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THE USE OF BATTERY MANAGEMENT SYSTEMS IN ELECTRIC VEHICLES

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Master's Thesis

Supervisor

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Kemal TUR

İmzası

ABSTRACT

THE USE OF BATTERY MANAGEMENT SYSTEMS IN ELECTRIC VEHICLES

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The rise in popularity of electric vehicles (EV) reshaped trend that is clearly boosting the automative market. This increases main three reasons are changes of customer preferences, innovativeness and protective laws from governments. Lately, governments from all around the world are legislating new laws, such as decreased EV taxes, to protect our ecosystem. This kind of situation increased the sales of EVs.

Keywords: BMS, Electrical Vehicles, Battery, SOC, SOH, SOT.

ÖZET

ELEKTRİKLİ ARAÇLARDA BATARYA YÖNETİM SİSTEMLERİNİN KULLANIMI

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Elektrikli araçların (EV) popülaritesindeki artış, otomotiv pazarını açıkça canlandıran trendi yeniden şekillendirdi. Bu artışın başlıca üç nedeni müşteri tercihlerindeki değişiklikler, yenilikçilik ve hükümetlerin koruyucu yasalarıdır. Son zamanlarda, dünyanın dört bir yanındaki hükümetler ekosistemimizi korumak için azaltılmış EV vergileri gibi yeni yasalar çıkarıyor. Bu tür durumlar EV satışlarını artırdı.

Anahtar Kelimeler: Batarya Yönetim Sistemi, Elektrikli Araçlar, Batarya, SOC, SOH, SOT.

.

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ABBREVIATIONS

SOC	:	State of Charge
SOH	:	State of Health
SOT	:	State of Thermal
EV	:	Electrical Vehicle
CBMS	:	Centralized Battery Management System
ICE	:	Internal Combustion Engine
BMS	:	Battery Management System
EIS	:	Electrochemical Impedance Spectroscopy

1. INTRODUCTION

Increasing of popularity of EVs is a trend that reshaped the automative market. This kind of growth, innovative ideas, supportive laws and customer preferences becoming more effective while new trends are advantageous to our world. This is boosting sales.

People also like electric vehicles because they are better for the environment. Electric vehicles are a cleaner alternative to conventional vehicles. They reduce greenhouse gas emissions and noise in cities.

However, the environmental benefits of electric vehicles are highly dependent on the electricity source used for charging. In regions where electricity is generated from renewable sources, the positive impact of electric vehicles is maximized. Conversely, if the energy comes from fossil fuels, the benefits are somewhat diminished, although advancements in decarbonizing the grid gradually enhance the overall sustainability of electric driving.

Battery Management Systems (BMS) are critical components responsible for managing and protecting the battery pack, the heart of electric vehicles. The primary function of a BMS is to monitor and regulate the state of charge (SOC), state of health (SOH), and overall performance of the battery, ensuring safety, efficiency, and longevity. [12]

A BMS actively balances the charge between battery cells, prevents overcharging and deep discharging, and monitors temperature to prevent thermal issues. These functions affect the battery's life and performance. A BMS can extend the battery's life, making the vehicle more reliable. [12]

The importance of a BMS extends beyond functional oversight. It also helps manage the car's energy, working with other systems to make the most of energy and regenerative braking, making the vehicle more energy efficient.

Battery Management Systems (BMS) help electric vehicles use energy more efficiently. They make sure the battery works well, which helps the vehicle use energy more effectively. This also means the vehicle can go further on a single charge.

Battery performance affects electric vehicle performance. The BMS makes sure all cells in the battery pack are working right. This makes the EV go faster and more powerful. A well-managed battery system helps to avoid battery failure. [1]

This paper explores the importance of electric vehicles and the role of battery management systems in operating them efficiently and in protecting the environment. Battery management systems are important for battery technology, especially for electric vehicles and for storing large amounts of energy. A BMS keeps the battery safe, in good condition and working well.

A BMS monitors the battery's voltage, current, temperature and state of charge. Monitoring the battery lets you check its overall condition and efficiency. This is important for safety and longevity. A BMS also controls charging and discharging to stop problems like being overcharged or deeply discharged, which can damage the battery.

A battery management system (BMS) has sensors that monitor the battery's voltage, current and temperature. The BMS then processes this data to evaluate the battery's status and make decisions about battery management tasks. Hardware is used to balance the charge levels of different cells in the battery pack, which increases the battery's capacity and lifespan. The BMS can also communicate with other parts of the vehicle or energy system.

These components work together to make the battery system safer and more efficient. By monitoring and managing battery functions, a BMS helps batteries last longer and is good for the environment.

A BMS watches and manages the whole system but especially temperature and charge status. It manages and causes increasing of remaining battery lifetime. the battery's state of charge and state of health. These parameters affect how long the battery lasts and how well it works. A BMS also balances the charge in each cell in a battery pack. This stops the battery wearing out too quickly and also saves money because you don't have to replace it as often.

A correctly integrated BMS manages energy use and regenerative braking, which transforms kinetic energy into stored energy in the battery during slowing down. This increases the driving range of the electric vehicle.

The BMS is important for electric vehicles. It makes sure the battery pack is safe and efficient. It also affects how long the vehicle lasts. As electric vehicles get better, more advanced BMS technologies will be needed to keep up.

2. BATTERY MANAGEMENT SYSTEM

Electric vehicles (EVs) are great tools for us to reduce carbon emission and increasing the health of our ecosystem. A BMS takes care of the health of the battery system and increase the battery lifetime. This growth leads to reduce consuming materials which is limited all around the world. Since the secondary battery cells are invented, we can recharge the batteries and it makes them reusable. The Battery Management System (BMS) plays the most important role at this point. It controls, communicates and make the battery work efficiently.[12]

BMS technology is advancing, but there are still some problems. It is still hard to correctly determine a battery's remaining charge and overall health because battery behaviour and external influences such as temperature are unpredictable [5]. As batteries get older, the condition of the cells inside can get worse. This makes it harder to balance how much energy is put into and taken out of the batteries. It's also important to manage the heat produced by the batteries to stop them breaking down or becoming unsafe. Universal solutions for different types of batteries and vehicles need to be adaptable.

We are developing new technology to improve BMS (battery management system) functionality. New technology uses algorithms like machine learning and AI to make SOC and SOH calculations nicer and more accurate. These technologies help the BMS learn from past data and adapt to different battery behaviours, improving prediction and Efficiency [5][11]. New ways of balancing cells are being developed to make batteries more efficient. New ways of controlling battery heat are being developed to make batteries last longer. Also, connecting the BMS to vehicle systems through advanced technology helps manage the vehicle better, making it more energy efficient and reducing battery wear.

BMS capabilities are being improved and new problems are being solved with new ideas. Cutting-edge approaches are driving these improvements. The evolution of BMS will be influenced by new technologies, particularly with the expansion of th

e electric vehicle market. BMS can connect to renewable energy systems, smart grids, and vehicle-to-grid systems, making electric vehicles more efficient and benefiting the environment. As more vehicles transition to full autonomy, the importance of BMS in maintaining battery health and delivering reliable energy solutions will make it even more crucial.

Battery Management Systems are key to electric vehicles. They ensure batteries are safe, efficient and long-lasting. New technology is helping to improve BMS, making electric vehicles safer and more efficient. This will help create a sustainable future. As BMS technology develops, it will become more important in managing energy around the world.

2.1 BATTERY MANAGEMENT SYSTEMS TASKS

A Battery Management System (BMS) is important for electric vehicles and other battery-powered applications. It keeps track of the battery pack and each cell. These parameters include voltage, current and temperature. The BMS monitors these to ensure the battery is working safely and efficiently. It also estimates the battery's remaining charge, which helps to determine the vehicle's remaining range. It also checks the battery's condition to see if it is wearing out [3][6].

Protection is a fundamental function of the BMS to ensure battery safety and longevity:

Prevents overcharging and deep discharging: The BMS disconnects the charger when the battery is fully charged and disconnects the battery when its charge drops below a critical level.

Manages overcurrent situations: Protects against high current draw that can occur during rapid acceleration or high-power charging.

Ensures safe temperature ranges: Prevents the battery from operating when it is too hot or too cold, which can damage the battery or reduce its efficiency.

Balancing the cells in a battery pack is crucial for maintaining battery performance and lifespan:

Active balancing: Uses additional circuitry and energy conversion to redistribute charge from higher charged cells to lower charged cells.

Passive balancing: Dissipates excess energy from more charged cells as heat, usually through resistors, to ensure all cells have the same charge level.

A BMS also controls the charging and discharging of the battery and communicates with other system components:

Charge control: Manages how the battery is charged in terms of rate and charging algorithm (e.g., constant current/constant voltage).

The BMS interfaces with vehicle systems, communicating with the car's onboard computer to relay information on battery status, energy management, and diagnostics. It also performs data logging and diagnostics by gathering data for future analysis and emergency troubleshooting, helping to anticipate and address issues before they result in battery failure.

The BMS helps to save energy and make the system more efficient by controlling the amount of power that is used and making sure that there is enough power available for the vehicle to work properly. It also helps to make the battery last longer by managing the energy that is returned to the battery when the vehicle is braking.

In conclusion, the functions of a BMS are of paramount importance for the optimal efficiency of batteries, the enhancement of safety, and the prolongation of battery lifespan. These factors are of critical significance for the reliability and performance of electric vehicles and other battery-reliant devices.

2.1.1 Voltage Measurement

Voltage is important for managing and using batteries in electric vehicles and other battery-powered devices. It helps to know how much charge is left in each cell in a battery pack. By monitoring cell voltage, it ensures that all cells operate within limits, preventing problems such as overcharging and deep discharging, which can lead to battery failure. The main way of measuring voltage in a BMS is using sensors to detect the voltage of each cell. These sensors are usually placed across the terminals of each cell to make it more accurate and to reduce noise. [7] [8]

Example: Consider a lithium-ion battery pack consisting of 100 cells. A BMS for this battery pack would use a system to measure and monitor each cell's voltage. This includes sensors that can detect small changes, as small as 1 mV. An analog-to-digital converter (ADC) transforms the analog voltage signals into digital data for the BMS to process. [1]

Table 2.1: Example of Voltage Data Collected from a BMS.

Number of Cells	Measured Voltage
1	3.7 V
2	3.69 V
...	...
100	3.71 V

Correctly measuring voltage across a battery pack is difficult. Calibration errors can cause inaccurate readings. Environmental factors like temperature and electromagnetic interference can also affect readings. Sensor drift over time also makes readings less reliable.

There have been some great advances in voltage measurement technology recently. IC solutions are now much more accurate, use less power and are better at dealing with noise. Wireless voltage sensing technologies are also coming along nicely, reducing wiring complexity and increasing reliability. Finally, data fusion techniques combine voltage data with other parameters, such as temperature and current, to give us more accurate SOC and SOH estimations. A recent study put an advanced voltage measurement system in a 400V high-capacity EV battery pack. They used the latest ICs to get more precise and reliable readings. The results showed that the battery was more efficient and lasted longer. [4]

Table 2.2: Impact of Improved Voltage Measurement on Battery Performance.

Parameter	Before Enhancement	After Enhancement
Ortalama SOC Hatası	5%	2%
Batarya Ömrü	5 Y	7 years

Voltage measurement is the key to managing batteries. New technology makes it possible to monitor voltage more accurately, improving battery safety and efficiency. Future developments may use machine learning and artificial intelligence to predict and fix any measurement issues, introducing new ways to manage batteries. [1]

2.1.2 Current Measurement

It would be beneficial to ensure accurate current measurement for the optimal performance and safety of Battery Management Systems (BMS) in electric vehicles (EVs) and other battery-operated devices. It may be said that BMS play an important role in ensuring the effective operation of battery packs. This can be seen as a way of guaranteeing safety, efficiency and durability. One of the primary responsibilities of BMS is current measurement, which is of great importance for keeping an eye on the energy flowing in and out of the battery. This measurement is useful for determining the battery's state of charge (SOC), state of health (SOH), and overall management of the battery system [3][4]. It is thought that accurate current measurement may support key BMS functions such as charge regulation, load management, and predictive maintenance.

a. Determination of SOC and SOH,
b. Effective management of charging and discharging processes,
c. It's important to be able to spot and stop anything that might damage the battery.

In a BMS, current measurement has a vital importance. If an overcurrent happens in a battery of an EV, that would cause some issues like fault at sensors, overcharge or deep-charge. There are many ways to measure the current however, in today’s technology measurement could be done via only two ways which will be extend in the near future for increasing the battery lifespan. This involves placing a low-resistance shunt resistor in series with the battery, after which the voltage drop across this resistor is measured and used to determine the current based on Ohm's Law ($I = V / R$). The second method is indirect measurement using Hall Effect sensors. This provides a non-invasive way to detect current flow by indirectly measuring the magnetic field around a current-carrying conductor.

If you would like to consider a Battery Management system which is configured with a 0.001 Ohm shunt resistor in a system with an expected maximum current of 100 A.

Table 2.3: Example of Current Data Using Shunt Resistor.

Current (A)	Voltage Drop (mV)	Calculated Current (A)
50	50 mV	50 A
100	100 mV	100 A
150	150 mV	150 A

When measuring the current, there are a few obstacles. To get better measurement, sensors should be calibrated before the enhancement and tested well. Temperature waving have bad impact on both circuit components and Hall Effect sensors. Results of these malfunctions causes electrical noises in the system.

Current measurement technologies are getting better and better every day. The shunt resistors and Hall Effect sensors are crucial for the certainty of the measurements. Thanks to recent developments the accuracy of the calculations is increasing day by day. These innovations include the development of more precise and temperature-resistant shunt resistors and Hall effect sensors, as well as the 360-degree enhancement of measurement accuracy through the integration of digital signal processing (DSP) techniques. Furthermore, the incorporation of smart sensors with built-in diagnostic capabilities has enabled real-time data 360-degree corrections and increased precision.

A study on using new ways to measure current in a battery management system for electric vehicles showed that it helped the battery last longer and perform better. The study used sensors and resistors to improve how the battery's state of charge and health are calculated. This helped to improve how the battery is managed. [4]

Table 2.4: The Effects of Developed Current Scaling at EVs Battery.

Parameter	Before Improvement	After Improvement
SOC Error	5%	2%
Battery lifespan	5 Years	7 Years

Battery management systems (BMS) use current measurements to improve efficiency, safety, and battery pack lifespan. Sensor technology and digital integration are improving these measurements. As more electric vehicles and other battery-dependent technologies are used, the need for better current measurement techniques will grow. This will lead to more research and innovation in this area. [1]

2.1.3 Heat Measurement

Thermal management is also important for using EVs safely, an efficient and durable battery. Efficient and impactful thermal regulation is one of the most important key factors for having durable and more efficient battery packs. Heat generations occur at batteries naturally due to energy conversion.

Efficient batteries with a well thermal management prevent to have high temperatures which causes inefficiency and unsafety at the battery. Recently, safety problems such as burning have occurred in electric vehicles of various companies.

Battery management systems (BMS) could measure the temperatures via various type of sensors such as thermistors, infrared sensors and fiber optic sensors.

Let's assume that we have the battery pack is equipped with distributed thermistors across multiple cells and modules, providing a comprehensive temperature profile.

It is important to understand how heat is generated and distributed in batteries. The main sources of heat in battery cells are:

a. Joule Heating: Heat generated due to resistance against current flow within the battery.
b. Reversible Heat: Heat produced or absorbed during charge and discharge cycles.

c. Irreversible Heat: Heat resulting from inefficiencies and side reactions within the battery.

Table 2.5: Classical Rate of the Heat Generation at a Lithium-Ion Battery.

Battery Status	**Heat creation rate (W/kg)**
In state of charge at 1°C	15 W/kg
In state of discharge at 1°C	12 W/kg
At Rest	0.5 W/kg

When measuring the temperature correctly, there are a few obstacles that researchers faced with. It is worth noting that accurate thermal measurement can present certain challenges. One of them is sensor placement which is vital for getting better precision and battery operations. To have a sustainable system, having sensors which can measure correctly in a long term. These “long-termed precious sensors” induce delaying recalibration date of these sensors. The another factor for the systems with many cells is that, having good CPU system to increase the number of temperature data collected by sensors.

New technologies have made thermal measurement more precise and efficient. Advanced computational models use simulation and modelling tools to forecast heat patterns. Integrated thermal management systems combine thermal measurement with cooling technologies. Machine learning algorithms can accurately predict temperature trends and refine thermal management strategies based on real-time data. [1]

A case study involving a well-integrated BMS with a high-capacity EV battery system showed that battery safety and lifespan improved.

Table 2.6: The Impact of Enhanced Thermal Management on Battery Safety and Performance

Parameter	Before Enhancement	After Enhancement
Average Operating Temperature (°C)	35°C	28°C
Peak Temperature (°C)	45°C	35°C
Battery Lifespan (Cycles)	800	1200
Safety Incidents	5	1

2.1.4 Data Controls

To increase efficiency and the lifespan of the battery, battery should be managed by collecting, processing and controlling data via Battery Management Systems (BMS). [1]

BMS data is information from sensors in the battery system, such as voltage, current, temperature, SOC, and SOH. This data is used for real-time monitoring and decision-making.

Table 2.7: Example of Data Collected by BMS.

Data Type	Description	Unit
Voltage	Electric potential between two points	Volt (V)
Current	Flow rate of electric charge	Amper (A)
Temperature	Temperature level of battery cells	Celsius (°C)
SOC	Battery remaining capacity	Percentage (%)
SOH	General condition of the battery	Percentage (%)

Data controls within a BMS ensure that the battery operates within safe and efficient parameters. They are essential for:

a. Protecting the battery from conditions that could cause damage or shorten its lifespan.
b. Optimizing the battery's performance in terms of energy output and charging efficiency.
c. To keep the vehicle and its passengers safe, we prevent dangerous situations like thermal runaway.

A BMS controls data from sensors on the battery. This data can be used to assess the battery's current state and for long-term health evaluation. It can also be used to communicate with other vehicle systems. It includes Data processing, communication, storage and collection from sensors.

The related simple SOC calculation via Coulomb counting has been shared down below:

$$SOC\ (new)=SOC\ (old)+C\int Idt\times 100\% \qquad (2.1)$$

i. I is the current in amperes,

ii. dt equals to the time interval in seconds

iii. C equals to the the complete battery capacity in ampere-hours.

Let’s consider that we have 50Ah battery which is applied by current flow with 10 A per hour:

$$SOC\ (new)=SOC\ (old)+5010\times 3600\times 100\%$$

$$SOC\ (new)=SOC\ (old)+72\% SOC\ (new)=SOC\ (old)+72\% \qquad (2.2)$$

With a well-integrated BMS, data controls provide some benefits to EVs. For example, it improves efficiency and the range. They also interface with the vehicle's navigation and energy systems to optimize route planning and energy consumption [1].

Table 2.8: Impact of Data Controls on EV Performance.

Parameter	With Data Control	Without Data Control
Average Distance	350 mil	300 mil
Battery Lifespan	8 years	5 years

Modern BMS uses advanced algorithms and machine learning to enhance data accuracy and decision-making processes:

Predictive Analytics: Utilizing historical data to predict future battery conditions.

Adaptive Algorithms: These algorithms adjust systems parameters according to real-time data for improving the performance of the system.

There are a lot of challenges when it comes to implementing effective data controls in a BMS. One of the main ones is making sure that the sensors and algorithms are accurate and precise.

Data controls are an integral part of the operation and success of Battery Management Systems in electric vehicles. As technology advances, the capabilities of data controls will also evolve, further enhancing the safety, efficiency, and performance of electric vehicles. Ongoing developments in this area promise more sophisticated, reliable, and efficient management of battery systems necessary for the future of transportation. [2]

2.2 BATTERY MANAGEMENT SYSTEMS

Battery packs are charged and discharged via Battery Management Systems (BMS). Rechargeable batteries use efficiently in many ways such as cycle times, lifespan, and safety. Since EV market grows, development of BMS will be increased as well.

Battery management systems differ in how complex and how much they can do, but are usually put into two main groups:

Passive BMS: This BMS type balances cells by draining energy from higher voltage cells through resistors. It is simpler and cheaper. However, this BMS type is lesser efficient.

Active BMS: More advanced than passive systems, active BMS redistributes energy from higher voltage cells to lower ones. This not only conserves energy but also improves the overall efficiency and balance of the battery pack. [12]

Table 2.9: Comparison of BMS Types.

BMS Type	Balancing Method	Efficiency	Cost
Passive BMS	Energy dissipated as heat	Lower	Cheaper
Active BMS	Redistributed energy	Higher	Expensive

Before the advent of modern electronic BMS, battery management was primarily manual and involved basic control and balancing without complex electronics. Early BMS focused on simple circuits designed to prevent overcharging and over-discharging, lacking the advanced data analysis and real-time feedback capabilities of modern systems.

BMS are used in various applications where batteries are essential. Battery management systems are essential for a number of applications, In the field of electric vehicles (EVs), for instance, they oversee the operation of the vehicle's battery packs, which are often large and intricate.

In electric vehicles, active BMS are often preferred despite their higher cost. These systems offer more precise control over battery balancing and can improve the vehicle's range and battery life. EV companies mostly care about trusty systems.

2.2.1 Modular Battery Management System

Modular Battery Management Systems (BMS) are a big step forward in battery technology. They are especially good for storing energy in electric vehicles (EVs) and renewable energy systems. Modular BMS helps battery technology and energy management by being flexible. With more and more industries using batteries, it is clear that we need better battery management systems. Modular BMS is leading the way with adaptable, flexible solutions for different battery sizes and configurations.

A modular BMS allows for controlling the separate management of different battery modules in the same EV. Despite of a traditional BMS, modular BMS treats each module as a separate unit with the ability to separately watch, manage, and optimize each one. This method also helps to increase trusty of the whole battery system. [8]

A modular BMS has three main parts: monitoring, control and communication. Monitoring tracks voltage, current and temperature for each battery module. Control gathers data from all modules and oversees the system. Communication uses advanced protocols to link the modules and control unit.

Modular BMS are essential in various applications where battery efficiency, scalability, and reliability are crucial. In energy storage systems, they offer the necessary flexibility and expandability for diverse battery configurations. They extend battery life and enhance safety in portable electronic devices with multiple battery cells. Their ability to optimise the performance of each battery module makes them increasingly popular in EVs, significantly boosting overall efficiency and range. Modular BMS also make it easier to maintain and replace battery modules, which is useful in cars.

Modular BMS began in the early 2000s with more complex battery technologies. It was used in small-scale applications, such as mobile phones and laptops, but has since evolved to handle larger, more complex systems. Today, modular BMS represents the cutting-edge in battery management, incorporating advanced features. [8]

In the future, modular BMS technology will use AI and machine learning to predict and fix problems in individual battery modules. It will also improve communication between modules and the CPUs.

Modular BMS is a big step forward in battery management. It is flexible and efficient. As more battery-reliant technologies like electric vehicles and renewable energy systems are developed, modular BMS will become more important. This will lead to more new ideas and improvements in this field.

2.2.2 Centralized Battery Management System

CBMSs are important for guaranteeing the safe and efficient operation of battery packs in various applications, including electric vehicles, renewable energy storage, and portable electronic devices. As energy solutions evolve, managing battery systems remains a significant challenge, particularly in electric vehicles and large-scale energy storage. CBMSs offer a solution to these challenges by controlling the whole battery system.

A CBMS oversees a battery pack as a single unit, rather than managing individual cells or modules separately. This system monitors, regulates, protects and communicates to ensure the battery performs well and lasts a long time. [6].

The operation of a CBMS comprises several essential components, such as sensors which provide measurements of voltage, current, temperature. The provided data later comes to CPU to utilize battery's conditions such as SOC, SOH and any other potential risks. According to these analyses, CBMS carries out the necessary actions. These actions contain balancing the charge among the battery units, organizing the current flow.

CBMS might be used in several applications:

EVs: Controlling the battery for increasing efficiency and make them more safety

UPS: Guarantees stability and reliability in power backup systems which is important at every level of users.

Electronic devices: Such as laptops and smartphones also increase battery life

In this paper mostly EVs have been pointed out. CBMS manages battery limits while increasing the efficiency of the battery. [12]

The first developments of CBSM started at late 90s because of the lack of efficient battery in electronical devices such as laptops and phones. At the first places these systems were basic. However, since the electronical devices have been improved and changed CBMS has been used for more complex systems for decision making and safety.

Nowadays, we can use CBMS with AI and machine learning for improving its safety and decision making ability. We can use them at EVs, CPUs. [12]

At the near future, we can integrate them to IoT which let devices communicate with eachother via internet. These will let us to use them at smart building and smart citys.

Since more efficient and reliable batteries are needed for our applications, CBMS will be more curicial and will be more improved. For EVs, it will be the same as well since the popularity of EVs increases.

2.2.3 Distributed Battery Management System

Distributed Battery Management Systems (DBMS) are such a big improvement on battery technology. It helps EVs to work with better battery performance and safety. As electric vehicles (EVs) get more complex and powerful, it's clear that we need better battery management. Distributed Battery Management Systems (DBMS) provides better enhanced scalability and reliability rather than centralized systems [10]. A Distributed Battery Management System controls each group of cells independently which provide well managed monitoring and certain control of each cell of the battery.

A DBMS has specific roles which provide us some features. DBMS monitors voltage, current and thermal status for each battery cell independently. It also manages data processing and decision making for each battery cell independently via local controllers. It also has sophisticated communication network which allows local controllers and CPU to work as coordinated.

DBSM also used in several high level of demands such as EVs, energy storage systems, portable power systems. In EVs it improves battery pack performance, lifespan and safety. In energy storage systems, it is mostly used for adopting battery packs to different load demands. Finally it is used for portable power systems uses it for increasing battery efficiency as well.

DBSM can be found in EVs while managing the battery pack to maintain balance, efficience and safety. It helps more certain battery measurements which improves SOC and SOH estimations. Since all the battery packs have been measured and examined independently, it also help to detect safety issues quickly.

The logic of DBMS becomes important for humanity sicnce complicated and larger batteries have been commissioned and used at early 20s. Since the early 20s to today, microcontroller and communication technology have became more enhanced, usage of DBMS become more efficient.

Nowadays, DBMS work with the improved algorithms advanced algorithms, machine learning techniques, and IoT Technologies. It allows predictive maintanence, which predicts and solve the faults, and real time adaptive balancing, which increase lifespan and performance of the battery.

Predictive Maintenance: Use historical data to predict and address potential failures in advance.

Real-Time Adaptive Balancing: Dynamically adjust charge levels between cells to extend battery life and maintain performance.

In the near future, developments in DBMS, with the help of technology, will be able to cooperated with the IoT and machine learning. With the help of these applications more autonomous and smart systems will be used. These new technologies will allow EVs and smart grids work together for managing energy more efficiently. DBMS will be more crucial BMS type at the future.

3. ELECTRIC VEHICLES AND BATTERY TECHNOLOGIES

Electric vehicles (EVs) help to reduce global impact of the greenhouse gases. EVs uses electricity as a fuel which is quieter, greener and cheaper. However, current battery technology is not enough for long-distance transportation.

Advanced BMS plays an essential role to improve performance. State of charge (SOT) is one of the most important metric for getting efficient BMS. Correct calculations of battery charge rate improving EVs' performance have become trend topic of academic research.

Safety, efficiency and powerful battery are the most important keys for efficient EVs. In EV's these keys are controlled via BMS. A BMS manages various critical parameters to optimise performance and prevent failure. It monitors SOC, SOH, SOT, and cell balancing.

3.1 INTERNAL COMBUSTION VEHICLES

Internal combustion engines (ICE), use sources like fossil fuels which increases the green gas effect. These vehicles include a tank to store fuel. The fossil fuels used as energy suppliers for these vehicles are gasoline, diesel, and hydrogen, which are still under research. The working principle of an internal combustion engine involves injecting fuel into the combustion chamber under high temperature and pressure, where it is mixed with air and ignited either by external ignition or auto-ignition, depending on the engine type. The resulting combustion produces energy, which is converted into kinetic energy to power the vehicle. The optimal mixture of air and fuel is essential for efficient combustion, as deviations can lead to inefficient burning and significant environmental pollution. [12]

3.2 HYBRID VEHICLES

Hybrid vehicles, which combine internal combustion engines with electric motors, have garnered significant attention as a practical solution to reduce environmental pollution and dependence on fossil fuels.

Hybrid vehicles have a rich history dating back over a century. Late of 19^{th} century, the first patent related to idea of combining different power sources has been done. Ferdinand Porsche developed earliest hybrid car in 1899. In this vehicle there is a gasoline engine which provides power to the electrical generators. In those years, Oil was cheaper and the system was looked like complicated. As a result of this situation, delayed further development until the late 20th century. This vehicle featured a gasoline engine powering an electric generator, which in turn powered electric motors located in the wheel hubs. However, the complexity and cost of such designs, combined with the dominance of cheap oil, delayed further development until the late 20th century.

Environmental concerns and the economic crisis of the late 1970s led to an increased interest in hybrid technologies. In early 1990s, automotive producers launched hybrid car models. It caused to according to more sustainable transport options. In 1997 Toyota released Prius which is world's first mass-produced hybrid car and it leads Honda Insight in North America. [12]

Hybrid vehicles use an internal combustion engine (ICE) and an electric motor to improve fuel efficiency and reduce emissions. We can examine hybrid cars in three main types:

Series Hybrids: The ICE does not directly drive the wheels, it produces electricity that powers the electrical motor. This electrical motor drives the wheels or charges the battery but not in the same time. [13]

Parallel Hybrids: ICE and the electric motor can directly drive the wheels, either separately or together.

Series-Parallel Hybrids: It becomes via the combination of both parallel and series hybrids. This type of cars can switch modes which let them to maximize efficiency and performance.

The engineering behind hybrid vehicles involves the complex coordination between the ICE and the electric motor. Key components include the engine, electric motor, generator, battery, and a sophisticated control unit that manages power distribution.

Internal Combustion Engine (ICE): In hybrids, the ICE is typically smaller and more efficient compared to those in conventional vehicles. It is optimized for specific power ranges, thereby reducing fuel consumption and emissions. [12]

Electric Motor: Functions as both a motor and a generator. Electrical motors supplies extra power for acceleration. In some hybrids, it also can drive the car in an independent way.It also recovers energy by regenerative braking. It transforms kinetic energy to electrical energy in battery which means that it also works as a generator.

Battery: It stores energy in hybrid vehicles. It powers the electric motor. Modern hybrid vehicles mostly use lithium-ion batteries due to their high energy capacities and long lifespans.

Control Unit: It is one of the most critical component of hybrid vehicles. It also manages to switch between modes such as the ICE and the electrical motor. In addition to that it also manages battery charge and distributes power to get healthy and efficient system.

Special electronic controls are needed to integrate these systems in order to increase efficiency and performance of the system, and switching modes without any fault. It give engineers chance to increase car's performance while getting rid of the environmental pollution.

3.3 BATTERY TYPES

Battery technologies are crucial for the EVs since the efficiency and the environmental impact of transportation.

3.3.1 Primary Cells

Primary cells cannot be recharged. When chemical components or the battery collapsed once, the battery cannot produce energy and it should be replaced with a new one. Zinc-carbon and alkaline compositions are most common component of this type of batteries. They are not suitable for high power applications, such as EVs.

3.3.2 Secondary Cells

Secondary cells can be recharged and reusable for many times since the chemical reactions are reversable. When external current applied to secondary cell, chemical composition of the battery is restored. Secondary cells plays vital role at high power applications such as EVs.

Since the secondary cells are rechargable and provide much more higher energy efficiency, it became more popular. In order of popularity, lithium-ion, nickel-metal hydride, and lead-acid batteries are mostly used. Each type is impactful according to their specific EV application.

Lithium-Ion Batteries: Since they have high energy density, long battery lifespan and lower weight, they are dominating the EV market. Lithium-Ion batteries are formed with cathode which is made by lithium, anode made by carbon and electrolyte. They consist of a lithium compound as the cathode material, a carbon intercalation compound as the anode, and an organic electrolyte. [12]

Nickel-Metal Hydride Batteries: Their primary feature is having high electrical energy density and its strength. They are made by an anode and cathode. Anode is made by hydrogen-ingesting alloy and cathode is made by nickel oxyhydroxide. In spite of having lower efficiency than lithium-ion batteries, they are good alternatives since they gave longer lifespan and tolerance of overcharging.

Lead-Acid Batteries: These batteries are the oldest and heaviest one among all other battery types. Since they are budget-friendly, they are still used by some EVs. They are mostly used as support power unit and they are less used as main power source of the system.

General Benefits of Secondary Cells:

Rechargeability: Reusing batteries let us use them cheaper and eco-friendly for EVs.

Energy Efficiency: Since we use especially lithium-ion batteries, let the EV system have more efficiency and make them to use as long distance EVs.

Environmental Impact: Compared to primary cells, secondary cells could be used much more times. Since we do not waste the batteries, it increases environmental sustainability.

Limitations of Secondary Cells:

Secondary cells come with the higher production costs, and the most expensive type of battery type is lithium-ion batteries. This situation leads the increasing the initial price of the EVs. The other limit of secondary cells is dependence of resources. Since the rare materials of battery comes from different regions which might be unstable causes ethical concerns. In addition to that, even if secondary batteries are rechargable many times, it causes aging degradation and reduced capacity.

In the near future, with the help of enhanced battery technology, EVs will improve the efficiency. The main purpose of the battery technologies increasing the efficiency of the EVs and batteries' capacity, reducing the source dependency and environmental impact. Recent, researches are mostly targeting alternative materials which might lead system to have higher capacities, energy densities and less with higher energy density and lower environmental impact.

In addition to these, governments and companies are focusing on recycling techs. Since the number of EV users increase, recycling secondary batteries becoming more and more vital. It will decrease at battery and resource wasting.

Lastly, primary cells are not the best option for EV apps due to not being able to be recharged again. According to this situation, transportation mostly exploit secondary cells, so the researches focus on increasing the quality of the secondary cells such as current limitation. While EVs become more popular globally, efficiency, sustainability and strong batteries will be main topic of innovative researches.

3.4 CRITICAL PARAMETERS OF BATTERY MANAGEMENT SYSTEMS

EVs becomes more popular at market. Since companies and end-users want to improve efficiency, security and longer lifespan times of the system, Battery Management Systems (BMS) technologies have been invested more. State of temperature (SOT), state of charge (SOC), state of Health (SOH) and cell balancing are vital parameters for optimizing the system. These parameters' data collected by BMS and it is checked by the CPU of the BMS and it takes steps to make the system optimum state. [12]

3.4.1 State of Charge

State of charge's (SOC) main task is providing usable battery capacity. This information is crucial for:

The primary importance of SOC lies in its ability to inform users and systems about the available battery capacity for use. This information is vital for:

Efficiency of operations: When BMS get informations about the situation of the battery, it can operates algorithms to finish tasks correctly.

Battery Health Maintenance: Monitoring SOC helps extend battery life by avoiding full discharges and overcharges, which can stress the battery.

Energy Management: In systems with multiple energy sources, such as hybrid electric vehicles or smart grids, SOC is critical for deciding when to switch energy sources or best manage energy flows.

Safety: Preventing the battery from operating outside its safe range (overcharging or deep discharging) is crucial for avoiding scenarios that could lead to thermal runaway or other battery-related failures.

Accurately measuring SOC is complex due to various factors that affect battery performance, including age, temperature, and discharge rate. Several methods are used to estimate SOC, each with its strengths and limitations. [13]

Voltage-Based Method: This simple method correlates the current battery voltage with its state of charge based on a voltage-discharge curve. However, voltage can be influenced by temperature and load conditions, making this method less reliable under varying operating conditions.

Coulomb Counting: Also known as ampere-hour integration, this method tracks the current flowing in and out of the battery. BMS calculates total energy transferred and predicts SOC by getting information by Coulomb Counting. This method gives healthier results than other voltage-depended methods. However, initial calibration should be known to get better estimations and results.

Kalman Filtering and Advanced Algorithms: These methods combine different data points to calculate SOC by using mathematical equations. These data are temperature, voltage and current. Managing the uncertainty and variability at battery is main function of the Kalman Filters.

To get better SOC estimation developers faces with some issues:

Battery Aging: Batteries affected by aging. Aging reduces maximum capacity of battery and which makes harder to estimate SOH.

Measurement Errors: If advanced sensors are not used at the BMS, It leads errors in measurement and data, in other way, it affects true estimation of SOC.

Even with these problems, improvement of the BMS still continues which leads to determine true estimation of SOC.

3.4.2 State of Health

The SOH is essential for systems which works with battery. Since the SOH ensuring safety, reliability of the system and efficiency, it helps them via these parameters:

Lifecycle Management: SOH helps to determine the remain life.

Performance Assurance: A battery with a high SOH will perform close to its intended capacity, ensuring the device or vehicle operates efficiently. Conversely, a battery with a low SOH may not meet operational demands, leading to reduced performance and potential system downtimes.

Safety: Batteries with deteriorated health can pose safety risks, including potential overheating or failure under load. Monitoring SOH allows for preventative measures to be implemented before critical issues arise. [13]

Cost Efficiency: By monitoring SOH, users and manufacturers can optimize battery usage, reducing costs associated with early replacements and maintenance.

Resale and Warranty Claims: For electric vehicles and other high-value battery systems, accurate SOH assessment provides a measurable metric of battery value, impacting resale value and warranty claims.

Determining SOH involves measuring and analyzing various aspects of the battery's performance and condition. [13] Several methods and technologies are used to evaluate SOH, each with its unique approach and level of complexity:

Capacity Measurement: The most direct way to examine SOH. It measures real capacity of the battery and compares it with the nominal capacity of the battery. It can be done via charge and discharge loops, and also determine the how much energy can be stored at battery.

Electrochemical Impedance Spectroscopy (EIS): This method measures the differences battery’s internal structure and electrochemical differences. It also helps to determine electrolyte disruption.

Voltage Analysis: Voltage analysis shows the changes of the voltage attiributes while battery is charging and discharging.

There are many factors leads to miscalculate SOH:

Battery Chemistry Complexity: Since the batteries are more complicated, SOH estimation affected by many factors such as thermal status, charge and discharge rate.

Measurement Variability: Since different measurement ways can be used, we can reach different results and since the external factors affect the system, these leads errors.

Aging Effects: Batteries affected by aging. Aging reduces maximum capacity of battery and makes breakdown at internal resistances which makes harder to estimate SOH.

In a nutshell, SOH so important to manage BMS. It affects performance, safety and lifespan of the battery. Since more detailed and enhanced sensors improved, SOH status can be more reliable and certain at BMS.

3.4.3 State of Temperature

The main function of the SOT (State of Temperature) is providing run the system within safe temperature limits. Since charging and discharging causes heat at battery via electrochemical reactions at internal resistance. If temperature extends the optimum temperature limits, it leads to reduce performance, safety issues and accelerated breakdown.

To monitore SOT, sensors and software alghoritms both used in the BMS. Mostly, temperature sensors, which provides real-time data, are placed at many different places at BMS to collect reliable data. Temperature data related with these factors:

Sensor Placement: To get better temperature data, sensors should be placed at near the cells, modules and critical positions. With the help of the correct placement most critical temperature data are monitored.

Data Collection: Temperature sensors provide real-time temperature data to the BMS via temperature sensors.

Data Analysis: The BMS checks the temperature data in real time to see if the temperature is in the safe limits or not. Advanced systems can also predict overheating by checking at the data.

Thermal Management Activation: If the temperature is too high, the BMS can activate thermal management strategies. These include adjusting the charge/discharge rates, activating cooling systems, or disconnecting the battery.

The importance of SOT in battery management can be understood from several key aspects:

Safety: Overheating is the most important risk for the batteries. When high temperature occurs, it leads the thermal runaway which causes later heating issues.

Performance Optimization: Battery performance changes due to temperature. Technically, most batteries works within specific temperature limits. At low temperatures chemical reactions becomes slower, at high temperatures battery breakdown and increase temperature unnecessarily.

Longevity: If the temperature extends the nominal limit repeatedly, battery breakdown rapidly. BMS keeps state of the temperature within limits for increasing lifespan.

In conclusion, SOT is the one of the most important parameters at BMS. The state of temperature is a critical parameter in the management of battery systems. Since the performance, safety and lifespan of the batteries are crucial at EVs and other applications, managing and controlling SOT becomes much and much important. In the future, battery and sensors technology will be more advanced.

3.4.4 Battery Balancing

Both multicell battery packs used EVs and high-capacity energy storage systems include a critical step that is managing battery balancing. Even small differences in cell voltages cause many problems such as inefficiency, low battery performance and short lifespan. All the cells within a battery pack should be equally charged and have almost equal charge levels over time. There are two methods of battery balancing: passive and active. Each method has its own mechanisms and pros and cons depending on the specific requirements of the application. [13]

3.4.4.1 Passive balancing

Passive balancing is simpler and more budget-friendly. It works by removing excess energy from more charged cells in the form of heat through resistors. When one cell is fully charged, the balancing circuit sends extra energy to a resistor connected to that cell. This resistor turns the extra energy into heat, which is released into the surrounding environment. [13]

Passive balancing is simple and cost-effective. It is easy to design and implement, and it is more reliable than active systems. Since their system is not complex systems, it reduces to components' failure.

Passive balancing is not an energy efficient procedure. It uses excess energy as heat rather than using it. This makes it slower, especially in larger battery packs.

3.4.4.2 Active balancing

In contrast, active balancing is transferring energy from cells which has higher energy to the cells which has lower energy. This method is much more complex than the passive balancing, it also needs additional equiments like capacitors, transformers and inductors. It can be said that this situation lead high-cost hardware components. These methods might occur with the help of hardware components, such as switched capacitor circuits or transformers. [13]

Active balancing is much more efficient compared to the passive balancing, the main reason of that it does not waste energy. It transforms the energy in the battery. It is also faster than the other method. This pro leads the active balanced batteries to change their batteries less because it is decreasing discharge rate, increasing charge rate.

The passive and active balanced EV can be chosen by various factors such as battery lifespan time, economical situations or specific needed vehicles. For low-demand applications passive balancing consumer electronics, passive balancing will satisfy the end-users in according to its simplicity and cost-effectiveness. However, for EV application, longer battery lifetime and performance would be more important so most of manufacturers prefers active balancing.

4. CONCLUSION

This thesis focuses and investigates the relationship between Battery Management Systems (BMS) and Electrical vehicles (EVs), with a particular focus on the role of BMS in enhancing the efficiency and advancement of EVs. BMS is not merely advantegous but is crucial for getting maximum efficiency, durability, long lifespan for the EVs according to results. The discussion shows how a BMS can improve battery reliability, performance and EVs' efficiency. The discussion underscores the importance of BMS in enhancing battery reliability, performance, and overall vehicle efficiency by summarizing its multifaceted roles.

Battery Management System are import for increasing EV batteries efficiency and last longer by monitoring and controlling battery cells' state of charge (SOC), state of health (SOH), state of temperature (SOT). This improves the performance of EVs and prevents them from potential battery issues.

Secondly, Battery Management Systems (BMS) also improve the safety of EVs. Lithium-ion, the most common EV battery among others, can catch fire or explode if they overheat or are overcharged. BMS watches the battery, analyzes the real-time situation and controls the system. Since safety comes at the first place for today's science, BMS let people use EVs safely.

BMS enhances battery performance and efficiency by precisely controlling the charging and discharging cycles. This maximizes the battery input/output efficiency and life-time, and also keeps SOC between safe limitations. This situation let EVs usable for longer ranges and eco-friendly. In addition to that, BMS employs cell balancing techniques to make sure that all battery cells contribute equally to the vehicle's operation, avoiding potential issues caused by imbalances which could lead to inefficient utilisation of battery capacity.

Economically, BMS makes EVs more cost-effective by providing them batteries that are longer durability. This longer lifespan lets users delay the replacement costs, less battery waste. Furthermore, This consequences are not only about being economical, it also refers that BMS reduces material waste and carbon emission which is important for our world.

Despite the meaningful advantages, using BMS comes with complexity and high-cost issues. These high costs elements are mostly software elements. However, advanced BMS systems will be improved by artificial intelligence and machine learning. Therefore, this continuous improvement of BMS will reduce the cost of software. This gives hope to the scientist.

In conclusion, advanced Battery Management Systems (BMS) cause a solid change on the vehicle market. It increases safety, enhances performance and longer battery lifetime. In addition to these beneficials BMS also makes our world greener and recuces carbon emission so next generations will live in a safer and clear world. This thesis emphasises the crutial role of BMS in EVs and advantages and disadvantages of battery and BMS types.

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