Hybrid Battery Energy System for Electric Vehicles

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Abstract—**The energy storage system has been the most essential or crucial part of every electric vehicle or hybrid electric vehicle. The electrical energy storage system encounters a number of challenges as the use of green energy increases; yet, energy storage and power boost remain the two biggest challenges in the development of electric vehicles. Because of the rapid improvement of, the range of electric vehicles on a single charge, the demand for electric cars is rising quickly. To solve the problem experienced by many EVs of low range, an efficient electrical energy storage technology is required so that we can be able to increase the range. Installing a supercapacitor to serve as an additional energy source is one of the practical and realistic choices for enhancing performance and meeting its characteristics of high energy and power density. Chemical batteries and ultra-capacitors / super-capacitors will make up the energy storage system. In this study, l will be exploring the benefits of using supercapacitors in electric vehicles to handle their low power dynamic load. In this paper, the MATLAB simulation results show the advantages and performance of utilizing super-capacitors with batteries in electric vehicles as well as the viability of this approach.**

Index Terms—**super-capacitor, battery, electric vehicle, MATLAB simulation**

I. INTRODUCTION

Electric vehicles are gaining a growing interest for having precise capabilities such as having low emissions, high efficiency, quiet operation, etc. Chemical batteries are currently the main dominant technology in the electric vehicle industry and they have long been used as the major system of energy storage in various industrial applications. The usage of these chemical batteries has a number of drawbacks, including a short lifespan, a low power density, and a high price [1]. One of the most efficient ways to increase the efficiency of electric vehicle energy use is through the hybridization of batteries with supercapacitors (SCs). There are several positive characteristics of the supercapacitor (SC), including its capacity to store a lot of energy, excellent efficiency, wide operating temperature range, extended life, and high-power density [2]. Daily low- cost super-capacitors are being released to the market, which opens the door for many creative applications of super- capacitors in electric vehicles (EVs). The super-capacitors can be utilized in EVs and hybrid EVs. In all of these situations, they serve as an intermediate energy storage device because of their large power capacity, which is used to store the energy obtained during regenerative braking. Super-capacitors allow for a size reduction of the major energy storage system (ESS), such as the electric vehicle (EV) batteries and fuel cell vehicles, while maintaining their operability at a higher functional level. In urban areas, buses, vehicles, and delivery vans are its top recipients, especially during rush hours. The use of the battery and super-capacitor together is very beneficial because it enables the average power demand to be met over a prolonged time with the battery and the peak power demand over a shorter period with the super-capacitor, which can handle the instantaneous EV load because of its high-power density characteristic. By using the super-capacitor in the hybrid ESS, the life of batteries will also be enlarged as the frequent charging and discharging is avoided and also the SC can also provide a large driving current when needed whilst the energy in the batteries could be saved hence prolonging the vehicle range [3]. Because they have a relatively high energy density compared to other battery technologies used in EVs, Li-ion batteries can accommodate these varied charges and fully recharge, but the drawback is the drastic shortening of the battery lifecycle. The compromise between power and energy will frequently result in the accomplishment of the required energy but, on the other hand, will overwhelm the electric vehicle. According to studies, combining super- capacitors and energy-dense batteries is a workable approach. An ESS could use a super-capacitor, which offers a higher level of efficacy and a transient energy source, to supply the huge power flows. Supercapacitors used for this reason reduce the stress and number of cycles put on batteries and hence increase the battery life. The performance of different battery configurations in relation to hybrid battery/SC was examined in the literature using principal models or generic models, either through numerical simulations or practical testing. In this research, we analyze the potential use of SCs as a backup power to control the various variations of power of the batteries used in electric vehicles [4]. Researchers have used various types of energy storage systems [5-19] in EVs, power systems, and distributed generation. In this paper, the goal is to develop a model and determine the effectiveness of electric vehicles through simulation. The model for the hybrid ESS was created using the MATLAB Simulink-Sim-scape Power Systems platform and was based on generic models [20].

II. MATLAB SIMULINK SUPERCAPACITOR / BATTERY HESS MODEL

A. Battery Model

Battery models serve many purposes that have made them an indispensable tool for the design of battery-powered systems, including battery characterization, algorithm development, system-level optimization, state-of-charge (SOC) and state-of-health (SOH) estimation, and real-time modeling for battery management system design. Fig 1 shows a basic illustration of an equivalent battery model in MATLAB; more intricate models may be created by including extra parts and taking into account variables like temperature and aging [21].

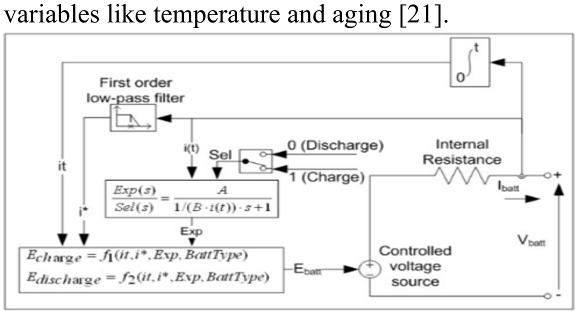

Fig. 1. MATLAB Simulink equivalent circuit of a battery

B. Supercapacitor model

The SC block displayed below embodies a general model that is parameterized to represent the majority of the common varieties of super-capacitors.

Important information about SC models is available in [22]. The super-capacitor model's analogous circuit is depicted in Fig. 2 below.

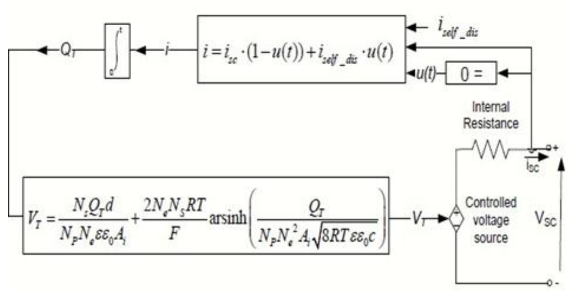

Fig. 2. Equivalent circuit of a super-capacitor in MATLAB

III. HYBRID ESS

A. Concept of hybridization

Batteries and supercapacitors are two energy storage devices that are frequently utilized in electric vehicles. Batteries have a high energy density and can store a lot of energy, whereas supercapacitors have a high-power density and can be charged and discharged quickly. Electric vehicles can benefit from the hybridization of these two technologies in a number of ways, including better performance, longer lifespan, and enhanced efficiency. The "supercapacitor- battery hybrid system" is one method for combining supercapacitors and batteries. In this system, the supercapacitor and battery are linked in parallel to give the car the ability to store a lot of energy while also producing a lot of power. During acceleration or regenerative braking, the supercapacitor can give power quickly, while the battery provides the energy storage needed for continuous driving.

As a result of this hybridization, the energy storage system which is formed is in a semi-active mode. This configuration's adaptability enables the realization of further hybrid energy source arrangements. In electric vehicles, the combination of supercapacitors with batteries can have a number of advantages. The technology, for instance, can lessen the stress on the battery and increase its longevity, which will ultimately lower the cost of ownership for electric vehicles. By offering high power and great energy storage capacities, the hybrid system can also enhance the vehicle's performance, making it more agile and effective [23]. The hybrid energy storage system simulation model was created using Sim power GUI in the MATLAB Simulink environment. The supercapacitor and battery models are the foundation of the model.

Lithium-ion battery packs utilized in Lucid air vehicles served as the basis for parameterizing the battery model, while the Maxwell supercapacitor was used to parameterize the supercapacitor. The MATLAB model for the Battery/SC HESS for the hybrid electric vehicle and the electric power train is shown in Fig.3 and Fig.4.

B. Purpose of hybridization

The limitations of batteries or super-capacitors are overcome by the battery super-capacitor hybridization and hence this reduces the stresses applied to batteries hence improving their life cycle. Hybridization can now be used in conjunction with environmentally acceptable energy carriers thanks to batteries and super-capacitors [24]. The primary goal of introducing this storage system is to reduce the dependency on ICE vehicles and increase vehicle efficiency. In order to take advantage of hybridization and maximize the energy efficiency of the storage system utilized in EVs, a variety of layouts are being deployed.

C. Regenerative Braking

The moving energy that an electric car gains during the time it is accelerating can be converted back into electrical energy during braking. Friction brakes typically convert braking energy to heat, but in an EV, the energy can be converted and sent to the battery in the form of electrical energy and used to charge the battery [25]. In a vehicle without a super-capacitor fitted, it may be able to capture

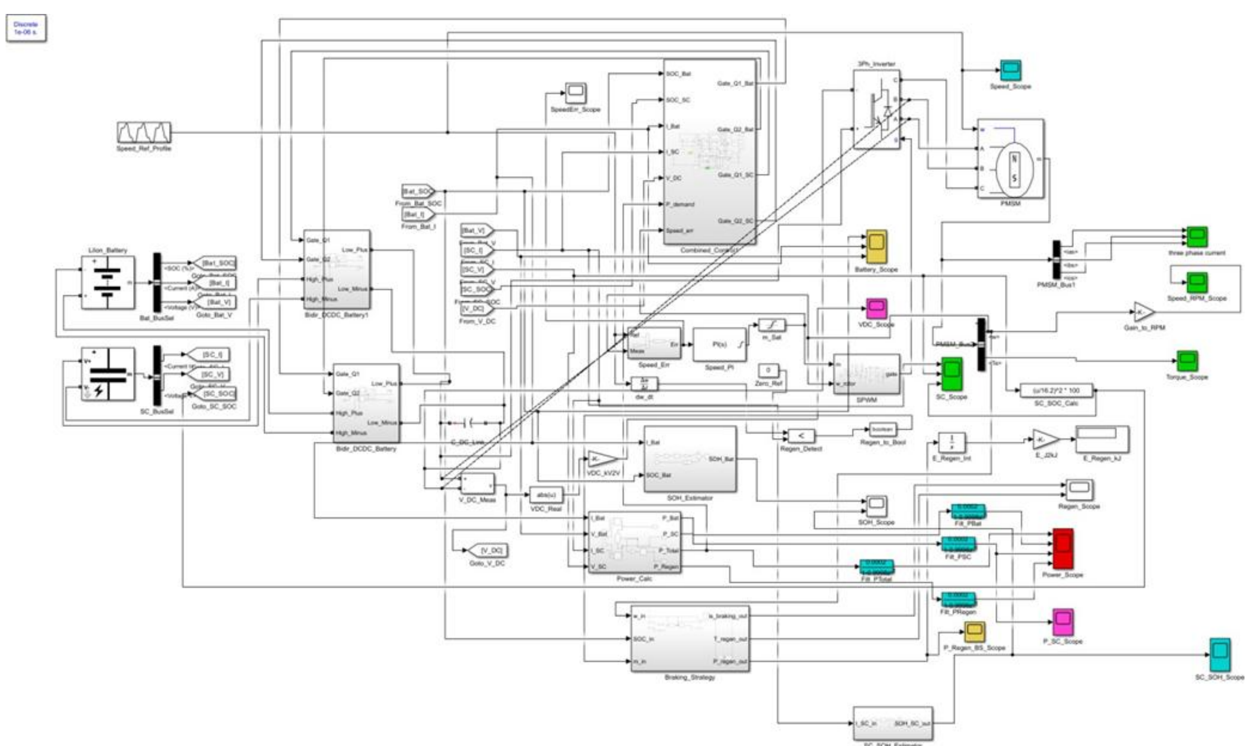

Fig. 3. Simulation model of the HBESS

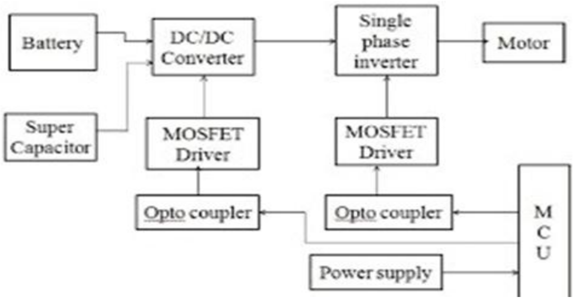

Fig. 4. Hybrid energy storage system

roughly 22% of the energy normally wasted as heat during braking, depending on the power, vehicle, and battery technologies but with a supercapacitor fitted can regenerate 60 to 80%.

This limit is mostly caused by the batteries' low power capability and the risk of damage from handling excessive instantaneous power; however, by adding a super- capacitor, this limit will be reduced since supercapacitors capture large amounts of energy without being damaged [26].

1) Improved energy efficiency

Supercapacitors are able to discharge and recharge faster than batteries because they have a higher power density. Because the supercapacitor can handle the peak power demands of the EV while the battery provides sustained power over time, pairing a supercapacitor and battery can increase the system's overall energy efficiency [27]. The performance of the EV can be enhanced by using a supercapacitor and battery together. While the battery can supply steady power for longer driving distances, the supercapacitor can deliver a burst of power for acceleration.

2) Extended battery life

By lowering the number of charge and discharge cycles, supercapacitors can contribute to longer battery life. The supercapacitor can help the battery last longer by handling the high-power requirements of acceleration and regenerative braking. Because supercapacitors charge quickly, the hybrid system can be charged more quickly than a battery by itself. For EVs with a short charging period, like those used in public transit, this is very helpful [28].

3) Reduced cost

Combining supercapacitors and batteries helps lower the overall cost of the energy storage system because supercapacitors are less expensive than batteries.

IV. MATLAB SIMULATION RESULTS AND DISCUSSION

This section presents the performance evaluation and simulation results of the Battery/Supercapacitor Hybrid Energy Storage System (HESS) for an electric vehicle. Simulations were conducted in MATLAB Simulink over a 20-second drive cycle encompassing acceleration, constant-speed cruising, deceleration, braking, and regenerative phases. The model is parameterized with Lucid Air lithium-ion battery packs and Maxwell supercapacitors.

A. Motor Speed Profile

Fig. 5 shows the motor speed (RPM) over the drive cycle. Speed rises to ~750 RPM (0-2 s), holds steady, then ramps to 1000 RPM peak (6-10 s). After t=10 s the motor decelerates to 300 RPM and stops at t≈17 s. Smooth tracking confirms adequate HESS power delivery throughout all phases.

Fig. 5. Motor Speed Profile (RPM) over Drive Cycle

B. Electromagnetic Torque

Fig. 6 shows the electromagnetic torque (Te). During acceleration, torque reaches -10 to -14 Nm with PWM ripple. As speed stabilizes, torque reduces (constant-power region). At t>10 s, torque transitions positive during regeneration. The SC absorbs transient surges, shielding the battery.

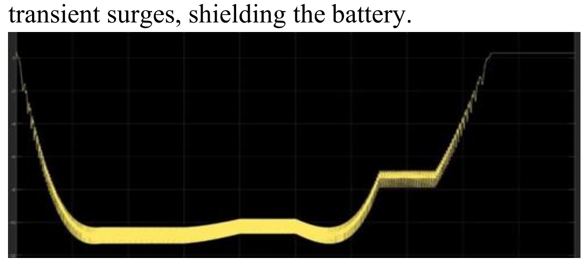

Fig. 6. Electromagnetic Torque (Te) over Drive Cycle

C. Three-Phase Stator Currents

Fig. 7 shows the three-phase stator currents (Iabc) at steady-state. Balanced sinusoids at ±20 A confirm correct field-oriented control (FOC). Symmetrical undistorted waveforms indicate low harmonic content and proper inverter modulation, validating the combined HESS drive system performance.

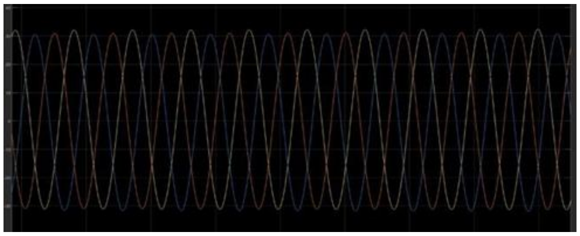

Fig. 7. Three-Phase Stator Currents (Iabc) at Steady State

D. Battery and Supercapacitor Power Distribution

Fig. 8 presents filtered power flows: Flt_PTotal (~10,000-12,000 W), Flt_PBat (sustained base), Flt_PSC (transient 500-1000 W peaks), and Flt_PRegen (active after t=10 s). The SC buffers transient demands while the battery provides sustained power, validating the semi-active hybrid control strategy. The battery is effectively shielded from power spikes and voltage surges.

Fig. 8. Filtered Power: Battery, SC, Total and Regenerated (W)

E. Supercapacitor Power Output

Fig. 9 shows SC instantaneous power. During 0-5 s, the SC discharges with oscillatory peaks of 600-1000 W handling acceleration demand. From t=5 s, SC settles to ~400 W at constant speed. Power drops to near zero at t=10 s as the motor decelerates, confirming SC role as a fast-response buffer that relieves the battery from rapid charge- discharge cycling.

Fig. 9. Supercapacitor Power Output (P_SC) over Drive Cycle

F. Regenerative Braking Performance

Fig. 10 shows the regen activation signal over the drive cycle, triggering at t=10 s and t=14.5 s during the two deceleration events. The SC rapidly absorbs recovered energy due to its high-power density. Fig. 11 shows recovered power (P_Regen_BS) peaking at ~5,400 W at braking onset and decaying exponentially. With the SC, the system recovers 60-80% of braking energy vs. ~22% for battery- only [26].

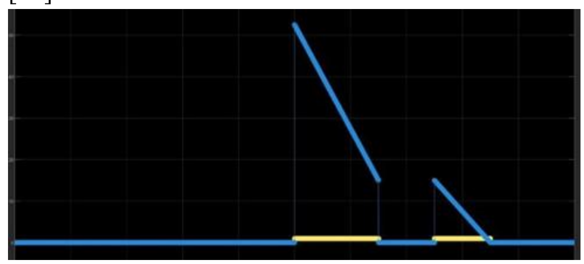

Fig. 10. Regenerative Braking Activation Signal

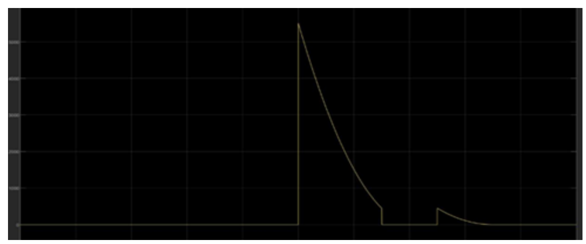

Fig. 11. Regenerated Power (P_Regen_BS) Fed Back to HESS (W)

G. Supercapacitor Voltage, Current and State-of-Health

Fig. 12 shows the SC DC bus voltage (VDC) oscillating 600-780 V (nominal ~700 V) from rapid PWM charge-discharge cycles. Fig. 13 shows the SC current control scope with duty cycle at ~75-78%, confirming stable bidirectional power flow. Fig. 14 shows SC State- of-Health (SC_SOH) declining from 1.000 to 0.9992 (only 0.08% degradation over 20 s), demonstrating exceptional cycle stability and confirming the economic case for SC use in EV HESS.

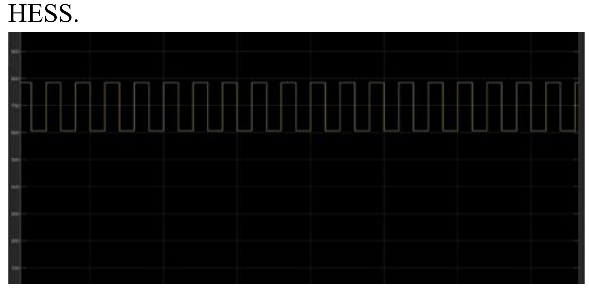

Fig. 12. Supercapacitor DC Bus Voltage (VDC)

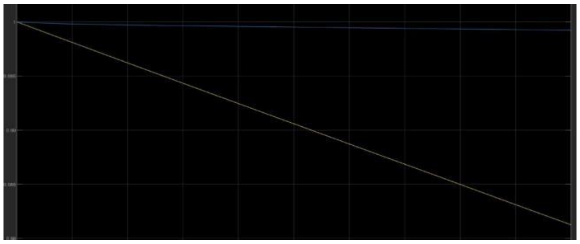

Fig. 16. Battery SOH: Hybrid HESS vs. Standalone Reference

The simulation results collectively demonstrate that the Battery/SC HESS significantly outperforms a battery-only system: the SC decouples high-frequency transient demands from the battery, regenerative energy is captured efficiently, and battery SOH degradation is minimized. These results validate the proposed HESS architecture as a practical, effective solution for next-generation EV powertrains.

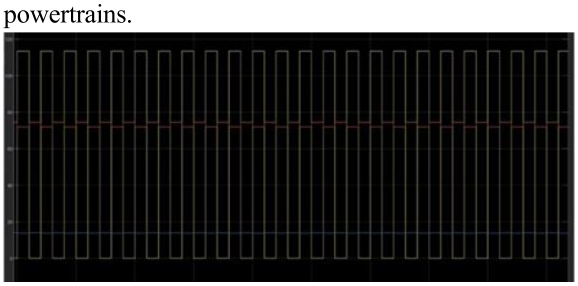

Fig. 13. SC Current Control Scope (Duty Cycle ~75-78%)

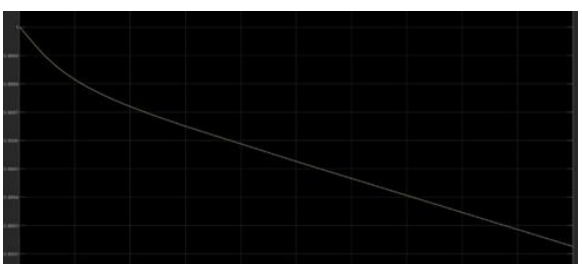

Fig. 14. Supercapacitor State-of-Health (SC_SOH): 1.0 to 0.9992

H. Battery Current, Voltage and State-of-Health

Fig. 15 shows the battery current (0-375 A) and voltage (~50-60 V) under PWM control. The SC absorbs all transient peaks, so the battery operates in a smooth near-constant-current regime. Fig. 16 compares battery SOH in the hybrid HESS (yellow, declining) against the standalone reference (blue, constant at 1.0). Battery SOH falls from 1.000 to ~0.982 (1.8% degradation over 20 s). A battery-only system would degrade significantly faster due to direct peak current exposure. The SC hybridization extends battery cycle life, with the SC contribution to range improvement assessed at approximately 21.5% [3].

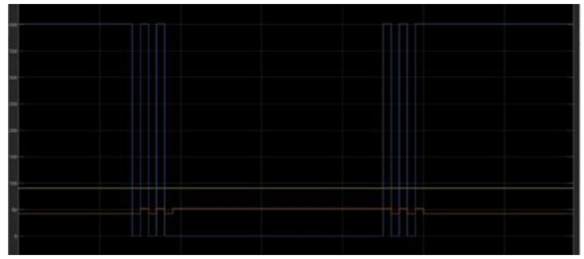

Fig. 15. Battery Current (I), SOH and Voltage (V) during Drive Cycle.

V. CONCLUSION

The simulation, analysis, and performance of the battery and supercapacitor hybrid energy storage system revealed that by maximizing energy and power usage due to hybridization, the efficiency and reliability of electric vehicles are significantly enhanced. In this work, the viability of using SCs to control power fluctuations in and out of the batteries in conjunction with parallel batteries in EVs was investigated. The simulation findings demonstrated that, after hybridization, a greater amount of the transient current was supplied by the SC energy storage source, resulting in a decrease in battery current used and consequently a decrease in battery stress.

Approximately 21.5% was assessed to be the contribution of hybridization's supercapacitor to range expansion. The following summarizes the primary benefits of battery/SC hybridization:

- The overall performance of the battery/SC HESS increases while the battery experiences fewer cycles, having a positive effect on battery aging and greatly enhancing vehicle range. Hybridization also enables a significant reduction in the size of the principal power source of EVs.
- The arrangement greatly reduces battery stress by supplying transient currents during acceleration and deceleration, transferring stress from the battery to the supercapacitor.
- The battery/SC HESS design, compared to a battery-only system, reduces peak currents and voltage surges, lowers electromagnetic

interference (EMI), and reduces the chance of overly low voltage failures.

This model plays an important role as a useful performance evaluation tool for electric vehicle hybrid energy storage systems and provides a foundation for future work on advanced energy management strategies and real-time HESS optimization.

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