Racing Battery Management System (BMS)
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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Rechargeable batteries are a convenient, cost-effective, and waste-minimizing alternative to single-use batteries and are used in many applications today [6]. One of the most common forms of rechargeable batteries is lithium-ion batteries. These batteries are implemented in a wide variety of devices such as phones, laptops, sensor systems, and electric vehicles. This form of rechargeable battery is so common because lithium-ion cells are efficient, have a high energy density-to-weight ratio, and are cost-effective compared to other ways to store charge [2]. Large lithium-ion batteries, such as those in electric vehicles, are made up of a considerable number of individual cells. These cells are batteries on their own, storing and expending charge, but when they are linked together they can drastically increase the total energy for a single output. However, these cells can hold slightly different charges from each other due to heat or unequal use which causes the cells, and therefore the battery, to quickly decay. Without proper management of these cells, lithium-ion batteries only last approximately 400 full charge/discharge cycles [3].

For any application involving lithium-ion batteries, especially those that can store a significant amount of charge, such as electric vehicles, an accompanying battery management system (BMS) is necessary to ensure the battery stays within safe operating conditions. Under unsafe operating conditions, such as too much heat, voltage, or current, the battery cells can degrade at a much faster rate and can even lead to fires and explosions [7]. By utilizing specific circuitry and sensors, dangerous conditions within the individual cells that make up the battery can be avoided so users and the battery can stay safe. One of the more novel functionalities that modern battery monitoring systems include is the ability to perform cell balancing. Cell balancing is when the BMS reroutes extra charge from individual cells into other cells. By utilizing cell balancing, the BMS not only prevents dangerous conditions but also improves the performance of the battery and extends its lifespan.

For my technical topic, I will describe the various battery management techniques and my role in creating a battery management system that implements cell balancing for an electric racing vehicle. For my STS discussion, I will discuss the importance of the differences in battery management systems implemented in devices that utilize rechargeable batteries, specifically comparing how the two main types of cell balancing differ in their effect on battery longevity, energy efficiency, implementation feasibility, and environmental impact. From my research, I will compile which type of cell balancing should be used based on application-specific conditions.

Technical Topic

Battery management systems customarily utilize various sensors for voltage, current, and temperature to avoid dangerous operating conditions. The BMS is created with threshold values for each of the sensors that indicate when unsafe operating conditions may occur. When any of these threshold values are reached, the sensors detect the unsafe condition and are able to deactivate the battery, and as an effect, the device. One of the more complicated functionalities of a BMS is a cell balancing system. As stated in the introduction, cell balancing is important to increase the lifespan of a multi-cell battery. This is because the cells can degrade at different rates and thus hold different charges than other cells in the same battery. Without any form of cell balancing, degraded cells will continue to be over-charged, causing them, and the battery as a whole, to quickly degrade. When this occurs, the total state of charge of the battery is diminished for two main reasons. 1) While charging the battery, the battery halts charging once a single cell is full and 2) while discharging, the battery is considered “drained” once a single cell is emptied. As the cells that are degraded hold a lower charge and as a result are charged and discharged quicker than the other cells, these two conditions are extremely problematic. In this way, a single degraded cell can cause a battery to lose a significant amount of its potential charge over time to the point of being unusable. There are two main cell-balancing solutions to this problem: passive and active cell balancing.

Passive cell balancing only occurs while the battery is charging. During this process, the cells that have a lower state of charge are subjected to a load that dissipates the excess energy as heat [5]. This method is simple to implement and is effective at increasing the longevity of the battery pack as cells are not packed with charge that is outside of their ability to hold. However, this method is wasteful as essentially all of the cells in a battery pack are given the same capacity as the weakest cell, resulting in extra energy that could have been stored in other cells being lost.

Active cell balancing occurs during charging and discharging. During this process, energy from cells with lower states of charge is routed to stronger cells that have higher states of charge. Just like passive cell balancing, active cell balancing keeps all cells within their optimum charge range, however, it also increases the total charge of the battery by routing energy during the discharge of the battery so all cells can be completely drained and not just the cell with the minimum state of charge [4].

The BMS on its own simply monitors certain conditions to make sure they are within a stable range for the battery. By sending warnings and shutdowns if any thresholds are exceeded, this system can save the battery pack from faulting. However, cell balancing techniques are necessary to optimize the longevity and sometimes even the amount of charge a battery can hold. Both forms of cell balancing are great at keeping the cells within their ideal operating conditions which increases the longevity of the battery pack. Active cell balancing is more productive than passive as it allows the battery to hold more charge while passive balancing does not affect the total charge of the battery. Passive cell balancing is less complicated and thus cheaper to implement than active cell balancing due to the passive cell balancing circuitry simply dissipating excess energy while the active cell balancing circuitry has to be configured to allow charge to be rerouted between the cells.

For my technical project, I am working with a team to design and implement the circuitry and communications for a battery management system that utilizes passive cell balancing for an electric vehicle, specifically, the Virginia Motorsports Formula Car. This system consists of three major components: the precharge-discharge circuit, the cell monitoring circuit, and the main control circuit.

The precharge-discharge circuit consists of switches and capacitors that allow the large voltage difference between the battery and the load to be equalized before they are electrically connected and drain voltage from the load when they are disconnected. The precharge portion of this circuit prevents current from rushing out of the battery and overloading the load on initial contact by having a capacitor with a small amount of charge but a large voltage be charged by the battery and released onto the connector to the load. This equalizes the voltage of the two sides of the circuit for a brief period so the connectors for both the battery and the load can come into contact without an excessive amount of current flowing. After the load and battery are disconnected, the discharge portion drains the capacitor, allowing the voltage on the load to be essentially zero so people can access the inner workings of the car safely.

The cell monitoring circuit consists of two BMS chips that connect to ten lithium-ion cells each. Once these chips are put into a specific configuration with capacitors, resistors, thermistors, and the cells themselves, they are specifically designed to monitor the system and perform cell balancing. This system will connect to the main control unit which will send it instructions on what sensors to read and what commands to perform. If any cells go over a threshold value, a shutdown signal will be sent which will activate a shutdown circuit, disconnecting the battery from the load or charging port. My team will not directly implement this shutdown functionality but we will create the conditions for it to be easily integrated into the system by the Motorsports club

The main control circuit consists of a microcontroller that communicates with the cell monitoring circuitry over the UART communication interface and relays the information over a CAN bus communication interface which can be used for logging, debugging, and communication throughout the rest of the vehicle's systems. This main control unit will be able to turn the cell monitoring circuitry on/off, set the threshold values for voltage, temperature, and current and it will be able to initiate cell balancing during charging. This main control unit is necessary as there will be five stacks of lithium-ion cell stacks in the final vehicle so there will need to be five monitoring circuits. The main control unit will be a simplified interface between a user and all the cells in the vehicle's battery, although most of the controls will be automated in the final design.

In order for the electric racing vehicle to register for the Formula competition it has to pass a stringent set of rules. These rules require battery monitoring for electric vehicles, but they do not require any form of cell balancing. We believe that most teams will opt to not use any form of cell balancing to simplify their design process. This will give our design a leg up on the competition and could be a useful way to demonstrate the effectiveness of cell balancing in an extreme racing environment.

STS Discussion

The applications of rechargeable batteries are broad. Ranging from powering small consumer electronics like phones and watches to electric vehicles. Specifically, rechargeable batteries are great for devices that draw a significant amount of power in a short period of time. In these use cases, a battery management system with cell balancing functionality is necessary as devices with rechargeable batteries are usually expensive and consumers want to purchase products that will last. In this section, I will focus on the effectiveness and sustainability of the two main cell balancing techniques for various applications.

The first main implementation that specifically relates to my technical topic is the use of cell-balancing technology for electric vehicles. Electric vehicles are a staple of sustainability as they have the potential to facilitate a transition from the majority of vehicles consuming harmful fossil fuels to using renewable energy sources. However, the creation of batteries for electric vehicles is not ecologically neutral as their creation requires vast amounts of lithium to be mined from the earth and refined. The creation of eclectic vehicle batteries uses approximately twice the amount of lithium as all other lithium applications combined, making it extremely important for these batteries to last [9]. This longevity can be achieved by both forms of cell balancing but active cell balancing is significantly better and has been shown to increase the longevity of electric vehicle batteries by up to 19.8% [5]. Another important feature for electric vehicles specifically is the maximum range of the vehicle as consumers would want their electric vehicle to go at least as far as conventional gas-powered vehicles. This also indicates that active cell balancing should be used as it allows the battery to hold more charge than passive cell balancing.

The other main use case I want to focus on is consumer electronics, specifically devices such as tablets and laptops. These devices have shown rapid development with new features being introduced annually, however, they have reached a stall in creating new features that users care about and instead are improving already existing features [10]. One of the main features that consumers overwhelmingly want improved is battery life, with nearly double the interest in battery life improvement over any other feature [9]. For this case, active cell balancing is preferred due to the excess charge it can store compared to passive. However, active cell balancing only gives an approximately 2% increase in charge compared to passive. For these smaller devices, that charge is equivalent to just minutes in extra battery life [4]. Active cell balancing is also complicated and expensive and implementing it on a small scale could be taking space from other critical components.

Overall, the creation of lithium-ion batteries is not sustainable. Lithium is a nonrenewable resource that has to be mined and refined. The mining scars the earth with long-term ecological damage, and the refining process consumes approximately five hundred thousand gallons of water per ton of lithium [2]. Consumer electronics are being thrown away after only a couple of years of use due to new products being consistently released. These devices and their batteries are commonly thrown in landfills where the batteries degrade and toxic chemicals leak into the environment [6]. With cell balancing, ideally, these unsustainable practices can be minimized as consumers no longer have to throw away devices after a couple of years due to the reliability of one of the most important aspects of the devices, it's power.

In terms of energy efficiency, passive cell balancing is particularly wasteful compared to active cell balancing. Passive cell balancing reduces the total potential charge of the battery and dissipates excess energy as heat. This is energy that could be used by an active cell balancing system, however, the amount is usually not very significant. On average, passive cell balancing wastes only approximately 2% of the total energy of the battery. This number is not large on its own, but for large batteries like those in electric vehicles, it could be a substantial amount of energy loss. Finally, the cost comparison between active cell balancing and passive favors passive as it is significantly less complex, requires fewer components, and will spend less time in development when compared to active cell balancing.

A battery management system is necessary for a system that utilizes rechargeable lithium-ion batteries and active cell balancing is a more energy-efficient way of implementing one. However, the comparatively cheaper but less energy-efficient passive cell balancing is still able to keep cells healthy and increase the overall battery life. The main question I want to answer is whether the added cost and complexity of active cell balancing are worth it to become an industry norm or if the simplicity of passive cell balancing is more sustainable for certain applications.

Conclusion

The BMS that my team and I have designed will ultimately be implemented in the Virginia Motorsports Formula Electric Vehicle, which, with some luck, will be able to participate in a competition in the spring. During this competition, there are multiple scoring categories that our BMS could influence, such as energy efficiency. By comparing the effectiveness of our vehicle against competitors who have different cell balancing systems, I can gain some form of personal insight into the effectiveness of the various forms of cell balancing for electric vehicles. Many factors will have to be considered for the data gathered to be reliable, but I will also be doing extensive research into the variations in performance between the two forms of cell balancing for my STS deliverable. This combination of technical work and STS research will inform my general analysis of the optimal form of cell balancing for a diverse set of applications from a technical and sustainability standpoint.

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