A Dual Energy Management for Hybrid Electric Vehicles

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***Abstract*—Electric vehicles (EVs) are gaining increasing recognition as an effective means to combat climate change and reduce greenhouse gas emissions. Lithium-ion batteries have emerged as the prevailing choice for energy storage in the automotive industry, offering superior attributes to alternative battery technologies. In the context of EVs and hybrid electric vehicles (HEVs), the singular reliance on a single battery unit presents a challenge. Any fault within the battery impacts the vehicle's performance and raises concerns about its overall reliability. In an effort to enhance vehicle reliability, this paper introduces a novel approach that involves the use of multiple smaller battery packs to collectively match the capacity of a single, larger battery pack. Also, to effectively distribute power between the vehicle's internal combustion engine and the various smaller battery packs utilized in the HEV configuration, this study proposes a dual energy management (EM) system. The first EM system allocates power between the engine and the battery packs with the primary objective of minimizing fuel costs. Meanwhile, the second EM system is responsible for distributing power among the different battery packs, aligning with the power requirements determined by the first EM system. To assess the viability and effectiveness of the proposed energy management solution, numerical simulations are conducted using MATLAB/Simulink. Two distinct scenarios are explored wherein the total capacity and the remaining capacity, often referred to as the State of Health (SoH), are varied for each of the smaller battery packs. Through these simulations, this paper aims to evaluate the practicality and performance of the designed energy management system under varying conditions.**

***Index Terms*—Battery, Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs), Energy Management (EM), State of Health, Remaining Capacity**

I. Introduction

THE increasing popularity of electric vehicles can be attributed to the volatility in the cost of non-renewable energy sources and the significant environmental consequences associated with them. Electric vehicles, whether they are fully electric (EVs) or hybrid electric vehicles (HEVs), contribute to mitigating environmental harm when compared to traditional internal combustion engine (ICE) vehicles. Lithium-ion (Li-ion) batteries have emerged as the most promising and favored battery technology for electric vehicles as of now [1], [3]. They offer numerous advantages over other battery technologies, rendering them exceptionally well-suited for EVs [4]. Li-ion batteries boast a superior energy density compared to their counterparts, signifying their ability to store a greater amount of energy within a smaller footprint. This intrinsic feature extends the range and augments the performance of electric vehicles, enhancing their overall capabilities. Moreover, Li-ion batteries exhibit a higher power density, enabling them to deliver power more rapidly [5]. This attribute is particularly vital for electric vehicles, which necessitate swift acceleration and the capability to surmount challenging terrains. Furthermore, the Li-ion battery's lightweight and compact nature, in contrast to other battery types, contributes to the heightened efficiency and streamlined design of electric vehicles [4].

The power generation relies on two primary sources, namely a battery and an internal combustion engine (ICE), in the most common type of HEVs. An energy management (EM) system plays a pivotal role in power allocation between these sources, contingent upon the power requirements of the powertrain [6], [7]. The role of EM in HEVs is explained in detail in studies [8]- [10]. Furthermore, either HEVs or full EVs conventionally employ large battery packs. However, in the pursuit of heightened reliability and fault tolerance, rather than relying on a single, large battery pack, an alternative approach can be considered. This involves the utilization of multiple smaller batteries, collectively matching the capacity of a larger singular pack [11].

This concept holds significant potential for applications in domains such as the military, as exemplified in the study conducted by [12] In military operations, particularly in HEVs, the susceptibility of a vehicle to damage during missions is a critical concern [13]. In scenarios where a single, large battery pack is in use, the risk of substantial battery damage in the event of an attack is a legitimate concern. However, the adoption of smaller battery packs offers an advantageous solution. In this configuration, even if one or a few small packs are compromised or damaged, a reservoir of other functional units remains available to seamlessly provide power to the vehicle, irrespective of the condition of the affected units [14]. This fortifies the vehicle's operational resilience and its ability to endure damage-inducing situations.

Also, the use of multiple smaller battery packs in HEVs or EVs offers a range of advantages. Firstly, as discussed earlier, it enhances the vehicle's reliability by reducing the impact of

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one pack's failure on overall performance, thus minimizing the risk of complete system failure. This enhanced reliability is further complemented by the reduced downtime and maintenance costs associated with smaller packs, which are easier to service and replace. Additionally, the system's scalability allows manufacturers to tailor the number of packs to suit specific vehicle models and applications, thereby enhancing design flexibility and performance adaptability. Moreover, the distribution of battery packs throughout the vehicle contributes to a more balanced weight distribution, improving stability and handling, particularly in larger or heavier vehicles like military vehicles [15].

However, using multiple smaller battery packs adds complexity to the system, especially in energy management systems. These systems must carefully distribute power evenly among each smaller battery pack to ensure efficient and reliable performance. Additionally, the extra space needed for multiple packs can reduce interior and cargo space. The weight of the duplicated components may add to the overall weight of the vehicle, which can reduce energy efficiency and range. A perpetual trade-off exists between system reliability and the related costs. These costs can be viewed as an investment in enhancing system reliability [16], [17].

A. Statement of Contribution

This paper presents a novel method to improve the operational reliability of HEVs by replacing a single large battery pack with smaller packs that collectively match its capacity. A dual EM system, comprising primary and secondary EMs, forms the core innovation. The primary EM optimally distributes power between the ICE and the battery to minimize fuel consumption, guided by a constrained objective function. Building upon this, the secondary EM further optimizes power distribution among four smaller battery packs. Its objective function minimizes the discrepancy between the total power required by the battery and that supplied by each pack, considering factors like state of charge (SoC) and remaining capacity (Q). Priority is given to batteries with a higher state of health (SoH) or Q and SoC, with a strategic emphasis on Q over SoC. This approach offers a promising solution to enhance HEV reliability and efficiency while adapting to smaller battery packs.

The remaining paper is segmented as follows: Section II explains the vehicle architecture considered in this study. Section III explains in detail the two types of EM considered in this study. The different operating scenario for different battery configurations to implement the proposed EM for the vehicle is explained in detail in Section IV. Finally, Section V provides the paper's conclusion and suggests future research directions.

II. Architecture of Hybrid Electric Vehicle

Hybrid electric vehicles (HEVs) are gaining increasing popularity as a sustainable mode of transportation. These vehicles employ a combination of energy sources, typically including at least one electric motor powered by electricity. HEVs can be categorized into various types based on their energy origins and power delivery systems. A commonly encountered configuration combines an internal combustion engine (ICE) with a battery to fulfill power demands. This research focuses on the series HEV configuration, a relatively uncomplicated and easily regulated sub-type within the realm of hybrid electric vehicles [18], [19].

In the series HEVs, the ICE is not directly linked to the drivetrain; instead, it drives a generator that converts its output into electrical power. This electricity serves either to recharge the battery or to drive the electric motor, which, in turn, propels the vehicle's wheels. This particular configuration grants precise control over power distribution to each wheel, thereby simplifying traction control [20], [21]. Power electronics technology has played a pivotal role in notably enhancing the efficiency and reliability of HEVs [22]- [24]. The series hybrid architecture brings forth many advantages, encompassing improved fuel efficiency, reduced emissions, and heightened command over power distribution to the wheels. Additionally, the absence of a direct mechanical link between the ICE and the drivetrain facilitates more versatile control and streamlines traction management.

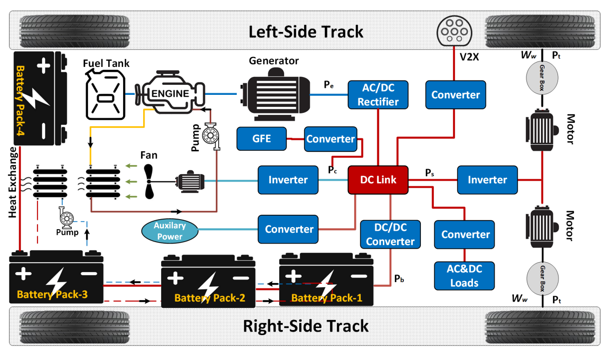


Fig. 1: PHEV architecture considered for the study.

The HEV model utilized in this research has been comprehensively addressed in prior research [12], with a detailed exposition of vehicle parameters and dynamic characteristics provided in [24]. This section presents a general overview of the electrical model of the HEV model used in this study. A DC link bus voltage of $600V$ is considered where both an ICE and a battery are connected to supply the power. Figure 1 illustrates the HEV model deployed in this study, where energy sources and loads are separated from the bus, facilitated by power electronics converters. Recent advancements in power electronics and the cost-efficiency of electronic components have rendered this design economically viable. A US06 drive cycle is considered as a reference drive cycle to drive this powertrain architecture. To calculate reference power for this drive cycle, essential vehicle dimensions and dynamic parameters are sourced from the referenced study [24]. This study deviates from the approach in [2], where a single large 73 kWh battery pack was employed by instead examining the utilization of four smaller modular battery packs, each with the same or varying ratings. The change in the vehicle model, especially the battery pack, is considered to evaluate the performance of HEV with modular battery packs. The ratings of the modular packs are selected so as to enhance flexibility and efficiency compared to their larger counterpart. Their ease of replacement or upgrade, as discussed previously, augments the vehicle's operational reliability.

III. Operation of Vehicle with Dual Energy Management

In HEVs, the presence of different power-generating sources demands an EM system. The objective of the EM system in the vehicle is to efficiently distribute the power among multiple power-generating sources present in the vehicle by maximizing fuel efficiency. The HEV vehicle considered in this study integrates two power-generating sources: an ICE and a battery. Unlike the conventional use of a single large battery pack, this study employs four modular battery packs of varying ratings to match the capacity of larger battery packs. Consequently, the use of smaller modular battery packs necessitates the introduction of a separate EM system. In response, this study introduces a dual EM approach comprising primary EM and secondary EM. The primary EM is responsible for fuel consumption reduction and power allocation between the battery and ICE, while the secondary EM allocates the power between different modular battery packs.

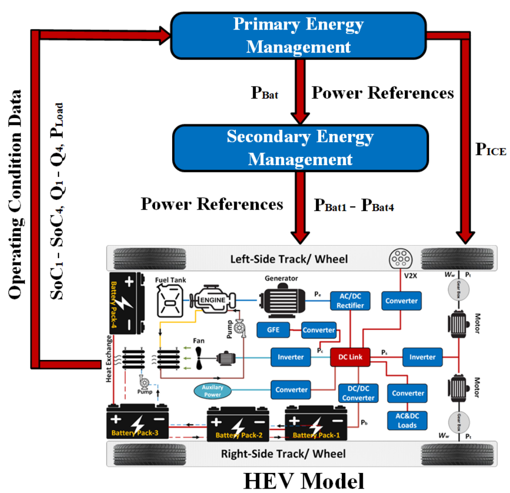


Fig. 2: PHEV architecture considered for the study.

Figure 2 illustrates a multilayer control architecture featuring two EM systems to control the HEV operations. This study uses a predefined US06 drive cycle to drive the powertrain. The vehicle's operational data, encompassing the total power demand, SoC, and Q of each modular battery pack, are relayed to the controllers housing the EM systems. The primary EM utilizes the battery's SOC and the vehicle's total power demands to generate reference powers, determining the power to be supplied by both the engine and the battery. Additionally, the power allocated to the ICE is directly routed to the vehicle from this layer, while the power to be supplied by the battery is conveyed as input to the secondary EM, alongside SoC and the Q data for each battery. This secondary EM, in turn, allocates power among the modular batteries and transmits these values to the HEV model.

A. Primary Energy Management

The general representation of EM optimization can be described as follows, utilizing an optimization function aimed at minimizing fuel costs [12].

$$\min \sum_{s \in \mathcal{S}} f_s(P_s(t_k)) \tag{1a}$$

$$P_s(t_k) \in \mathcal{P} \tag{1b}$$

where t_k is the time instant in the discrete domain, $\mathcal{S}$ is the set of indices of energy sources, and $P_s(t_k)$ is power generated by source s at t_k, and $\mathcal{P}$ is correspondingly the constraints set of $P_s(t_k)$. For the sake of presentation, t_k is omitted. Additionally, there are several constraints that should be considered and are explained in detail in this section.

The EM optimization is formulated as a constrained optimization problem, incorporating various constraints. These constraints encompass the power limits of the vehicle's power sources, the total load demand and the SoC of the battery. To tackle this optimization problem effectively, the Sequential Quadratic Programming (SQP) algorithm is employed. SQP is an iterative approach specifically designed for solving nonlinear programming problems with constraints. Its main objective is to identify the minimum or maximum of the objective function while satisfying the defined constraints throughout the iterative process.

It is worth noting that every energy source has its generation capacity limits. Therefore, one of the constraints of (1b) is lower and upper generation limits as

$$\underline{P_{bat}} \leq P_{bat} \leq \overline{P_{bat}} \tag{2a}$$

$$\underline{P_{ICE}} \leq P_{ICE} \leq \overline{P_{ICE}} \tag{2b}$$

The main goal of the powertrain is to supply loads properly. The total generation should meet the total load, including any losses. With the considered configuration, the following constraint (3) can be formed.

$$P_{Bat} + P_{ICE} = P_{Load} \tag{3a}$$

$$P_{Load} = P_{AC\ load} + P_{DC\ load} + P_{propulsion} + P_{V2X} + P_{loss} \tag{3b}$$

where P_{bat} is power generated by the battery, P_{ICE} is power generated by the ICE, and P_{Load} is the sum of all powers demanded by the loads. Here, $P_{AC\ load}$ is AC load, $P_{DC\ load}$ is DC load, $P_{propulsion}$ is propulsion load, P_{V2X} is power used for V2X mode, and P_{loss} is the total loss.

Each system has its own internal constraints, as stated in (4). The components considered in this study are ICE and battery; hence, the following constraints are assumed for these power-generating sources.

$$|P_{ICE}(t_{k+1}) - P_{ICE}(t_k))| < rr_{ICE} \tag{4a}$$
$$|P_{bat}(t_{k+1}) - P_{bat}(t_k)| < rr_{bat} \tag{4b}$$
$$\underline{SoC_{bat}} \leq SoC_{bat} \leq \overline{SoC_{bat}} \tag{4c}$$
$$SOC_{bat}(t_{k+1}) = SOC_{bat}(t_k) - \frac{\delta T i_{bat}}{Q_{nom}} \tag{4d}$$

where $\delta T = t_{k+1} - t_k$. Constraints (4a) and (4b) indicate that both the battery and the ICE have ramp rate limits when adjusting their generation. Constraints (4c) and (4d) are the battery's State of Charge (SoC) constraints. Q_{norm} is the nominal capacity of the battery.

As discussed previously, the main objective of this primary EM system is to distribute the power between the ICE and the battery efficiently. The distribution of power between these sources is illustrated in Figure 3, where an emphasis on minimizing fuel consumption is given, satisfying all the system constraints. Consequently, the power supplied by the battery under this EM is subsequently utilized as input for the secondary EM.

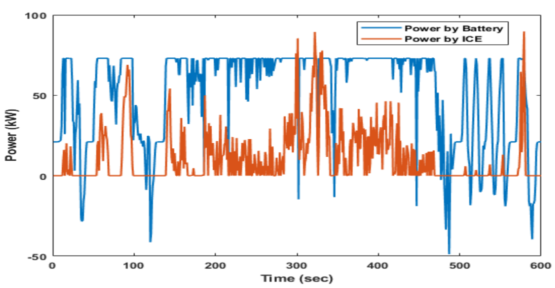


Fig. 3: Power allocated by primary EM.

B. Secondary Energy Management

Secondary energy management involves the management of multiple separate energy storage units that collectively provide the same total energy capacity as allocated by the primary EM to the battery. The aim of this EM is to efficiently utilize the multiple energy storage systems present in the vehicle depending upon their SoC and Q.

As discussed earlier, there are four different modular battery packs instead of one large battery pack. Hence, the objective of this EM is to allocate the power to these batteries depending on their SoC and Q. More weight is given to Q than SoC while developing the objective function with the basic concept that a degraded battery shall supply less power than a fresh battery. The objective function for this EM is given by (5) subjected to additional constraints given by (6), (7), and (8), respectively.

$$\min \left(P_{Bat}(t_k) - \sum_{i \in n} (P_{Bat_i}(t_k)) \right) \tag{5a}$$
$$P_{Bat_i}(t_k) = f(Q, SoC) \tag{5b}$$

where P_{Bat} is the total power to be generated by the battery, P_{Bat_i} is the power to be generated by the modular battery packs, which depends on the Q and SoC, and n is the number of modular battery packs which is equal to 4.

$$P_{Bat} = \sum_{n=1}^{4} P_{Bat_n} \tag{6}$$

(6) provides the power equality constraint where the total power supplied by the modular battery packs must be equal to the power allocated by the primary EM to the battery (P_{Bat}).

$$\underline{P_{Bat_n}} \leq P_{Bat_n} \leq \overline{P_{Bat_n}} \tag{7}$$

Each of the modular battery packs used here has lower and upper limits, which are given by (7). The lower limit for each of them is 0, and the upper limit is adjusted based on the specific case studies, which is provided in Table I.

$$0.2 \leq SoC_n \leq 0.95 \tag{8a}$$
$$0.8 \leq Q_n \leq 1 \tag{8b}$$

Similarly, the SoC and Q constraints are given by (8). The lower limit for the Q, is set at 0.8. This value is chosen to align with EV applications, where the battery is typically utilized up to 80% of its initial capacity to ensure reliable operation [4]. Also, the modular battery is operated between 95% and 20% and the SoC of the batteries changes depending upon the power supplied by them given by (4d).

IV. Numerical Simulation

In this section, numerical simulations are employed to validate the proposed dual EMs within the context of HEVs. The HEV powertrain, depicted in Figure 1 and featuring two power sources, namely the ICE and the battery, is utilized for this validation. The rating of the ICE and the battery are considered to be 180 kW and 73 KWh, respectively. All vehicle parameters are adopted from the study [24], serving as the basis for calculating the propulsion power pertaining to the US06 drive cycles via Ansys Motor-CAD. The propulsion load corresponding to the US06 drive cycle is visualized in Figure 4. Additional loads integrated into the simulation encompass a 10 kW AC load, a 10 kW DC load, and an assumed 1 kW power loss. Despite the presence of a V2G port within the vehicle, this study conservatively considers it as 0.

With all the mentioned information above, MATLAB/Simulink is employed to conduct the simulation. The power allocation by the primary EM is illustrated in Figure 3. Subsequently, depending upon the power to be supplied by the battery, three distinct scenarios are simulated to find the optimal power to be supplied by four modular battery packs as outlined below:

TABLE I: Power allocation to each modular battery pack for different cases

	Case-I				Case-II			
	Bat-1 20kWh, 100%	**Bat-2** 20kWh, 100%	**Bat-3** 20kWh, 100%	**Bat-4** 20kWh, 100%	**Bat-1** 20kWh, 100%	**Bat-2** 20kWh, 95%	**Bat-3** 20kWh, 90%	**Bat-4** 20kWh 85%
P_{Total} = 40	10	10	10	10	17.41	10.17	9.81	2.58
P_{Total} = 60	15	15	15	15	20	16.68	15.48	7.83
P_{Total} = 80	18.25	18.25	18.25	18.25	20	20	20	13

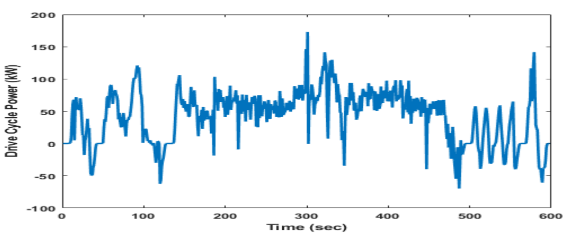
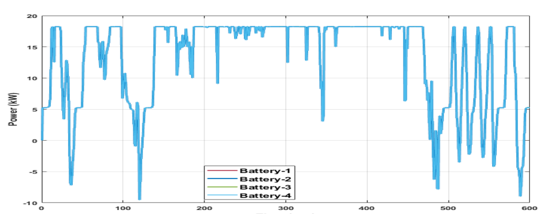


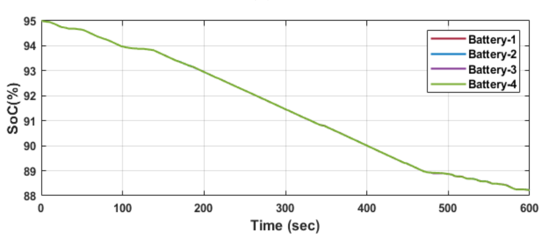
Fig. 4: Propulsion power for US06 drive cycle.

A. Case-I: Total Capacity of all Batteries are Equal

In this particular scenario, each of the modular battery packs is assumed to have a total capacity of 20 kWh and a 100% remaining capacity. Additionally, the state of charge (SoC) for each of these battery packs is initially set at 95%. This total capacity slightly exceeds that of a single 73 kWh battery pack, as previously discussed. Given that the secondary EM optimally allocates power based on the SoC and Q of the battery, all modular battery packs are expected to provide an equal amount of power, as depicted in Figure 5a. The figure illustrates the power distribution in accordance with the US06 drive cycle and the power allocated to the batteries by the primary EM. Also, since these batteries supply equal power, the change in SoC is also same, which is shown in Figure 5b.



(a)

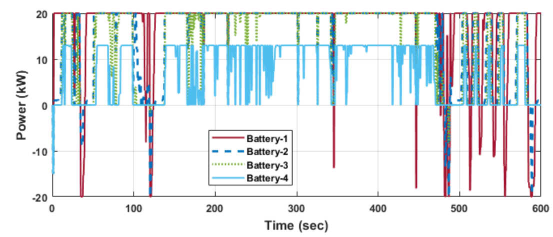


(b)

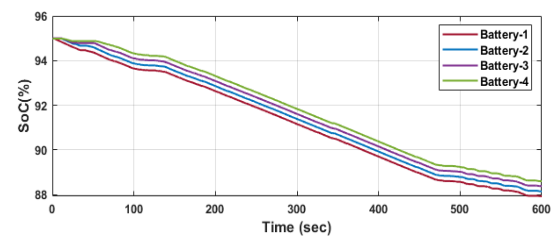
Fig. 5: Result for Case-I: (a) Power supplied by each battery pack, (b) SoC of each battery pack

To have a clear view of how the secondary EM allocates power, three constant loads of $40, 60$ and $80kW$ are considered, as detailed in Table I. It is evident that, for all three constant loads, each modular battery pack contributes an equivalent share of the load. Notably, when the considered load is 80 kW, the power supplied by each battery is 18.25 kW instead of the full 20 kW. This reduction is due to the primary EM allocating 73 kW to the battery and 7 kW to the engine, thereby restricting the maximum power that the battery pack can deliver.

B. Case-II: Remaining Capacity of Batteries are Different



(a)



(b)

Fig. 6: Result for Case-II: (a) Power supplied by each battery pack, (b) SoC of each battery pack

In this scenario, the modular battery packs exhibit varying remaining capacities, specifically 100%, 95%, 90%, and 85%, while maintaining an equal total capacity of 20 kWh across all packs. The initial state of charge (SoC) for each battery pack is set at 95%. It's important to note that the power contributed by each modular battery pack varies, contingent on the respective Q of the battery packs. Batteries with larger remaining capacities, indicating non-degraded batteries, contribute a greater share of the load, while the degraded packs with less Q supply a relatively smaller portion, as visually depicted in Figure 6a. This figure also illustrates the corresponding changes in SoC for each of the battery packs, which fluctuate in response to the power supplied by each pack as shown in Figure 6b.

For a more comprehensive understanding, the insights derived from Table I prove particularly informative, especially in the context of three distinct load scenarios. When the total load is set at 40 kW, the most degraded battery contributes less power, while the healthier battery shoulders the majority of the load. This trend persists in the other two scenarios, with the degraded battery also required to supply higher power to meet the load demand, as evidenced in these cases.

V. Conclusion

This paper introduces a novel dual energy management (EM) system tailored for hybrid electric vehicles (HEVs). It introduces a new concept, promoting the utilization of smaller modular battery packs instead of a single, large battery pack in an HEV. The shift toward modular battery packs increases the system complexity and requires an additional EM system. Thus, the study augments the conventional HEV control paradigm by integrating an extra EM system, named as secondary EM, that interfaces with the primary EM system and the vehicle model.

This study presents three different scenarios that involve altering the total capacity and state of health (or Q) of the modular battery packs to explore the distribution of load among them. To validate the proposed concept, numerical simulation for each case is conducted in MATLAB/Simulink. The results affirm the feasibility of modular batteries to shoulder the total load collectively, demonstrating the successful integration of an additional EM system into the control architecture of HEV vehicles.

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