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Overview of Electric Vehicles Interconnected Subsystems

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***Abstract*— This paper examines electric vehicles (EVs) subsystems operation and will focus on power management (PM). PM is always concerned with the EVs battery performance, efficiency and lifetime. The battery plays a vital role in the EV's performance, to provide the vehicle driving system with the energy needed for operation. Lithium-ion batteries have emerged as the battery of choice for EV manufacturers due to their high energy density and lightweight as compared to other energy storage. For the safe and dependable functioning of EV batteries, condition assessment of the batteries is significant. This is attained by a battery management system (BMS). In addition to the BMS, the optimal flow of energy between the battery, converters and additional vehicle components should also be regulated. This is called a power management control (PMC), where the vehicle's optimum performance depends heavily on the nature of PMC. Therefore, the design of PMC is critical to reduce energy consumption, increase system efficiency and maximise battery life. This paper presents an overview of EVs battery modelling, technologies and properties. It shows the BMS performance indicator and the benefits of integrating battery and supercapacitor to optimise the energy consumption of EVs.**

***Keywords—Electric Vehicle, Battery Management System, Power Management** (keywords)*

I. INTRODUCTION

Transportation is one of the largest contributors to Greenhouse gas emissions (GHG), according to the UK government whitepaper, it contributes 28% of the CO_2 total emission [1]. Electrification of transport sectors is becoming a vital tool besides other technologies to achieve the UK's net-zero goals. This includes electrifications of railways, the use of low carbon hydrogen and the radical change in converting to EVs on the main roads for domestic and commercial journeys. The UK Government takes a historic step towards net-zero with the end of the sale of new petrol and diesel cars by 2030 [2].

One of the main challenges in EVs deployment is the battery constraints operation to satisfy various driving statuses and conditions. For example, EVs need high power during accelerating up-hill and energy regeneration during deceleration. To overcome these obstacles, researchers have proposed several developments to integrate onboard charging/discharging to save energy. In addition to this, researchers are studying the integration of high energy density devices with batteries to optimise EVs performance on different roads. This includes the integration of high energy storage facilities.

A. MATHEMATICAL MODELLING OF EVs BATTERIES

As illustrated in Table 1, electrochemical energy storage systems are the common form of energy storage for EVs [3], [4]. Electrochemical models and equivalent circuit models are used to study the behaviour of battery cells [5]. 2nd order equivalent circuit models are widely used because of their simple structure and ease to estimate the state of charge (SOC). Figure 1 shows the 2nd order mathematical model which consists of two pairs of resistors and capacitors connected in parallel to improve the accuracy. Three resistors represent the three different types of resistance that occur in the cell [5].

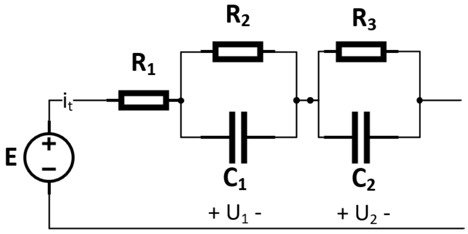


Figure 1. Battery 2nd order equivalent circuit [5]

Table 1. A survey of different battery technologies [3], [4], [6], [7]

	LA	NiCad	NiMH	Lithium
Energy Density (Wh/Kg)	40 - 60	35 - 54	70 - 100	110 - 160
Power Density (W/L)	100 - 400	80 - 600	250 - 1000	1500 - 10000
Life Cycle	1500	500	200 - 300	500 - 1000
Cell Voltage (V)	1.2	1.2	2	3.6
Load Current (A)	>2C	0.5-1C	0.2C	2C
Operating Temperature (^{O}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60
Depth of Discharge (%)	50	85	100	95
Round Trip Efficiency (%)	70	80	75	80
Estimated Cost (USD/kWh)	150	632 - 1256	500	700

II. POWER MANAGEMENT CONTROL SYSTEMS

In EVs, there are multiple layers of power management control (PMC) [5],[6], which consists of low-level hardware-based control and high-level software-based supervision that can be split into two control layers: low-level component and low-level control. To optimise the power management system in EVs, both the hardware and software control layers collaborate, where it consists of the following;

- Low level – hardware
- High level – software

A. Hardware Level

The hardware, specifically the vehicle powertrain, affects the PMC design. EV powertrain is arranged into different configurations, to produce ideal power management outcomes, improve vehicle performance and resilience, and reduce transmission energy loss [8], [9].

Existing powertrain EVs can be classed into two types based on the number of motors utilised in the vehicle and their configuration: centralised single motor driven powertrain and distributed multi-motor driven powertrain [10]. Some EVs are focused on distributed multi-motor driven powertrains and it's mainly classified into three categories: dual-motor powertrain, triple motor powertrain, and four motor powertrain [10].

1) Centralised Single Motor-Driven Powertrain

The centralised single motor speed-driven powertrain is the most common structure in modern EV, as shown in Figure 2)i) The electric motor is mounted as a front-wheel-drive in a single motor configuration. There is also a differential, which allows the wheels to rotate at various speeds. The motor converts electrical energy from the battery into mechanical energy, allowing the vehicle to move. During the regenerative process, it acts as a generator, sending energy back to the energy source [10].

Pros of single motor configuration are that fewer components are needed to create a single motor system and adapted conventional transmission used, which makes it all in all cheaper to build. However, this powertrain system lacks a second motor to create power. This limitation makes it inefficient compared to the dual-motor system [10].

2) Distributed Multi-Motor Driven Powertrain

Distributed multi-motor driven powertrains are classified as dual-motor powertrain systems, triple powertrain systems and four motor powertrains [10].

When it comes to a dual-motor [10], it is expected to have a pair of motors that are placed in different spots of the vehicle, as shown in Figure 2)ii). It’s relatively clear that a car with two motors should be able to offer more horsepower behind the wheel. The combination of the torque from both motors ensures there is a significant boost in acceleration for the driver. It is important to note that the same is also true for a single motor for an electric car, however, a dual is going to outperform a single motor in terms of efficiency and speed at a higher altitude [10].

Two motors are provided in this system [11], one on each axle, and are coupled via planetary gear, with torque coupled via shaft fixed gear. Front and rear motor drives are powered by one or two separate battery packs. It is possible to choose different power and torque sizing for the drives as well as different gear ratios for the gearboxes when using a two-motor, two-axle configuration [10].

When compared to a single drive with the same total power rating [10-, 11], using two traction drives improves overall tractive effort delivery across the whole speed range. Having several traction motors increases the degree of freedom in vehicle torque vectoring for greater traction and stability control and the traction system's overall reliability. Pros of the dual-motor system include having higher speed, also having the ability to stop quickly and one of the motors can be used to power up the car while another set of batteries can be recharged, this gives the user the ability to travel further without worrying about charging up. Limitations are that dual-motor systems are expensive because they are more complicated to put together and there is a lack of standard transmission [10].

In a triple motor powertrain system, one motor is placed on the front axle while two motors are fitted to the rear axle, thus making the car all-wheel drive. The two motors drive each wheel of the rear axle to improve efficiency and are solely responsible for powering the car in normal driving conditions. The third front-mounted motor comes to life when the driver needs more performance. A single-speed transmission connects each of the electric motors to the appropriate wheel on the rear axle. Electric torque vectoring mechanism avoids the requirement for a mechanical differential. This improves the all-wheel-drive system's performance by a significant margin, and the car’s handling, stability, and grip [10].

Four motor powertrain systems that can be shown in Figure 2)iv), can also be classified as super handling all-wheel-drive systems that can precisely apply positive or negative torque to each wheel thanks to a dedicated motor at each corner. Torque vectoring is ensured by the use of four motors. An EV with four electric motors can also be faster and more responsive because torque is adjusted electronically by how much power is sent to each motor rather than mechanically [10].

B. Software Level

The high-level supervisory control approach is the second stage control strategy, which boosts the vehicle's overall performance. Different control methods considered to improve vehicle performance can be demonstrated in Figure 3, which are rule-based and optimisation approach controlled [8], [9]. Rule-based control is formed on human knowledge, heuristic, intuition, and even mathematical model and driving cycles. The control of the optimisation approach is formed on an analytical or numerical procedure to mimic the cost function [8], [9]. To this extent optimisation approaches such as global optimisation are popular options. Numerous methodologies fall under the category of global optimisation, such as linear programming, optimal control, dynamic programming (DP), stochastic DP and genetic algorithm [9]. The comparison of global optimisation algorithms is shown in Table 2.

C. Power Management Discussion

The selection of the suitable topology demands full knowledge of the vehicle's intended usage and research into driving cycles, vehicle size and weight, desired performance, and application type. The second phase, after the topology has been established, is to create a PMC approach, which is critical for an optimal EV [8], [9].

III. ADVANCEMENT OF THE BMS

Lately, lithium-ion batteries are becoming desired for many applications. Batteries are combined into many cells either in series or parallel to create a module and then connect many modules to create a pack. At pack level, lithium-ion battery performance becomes difficult to manage, because the cell can get charged and discharged at varying rates and can be derating under different conditions, due to their different operational state in terms of the following;

- Cell Current, Voltage and Temperature
- The State of Charge
- The State of Health (SOH)

A complex electronic control system known as a battery management system (BMS) is required to monitor charge rates across the whole pack up to a safe level, to ensure peak performance and prolong the battery life [3], [4]. Cells come in various formats, which have different characteristics. Modules are formed by connecting multiple cells by providing mechanical support structures, thermal interfaces, and attaching.

A. Key functions of BMS

Figure 4 shows a BMS which plays an important role to acquire battery status, where it takes measured current voltage and current from the battery and estimates the state of charge (SOC), state of health (SOH), thermal management and charge balancing [3],[4].

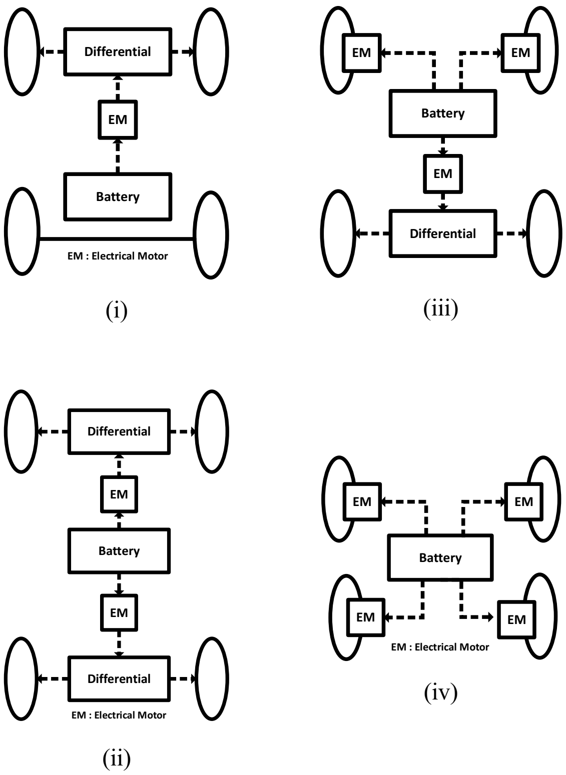


Figure 2. EV Powertrains: (i) Single Motor Powertrain, (ii) Dual Motor Powertrain, (iii) Triple Motor Powertrain, (iv) Four Motor Powertrain [10]

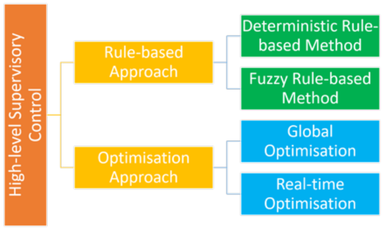


Figure 3. High-level supervisory control strategies

Table 2. Comparison of global optimisation algorithms [8]

	Computation Intensity	Robust	Real-time	Analytical Solution	Compile Structure
Linear Programming	+ +	-	- -	-	-
Optimal Control	- -	- -	-	+	-
DP	-	-	-	-	+
Stochastic DP	- -	-	-	-	+
Genetic Algorithm	-	+	-	-	+ +

++ Very High, + High, - Low, -- Very Low

B. *SOC*

Battery SOC estimation is the main factor of the BMS, which helps to analyse how much charge is available in the battery. SOC is the ratio between present charge and full charge capacity. SOC is calculated by taking the difference between present charge and full charge capacity [12]. It is expressed in eq(1) [13].

$$SoC = \frac{Q_{Remainng}\,(t)}{Q_{Max}\,(t)} * 100\,\% \qquad (1)$$

Where $Q_{Remaining}$ is the remaining capacity and Q_{Max} is the total capacity.

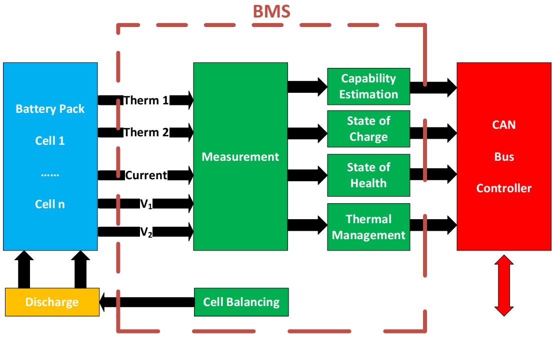


Figure 4. BMS block diagram [3]

To determine SOC the following methods are used:

- Book-keeping estimations – Coulomb counting
- Direct measurements – Voltage method
- Model-based – Kalman filtering

- Coulomb counting (CC) method – Frequent method for estimating the SOC. Calculates the charge transferred in or out of the battery by simply adding up the charge transported in or out of the battery [12].
- Voltage method – A discharged test under controlled conditions is used to determine the voltage. Using the battery's known discharge curve, the voltage technique transforms a battery voltage reading to the equivalent SOC value (Voltage vs SOC) [12].
- Kalman filter (KF) method – Approach is an algorithm for estimating the inner states of any dynamic system [12], [14].

Table 3. Survey of different estimation methods [4]

Method	Pros	Cons	EV Compatible
CC	Simple and computationally inexpensive	Any error in measurement of the current will accumulate, making the safe charge diverge from the true value until reset it	Yes
Voltage	Simple and easy to implement	Not 100% accurate	No
KF	In real-time, the system is impacted by external disturbances, and it must estimate the state with high precision	It cannot be used to estimate the state of a nonlinear system directly.	Yes

C. *SOH*

SOH of a battery helps to analyse the neediness of a battery replacement. It is expressed as the ratio between present full charge capacity and original full charge capacity [12]. It is expressed in eq(2).

$$SOH = \frac{Q_{Present}}{Q_{Fresh}} * 100\,\% \qquad (2)$$

Where $Q_{Present}$ is the present capacity and Q_{Fresh} is the full charge capacity.

SOH is very important for BMS operation as it calculates the remaining lifetime and estimates its failure condition [12].

Temperature and discharge/charge current rate are the key elements that cause battery ageing, according to many researchers [12], [13], [15]. However, no accurate mathematical models to estimate the battery SOH exists due to lithium-ion batteries' complicated and frequently poorly understood internal dynamics.

Many studies [12], [13], [15] feel that simply monitoring voltage, whether using online voltage monitoring devices or conducting in-person voltage testing, is sufficient. However, monitoring voltage alone will not provide a whole picture. Voltage is merely a measure of a battery's state of charge, not its health.

One of the most effective ways to assess a battery's health is to measure its impedance. This allows to have a better knowledge of the battery's internal resistance and, as a result, get a better image of its overall health. Impedance readings appear to be valuable trending tools signalling possible problems far earlier than voltage testing alone when measurements are done over time. The internal resistance, or impedance, of a battery, often increases over time, suggesting cell breakdown [13], [15].

D. THERMAL MANAGEMENT

Lithium-ion batteries each have an acceptable operating temperature range. Lithium-ion batteries operating outside of their safe temperature range will cause performance degradation and irreversible damage to the cells. In extreme cases, it can even cause thermal runaway, excessive overheating of the cell, and possible combustion. BMS control the temperature of the battery through heating or cooling. Temperature sensors are installed in the pack to provide cell temperature information. BMS uses this information to distribute coolant where it's needed to maintain the ideal temperature range. Common coolants used are air, water/glycol, dielectric oil and refringent [3].

E. CELL BALANCING

One of the major control algorithms of the BMS is cell balancing. Cell balancing is the process of equalising the voltages among individual cells. Each cell in the battery pack has a different state of charge and this changes with an increase in the number of charge-discharge cycles. Battery cell balancing is needed as each cell needs to be charged and discharged properly otherwise it can lead to thermal runaway and can cause catastrophic failures. There are two techniques of cell balancing [3]:

1. Passive

Passive balancing is being used to discharge the excess voltage of a cell that is at a higher voltage, to equalise with other cells. This excess voltage/charge is dissipated as heat. Nevertheless, this type of cell balancing is not suggested as when the battery is being discharged, the module of all battery cells will be limited by the weakest cell [3].

2. Active

Active balancing is a more energy-efficient way to balance cell energy compared with passive balancing. It redistributes the energy amongst cells, rather than dissipating and wasting it. Power electronic devices move energy from the strongest cells to the weakest cells, maximising the available energy and increasing the effects of the capacity of the module [3].

F. BMS TOPOLOGIES

BMS consists of three different topologies, which are centralised, modular and distributed. Table 4 illustrates the pros and cons of each BMS topology. In centralised BMS topology, each cell is directly connected to the master control unit. All of the cells are protected and balanced by the controller unit [16]. In modular BMS topology, to face the data and convey it to the master controller, many slave BMS controllers are used [16]. In distributed BMS topology, there are small voltage and discharge monitored circuits, which communicate with the master controller of the BMS [16].

Table 4. Overview of BMS topologies [16]

Topology	Pros	Cons
Centralised	Less hardware Single assembly	The controller is the only source of cell balance, excessive heat can be generated.
Modular	Wire's to cells are easier to manage Simple extension to larger battery packs	Communication is quite difficult Cost is slightly higher compared to centralised
Distributed	Simple Reliable	The difficulty of mounting every cell

IV. OVERVIEW OF SUPERCAPACITORS AND ENERGY STORAGE SYSTEMS

Another way of storing energy is through capacitors. A capacitor stores energy by separating charge to induce a voltage in a parallel plate's capacitor, this is done by opposing plates separated by a dielectric, unlike batteries, no chemical reaction occurs during operation. A supercapacitor (SC) is distinguished from a normal capacitor, where electrolyte and a very thin insulator are used rather than dielectric between plates, hence thin insulator is made of cardboard or paper [17].

SC can be classified as an energy storage system that has been gaining popularity in recent years, where they have a very high capacitance compared to the traditional capacitor, a longer life cycle and a high-power density. Supercapacitors, on the other hand, typically have a substantially lower energy density than lithium-ion batteries. As a result, a hybrid energy storage system (HESS) may fully utilise the benefits of these two types of energy storage devices while avoiding their limitations, which will be explained further on [18]. Types of SCs include ELDC, pseudo-capacitors, and hybrid.

A. *Electrostatic Double Layer Capacitor (EDLC)*

This type of SC has a phenomenon called the Helmholtz double-layer, where layers in between electrodes are made thinner, which leads to idiocies having a much higher energy density, however, compared to batteries this is still quite low [19].

B. *Pseudo-Capacitors*

This type of SC can operate in two ways. The first way is similar to EDLC, which stores energy electrostatically. The second type stores energy electrochemically, where electron charge shifts between the electrode and electrolyte, specifically selected materials permit the electrodes to host a very fast sequence of redox reactions that allow storing energy electrochemically [19].

C. *Hybrid SC*

Combining EDLC and pseudo-type, where the electrodes store energy electrostatically and electrochemically. This combines the fast charge and discharge of EDLC with the higher energy density of the pseudo-capacitor [19].

D. *Energy Storage*

There is an increasing demand for EVs to support the decarbonisation of transportation. The increased demands drive the development of stored electrical energy to be re-used in driving EV sector. EV batteries are always advised to have a shorter recharge time and longer time to use before recharge. Two types of electrical energy storage devices are particularly attracting great attention, these are SC and lithium-ion batteries. The plot between energy and power density can be seen in Figure 5 [17]. It can be seen that SCs have a moderate energy density but a higher power density. Lithium-ion batteries have a low power density and a high energy density [17]. The target of the energy storage system is to get higher energy and higher power at the same time and that phenomenon is called a hybrid energy storage system (HESS), which is based on combing SC and lithium-ion batteries.

The battery and SC systems are given a lot of attention, with an energy-dense battery functioning as a long-range energy source and a SC pack functioning as a peak power source, releasing bursts of high power during acceleration and recovering regenerated energy during brake [20]. Many HESS topologies that combine both battery and SC are commonly employed. The following are the details:

1) *Passive Parallel*

The simplest setup [21]–[23] is the passive parallel connection presented in Figure 6)i), in which both the battery pack and the SC are connected directly to the motor. Considering the system's ease, the lack of control on the DC side is the system's primary flaw. As SC is connected in parallel with the drive, the SC's control parameter should be adjusted to the motor drive's demand. The proportion of energy that can be extracted from the SCs is limited by such an operational range restriction.

2) *Semi-active*

Semi-active HESS design is comprised of controlled SC and controlled battery.

The controlled SC HESS [21]–[23] presented in Figure 6)ii), addresses the major limitations of the passive parallel HESS. The battery pack is directly connected to the DC bus, hence the power contribution from the SC is controlled by connecting to DC/DC converter. The main disadvantage of this approach is that the connecting DC/DC converter should be adjusted for the system's peak power demand. As more power is transported through the interface converter, this leads to greater costs and lower system efficiency.

The controlled battery HESS [21]–[23] presented in Figure 6)iii) is opposite to controlled SC HESS, where the battery is regulated separately through a DC/DC converter and SC is connected to a DC bus and performs as a low pass filter. The limitation with this configuration is the need for a full-size converter.

3) *Fully Active*

The fully active topology [4][6] shown in Figure 6)iv), uses two DC/DC converters to isolate the battery and SC from the DC bus. The battery and SC voltages can be separately adjusted lower than the DC bus voltage, permitting SC to be fully utilised. The control scheme for this configuration, on the other hand, is quite sophisticated. Additionally, this configuration utilises two full-sized converters, which may lead to a reduction in system performance and also an added expense.

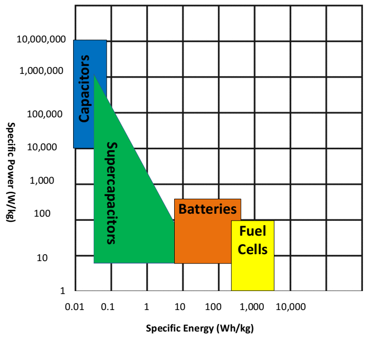


Figure 5. SCs and batteries are compared in terms of specific power vs. specific energy densities [24].

V. Traction Motor Selection

An EV motor works using a physical process that consists of using a current to create a magnetic field at the fixed part of the machine called the stator, whose displacement sets in motion a rotating part called the rotor. Understanding the operation of electrical motors will be discussed in this section, as well as the different types of electric motors.

A. *EV Motors*

According to [25]–[27], most of the electric motors used in EVs are brushless DC motors (BLDC), AC induction motors (IM), permanent magnet synchronous motors (PMSM) and switch reluctance motors (SRM). In BLDC motors, the use of brushes is no longer required, therefore have no wear and tear associated with them and commutation is done electronically.

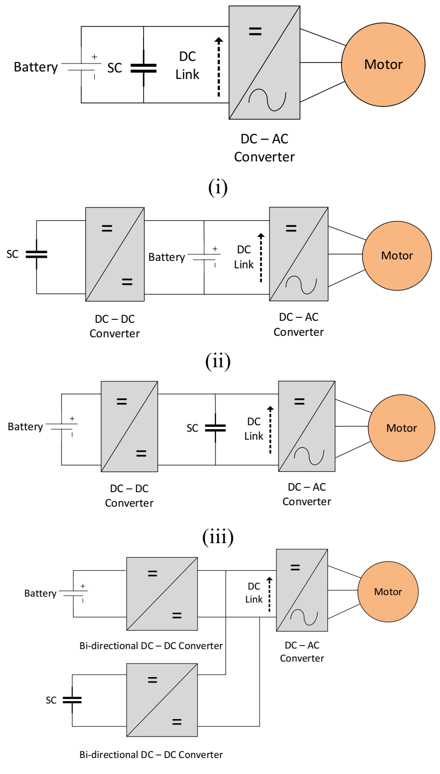
IM, a sinusoidal alternating current is utilised to stimulate the stator, resulting in a rotating magnetic field that induces a current in the rotor, which generates a magnetic field in the rotor. The magnetic fields in the rotor and stator fluctuate at relatively different frequencies, resulting in torque. In PMSM field excitation is provided by permanent magnets on the rotor. A switching inverter is used for this operation. SRM rotor always tries to align along the lowest reluctance path [25]–[27].

AC motors are primarily used as they do not require mechanical commutators, they have a much longer lifetime compared to DC motors, higher power density and higher efficiency. Table 5 illustrates the features of different EV motors.

VI. Conclusions

This paper discusses the control strategies of PM, where each control approach, from high to a low level, has merits and limitations. The ideal vehicle performance is significantly reliant not just on the low-level component control employed, but also on the high-level control algorithm. In addition to this, BMS is playing an essential role to ensure the reliability and safety of the battery and its operation. It is based on estimating SOC, SOH, thermal management and cell balancing of the battery. HESS has been briefly discussed as well as the benefits of SC. The following represents potential research areas that need further investigation:

- Thermal management when the batteries are unbalanced
- Investigating appropriate optimisation techniques for BMS
- Discussing the inverster losses with the support from SC



(i)

(ii)

(iii)

(iv)

Figure 6 HESS configurations: (i) passive parallel, (ii) controlled SC, (iii) controlled battery, (iv) fully active [21]

Table 5. Features of EV motor [26]

Motor		Pros	Cons
DC	BLDC	Low Maintenance High starting torque High Efficiency	High cost of permanent magnets High heat weakens magnets
AC	IM	Self-starting Robust Low cost	Power factor is low during light load
	PMSM	High power density High efficiency	High cost
	SRM	Self-starting Starting torque is high High torque inertia ratio	Complexity in control The noise level is high

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