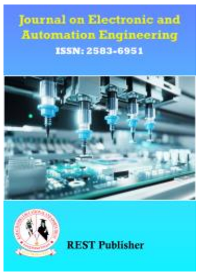
Journal on Electronic and Automation Engineering

Vol: 4(1), March 2025

REST Publisher; ISSN: 2583-6951 (Online)

Website: https://restpublisher.com/journals/jeae/

DOI: https://doi.org/10.46632/jeae/4/1/7



A Novel Model Predictive Controller Based Power Management Plan for Grid Connected Photo Voltaic Systems with Hybrid Energy Storage

[*] P. Rama Mohan, Y.S.V. Srikar, Guraiahgari Pavan Kalyan

Annamacharya Institute of Technology & Sciences (Autonomous) Kadapa, Andhra Pradesh, India

[*] Corresponding Author E-mail: rammohan.kadapa@gmail.com

Abstract: *The increasing penetration of renewable energy sources (RESs) in the distribution system presents challenges in ensuring power quality, stability, and reliable operation. The intermittent nature of photovoltaic (PV) energy, coupled with unpredictable load variations, necessitates an advanced energy management strategy. This paper proposes a Model Predictive Control (MPC)-based energy management system for a grid-connected PV system integrated with a hybrid energy storage system (HESS) consisting of a battery and a supercapacitor. The supercapacitor handles transient power fluctuations, while the battery manages long-term energy storage, thereby enhancing system stability and efficiency. The proposed control strategy ensures optimal power distribution by considering the state of charge (SOC) of the battery while effectively smoothing PV power variations. Additionally, the use of a supercapacitor reduces battery stress, extending its lifespan. The effectiveness of the proposed energy management scheme is validated through simulation studies, demonstrating improved DC-link voltage stability and enhanced power quality.*

1. INTRODUCTION

The increasing integration of renewable energy sources (RESs), particularly photovoltaic (PV) systems, into modern power grids has introduced new challenges in ensuring grid stability, power quality, and reliable operation. The intermittent and unpredictable nature of solar energy, combined with fluctuating load demands, can cause voltage instability, power imbalances, and operational inefficiencies in the distribution network. This variability necessitates advanced control and energy management strategies to ensure the stable and efficient operation of the power system. Energy storage systems (ESSs) play a crucial role in mitigating these issues by providing power balancing, stabilizing voltage fluctuations, and enhancing overall reliability. Among the various types of energy storage solutions, hybrid energy storage systems (HESS) that combine batteries and supercapacitors offer significant advantages. Batteries, with their high energy density, provide long-term energy storage and help maintain energy balance over extended periods. Meanwhile, supercapacitors, which possess high power density and rapid charge-discharge capabilities, handle transient power fluctuations and compensate for sudden changes in power demand or generation. However, effective utilization of a hybrid storage system requires an advanced energy management strategy that can dynamically allocate power among different system components. Traditional energy management techniques, such as rule-based control or simple proportional-integral-derivative (PID) controllers, often struggle to provide optimal performance under varying operating conditions. These methods fail to fully exploit the capabilities of hybrid storage and often lead to inefficient power distribution, increased battery degradation, and reduced system lifespan. To address these challenges, this study proposes a Model Predictive Control (MPC)-based energy management system for a grid-connected PV system with hybrid energy storage. MPC is an advanced control technique that enables real-time optimization by predicting future system behavior and making proactive control decisions. By incorporating constraints and system dynamics, MPC ensures optimal power distribution between the battery, supercapacitor, and the grid, thereby enhancing system stability and efficiency. Energy management strategies and hybrid storage systems are essential for optimizing the integration of renewable energy, improving grid stability, and enhancing system efficiency. Energy management strategies focus on optimizing energy generation, storage, and consumption through techniques such as demand-side management (DSM), optimization algorithms, and predictive modeling. These strategies aim to reduce costs, improve efficiency, and balance supply and demand, with a strong emphasis on forecasting renewable energy generation and consumption patterns. Advanced methods, including machine learning and artificial intelligence, are increasingly being integrated into these strategies for more effective and real-time decision-making. Hybrid storage systems combine different energy storage technologies, such as batteries, supercapacitors, and flywheels, to leverage the unique benefits of each and optimize energy storage and delivery. These systems are particularly useful in addressing the variability and intermittency of renewable energy sources like wind and solar. Hybrid systems offer enhanced flexibility, performance, and cost-effectiveness by combining short-term, high-power storage with long-duration, high-energy storage. The management of these systems relies on sophisticated control strategies that ensure optimal coordination between different storage elements, ultimately improving energy reliability and reducing environmental impact. As energy systems continue to evolve, the development of more efficient hybrid storage systems and advanced energy management algorithms is key to meeting the growing demand for sustainable and reliable energy solutions. However, challenges such as scalability, system complexity, and integration with renewable energy sources remain. Future research is expected to focus on overcoming these challenges, advancing energy storage technologies, and improving the overall performance and cost-effectiveness of hybrid storage systems.

2. SYSTEM ARCHITECTURE AND POWER MANAGEMENT SCHEME

The architecture of grid-coupled PV with HESS is presented in Fig. 1, where L1, L2, C1, and C2 are the inductors and capacitors connected to quadratic boost converter, respectively; D1, D2, and D3 are the diodes of quadratic boost converter; Vg, Vdc, and VB are the grid voltage, voltage at DC bus, and battery voltage, respectively; Cb and Cdb are the capacitors of the battery and bi-directional converter, respectively; Csc is the supercapacitor capacitance; Lf , Rf , and Cf are the inductance, resistance, and capacitance of the LC filter, respectively; Vsc is the terminal voltage of supercapacitor; Vpv is the open-circuit voltage of PV; S is the switch of quadratic boost converter; S1, S2, S3,and S4 are the insulated gate bipolar transistor (IGBT) switches of the microgrid converter; Sb1 and Sb2 are the IGBT switches of the battery bi-directional converter; Rnl and Lnl are the resistor and inductor connected to 1φ bridge rectifier for non-linear load, respectively; RLac and RLdc are the resistive AC and DC linear loads, respectively; Lb is the inductor connected to battery bi-directional converter; Rb is the resistor connected to battery bi-directional converter; Lsc is the inductor connected to the supercapacitor bi-directional converter; and SS1 and SS2 are the IGBT switches of the supercapacitor bi-directional converter. To get the required DC-link voltage, the output voltage of DC-DC converter should be sufficiently high for the integration of a low-voltage PV system with the distribution system. Hence, a quadratic boost converter is used with a PV system to get a high conversion ratio with high efficiency for a wide range of voltage [14]. For energy storage, supercapacitors and batteries are utilized along with the bi-directional boost DC-DC converter (BDDC) for the regulation of power transfer among the grid and the ESSs. The AC utility grid is linked to the DC microgrid via a VSC, which can operate as an inverter or a rectifier according to the mode of operation. The LC filter is used at the output of VSC to smooth the voltages and currents at the AC side. In this system, both linear and non-linear loads are connected to check the performance of the proposed scheme under different operating conditions. This power management structure mainly comprises the generation of reference current, an algorithm for power management, and control of various currents converters. The suggested power management arrangement for grid-connected system is explained in Fig. 2, where PRavg and PRtrans are the average and transient power required for PV, respectively; and ipvr is the reference PV current. A low pass filter (LPF) is used to extract the average current component for the utility grid and battery [15], [16]. The transient current for the supercapacitor is extracted by taking away the average current from the total required current. Also, an error co-efficient of uncompensated battery current is added to the transient current to advance the dynamics of DC-link voltage. A moving average filter (MAF) is employed to estimate the AC load requirement. MAF is a linear phase finite impulse response (FIR) filter that can operate as an ideal LPF under some specific conditions [17]. Depending on the PV generation and load requirement, the power management algorithm (PMA) selects the mode of operation and produces the current references. Then, these reference currents undergo the current control stages and finally, produce the switching pulses for all the power converters.

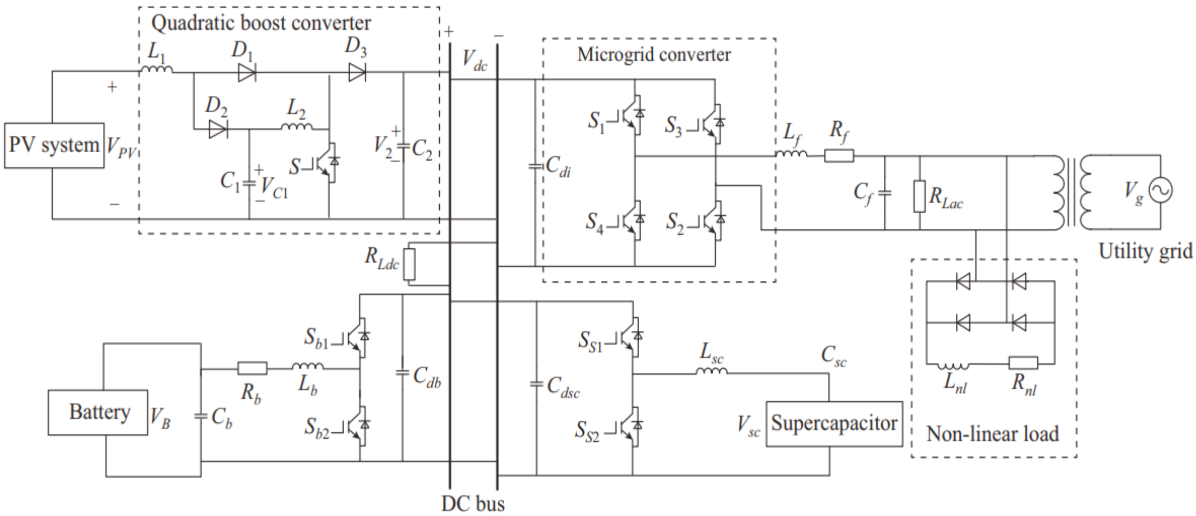


FIGURE 1. Architecture of grid-coupled PV with HESS

3. MODEL PREDICTIVE CONTROL (MPC) OVERVIEW

Model Predictive Control (MPC) is an advanced control strategy that uses an optimization-based approach to predict the future behavior of a system and determine the control actions at each time step. The core idea is to solve an optimization problem at each sampling instant, considering both the system dynamics and constraints, to determine the optimal control input over a prediction horizon. Once the optimal control sequence is obtained, only the first control action is applied, and the process is repeated at the next time step.

In the context of a grid-connected PV system integrated with a Hybrid Energy Storage System (HESS**)**, the MPC aims to balance the power flow between the PV, the grid, the battery, and the supercapacitor. The objective is to ensure that the system operates efficiently while satisfying various constraints such as energy storage limits, grid requirements, and the need to smooth out fluctuations in the PV power generation.

System Model

The MPC-based energy management system generally models the components (PV, battery, supercapacitor, and grid) using dynamic equations. These equations represent the system's behavior over time and provide a framework for predicting future states.

Photovoltaic (PV) Power Generation Model:

The output of the PV system is typically expressed as a function of solar irradiance and temperature:

$$P_{\mathrm{PV}}(t) = f(I(t), T(t))$$

where:
PPV(t) is the power generated by the PV system at time t,
I(t) is the solar irradiance at time t,
T(t) is the temperature at time t.

Battery Power and Energy Model:

The battery energy dynamics are modeled by considering its charging and discharging behavior, along with the state of charge (SOC):

$$E_{\mathrm{battery}}(t+1) = E_{\mathrm{battery}}(t) + \eta_{\mathrm{charge}} \cdot P_{\mathrm{battery}}(t) \cdot \Delta t$$

where:

- Battery (t) is the energy stored in the battery at time t,
- Battery (t) is the power delivered to or from the battery at time t,
- ηchargeis the efficiency of the battery during charging,
- Δtis the time step (in seconds).

The state of charge (SOC) of the battery is defined as:

$$SOC_{\text{battery}}(t) = \frac{E_{\text{battery}}(t)}{E_{\max}}$$

Where Emax is the maximum battery capacity.

Supercapacitor Power and Energy Model:

Similar to the battery, the supercapacitor's energy is governed by a charging and discharging model:

$$E_{\text{SC}}(t+1) = E_{\text{SC}}(t) + \eta_{\text{SC}} \cdot P_{\text{SC}}(t) \cdot \Delta t$$

where:

- ESC(t) is the energy stored in the supercapacitor at time t,
- PSC(t) is the power delivered to or from the supercapacitor at time t,
- ηSCis the efficiency of the supercapacitor during charging.

Grid Power Model:

The power delivered by the grid can be expressed as the difference between the total load and the available power from the PV system and the hybrid storage:

$$P_{\text{grid}}(t) = P_{\text{load}}(t) - P_{\text{PV}}(t) - P_{\text{battery}}(t) - P_{\text{SC}}(t)$$

where:

- Pload (t)is the power demand from the system,
- Pbattery (t)and PSC(t)are the power contributions from the storage units.

Objective Function

The MPC formulation involves defining an **objective function** that reflects the system's goals, typically aiming to minimize operational costs (if applicable), improve energy efficiency, and ensure system stability. The objective function can be formulated as follows:

$$J(t) = \sum_{k=0}^{N-1} \left[\lambda_1 \cdot \left(P_{\text{grid}}(t+k)\right)^2 + \lambda_2 \cdot \left(P_{\text{battery}}(t+k)\right)^2 + \lambda_3 \cdot \left(P_{\text{SC}}(t+k)\right)^2 \right]$$

where:

- N is the prediction horizon,
- λ1, λ2, λ3are weighting factors that prioritize the importance of minimizing grid power, battery power, and supercapacitor power, respectively.

The goal is to minimize the objective function subject to the system's constraints.

4. CONSTRAINTS

Energy and Power Limits: Battery charging/discharging power must lie within a specified range:

$$P_{\text{battery, min}} \leq P_{\text{battery}}(t) \leq P_{\text{battery, max}}$$

Supercapacitor power must also satisfy its limits:

$$P_{\text{SC, min}} \leq P_{\text{SC}}(t) \leq P_{\text{SC, max}}$$

The state of charge (SOC) of the battery and supercapacitor must remain within defined limits:

$$SOC_{\text{battery, min}} \leq SOC_{\text{battery}}(t) \leq SOC_{\text{battery, max}}$$

$$E_{\text{SC, min}} \leq E_{\text{SC}}(t) \leq E_{\text{SC, max}}$$

Grid Power Constraints: The power drawn from the grid is constrained by the grid's capacity:

$$P_{\text{grid}}(t) \leq P_{\text{grid, max}}$$

Optimization Problem: At each time step t, the MPC optimizes the future power profiles of the battery, supercapacitor, and grid by solving the following optimization problem:

$$\min_{P_{\text{battery}}, P_{\text{SC}}, P_{\text{grid}}} J(t)$$

subject to:

$$E_{\text{battery}}(t+1) = E_{\text{battery}}(t) + \eta_{\text{charge}} \cdot P_{\text{battery}}(t) \cdot \Delta t$$

$$E_{\text{SC}}(t+1) = E_{\text{SC}}(t) + \eta_{\text{SC}} \cdot P_{\text{SC}}(t) \cdot \Delta t$$

and other system constraints (e.g., power limits, SOC limits, etc.).

5. IMPLEMENTATION AND RESULTS

The optimization problem is solved in real-time, typically using quadratic programming (QP) or other suitable solvers. The first optimal control action is implemented, and the process is repeated at the next time step, with updated measurements of PV generation, load demand, and battery/SOC status. In practical power systems, non-triplen odd harmonics and odd harmonics are typically the most dominant harmonic components. To mitigate these harmonic components, the window length of the Moving Average Filter (MAF) should be half of the fundamental period of the grid voltage. In this context, the cut-off frequency of the MAF is set to 100 Hz, assuming a fundamental frequency of 50 Hz for the system. To validate the proposed energy management scheme, the values of both linear and non-linear loads are intentionally varied in the simulation, allowing for a comprehensive analysis of the system's response under different conditions. Additionally, the photovoltaic (PV) power generation is adjusted by changing the irradiance value to assess how variations in generated power affect the system's performance. The simulation parameters used for the validation of the proposed scheme are derived from [18] and are summarized in Table I. Among the key parameters, ipi_pip represents the maximum peak current, and imci_{mc}imc denotes the maximum continuous current. These parameters play a crucial role in ensuring that the system operates within safe limits while maintaining high power quality and stability during operation. The dynamic response to changes in the load and PV generation is further analyzed, demonstrating the robustness and flexibility of the Model Predictive Control (MPC)-based energy management approach.

TABLE 1. Parameters Used for System Simulation

Specification	Parameter	Value
PV array	V_{pv}	40 V
	i_{pv}	20 A
Supercapacitor	V_{sc}	16.2 V
	i_p	200 A
	C_{sc}	58 F
	i_{mc}	19 A
Battery	C_B	14 Ah
	V_B	12 V
Battery BDDC	R_b	0.5 Ω
	L_b	5 mH
	C_b	220 µF
	C_{db}	220 µF
Supercapacitor BDDC	L_{sc}	5 mH
	C_{dsc}	220 µF
VSC	L_f	10 mH
	C_f	1 µF
	C_{di}	2200 µF
Quadratic boost PV converter	$L_1 = L_2$	5 mH
	C_1	110 µF
	C_2	220 µF
Linear and non-linear load parameters	R_{Ldc}	50 Ω
	R_{Lac}	10 Ω
	R_{nl}	30 Ω
	L_{nl}	1 mH
Utility grid	V_g	230 V
	f	50 Hz
DC bus voltage	V_{dc}	100 V
LPF	f_{LPF}	1 Hz
MAF	f_{MAF}	100 Hz

Performance of MPC Controller with Variation in PV Power: The active performance of the proposed control strategies under varying PV power generation conditions is demonstrated in Figures 5 and 6. At t=2 st = 2 \, \text{s}t=2s, the PV power generation is reduced by adjusting the irradiance from 1000 W/m^2 to 600 W/m^2. This reduction in PV power is clearly observed in Figure 6. Despite the change in PV power, the DC bus voltage stabilizes back to its reference value within 0.15 seconds, with an overshoot of just 1V—well within the permissible limits outlined in IEEE Standard 929-2000 [13], as shown in Figure 5. At the point of change, the transient power surge is managed by the supercapacitor, while the average power is supported by the combined effort of the battery units and the grid, maintaining a constant DC link voltage. The combination of battery and supercapacitor effectively reduces the settling time and voltage dip at the moment of PV generation change. Consequently, the DC bus voltage quickly settles to its final value, within the specified error limits. Figures 5 and 6 show the voltages and powers of the DC link, battery, supercapacitor, and other system components during the PV power variation. The Total Harmonic Distortion (THD) of the utility grid current during PV power variation is shown in Figure 7. The THD value is 1.11%, which is well within the acceptable range according to IEEE Standard 519 [21]. Harmonics in the system can lead to excessive heating, equipment malfunction, and increased losses in capacitors, all of which can reduce the lifespan of appliances. Therefore, maintaining harmonics within specified limits is crucial.

Performance with Variation in Load: The performance of the control strategies under load variation is shown in Figures 8 and 9, tested under insufficient power conditions. The DC load is increased at t=2 st = 2 \, \text{s}t=2s by changing the linear DC load from RLdc=50 ΩR_{Ldc} = 50 \, \OmegaRLdc=50Ω to RLdc=25 ΩR_{Ldc} = 25 \, \Omega RL dc=25Ω. The abrupt variation in DC load power is evident in Figure 8. The average power demand to maintain the DC bus voltage is handled by the power grid, while transient power is supplied by the supercapacitor. Despite the sudden load change, the DC bus voltage experiences a 2V dip, which is within the acceptable limit [13], and stabilizes within 0.2 seconds, as shown in Figure 8. Figures 9 and 10 illustrate the power distribution and frequency waveform with variation in load. A frequency deviation of ±0.01 Hz occurs at t=2 st = 2 \, \text{s}t=2s, which is within the standard allowable limits defined in IEEE Standard 929-2000 [13]. Maintaining frequency stability is essential for ensuring power quality, especially in microgrids connected to renewable sources.

Performance with IPM (Intelligent Power Management)

In this section, the performance is evaluated based on the State of Charge (SOC) of the storage devices, and four operational states are defined:

- **State 1 (0-2 s)**: Both battery and supercapacitor are above the lower SOC limit (SOC > L). The power grid and battery supply the average power, while the supercapacitor handles transient power.
- **State 2 (2-4 s)**: The battery's SOC drops below the lower limit (SOC < L), while the supercapacitor remains above its lower limit. The supercapacitor takes over the transient power, while the grid manages the average power.
- **State 3 (4-6 s)**: The battery's SOC is above the lower limit (SOC > L), but the supercapacitor's SOC falls below its lower limit (SOC < L). The battery now supplies the total power, while the grid compensates for the remaining power.
- **State 4 (6-8 s)**: Both the battery and supercapacitor have fallen below their SOC lower limits. The power grid alone supplies the required power to maintain the DC link voltage.

In all states, the DC bus voltage restores quickly, as demonstrated in Figure 11. Figures 12 and 13 show the corresponding power distributions and grid current, respectively. The VSC (Voltage Source Converter) ensures the grid current IgI remains constant, achieving a unity power factor throughout the simulation. This is confirmed in Figure 13. The VSC current behavior during IPM is shown in Figure 14. The supercapacitor smoothens VSC current changes, especially when it is within its SOC limits, contributing to stable operation. A sudden change in VSC current is observed when the supercapacitor’s SOC falls below the lower limit, highlighting its crucial role in microgrid stability.

Performance with SPM (State-based Power Management)

In this section, four states are defined based on the SOC of the storage devices:

- **State 1 (0-2 s)**: Both the battery and supercapacitor are charged based on their respective rated charging currents. After charging the storage devices, excess power is sent to the grid.
- **State 2 (2-4 s)**: The battery charges until it reaches its upper SOC limit, while the supercapacitor handles the transient power. The grid manages the average power.
- **State 3 (4-6 s)**: The supercapacitor charges to its upper SOC limit, while the grid provides the overall power demand.

- **State 4 (6-8 s)**: The supercapacitor handles the transient power, and excess PV power is supplied to the grid.
- Figures 15 and 16 illustrate the voltage and power distribution during these states. Regardless of the state, the DC link voltage remains stable and restores quickly.

Performance Analysis of Various Power Management Schemes

To assess the robustness and effectiveness of the proposed scheme, a comparative analysis of the settling time tst_sts , voltage overshoot/undershoot MpM_pMp, and Total Harmonic Distortion (THD) is presented in Figure 17. Scheme 1 is from [18], Scheme 2 from [22], and Scheme 3 from [12]. The proposed scheme demonstrates superior performance, with minimal peak overshoot, quick settling time, and reduced harmonic distortion compared to the other schemes. Figures 17(a), (b), and (c) provide a graphical comparison of the settling time, voltage overshoot/undershoot, and THD across different schemes.

6. CONCLUSION

The proposed MPC-based power management scheme for grid-connected PV systems with hybrid energy storage devices (HESS) demonstrates significant improvements in ensuring power quality, voltage and frequency regulation, and efficient management of energy storage devices. Through simulation results, the scheme has proven its effectiveness in maintaining a stable DC link voltage and regulating power flow under varying PV power and load conditions. Key power quality parameters, including settling time, overshoot/undershoot, and Total Harmonic Distortion (THD), show that the proposed approach outperforms other conventional power management schemes. The integration of HESS in the system, with the use of batteries and supercapacitors, enables efficient handling of both transient and average power demands. The Model Predictive Control technique allows for optimal coordination of power storage and flow, ensuring that the State of Charge (SOC) of the storage devices remains within acceptable limits, thus enhancing the longevity and efficiency of the system. In summary, the proposed scheme offers a robust solution for managing power flow and maintaining power quality in grid-connected PV systems. It can be extended to isolated microgrids and has the potential to be implemented in practical energy systems for both residential and commercial applications.

7. FUTURE SCOPE

While the current MPC-based power management scheme demonstrates excellent performance, there are several areas for future improvement and expansion:

- Peak and Off-Peak Demand Management: The current scheme does not consider peak and off-peak hour demands. Integrating these factors could further optimize the use of stored energy, minimizing energy costs and improving the efficiency of the system, especially in grid-connected applications where energy pricing varies throughout the day.
- Extended Application to Isolated Microgrids: The proposed scheme is suitable for grid-connected applications, but its capabilities can be extended to isolated microgrid systems. A robust control strategy for microgrids with renewable generation and hybrid storage would improve the reliability and autonomy of off-grid systems, especially in remote areas.
- Small Signal Stability Analysis: A more detailed stability analysis, such as small-signal analysis, could be performed to assess the system's stability under a wider range of operating conditions. This would help ensure the control strategy can handle dynamic changes in power generation and load demand while maintaining stable operation.
- Real-Time Implementation: Future research could focus on the real-time implementation of the proposed MPC-based scheme in hardware. Testing the scheme under practical conditions with real-time controllers would validate its performance and reliability, ensuring that it meets the operational requirements of real-world systems.
- Advanced Control Techniques: Further enhancements to the MPC can include the use of adaptive or robust control techniques that can handle unpredictable disturbances and system uncertainties, such as sudden weather changes affecting PV power generation or unexpected load spikes.
- Energy Market Integration: The scheme can be expanded to integrate with energy markets, where it could participate in demand response programs or ancillary services. By intelligently managing energy storage and power flow, the system could help balance supply and demand, contributing to grid stability and reducing operational costs.

REFERENCES

[1]. S. K. Kollimalla and M. K. Mishra, “A novel adaptive P&O MPPT algorithm considering sudden changes in the irradiance,” IEEE Transactions on Energy Conversion, vol. 29, no. 3, pp. 602-610, May 2014.
[2]. S. Mishra and R. K. Sharma, “Dynamic power management of PV based islanded microgrid using hybrid energy storage,” in Proceedings of IEEE 6th International Conference on Power Systems (ICPS), New Delhi, India, Mar. 2016, pp. 1-6.
[3]. C. Natesan, S. Ajithan, S. Chozhavendhan et al., “Power management strategies in microgrid: a survey,” International Journal of Renewable Energy Research, vol. 5, no. 2, pp. 334-340, Jan. 2015.
[4]. Z. Yi, W. Dong, and A. H. Etemadi, “A unified control and power management scheme for PV-battery-based hybrid microgrids for both grid-connected and islanded modes,” IEEE Transactions on Smart Grid, vol. 9, no. 6, pp. 5975-5985, Nov. 2018.
[5]. S. Pannala, N. Patari, A. K. Srivastave et al., “Effective control and management scheme for isolated and grid connected DC microgrid,” IEEE Transactions on Industry Applications, vol. 56, no. 6, pp. 1-14, Dec. 2020.
[6]. P. Singh and J. S. Lather, “Variable structure control for dynamic power-sharing and voltage regulation of DC microgrid with a hybrid energy storage system,” International Transaction Electrical Energy System, vol. 30, no. 9, pp. 1-20, Jun. 2020.
[7]. N. R. Tummuru, U. Manandhar, A. Ukil et al., “Control strategy for AC-DC microgrid with hybrid energy storage under different operating modes,” Electrical Power and Energy Systems, vol. 104, pp. 807- 816, Jan. 2019.
[8]. J. Hu, Y. Shan, Y. Xu et al., “A coordinated control of hybrid AC/DC microgrids with PV-wind-battery under variable generation and load conditions,” Electrical Power and Energy Systems, vol. 104, pp. 583- 592, Jan. 2019.
[9]. H. Mahmood, D. Michaelson, and J. Jiang, “A power management strategy for PV/battery hybrid systems in islanded microgrids,” IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 4, pp. 870-882, Jun. 2014.
[10]. P. Sanjeev, N. P. Padhy, and P. Agarwal, “Peak energy management using renewable integrated DC microgrid,” IEEE Transactions on Smart Grid, vol. 9, no. 5, pp. 4906-4917, Sept. 2018.
[11]. S. Sahoo, S. Mishra, and N. P. Padhy, “A decentralized adaptive droop-based power management scheme in autonomous DC microgrid,” in Proceedings of IEEE PES Asia-Pacific Power and Energy Conference, Xi’an, China, Dec. 2016, pp. 1018-1022.
[12]. P. Singh and J. S. Lather, “Power management and control of a gridindependent DC microgrid with hybrid energy storage system,” Sustainable Energy Technologies and Assessments, vol. 43, pp. 1-11, Feb. 2021.