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High-power PV applications using hybrid battery-supercapacitor storage: state-of-the-art solutions for fast transients and power quality

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ABSTRACT

High-power photovoltaic (PV) systems introduce grid stability challenges due to rapid irradiance fluctuations, leading to fast transients, voltage deviations, and frequency instability. Conventional battery-only storage has limited response capability and degrades more rapidly under frequent dynamic stress. Hybrid battery–supercapacitor energy storage systems (HESS) offer a promising solution by combining high energy density with fast transient response. This paper reviews hybrid architectures and control strategies for fast transient mitigation in high-power PV applications. Passive, semi-active, and fully active topologies are examined with respect to dynamic performance and implementation complexity. Control methods, including frequency-based power decomposition, ramp-rate control, and adaptive coordination, are analyzed for their effectiveness in improving voltage and frequency stability. Comparative analysis shows hybrid systems reduce direct current-link (DC-link) voltage deviation, battery current ripple, and electrochemical stress while enhancing multi-time-scale response capability. Key research gaps include degradation-aware control, grid-forming integration, and large-scale validation. Hybrid battery–supercapacitor systems are essential for stable, reliable, and resilient renewable-based power systems in future energy networks worldwide today.

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1. INTRODUCTION

The rapid expansion of high-penetration photovoltaic (PV) systems is significantly reshaping modern power systems [1]. Utility-scale PV plants are increasingly deployed to meet decarbonization targets and reduce dependence on fossil-based generation [2]. However, the inherent intermittency of PV generation introduces significant operational challenges. In particular, fast irradiance fluctuations caused by cloud movement can induce steep power ramps within a few seconds, leading to rapid variations in active power output [3], [4]. These fluctuations directly affect grid performance, resulting in voltage rise, frequency deviation, harmonic distortion, and flicker, especially in distribution networks and weak grids with low short-circuit capacity [5], [6].

In addition to variability, the increasing penetration of inverter-based resources (IBRs) fundamentally alters system dynamics. The replacement of synchronous generators with inverter-interfaced

PV systems leads to a reduction in system inertia [7]. Unlike conventional machines, inverters do not inherently provide rotational inertia or damping capability. Consequently, low-inertia power systems become more vulnerable to rapid disturbances, in which even short-duration changes in irradiance or load can trigger frequency excursions and transient instability [8], [9]. This issue becomes more critical in high-power PV plants connected to weak or isolated grids.

Energy storage systems are widely deployed to mitigate PV variability and enhance grid stability [10]. Battery energy storage systems (BESS) are particularly effective for energy balancing over seconds to minutes [11]. However, battery-only configurations exhibit inherent limitations under high dynamic conditions. Their transient response is relatively slow compared to fast fluctuations in PV power. Moreover, frequent high C-rate charge–discharge cycles accelerate electrochemical degradation, increase thermal stress, and reduce battery lifetime [12]. These limitations become more pronounced in megawatt (MW)-scale PV applications, where both fast transient mitigation and long-term reliability are required simultaneously.

To address these challenges, hybrid battery–supercapacitor energy storage systems have emerged as a promising solution [13]. By combining the high energy density of batteries with the high power density and fast response of supercapacitors, hybrid systems enable effective time-scale decoupling of power fluctuations [14]. In such configurations, high-frequency components of PV power variations are absorbed by the supercapacitor, while the battery handles low-frequency components [15]. This coordinated operation reduces battery stress, improves transient response, and enhances overall system stability and lifetime [16].

Despite the growing interest in hybrid energy storage systems (HESS), the existing literature remains fragmented and lacks a unified perspective for high-power PV applications [17]. Several studies focus on advanced control strategies such as rule-based or optimization-based energy management, but are limited to simulation-level validation or low-power prototypes [18], [19]. Other works investigate converter topologies or hybrid configurations without explicitly addressing grid-level impacts such as voltage regulation and frequency stability [19]. In addition, many studies evaluate hybrid systems under simplified operating conditions, without considering realistic scenarios such as weak grid conditions, high PV penetration, and low system inertia [20], [21]. As a result, a comprehensive, application-oriented review that systematically connects hybrid architectures, control strategies, and power-quality improvement in MW-scale PV systems remains lacking [17].

Therefore, this paper aims to address the identified gap by providing a focused, structured review of hybrid battery–supercapacitor energy storage systems for high-power PV applications. Specifically, this study analyzes the dynamic challenges of high-penetration PV systems, particularly under low-inertia grid conditions. This paper reviews hybrid battery–supercapacitor architectures and their roles in mitigating transient power fluctuations. Furthermore, this paper critically evaluates existing control and energy management strategies for voltage regulation, frequency support, and ramp-rate smoothing. A comparative assessment between battery-only and hybrid energy storage configurations is also presented in terms of dynamic performance and reliability. In addition, this paper identifies key research gaps and proposes future research directions to effectively integrate hybrid energy storage systems into grid-support applications. Overall, this review is expected to provide valuable insights for researchers and engineers in designing stable, resilient, and power-quality-compliant PV-dominated power systems.

2. HIGH-POWER PHOTOVOLTAIC DYNAMIC CHALLENGES

High-penetration PV systems introduce multi-time-scale dynamic disturbances to the grid [22]. These disturbances arise from environmental variability, inverter control limits, and grid conditions [23]. Their impact depends strongly on the time scale of the event [24]. In high-power PV plants, dynamic mismatches between power generation and grid demand can degrade voltage quality and frequency stability. A time-domain perspective is therefore essential to understand the required storage response [1].

2.1. Milliseconds: fault and converter dynamics

At the millisecond level, grid faults and switching events dominate system behavior. During voltage sags or short-circuit events, PV inverters must comply with fault ride-through (FRT) requirements [25]. However, inverter current limits restrict active power injection during faults [26]. This may cause direct current (DC)-link overvoltage or a temporary power imbalance. In low-inertia systems, even short disturbances can trigger frequency excursions [27]. Battery-only systems are generally too slow to react at this time scale. Their response is constrained by the converter's limited multi-time-scale response capability and the inherently slower electrochemical processes of the battery [12].

2.2. Seconds: cloud-induced ramp events

At the second scale, cloud movement causes rapid fluctuations in irradiance. Large PV plants can experience steep ramp-rate events within a few seconds [28]. These ramps lead to voltage rise, frequency

deviation, and power oscillations, particularly in distribution networks with high PV penetration [29]. Weak grids are especially vulnerable due to their limited inertia and voltage regulation capability [30]. Conventional ramp-rate control using batteries requires high C-rates to compensate for rapid power variations. Repetitive fast cycling increases thermal stress and accelerates battery degradation. As PV capacity increases, second-level dynamics become a major concern for grid stability, motivating the use of hybrid or fast-response energy storage systems to smooth power [16].

2.3. Minutes: energy imbalance and regulation

At the minute scale, sustained irradiance variations introduce prolonged active power imbalance in PV-dominated systems. These deviations influence system frequency and voltage regulation over extended time horizons [31]. BESS are particularly suitable for this time scale due to their high energy capacity and dispatchability [32], [33]. However, when batteries are tasked with both low-frequency energy balancing and high-frequency transient mitigation, increased C-rate operation and frequent cycling accelerate degradation mechanisms [34]. Consequently, efficiency decreases and lifetime is significantly shortened [31].

3. HYBRID BATTERY–SUPERCAPACITOR ARCHITECTURE

Hybrid battery-supercapacitor energy storage systems (HESS) are designed to address the multi-time-scale dynamics of high-power PV plants [35]. The main objective is to decouple fast and slow power components. This decoupling improves transient response while reducing battery stress [16]. The architecture combines the high energy density of batteries with the high power density and ultra-fast response of supercapacitor devices [36], [37]. The resulting system achieves broader time-scale response capability than battery-only configurations [38].

In high-power PV applications, time-scale response capability is a critical parameter [39]. Batteries are effective for balancing energy on a second-to-minute scale [40]. However, their response to millisecond disturbances is limited. In contrast, supercapacitors can deliver or absorb high power within milliseconds. Their high cycle life enables frequent charge-discharge events without significant degradation. By allocating high-frequency power components to the supercapacitor and low-frequency components to the battery, the hybrid system enables effective power decoupling across time scales [41]. Each configuration exhibits distinct characteristics in control flexibility, system complexity, and power-sharing capabilities on the grid or load. Configurations of the HESS topologies are shown in Figure 1.

3.1. Passive topology

In a passive topology, the battery and supercapacitor are connected in parallel and directly supply power to the DC–AC converter, which connects the system to the AC bus and the grid or load as show in Figure 1(a). The power sharing between the battery and supercapacitor is inherently governed by their internal impedance characteristics rather than active control mechanisms [18].

The supercapacitor naturally responds to high-frequency transient components, effectively absorbing rapid power fluctuations. Meanwhile, the battery predominantly handles slower, energy-dominant variations. This intrinsic behavior enables a basic level of dynamic decoupling without requiring complex control strategies.

The passive topology offers significant advantages in simplicity, low cost, and high reliability by minimizing the number of power electronic components [18]. However, the absence of active control severely limits its flexibility and performance. The power distribution between storage elements cannot be precisely regulated, leading to suboptimal utilization and potential stress on the battery under dynamic conditions [42]. Consequently, passive configurations are less suitable for high-power PV applications, particularly in MW-scale systems that require strict voltage regulation, frequency support, and fast transient mitigation.

3.2. Semi-active topology

In a semi-active topology, energy storage, such as a supercapacitor, is connected to the DC link via a bidirectional DC-DC converter, while the battery is connected directly to the DC link [37]. Semi-active power converter topology configuration as shown in Figure 1(b). This configuration enables partial control of power flow, allowing selective regulation of one storage unit while maintaining a relatively simple system structure.

The presence of the DC–DC converter enables fast-transient power components to be actively directed to the supercapacitor. Due to its high-power density and rapid charge–discharge capability, the supercapacitor effectively compensates for high-frequency fluctuations. Meanwhile, the battery supplies the low-frequency and energy-dominant components, which are associated with longer time-scale variations in

PV output [43]. This coordinated behavior improves dynamic power sharing compared to passive configurations.

Compared to the passive topology, the semi-active configuration offers enhanced controllability and improved transient response while maintaining moderate implementation complexity. It is particularly suitable for applications requiring ramp-rate smoothing and short-term power stabilization in PV systems [44]. However, since only one storage element is actively controlled, the flexibility of power management remains limited compared to fully active architectures. In addition, challenges related to scalability, converter sizing, and coordination control become more pronounced in high-power, MW-scale PV installations.

3.3. Active topology

Active configurations employ separate DC–DC converters for both the battery and the supercapacitor. This architecture provides independent control of each storage element. Active power converter topology configuration as shown in Figure 1(c). This configuration enables full and decoupled control of each energy storage element, allowing precise regulation of power flow based on system dynamics.

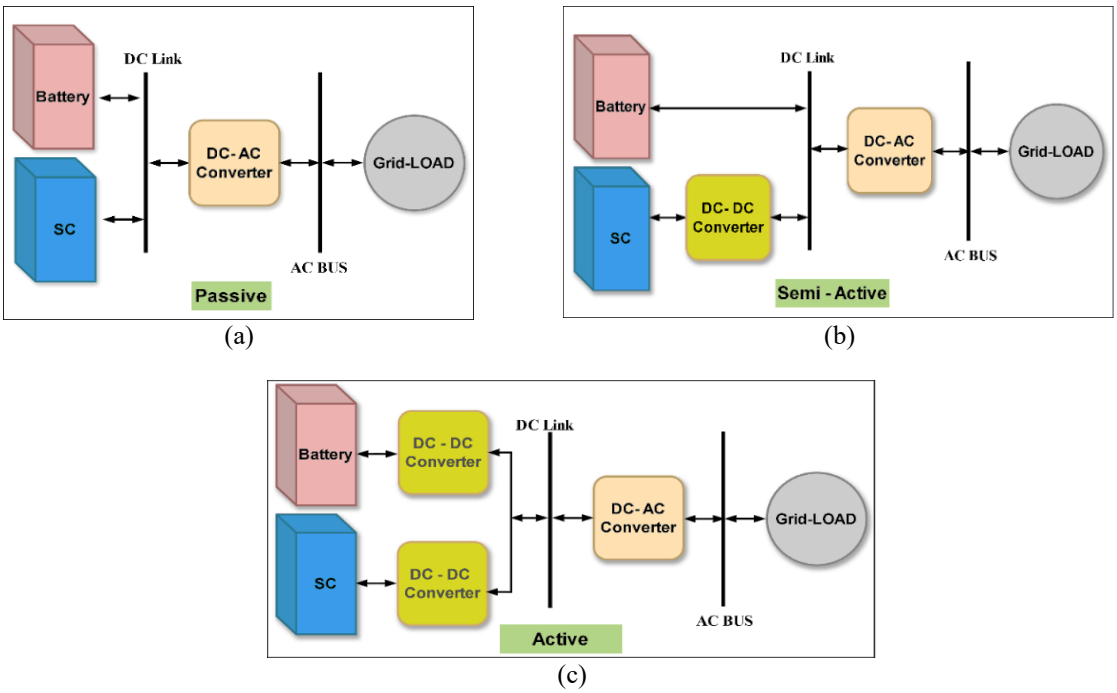


Figure 1. Hybrid battery–supercapacitor energy storage topologies; (a) passive, (b) semi-active, and (c) active configurations

By employing dedicated converters, the hybrid system can explicitly separate power components across multiple time scales. The supercapacitor is assigned to compensate for high-frequency transients due to its fast charge–discharge capability, while the battery handles low-frequency, energy-dominant variations associated with longer-duration fluctuations. This coordinated power allocation results in a significantly broader multi-time-scale response capability compared to battery-only or partially controlled configurations [45].

The independent control structure enhances the accuracy of power decoupling and allows more effective coordination of key grid-support functions. In particular, voltage regulation, frequency stabilization, and DC-link voltage control can be simultaneously optimized under dynamic operating conditions. This capability is especially beneficial for MW-scale PV systems operating in low-inertia grids, where fast and flexible response is required to maintain system stability [46].

However, these advantages come at the cost of increased system complexity. The use of multiple converters introduces higher capital cost, additional control requirements, and increased power conversion losses [42]. Consequently, the design of fully active systems must carefully balance performance improvements with efficiency and implementation constraints.

4. MULTI-TIME-SCALE CONTROL STRATEGIES FOR HYBRID BATTERY SUPERCAPACITOR SYSTEMS

Fast transients in high-power PV systems are mainly driven by rapid irradiance variations [6]. Cloud movement causes steep power ramps within short time intervals [47]. These fluctuations propagate to the DC-link and the grid interface. Uncontrolled transients lead to voltage deviation and frequency instability under dynamic operating conditions [48].

Hybrid battery–supercapacitor energy storage systems mitigate these fast dynamics through coordinated control [20]. The effectiveness of transient mitigation depends on the power sharing strategy between the battery and supercapacitor [49]. The control scheme separates slow and fast power components based on disturbance characteristics. The supercapacitor compensates fast transient components, while the battery manages slower energy variations [18]. The coordinated control framework for the hybrid energy storage system is illustrated in Figure 2, where the power-sharing controller generates independent power references for each storage unit. This coordinated operation improves transient containment and enhances dynamic stability in PV-integrated power systems.

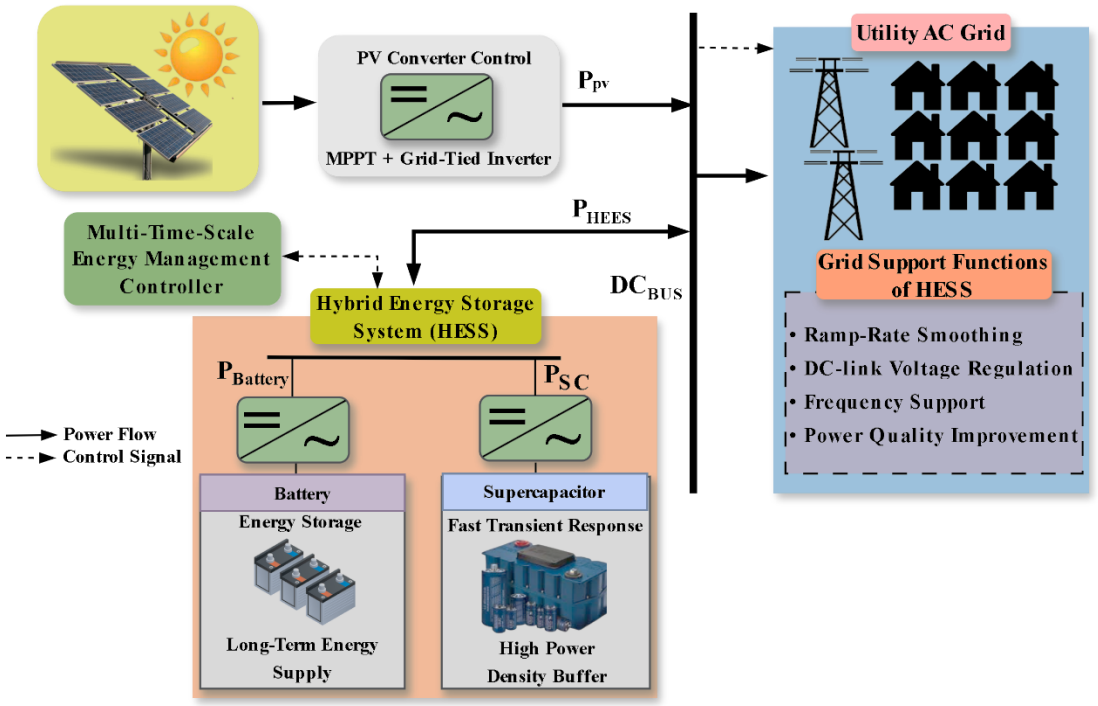


Figure 2. Hybrid battery–supercapacitor with power sharing control for fast transient mitigation in high-power PV applications

4.1. Frequency-based power decomposition

Frequency-based power decomposition is one of the most commonly applied methods for transient mitigation. In this approach, the PV output power is separated into low-frequency and high-frequency components [50]. A low-pass filter extracts the slowly varying component, while the remaining signal contains fast transients. Battery storage systems are tasked with compensating for slow variations in power. This is consistent with their higher energy density and slower dynamic response [51]. Meanwhile, supercapacitor storage systems handle high-frequency fluctuations due to their fast charge-discharge capabilities.

The cutoff frequency determines the limit between slow and fast dynamics [14]. Proper tuning for this parameter is crucial. If the cutoff frequency is set too high, the battery will experience excessive dynamic stress. However, if set too low, the supercapacitor can reach its operational limits. Therefore, the filter design must reflect expected irradiance variability and system scale [52]. This strategy is computationally simple and suitable for large-scale PV plants. However, fixed cutoff frequencies may not provide optimal performance under highly variable weather conditions [50].

4.2. Ramp-rate control strategies

Ramp-rate control directly limits the rate of change of PV output power. The controller continuously monitors the time derivative of the power signal. When the ramp exceeds a predefined threshold, the energy storage system compensates for the excess variation [53]. In this framework, the supercapacitor mitigates short-duration and high-magnitude ramps. The battery supports longer-duration variations [13]. This coordinated response reduces abrupt power injections into the grid. It also improves DC-link voltage stability.

Ramp-rate control is particularly relevant for grid-code compliance [54]. Many grid operators impose strict limits on allowable power ramp rates [55]. By enforcing these limits internally, the hybrid storage system enhances grid compatibility [56]. Despite its practical advantages, ramp-rate control requires accurate power measurement and fast detection mechanisms. Delays in sensing or control actions may reduce the effectiveness of mitigation [57].

4.3. Adaptive transient mitigation

Adaptive control strategies enhance transient mitigation by adjusting parameters in real time [16]. Instead of using fixed boundaries, the system adjusts power-sharing rules based on operating conditions [58]. Relevant indicators include state of charge, irradiance variability, and load demand [21]. During periods of high variability, a larger portion of dynamic compensation is assigned to the supercapacitor [59]. When in stable conditions, the role of the battery storage system increases. This adaptive allocation improves energy utilization and reduces unnecessary stress on either device [60].

Adaptive strategies enhance robustness against prolonged disturbances [16]. They also improve recovery speed after transient events. Although implementation complexity increases, adaptive control provides superior performance in realistic PV environments [61].

5. PERFORMANCE COMPARISON: BATTERY-ONLY VS HYBRID SYSTEMS

The effectiveness of transient mitigation strategies can be evaluated using measurable performance indicators [62]. Key metrics include DC-link voltage deviation, ramp-rate reduction, frequency nadir improvement, and battery current ripple suppression [63]. These indicators provide a systematic basis for comparing conventional battery-only systems with hybrid battery–supercapacitor configurations [64].

5.1. Evaluation criteria

Transient mitigation performance should be evaluated from both electrical stability and storage reliability perspectives [56]. From the electrical viewpoint, DC-link voltage deviation is a primary indicator of dynamic regulation quality [65]. Smaller voltage excursions during rapid irradiance changes indicate effective transient containment [16]. In addition, the damping of high-frequency oscillations reflects the controller's ability to suppress fast power disturbances before they propagate to the grid interface [58].

Ramp-rate reduction is another essential metric, particularly in grid-connected PV systems. By limiting the rate of change of injected power, the system enhances compliance with grid-code requirements [54]. Frequency nadir improvement further indicates the effectiveness of transient mitigation, especially in weak grids or high-penetration PV scenarios [66]. Together, these indicators quantify the contribution of the control strategy to overall grid stability.

From the storage perspective, battery current ripple and peak current magnitude serve as critical reliability indicators [64]. High current spikes accelerate thermal stress and electrochemical degradation [67]. Reducing these dynamic stresses directly contributes to longer battery lifetime and improved operational efficiency [60]. Therefore, a comprehensive evaluation framework must integrate both dynamic regulation metrics and long-term storage impact to accurately assess system performance [62].

5.2. Comparative analysis

The comparative performance between battery-only systems and hybrid battery–supercapacitor energy storage systems reveal significant differences in transient response capability and storage stress distribution [68]. In battery-only configurations, all power fluctuations, including high-frequency transients, are directly absorbed by the electrochemical storage layer. This results in elevated current ripple, higher C-rate operation, and increased thermal stress during rapid irradiance variations [16].

In contrast, hybrid systems allocate high-frequency components to the supercapacitor while reserving the battery for low-frequency and energy-dominant variations [58]. This dynamic decoupling enhances transient containment and reduces electrochemical stress [60]. The supercapacitor acts as a high-frequency buffer, thereby limiting sharp current spikes in the battery branch [69]. As a result, the overall system demonstrates improved voltage stability and smoother ramp-rate characteristics [63].

From a dynamic perspective, the hybrid configuration effectively expands the multi-time-scale response capability of the energy storage system. Fast disturbances are mitigated locally, preventing propagation to the DC-link and grid interface [65]. Simultaneously, reduced battery C-rate operation contributes to enhanced lifetime expectancy and improved operational reliability [60]. These advantages become more pronounced in large-scale PV plants subject to frequent and rapid irradiance fluctuations [70]. To summarize the technical differences, Table 1 presents a structured comparison between battery-only and hybrid configurations based on key performance indicators.

To complement the qualitative comparison presented above, several studies have reported quantitative improvements achieved by hybrid battery–supercapacitor systems. In literature [71], hybrid configurations have been shown to reduce DC-link current ripple by approximately 30% compared to conventional battery-only systems, significantly alleviating high-frequency stress on the battery. Other studies demonstrate substantial suppression of low-frequency current ripple, thereby improving power quality and enhancing storage reliability [72]. From the voltage regulation perspective, the study [51] indicates that voltage fluctuations can be reduced by around 4%, with steady-state voltage ripple maintained below 2% under dynamic operating conditions. These improvements highlight the effectiveness of supercapacitor-based buffering in stabilizing the DC-link during rapid transient events.

Moreover, the design-oriented studies suggest that battery current ripple is typically constrained to within 10% of nominal current to ensure reliable operation [73]. Hybrid configurations help maintain operation within this limit by absorbing fast transient components. In terms of overall system performance, improved DC-link stabilization has been associated with approximately 2% efficiency gains in experimental power electronic systems [74]. Furthermore, hybrid energy storage integration has been shown to effectively smooth power fluctuations and maintain DC-link stability under large disturbances and fault conditions in high-power systems [75]. These quantitative findings confirm that hybrid battery–supercapacitor systems provide not only qualitative advantages but also measurable improvements in transient response, power quality, and storage reliability.

Table 1. Performance comparison between battery-only and hybrid HESS

Performance metric	Battery-only system	Hybrid HESS	Improvement mechanism	Ref.
DC-link voltage deviation	Larger excursions during fast transients	Reduced voltage overshoot and undershoot	High-frequency buffering by supercapacitor	[76]–[78]
Ramp-rate smoothing	Limited capability under steep ramps	Effective ramp limiting	Dynamic power decoupling between battery and supercapacitor	[79], [80]
Frequency nadir support	Slower response to abrupt disturbances	Faster transient containment	Expanded multi-time-scale response capability	[38], [56], [81]
Battery current ripple	High ripple amplitude	Significantly reduced ripple	Supercapacitor absorbs fast fluctuations	[16], [69], [82]
Battery C-rate	Higher peak C-rate during transients	Lower peak C-rate	Reduced battery dynamic loading	[22], [34], [60]
Thermal stress	Elevated during rapid cycling	Lower thermal fluctuation	Suppressed current spikes	[16], [64], [67]
Lifetime expectancy	Accelerated degradation	Extended operational life	Reduced electrochemical stress	[41], [60], [67]

6. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite significant progress in hybrid battery-supercapacitor for high-power PV applications, several technical challenges remain unresolved [36], [56]. Most existing studies focus on simulation-based validation under limited operating scenarios [19], [83]. However, large-scale PV plants operate under highly variable and uncertain conditions [55]. This gap highlights the need for more comprehensive and scalable control frameworks [62].

One critical challenge lies in coordinating the response capability between battery and supercapacitor units in MW-scale systems [58]. While frequency-based decomposition is widely applied, optimal boundary selection remains largely heuristic [16], [59], [60]. In large installations, converter dynamics, communication delay, and measurement noise complicate multi-time-scale coordination [84]. A systematic methodology for dynamic response capability allocation under realistic operating conditions is still lacking [60].

Another major research direction involves degradation-aware real-time control [60]. Most existing strategies prioritize transient mitigation without explicitly considering electrochemical aging [58], [59]. However, battery lifetime is strongly influenced by dynamic current profiles and C-rate variation [60], [85].

Future control schemes should integrate health-aware optimization, enabling real-time trade-offs between dynamic performance and long-term reliability [56], [60].

Integration with grid-forming inverters also represents an emerging research frontier. As PV penetration increases, inverter-dominated grids require stronger voltage and frequency support [55]. Hybrid storage systems must coordinate not only internally but also with grid-forming control structures [84]. The interaction between transient buffering and virtual inertia emulation remains insufficiently explored [55].

Furthermore, there is a lack of standardized performance benchmarks for evaluating hybrid storage systems. Current studies often use different metrics, test profiles, and comparison baselines. This inconsistency limits objective assessment across research works. Establishing unified evaluation criteria would significantly improve comparability and technological maturity.

Finally, large-scale experimental validation remains limited. Most reported results rely on simulation platforms or laboratory-scale prototypes. Field validation under MW-scale PV conditions is still scarce. Practical deployment challenges, including thermal management, converter scalability, and economic feasibility, require further investigation.

Addressing these research gaps will accelerate the maturation of hybrid storage solutions for high-power PV systems. Future work should emphasize scalable coordination strategies, degradation-aware optimization, and standardized evaluation frameworks to enable reliable large-scale implementation.

7. CONCLUSION

The increasing penetration of high-power PV systems introduces significant dynamic challenges in modern power grids. Fast irradiance variations cause rapid power transients in PV-integrated systems. These transients create voltage deviation at the grid interface. These disturbances also produce frequency instability in weak grid conditions. Conventional battery-only energy storage systems exhibit limited response capability during rapid power fluctuations. These systems exhibit slower dynamic behavior in response to transient disturbances under high-variability conditions. High C-rate operation accelerates battery degradation in frequent transient scenarios. This degradation reduces battery lifetime in long-term PV applications. These technical limitations highlight the need for advanced energy storage configurations in high-penetration PV systems. Modern PV-integrated grids require storage systems with multi-time-scale response capability for stable operation. Hybrid energy storage systems provide effective transient mitigation in dynamic PV environments.

Hybrid battery–supercapacitor energy storage systems provide an effective solution for high-power PV applications. These systems combine high energy density and fast transient response capability in a unified storage configuration. The supercapacitor mitigates rapid power fluctuations during fast transient events. The battery manages slower energy variations over longer time intervals. This coordinated operation improves DC-link voltage stability under dynamic operating conditions. This operation also reduces ramp-rate variations at the grid interface. In addition, this configuration minimizes battery stress during frequent transient disturbances. As a result, hybrid systems significantly enhance dynamic stability in PV-integrated grids. Even further, systems also improve overall system reliability in high-penetration PV environments.

Hybrid energy storage systems provide essential support for high-penetration PV grids under dynamic operating conditions. Hybrid battery–supercapacitor configurations improve transient containment during rapid power fluctuations. Hybrid storage systems reduce disturbance propagation at the grid interface. Hybrid storage systems reduce the propagation of disturbances at the grid interface, thereby improving grid compatibility in PV-integrated power systems. This reduction in the stress experienced by electrochemistry can extend the life of batteries in hybrid energy storage systems during frequent transient events. Lower battery current ripple improves long-term performance in large-scale PV applications. Enhanced storage coordination supports reliable operation under highly variable irradiance conditions. These performance improvements make hybrid energy storage systems suitable for large-scale deployment.

Hybrid battery–supercapacitor systems represent key enabling technologies for resilient renewable-based power systems. Hybrid storage systems provide coordinated multi-time-scale response during transient and steady-state conditions. This coordinated response supports stable and reliable PV integration in modern power grids. Continued advancements in control strategies, system integration, and large-scale validation will accelerate hybrid system adoption in future renewable-dominated energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study

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