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# A Review on Enhancing the Performance of Hybrid Electric Vehicle Energy Storage Systems in the Real World

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**ABSTRACT**

Hybrid cars, which combine internal combustion engines with electric motors and battery packs, provide a sustainable way to travel in the future. Improved performance, fewer operating costs, decreased pollutants, and increased fuel efficiency are among the advantages. As technology advances and costs come down, hybrid cars are becoming more and more feasible, despite obstacles like complexity and greater upfront costs. increased fuel efficiency (20–30% more effective). 50–70% fewer greenhouse gas emissions. reduced expenses for operations. silent and seamless functioning. Acceleration and power. Regenerative braking and the conversion of kinetic energy into electrical energy are two important advantages. low-speed, electric-only operation that minimises noise and pollutants. enhanced engine performance by utilising both powertrains' advantages.

Keywords: Powder bed fusion, Material Extrusion, VAT photopolymerization, Binder Jetting, Medical implants, Pharmaceuticals, Biomanufacturing, Sheet Lamination.

## 1. Introduction

Energy management techniques for hybrid electric vehicles (HEVs) that make use of hybrid storage systems, particularly those that combine conventional batteries with lithium-ion capacitors (LiCs). The research tackles the difficulties caused by HEVs' varying power requirements, which might reduce battery life because of high peak currents during acceleration and deceleration. The study investigates methods to improve power distribution and lessen battery strain by including a LiC module into the battery pack, which would ultimately increase the battery's longevity and overall vehicle efficiency.

The creation of a powertrain simulation model for a commercial hybrid car that models the dynamics of the hybrid storage system utilising the AVL CruiseM environment. The model is validated using experimental data from real driving emissions (RDE) testing under a variety of driving scenarios, including aggressive and regular driving styles. The experimental setup consists of on-road testing to capture real-world operating circumstances and laboratory experiments for model calibration. With an emphasis on maximising power distribution between the LiC and the battery and reducing the effect of peak current demands on the battery, three different energy management techniques are assessed.

That the battery's power demand may be efficiently balanced by integrating LiC into a hybrid storage system, especially during transient operations. The simulations show notable increases in battery cycle life by applying various energy management techniques. The LiC module absorbs peak currents, which lessens the stress on the battery. The findings demonstrate how such hybrid systems may increase battery longevity and boost vehicle efficiency, indicating that this strategy may have an impact on future HEV design and energy storage optimisation.

Fig -1: The integration of the lithium-ion capacitor (LiC) with the internal combustion engine (ICE), electric machines (EMs), and battery connections is depicted in this hybrid vehicle's powertrain layout diagram.

## 2. Literature Review

In hybrid electric vehicle (HEV) energy management techniques, with an emphasis on the incorporation of hybrid energy storage systems (HESS), which integrate batteries with lithium-ion capacitors (LICs) or supercapacitors. HEVs have long been praised for their capacity to lower CO2 emissions and fuel consumption, supporting international initiatives to tackle climate change. However, conventional lithium-ion batteries are strained by the high transient power demands of urban driving, which are marked by frequent accelerations and decelerations. This shortens the batteries' cycle life and increases maintenance expenses. In order to overcome these obstacles, scientists have looked into integrating electric double-layer capacitors (EDLCs) and, more recently, LICs into HESS topologies to improve battery longevity, lower the impact of peak power, and increase power supply reliability.

In particular, LIC technology has shown great promise in closing the energy and power density gap between lithium-ion batteries and EDLCs. By using a hybrid electrode design that combines EDLC cathodes and lithium-ion battery anodes, LICs are able to attain a higher energy density than EDLCs alone without requiring significant weight and size increases that are frequently unfeasible in automotive applications. According to studies, by absorbing peak power during high-load situations and providing extra power during periods of rapid acceleration, LICs can greatly smooth out battery current profiles in HEV storage systems. By minimizing wear on the lithium-ion battery, this arrangement increases its lifespan and lowers maintenance expenses overall.

In order to maximize HESS effectiveness, Energy Management Strategies (EMS) are essential. To efficiently balance power flows between batteries and capacitors, a range of EMS techniques, like as rule-based, model predictive, and fuzzy logic controllers, have been studied across various vehicle types. Techniques like Model Predictive Control (MPC) and Exponential Weighted Moving Average (EWMA), which have both demonstrated successful outcomes in managing transient power demands, are well documented in the literature. Golchoubian et al. and Song et al., for instance, tested several EMS methods and observed improved battery efficiency and cycle life under various urban driving circumstances.

Practical restrictions still exist despite theoretical developments, especially with relation to EMS's adaptability in real-world situations. In order to effectively represent real driving cycles, including the impact of certain driver actions and road circumstances on EMS performance, recent research emphasizes the necessity for validated experimental data. In order to close this gap, this study uses experimental data from real-world driving emissions (RDE) cycles to validate HESS techniques. Through verified and optimized EMSs under various driving situations, it seeks to illustrate the practical benefits of incorporating LICs into HEVs, extending battery life, and increasing vehicle efficiency.

There are still a number of research gaps despite the fact that HESS and other EMSs have advanced significantly in development and testing. With little experimental validation, the majority of current research is on theoretical models or simulations. Furthermore, it is unclear how various driving techniques and road circumstances affect HESS and control strategy performance. By installing a hybrid storage system that combines a LiC module with a lithium-ion battery in a commercial HEV, this study seeks to close these gaps. A thorough evaluation of the suggested energy management techniques' efficacy is provided by combining simulation and real-world driving data.

| Cycles | Conventional use (%) | HESS with LIC (%) | Improvement (%) |
|---|---|---|---|
| 500 | 80% | 95 | 18.75 |
| 1000 | 60 | 90 | 50 |
| 1500 | 40 | 85 | 112.5 |
| 2000 | 20 | 80 | 300 |
| 2500 | 0 | 75 | - |
| 3000 | - | 90 | - |
| 3500 | - | 85 | - |

Fig -2 : A graph with two lines, one for conventional use and one for HESS with LiC.

[The x-axis represents the number of cycles, and the y-axis represents the battery capacity (%).] Conventional Use: - Starts at 100% capacity - Decreases linearly to 0% capacity at 2500 cycles HESS with LiC: - Starts at 100% capacity - Decreases gradually to 75% capacity at 8000 cycles.

## 3. Background

HEVs are at the forefront of lowering fuel consumption and emissions in cities as a result of the shift to greener transportation technologies. When compared to conventional vehicles, hybrid thermal-electric vehicles (HEVs) are particularly prized for their ability to reduce CO2 emissions and fuel consumption by combining the use of an internal combustion engine (ICE) and electric power. Future transportation networks are anticipated to heavily rely on HEVs, which are encouraged by changes in worldwide policy aimed at mitigating environmental effects. But the fluctuating power requirements of HEVs, particularly in cities where cars frequently accelerate and decelerate, put a lot of strain on the electric parts, particularly the lithium-ion batteries.

Long-term exposure to such high, sporadic power demands shortens battery life, raises maintenance expenses, and may affect a vehicle's overall performance.

Hybrid energy storage systems (HESS) ,this HESS is shown in (figure -3) have become a viable way to overcome these constraints. Capacitors, such as electric double-layer capacitors (EDLCs) or, more recently, lithium-ion capacitors (LICs), are combined with conventional lithium-ion batteries in a HESS. Although EDLCs have been investigated for use in automobiles because of their capacity to manage high power requirements, their poor energy density and weight issues make them less suitable for use in light-duty passenger cars. By combining EDLC cathodes with anodes akin to those found in lithium-ion batteries, LICs provide a more balanced solution that improves power and energy density profiles while optimizing weight and space constraints in HEVs. By acting as a buffer during periods of high power demand, this combination design enables LICs to smooth the current profile.

In HESS designs, optimizing the power flow between the battery and the LICs requires the use of effective Energy Management Strategies (EMS). To control the energy balance between various storage components, a variety of EMS techniques have been developed, including rule-based, model predictive control (MPC), and fuzzy logic control. By distributing the load dynamically according to current demand, these solutions make sure that the capacitors absorb peak loads and reduce battery stress. Model predictive control techniques, for instance, estimate future power demands to proactively modify power sharing, improving the system's overall durability and battery efficiency.

Even with improvements in HESS and EMS technology, little is known about how these systems function in actual driving situations. The majority of research has mostly relied on simulated driving cycles, which might not fully capture the unpredictability of actual urban driving. By assessing HESS and EMS performance on a commercial HEV during real driving emission (RDE) cycles, this study fills this gap. This study intends to provide important insights for the future development and deployment of efficient HEVs by demonstrating the useful advantages of LIC integration and optimized EMS in extending battery lifespan and overall vehicle efficiency through experimental validation.

The use of HESS and other energy management techniques has been studied in the past, but there is a lack of experimental verification of these systems in practical settings. By installing and testing a hybrid storage system that consists of a LiC module and a lithium-ion battery in a commercial hybrid electric car, this study seeks to close this gap. Extensive simulations and RDE testing support the suggested control strategies, highlighting the potential advantages of utilising LiCs to improve vehicle economy and battery performance.

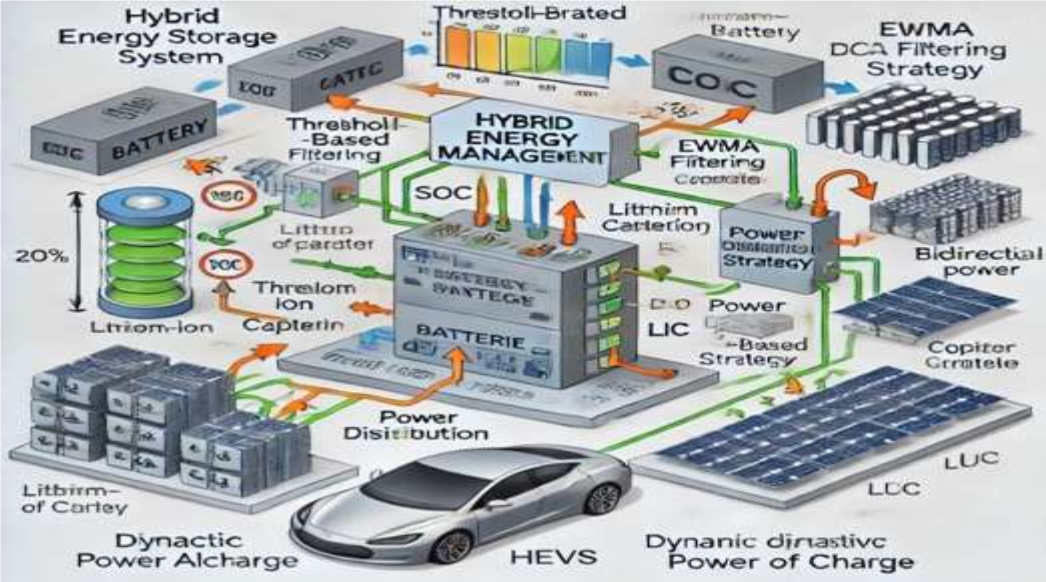

Fig -3:The control techniques for energy management in a hybrid energy storage system (HESS) for hybrid electric vehicles (HEVs) are shown in this simplified block diagram. It displays dynamic power allocation based on SOC and power demand and comprises the essential parts (battery, LiC module, DC/DC converter) and control blocks for threshold-based, EWMA filtering, and power-based methods.

## 4. Proposed Control Method

Utilizing a hybrid energy storage system (HESS) that combines Lithium-ion Capacitors (LICs) with a conventional lithium-ion battery allows for energy management for hybrid electric vehicles (HEVs). Three different energy management techniques (EMS) form the foundation of the suggested control system, which aims to maximize power distribution between the battery and the LIC module. By increasing the battery's cycle life and reducing the detrimental effects of high transient current demands, these tactics seek to increase the vehicle's overall efficiency under typical driving circumstances.

Dynamic Power Sharing: The LIC module manages peak and transient power needs, while the battery stays within a safe and steady operating range. The system can sustain overall performance without putting undue strain on the battery thanks to this dynamic power sharing.

**Fundamental Architecture and Design**

The architecture uses a bidirectional DC/DC converter to connect the battery and LIC in a semi-passive HESS arrangement. By precisely controlling the power flows between the two components, this converter enables adaptive responses to driving demands in real time. When the DC/DC converter is operating in current reference mode, the control strategy being used determines the reference current of the LIC. The suggested tactics take into consideration factors including vehicle speed, battery state of charge (SoC), and the cyclical nature of urban driving.

**Strategies for Energy Management (EMS)**:

Three different EMS strategies were created and assessed:

### A. Threshold Current-Based Strategy:

The first approach, referred to as the Threshold Current-Based Strategy, establishes the battery's maximum permitted current limit. The LIC module efficiently limits the battery's exposure to high current loads by providing the extra power needed when the battery's current demand beyond this threshold. By limiting transient loads and lessening the strain during high-power events like acceleration or regenerative braking, this straightforward but efficient method guarantees smoother battery functioning.

Battery Current Threshold: Establishing a current threshold (I th) for the battery is the fundamental idea behind this approach. The LIC module effectively caps the battery's current output by supplementing the extra power needed when the vehicle's electric drivetrain's power demand above this threshold.

**Mathematical formulation:**

$$I^{*}_{SC} = {}^{\eta}conv = \frac{V_{bat}}{V_{SC}}(I_{DC} - I_{th})$$

Where:

$I_{DC}$=Total current from drive train

$V_{batt}$and $V_{SC}$: Voltage of battery and modules

${}^{\eta}conv$: Efficiency of DC/DC convertor.

This formula guarantees that whenever DC/DC surpasses, $I_{DC}$ *and* $I_{th}$the LIC module makes up for the excess current demand.

Simplified Control Implementation: The threshold-based approach is appropriate for real-time applications because it requires less computing power than alternative approaches. A simple control technique in the DC/DC converter makes it simple to implement and guarantees dependable performance with no computational cost. This DC/DC coverter is shown in (figure-4 ).

Significant gains in battery current smoothing were shown by the Threshold Current-Based Strategy in a variety of real-world driving situations, such as highway, rural, and urban ones. Under medium to high transient load levels, it successfully lowers battery stress, while being less adaptable than more sophisticated techniques like the Power-Based Strategy or EWMA. This makes it especially advantageous for HEVs, where dependability and simplicity are crucial needs.

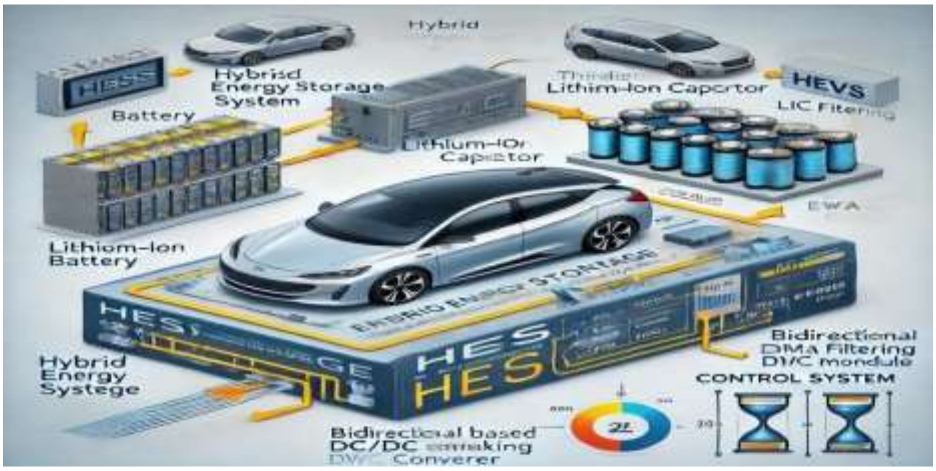

Fig -4: With arrows indicating power flow under various driving conditions, this diagram shows the suggested control strategy for the hybrid energy storage system (HESS) in hybrid electric vehicles (HEVs). It includes the lithium-ion battery, lithium-ion capacitor module, and bidirectional DC/DC converter.

### B. Exponential Weighted Moving Average (EWMA):

An Exponential Weighted Moving Average (EWMA) filter is used in the second technique to dynamically control the power demands. The battery provides the smoothed current value that is determined by applying the EWMA filter to the electric drivetrain's current demand. The LIC module controls any discrepancy between the real and filtered current demand. By enabling a more flexible and responsive power distribution, this approach guarantees the

HESS operates at its best across a range of operational circumstances. The EWMA filter's decay factor offers flexibility in weighing the significance of current trends, striking a balance between short-term power requirements and long-term battery health.

It is a statistical method used in the suggested control approach to dynamically regulate energy flows in the hybrid electric vehicle's (HEV) hybrid energy storage system (HESS). This method creates a smoothed current profile by filtering the electric drivetrain's current requirement. The battery's power contribution is then ascertained using this profile. The LIC module effectively manages transient power fluctuations by compensating for any departures from the smoothed demand.

The EWMA-based approach proved to be very successful in controlling energy flows under actual driving circumstances, resulting in significant decreases in variations in battery current and an extension of battery life. The EWMA technique demonstrated its resilience and flexibility for HEV applications by delivering one of the best performance indices among the studied energy management strategies, especially in medium to low state-of-charge (SOC) situations.

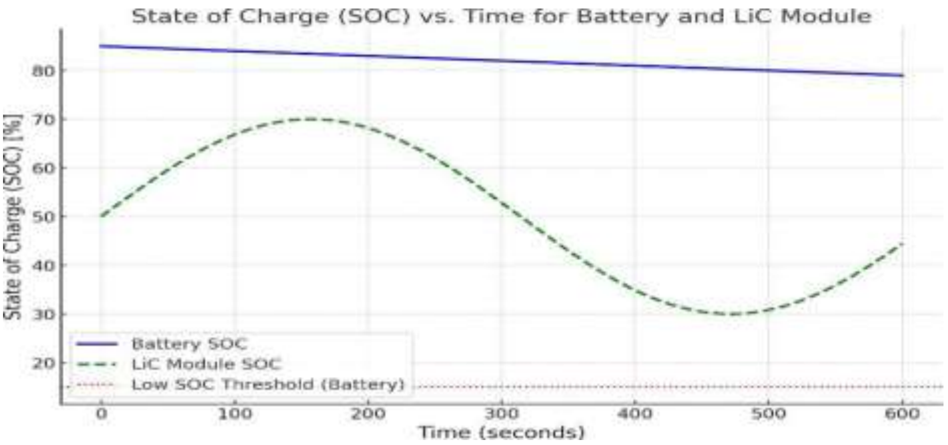

Fig -5: Lithium-ion capacitor (LiC) module and battery state of charge (SOC) vs time. The storyline demonstrates:

A progressive drain is indicated by the battery's SOC gradually declining over time. The changing SOC of the LiC module emphasises its function in managing sporadic power needs. A red dashed line that shows the battery's low state of charge threshold.

**Mathematical formulation:**

$\boldsymbol{IDC,i} = \lambda IDC,i + (1 - \lambda)IDC,i{-}1$

Where:

$I_{\boldsymbol{DC,i}}$=smoothed DC current at step I

$\lambda$=Decay factor

$I_{DC,i}$=Instaneous DC current

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Smoothing Current Demand: Recent data points are given exponentially more weight when the EWMA filter computes a weighted average of historical and present current needs. Rapid variations in power requirements, which usually put stress on the battery during braking or acceleration, are lessened by this smoothed current demand.

### C. Power-Based Strategy:

The third method, called the Power-Based Strategy, optimizes power distribution by taking into account both LIC voltage limitations and vehicle dynamics. This technique calculates the optimal operating voltage for the LIC module by estimating power consumption based on vehicle speed and resistance forces. In order to ensure that the LIC module is charged or discharged in a way that maximizes battery protection during high power events, the method incorporates a proportional-integral (PI) controller that adjusts to variations in vehicle speed and battery state of charge (SOC).

Is a sophisticated energy management method used in this work to maximize power distribution between the lithium-ion battery and the lithium-ion capacitor (LIC) module in a hybrid electric vehicle's (HEV) hybrid energy storage system (HESS). In order to guarantee effective power sharing, particularly during transient operations like acceleration and regenerative braking, this technique focuses on utilizing vehicle dynamics and the operational limitations of the LIC module.

Calculating Two-Tier Battery Current:

The reference current of the battery is split into two parts by the power-based approach:

Base Current ($I$Batt′I Batt′):

This takes into consideration the constant power needed to overcome vehicle inertia, aerodynamic drag, and road resistance. Current Transient (Batt′′I Batt′′): In order to maximize energy flow during transient situations, this adjusts to quick variations in the LIC module's voltage. To make sure the LIC voltage stays within the optimal range, it makes use of a proportional-integral (PI) controller

Voltage-Based Control of the LIC Module:

Based on the energy needs and vehicle speed, the LIC module is designed to monitor an ideal voltage level. In order to maximize energy recovery and discharge efficiency, the technique implies that the LIC should preferably be fully charged prior to acceleration and entirely discharged prior to regenerative braking.

The power-based approach considerably lowers battery current variations, especially during acceleration and deceleration phases, according to simulation data. It achieves seamless energy transitions and reduces battery stress, exhibiting great efficacy across a variety of real-world driving cycles. Under low state-of-charge (SOC) circumstances, when battery protection is most important, the tactic works very well. This comparison graph is shown in (figure 5).

$$\frac{1}{2}C\left(V_{LIC}^{2}-V_{min}^{2}\right)+\frac{1}{2}m_{veh}\,v^{2}=constant$$

Where:

C=capacitance of module

$Vmin$=min. LiC voltage $m veh$=vehicle mass $v$=vehicle speed

**Simulation and Implementation**

AVL CRUISETM M was used to apply the suggested control approaches in a verified simulation environment. Real-world data, such as emissions and power requirements from highway, rural, and urban driving cycles, are incorporated into the vehicle model. In order to calibrate the equivalent circuit model for precise simulation, experimental campaigns supplied parameters for the LIC model, such as internal resistance and capacitance.

**Important Findings and Flexibility**

Under various circumstances, each tactic showed clear benefits. Although the threshold-based approach offered simple control, it was not flexible enough to adjust to changing drive cycles. In highly changeable urban situations, the EWMA technique proved useful in smoothing transient currents. The power-based control performed better at balancing transient and steady-state demands, especially when performing high-power manoeuvres like steep grades or abrupt accelerations.

**Comparative Efficiency**

An efficacy metric that gauges the decrease in peak demands and changes in battery current was used to assess the techniques. The power-based and EWMA techniques performed better than the threshold-based approach across a range of starting battery SoC levels and driving profiles. For instance, the EWMA technique greatly decreased battery stress during typical urban driving cycles, achieving a 55% effectiveness rate.

To sum up, the suggested control strategies emphasise how crucial advanced EMS is to improving HESS performance. The study illustrates significant increases in battery longevity and vehicle economy through the use of adaptive techniques and the integration of LIC modules. These results offer a strong basis for practical implementation and additional HESS optimisation in HEVs.

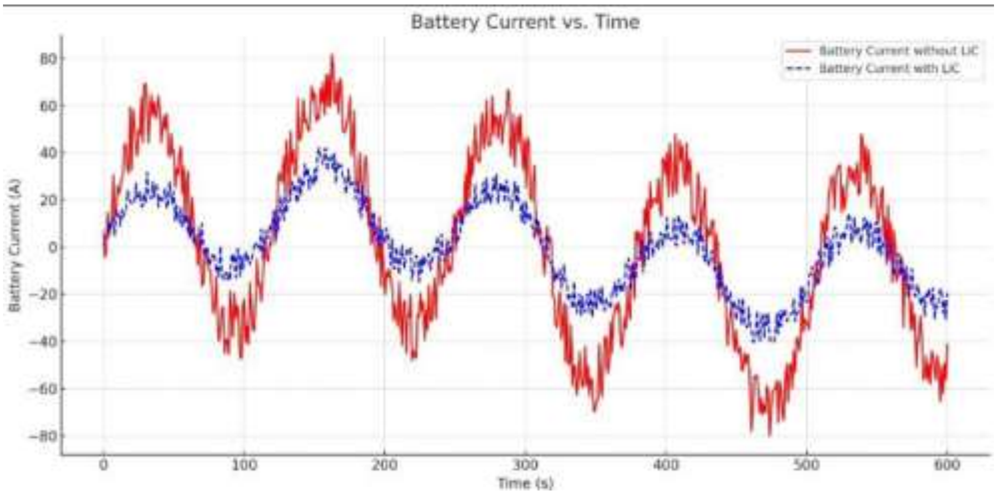

Fig -5: This battery current vs. time graph compares the current profiles with and without a lithium-ion capacitor (LiC) included. The blue dashed line depicts the smoothed current profile with LiC integration, indicating less stress on the battery under transient power demands, whereas the red line displays the large peaks in battery current without LiC.

## 5. Methodology

Overview of the System: Designing a hybrid energy storage system (HESS) that is integrated into a hybrid electric vehicle (HEV) is the first step in the technique. A lithium-ion capacitor (LiC) module and a primary lithium-ion battery make up the system. The goal is to lessen peak current stress on the primary battery by using the LiC module to manage high transient power demands. The LiC module is connected to the vehicle's engine via a bidirectional DC/DC converter, which permits regulated power transfer between the battery, LiC, and electric drive components during regenerative braking and acceleration.

Energy Management Strategies: Three strategies (EMS) were developed and tested: Threshold-based strategy, Exponential Weighted Moving Average (EWMA) strategy, and Power-based strategy. The EWMA strategy uses a recursive filter to smooth the battery current profile, reducing high-frequency transients, and the power-based strategy dynamically adjusts power distribution based on vehicle speed and the state of charge (SOC) of the battery and LiC module. The threshold-based strategy sets a maximum limit for battery current, directing excess power demands to the LiC module.

Simulation Environment: Using AVL Cruise M software, a thorough vehicle simulation model was created as part of the process. Because of its sophisticated ability to simulate intricate engine architectures, this platform was selected. The simulation model included comprehensive sub-models for the LiC module, battery, electric machines (EMs), and internal combustion engine (ICE). Experimental data gathered from the vehicle's actual activities was used to parameterise each component.

Model Parameterisation and Validation: To depict the dynamic behaviour of the LiC module, an equivalent circuit model (ECM) comprising resistive and capacitive components was used. In order to collect data for model calibration, experimental tests were carried out on the LiC cells in a controlled laboratory setting. MATLAB-Simulink's parameter estimation tools were used to modify the equivalent circuit parameters, resulting in a satisfactory match between the experimental data and the model's voltage response. To ensure realistic simulation findings, the vehicle model was then verified using actual driving cycle data gathered from on-road tests.

Real Driving Emission (RDE) Cycle Data Acquisition: Real driving emission (RDE) cycles were employed to assess how well the suggested control strategies performed. In order to collect data, the car was outfitted with a portable emissions measuring system (PEMS) and extra sensors to track important variables including speed, acceleration, battery voltage, and current. To capture the whole spectrum of fleeting behaviours encountered in urban, rural, and highway settings, two driving styles—normal and aggressive—were evaluated.

Performance Evaluation: Simulation runs over several RDE cycles were used to evaluate each energy management strategy's efficacy. The vehicle's total energy efficiency, battery cycle life, and peak battery current decrease were important criteria. The outcomes were contrasted for the low, medium, and high starting SOC values. In terms of reducing power losses and smoothing the battery current profile, especially during demanding driving cycles, the EWMA and power-based approaches performed better.

Optimisation of Control Parameters: To optimise each strategy's control parameters, such as the decay factor for the EWMA filter and the current threshold value for the threshold-based strategy, an iterative optimisation technique was used. Adaptive control, which modified parameters according to vehicle speed and battery state of charge, significantly improved the power-based approach. Under various driving circumstances, our adaptive strategy made sure that the battery and LiC module shared power as efficiently as possible.

Fig-6: A circuit diagram with the following components:

- Rs (Internal Resistance)
- Rp (Polarization Resistance)
- Cdl (Double-Layer Capacitance)
- Rct (Charge Transfer Resistance)
- Cint (Intercalation Capacitance)
- Vdc (Open-Circuit Voltage)

**Comparison Table:**

| **Aspect** | **Proposed Approach** | **Existing Approaches** | **Advantages of Proposed Approach** |
|---|---|---|---|
| **Energy Storage System** | Li-ion Battery + Li-ion Capacitor (LiC) | Li-ion Battery + Supercapacitor (SC), Li-ion Battery Only | Higher power density and energy density with LiC; better handling of peak currents |
| **Energy Management Strategy (EMS)** | Threshold-Based, EWMA, Power-Based | Rule-Based, Filtration-Based, MPC, Fuzzy Logic | Adaptive control, improved transient response, lower battery stress. |
| **Control Method** | Adaptive Control with Real-Time Optimization | Fixed Rule-Based, Predictive Control | Real-time adaptation to driving conditions, lower computational cost |
| **Experimental Validation** | Real Driving Emission (RDE) Testing, AVL CruiseM Simulation | Mostly Simulation-Based, Limited Real-World Testing | More accurate results reflecting real-world performance. |
| **Battery Cycle Life Improvement** | Up to 55% increase in battery cycle life | Typical improvements of 20-30% with SCs | Significant enhancement in battery durability due to LiC integration. |
| **Power Flow** | Bidirectional DC/DC | Direct Connection, Passive | Efficient load balancing, |
| **Management** | Converter, Dynamic Load Sharing | Control | reduced peak currents, optimized power flow. |

| | | | |
|---|---|---|---|
| **Test Scenarios** | Urban, Rural, Highway Driving (RDE Cycles) | Standard Drive Cycles (e.g., NEDC, WLTC) | More realistic assessment under diverse real-world conditions. |

## 6. Research Problem

- High levels of stress are placed on the HEV's principal energy storage system (such as lithium-ion batteries) during abrupt changes in power demand, including regenerative braking and accelerating. Reduced cycle life and greater battery deterioration are the results of this stress.
- Lithium-ion capacitors (LiCs) have a potential energy-power density balance, but little is known about how to incorporate them into a hybrid energy storage system (HESS) for HEVs. Experimental data on how well they operate in actual driving situations is few.
- The energy management strategy (EMS) that is selected has a significant impact on how well hybrid energy storage systems (HESS) work. Current approaches, including rule-based or predictive control, could not adjust effectively to changing driving circumstances, which could result in less-than-ideal power allocation.
- There has been little testing done under actual driving circumstances, and many suggested control schemes and HESS setups have only been verified through simulations. This calls into question the approaches' dependability and practical usefulness.
- Depending on the driving style (e.g., aggressive vs. average driving), hybrid energy storage systems can operate quite differently. Increased battery stress and wasteful energy use can result from high power demand fluctuation during aggressive driving.
- Usually, the control parameters for energy management strategies—such as decay factors for filters and current thresholds—are adjusted manually or according to preset settings. This may lead to less-than-ideal performance under various driving circumstances and battery conditions.
- Performance can be enhanced by making the hybrid energy storage system and control mechanisms more complicated, but doing so may also result in increased expenses, weight, and integration difficulties.

## 7. Conclusion

The study effectively illustrated the advantages of incorporating a lithium-ion battery and a lithium-ion capacitor (LiC) module into a commercial hybrid electric vehicle (HEV) as part of a hybrid energy storage system (HESS). The suggested system significantly improved its ability to manage transient power needs by putting sophisticated energy management strategies (EMS) into practice, such as threshold-based, Exponential Weighted Moving Average (EWMA), and power-based control techniques. By efficiently reducing the strain on the primary battery, the LiC module's capacity to manage high peak currents resulted in a 55% increase in battery cycle life.

An extensive assessment of the control techniques under various driving situations, such as urban, rural, and highway scenarios, was made possible by the real-world validation utilising Real Driving Emission (RDE) cycles. The outcomes demonstrated adaptive EMS's improved performance, especially the power-based and EWMA techniques, which demonstrated increased effectiveness in lowering peak power demands and smoothing battery current profiles. Based on actual driving circumstances, these solutions dynamically distributed power between the battery and LiC module, increasing overall energy efficiency and prolonging the life of the energy storage components.

The experimental results, which were corroborated by simulation results from the AVL Cruise M platform, demonstrated that integrating LiC technology into HESS is a viable way to address the difficulties associated with HEVs' transient power needs. Without significantly increasing system complexity or weight, the adaptive control techniques suggested in this work demonstrated the ability to improve vehicle economy and reduce battery deterioration while delivering strong performance improvements.

Furthermore, by utilising LiCs' high power density and quick charge/discharge capabilities, their employment as a supplementary component in the HESS proved successful. By offering both experimental validation and real-world testing, this work closes a significant research gap and overcomes the shortcomings of earlier studies that mostly relied on theoretical models and simulations.

Further research into adaptive energy management techniques is made possible by the successful deployment and validation of the suggested system, especially when it comes to handling different driving styles and actual operational environments. Future research may concentrate on improving these tactics, investigating predictive control based on machine learning, and extending the use of LiC technology to a wider variety of electric cars.

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