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Effect of Supercapacitor Contribution on Discharge Performance and Efficiency in a Battery–Supercapacitor Hybrid Energy Storage Architecture

Ramalan Abubakar[1*], Abdullahi Zakari[2]

[1]*Department of Physics, University of Abuja, Abuja, Nigeria*

[2]*Department of Physics with Electronics, Air Force Institute of Technology (AFIT), Kaduna, Nigeria*

Corresponding author: Ramalan Abubakar (e-mail: abubakar.ramalan@uniabuja.edu.ng).

ABSTRACT Hybrid energy storage systems (HESS) that combine batteries and supercapacitors are becoming increasingly important as they reduce the load on the batteries by offloading peak loads to the supercapacitor. This increases system efficiency and extends battery life. Although the configuration of the HESS is important, there are only a few studies that have investigated the influence of power distribution on battery capacity, energy conservation and system efficiency using simulations. Therefore, this study created a dynamic model of a battery-supercapacitor HESS using OpenModelica and simulated the discharge process for three power distribution patterns (battery only: α =0, Hybrid with low supercapacitor proportion: α =0.3, Hybrid with high supercapacitor proportion: α =0.6). In this model, a Parameter α is introduced that divides and determines the load, What proportion of the total load current is absorbed by the supercapacitor? The Simulation was conducted with a fixed load current of 5.0 A and a discharge time of 10 minutes. The results show that as the proportion of supercapacitor increases, the battery consumption decreases and the system efficiency increases. In pure battery operation, the residual charge after discharge dropped to 16.67 %, and the system efficiency remained at 32.43 %. In the hybrid configuration with a higher supercapacitor proportion, the residual charge remained at 66.67 %, and the initial system efficiency reached 85.04 %. The remaining battery energy at end of simulation increased from 2,220 J (battery only) to 8,880 J (hybrid configuration with high supercapacitor proportion) — a fourfold improvement in energy retention. This study clearly demonstrates the performance advantages of the HESS configuration and shows that OpenModelica is an effective platform for dynamic simulations of hybrid electrochemical energy storage systems.

KEYWORDS: Hybrid Energy Storage System, Battery, Supercapacitor, OpenModelica, Power Sharing, State of Charge, Energy Efficiency, Battery Stress Reduction

I. INTRODUCTION

With the increasing use of renewable energy systems, electric vehicles and portable electronic devices, the need for energy storage solutions that combine high energy density and high performance is increasing. Electrochemical batteries such as lithium-ion and lead-acid batteries do have high energy density, but have weaknesses such as low power density, low capacity at high discharge currents and Degradation due to repeated current peaks (Tarascon & Armand, 2001). Supercapacitors, on the other hand, are characterized by high power density, fast charging and discharging, and long cycle life, but their energy storage capacity per unit mass/volume is significantly lower (Conway, 1999). Against this background, the "battery-supercapacitor Hybrid energy storage system (HESS)", which combines the advantages of both technologies, is gaining importance as a promising solution. In HESS, the battery delivers the energy gradually, while the supercapacitor absorbs the short-term peak power and thus

relieves the battery (Khaligh & Li, 2010). This division of tasks reduces the internal resistance loss and heat generation in the battery, thus preventing capacity loss and shortened service life-all crucial factors for electric vehicles and the storage of grid energy (Cao & Emadi, 2012).
The effectiveness of HESS depends significantly on the power distribution strategy chosen. The ratio (α) of the load current distributed to the supercapacitor determines the balance between the reduction of battery load and the wear of the supercapacitor. If α is too small, the battery remains the primary energy source, and a significant reduction in load is not expected. If α is too large, the supercapacitor takes over most of the instantaneous current, significantly reducing the discharge rate of the battery, but at the same time leads to uncontrollable discharge (Dougal et al., 2002). A sound numerical understanding of this conflict of objectives is essential for system design and selection of control strategies. Dynamic simulations are a cost-effective method to evaluate the performance of HESS under various conditions without having to build a physical prototype. OpenModelica is a free, open-source, equation-based simulation environment based on the Modelica modelling language and is therefore well suited to modelling dynamic electrochemical systems (Fritzson, 2014). RC equivalent circuits are widely used to describe the behaviour of batteries and supercapacitors and to compute discharge characteristics, voltage curves, and energy losses (Zubieta & Bonert, 2000; Chen & Rincon-Mora, 2006). In this study, a HESS model was developed in OpenModelica and used to simulate the discharge behaviour under three load distribution scenarios: battery alone, low supercapacitor contribution, and high supercapacitor contribution. Battery state of charge (SOC), supercapacitor voltage, terminal voltage, output power, energy retention, and system efficiency during a 10-minute constant-current discharge are reported and systematically compared across the three scenarios.

II. MODEL DEVELOPMENT

A. System Architecture

The HESS was modelled as a battery and a supercapacitor connected in parallel to a common load. A static power-sharing parameter $\alpha \in [0, 1]$ governed the fraction of total load current supplied by the supercapacitor at every instant. The battery supplied the remaining fraction $(1 - \alpha)$ of the load current. This formulation is consistent with rule-based power management strategies commonly studied in HESS literature (Dougal et al., 2002; Shen et al., 2014).

B. Governing Equations

The load current split was defined as:

$$I\_sc = \alpha \times I\_load$$

$$I\_bat = (1 - \alpha) \times I\_load$$

Battery state of charge and supercapacitor voltage evolved according to:

$$dSOC\_bat/dt = -I\_bat / C\_bat$$

$$dV\_sc/dt = -I\_sc / C\_sc$$

Battery terminal voltage, power outputs, remaining energy, and system efficiency were computed as:

$$V\_bat = V\_oc - I\_bat \times R\_bat$$

$$P\_bat = V\_bat \times I\_bat, \quad P\_sc = V\_sc \times I\_sc$$

$$E\_bat = SOC\_bat \times C\_bat \times V\_oc$$

$$\eta = (P\_bat + P\_sc) / (P\_bat + P\_sc + I\_bat^2 R\_bat + I\_sc^2 R\_sc) \times 100\%$$

C. Simulation Scenarios and Parameters

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Three scenarios were simulated. In the Battery Only scenario (α = 0), all load current was supplied by the battery and the supercapacitor was inactive. In the Hybrid Low SC scenario (α = 0.3), the supercapacitor supplied 30% of the load current. In the Hybrid High SC scenario (α = 0.6), the supercapacitor supplied 60% of the load current and was assigned a larger capacitance (100 F) and lower ESR (0.03 Ω) to reflect a more capable supercapacitor unit. Table 1 summarises the full parameter set for each scenario.

Table 1. OpenModelica Model Parameters for the Three HESS Simulation Scenarios.

Scenario	R_bat (Ω)	C_bat (C)	C_sc (F)	R_sc (Ω)	I_load (A)	α
Battery Only	0.5	3600	50	0.05	5.0	0.0
Hybrid Low SC	0.5	3600	50	0.05	5.0	0.3
Hybrid High SC	0.5	3600	100	0.03	5.0	0.6

D. Model Assumptions

The following assumptions were applied throughout: (1) the load current demand is constant at 5.0 A; (2) the power-sharing fraction α is fixed and does not respond dynamically to system state; (3) battery open circuit voltage is constant at 3.7 V; (4) temperature, electrolyte resistance, and self-discharge are neglected; (5) the supercapacitor is modelled as an ideal capacitor in series with ESR; (6) the model evaluates comparative performance trends under identical conditions rather than predicting absolute behaviour of a specific device.

E. Simulation Setup

All simulations were executed in OpenModelica OMEdit. Each scenario was simulated from t = 0 to t = 600 s (10 minutes) with battery initial SOC = 1.0 and supercapacitor initial voltage = 2.5 V. Output was generated at 500 intervals and exported as CSV for post-processing.

III. RESULTS AND DISCUSSION

A. Battery State of Charge

Figure 1 shows the battery SOC over the 10-minute discharge period for all three scenarios. The battery-only scenario exhibited the most rapid SOC decline, falling from 100% to 16.67% by the end of simulation. This steep depletion reflects the full 5.0 A load current being drawn exclusively from the battery throughout the discharge period. In contrast, the Hybrid Low SC scenario reduced battery depletion to a final SOC of 41.67%, and the Hybrid High SC scenario preserved 66.67% of battery charge, a fourfold improvement over the battery-only case. charge, a fourfold improvement over the battery-only case.

The linear SOC trajectories reflect the constant-current discharge and constant power-sharing fractions in the model. The slope of each curve is directly proportional to the battery current fraction (1 − α), confirming that higher supercapacitor contribution reduces battery discharge rate in a predictable and controllable manner.

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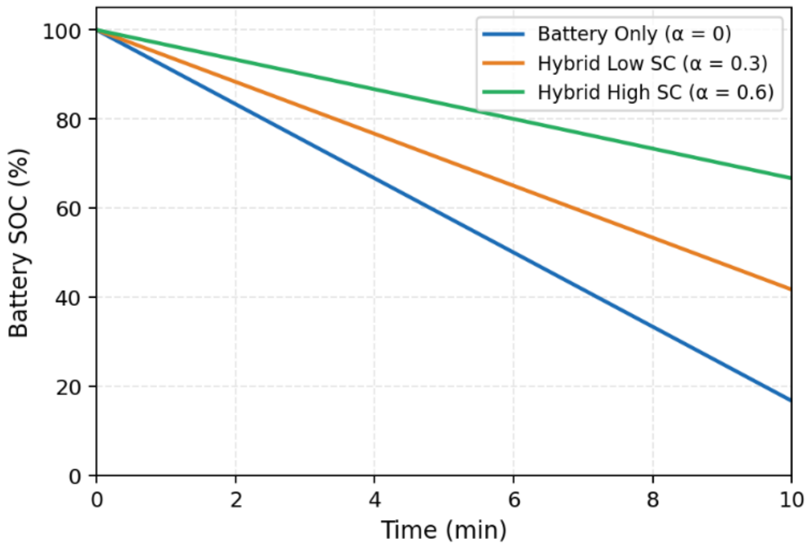

Figure 1. Simulated Battery State of Charge Versus Time for all Three Scenarios

B. Supercapacitor Voltage

Figure 2 shows the supercapacitor voltage decline for the two hybrid scenarios. Both hybrid supercapacitors deplete well within the 10-minute discharge window. Applying the governing equation $dV_{sc}/dt = -I_{sc} / C_{sc}$ with a fixed discharge current, the depletion time is given by $t_{dep} = V_{sc0} \times C_{sc} / I_{sc}$. For the Hybrid Low SC scenario ($C_{sc} = 50$ F, $I_{sc} = 1.5$ A, $V_{sc0} = 2.5$ V), this yields $t_{dep} = 83.3$ s (approximately 1.4 minutes). For the Hybrid High SC scenario ($C_{sc} = 100$ F, $I_{sc} = 3.0$ A), $t_{dep} = 83.3$ s as well, since the larger capacitance is offset by the proportionally higher current drawn. After depletion, the full load current reverts to the battery, which reduces but does not eliminate the benefit of the hybrid configuration over the preceding 1.4 minutes. This highlights an important design constraint: supercapacitor sizing must account for both capacitance and the fraction of load current assigned (α), and the present scenarios represent a short-duration peak-shaving configuration rather than full-cycle protection.

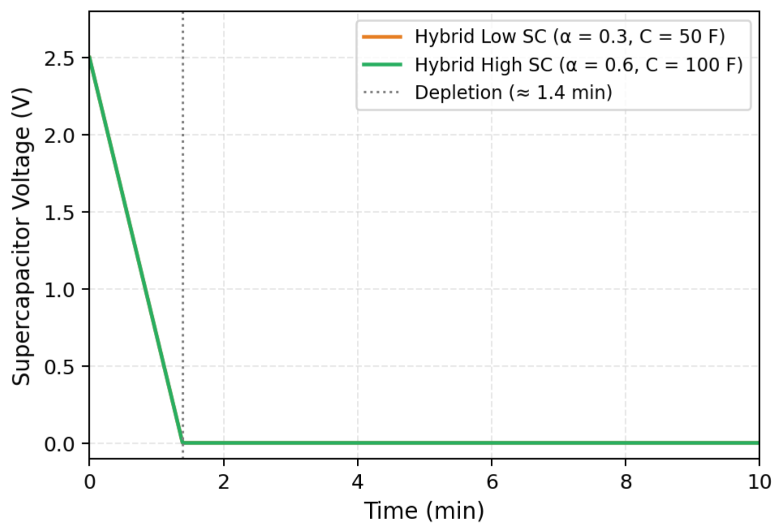

Figure 2. Simulated Supercapacitor Voltage versus Time for the Hybrid Low SC and Hybrid High

B. Battery Terminal Voltage

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Figure 3 shows the battery terminal voltage profiles. In the battery-only scenario, the constant internal resistance drop (I_bat × R_bat = 5.0 × 0.5 = 2.5 V) produces a terminal voltage of 1.2 V throughout discharge — significantly below the open circuit voltage of 3.7 V, indicating large resistive losses. The Hybrid Low SC scenario reduces battery current to 3.5 A (α = 0.3), raising terminal voltage to 1.95 V. The Hybrid High SC scenario further reduces battery current to 2.0 A (α = 0.6), raising terminal voltage to 2.7 V and substantially reducing the resistive overpotential.

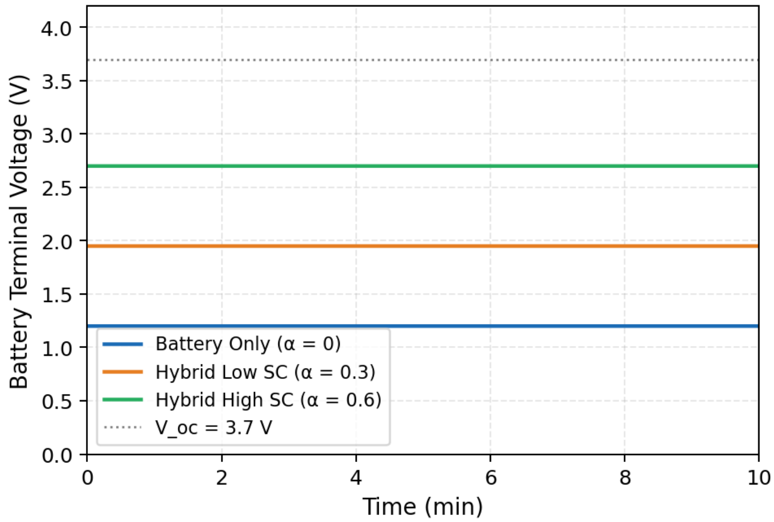

Figure 3. Simulated Battery Terminal Voltage versus Time for all Three Scenarios.

C. Poweroutput

Figure 4 shows battery power output over time. The battery-only scenario maintains a constant power output of 6.0 W throughout discharge. The Hybrid Low SC scenario increases battery power slightly to 6.825 W, reflecting the higher terminal voltage at lower current. The Hybrid High SC scenario reduces battery power to 5.4 W, as the battery current is reduced to 2.0 A.

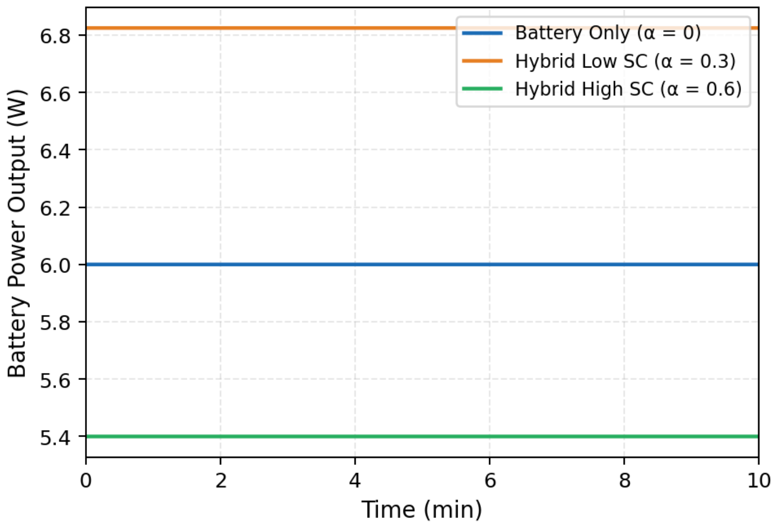

Figure 4. Simulated Battery Power Output versus Time for all Three Scenarios

D. Supercapacitor Power Output

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Figure 5 shows supercapacitor power output for the two hybrid scenarios. The Hybrid High SC supercapacitor delivered higher initial power (7.5 W at t = 0) compared to the Low SC case (3.75 W), consistent with its larger current fraction and initial voltage. Both supercapacitor power curves decline over time as the supercapacitor voltage falls, reflecting the capacitive discharge behaviour.

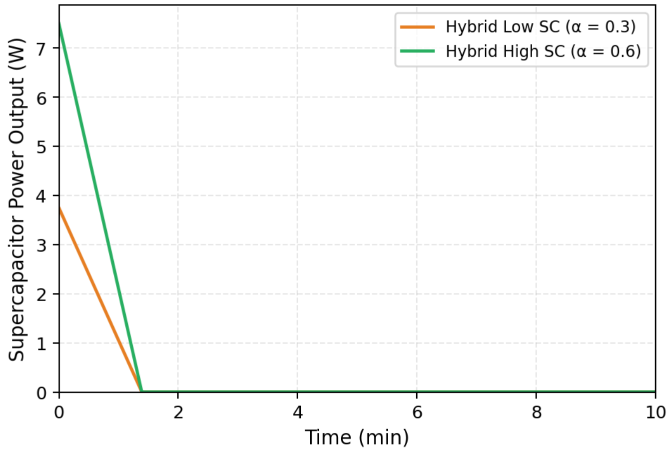

Figure 5. Simulated Supercapacitor Power Output versus Time for the Two Hybrid Scenarios.

E. Battery Energy Retention

Figure 6 shows remaining battery energy computed from E_bat = SOC_bat × C_bat × V_oc over the discharge period. In the battery-only scenario, remaining battery energy fell from 13,320 J to 2,220 J — a reduction of 11,100 J over 10 minutes. The Hybrid Low SC scenario retained 5,550 J and the Hybrid High SC scenario retained 8,880 J of battery energy at the end of simulation. It should be noted that these values represent energy remaining in the battery, not total system energy generated or stored. The improvement reflects reduced battery discharge due to supercapacitor current-sharing, not any net increase in stored energy. Expressed as a fraction of initial battery energy, the Hybrid High SC scenario preserved 66.7% of battery charge compared to only 16.7% in the battery-only case. In applications such as electric vehicles or backup power systems, a HESS with α = 0.6 would therefore extend effective battery runtime by approximately four times under the same load.

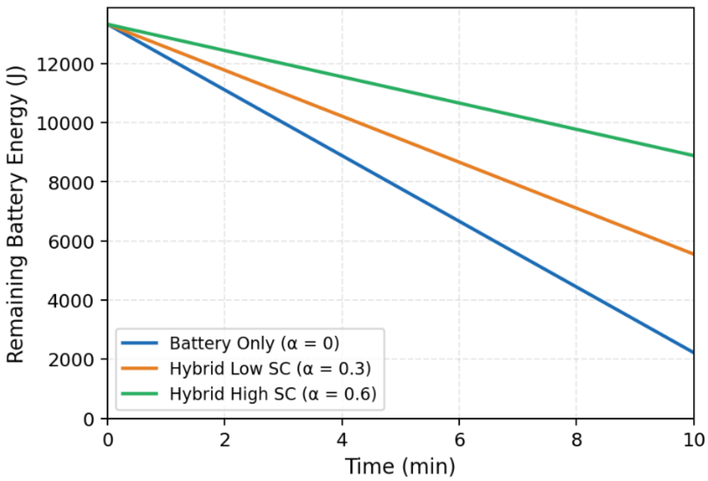

Figure 6. Simulated Battery Energy Remaining versus Time for all Three Scenarios.

F. System Energy Efficiency

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Figure 7 shows system energy efficiency over time. The battery-only scenario maintained a low constant efficiency of 32.43% throughout discharge, reflecting the large resistive losses associated with high battery current (5.0 A through 0.5 Ω internal resistance). The Hybrid Low SC scenario achieved an initial efficiency of approximately 62.9%, and the Hybrid High SC scenario achieved 85.04% at the start of discharge. The improvement arises from two mechanisms: reduced battery current lowers I^2R losses in the battery, and the supercapacitor ESR (0.03–0.05 Ω) is an order of magnitude lower than the battery internal resistance, so supercapacitor losses are minimal.

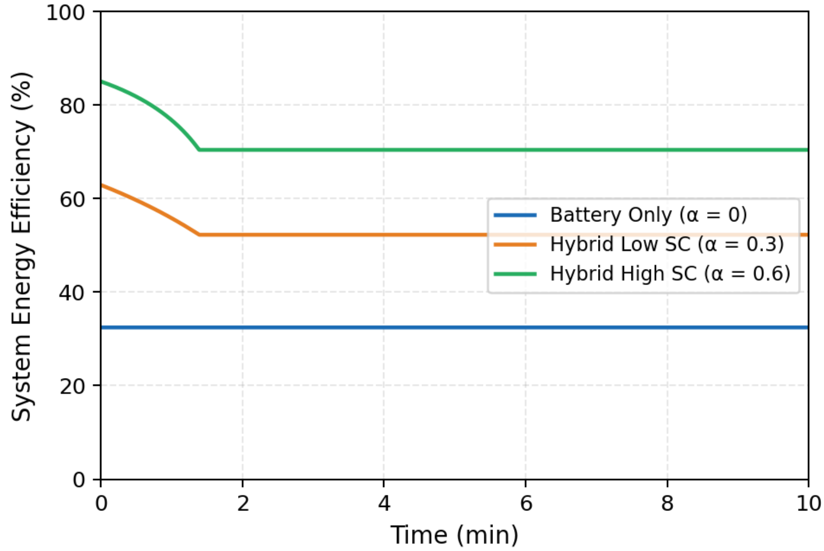

Figure 7. Simulated System Energy Efficiency versus Time for all Three Scenarios.

G. Comparative Summary

Figure 8 presents side-by-side bar chart comparisons of final battery SOC and initial system efficiency across the three scenarios. The monotonic improvement from battery-only to hybrid high SC across both metrics clearly illustrates the performance benefit of increasing supercapacitor contribution. Table 2 provides the full numerical summary.

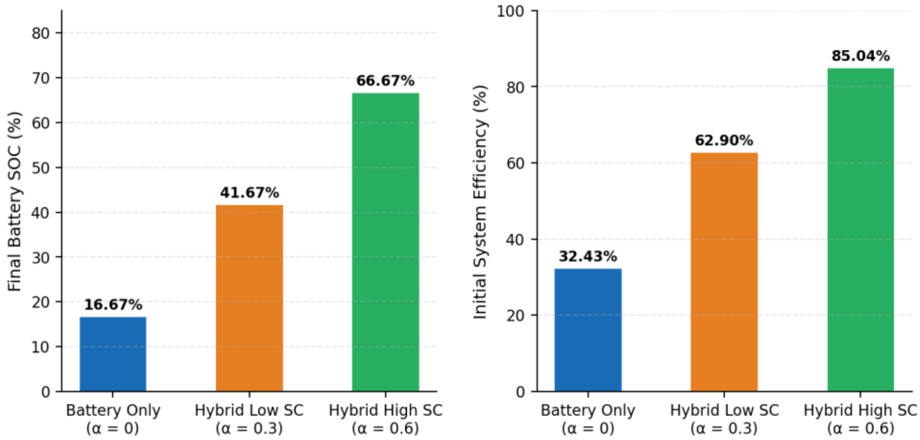

Figure 8. Comparative Bar Charts of Final Battery SOC and System Efficiency across all Three Scenarios.

Table 2. Summary of OpenModelica Simulation Results at t = 10 min for all Three Scenarios.

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Scenario	Final SOC (%)	E_bat (J)	P_bat (W)	Efficiency (%)	SC Contribution
Battery Only	16.67	2,220.00	6.00	32.43	0%
Hybrid Low SC	41.67	5,550.00	6.825	62.90	30%
Hybrid High SC	66.67	8,880.00	5.40	85.04	60%

H. Design Implications

The simulation results showed three important points for the design of a hyperenergy storage system (HESS). First, the contribution factor α of the supercapacitor significantly affects the battery load. A doubling of α from 0.3 to 0.6 doubles the energy remaining in the battery at the end of discharge. Second, the choice of supercapacitor capacity should be made carefully. Components with low capacity, such as 50 F, are consumed quickly at high discharge current. Therefore, the capacity must be matched exactly to the desired α value and discharge time. Third, the overall efficiency of the system is extremely sensitive to the internal resistance of the battery. By effectively using low resistance supercapacitors, the largest source of loss can be avoided in pure battery operation. At α =0.6, the efficiency can be increased by up to 2.6 times.

I. Limitations

In this model, the power distribution ratio is fixed, and dynamic Control methods such as Fuzzy Control, rule-based switching and model predictive Control, which more accurately depict the operation of real hybrid energy storage systems (HESS), are not applied. The no-load voltage of the battery is assumed to be constant, although in reality it varies depending on the state of charge (SOC), temperature and aging. In addition, self-discharge, thermal effects, electrolyte resistance and self-discharge of the supercapacitor are not modeled. Since the power distribution parameter α does not vary with the state of discharge of the supercapacitor, the redistribution behavior in which the full load is returned to the battery after supercapacitor depletion is not dynamically captured in the model. As shown in Section 3.2, with the parameters selected both hybrid supercapacitors deplete within approximately 1.4 minutes; the SOC and energy retention benefits reported in Sections 3.1 and 3.5 therefore reflect the combined effect of the peak-shaving period and the subsequent battery-only discharge. A dynamic model that clamps supercapacitor current to zero upon depletion and reassigns full load to the battery would more precisely capture this transition, and is recommended for future work. In addition, the model assumes constant battery open-circuit voltage, neglects temperature and aging effects, and uses a fixed α rather than a real-time energy management strategy. Future work should integrate dynamic control algorithms, SoC-dependent open-circuit voltage curves, and experimentally verified impedance parameters. Experimental validation against physical devices is also required before the results can be applied to specific hardware design.

VI. CONCLUSION

In this study, we developed a dynamic simulation framework using OpenModelica to evaluate the discharge performance of a battery-supercapacitor hybrid energy storage system (HESS) under three different power distribution patterns. The model controls the load current distribution using a static distribution parameter α. Based on a 10-minute constant load discharge, we predicted the state of charge (SOC) of the battery, supercapacitor voltage, terminal voltage, output power, energy storage rate and system efficiency. The simulation results were clear and consistently showed the superiority of the HESS configuration over pure battery operation. For example, increasing the supercapacitor contribution from α = 0 to α = 0.6 improved the final SOC of the battery from 16.67% to 66.67%, increased the remaining

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battery energy from 2,220 J to 8,880 J (a fourfold improvement in energy retention), and increased the initial system efficiency from 32.43% to 85.04% These improvements are due to the reduced current flow through the battery, the reduced I^2R losses, and the fact that the equivalent series resistance (ESR) of the supercapacitor is lower than the internal resistance of the battery. The study reconfirmed that OpenModelica is an effective and user-friendly platform for comparative simulations of hybrid electrochemical energy storage systems (HESS), and that the power density and capacity Design of supercapacitors are extremely important parameters in HESS Design. The simulation framework presented here provides the basis for future research. It enables the Integration of dynamic energy management strategies, the use of component parameters based on real-world measurements, and even extensions to include thermal and degradation models.

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