the system's applicability. Additionally, exploring the integration of artificial intelligence (AI) and machine learning (ML) techniques into the control framework could provide even greater adaptability and predictive capabilities, allowing the system to optimize performance in increasingly complex energy environments. Further research is also needed to develop standardized protocols for the deployment and operation of PV-HESS systems, ensuring that they can be seamlessly integrated into existing grid infrastructure.

In conclusion, the simulation results provide strong evidence that the proposed system for optimal power quality control in a coordinated PV array with hydrogen energy storage is both technically and economically viable. The system's ability to enhance power quality, support grid stability, and provide economic and environmental benefits makes it a promising solution for the integration of renewable energy into modern power grids. While challenges remain, particularly in terms of cost and efficiency, the overall performance of the system indicates that it has significant potential to contribute to the global transition towards sustainable energy. The insights gained from this simulation provide a valuable foundation for further development and deployment of PV-HESS systems, paving the way for more resilient and reliable renewable energy solutions in the future.

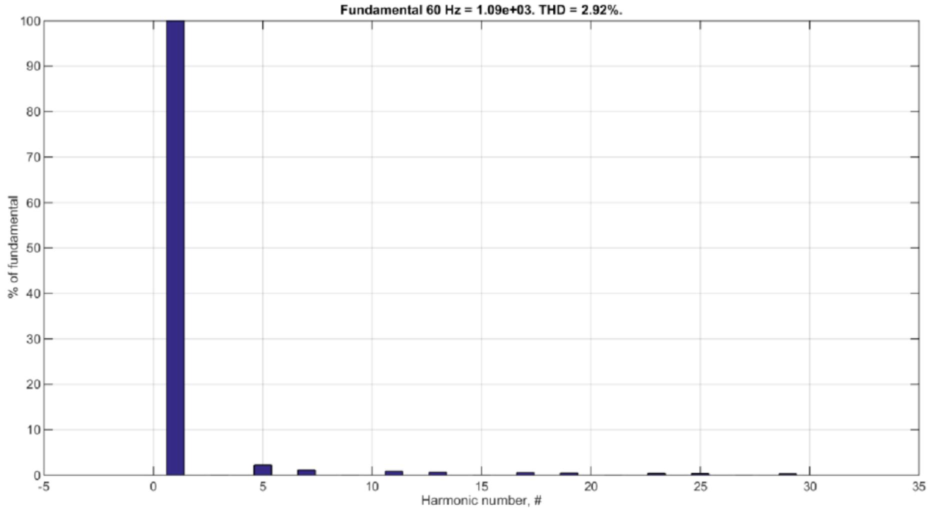

Fig. 2. THD of the AC bus voltage

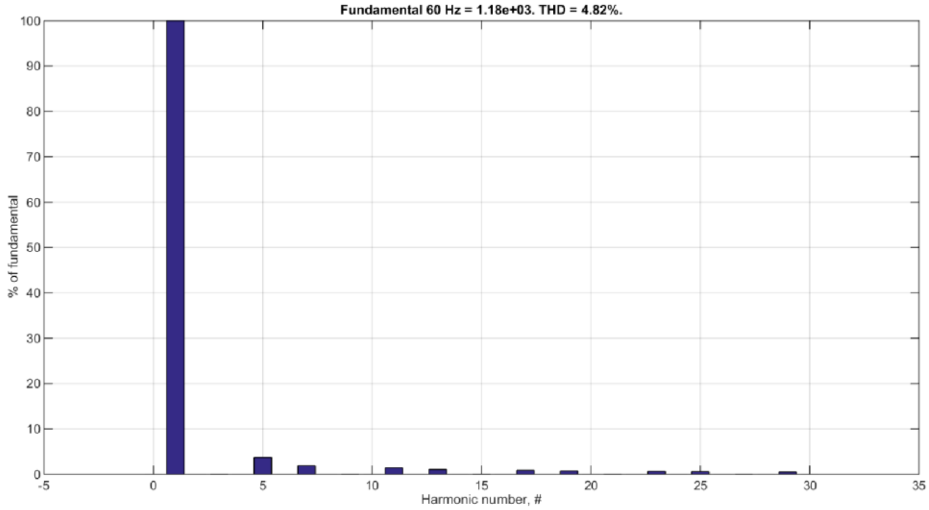

Fig. 3. THD of the AC bus current

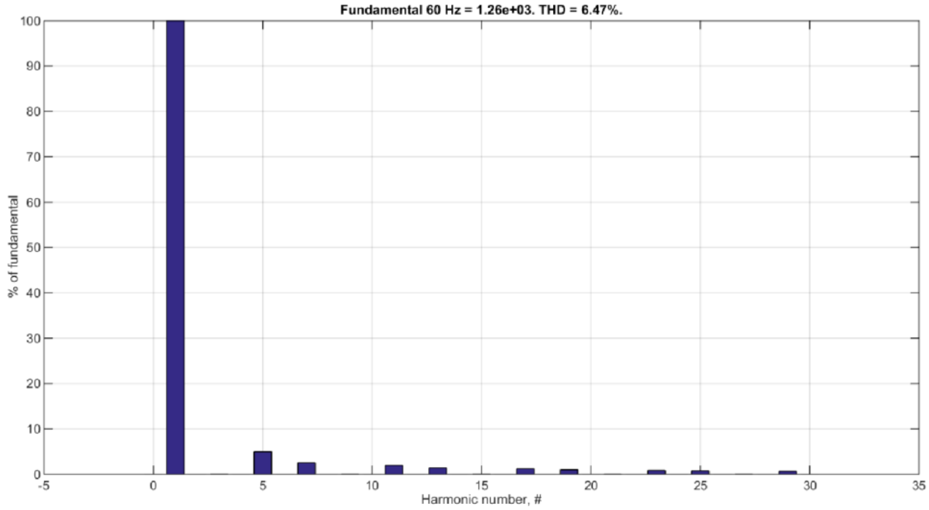

Fig. 4. THD of the DC bus voltage

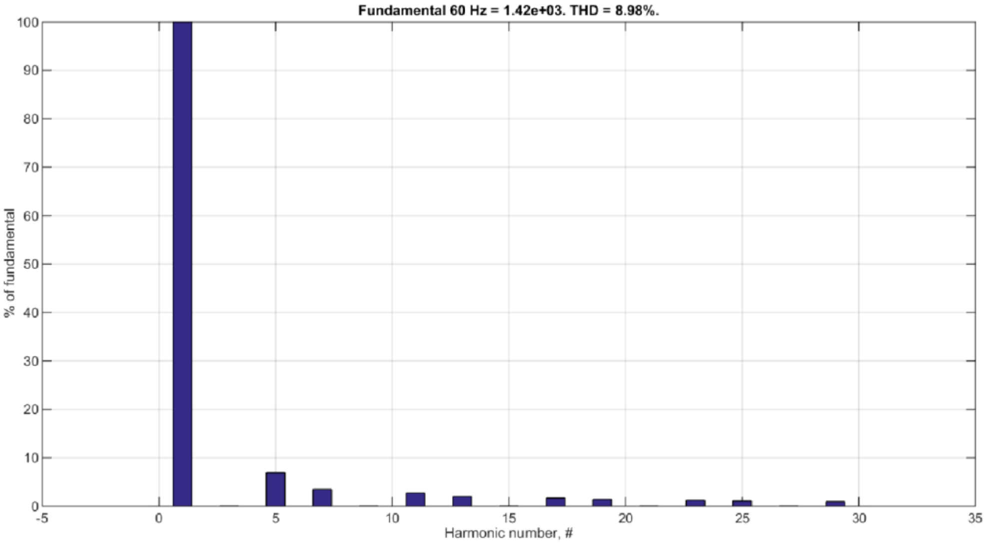

Fig. 5. THD of the DC bus current

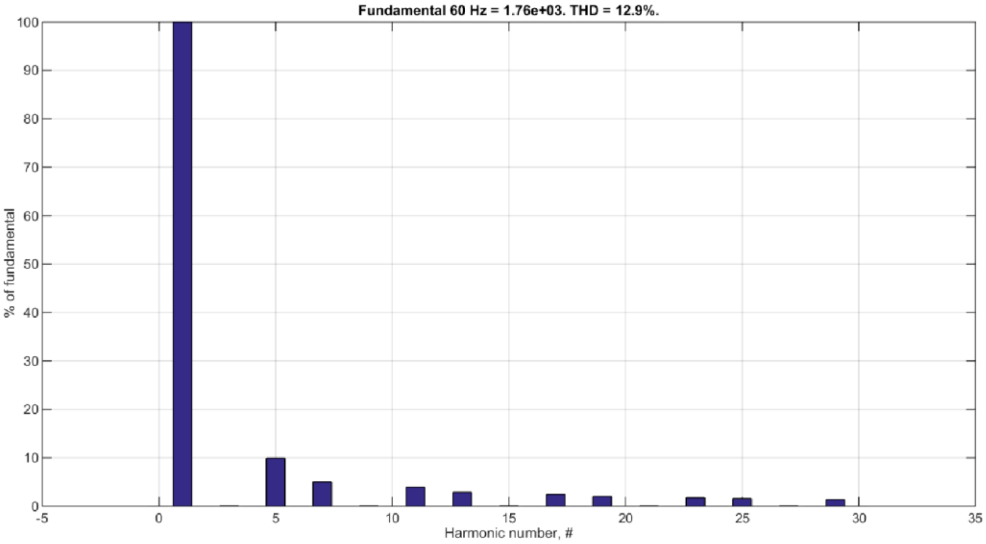

Fig. 6. THD of the AC bus voltage without the proposed controller.

IV. CONCLUSIONS

The study concludes that integrating hydrogen energy storage with photovoltaic (PV) arrays offers a highly effective solution for enhancing power quality and ensuring grid stability, particularly in scenarios characterized by the intermittent and variable nature of solar energy. Through the development and implementation of the MOPSO integrated with MPC, the system can dynamically manage energy flow between the PV array, hydrogen storage, and the power grid. This ensures that critical power quality parameters, including voltage stability, frequency regulation, and harmonic distortion, are maintained within acceptable limits. The use of hydrogen as an energy storage medium addresses the limitations of traditional battery storage systems by providing long-term storage capabilities and enabling the system to respond effectively to prolonged periods of low solar irradiance or high demand. Additionally, the system's ability to supply ancillary services, such as reactive power support and frequency stabilization, further enhances its value to the grid, making it a versatile solution for both grid-connected and off-grid applications. The findings indicate that by optimizing the interaction between the PV array and hydrogen energy storage, it is possible to significantly reduce power quality issues associated with renewable energy generation, thereby increasing the reliability and efficiency of the overall energy system. In addition, the proposed system has significant economic and environmental benefits. The reduction in reliance on fossil fuels and the associated decrease in greenhouse gas emissions contribute to a more sustainable energy future, while the potential for cost savings through grid services and improved energy efficiency makes the system financially attractive. However, challenges remain, particularly in terms of the initial costs of hydrogen production and storage infrastructure, as well as the efficiency of energy conversion processes. Addressing these challenges will require ongoing research and development, particularly in improving the cost-effectiveness of hydrogen technologies and further refining the control algorithms to enhance system performance. In conclusion, the coordinated operation of PV arrays with hydrogen energy storage, underpinned by sophisticated control strategies, presents a promising pathway for achieving optimal power quality in renewable energy systems, supporting the global transition to a more resilient and sustainable energy landscape.

REFERENCES

[1] Xiaoshun Zhang, Die Meng, Jiahui Cai, Guiyuan Zhang, Tao Yu, Feng Pan, Yuyao Yang, A swarm based double Q-learning for optimal PV array reconfiguration with a coordinated control of hydrogen energy storage system, Energy, Volume 266, 2023, 126483, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2022.126483.

[2] Jing Wang, Lixia Kang, Yongzhong Liu, Optimal design of a renewable hydrogen production system by coordinating multiple PV arrays and multiple electrolyzers, Renewable Energy, Volume 225, 2024, 120304, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2024.120304.

[3] Yijun Fu, Zhichao Wang, Xiaofeng Li, Wei Xu, Ce Xu, Hao Li, Weihua Lyu, Chunling Wu, Numerical research on building energy balance and grid stability realization of PV/T-ASHP system through electrical-hydrogen coupled storage technology, Energy, Volume 307, 2024, 132676, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2024.132676.

[4] Xiaolun Fang, Xinyu Zhong, Wei Dong, Fan Zhang, Qiang Yang, Fuzzy logic-based coordinated operation strategy for an off-grid photovoltaic hydrogen production system with battery/supercapacitor hybrid energy storage, International Journal of Hydrogen Energy, Volume 84, 2024, Pages 593-605, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2024.08.188.

[5] Hegazy Rezk, Ahmed Fathy, Hydrogen reduction-based energy management strategy of hybrid fuel cell/PV/battery/supercapacitor renewable energy system, Journal of Energy Storage, Volume 86, Part B, 2024, 111316, ISSN 2352-152X, https://doi.org/10.1016/j.est.2024.111316.

[6] R. Teodorescu, M. Liserre, and P. Rodríguez, "Grid Converters for Photovoltaic and Wind Power Systems," John Wiley & Sons, 2011.

[7] S. Kouro, J. I. Leon, D. Vinnikov, and L. G. Franquelo, "Grid-Connected Photovoltaic Systems: An Overview of Recent Research and Emerging PV Converter Technology," IEEE Ind. Electron. Mag., vol. 9, no. 1, pp. 47–61, 2015.

[8] A. Khaligh and O. C. Onar, "Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems," CRC Press, 2017.

[9] M. A. Rosen and S. Koohi-Fayegh, "The Prospects for Hydrogen as an Energy Carrier: An Overview of Hydrogen Energy and Hydrogen Energy Systems," Energy Ecol. Environ., vol. 2, no. 3, pp. 125–137, 2017.

[10] E. F. Camacho and C. Bordons, "Model Predictive Control," 2nd ed., Springer, 2007.

[11] M. Sugeno and G. T. Kang, "Structure Identification of Fuzzy Model," Fuzzy Sets Syst., vol. 28, no. 1, pp. 15–33, 1988.

[12] J. A. Rosero, J. I. Leon, M. A. M. Prats, and L. G. Franquelo, "Advanced Control Structures for the Optimization of PV-Hybrid Systems," IEEE Trans. Ind. Electron., vol. 55, no. 7, pp. 2624–2633, 2008.

[13] A. Kusiak and W. Li, "The Prediction and Diagnosis of Wind Turbine Faults," Renew. Energy, vol. 36, no. 1, pp. 16–23, 2011.

[14] G. M. Tina and F. Arcidiacono, "Photovoltaic-Hydrogen Hybrid Systems for Off-Grid Applications: A Case Study in Sicily," Int. J. Hydrog. Energy, vol. 37, no. 11, pp. 8845–8853, 2012.

[15] M. C. Argyrou, P. Christodoulides, and S. A. Kalogirou, "Energy Storage for Electricity Generation and Applications," Renew. Sust. Energy Rev., vol. 94, pp. 804–821, 2018.

[16] Qi Li, Ruirui Li, Yuchen Pu, Shuo Li, Cai Sun, Weirong Chen, Coordinated control of electric-hydrogen hybrid energy storage for multi-microgrid with fuel cell/ electrolyzer/ PV/ battery, Journal of Energy Storage, Volume 42, 2021, 103110, ISSN 2352-152X, https://doi.org/10.1016/j.est.2021.103110.

[17] Junjie Zhao, Zhengkai Tu, Siew Hwa Chan, Energy management strategy for accurate thermal scheduling of the combined hydrogen, heating, and power system based on PV power supply, International Journal of Hydrogen Energy, Volume 78, 2024, Pages 721-730, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2024.06.341.

[18] Xiaoshun Zhang, Tao Yu, Xiaoguang Ma, Lexin Guo, An efficient multi-agent negotiation algorithm for multi-period photovoltaic array reconfiguration with a hydrogen energy storage system, Energy Conversion and Management, Volume 256, 2022, 115376, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2022.115376.

[19] Guoming Yang, Hao Zhang, Wenting Wang, Bai Liu, Chao Lyu, Dazhi Yang, Capacity optimization and economic analysis of PV–hydrogen hybrid systems with physical solar power curve modeling, Energy Conversion and Management, Volume 288, 2023, 117128, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2023.117128.

[20] Shengqing Li, Bowen Liu, Xin Li, A robust and optimal voltage control strategy for low-voltage grids utilizing group coordination of photovoltaic and energy storage systems via consensus algorithm, International Journal of Hydrogen Energy, Volume 78, 2024, Pages 1332-1343, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2024.06.374.