Smart Hybrid Charging Station Using Supercapacitor

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***Abstract*—The rapid growth of electric vehicles (EVs) has increased demand for charging infrastructure that is fast, efficient, and grid-friendly. Conventional battery-only charging stations suffer from limited power delivery during peak charging demand, reduced battery cycle life due to high-current stress, and poor transient response to sudden load variations. This paper proposes a Smart Hybrid Charging Station (SHCS) that integrates a supercapacitor bank with a battery energy storage system and renewable input (solar photovoltaic) to form a hybrid energy buffer. The supercapacitor handles high-power, short-duration transients such as fast-charging surges and regenerative pulses, while the battery supplies sustained energy over longer durations, thereby reducing battery degradation and improving overall system efficiency. A bidirectional DC-DC converter with an intelligent energy management algorithm, based on state-of-charge (SoC) monitoring and load-power thresholding, coordinates power flow between the grid, solar input, battery, supercapacitor, and EV load. The proposed architecture, control strategy, and expected performance benefits are discussed, and a comparative analysis with conventional charging stations is presented, showing potential improvements in charging speed, ripple reduction, and battery lifespan.**

***Index Terms*—Supercapacitor, Hybrid Energy Storage System, Electric Vehicle Charging, Bidirectional DC-DC Converter, Energy Management System, State of Charge, Renewable Integration, Fast Charging.**

I. INTRODUCTION

The global shift toward electric mobility has placed increasing pressure on charging infrastructure to deliver fast, reliable, and efficient power to electric vehicles (EVs). Fast-charging stations demand high instantaneous power, which, when drawn directly from batteries or the grid, causes voltage sag, thermal stress, and accelerated degradation of storage elements. Batteries, while offering high energy density, have comparatively low power density and limited cycle life under high-rate charge/discharge conditions.

Supercapacitors (SCs), also known as ultracapacitors, offer high power density, rapid charge/discharge capability, and a very high cycle life (in the order of hundreds of thousands of cycles) but relatively low energy density compared to batteries. Combining batteries and supercapacitors into a Hybrid Energy Storage System (HESS) exploits the complementary characteristics of both devices: the battery supplies steady-state energy while the supercapacitor absorbs and delivers transient power spikes. This paper proposes a Smart Hybrid Charging Station (SHCS) architecture that integrates a supercapacitor-battery hybrid buffer with solar photovoltaic (PV) input and an intelligent energy management system (EMS) to enable fast, efficient, and grid-friendly EV charging.

II. LITERATURE REVIEW

Several studies have explored hybrid energy storage combining batteries and supercapacitors for electric vehicle and renewable energy applications. Passive, semi-active, and fully active topologies have been reported for interfacing supercapacitors with batteries, with active topologies using dedicated DC-DC converters shown to provide the best control flexibility at the cost of additional complexity and converter losses.

Kuperman and Aharon reviewed passive, semi-active, and active hybridization schemes and concluded that fully active topologies, though costlier, offer the greatest degree of independent control over battery and supercapacitor currents. Lukic et al. surveyed energy storage technologies for automotive applications and highlighted the power-density/energy-density trade-off that motivates hybridization of batteries with supercapacitors.

Rule-based, fuzzy-logic, and optimization-based energy management strategies have been proposed to split power demand between the battery and supercapacitor based on frequency content, state of charge, and load power level. Choi et al. formulated an SoC-based optimization framework for battery/supercapacitor hybrid storage that reduced battery root-mean-square current compared to battery-only operation. Thounthong et al. demonstrated a flatness-based control strategy for a fuel-cell/battery/supercapacitor hybrid source, showing that the supercapacitor could absorb load transients within milliseconds, far faster than the battery's response time. Yin et al. proposed a utility-function-based real-time controller that dynamically apportions power between storage elements according to their instantaneous cost of use, improving overall system efficiency.

Solar-assisted EV charging stations have also been widely investigated to reduce dependence on grid power and lower the carbon footprint of transportation electrification, typically employing MPPT-controlled PV converters feeding a common DC bus alongside grid rectifiers. Camara et al. and Samosir and Yatim both examined bidirectional DC-DC converter designs specifically for supercapacitor interfacing, reporting that closed-loop current-mode control provides stable operation across wide SoC ranges. However, limited work integrates supercapacitor-based transient buffering specifically within solar-assisted smart charging stations with a unified SoC-based coordination strategy that simultaneously considers grid power, PV generation, battery health, and EV load dynamics, which motivates the present work. Table II summarizes representative prior approaches against the proposed system.

TABLE II. SUMMARY OF REPRESENTATIVE PRIOR APPROACHES

Study	Storage Combination	Control Approach	PV Integration
Kuperman & Aharon [1]	Battery + SC	Passive/Active topology review	No
Choi et al. [2]	Battery + SC	SoC-based optimization	No
Thounthong et al. [7]	Fuel Cell + Battery + SC	Flatness-based control	No
Camara et al. [8]	Battery + SC	Current-mode converter control	No
Proposed SHCS	Battery + SC + PV + Grid	SoC & threshold-based EMS	Yes

III. PROPOSED SYSTEM ARCHITECTURE

The proposed Smart Hybrid Charging Station consists of five major subsystems: (i) a grid/solar PV input stage, (ii) a battery energy storage bank, (iii) a supercapacitor bank, (iv) bidirectional DC-DC converters interfacing the battery and supercapacitor to a common DC bus, and (v) an energy management and control unit. A block-level layout of the system is described below.

Grid power is rectified and regulated through an AC-DC front-end converter, while solar PV power is conditioned through a maximum power point tracking (MPPT) DC-DC converter. Both sources feed a common DC bus that supplies the EV charging port. The battery and supercapacitor are each interfaced to the DC bus through independent bidirectional buck-boost converters, allowing them to source or sink current depending on instantaneous load demand and their own state of charge.

IV. MATHEMATICAL MODELING

This section presents the key equations governing supercapacitor energy storage, hybrid power sharing, and converter duty-ratio control used in the design of the proposed system.

A. Supercapacitor Energy and Power

The energy stored in a supercapacitor bank is given by

$$E_{sc} = \tfrac{1}{2} C_{sc} (V_{max}^2 - V_{min}^2) \quad (1)$$

where C_{sc} is the supercapacitor bank capacitance, and V_{max} and V_{min} are the maximum and minimum allowable terminal voltages, respectively. The usable energy window is deliberately bounded between V_{max} and V_{min} (typically 50% of V_{max}) since supercapacitor terminal voltage varies almost linearly with SoC, unlike a battery.

The instantaneous power delivered or absorbed by the supercapacitor is

$$P_{sc}(t) = V_{sc}(t) \cdot I_{sc}(t) \quad (2)$$

B. Hybrid Power Balance

At any instant, the total load power demanded by the EV charging port must be supplied jointly by the grid/PV front end, the battery, and the supercapacitor:

$$P_{load}(t) = P_{grid}(t) + P_{pv}(t) + P_{batt}(t) + P_{sc}(t) \quad (3)$$

The high-frequency (transient) component of the load power is separated from the low-frequency (average) component using a low-pass filter of time constant τ:

$$P_{avg}(t) = (1/\tau) \int P_{load}(t)\, dt, \quad P_{trans}(t) = P_{load}(t) - P_{avg}(t) \quad (4)$$

The battery reference is set to track Pavg(t), while the supercapacitor reference tracks Ptrans(t), forming the basis of the frequency-domain power-splitting rule used within the EMS.

C. Converter Duty Ratio

For the bidirectional buck-boost converter interfacing each storage element to the DC bus of voltage Vbus, the duty ratio D in boost (discharging) mode is

$$D = 1 - (V_{storage} / V_{bus}) \quad (5)$$

and in buck (charging) mode the storage-side voltage is regulated as Vstorage = D · Vbus.

The current controller regulates inductor current Iref, generated by the outer voltage loop, using a standard PI compensator:

$$I_{ref}(t) = K_p \cdot e(t) + K_i \int e(t)\, dt, \quad e(t) = V_{bus,ref} - V_{bus}(t) \quad (6)$$

D. State of Charge Estimation

Battery and supercapacitor SoC are estimated using coulomb counting:

$$SoC(t) = SoC(0) - (1/Q_{rated}) \int i(t)\, dt \quad (7)$$

where Qrated is the rated charge capacity of the respective storage element and i(t) is its discharge current. These SoC values are the principal inputs to the energy management rules described in Section VI.

V. METHODOLOGY

A. Hybrid Energy Storage Sizing

The battery bank is sized to meet the average energy requirement of the expected EV charging load profile, while the supercapacitor bank is sized to handle the peak power transients above the average load, typically occurring during the initial constant-current fast-charging phase or during sudden load steps. This division of duty reduces the peak current drawn from the battery, thereby reducing internal heating and capacity fade.

B. Bidirectional DC-DC Converter

A bidirectional buck-boost converter topology is used for both the battery and supercapacitor interfaces, enabling power flow in both directions to support regenerative energy capture and controlled discharge. Each converter is controlled through a closed-loop current controller with an outer DC-bus voltage regulation loop.

C. Energy Management Strategy

The EMS uses a threshold and state-of-charge based rule set: (1) if the instantaneous load power exceeds a defined threshold above the average demand, the supercapacitor supplies the additional power; (2) if the supercapacitor SoC falls below a minimum limit, the battery assumes full load and simultaneously trickle-charges the supercapacitor during low-demand intervals; (3) surplus solar PV power, when available, is prioritized to recharge the battery and supercapacitor before being exported to the grid. This layered control minimizes high-rate battery cycling while ensuring the supercapacitor remains available for the next transient event.

VI. WORKING PRINCIPLE

During the start of a fast-charging event, the sudden increase in current demand is met primarily by the supercapacitor owing to its low equivalent series resistance and fast response time, preventing voltage sag on the DC bus. As the supercapacitor SoC decreases and the load stabilizes, the battery gradually takes over to sustain the charging current for the remainder of the session. When the EV disconnects or load demand drops, any surplus power from solar PV or regenerative sources is used to replenish the supercapacitor first, restoring its readiness for the next transient demand, followed by battery recharging.

Algorithmically, the EMS executes the following sequence at each control-loop interval: (1) measure Pload, Ppv, SoCbatt, and SoCsc; (2) compute Pavg and Ptrans using the low-pass filter of (4); (3) if Ptrans > 0 and SoCsc is above its minimum threshold, command the supercapacitor converter to source Ptrans; (4) if SoCsc falls below the minimum threshold, transfer the transient duty to the battery and flag the supercapacitor for recharging during the next low-demand interval; (5) direct any PV surplus, computed as Ppv − Pload when positive, to recharge the supercapacitor first and then the battery. This sequence repeats continuously throughout each charging session.

VII. SIMULATION PARAMETERS

For evaluation purposes, representative system parameters, summarized in Table III, were adopted based on typical values reported in the hybrid energy storage literature and standard fast-charging port ratings. These parameters define the operating envelope used to characterize the expected converter and control performance.

TABLE III. REPRESENTATIVE SYSTEM PARAMETERS

Parameter	Typical Value
DC bus voltage (Vbus)	400 V
Battery bank capacity	30 kWh (Li-ion)
Supercapacitor bank	6 F, 400 V (module)
PV array rating	10 kWp
Rated EV fast-charge power	50 kW
Converter switching frequency	20 kHz
SC SoC operating window	50%–100%
Battery SoC operating window	20%–90%

VIII. RESULTS AND DISCUSSION

Evaluation of the proposed architecture against these parameters is expected to demonstrate three principal benefits over a conventional battery-only charging station: (i) reduced peak current stress on the battery during fast-charging events, (ii) reduced DC-bus voltage ripple and improved transient response due to the supercapacitor's fast dynamic support, and (iii) improved round-trip efficiency by minimizing high-rate battery losses. A qualitative comparison of the proposed hybrid configuration against a conventional battery-only station is summarized in Table I.

TABLE I. COMPARISON OF CONVENTIONAL AND PROPOSED CHARGING STATIONS

Parameter	Battery-Only Station	Proposed Hybrid Station
Peak battery current stress	High	Reduced
DC-bus voltage ripple	Higher	Lower
Transient response speed	Moderate	Fast
Battery cycle life impact	Higher degradation	Reduced degradation
Renewable energy utilization	Limited	Improved (PV-assisted)

The reduction in peak battery current stress follows directly from the power-splitting relation in (4): since the supercapacitor absorbs Ptrans(t), the battery current amplitude is bounded by the average load component alone, which for a typical fast-charging profile with brief high-power surges can reduce the battery's peak C-rate substantially. This lower C-rate operation is significant because battery capacity fade accelerates supra-linearly with charge/discharge rate, so even a modest reduction in peak current can translate into a proportionally larger extension of usable battery cycle life.

The reduction in DC-bus voltage ripple stems from the supercapacitor's low equivalent series resistance (ESR), typically an order of magnitude lower than a battery's internal impedance, which allows it to respond to step-load changes within milliseconds rather than the seconds-scale response of a battery-only converter loop.
This faster response keeps the DC bus voltage closer to its regulation set-point during the initial transient of a fast-charging session, improving power quality delivered to the EV charger's front end.
Round-trip efficiency improvement arises because high-rate battery cycling incurs disproportionately larger I^2R losses and heat generation than low-rate cycling; by diverting the highest-rate current

components to the supercapacitor, average battery losses per charging session are expected to decrease, partially offset by the additional conduction and switching losses of the extra supercapacitor-side converter. Overall system-level efficiency gains are therefore expected to be most pronounced for charging profiles with frequent, sharp power transients, such as opportunistic highway fast-charging, and comparatively smaller for steady, low-power overnight charging.

IX. COST AND FEASIBILITY ANALYSIS

A practical concern for hybrid storage systems is the added capital cost of the supercapacitor bank and its dedicated converter relative to a battery-only design. However, this incremental cost is expected to be partially offset over the station's operating life through two mechanisms: reduced battery replacement frequency due to lower cycling stress, and reduced oversizing of the battery bank that would otherwise be needed to meet peak power ratings alone. Supercapacitors also require substantially less maintenance than batteries, as they are largely unaffected by deep-discharge or high-temperature degradation mechanisms, further improving lifecycle economics for high-utilization public charging stations.

From a feasibility standpoint, the proposed architecture uses standard, commercially available components: Li-ion battery modules, supercapacitor modules rated for automotive and grid-support applications, and bidirectional buck-boost converter topologies that are well established in industry. This makes the architecture readily deployable using existing supply chains, with the primary engineering effort concentrated in the EMS control software rather than in custom power-electronic hardware.

X. ADVANTAGES AND APPLICATIONS

The proposed Smart Hybrid Charging Station is suited for public fast-charging hubs, highway charging corridors, and renewable-integrated microgrid charging stations.
Key advantages include extended battery life due to reduced high-rate cycling, improved power quality on the DC bus, better utilization of intermittent solar generation, and enhanced capability to support short, high-power charging bursts without oversizing the battery bank. The architecture is also well suited to depot charging for electric buses and fleet vehicles, where charging sessions are frequent, time-constrained, and often require repeated high-power bursts that would otherwise significantly stress a battery-only storage bank.

XI. CONCLUSION AND FUTURE SCOPE

This paper presented the design concept of a Smart Hybrid Charging Station that combines a supercapacitor-battery hybrid energy storage system with solar PV input and an SoC-based energy management strategy to improve the performance and longevity of EV charging infrastructure. By allocating transient high-power demand to the supercapacitor and steady-state energy delivery to the battery, the proposed system is expected to reduce battery stress, improve transient response, and better utilize renewable energy input.

Mathematical models for supercapacitor energy storage, hybrid power balance, converter duty-ratio control, and SoC estimation were formulated to support the control strategy, and a qualitative cost and feasibility discussion indicated that the architecture is realizable using commercially available components.

Future work will focus on hardware-in-the-loop validation of the proposed control algorithm, optimization of the energy management strategy using machine learning or fuzzy-logic techniques to adapt thresholds to real-world traffic and irradiance patterns, and a detailed techno-economic analysis of large-scale deployment across highway and urban charging networks.
Additional future directions include extending the architecture to support vehicle-to-grid (V2G) power flow and multi-port simultaneous charging with shared hybrid storage resources.

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