A NOVEL ENERGY MANAGEMENT APPROACH FOR HYBRID BATTERY-SUPERCAPACITOR CONFIGURATIONS IN ELECTRIC VEHICLES

Ashwanth S, Assistant Professor, Velalar College of Engineering and Technology, Erode, Tamilnadu.

Yamuna S, Assistant Professor, Velalar College of Engineering and Technology, Erode, Tamilnadu.

Gogulabrindha S, Assistant Professor, Velalar College of Engineering and Technology, Erode,

Sreedhar M, Professor, Velalar College of Engineering and Technology, Erode, Tamilnadu.

***Abstract* -** Presently, supercapacitors and batteries are essential energy storage devices in industrial settings, especially electric cars. Both the high-power density of supercapacitors and the high energy density of lithium batteries are advantageous for electric vehicles. A strong and effective energy management system must coordinate energy flows between these two storage systems to ensure road safety. In order to create reliable control between the lithium-ion battery and the supercapacitor, we create a new rule-based technique in this work named “Dynamic Battery Power Limiting for Continuous Regulation”. To compare the effectiveness of this suggested strategy to traditional approaches, a comparative analysis is carried out. By preventing the main energy source from being depleted and greatly improving driving comfort, this method yields a gain of over 30% as compared to an electric vehicle that uses lithium-ion batteries.

Keywords: Electric Vehicle, Li Batteries, Supercapacitors, Energy Management, Hybrid Source, Dynamic Battery Power Limiting

I. INTRODUCTION

Fossil resources are strongly related to the transportation market, which includes trucks, cars, and airplanes. Nearly two-thirds of energy consumption comes from oil, whereas 15% comes from renewable sources. As seen in Figure 1, "energy and electricity" is the main contributor to CO2 emissions, accounting for the largest percentage. After this, 24.4% of CO2 emissions come from the transportation sector, which includes automobiles. Road vehicles produce more air pollution than boats, airplanes, etc., according to research from the World Health Organization. Specifically, the two primary sources of air and water pollution are gasoline and diesel. Furthermore, it has a detrimental effect on human health, causing severe diseases with a high death rate. It is obvious that the unwelcome emissions from these gasoline-powered cars pose a major risk to both the stability of the environment and human societies[1].

Politicians are compelled to enact stricter regulations and raise tariffs on cars that emit more pollutants as a result of the massive pollution levels. By utilizing cleaner and more sustainable resources, battery electric vehicles (BEVs) have recently begun to stray slightly from traditional fuels. Norway intends to outlaw polluting automobiles starting in 2025, while nations like China, France, and the United Kingdom (UK) intend to stop selling gasoline and diesel vehicles by 2040. With almost 90% of the worldwide car market, China continues to lead the electric mobility space, with the US market coming in second. Despite this, Norway leads Europe with a 40% market share, performing well on its scale. These days, this clean car first approach seems like a good way to go. With 6.75 million BEVs sold in 2021 across many nations globally, the market continued to grow in 2022.

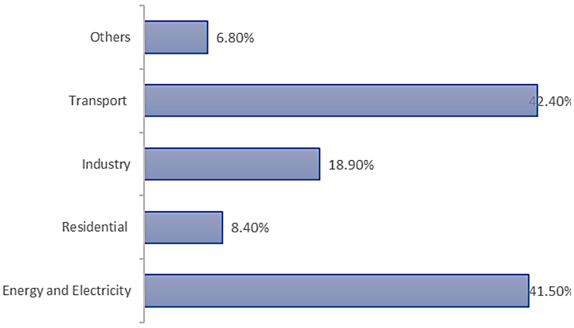

Figure 1. proportion of global CO2 emissions by industry, as reported by the AIE organization

In order to increase vehicle autonomy and battery life, a second transition that targets hybrid-source electric vehicles (HEVs) and comprises a collection of energy storage systems (ESSs) may be offered. The quick capacity of the SC for energy storage with an almost infinite number of charge and discharge cycles is combined with the higher energy density properties of the Li-ion battery in this hybridization[2]. The power management system (PMS) becomes more complex when a Li-ion battery main source and SC secondary source are combined, but the HEV range is increased. Consequently, a balance between these two crucial elements ought to be taken into account.

Furthermore, optimizing the PMS and HEV safety is made feasible by a precise calculation of the state of charge (SOC) of these two energy sources. A PMS management system typically achieves a better level of control by merging the capacity management system (CMS) and battery management system (BMS) systems. The PMS's primary purpose is to prevent excessive use of battery/SC cells and high ripple currents at low frequency levels, which are vulnerable to any heating effect. Protection against fires and explosions can be guaranteed while operating an electric car with a hybrid source thanks to the proposed PMS system. It does, in fact, shorten battery life.

In this paper, we present a unique approach to efficient power management in hybrid electric vehicles (HEVs) called "Dynamic Battery Power Limiting for Continuous Regulation”.This strategy is a major advancement in maximizing the interaction between lithium-ion batteries and supercapacitors (SCs), which are essential to the longevity and effectiveness of HEVs.

The accurate calculation of non-directly observable factors, such as the battery and SC state of charge (SOC), is essential to the effectiveness of our suggested management system. Accurate SOC calculations are essential to the suggested approach, as are measurable inputs like voltage and current. As a result, we use a robust extended Kalman filter (EKF) algorithm that combines recursive least squares (RLS) and open-circuit voltage measurements (OCVs). An accurate and thorough assessment of SOC is guaranteed by this hybrid modeling approach, which is essential for efficient energy management.

Building on this framework, our approach adjusts the battery's current restrictions in real time based on SOC data and dynamically controls the energy exchange between the battery and the SC. The SC's suggested method optimizes the SC's recharge cycles while significantly lowering the operational load on the battery by dynamically modifying these restrictions in proportion to the SC's state of charge. Maintaining energy efficiency and prolonging the life of the storage components, particularly under varied load and driving situations, depend on this balance.

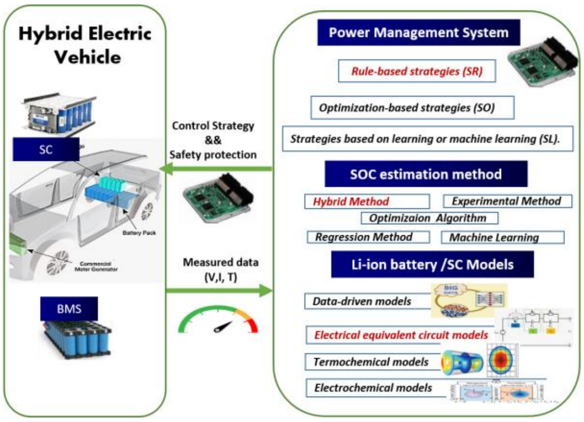

Figure 2. hybrid energy source in an electric car

Extensive experimental implementation in real-world driving circumstances validates the effectiveness and practicality of the suggested "Dynamic Battery Power Limiting for Continuous Regulation" technique. These experiments, which were carried out with a MATLAB-dSPACE interface and an ARTEMIS rolling cycle, confirm that the approach is successful in improving HEV energy management, opening the door to new environmentally friendly and effective transportation options.

II. BATTERY/SC ENERGY STORAGE IN AN ELECTRIC VEHICLE

A. Dynamics Model for Hybrid Electric Vehicles

To fully understand how PMS works and look at how it affects battery/SC energy-storage-based electric vehicles, a dynamic model of the vehicle is required. The parallel arrangement of the electric car under study that has a supercapacitor and a lithium battery is shown in Figure 3.

B. Cycle of Drive

Different organizations create driving cycles to assess a vehicle's performance based on a variety of factors, such as electric vehicle range, fuel efficiency, and pollutant emissions. The efficiency of related parts such as internal combustion engines, transmissions, batteries, and electric drive systems can also be estimated using these driving cycles[3].

Since 1973, the New European Driving Cycle (NEDC) has been widely accepted as a depiction of the speed profile of a vehicle over time. For new car models, it was superseded in September 2017 by the World Harmonized Light Vehicle Test Procedure Cycle (WLTP). The primary difference is that the old normalized cycles included straight acceleration and periods of constant speed. The WLTP, on the other hand, takes into account a range of speed variances. Transient cycles now use real-driving data to create a more accurate picture of on-road conditions, closely matching real-world driving scenarios and better reflecting real-world performance.

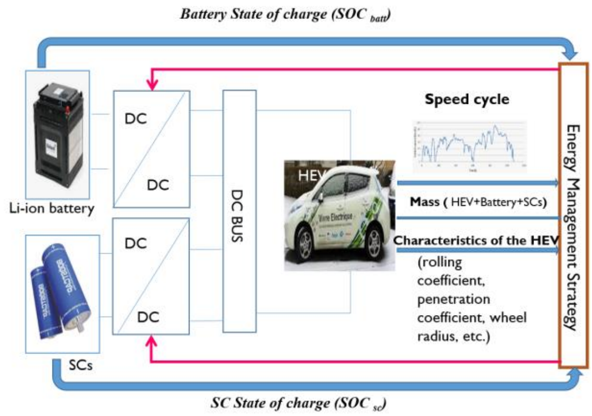

Figure 3. The hybrid-powered electric car under study's architecture

C. Hybrid Source Sizing

It is challenging to handle the complex challenge of EV scaling with hybrid energy storage systems (ESSs) using a traditional sequential strategy. The vehicle's features (mass, surface, air penetration coefficient, curve rolling resistance coefficient, etc.) and mission (driving cycle) interact strongly during each dimensioning procedure. In order to meet the actual needs of the users and the vehicle's mission profile, the number of series cells (Ns,b) or parallel cells (Np,b) of the battery and cells (Ns,sc; Np,sc) of the SC must be adjusted[4,5].

In earlier research, we created the hybrid optimization method (algorithm) (PSO/NM). The dimension criterion and another effective power criterion were successfully included in this algorithm's goal for the multi-physics model identification procedure. This thus makes it possible to determine how many elements Ns,b, and Np,b the battery pack contains while accounting for changes in consumption based on the mass of the source.

Equation makes it possible to calculate the required values of the battery elements Ns,b and Np,b, which in turn supply the quantity of energy required for the EV to operate properly and guarantee the vehicle's autonomy.

$$N_{s,b} \cdot N_{p,b} = \frac{E_{cons}(1+\sqrt{(1+4(E^{el}_{max,b}-1.4\sigma^{cons}_{E}\cdot m^{el}_{b})\cdot\frac{R^{el}_{0,b}}{U^{2}_{min,b}}}}{2(P^{el}_{disch,b}-1.4\cdot\sigma^{cons}_{E}\cdot m^{el}_{b})}$$

Therefore, when the SC pack focuses on the power peaks during accelerating and braking, the Li-ion battery pack's primary job is to store the energy required for the vehicle's autonomy. Thus, with the SC's maximum discharge depth of 75%, we compute the energy required to supply and absorb the maximum power in discharge and charging.

III. ESTIMATING THE STATE OF CHARGE AND MODELING

Technological details, including electrochemical processes, internal resistance, self-discharge, temperature sensitivity, and, in particular, charge and discharge characteristics, are taken into account while modeling battery and supercapacitor energy sources in this work. Additionally, the main objective is to establish a strong foundation and develop a simpler model that can accurately simulate the behavior of the battery or the SC in real time for the best possible adaptability to EV applications. We employed models based on equivalent electrical circuits (ECMs) to accomplish these goals because they offer a fair trade-off between simulation quality and calculation time[7].

A. Online SOC estimation and battery ECM model

Lithiumion batteries have played a crucial part in the development of electric cars. These batteries are now necessary parts that are revolutionizing the transportation industry. Their importance encompasses a number of factors, including market dynamics, environmental concerns, technological developments, and the larger shift toward electric and sustainable mobility options. Several models have been created in the field of battery modeling to represent the behavior of lithium-ion cells. These models take into account the dynamic and nonlinear nature of battery parameters, which include variations in the state of charge (SOC) and changes throughout the charging and discharging cycles[8].

As shown in Figure 4, Thevenin's model with two branches (RCs) is thus used to model the Li-ion battery under study. Actually, there are four primary components to Thevenin's model:

The potential between the electrodes when the battery is fully unplugged (in a condition of rest or relaxation) is known as the open-circuit voltage, or OCV.

- The resistance of the electrolyte, pins, and active material causes the internal resistance, also known as the series resistance, R0, to exhibit an instantaneous ohmic voltage drop. Transient voltages like double-layer effects and transition effects between ionic and electrical conductance are taken into consideration by the first parallel branch, Rct-Cct. The time constant $\tau1$, which is the product of Rct and Cct, is of the order of a few seconds for these brief occurrences.
- Long-term transient effects are taken into account as the relaxation effect by the second parallel circuit element, Rdiff-diff. The formula is τ = Rdiff. The time constant for these effects, which is on the order of several minutes, is shown by Cdiff.

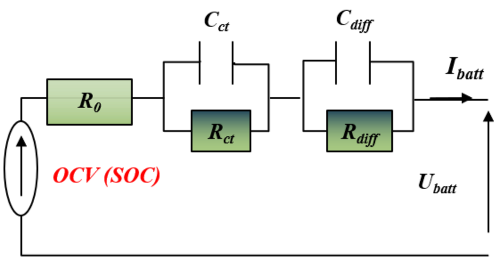

Figure 4 shows a model of Li-ion batteries.

The robust hybrid estimation approach suggested by Jarraya et al. in Refs. is used in this study to estimate the state of charge (SOC) for a Li-ion battery. This hybrid estimator combines the offline open-circuit voltage (OCV) direct measurement method with the online recursive least squares with forgetting factor (RLS) and extended Kalman filter (EKF) approaches. Real-time online estimation of Li-ion battery parameters (R0, Rct-Cct, and Rdi f f -Cdi f f) with correction and an update function based on OCV = f (SOC) are among the noteworthy aspects of the hybrid SOC estimation tool[9,10].

Furthermore, the EKF employed in this study exhibits superior noise reduction and compensation capabilities, successfully taking into account differences in measurement sensors and acquisition apparatus.

This hybrid algorithm offers a dependable and precise method for figuring out the state of charge (SOC) of several lithium-ion battery types. Less than 0.7% is the average error of the battery's projected state of charge.

B. Model of Supercapacitor ECM

The comparable circuit model put forth by Rizoug et al. is used in this article to mimic the dynamic behavior of the supercapacitor (SC) during the charging and discharging phases, as shown in Figure 5.

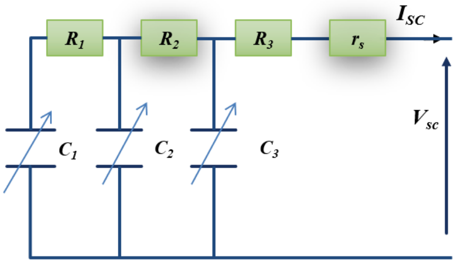

Figure 5. Model of supercapacitors.

To depict the charge propagation from the electrode surface, this model includes parallel branches made up of R1C1, R2C2, and R3C3. The model also incorporates the series resistance rs, which takes into consideration joule losses in the electrolytes and metallic conductors, especially at the collector-contact interfaces and activated carbon collector. The MAXWELL BCAP0350 (2.7V) supercapacitor technology was used in this investigation to improve the Li-ion battery's performance.

The SC parameters R1, C1, R2C2, R3C3, and rs can also be found by temporal characterization using a supercapacitor cell discharge load test. The basic idea is to use an RC circuit model to mimic the supercapacitor's discharge behavior. The model is then fitted to the experimental data in order to determine the model parameters[11]. By conducting a load test and tracking the supercapacitor's voltage and current at different points in time, we can obtain a collection of experimental data.

IV. ENERGY MANAGEMENT TECHNIQUES THAT ARE ACTIVE FOR HYBRID STORAGE SOURCES

A. Modern Techniques for Energy Management

Two energy sources combined with bidirectional converters give electric vehicles (EVs) with hybrid storage sources further degrees of freedom. A power management system (PMS) is responsible for the efficient management of these sources. The PMS maximizes the efficiency of all resources and guarantees the structural integrity of the vehicle. In real time, it determines the best power distribution between the energy sources and the load by monitoring the different parts of the EV and managing energy exchange. The PMS's main objective is to make it easier to convert between operating modes efficiently, which will increase the Storage Systems' (SSE) longevity and safety[12].

To identify the best PMS strategy in terms of cost, robustness, reliability, optimization, and ease of deployment, several strategies have been developed in recent decades. An overview of these PMS techniques as grouped in the literature is given in Figure 6, which can be roughly divided into three primary methods:

- Statics based on rules (SR);
- Strategies based on optimization (SO);
- Machine learning (SL) or learning-based strategies.

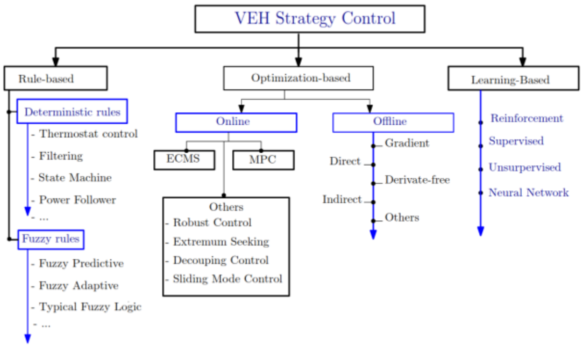

Figure 6. Categorization of control techniques for hybrid electric vehicles

B. Constant Control with Adaptive Battery Power Limiting

Advanced power distribution systems are required for innovative energy management in hybrid electric vehicles (HEVs). Because of their simplicity and ease of real-time implementation, traditional rule-based procedures such as the limit method (ML) and filter method (MF) offer a basis.

However, by introducing the "Dynamic Battery Power Limiting for Continuous Regulation " technique, our research marks a substantial development. The control of the supercapacitor's state of charge (SOCsc) is the main focus of this innovative algorithm. Its main goal is to dynamically control the SOCsc in order to reduce the possibility of overcharging or deep draining the supercapacitor, which will increase its lifespan and dependability[13].

Let's take a quick look at these conventional tactics to set the scene and compare them:

- Limiting Method (ML [Limit inf/Limit Sup]): ** The ML approach efficiently controls the Li-ion battery's power or current within a certain range, as indicated by LimitSup and Limitinf. By balancing load requirements and battery protection, it guarantees that the supercapacitor (SCsc) can handle any demand that exceeds these limits.
- Filter technique (MF[τf]): ** Using a low-pass filter, the MF technique divides the power demand between the battery and SCsc while operating on an open-loop control scheme. While the Li-ion battery handles consistent, low-frequency needs, the SCsc is tasked with handling high-frequency power requirements. This method improves response efficiency and successfully reduces battery stress.

Our "Dynamic Battery Power Limiting for Continuous Regulation " approach has advanced significantly with the addition of a linear relationship between the SOCsc and the battery's maximum discharge current.

V. VERIFICATION OF ENERGY MANAGEMENT TECHNIQUES

This paper evaluates the feasibility and efficacy of our Continuous Regulation with Dynamic Battery Power Limitation Improvement Solution using six management techniques. In order to ensure safe control and coordination between power-producing units, converters, and the load, this platform provides unbreakable electrical, mechanical, and computer security in any actual application of this management[14]. The test bench's synoptic, which consists of converters, a lithium-ion pack, and a SC pack emulation, is shown in Figure 7.

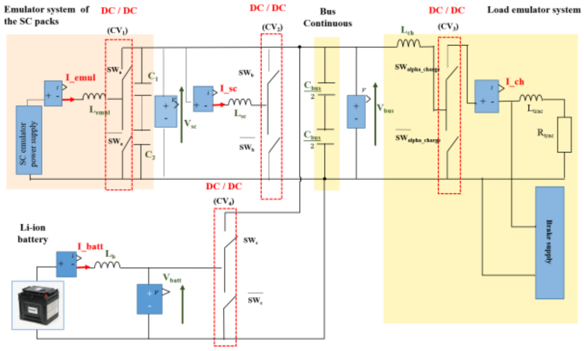

Figure 7. An overview of the testing bench

The suggested hybrid design incorporates two converters (CV1 and CV2) to control the power transfer between the DC bus and the SC emulation supply. The first converter, CV1, is utilized to simulate the SC's behavior during the load phase. However, the second converter (CV2) will regulate the SC's discharge phase. Conversely, the Li-ion battery and charge emulation system are connected to the DC bus (CV3 and CV4) via two bidirectional converters. The power is dissipated in a resistor by the CV3 converter, which supplies the traction current needed by the load. The braking part of the procedure is simulated by a configurable "brake supply."

VI. CONCLUSION

This study concludes by emphasizing the critical role that batteries and supercapacitors play as essential energy storage devices in industrial settings, especially in the electric vehicle (EV) industry. EVs benefit greatly from the synergistic combination of the powerful power density of supercapacitors and the increased energy density inherent in lithium batteries. However, in order to achieve these advantages, a strong and effective energy management system must be put in place, guaranteeing both safe operation and peak performance.

The study grants "Dynamic Battery Power Limiting for Continuous Regulation", a ground-breaking rule-based method specifically engineered to manage the intricate interplay of energy flows between the supercapacitor and lithium-ion battery. This method seeks to create reliable control while enhancing the overall performance of hybrid energy storage systems in electric cars. The observable outcomes show notable advancements in limiting the depletion of the principal energy source. Notably, a noteworthy 30% improvement has been made when compared to traditional electric vehicles that use lithium-ion batteries. Additionally, the supercapacitor's charge is strategically replenished at the end of each drive cycle thanks to the innovative rules-based approach. The overall cost of batteries is greatly decreased by this clever charging and discharging rhythm adjustment. Both the lithium-ion battery and the supercapacitor experience increased efficiency and longer lifespans as a result of this coordinated cycle optimization.

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