
Research article

A hybrid NMC–LFP lithium-ion battery architecture for UAV applications: Maximising energy readiness and minimising calendar aging

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Abstract: Monolithic lithium-ion (Li-ion) battery designs continue to pose challenges in meeting diverse application requirements. This paper proposes a solution by introducing a novel hybrid battery architecture that considers combining two different Li-ion chemistries to mitigate each other's limitations. The potential of this concept is demonstrated by considering the application of unmanned aerial vehicles (UAVs) used for emergency deployment, which require high energy density during deployment and good longevity during their long off-duty periods. For the given application, the study identifies the optimal capacity proportions for the hybrid architecture using nickel manganese cobalt (NMC) and lithium iron phosphate (LFP) chemistries to balance energy availability and degradation, while keeping the change in weight, volume, and cost within acceptable limits compared to a typical single-chemistry battery pack. The optimal configuration showed an improvement of up to 35% in energy availability with a mere increase of less than 1% in calendric degradation compared to existing single-chemistry battery packs used for the same application. However, the weight and volume were penalised by 8%, while the cost dropped by around 4%. This result shows that no single hybrid configuration is universally optimal. The paper thereby establishes the broad potential that the architecture carries in a wide context.

Keywords: battery degradation modelling; hybrid battery system; multi-chemistry battery design; unmanned aerial vehicle; battery cyclic ageing model; battery calendar ageing model

1. Introduction

In the current global decarbonisation efforts, lithium-ion batteries have almost become indispensable [1,2], playing a crucial role across consumer and large-scale applications, such as electronics and electric vehicles (EVs) and grid energy storage and aerospace applications, respectively [3–5]. Their high energy and power densities, complemented by their relatively high efficiency, have recently helped facilitate an uptake in the mobility sector [6], whilst also being suitable for stationary applications like grid storage for the purpose of peak shaving and renewable integration [7,8]. With the adoption of Li-ion battery technologies for more diverse applications, there are increased requirements that need to be met by current battery technologies, which poses a challenge, since the majority of current technologies are mostly monolithic in design [9,10]. Therefore, achieving a single battery technology that fits universal applications continues to be a significant engineering challenge, highlighting the further need for extensive research in such technologies down to niche applications [11,12]. Additionally, each battery technology consists of further subdivisions of chemistries that come with their own pros and cons. For instance, although Li-ion batteries are commonly referred to as a single battery technology, they actually encompass a family of chemistries that differ significantly in composition and, thereby, characteristics [13,14].

Despite the significant progress in Li-ion battery versatility across sectors, their performance characteristics vary significantly depending on the active material chemistry [15]. Commercial variants of lithium-ion chemistries include lithium cobalt oxide, nickel manganese cobalt oxide (NMC), nickel cobalt aluminium oxide (NCA), lithium iron phosphate (LFP), and lithium manganese cobalt oxide, each offering distinct trade-offs between energy density, cycle life, safety, and cost [13–15]. High specific energy chemistries, such as Lithium Cobalt Oxide (LCO) and NMC, are favoured in mobile and aerospace applications, yet they are prone to thermal instability and accelerated degradation when stored at an elevated state of charge [16,17]. Cell chemistries such as LFP and Lithium Manganese Oxide (LMO) offer good thermal stability and cycle life at the expense of volumetric energy density [18]. In addition, NCA delivers high energy density but requires stringent thermal management [19,20]. These trade-offs highlight that no single chemistry satisfies the combined requirements of high energy density, long life cycle, and stability under various loads and environmental conditions [21].

The divergence in performance and stability among these chemistries has increased the interest in the hybridisation of Li-ion cells, combining electrochemical characteristics that complement each other to deliver high energy, rapid response, and extended battery life within a single configuration [22,23]. Prior research has largely focused on hybridising lithium-ion batteries with supercapacitors and alternate storage technologies [24]; however, the hybridisation of different Li-ion chemistries remains sparse [25]. Recent studies have highlighted that mixed cell chemistries, such as the combination of lithium-ion and zinc-ion components or multi-anion compounds, are under investigation and remain immature compared to single-chemistry systems [26–28]. For instance, Wang et al. (2024) discussed Li-ion batteries that combine multiple ion types (e.g., Zn^{2+} and Na^+) to merge the strengths of different chemistries and highlighted that key mechanisms and stability challenges remain unresolved [27]. Zhang et al. (2021) identified the potential of mixed-salt electrolytes for aqueous batteries but noted major drawbacks: chemical complexity and poor predictability [29]. In addition, Xiao et al. (2020) observed that most established cell chemistries introduce significant interface instability and ionic conductivity trade-offs [30]. Therefore, it is clear that battery systems with hybrid chemistries could

theoretically mitigate each other's trade-offs, but their practical implementation continues to remain experimental. Applications that demand a combination of advantages from different Li-ion chemistries can benefit from such a hybrid chemistry implementation. One such example is the unmanned aerial vehicles (UAVs) used for emergency deployment, where unique operational requirements require high energy density during deployment and good longevity during their long off-duty periods [31–33]. In this case, conventional Li-ion batteries, built around a single chemistry, struggle to balance performance with long-term stability. Hence, developing a hybrid system that strategically combines multiple Li-ion chemistries could help enhance energy availability without compromising degradation at higher state of charge (SOC).

While prior studies have primarily focused on the hybridisation of batteries with other energy storage systems or the improvement of the current state of battery technology, hybridising two commercial Li-ion batteries to mitigate each other's limitations has yet to be further explored. This paper addresses this research gap by choosing and optimising the proportion of two Li-ion chemistries for the application of UAVs for emergency deployment. The system proposed in this paper aims to minimise calendric ageing while retaining a higher SOC during storage to ensure energy readiness during deployment. A battery degradation model is developed in MATLAB/Simulink that includes both calendar and cyclic ageing. Battery modelling is also modified to accept chemistry-specific parameters to mimic different Li-ion chemistries. The battery model is then used to create two battery systems, namely the existing and the proposed system. The existing system uses the battery model to mimic a single chemistry NMC battery. On the other hand, the proposed system comprises two battery blocks that mimic NMC and LFP chemistries operating in parallel. The NMC battery serves as the primary energy source, owing to its high energy density, strong power output, and long life cycle [18,19]. In contrast, the LFP battery functions as the secondary storage unit due to its excellent thermal stability, safety profile, and exceptionally low degradation at high SOC [15,19,34]. NMC batteries typically possess higher energy density than LFP batteries; nevertheless, LFP batteries come with superior calendar life and better resistance to thermal runaway, making them an attractive option for energy retention during idle periods. In the proposed system, both batteries are equipped with respective control units that regulate charge–discharge behaviour according to the load profile and idle-state duration. It is important to clarify that the control unit mentioned here does not include the typical Battery Management System (BMS) functions, and the units of the batteries are assumed as auxiliary units, which will be highlighted in the sections ahead.

During prolonged inactivity, conventional single-chemistry systems discharge to low-to-mid SOC to mitigate degradation [35,36]. The proposed hybrid system, however, attempts to retain a higher SOC by increasing the depth of discharge in the primary battery and keeping the secondary battery at a high SOC. During the idle state, if the secondary battery's charge is below full capacity and the overall system SOC exceeds 0.6, the controller initiates a passive energy transfer from the primary to the secondary battery until the SOC of the secondary battery reaches full capacity. This unique control strategy optimises energy distribution, emulates the degradation performance of a 50% SOC system, and maintains substantially higher usable energy for mission-critical applications such as UAV operations. The main contributions of the paper can be summarised as follows:

- Introduction of a novel concept of hybridising two commercial Li-ion batteries to mitigate each other's limitations.
- Demonstration of the benefits of the proposed concept for a niche application, namely, UAVs for emergency deployment. This includes a control strategy that leverages the strength of the

introduced concept.

- Development of a MATLAB/Simulink model of a battery that includes degradation and can also mimic any specific Li-ion chemistry, thereby providing a tool for researchers to test and validate their ideas that require a battery degradation model in Simulink.

The structure of this paper is as follows: Section 2 outlines the operational principles of the proposed system, providing a detailed description of its working mechanism. Section 3 presents the mathematical modelling of all the components used in the study, along with the respective equations governing their behaviour. Section 4 explains the simulation procedure in detail for the given UAV load profile, with a focus on a comparison of SOC readiness and yearly degradation. The interpretation of the simulation results is covered in Section 5, which carefully compares the existing and proposed systems under different configurations. Section 6 summarises the key findings and provides the overall conclusions of the study.

2. Proposed system

Before discussing the proposed system, it is essential to highlight the assumptions considered while validating the concept. A controllable simulation environment is created for the application of a UAV used for emergency deployment. Digital twins of an existing battery system, along with the proposed battery system for this specific application, are modelled and compared to demonstrate the energy readiness and degradation. As the simulation requires fixed and controlled conditions to study the metrics of both systems, several simplifying assumptions are introduced, as follows:

- Auxiliary losses are constants: Inefficiencies from converters, controllers, and thermal management units are represented as fixed values rather than dynamic functions. This is done to reduce computational complexity. The proposed system additionally includes auxiliary losses due to the controller circuit that is introduced in the paper.
- Check uniform nominal voltage: Both battery systems are considered to operate at an output voltage of 24 V, for ease of comparison of their output characteristics. This is in direct comparison with an actual drone model chosen for reference, namely, the IF800 Tomcat.

The proposed system in this paper aims to minimise calendric ageing while retaining higher SOC during storage to facilitate higher energy for rapid deployment. A battery degradation model is modelled in Simulink that considers both calendric and cyclic ageing. The model is capable of mimicking different Li-ion chemistries by accepting chemistry-specific data. Two different systems are built using the model: the existing system and the proposed system. The existing system represents a conventional single-chemistry Li-ion battery system. An NMC battery chemistry is considered for the existing system, since it is the most used battery chemistry [37]. As mentioned earlier, an actual drone model named IF800 Tomcat with a battery having a cell configuration of 6s1p is considered for direct comparison. The model considered is one such example of a drone model used for emergency deployment situations. On the other hand, the proposed system comprises what is addressed as the primary and secondary batteries. The NMC chemistry is chosen for the primary battery in the proposed system, following a 7s1p module configuration, while the LFP chemistry is chosen for the secondary battery in the proposed system following an 8s1p module configuration to meet the 24 V requirement. When the primary and secondary battery proportions are varied, as shown in further sections, the respective capacity is assumed to be varied with the same cell configuration mentioned. The NMC chemistry is chosen for the primary battery in the proposed system, while the LFP is chosen for the

secondary battery in the proposed system. The NMC battery is employed as the primary energy source owing to its high energy density, strong power output, and long-life cycle, which make it suitable for high-performance applications. In contrast, the LFP battery is employed as the secondary storage unit owing to its excellent thermal stability, safety profile, and, particularly, its exceptionally low degradation at high SOC. Although LFP batteries typically offer lower energy density than NMC, their superior calendar life and resistance to thermal runaway make them particularly suitable for energy storage during idle periods. A BMS is assumed to be incorporated in each battery pack (one in primary and one in secondary). For charging and discharging of the batteries, a BMS typically follows two strategies: (i) Passive equalisation is done by drawing out excess current by connecting the resistors in parallel. This method is less efficient but is widely used in UAVs today because it is less expensive and well-developed. (ii) Active equalisation involves transferring energy, which is more efficient but more complex and does not meet practical standards. However, some studies use both active and passive methods. Since the objective of this study is to evaluate the calendar ageing of a hybrid chemistry battery, BMS equalisation is abstracted and not explicitly modelled; it is instead considered as a constant auxiliary loss.

To preserve calendric ageing in NMC-based batteries, typical battery systems discharge the battery to a low-to-mid SOC during long idle periods. The modelled system in this paper has dedicated controller units for the existing and proposed systems that detect extended periods of inactivity and shift the system into idle mode to discharge their respective battery system to a specific SOC value, directing the focus towards minimising ageing. The controller units also charge and discharge their respective battery systems based on the load profile and pre-defined charging period. In typical existing battery systems, the SOC is discharged to 0.5, while the proposed system aims to discharge to a SOC value higher than 0.5, while more or less maintaining the same degradation per year. During charging and discharging in the proposed system, both batteries operate at identical SOC, except when they are stored in idle conditions. When the system shifts to the idle state, the LFP is charged to an SOC of 1 using the NMC battery, and the NMC is discharged to a lower SOC, as in typical systems. During the next active state—when the battery is discharged—the controller of the proposed system gradually brings both batteries to an equal SOC value for reliable operation. The study is carried out for combinations of different proportions of the primary and secondary batteries and different SOC values that the primary battery is discharged to in the idle state. All combinations are then compared to an existing single-chemistry battery system in an equivalent fashion.

3. System components

This section outlines the complete modelling methodology for the components used in the study. The entire model focuses on evaluating the operational performance, degradation, and energy behaviour of the proposed system against an existing system by considering a simple UAV load profile as the application. The implemented real-time control logic, state estimation, and degradation modelling capture the interaction between multiple battery chemistries to help optimise their utilisation. The major components in the study include the battery and its respective controller units.

3.1. Battery

The most important component is the battery. The battery modelled in the paper is adopted from

the existing MATLAB Simulink battery model, but with the inclusion of calendric and cyclic ageing. The battery model can mimic the ageing of any specific Li-ion chemistry, given that respective parameter inputs are provided. The ageing parameters are also modelled to be modular and scalable to adapt to any capacity for that given chemistry, allowing them to be used for any scale of application. Calendar ageing is based on the Arrhenius equations that are sensitive to SOC, temperature, and time [38], expressed as follows:

$$\ln(\nabla Q_{cal}) = f \cdot e^{\{g \cdot SOC\}} \cdot e^{\left\{\frac{h}{T}\right\}} \cdot t^{\{z\}} \quad (1)$$

where ∇Q_{cal} is the capacity fade, and f , g , h , and z are constants specific to Li-ion battery chemistry. The specific parameters for LFP and NMC are depicted in Table 1 [38]. This model reflects the exponential relationship between ageing and stress conditions like elevated SOC and thermal exposure.

Table 1. Obtained values for ageing parameters for NMC and LFP batteries.

Parameter	NMC 20 Ah	A123 ANR26650M1
a	1.2787×10^{-7}	2.0916×10^{-8}
b	-7.6845×10^{-5}	-1.2179×10^{-5}
c	0.0116	0.0018
d	-0.0065	-1.7082×10^{-6}
e	-1.3745	0.0556
f	1.1363×10^{12}	5.9808×10^6
g	4.6996	0.6898
h	-1.0772×10^4	-6.4647×10^3
z	0.5	0.5

Cycling degradation is modelled by a capacity fade equation that depends on temperature, C rate, and ampere-hour throughput (Ah) [39], given by

$$\ln(\nabla Q_{cyc}) = (a \cdot T2 + b \cdot T + c) \cdot e(d \cdot T + e) \cdot C_{rate} \cdot AH \quad (2)$$

$$dT = \frac{(Q_{pwrloss} + Q_{entropic} - Q_{convection})}{mC_p} \quad (3)$$

$$Q_{convection} = C \cdot \left(\sqrt[6]{(V_{induced})^2 + (V_{forward})^2} \right) \cdot (T_{t-1} - T_{amb}) \cdot A \quad (4)$$

Equation (2) estimates the impact of repeated charge-discharge activity, accounting for internal resistance build-up, lithium plating, and thermal effects. Therefore, with the chemistry-specific parameters entered, an NMC battery stored at a higher SOC would reflect higher degradation compared to an LFP battery. The same would apply for other chemistries of Li-ion batteries, such as LCO, NCA, and LMO, as long as chemistry parameters are provided. The temperature of the battery is dynamic. The heat increases due to the current consumption from the battery, while it is simultaneously cooled by blade airflow and airflow during the forward motion of the drone. This is modelled by Eq (3) [40,41], where $Q_{powerloss}$ is the heat gained due to power loss, $Q_{entropic}$ is the reversible heat gain, $Q_{convection}$ is the heat lost due to cooling, m is the mass of battery, and C_p is the specific heat capacity of the battery

material. The $Q_{\text{powerloss}}$ and Q_{entropic} are provided by the MATLAB battery model, while $Q_{\text{convection}}$ is calculated using Eq (4) [42–44], where C is the constant involving the thermal conductivity of air and the length of the battery, A is the surface area of the battery exposed to air, T is the battery temperature, T_{amb} is the ambient temperature, V_{induced} is the velocity of the air induced by the drone's blades, and V_{forward} is the velocity of the air due to forward motion of the drone. Velocity values depend on the mass and instantaneous power of the drone. The battery model is shown in Figure 1, and the dynamic temperature modelling is shown in Figure 2. The convective term in Eq (4) depends effectively on the airflow velocity over the battery surface. The airflow is a combination of both rotor-induced downwash [42] and airflow from forward flight. Comparable dynamic thermal modelling has been reported for electronic equipment on high-altitude platforms [43]. This approach allows the battery temperature to respond to both the heat generated by current draw and the cooling from airflow. For idle periods, the temperature varies only slightly and has little effect on the degradation results.

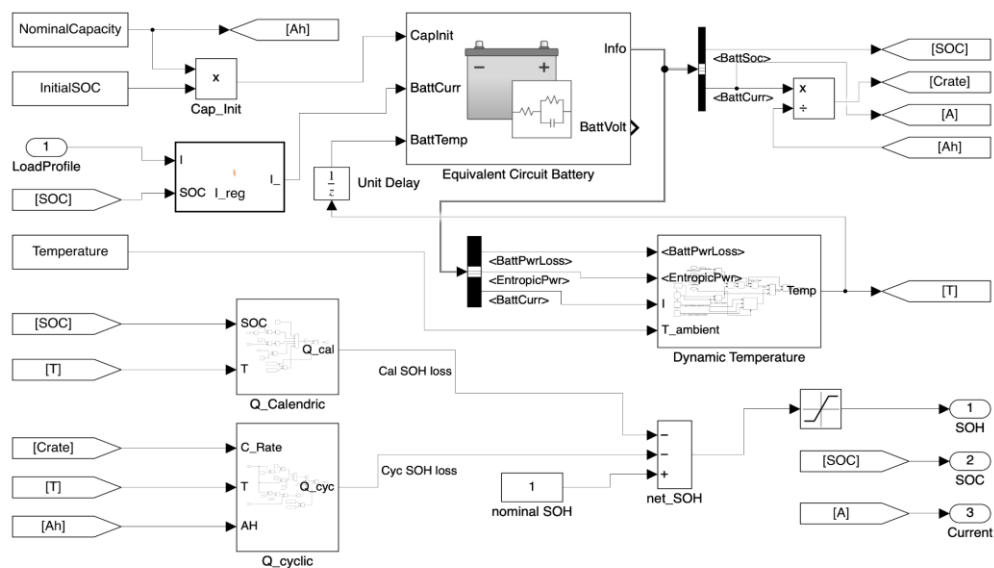


Figure 1. Simulink model of a battery with ageing.

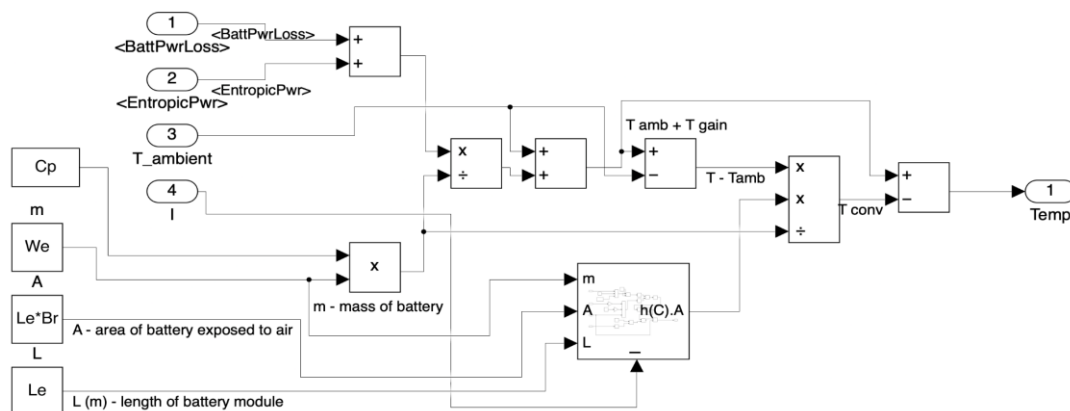


Figure 2. Dynamic temperature model of a battery.

3.2. Controller

The controller design differs between the existing and proposed battery systems. The existing system only requires a controller for the charging command, load profile, and idle state discharging. The proposed system additionally requires an algorithm to balance the SOC between the primary and secondary battery when the proposed battery system switches back to active mode after a long idle state. The internal states of the controllers are modelled completely in Simulink, as shown in Figure 3 for the existing system and in Figure 4 for the proposed system. In both scenarios, the values *idleDays*, *d_t_SOC*, and *Ah* denote the number of idle days before the controller switches to the idle mode, the depth of discharge, and the rated capacity of the battery system, respectively. The *d_t_SOC* value is the only value that is not necessarily the same for the existing and proposed systems.

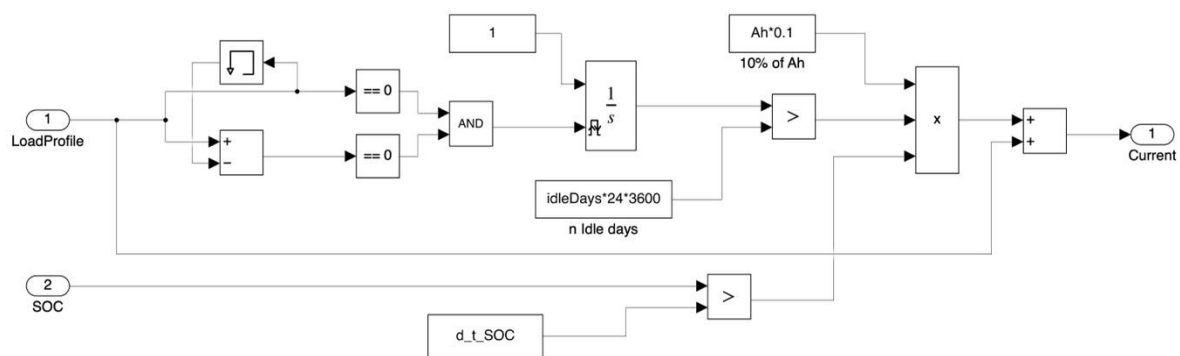


Figure 3. Simulink model of a controller for the existing system.

In the case of the controller for the proposed system, an additional distinctive feature is the inter-battery energy transfer mechanism to balance the SOC between the primary and secondary batteries for two operating modes: pre-deployment charging and discharging. During pre-deployment charging, the controller supplies more current to the primary (NMC) battery, which has a lower SOC, and less current to the secondary (LFP) battery, the one with a higher SOC. This lets the packs reach usable SOC quickly. When the SOC of the primary battery reaches that of the secondary, both batteries then charge equally to full capacity. On the other hand, during discharging, the secondary (LFP) battery is prioritised to be fully charged during long idle situations, thereby reducing the load on the primary (NMC) battery at a rate of 0.1 C (10%) of the primary battery's rated capacity until the secondary battery reaches a SOC of 1. Once the secondary battery is charged to an SOC of 1, the controller then discharges the primary battery to the specified threshold. However, if the primary battery is already under the specified threshold, it simply charges the secondary battery to an SOC of 1, and no further action is taken on the primary battery. Therefore, by systematically offloading storage duties to the secondary battery and shielding the primary battery from high SOC exposure, the system effectively extends calendar life without compromising instantaneous energy availability. The integration of these control policies facilitates a balanced utilisation of both chemistries, exploiting their complementary strengths. The proposed system's controller additionally includes two more parameters, namely the *P_ratio* and *S_ratio*, which determine the ratio of primary and secondary

battery capacities to the net capacity of the proposed system. This is vital in determining how much of the secondary battery accounts for the total capacity of the system, which is a deciding factor between the energy availability and degradation of the proposed system. Figure 5 illustrates the algorithm of the control strategy of the proposed system.

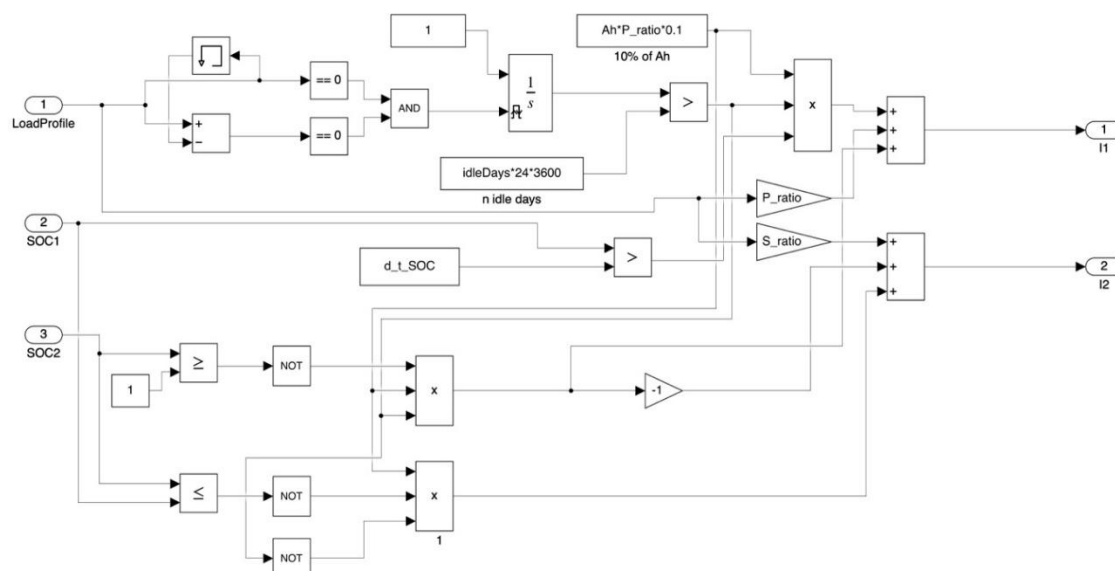


Figure 4. Simulink model of a controller for the proposed system.

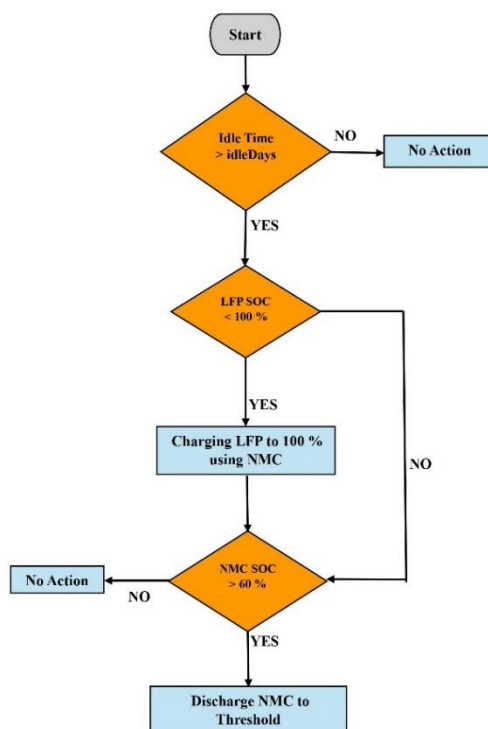


Figure 5. Algorithm for the proposed system controller.

4. Simulation

The existing and proposed systems are modelled to accept a load profile and compare their degradation. This is where the load profile becomes an important factor in the simulation. Since the calendric ageing of the battery systems at high SOC is considered for evaluation, it is essential to carry out the simulation for at least one year. Additionally, it is important to consider a load profile of an application where the battery system is kept ideal for long periods and, at the same time, requires high energy density. The lack of such a specific application would simply rule out the advantage that such a system brings to the table. For an application where the battery system is not kept idle for long periods, a typical NMC battery would simply be a better choice. On the other hand, for applications where longevity and cost play an important role, a typical LFP battery would be a better choice. Therefore, it is critical to compare the existing and proposed systems with a load profile of specific applications in which the typical single-chemistry battery system is not a perfect fit.

To compare the systems with an application, a simple load profile of a UAV is considered. Specifically, an emergency UAV is considered due to the nature of its application, since these drones are typically kept idle for long durations until required and, during deployment, are expected to have the highest energy availability; in other words, high energy density. A simple load profile of a UAV is the reference for the comparison, as there is currently no globally adopted load profile for UAVs, unlike the Worldwide harmonised Light vehicles Test Procedure (WLTP) load profile for vehicles. While the considered load profile does not accurately replicate real-world operating conditions, it considers the typical flight manoeuvres of a UAV, based on real-world missions, to recreate a simple load profile that includes all flight modes [45]. The load profile is modelled to be flexible, such that the profile consumes a major portion of the battery system's capacity according to the rated capacity of the battery. This, therefore, also requires the rated capacity of the battery system to be given as an input to scale the load profile accordingly. For all the combinations simulated in this study, the overall rated capacities of the proposed and existing systems are always the same.

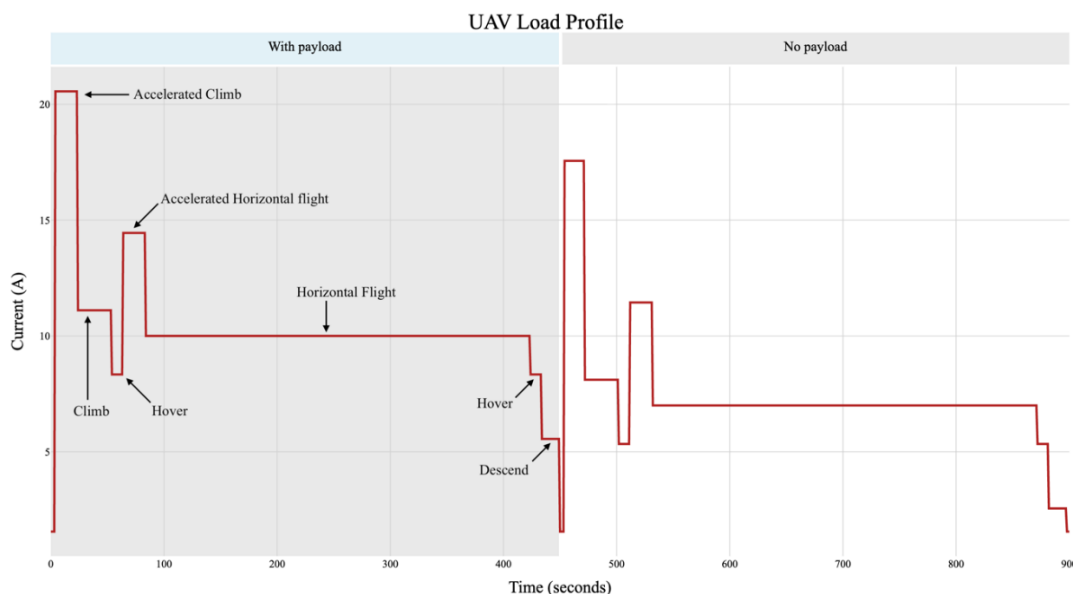


Figure 6. UAV load profile.

The profile represents the varying power demands of a UAV during a typical flight cycle consisting of take-off, climb, hover, horizontal flight, and descending phases, as illustrated in Figure 6. The take-off and ascending phases typically require the highest power demand, while the descending and landing phases require a lower power demand. The cruising mode of the UAV requires the least power amongst all flight manoeuvres. The profile is constructed as a time-dependent input signal (in seconds) representing the dynamic load current by the battery system. The signal is implemented using a Simulink timeseries block and serves as the primary driving force to consider both battery systems' cyclic ageing. Additionally, the load profile is fed to the battery systems a few times in a year, simulating a deployment of once every two months. The load profile block also takes in a parameter to change the frequency of deployment (load profile). The batteries are assumed to be charged for a short duration before deployment (like in real-time applications), followed by the load profile input to the battery systems. This is preceded by charging the systems again after the end of their deployment (load profile) for their next usage.

Since the metrics are all parameters of comparison between the existing and proposed systems, differences in their degradation are compared during a year, along with the difference in their SOC that is compared during the idle state. It is important to note that the difference in SOC depends on the input variables, as it is determined by the user. The difference in their SOC is the same during every extended idle state. Additionally, their costs, weight, and volume are also considered for comparison. These factors, however, are independent of operation but are considered since they are critical for practical applications [46–48].

5. Results and discussion

A key distinction between the proposed system and the existing system can be observed at the baseline discharge threshold of 0.5 SOC. While both configurations are discharged to the same value, the SOC of the proposed system is approximately 0.1 higher than that of the existing system. The difference between the two systems comes from their underlying architecture. While the existing system exclusively relies only on one chemistry—in this case, NMC—the proposed system relies on two different Li-ion chemistries split in unequal ratios. The battery chemistry with the higher energy ratio is called the primary battery, while the one with the lower ratio is called the secondary battery; in this case, NMC and LFP, respectively. When the existing and proposed systems are compared with the same depth of discharge, for instance, 0.5 SOC, the existing system is discharged to 0.5, while only the primary battery in the proposed system is discharged to 0.5 SOC, and the secondary battery is stored at 1 SOC, increasing the overall SOC of the system. This sets the basis for the offset in SOC between the existing and proposed systems.

To determine the optimal configuration of the proposed system, multiple simulations are carried out for a permutation of the ratio of the primary–secondary batteries and the depth of discharge. This parametric study helps to examine the pros and cons of the proposed system against different depth-of-discharge values of the existing system. The primary goal was to find the configuration for which the highest SOC retention is achieved with the least deviation in yearly degradation, without compromising other physical characteristics. In one of the configurations, where the existing system was discharged to 0.5 SOC, the proposed system retained an SOC of 0.86, which is 77% higher, while the corresponding yearly degradation is only 2.6% higher. If an existing system were to retain an SOC of 0.86 the proposed system did, the yearly degradation of the system would

be 4% higher than that of the existing system in 0.5 SOC. It is then apparent that the hybrid system achieves the same level of SOC availability while exhibiting nearly less than half of that degradation. These results illustrate that the hybrid system's strength is not only its ability to maintain a higher state of charge but also to do so at lower ageing penalties, which primarily limits the single-chemistry solution. Therefore, this demonstrates that a combination of readiness and longevity cannot be achieved simultaneously using the existing system. Figure 7 illustrates the percentage increase in average SOC retained before deployment of different configurations with varying depth of discharge in the proposed system. The x-axis represents the SOC to which the battery is discharged, and the y-axis represents the corresponding improvement in SOC retention when compared with the corresponding existing system. Four curves are represented, each corresponding to a different discharge limit of the existing system. It is evident that the hybrid system achieves higher SOC retention than the baseline across configurations.

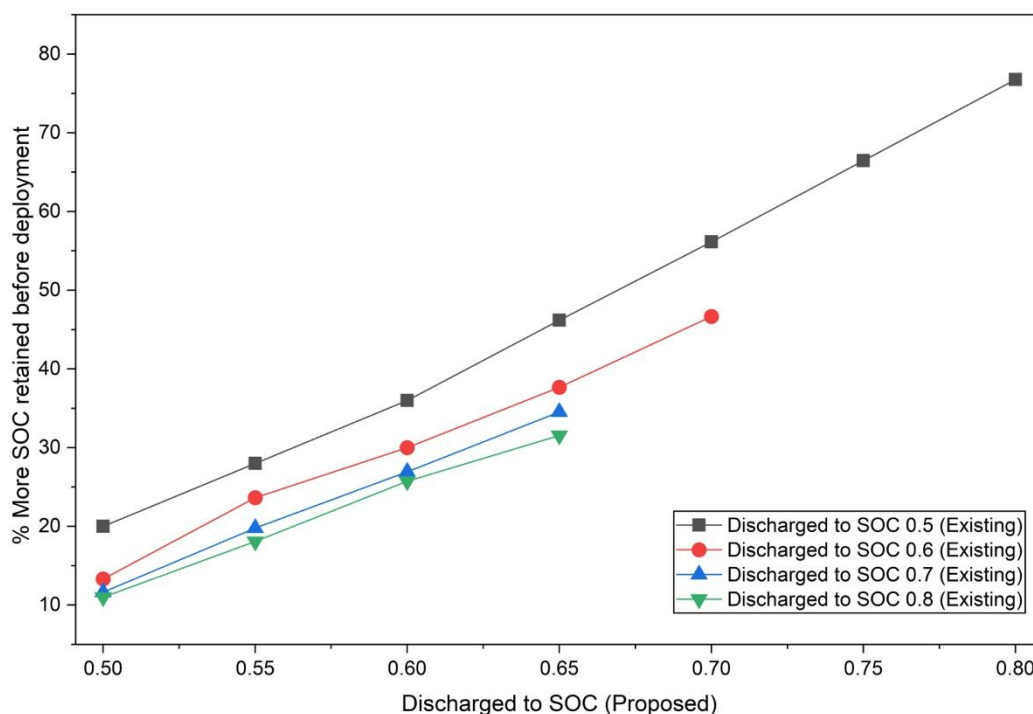


Figure 7. Comparison of SOC retained during a long idle state.

Figure 8 illustrates the change in yearly degradation by varying the depth of discharge of the proposed systems for the respective existing systems' depth of discharge. The x-axis represents the SOC to which the proposed system is discharged, and the y-axis represents the corresponding degradation compared to the baseline setup (0.5 SOC of the existing system). The resulting difference in degradation of the proposed system configurations lies in the range of -0.289% to 2.99% per year. The negative values denote configurations with lesser degradation than that of existing systems. For applications with only degradation taken into consideration, configurations with negative values show better potential than existing battery systems. However, the configuration with the least degradation does not necessarily mean it is the optimal choice, as the increase in SOC retention is only minimal.

Although the SOC retained is still 13% higher than the corresponding existing system, this displays the potential of such hybrid chemistry systems. However, this configuration is not ideal for the chosen application. For mission-critical UAV applications, an annual degradation of only roughly 1.2% is considered acceptable. Several configurations within this limit offer a reasonable balance between SOC availability and long-term durability. The suitable configuration for the UAV use case occurs when the proposed system is discharged to 0.68 SOC, at which the system retains around 36% more SOC while incurring only 0.74% annual degradation relative to the baseline system.

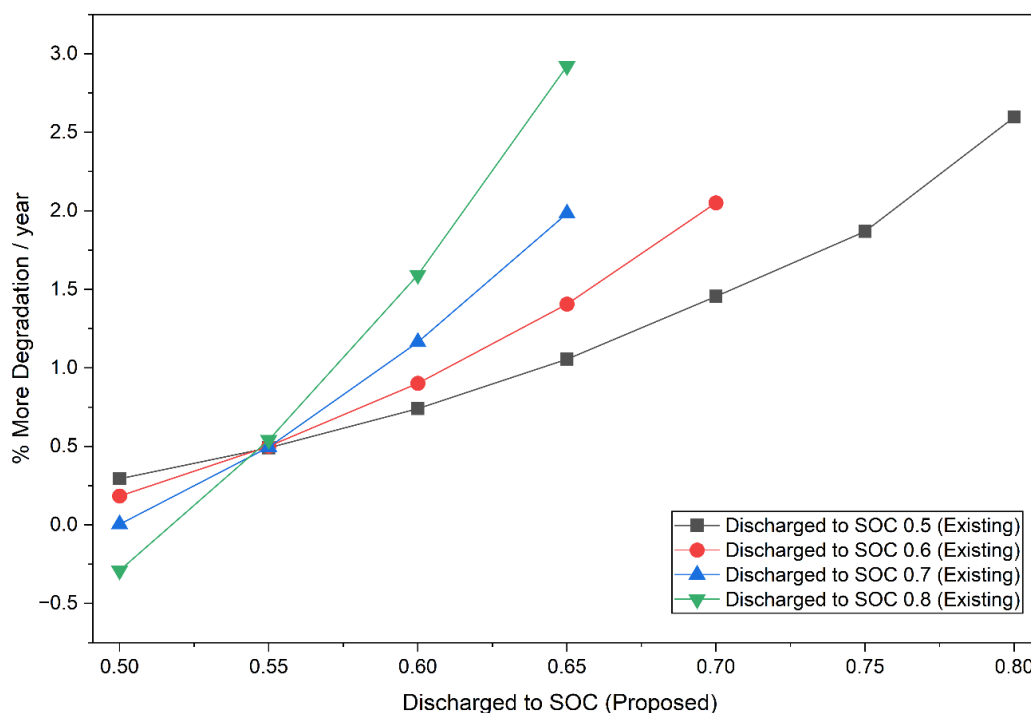


Figure 8. Comparison of degradation per year.

Figure 9 illustrates how the cost, weight, and volume of the proposed system change as the ratio of the primary battery varies. The x-axis represents the fraction of the total capacity assigned to the primary unit, and the y-axis represents the percentage change in each parameter relative to the baseline system. Three curves are represented: one for the percentage in cost reduction and two for the percentage increase in weight and volume. The results indicate that using a smaller ratio of primary battery share leads to the largest cost reduction, reaching up to 4.3% at the lowest ratio considered. This benefit, however, comes with trade-offs; both weight and volume nearly rise by 8% under the same conditions. As the ratio of the primary battery increases, the weight and volume disadvantages decrease gradually. However, the cost reduces proportionally with the primary battery's ratio. For the selected application of UAV for emergency situations, it is also important to consider the weight and volume, as these could, in turn, impact the use of energy in this application. However, for non-mobile applications, physical factors should not impact the decision. Therefore, this requires meticulous selection of the hybrid configuration based on the requirements posed by the specific application. The results from Figures 7–9 can be used to achieve the right configuration for each application. In addition

to the cost, weight, and volume trade-offs discussed above, the proposed architecture is more complex than a single-chemistry pack. It requires a path for energy transfer between the two batteries, separate SOC monitoring for each chemistry, and additional balancing control, all of which add hardware and cost and introduce further points of failure. The additional controller circuitry in the proposed system introduces an auxiliary loss. Following the assumptions in Section 2, this loss is treated as a constant rather than a time-varying quantity. A detailed study of reliability and battery management system design is outside the scope of this work, which focuses on demonstrating the feasibility of the concept, and is left for future work.

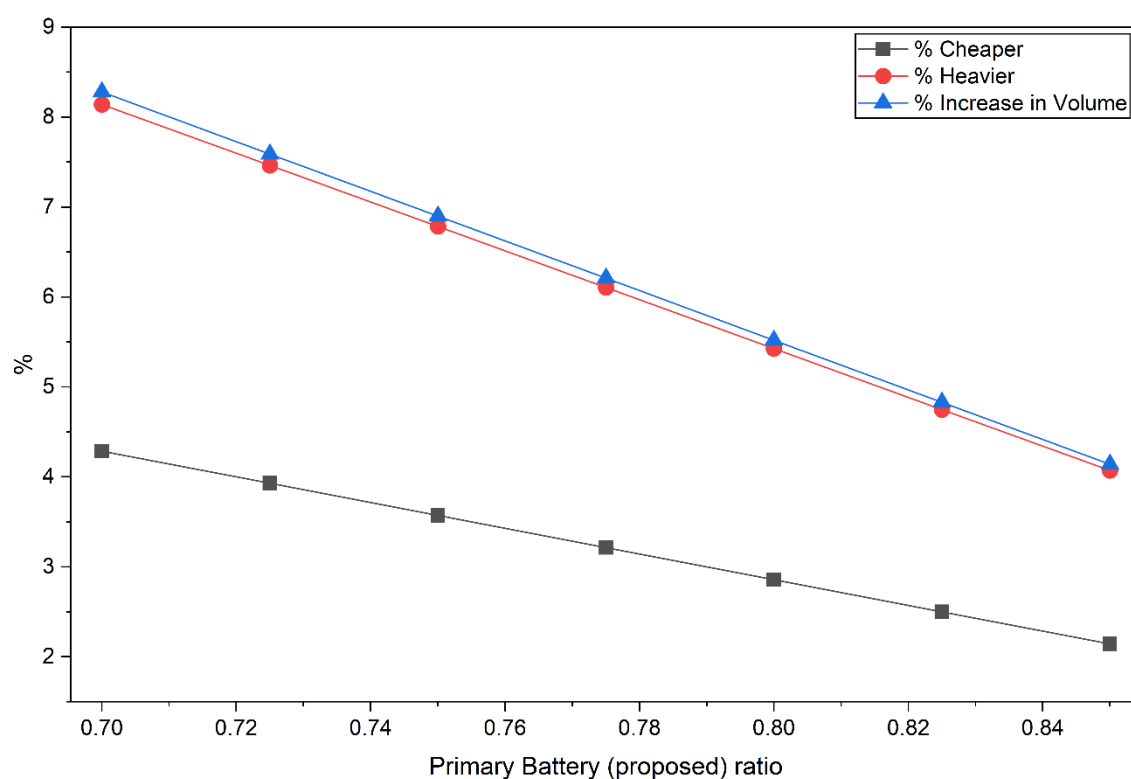


Figure 9. Comparison of cost, weight, and volume for different ratios of the proposed system.

6. Conclusions

The paper addresses an inherent limitation of monolithic Li-ion battery architectures. While monolithic battery chemistries present fixed merits and drawbacks, the paper introduces a concept that allows varying such merits according to specific application needs by hybridising different Li-ion battery chemistries. For any given application, by choosing the right chemistries and optimising their proportions by capacity, we can further tap into the hidden potential of existing battery technology without having to wait for a technical breakthrough. The paper clearly demonstrates this by choosing an example application of UAVs for emergencies, where the proposed hybrid system shows a significant increase in energy-readiness while keeping degradation almost the same and, in some proportions, even lower than the conventional system. While the study focuses only on UAVs as an

example, the concept introduces a new horizon of applications and combinations of battery chemistries that can prove to be significantly better than conventional systems, especially for niche applications. While the system does get more complex than conventional systems, as well as more inefficient with the auxiliary losses that come with the complexity, the benefits could still far outweigh them and could potentially get better with further research. Future work could simply eliminate assumptions and test them in real-world systems.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Surender Reddy Salkuti is an editorial board member for AIMS Energy and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

Author contributions

Conceptualisation, V.R.; methodology, V.R.; software, V.R. and V.A.; validation, V.R. and S.R.S.; formal analysis, V.R.; investigation, V.R.; resources, V.R. and S.R.S.; data curation, V.R. and V.A.; writing—original draft preparation, V.A.; writing—review and editing, V.R. and V.A.; visualisation, V.R. and V.A.; supervision, V.R. and S.R.S.; project administration, V.R.; funding acquisition, S.R.S. All authors have read and agreed to the published version of the manuscript.

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