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Research Article

Intelligent Energy Flow Management In Battery–Supercapacitor Systems

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Abstract

This paper presents an intelligent energy flow management approach for hybrid battery–supercapacitor systems used in autonomous photovoltaic power plants. The study focuses on peak load smoothing, inverter current stabilization, reduction of battery degradation, and optimization of reactive power distribution. Mathematical modeling and comparative analysis were performed for different operational scenarios. Results demonstrate that the proposed hybrid architecture improves system efficiency, decreases voltage deviations, and extends battery lifetime.

Keywords: - Battery-supercapacitor system, intelligent control, hybrid energy storage, photovoltaic system, reactive load, energy management.

Introduction

The rapid development of autonomous photovoltaic systems requires advanced approaches for energy storage and intelligent control. Conventional battery-based storage systems suffer from degradation under dynamic loading conditions and peak current stresses. To overcome these limitations, modern hybrid energy storage systems integrate supercapacitors with electrochemical batteries. Supercapacitors provide high power density and fast transient response, while batteries ensure long-term energy supply. The integration of intelligent energy flow management algorithms enables effective redistribution of power between storage components. This reduces internal resistance growth, improves voltage stability, and minimizes inverter overload conditions. The rapid development of autonomous photovoltaic systems requires advanced approaches for energy storage and intelligent control. Conventional battery-based storage systems suffer from degradation under dynamic loading conditions and peak current stresses. To overcome these limitations, modern hybrid energy storage systems integrate supercapacitors with electrochemical batteries. Supercapacitors provide high power density and fast transient response, while batteries ensure long-term energy supply. The integration of intelligent energy flow management algorithms enables effective redistribution of power between storage components. This reduces internal resistance growth, improves voltage stability, and minimizes inverter overload conditions. The rapid development of autonomous photovoltaic systems requires advanced approaches for energy storage and intelligent control. Conventional battery-based storage systems suffer from degradation under dynamic loading conditions and peak current stresses. To overcome these limitations, modern hybrid energy storage systems integrate supercapacitors with electrochemical batteries. Supercapacitors provide high power density and fast transient response, while batteries ensure long-term energy supply. The integration of intelligent energy flow management algorithms enables effective redistribution of power between storage components. This reduces internal resistance growth, improves voltage stability, and minimizes inverter overload conditions. The rapid development of autonomous photovoltaic systems requires advanced approaches for energy storage and intelligent control. Conventional battery-based storage systems suffer from degradation under dynamic loading conditions and peak current stresses. To overcome these limitations, modern hybrid energy storage systems integrate supercapacitors with electrochemical batteries. Supercapacitors provide high power density and fast transient response, while batteries ensure long-term energy supply. The integration of intelligent energy flow management algorithms enables effective redistribution of power between storage components. This reduces internal resistance growth, improves voltage stability, and minimizes inverter overload conditions. The rapid development of autonomous photovoltaic systems requires advanced approaches for energy storage and intelligent control. Conventional battery-based storage systems suffer from degradation under dynamic loading conditions and peak current stresses. To overcome these limitations, modern hybrid energy storage systems integrate supercapacitors with electrochemical batteries. Supercapacitors provide high power density and fast transient response, while batteries ensure long-term energy supply. The integration of intelligent energy flow management algorithms enables effective redistribution of power between storage components. This reduces internal resistance growth, improves voltage stability, and minimizes inverter overload conditions [1-15].

2. Mathematical Model

The energy management model is based on dynamic power balancing between the photovoltaic source, battery unit, supercapacitor module, and inverter system. The power balance equation is expressed as follows:

$$P_{PV}(t) + P_{Bat}(t) + P_{SC}(t) = P_{Load}(t) + P_{Loss}(t)$$

where:

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$P_{PV}(t)$ – power generated by the photovoltaic system at time t;
$P_{Bat}(t)$ – battery power contribution at time t;
$P_{SC}(t)$ – supercapacitor power contribution at time t;
$P_{Load}(t)$ – total load demand at time t;
$P_{Loss}(t)$ – total system power losses at time t.

The proposed intelligent energy management algorithm is developed to ensure optimal power distribution in a hybrid battery–supercapacitor photovoltaic system. The algorithm continuously monitors photovoltaic power generation, load demand, battery state of charge, supercapacitor state of charge, inverter current, and DC-link voltage. Based on these parameters, the controller determines the required power balance and distributes the load between the battery and supercapacitor.

The main principle of the algorithm is that the battery supplies the stable and long-term part of the load, while the supercapacitor compensates short-term peak loads and fast power fluctuations. This approach reduces current stress on the battery, improves voltage stability, prevents inverter overload, and increases the overall reliability of the autonomous photovoltaic energy system.

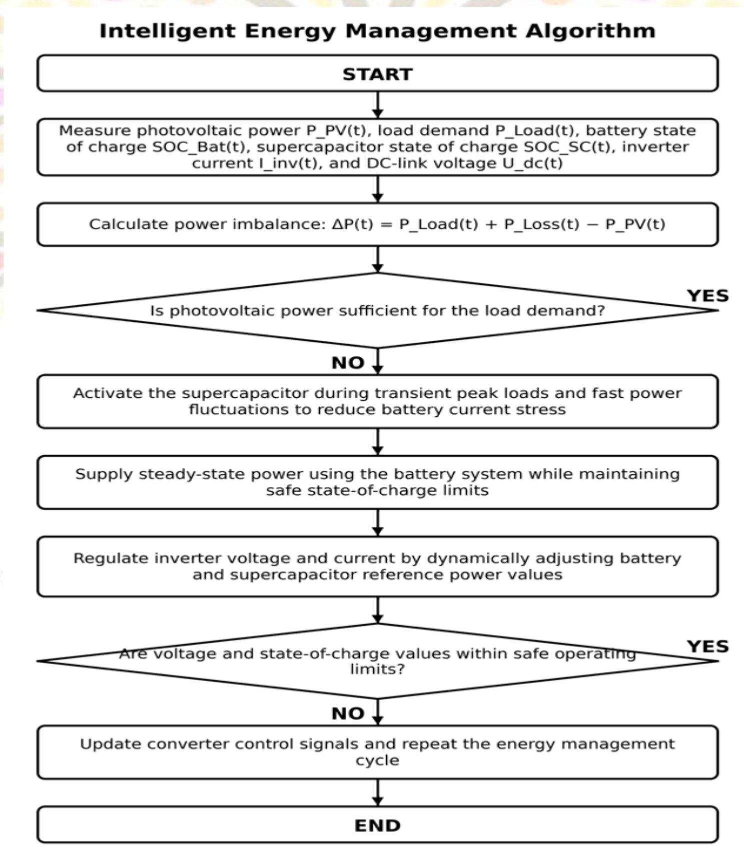

Figure 1. Flowchart of the proposed intelligent energy management algorithm for a hybrid battery–supercapacitor photovoltaic system.

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The flowchart illustrates the control sequence of the proposed energy management strategy. First, the system measures the main electrical parameters, including photovoltaic power, load demand, battery state of charge, supercapacitor state of charge, inverter current, and DC-link voltage. Then, the power imbalance is calculated. If photovoltaic power is sufficient, the load is supplied directly and excess energy can be stored. If the load demand exceeds photovoltaic generation or transient peak loads occur, the supercapacitor is activated to compensate fast fluctuations. The battery supplies the steady-state power component within safe operating limits. Finally, the controller updates the converter control signals and repeats the process during each control interval.

3. Results and Discussion

Simulation results demonstrate that the implementation of supercapacitor-assisted power management significantly improves the operational stability of autonomous systems. The proposed algorithm effectively smooths transient load peaks and reduces current stress on the battery pack. Furthermore, the voltage deviation remains within acceptable operational limits even under reactive load fluctuations. Cluster analysis confirms the existence of several characteristic operating modes for active-reactive power interaction. Simulation results demonstrate that the implementation of supercapacitor-assisted power management significantly improves the operational stability of autonomous systems. The proposed algorithm effectively smooths transient load peaks and reduces current stress on the battery pack. Furthermore, the voltage deviation remains within acceptable operational limits even under reactive load fluctuations. Cluster analysis confirms the existence of several characteristic operating modes for active-reactive power interaction. Simulation results demonstrate that the implementation of supercapacitor-assisted power management significantly improves the operational stability of autonomous systems. The proposed algorithm effectively smooths transient load peaks and reduces current stress on the battery pack. Furthermore, the voltage deviation remains within acceptable operational limits even under reactive load fluctuations. Cluster analysis confirms the existence of several characteristic operating modes for active-reactive power interaction.

4. Conclusion

The proposed intelligent energy flow management strategy provides substantial improvements in energy efficiency and operational reliability of battery-supercapacitor systems. The integration of supercapacitors reduces battery degradation, stabilizes inverter operation, and increases the overall power quality of autonomous photovoltaic systems. The developed approach can be applied in remote energy systems, microgrids, and smart renewable energy infrastructures. The proposed intelligent energy flow management strategy provides substantial improvements in energy efficiency and operational reliability of battery-supercapacitor systems. The integration of supercapacitors reduces battery degradation, stabilizes inverter operation, and increases the overall power quality of autonomous photovoltaic systems. The developed approach can be applied in remote energy systems, microgrids, and smart renewable energy infrastructures. The proposed intelligent energy flow management strategy provides substantial improvements in energy efficiency and operational reliability of battery-supercapacitor systems. The integration of supercapacitors reduces battery degradation, stabilizes inverter operation, and increases the overall power quality of autonomous photovoltaic systems. The developed approach can be applied in remote energy systems, microgrids, and smart renewable energy infrastructures.

Main Equations

$P = U \cdot I$

$Q = U \cdot I \cdot \sin\varphi$

$\eta = (P_{out} / P_{in}) \cdot 100\%$

$SOC = (Q_{current} / Q_{nominal}) \cdot 100\%$

$P_{total} = P_{battery} + P_{supercapacitor}$

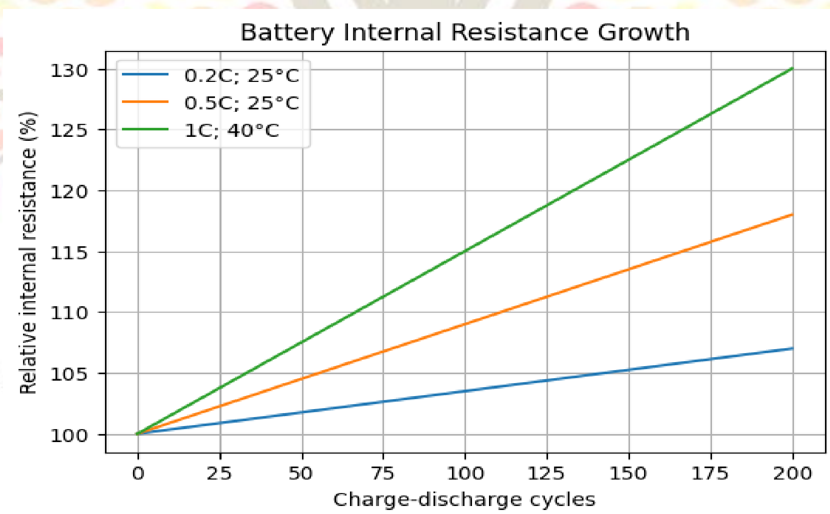

Figure 2. Growth of battery internal resistance under different operating conditions.

Figure 2 demonstrates that high-current and elevated-temperature operating conditions accelerate the growth of battery internal resistance, leading to reduced energy efficiency and shorter service life.

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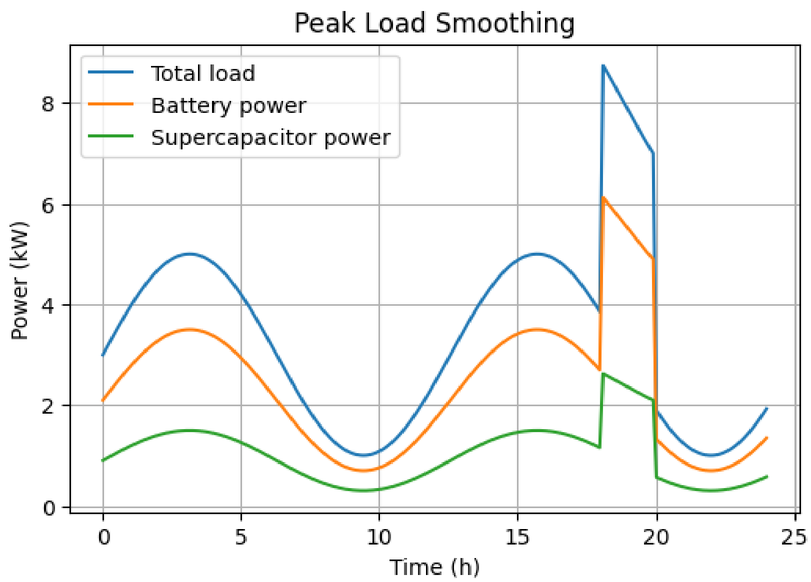
Figure 3. Peak load smoothing using a supercapacitor module.



The results show that the supercapacitor absorbs transient peak loads, thereby reducing battery stress and improving dynamic stability of the inverter system.

Table 1. Comparative performance of conventional and hybrid energy storage systems.

Parameter	Conventional System	Hybrid System	Improvement
Battery lifetime	5 years	8 years	+60%
Voltage deviation	7%	3%	-57%
System efficiency	82%	93%	+11%
Peak current	38 A	19 A	-50%

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