A REVIEW OF BATTERY ELECTRIC VEHICLE POWERTRAIN SYSTEM REQUIREMENTS AND LIMITATIONS

Bachelor Thesis

Submitted in fulfillment of the requirements for the degree of
Electrical Engineering Bachelor

By

Fatema ALAMMAL

Under the supervision of:

Chair: Prof.dr.ir. Gert RIETVELD
&
Supervisor: Dr. Prasanth VENUGOPAL

UNIVERSITY
OF TWENTE.

Electrical Engineering, Mathematics and
Computer Science Department (EEMCS)
Power Electronics Electromagnetic Compatibility (PE)

July 9, 2021

UNIVERSITY OF TWENTE

Abstract

Bachelor of Engineering

A REVIEW OF BATTERY ELECTRIC VEHICLE POWERTRAIN SYSTEM REQUIREMENTS AND LIMITATIONS

by Fatema ALAMMAL

Rising greenhouse gas emissions led to environmental concerns regarding climate change. The automotive industry produces vast amounts of greenhouse gases every day. The adoption of stricter regulations has motivated a notable development in technological advances of EV systems during the past few decades. Such advances have been reported in the literature for specific powertrain subsystems. This report reviews the characteristics, topologies, trends, and limitations in the advancement of the major subsystems in the electric powertrain. Literature and the EV market are reviewed to identify trends in WBG devices in power converters, rising DC link voltages, Li-ion battery development, and electric machine applications. Overall, technological advancements in EV powertrain are under continual effort to increase the efficiency of powertrain subsystems to compensate for the limited energy density of battery technologies, which stems from a need to increase the drive range of EVs while maintaining or reducing the cost of manufacturing.

Nomenclature

AC	Alternating Current
BEV	Battery Electric Vehicle
CCS	Combined Charging System
CSI	Current Source Inverter
DC	Direct Current
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
$G2V$	Grid to vehicle
GaN	Gallium Nitride
HEV	Hybrid Electric Vehicle
IM	Induction Machine
LCO	Li Cobalt Oxide
LFP	Li Iron Phosphate
$Li-ion$	Lithium-ion
LMO	Li Manganese Oxide Spinel
LTO	Li Titanate Oxide
NCA	Li Cobalt Aluminum Oxide
NCM	Li Nickel Cobalt Manganese Oxide
NCA	Plugin Hybrid Electric Vehicle
$PHEV$	Permanent Magnet Synchronous Motors
$PMSM$	Permanent Magnet Synchronous Motors
PWM	Pulse Width Modulation
Si	Silicon
SiC	Silicon Carbide
THD	Total Harmonic Distortion
$V2G$	Vehicle to Grid
VSI	Voltage Source Inverter
WBG	Wide Band Gap
ZSI	Z-source Inverter

Contents

1 Introduction

Demands for lower greenhouse emissions have led to stricter regulations, causing a higher need for vehicle electrification. Consequently, this has resulted in an increase in the amount of electric vehicle production over the years [1]. Electric vehicles are not a new technology. Their production dates to the 1800s where they gained a substantial share of the market by the 1900s. Electric vehicles then lost their place in the market as combustion vehicles such those reliant on gasoline and diesel were more powerful and cheaper [2]. Decades later General Motors' EV1 appears as the first mass produced electric vehicle to be used practically after the fall of the electric vehicle era. Despite its lack of market penetration, it formed a starting point for a wider range of EVs to appear later.

The comeback of electric vehicles has its advantages. The electric powertrain has higher efficiency when compared to that of an ICE vehicle. EVs have a lower level of pollution, as fully electric vehicles do not consume combustion fuel and therefore do not emit greenhouse gases, besides emissions that go into their production. EVs also benefit from lower noise, smoother operation, and regenerative braking [2]. Such compelling features have contributed to making the electric powertrain an attractive system, although it does fall short on certain performance aspects. Compared to conventional ICE vehicles, electric vehicles have lower drive ranges, long charging times, lack of available charging points, and they suffer from high cost. One of the factors that influence vehicle performance is the electric powertrain efficiency. It is increased by reducing losses, as the vehicle can travel a longer distance without needing to be charged. Powertrain efficiency plays a vital role in enabling longer driving ranges. Therefore, this report aims to review the electric powertrain subsystems from an efficiency and power loss standpoint.

1.1 Types of electrified vehicles

A variety of electrified vehicles exist based on differences in energy sources and vehicle characteristics. Electrified vehicles can be divided into autonomous and plug-in electric vehicles, where autonomous vehicles include HEVs and FCVs [3]. They are referred to as autonomous hence they require no charging by plugging into an electric socket. The other category includes BEVs and PHEVs. These two types run completely or primarily on electric power as a source of energy.

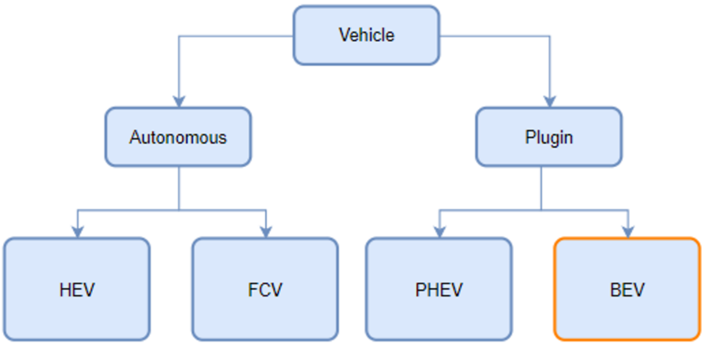

Figure 1: A classification of electrified vehicles

FCVs run on energy generated from hydrogen through the use of fuel cells, and the electricity generated from it is used to drive the vehicle or is stored in the battery component of the vehicle's powertrain [3]. Around a decade ago, FCVs were still under development due to technical, storage, and hydrogen production limitations [3]. Increases in electrification in the automotive industry have also led to the creation of HEV which rely on dual use of both a combustion engine and a traction battery to drive the vehicle. PHEVs are the plugin alternative of HEVs, which still rely on dual use of combustion fuel, but can also be charged from a power supply.

HEVs have been widely used among the electrified type of vehicles. They formed an intermediate step to full electrification, as they benefit from the efficiency of the electric machine [4], and the long range provided by the ICE. As a more fuel-efficient vehicle, HEVs have undergone development, design processes, and mass production over the years. This has resulted in varying powertrain topologies which are preferred for different reasons depending on vehicle requirements and application. HEVs can be classified in accordance with their electrification level. With increasing electrical system voltage levels, they include micro, mild, and full HEVs [5]. Another classification can be done according to configuration type, which are parallel, series, power-split, and multi-mode configuration. In the series configuration, the ICE drives the electric motor only while in parallel HEVs, the ICE drives the electric motor as well as the wheels [4]. Series HEVs are simpler to design whereas parallel HEVs require a complex control system and overall system design [6]. The fourth configuration type, multi-mode HEVs, demonstrated the best fuel efficiency hence it utilises the advantages of the first three types [5]. As for PHEVs, this type of vehicles may be charged externally and has a higher level of electrification compared to other HEVs [6]. PHEVs benefit from longer driving ranges compared to other HEVs as they have a battery pack with a higher energy density.

1.2 BEVs

Less commonly, but continually increasing in the market, are BEVs which are primarily powered by a traction battery with a possibility of combining it with another form of energy source such as a supercapacitor. BEVs run solely on stored electric energy. A major benefit of BEVs is their relatively high level of efficiency compared to hybrid and regular combustion vehicles, with their motor efficiency being 90% and 30% respectively [2]. Main powertrain components in an EV include power converters, battery pack, motor, and the transmission system. A common feature of EVs is their use of regenerative braking, which serves to generate power from frictional losses that occur while braking [2]. BEVs are limited by driving range, however, research in this area is continuing to further the developments. Therefore, the scope of this review covers BEVs as the primary choice of an electrified vehicle.

2 EV Powertrain Overview

The electric powertrain constitutes the primary flow of power in a BEV. Figure 2 displays a power flow model of the electric powertrain. The power flow begins at the power supply, which is typically a wall socket, or a charging station connected to the power grid. The power supply is in the form of one or three phase AC power. This is fed to the charger, of which its main purpose is to convert AC to DC power, and level the voltage such that the battery can be charged. This is done through a power converter. A charger can be on board, or off-board the vehicle. On-board chargers are placed within the vehicle body, whereas off-board chargers would be located at an external place such as the charging station.

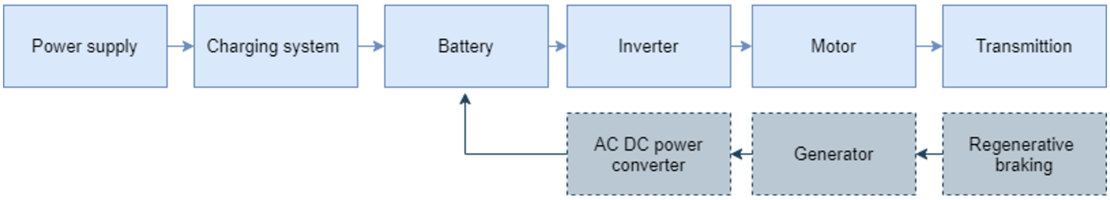

Figure 2: EV system power flow model

The output voltage of the charger will then be levelled to that which can enable battery charging. The traction battery will either store the incoming energy, or dissipate it to enable driving the vehicle. For driving, the power dissipated from the battery is in the form of DC. This must first be converted to AC before being fed into the motor, which is typically an AC motor. This is done by an inverter, which can also be one or multiple stage power converter. The AC power is then taken by the motor to enable vehicle drive by converting electrical power into mechanical power.

Another feature that electric powertrains typically have is bidirectionality of power flow. Frictional forces due to braking result in power which might otherwise be wasted, is converted back into electrical energy to enable charging the battery. This is made possible by the use of a motor that can also act as a generator, and an inverter which act as an AC to DC power converter, rectifying the AC signal to generate DC voltage to be able to store the generated energy in the battery. By making use of these frictional losses the EV develops a more efficient powertrain system.

3 Charging system

Charging systems can be considered in terms of whether it is on-board or off-board, isolation, and directionality of power flow, and whether it facilitates inductive or conductive charging. A charging block is made up of power converters, which could be one or two stages, and interfaces between the power grid and the battery pack. In the case of a single stage charger one AC-DC converter will take care of the power conversion process, while two-stage chargers claim one AC-DC converter followed by a DC-DC converter. Processes that are undergone in this unit take a three phase or one-phase AC input from the grid and performs rectification and smoothing, power factor correction, and often DC-DC voltage levelling to enable charging the battery. This section reviews the primary ways to classify charging systems in an EV powertrain, the requirements of chargers, and power losses and efficiency potential.

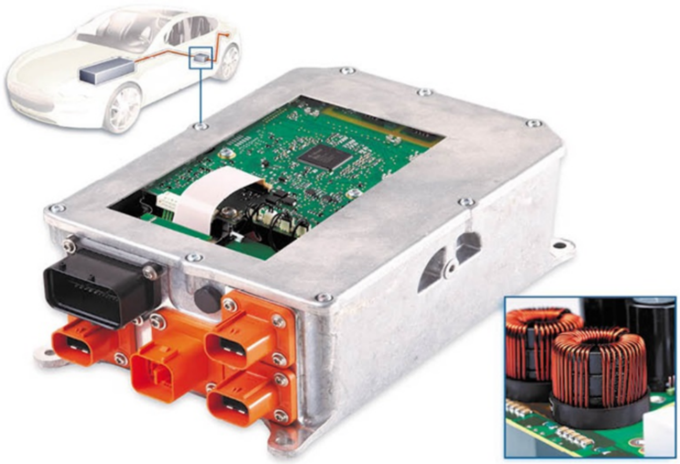

Figure 3: On-board charger system by Kostal Group [7]

3.1 Conductive charging topologies and characteristics

An on-board charger provides more flexibility in terms of portable charging, at the expense of additional weight for the EV [8]. Although on board chargers provide low-power and slow charging, they can be used in a common utility supply such as in a home, office, or a parking lot [9]. Off board chargers are installed in a semi-permanent location and the EV has to travel to the designated location to charge its batteries [8]). Despite off-board chargers being more costly and take more space [10], they can deliver up to dozens or hundreds of kW [8], allowing for faster charging. Off-board chargers facilitate DC charging and can be found in public areas like a gas station [9]. DC charging is referred to as such hence AC power is converted to DC outside the vehicle. In DC charging, the charger is able to deliver higher power since off-board chargers are not limited by space and weight in the same way that on-board chargers are. Therefore, they can be larger and heavier due to more components, to be able to deliver at higher power levels. Most passenger EVs, however, utilise AC charging using lower power on-board chargers.

Furthermore, on-board chargers may differ in the directionality of power flow they offer. Unidirectional chargers allow power to flow in one direction only, namely from the power grid to the vehicle storage system. These types of chargers have the advantage of simpler hardware and lower battery degradation [11]. Alternatively, bidirectional chargers allow power to flow back from the vehicle into other systems such as a residential house when needed. It can also benefit the power grid by providing services such as frequency control, demand response, spinning reserves and energy shifting [12]. Therefore, bidirectionality in chargers enables two modes of operation, V2G mode and the default G2V mode that is used for charging.

Disadvantages of V2G mode is in battery degradation since frequently charging and discharging the battery compromises its durability, despite becoming more widely used in on board chargers [13]. Amongst other battery degradation factors, V2G mode has been identified as a contributor to degradation when uncontrolled battery cycling is used [11]. This leads to an undesirable impact of reducing the battery lifetime. These studies [14] and [15] demonstrated that optimisation of battery cycling leads to decreased battery degradation. In [15], V2G performance was compared to the typical G2V mode that is in unidirectional chargers, and it was found that using a smart-grid algorithm there are circumstances which in fact extend the battery lifetime. Those results were mainly in simulations, however, their experimental results show that the capacity fade experienced by the battery is reduced by 9.1%. Nevertheless, the results of lower and possibly improved battery lifetime are promising given that smart control algorithms are analysed further.

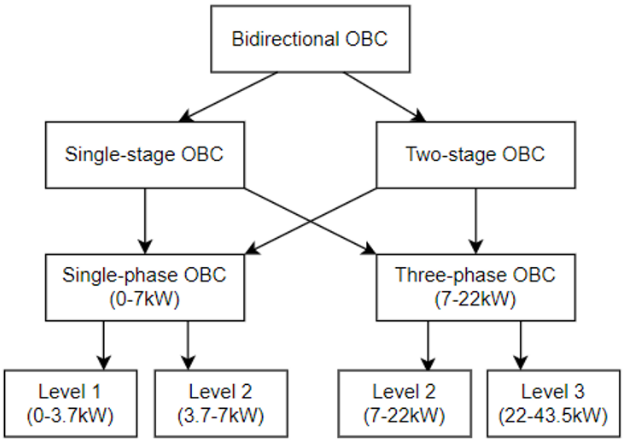

Figure 4: A classification of on-board charger topologies. Adapted from [10]

Considering the wide availability of on-board chargers, a classification of their topologies is shown in figure 3. The lowest level of charging is generally not suitable with bidirectional chargers as it does not deliver at high enough power levels [10]. Level 2 charging accepts a single or two-phase AC supply [9]. Most OBCs by 2020 can achieve up to 6kW to 10kW power level utilised by level 2 charging [10]. In Europe, level 2 charging can be utilised with the SAE J1772 Type 1 EVSE plug [16].

Higher charging levels are available, such as that of level 3. The Renault Zoe is an example of an EV that can reach up to 22kW and up to 50kW DC charging [17]. Higher charging levels use off-board DC fast chargers, which are typically found in public places. Extreme fast charging is a technology that can be used in off-board chargers where the size of the charger is reduced, enabling higher power for the same available space [18], which in return increases the charger's power density.

3.2 Comparing conductive and inductive charging systems

On-board and off-board chargers discussed earlier, belong to conductive charging systems [16]. Conductive charging involves a physical connection to charge the vehicle. Alternatively, inductive charging has been investigated in the literature, despite little adoption of it in the market. The SEA announced its first wireless charging standard for EVs in 2020 (SAE J2954), however, it is still an area undergoing development by research.

Inductive charging is enabled by the principle of Inductive Power Transfer by varying a magnetic field [19]. Its advantages are in providing convenience to the user hence cables and cords are eliminated [20]. It allows for interoperability between different cars while keeping the same charger, as opposed to conductive charging in which charging an EV depends on the type of designated plug [21]. Inductive systems have disadvantages of lower efficiency than conductive charging, lower power density, and large size [20].

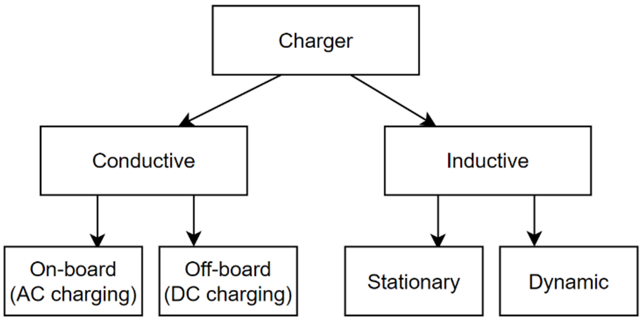

Figure 5: Overview of the types of EV chargers

Inductive chargers are less suitable for use in home charging since they use larger and more expensive components than in conductive charging. Conductive charging can be facilitated by local AC plugs in homes or public charging places as they are smaller and more readily available with the current energy delivery infrastructure. Both, however, can facilitate bidirectional charging. Since the use of inductive charging is expected to only be feasible within charging places, a better application is in enabling interoperability of both inductive and conductive charging techniques by enabling both functionalities in the vehicle [22]. Another clear distinction between conductive and inductive charging is the concept of dynamic charging which is expected to be only feasible in inductive chargers. This is done by building chargers along the road where vehicles can be charged while driving, resulting in reducing the stress on building a fast-charging infrastructure [20]. Although this is a solid attempt at reducing EV range anxiety, lower efficiencies have been reported for dynamic inductive chargers compared to stationary inductive charging [23].

An advantage and desired characteristic of inductive charging systems is inherent isolation [24]. This feature may be implemented in the EV system regardless of whether an inductive or conductive charger is used. Isolation need not be used in all the power converter stages, for instance in a two-stage charging system. Isolation is performed by means of a transformer [10]. The transformer may be placed between the grid and the AC-DC converter or between DC-DC converter and the traction battery [18]. Isolation provides electromagnetic interfacing between two electrical connections. It is desired for satisfying safety requirements as it aids in preventing electric shock to human operators. Additionally, the high voltage DC bus that is connected to multiple expensive systems, namely the charger, inverter, and the battery, can benefit from isolation. Hence, it can provide protection from damage due to high voltage in the case of short circuiting. When used in an inductive charger, it avoids the use of exposed cables thus creating a lower risk of short circuiting due to weather conditions such as water inflow [22].

3.3 Charging requirements and limiting factors

The charging system is a subsystem which, much like other subsystems in the powertrain, must meet certain requirements to comply with overall system demands. Charging system requirements include faster charging times, higher power density, higher efficiency, lower costs, and safety [10]. A charging experience similar to that of refuelling an ICE car is desired [25].

Charging time is an overall EV requirement that is influenced by the power density of a charger. The relationship between charging time and power level is inversely proportional [10]. Bidirectional on-board chargers are limited to a few kW of power [8]. Reasonable power levels include 1.7kW, 6.6kW, 11kW, 22kW, and even 40kW [10]. Previously, however, EV chargers have had power levels around 3.3 kW [20]. Power levels in chargers have been increasing, which can be attributed to an increase in battery capacity in response to higher drive range demands [16]. Besides charger power levels, charging can be limited by the battery capacity, state of charge, temperature, battery chemistry, the charger connector, and the cable used [18][26].

Furthermore, achieving higher levels is also limited by the rated current and voltage levels of the charger. For instance, taking a 50kW charger with a 400V battery voltage level gives 125A of current [18]. Higher currents lead to heavier and bulkier cables that have a limit, which can result in heavier weights than the healthy amount that a person can handle. According to OSHA, this limit is 22.7kg. By increasing the voltage level, the rated power can be increased with respect to the limit that is given by this weight. With 800V battery voltage level and the maximum cable weight given, a maximum power level of 350kW can be achieved [27]. Currently there are no passenger EVs that can use a 350kW charger, however it is expected that future adjustments to this system will enable faster charging [28].

In terms of efficiency, the highest efficiency achieved by 2020 was estimated to be 97% [10]. A peak efficiency of 98% is desired according to the US Drive roadmap by 2025 [29]. A comparison of commercially available on-board chargers is presented in [16], specifying an efficiency range between 90% and 95.8%. The number of power conversion stages in a charging system affects the power density of the charger. Peak efficiencies for different types of DC chargers were reported to range between 91% and 95% for the Tesla Supercharger and the ABB Terra HP charger respectively [18].

In increasing the efficiency of a charging system, WBG devices can aid in achieving such requirements. Bidirectional on-board converters have been facing an increase in the use of WBG devices [10]. Furthermore, in a two-stage charging system in medium to high power applications exude more power losses, lower efficiency, and higher manufacturing costs due to usage of a higher number of semiconductors and reactive components than their one stage counterparts [30]. When an OBC charger is made up of two stages, the AC-DC and DC-DC sandwich a DC link capacitor, which has undesirable features of being large and with a limited lifetime [10]. A single stage eliminates this capacitor, enabling it to have a higher power density, a reduction of components and overall cost [10].

4 Battery

Electric vehicles are greatly limited by vehicle range, which is primarily influenced by the battery performance. EVs have a traction battery, which is the main storage device for the energy that drives the vehicle, however they also have a lower voltage auxiliary battery which is responsible for low power requirements such as rolling the windows up and down. In this chapter we focus on the drive battery, also known as the traction battery, as it is responsible for meeting EV performance requirements.

Figure 6: An EV battery [31]

4.1 Battery Chemistries

Initially, most EVs used lead acid batteries in the early 1900s, which were invented by Sinsteden (1854) and Planté (1859) [32]. After the comeback of EVs, various other battery types were already developed and in rechargeable forms. The various types of battery chemistries have different applications, however in EVs, most EV batteries use Li based cells. Other types of storage devices have also been investigated such supercapacitors, which have the potential to be used in conjunction with the main battery. Li-ion battery types consist of four main components: the cathode, anode, electrolyte, and the separator [33]. The anode is typically graphite, while the cathode has more variations [34]. These variations include LMO, LFP, NMC, NCA, and LCO [35], and some cells use an anode of LTO [34].

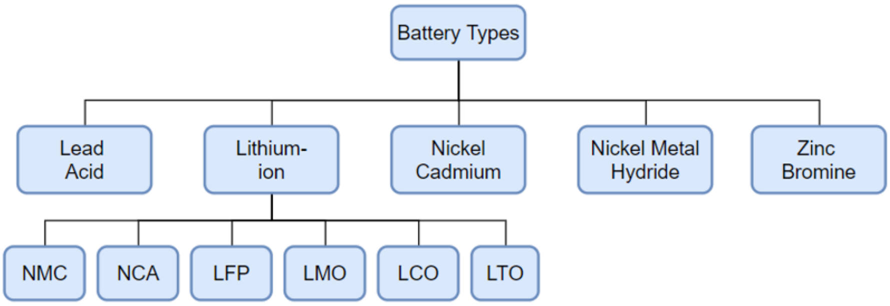

Figure 7: An overview of battery chemistries with traction application potential

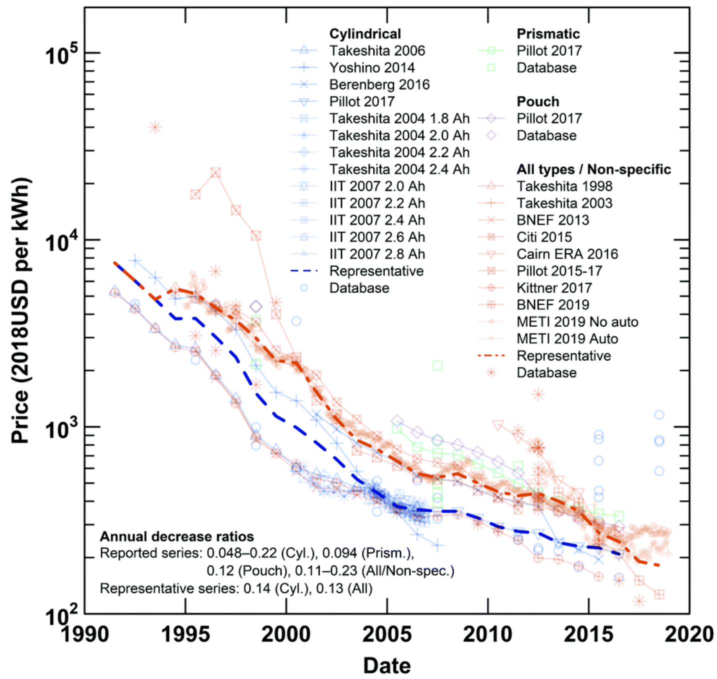

Figure 8: Study on the cost decline of Lithium-ion battery technology. Adapted from [36]

4.2 Battery requirements and current value ranges

Battery requirements consider specific energy, specific power, capacity, cycle life, C-rate, durability, safety, and cost [37],[38]. Specific energy and specific power refer to the amount of energy and power per unit mass, respectively. For EVs, the specific power of a battery must be high enough to meet acceleration demands [37]. This is because power is the rate at which energy can be dissipated or absorbed.

In the case of acceleration, power is being dissipated from the battery to the inverter, therefore a preference for higher acceleration will require higher specific power to propel the vehicle forward fast enough. Higher specific energy, on the other hand, is necessary to meet longer vehicle drive ranges to reduce range anxiety. Therefore, vehicle requirements call for higher specific energy and specific power values, making Li-ion batteries the most suitable for automotive applications. Li-ion batteries have a profile of parameters that benefits from high specific energy and specific power [34]. Additionally, these types of batteries benefit from high efficiency and low self-discharging rates [39].

Several battery technologies have been selected and compared in Table 1. Amongst the other battery types, we find that Li-ion batteries outperform other technologies in terms of specific energy. It also has acceptable specific power characteristics. The separate sub-chemistries of Li-ion have similar characteristics, however NMC and NCA have higher specific energy than other Li-ion battery technologies. In 2016 the Tesla Models S and X, two vehicles with high drive ranges, use Li-ion NCA technology for their battery packs [40]. NMC and NiMH technologies are often used for HEVs [40], [41]. NMC and NCA have similar properties, however NMC is more commonly used in commercial EVs due to easier manufacturing [40]. Furthermore, from a cost perspective, lithium-ion batteries have experienced a major decline in battery costs and increase in production.

Table 1: Battery chemistry characteristics

Battery Technology	**Specific Energy (Wh/kg)**	**Specific Power (W/kg)**	**Cycle Life**	**Operating Temperature (°C)**	**Thermal Runaway (°C)**	**Cost (USD/ kWh)**	**Source**
Li-ion in general	100 - 265	800	1000 - 5000	-20 – 60	190	140	[33, 42, 43, 44]
Li-ion NMC	150 - 200	-	1200 - 2000	-20 – 60	210	366 - 530	[45, 46, 47, 48]
Li-ion NCA	200 - 260	-	-	-20 – 60	150	350	[48, 49]
Li-ion LFP	90 - 120	-	1000 - 10000	-20 – 50	-40 – 80	362 - 519	[34, 50, 51, 46]
Li-ion LTO	50 - 96	-	3000 - 7000	-30 – 55	Very safe	1005	[48, 52, 53]
Lead acid	35 - 40	250	1500 - 5000	-20 – 60	-	150 - 200	[42, 33]
Nickel Cadmium	45 - 80	150	1500	-40 – 60	-	-	[33]
Zinc Bromine	35 - 54	70 - 100	>2000	-20 – 60	Low stability	-	[33]
NiMH	60 - 120	1500	>1000	-20 – 60	-	-	[54, 55, 56]

The results of a cost analysis study, providing estimations of Li-ion battery costs during the span of three decades is provided in figure 8. Their costs have fell from 1000 USD/kWh in 2003 [36], to 140 USD/kWh in 2021 [44]. This accounts for an 86% drop in costs, and is expected to reduce further due to battery cost requirements remaining relevant, as they continue to be compared to ICE vehicles. Further projections on the next decades can be found in [36].

4.3 Trends in battery development

In recent literature, a significant increase in battery voltage levels has been reported. The Porsche Taycan is one of the first EVs to design an 800V battery [16], almost double the voltage level that EV systems are accustomed to. In figure 9, the battery voltage and capacity of recent EV models are represented with respect to the vehicle model year. It is evident that although newer models are manufactured with both 400V and 800V voltage levels, there is a shift in the battery voltage levels as indicated by the trend line. According to [57], the Porsche Taycan was able to drop 30 kgs of conductive material weight after increasing the battery voltage. Other benefits from increasing the DC-link have been noted in literature, such as lighter cables, higher power density, faster charging, more efficient motors [58].

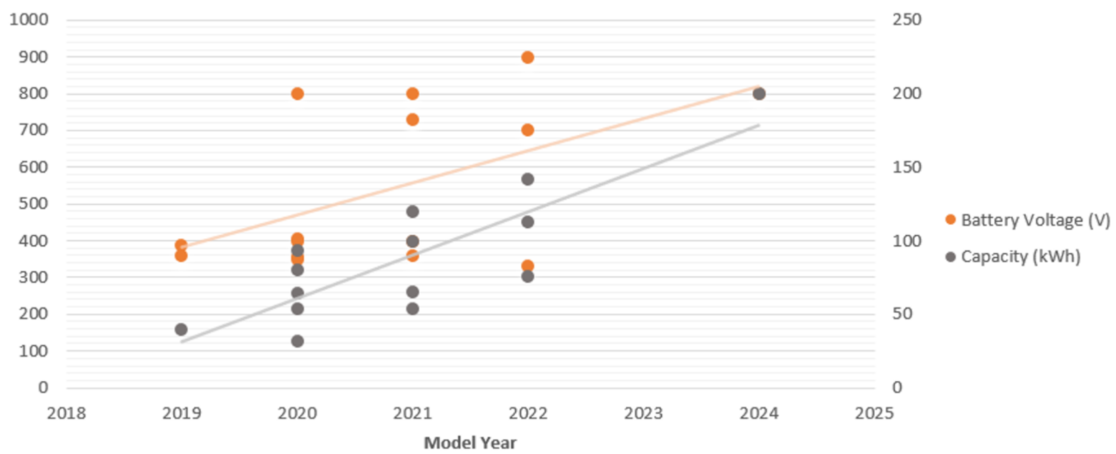

Figure 9: Battery voltage and capacity of new EVs in the market [59]–[67]

Increasing the DC-link voltage high enough allows for lower currents as well as higher power. Copper is one of the main materials that are used for cables, in the battery, and the motor. Lower currents require cables smaller in diameter and consequently in weight. Charging cable weight is important as there is a limit until which it is considered unsafe for the average person to carry. In addition to lower cable weight, a reduction of current levels leads to lower power losses [28].

For fast DC chargers 400 kW is a typical power level [18]. With this power level, cables for both 400V and 800V systems exceed the 22.7kg limit, and only stays within the limit when around 1kV DC link voltage is used [27]. Hence, the CCS Combo 2 set a standard that places this limit on the DC link voltage. Similarly, CHAdeMO charging standard sets 1kV, 400kW ratings [68], although CHAdeMO is collaborating with the China Electricity Council to create a higher power charger, the ChaoJi charger [69]. This charger is intended to have 900kW, 1500V, 600A ratings which greatly surpasses current charging rates. Such ratings require greater emphasis on safety testing and cooling requirements. A change of this extent requires the maturity of the market towards larger voltage battery levels [16].

4.4 Li-ion challenges and alternative approaches

Li-ion batteries have been used for their compelling features, which allow EV manufacturers to reach closer to vehicle requirements resulting from market demands. Despite that, Li-ion batteries have properties which raise challenges that require attention. Compared to other battery chemistries, Li ion batteries have a high specific energy, reaching up to 265Wh/kg, however it is still quite low when placed against gasoline, which has a specific energy of 12000 Wh/kg [70]. In terms of safety, Li ion batteries have a higher risk of fire and explosion and can experience electrolyte spill [22]. Additionally, Li ion batteries experience capacity fade and lower lifetime due to constant charging and discharging [22].

Efforts to increase Li-ion batteries' specific energy have been explored. It is expected that more cathode battery chemistries that are less dependent on cobalt will be produced, which will not only increase its specific energy it would also reduce their cost (iea report). Furthermore, other approaches to develop EVs' energy sources include developing other battery chemistries that can provide higher energy and power densities. A method by which positive electrodes are replaced with an air electrode from fuel cells is expected to reduce the weight and increase the specific power and energy, making metal air batteries [37]. This is known as metal air batteries, such as zinc air and Li air, which are currently under construction for automotive applications [71]. Zinc air batteries are considered the most mature metal air technology, with specific energy range 470-650 Wh/kg. Li-air batteries in particular are considered for EV applications [72]. Currently metal air battery technology is disadvantaged by low efficiency, which is around 50% [72].

5 Inverter

Being the primary consumer of the energy stored in the traction battery, the inverter forms a subsystem which needs to perform with high efficiency to enable longer ranges [73]. Depending on the load required in transmission, the inverter will require higher power consumption. In terms of efficiency, it is of a higher importance unit in the EV powertrain, hence higher losses at this stage will lead to faster consumption of the traction battery stored energy. Reducing inverter power losses, therefore, creates a way to maintain lower charging cycles and increases vehicle range.

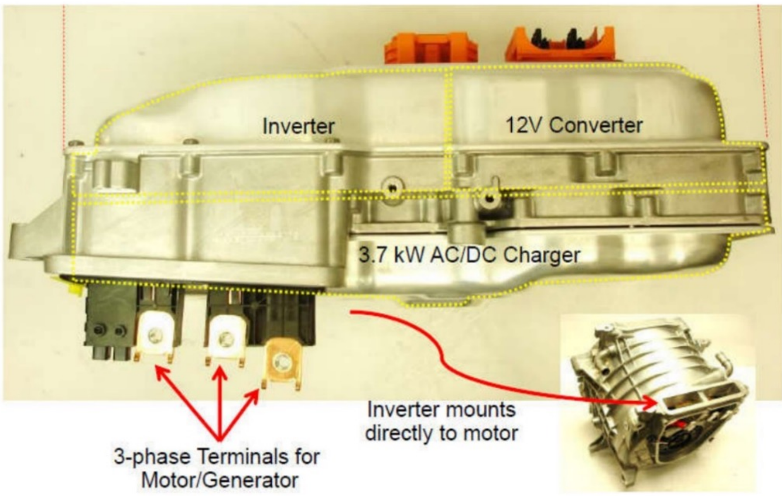

Figure 10: BMW i3 inverter converter unit and its three-phase motor (DOE Roadmap)

5.1 Inverter types and characteristics

Being a mature technology, all passenger EVs in the market are voltage-source two level inverters until a few years ago [74][75]. They have lower DC link voltage compared to their higher level counterparts, as well as simpler implementation and design [58]. Two level inverters can be classified in various ways according to the type of input that is being supplied. The most common type is a VSI taking the input voltage from either the DCDC converter or the traction battery voltage output. VSIs are a reliable, mature, and rhobust technology. Other inverter types also exist, namely CSIs and ZSIs. CSIs have higher efficiency, but also higher cost, whereas ZSIs combine the characteristics of VSIs and CSIs so that either a voltage or current source can be connected at the input. Three level inverters were built as an alternative to VSIs, with the NPC, and T-type inverters being the most successful types [76]. They are seen as a promising alternative to two level inverters due to higher efficiency levels (at higher frequencies) [77]. The T-type inverter possesses the following advantages when compared to NPC inverters: a smaller number of galvanically isolated power supplies, leading to reduced driver costs [77], and being able to operate as a two-level inverter if one of the semiconductor devices fail [78].

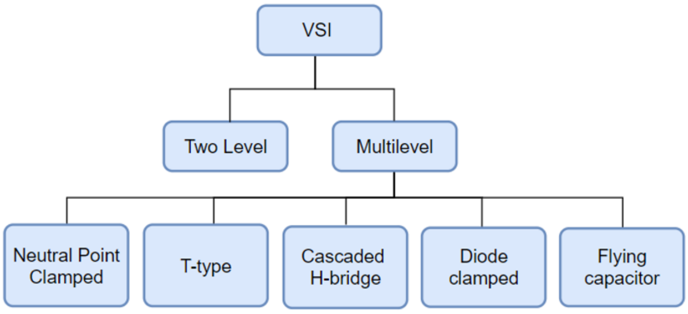

Figure 11: A classification of VSIs in EV applications

Three-level inverters are a sub-category of multilevel inverters. Multilevel inverters benefit from lower THD compared to two level inverters [58]. They are used for medium to high voltage high power applications [76]. Multilevel inverters applications are in electrified trains, ships, and tramways. In [79], a MOSFET based three-level and five-level inverters were compared to a two level IGBT inverter, resulting in higher energy savings particularly in partial loads.

The traction inverter is often, but not necessarily, combined with a DC DC boost power converter, which acts as a controled voltage source to the inverter [74]. The voltage is stepped up to benefit from lower current characteristics. This DC DC converter may be of isolated and non isolated types. Isolated converters have the advantage of higher voltage gain, while non isolated topologies benefit from simpler design but suffer more from switching losses due to hard switching [80]. Hard switching involves the semiconductor switch being turned on and off at arbitrary input voltage levels, while soft switching allows the voltage to reach close to zero to perform the switching.

5.2 Inverter requirements and current values

Inverter requirements include higher efficiency, higher power density, increased compactness, reduced cost, and safety, as well as thermal management such as cooling [80][74][81]. The US Department of Energy (DOE) have placed power density requirements to achieve 1oo kW/L and inverter cost requirements of 2.7$/kW by 2025 [29]. Part of their strategy to achieve this is in enabling significantly higher switching frequencies. Additionally, to have a more compact integration of inverter subcomponents, while requiring packaging that is capable of thermal and electrical isolation. A SiC inverter was made by TM4 with a reported power density of 195 kW/L and a capability of voltage range 450-900 V which accounts for the recent increase in the DC link voltage of some EVs [82]. This traction inverter outperforms other EV inverters in the market [58].

Although cost requirements are desired to be lower, WBG semiconductor devices in the inverter, which are seen as a potential replacement for Si based devices, are significantly more expensive than the latter. For instance, a WBG device such as a SiC MOSFET and a Si IGBT are estimated to be \$5.03 and \$42.06, for 650V/100A and 650V/93A ratings, respectively [81]. In terms of safety, galvanic isolation can be used to achieve higher safety. It helps to avoid electric shock to human operators for instance. Isolation is also used so that expensive components in the electric powertrain do not get damaged.

5.3 Power losses and efficiency

The inverter unit is one which has experienced and continues to be developed as a technology. There are continual advancements towards reducing losses in the inverter, which are mainly caused by switching and conduction losses in the semiconductor devices [83]. Conduction losses occur when the switch is carrying current, while switching losses are experienced when the switches turn-on and off [84]. Furthermore, conduction losses are not dependent on frequency of switching, but switching losses are directly proportional to it [84]. Lock and control losses are also present, however they are more insignificant [83]. Another factor that lowers inverter efficiency is heat dissipation [74]. In [85] and [86], it has been identified that high temperatures are a major cause of failure of power converters, which also reduces their lifetime and reliability.

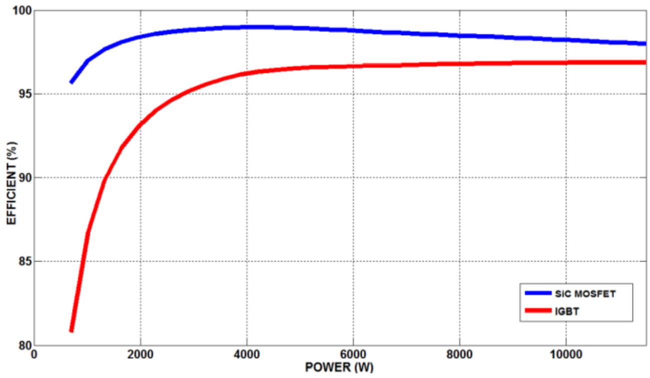

Figure 12: Efficiency levels for varying power loads in traction inverters. Adapted from [87]

Inverters typically use MOSFETS and IGBTs as a choice for semiconductors in the power converter stage(s). IGBTs are typically used due to their lower cost, good conduction performance, and being a mature robust technology [88]. However, they do not have satisfactory performance at lower currents [88]. Alternatives in literature look at materials with lower switching and conduction losses to increase the inverter subsystem further. WBG devices have shown many benefits over conventional Si IGBTs. Of all WBG devices, SiC and GaN are the most promising materials, with SiC showing more attractive features for traction inverters including its high heat operation [74]. SiC based power modules also benefit from occupying less space due to a smaller die area [89]. Tesla Motors was the first Sedan to implement a SiC based inverter using SiC MOSFETs in the Model 3 design [81].

The efficiency of the inverter and the power electronics in it vary according to operating conditions. With higher loads, and consequently power, the efficiency level initially increases reaching its peak and eventually stabilising or dropping. It is evident that other factors besides power play a role in the efficiency level of an inverter. Reported factors affecting the efficiency include the switching frequency, modulation scheme. In [90] efficiency curves differ for varying switching frequencies. In [91] efficiency curves differ for the different modulation schemes that are tested, namely with conventional constant switching frequency PWM and variable switching frequency PWM.

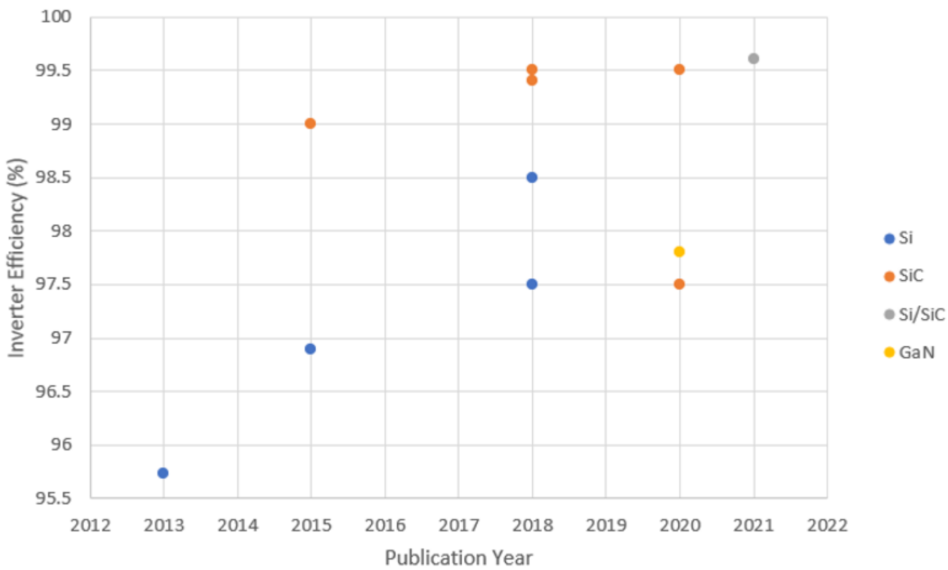

Figure 13: A comparison of efficiencies of inverter designs in literature for various semiconductor devices presented with respect to their year of publication [87],[92] – [90]

In literature, inverter designs and efficiency optimisation continue to be proposed (see figure 8). Power electronic efficiencies range between 85%-95%, however it can be higher than 95% at higher speeds, where the inverter requires more load [83]. Similar efficiency ranges are found in DC-DC converters in the inverter subsystem, where in [80], a peak efficiency of 97% is reached for an isolated multilevel bidirectional inverter. However, the overall efficiency of the inverter unit is typically higher than 90% for inverters that are rated higher than a 1kW of power. These efficiency values are higher in WBG devices [73], which can further be seen in figure 7. In this figure, the efficiency of IGBT based inverter and a SiC MOSFET based inverter as simulated with varying power loads [87]. The efficiency of the SiC based inverter is higher overall due to better switching performance. At lower loads there is a larger discrepancy between the two inverters, with SiC inverter performing at a much higher efficiency.

While WBG devices have properties that are desirable for inverter requirements, they are not as easy to implement in commercial applications. According to [97], the issue with implementing SiC based devices at the moment is that although they are able to operate at high temperature, the surrounding materials used in the inverter unit still needs to undergo development to be able to tolerate the same temperature ranges [97]. Other endeavours to reduce inverter power losses have been investigated in literature. For instance, gate driver design is seen as an area in the inverter unit which influences the efficiency of the inverter. According to [74], designs were reported with a 30% reduction in turn off losses in IGBTs, making active gate driver ICs expected to become widely available in automotive inverters. Similarly [98] proposed a gate driver design with dynamic turn off transient control, resulting in 20% 35% lower turn-off switching losses.

Other proposals in literature attempted to design hybrid inverter technologies to gain benefits of both Si and SiC based semiconductor devices. Si IGBTs have better conduction performance at higher currents while SiC based devices have excellent performance at lower currents as well [88]. Furthermore, since standardised patterns have shown that EV consumers operate their vehicle at low partial loads during most of the driving cycle [99], a hybrid Si/SiC inverter could make use of the SiC switching device during the lower power loads. In this way, a more efficient inverter is created without drastically increasing the overall cost. In [88] a hybrid of the two was made by paralleling SiC MOSFETs and Si IGBTs, however practical issues appeared, displaying false turn on switching and suffered from high current stress.

6 Motor

In this section, the types, characteristics, and efficiencies of the electric motor will be discussed. This is the beginning of the propulsion stage of the vehicle and where electrical power transforms into mechanical power.

Figure 14: Permanent magnet synchronous motor [100]

The five main electric motor types are DC, induction, permanent magnet synchronous, switched reluctance, and brushless DC motors [101]. PMSM types can be interior PMSMs or surface mounted PMSMs. A further classification of the topologies within all four motor types is presented in [102]. Out of these types, the dominant types implemented in EVs are the PMSM and IM, however switched reluctance motors and DC brushless motors are used less frequently [103]. Despite this, most EVs remain dominated by the use of PMSMs. Tesla Motors is one of the OEMs that incorporates an IM in its powertrain system [104], which uses it in conjunction with a PMSM. IMs have the advantage of being low maintenance, robust, low cost, and reliable, while suffer from lower efficiency and lower specific power when compared to PMSMs [101][105]. A few vehicle models use the IM such as the Mercedes Benz EQC, Tesla model S, and model 3, as can be seen in table 2.

EVs are required to have high power and efficiency, robustness, ease in control, low noise and cost, and a small size to maximise the gravimetric power density and minimise weight [106]. For efficiency, this needs to be high for a wide range of vehicle loads [107]. IM efficiencies vary approximately between 78% and 87% which varies according to the motor load [108]. Generally, higher efficiencies are attained at higher loads. As high efficiency and power density are one of PMSMs salient merits, this could explain the higher usage of PMSMs in vehicles in the market [109][106]. Despite its high costs due to rare earth metals, PMSMs dominate the majority of practically used motors [8]. Refer to table 2 for examples of motor types in EVs in the market. In [110], a PMSM design gained a peak efficiency of 97.4%. A comparison between IM and PMSM was performed in [111], further emphasising the higher efficiency of PM motors over the IM.

Table 2: Battery chemistry characteristics

Car Model	Model Year	Number of Motors	Type	Power(kW)	Source
Porsche Taycan Turbo S	2020	2	PMSM	460	[59, 60]
Hyundai kona electric	2020	1	PMSM	150	[61]
Aspark Owl	2021	4	PMSM	880 (combined)	[62]
Faraday Future 91	2021	3	-	261 (per motor)	[63, 64]
Rimac Nevera	2021	4	PM	2 x 250 (rear) 2 x 450 (front)	[65]
Byton M-Byte	2021	2	-	200 (rear) 150 (front)	[66]
Jaguar I-Pace	2019	2	PMSM	1 x 47 (rear) 1 x 47 (front)	[67]
Tesla Model Y	2021	2	PMSM (rear) IM (front)	-	[67]
Mercedes Benz EQC	2020	2	IM (rear) IM (front)	-	[67]
BMW iX	2022	2	PMSM	250 (rear) 200 (front)	[67]
Tesla Model 3 RWD	2021	1	PMSM	211	[67]
Renault Zoe R110	2020	1	PMSM	80	[67]
Mini Cooper	2020	1	PMSM	135	[67]
Nissan Leaf	2019	1	PMSM	110	[67]
Tesla Model S	2021	2	IM (rear) PMSM (front)	375 (rear) 205 (front)	[67]
Volkswagen ID.3 Pro S	2021	1	Brushless DC	110	[67]
KIA e-Niro 4	2020	1	PMSM	150	[67]
Mustang AWD	2021	1	-	198	[67]
Mini Cooper SE Level III	2020	1	PMSM	135	[67]
Volvo XC40 Recharge P8 AWD	2021	2	PMSM	1 x 150 (rear) 1 x 150 (front)	[67]
ŠKODA CITIGOe iV Ambition	2020	1	PMSM	61	[67]

Although PMSMs have higher efficiency levels, they still experience power losses. Losses are found from the stator windings, stator iron losses, iron losses in the stator tooth, and rotor losses [112]. Higher level inverter topologies such as three level inverters were demonstrated to reduce iron losses [113]. Furthermore, as discussed in chapter 4, trends in higher DC link voltage affect the majority of the electric powertrain including the motor. It has been identified that by increasing the DC link voltage the motor's rated voltage is consequently increased, making it able to realise smaller, faster, and more efficient motors [58].

Moreover, control strategies are an essential aspect of motor operation and are used to maximise efficiency of motors. Field-oriented control is the most common control method due to a wide range of speeds, however other control methods exist [114]. For instance, control strategies in [115] and [116] are used to find optimal efficiency levels using loss model algorithms. A control optimisation method based on direct torque control is presented in [117] which increases efficiency levels under light load conditions. Obtaining rare earth materials such that they are viable for use in EV motors is a primary reason for PMSM's high cost. Rare earth materials are available in the earth's core, however separation complexity and the concentration of the desired materials are only applicable in certain geographical locations [118]. Therefore, the primary challenge is in the availability of usable rare earth materials for many countries. Developments in material extraction methods is expected to aid in reducing electric motor costs and reaching desired cost reduction in EVs.

7 Regenerative braking

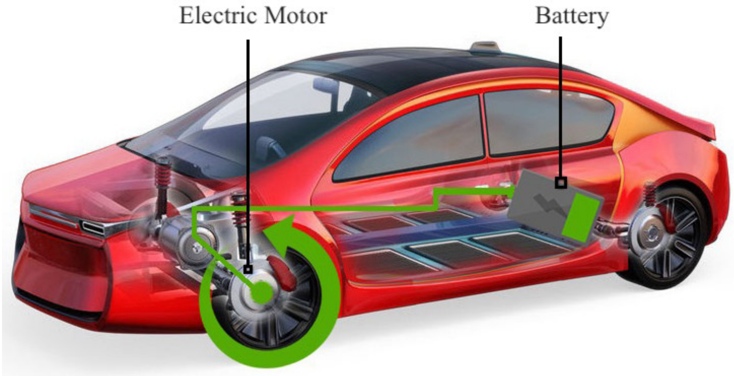

Figure 15: Typical Generative Braking system in EVs

A contributing factor to the efficiency of a BEVs is the use of regenerative braking. The use of regenerative breaking calls for bidirectionality of certain powertrain components. This includes the motor and the inverter. Regenerative braking is active during vehicle breaking time. The resistance caused by braking creates a negative torque, allowing the motor to act as a generator and the output power to flow back to the battery [3],[9]. The inverter, on the other hand acts a rectifier by controlling the switches in it [84]. During regenerative braking, the energy gained by the battery from braking is dependent on the efficiency of the bidirectional powertrain subsystems. Lower efficiencies will compromise the amount of energy that can be transferred to charge the batteries. This stresses further the importance of identifying and improvement of power converters and electric machines to maximise benefit from regenerative braking.

8 Conclusion

Literature publications including review papers related to EVs focus on specific aspects of the technologies in the electric powertrain. In this review, a study of the primary subsystems in EVs that contribute to electrical losses is performed, facilitating a system engineering viewpoint on the functionality of electrified powertrains. Key findings are summarised as follows:

- A notable trend in increasing DC link voltage in EVs in the market, reaching up to 900V, enabling higher charging rates amongst other benefits.
- A trend in increase in the application of WBG devices in power converters to aid in increasing efficiency levels.
- Li-ion battery costs are declining, however still pose limitations in the level of specific energy available.
- A wider use of PMSMs is still limited by cost factors resulting from lack of feasibility in retrieval of rare earth materials used in this type of electric machine.

Future research is directed to the limitations in achieving higher requirements for each subsystem. Namely, for the charging system, DC link voltages exceeding the 1kV limit are expected to need regulation of battery and thermal management. For inverters, WBG devices are a young technology which must be optimised to its fullest potential by using them within systems that are able to tolerate the same temperature levels as SiC and GaN materials. Furthermore, metal air batteries have the potential to vastly improve battery drive ranges however they are currently significantly unstable. Lastly, research in rare earth material extraction is required to further improve current available methods.

Bibliography

[1] A. Schönknecht, A. Babik, and V. Rill, "Electric powertrain system design of bev and hev applying a multi objective optimization methodology," *Transportation Research Procedia*, vol. 14, pp. 3611–3620, 2016.

[2] A. Emadi, *Advanced electric drive vehicles.* CRC Press, 2014.

[3] S. R. Khasim and C. Dhanamjayulu, "Selection parameters and synthesis of multi-input converters for electric vehicles: An overview," *Renewable and Sustainable Energy Reviews*, vol. 141, p. 110804, 2021.

[4] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704–718, 2007.

[5] W. Zhuang, S. Li, X. Zhang, D. Kum, Z. Song, G. Yin, and F. Ju, "A survey of powertrain configuration studies on hybrid electric vehicles," *Applied Energy*, vol. 262, p. 114553, 2020.

[6] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Transactions on industrial electronics*, vol. 55, no. 6, pp. 2237–2245, 2008.

[7] D. Flörecke, "Leading technology from Germany's Sauerland region." Available at: https://www.kostal.com/en-gb/news/aktuelles/2019/obc-spitzentechnologie-aus-dem-sauerland—cloned/.

[8] J. L. Afonso, L. A. Cardoso, D. Pedrosa, T. J. Sousa, L. Machado, M. Tanta, and V. Monteiro, "A review on power electronics technologies for electric mobility," *Energies*, vol. 13, no. 23, p. 6343, 2020.

[9] C. A. Sam and V. Jegathesan, "Bidirectional integrated on-board chargers for electric vehicles—a review," *Sādhanā*, vol. 46, no. 1, pp. 1–14, 2021.

[10] J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers, and A. Emadi, "A review of bidirectional on-board chargers for electric vehicles," *IEEE Access*, 2021.

[11] K. Uddin, T. Jackson, W. D. Widanage, G. Chouchelamane, P. A. Jennings, and J. Marco, "On the possibility of extending the lifetime of lithium-ion batteries through optimal v2g facilitated by an integrated vehicle and smart-grid system," *Energy*, vol. 133, pp. 710–722, 2017.

[12] M. Dubarry, A. Devie, and K. McKenzie, "Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis," *Journal of Power Sources*, vol. 358, pp. 39–49, 2017.

[13] J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers, and A. Emadi, "A review of bidirectional on-board chargers for electric vehicles," *IEEE Access*, vol. 9, pp. 51501–51518, 2021.

[14] A. Marongiu, M. Roscher, and D. U. Sauer, "Influence of the vehicle-to-grid strategy on the aging behavior of lithium battery electric vehicles," *Applied Energy*, vol. 137, pp. 899–912, 2015.

[15] K. Uddin, M. Dubarry, and M. B. Glick, "The viability of vehicle-to-grid operations from a battery technology and policy perspective," *Energy Policy*, vol. 113, pp. 342–347, 2018.

[16] A. Khaligh and M. D'Antonio, "Global trends in high-power on-board chargers for electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3306–3324, 2019.

[17] "De renault zoe."

[18] H. Tu, H. Feng, S. Srdic, and S. Lukic, "Extreme fast charging of electric vehicles: A technology overview," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 861–878, 2019.

[19] A. Khaligh and S. Dusmez, "Comprehensive topological analysis of conductive and inductive charging solutions for plug-in electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3475–3489, 2012.

[20] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE transactions on Power Electronics*, vol. 28, no. 5, pp. 2151–2169, 2012.

[21] A. A. Mohamed, E. Wood, and A. Meintz, "In-route inductive versus stationary conductive charging for shared automated electric vehicles: A university shuttle service," *Applied Energy*, vol. 282, p. 116132, 2021.

[22] C. Mi, “Safely charging ev and phev from the electricity grid.” Available at: https://energychallenge.weebly.com/uploads/6/4/2/8/6428791/chris$_{m}i_{-s}afely_{c}haring_{e}v_{b}atteries.pdf$.

[23] M. Budhia, G. A. Covic, and J. T. Boys, “Design and optimisation of magnetic structures for lumped inductive power transfer systems,” in *2009 IEEE Energy Conversion Congress and Exposition*, pp. 2081–2088, IEEE, 2009.

[24] G. Covic, J. Boys, and H. Lu, “A three-phase inductively coupled power transfer system,” in *2006 1ST IEEE Conference on Industrial Electronics and Applications*, pp. 1–6, IEEE, 2006.

[25] H. Tu, H. Feng, S. Srdic, and S. Lukic, “Extreme fast charging of electric vehicles: A technology overview,” *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 861–878, 2019.

[26] Fastned, Feb 2020.

[27] A. Burnham, E. J. Dufek, T. Stephens, J. Francfort, C. Michelbacher, R. B. Carlson, J. Zhang, R. Vijayagopal, F. Dias, M. Mohanpurkar, *et al.*, “Enabling fast charging–infrastructure and economic considerations,” *Journal of Power Sources*, vol. 367, pp. 237–249, 2017.

[28] C. Suarez and W. Martinez, “Fast and ultra-fast charging for battery electric vehicles–a review,” in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 569–575, IEEE, 2019.

[29] Oct 2017.

[30] L. Huber, L. Gang, and M. M. Jovanovic, “Design-oriented analysis and performance evaluation of buck pfc front end,” *IEEE Transactions on power electronics*, vol. 25, no. 1, pp. 85–94, 2009.

[31] “The price of an electric car battery.”

[32] R. Schmuch, R. Wagner, G. Hörpel, T. Placke, and M. Winter, “Performance and cost of materials for lithium-based rechargeable automotive batteries,” *Nature Energy*, vol. 3, no. 4, pp. 267–278, 2018.

[33] M. A. Hannan, M. M. Hoque, A. Hussain, Y. Yusof, and P. J. Ker, “State-of-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations,” *Ieee Access*, vol. 6, pp. 19362–19378, 2018.

[34] I. Carrilero, J. Alonso, P. G. Pereirinha, D. Ansean, J. C. Viera, and M. Gonzalez, “Lithium iron phosphate and lithium titanate oxide cell performance under high power requirements of electric bus applications,” in *2018 IEEE Vehicle Power and Propulsion Conference (VPPC)*, pp. 1–6, 2018.

[35] X. Zeng, M. Li, D. Abd El-Hady, W. Alshitari, A. S. Al-Bogami, J. Lu, and K. Amine, “Commercialization of lithium battery technologies for electric vehicles,” *Advanced Energy Materials*, vol. 9, no. 27, p. 1900161, 2019.

[36] M. S. Ziegler and J. E. Trancik, “Re-examining rates of lithium-ion battery technology improvement and cost decline,” *Energy & Environmental Science*, vol. 14, no. 4, pp. 1635–1651, 2021.

[37] K. Young, C. Wang, K. Strunz, *et al.*, “Electric vehicle battery technologies,” in *Electric vehicle integration into modern power networks*, pp. 15–56, Springer, 2013.

[38] “2.2.1 lecture: Ev battery parameters.”

[39] A. Khaligh and Z. Li, “Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art,” *IEEE transactions on Vehicular Technology*, vol. 59, no. 6, pp. 2806–2814, 2010.

[40] G. E. Blomgren, “The development and future of lithium ion batteries,” *Journal of The Electrochemical Society*, vol. 164, no. 1, p. A5019, 2016.

[41] B. Scrosati, J. Garche, and W. Tillmetz, *Advances in battery technologies for electric vehicles*. Woodhead Publishing, 2015.

[42] G. J. May, A. Davidson, and B. Monahov, “Lead batteries for utility energy storage: A review,” *Journal of Energy Storage*, vol. 15, pp. 145–157, 2018.

[43] P. Liu, C. Liu, K. Yang, M. Zhang, F. Gao, B. Mao, H. Li, Q. Duan, and Q. Wang, “Thermal runaway and fire behaviors of lithium iron phosphate battery induced by over heating,” *Journal of Energy Storage*, vol. 31, p. 101714, 2020.

[44] T. E. Newspaper, “Lithium battery costs have fallen by 98% in three decades.” Available at: https://www.economist.com/graphic-detail/2021/03/31/lithium-battery-costs-have-fallen-by-98-in-three-decades, Mar 2021.

[45] P. Patel, "Improving the lithium-ion battery," *ACS Central Science*, vol. 1, no. 4, pp. 161–162, 2015. PMID: 27162967.

[46] "Lithium-ion battery (lfp and nmc)." Available at:https://www.pnnl.gov/lithium-ion-battery-lfp-and-nmc.

[47] "Lithium-ion(nmc) battery pack specification." Available at: https://www.hybridpower.com.au/files /specs/NMC$_7 - 5kwh.pdf, Apr$2019.

[48] B. University, "Bu-205: Types of lithium-ion." Available at: https://batteryuniversity.com/article/bu-205-types-of-lithium-ion, Mar 2020.

[49] "Specifications for NCR18650GA." Available at: https://cdn.shopify.com/s/files/1/0674/3651/files/panasonic-ncr18650-ga-spec-sheet.pdf?6594479572025043155.

[50] A. Beck, "Lithium iron phosphate vs. lithium-ion: Differences and advantages."

[51] V. Energy, "Datasheet 12,8V Lithitum iron phosphate batteries." Available at: https://web.archive.org/web/20160921122814/https://www.victronenergy.nl/upload/documents/Datasheet-12,8-Volt-lithium-iron-phosphate-batteries-EN.pdf.

[52] K. Melvin, "Toshiba Rechargeable Battery." Available at: https://www.global.toshiba/content/dam/toshiba/ ww/products-solutions/battery/scib/pdf/ToshibaRechargeableBattery-en.pdf, 2020.

[53] P. P. Corp, "Category : Lto batteries." Available at: https://www.batteryspace.com/Lithium-Titanate-Battery.aspx.

[54] L. Keith Araujo Epec, "Battery cell comparison."

[55] M. Fetcenko, J. Koch, and M. Zelinsky, "6 - nickel–metal hydride and nickel–zinc batteries for hybrid electric vehicles and battery electric vehicles," in *Advances in Battery Technologies for Electric Vehicles* (B. Scrosati, J. Garche, and W. Tillmetz, eds.), Woodhead Publishing Series in Energy, pp. 103–126, Woodhead Publishing, 2015.

[56] B. Hariprakash, A. Shukla, and S. Venugoplan, "Secondary batteries – nickel systems | nickel–metal hydride: Overview," in *Encyclopedia of Electrochemical Power Sources* (J. Garche, ed.), pp. 494–501, Amsterdam: Elsevier, 2009.

[57] D. VanderWerp, "Porsche taycan's 800-volt architecture enables slimmer wiring, faster charging, less heat," Nov 2020.

[58] A. Poorfakhraei, M. Narimani, and A. Emadi, "A review of multilevel inverter topologies in electric vehicles: Current status and future trends," *IEEE Open Journal of Power Electronics*, vol. 2, pp. 155–170, 2021.

[59] Porsche, 2019.

[60] "The technology behind the new Porsche Taycan." Available at:https://newsroom.porsche.com/dam/jcr:93483663-c12b-43ca-98f5-b1b8b845e321/PAG$_{T}aycan_{T}echnology_{P}M_{E}N.pdf.PDF$.

[61] Hyundai, 2020.

[62] ASPARK. Available at:https://www.aspark.co.jp/ev/PressInfoOwl.pdf, 2018.

[63] "Faraday Future." Available at:https://genesis-cdn.ff.com/Investors/FF-PIPE-Presentation.pdf, Feb 2021.

[64] The Faraday Future Inverter, "Experience a new species." Available at: https://www.ff.com/us/futuresight/The-Faraday-Future-Inverter/.

[65] Nevera, "Rimac automobili." Available at:https://www.rimac-automobili.com/nevera/, Jun 2021.

[66] T. Morgan, "2019 byton m-byte electric suv digital dashboard revealed."

[67] "Electric vehicle specifications, electric car news, ev comparisons."

[68] C. Association, "Chademo releases the latest version of the protocol enabling up to 400kw." Available at: https://www.chademo.com/chademo-releases-the-latest-version-of-the-protocol-enabling-up-to-400kw/: :text=Primary Menu-,CHAdeMO releases the latest version of the protocol enabling up,such as trucks and buses., Jun 2018.

[69] "Chaoji: next-gen ultra-high-power protocol progress update," Jun 2020.

[70] S. Li and C. C. Mi, "Wireless power transfer for electric vehicle applications," *IEEE journal of emerging and selected topics in power electronics*, vol. 3, no. 1, pp. 4–17, 2014.

[71] Z. Zhang, T. Ding, Q. Zhou, Y. Sun, M. Qu, Z. Zeng, Y. Ju, L. Li, K. Wang, and F. Chi, "A review of technologies and applications on versatile energy storage systems," *Renewable and Sustainable Energy Reviews*, vol. 148, p. 111263, 2021.

[72] M. Aneke and M. Wang, "Energy storage technologies and real life applications – a state of the art review," *Applied Energy*, vol. 179, pp. 350–377, 2016.

[73] S. Chowdhury, E. Gurpinar, G.-J. Su, T. Raminosoa, T. A. Burress, and B. Ozpineci, "Enabling technologies for compact integrated electric drives for automotive traction applications," in *2019 IEEE Transportation Electrification Conference and Expo (ITEC)*, pp. 1–8, IEEE, 2019.

[74] J. Reimers, L. Dorn-Gomba, C. Mak, and A. Emadi, "Automotive traction inverters: Current status and future trends," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3337–3350, 2019.

[75] S. Brueske, S. Walz, M. Liserre, and F. W. Fuchs, "Loss balancing of three-level inverters in electric vehicles for low speed operation," in *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*, pp. 1–10, IEEE, 2016.

[76] J. I. Leon, S. Vazquez, and L. G. Franquelo, "Multilevel converters: Control and modulation techniques for their operation and industrial applications," *Proceedings of the IEEE*, vol. 105, no. 11, pp. 2066–2081, 2017.

[77] M. Schweizer, *System-oriented efficiency optimization of variable speed drives*. PhD thesis, ETH Zurich, 2012.

[78] S. Brueske, B. Benkendorff, R. Kulpe, and F. W. Fuchs, "Comparison of the power semiconductor design rating of different inverter topologies for the drive inverter of electric vehicles," in *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 3643–3650, IEEE, 2015.

[79] A. Kersten, E. Grunditz, and T. Thiringer, "Efficiency of active three-level and five-level npc inverters compared to a two-level inverter in a vehicle," in *2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe)*, pp. P–1, IEEE, 2018.

[80] V. Rathore, K. Rajashekara, and P. Nayak, "An isolated multilevel bi-directional dc-dc converter to interface hv battery and traction inverter in evs," in *2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 1727–1733, IEEE, 2020.

[81] M.-C. Lu, "Comparative study on power module architectures for modularity and scalability," *Journal of Electronic Packaging*, vol. 142, no. 4, p. 040801, 2020.

[82] "Dana features silicon-carbide technology inverters at cti berlin," Dec 2019.

[83] P. Wacker, L. Wheldon, M. Sperlich, J. Adermann, and M. Lienkamp, "Influence of active battery switching on the drivetrain efficiency of electric vehicles," in *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, pp. 33–38, IEEE, 2017.

[84] A. Bhalla, "Are you sic of silicon?." Available at: https://www.powersystemsdesign.com/articles/are-you-sic-of-silicon-part-1/22/14274.

[85] V. Smet, F. Forest, J.-J. Huselstein, F. Richardeau, Z. Khatir, S. Lefebvre, and M. Berkani, "Ageing and failure modes of igbt modules in high-temperature power cycling," *IEEE transactions on industrial electronics*, vol. 58, no. 10, pp. 4931–4941, 2011.

[86] Y. Yamada, Y. Takaku, Y. Yagi, I. Nakagawa, T. Atsumi, M. Shirai, I. Ohnuma, and K. Ishida, "Reliability of wire-bonding and solder joint for high temperature operation of power semiconductor device," *Microelectronics Reliability*, vol. 47, no. 12, pp. 2147–2151, 2007.

[87] S. Ozdemir, F. Acar, and U. S. Selamogullari, "Comparison of silicon carbide mosfet and igbt based electric vehicle traction inverters," in *2015 International Conference on Electrical Engineering and Informatics (ICEEI)*, pp. 1–4, IEEE, 2015.

[88] C. Tan, M. Stecca, T. B. Soeiro, J. Dong, and P. Bauer, "Performance evaluation of an electric vehicle traction drive using si/sic hybrid switches," in *2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC)*, pp. 278–283, IEEE, 2021.

[89] G. Mauromicale, A. Raciti, S. A. Rizzo, G. Susinni, L. Abbatelli, S. Buonomo, D. Cavallaro, and V. Giuffrida, "Sic power modules for traction inverters in automotive applications," in *IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society*, vol. 1, pp. 1973–1978, IEEE, 2019.

[90] K. Ohta, Y. Kanazawal, H. Akatuka, S. Hori, S. Doki, H. Tadano, and K. Shiozaki, "Variable switching frequency control for efficiency improvement of motor drive system by using gan three phase inverter," in *2020 IEEE International Conference on Industrial Technology (ICIT)*, pp. 119–123, IEEE, 2020.

[91] Z. Xu, F. Xu, D. Jiang, W. Cao, and F. Wang, "A high temperature traction inverter with reduced cooling and improved efficiency for hev applications," in *2013 IEEE Energy Conversion Congress and Exposition*, pp. 2786–2792, IEEE, 2013.

[92] J. Zhu, H. Kim, H. Chen, R. Erickson, and D. Maksimović, "High efficiency sic traction inverter for electric vehicle applications," in *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 1428–1433, 2018.

[93] A. Allca-Pekarovic, P. J. Kollmeyer, P. Mahvelatishamsabadi, T. Mirfakhrai, P. Naghshtabrizi, and A. Emadi, "Comparison of igbt and sic inverter loss for 400v and 800v dc bus electric vehicle drivetrains," in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 6338–6344, 2020.

[94] T. Miyazaki, H. Otake, Y. Nakakohara, M. Tsuruya, and K. Nakahara, "A fanless operating trans-linked interleaved 5 kw inverter using sic mosfets to achieve 99Electronics, vol. 65, no. 12, pp. 9429–9437, 2018.

[95] K. Kumar and S. B. Santra, "Performance analysis of a three-phase propulsion inverter for electric vehicles using gan semiconductor devices," *IEEE Transactions on Industry Applications*, vol. 54, no. 6, pp. 6247–6257, 2018.

[96] Y. P. Siwakoti, A. Palanisamy, A. Mahajan, S. Liese, T. Long, and F. Blaabjerg, "Analysis and design of a novel six-switch five-level active boost neutral point clamped inverter," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 12, pp. 10485–10496, 2020.

[97] U. Drive, "Electrical and electronics technical team roadmap," *Partnership Plan, Roadmaps, and Other Documents*, 2013.

[98] Y. Zhou, L. Chen, S. Yang, F. Xu, and A. Khorshed, "A low cost gate driver with dynamic turn-off transient control for hev/ev traction inverter application," in *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 3200–3204, IEEE, 2017.

[99] A. Semon and A. Crăciunescu, "Study to increase the efficiency of the electric drive system of a vehicle at different speeds," in *2019 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, pp. 1–7, IEEE, 2019.

[100] "Permanent magnet synchronous motor 40kw-product solution-idear-hanyu group: Hanyu electric vehicle core component department."

[101] N. Hashemnia and B. Asaei, "Comparative study of using different electric motors in the electric vehicles," in *2008 18th International Conference on Electrical Machines*, pp. 1–5, IEEE, 2008.

[102] C. Liu, K. Chau, C. H. Lee, and Z. Song, "A critical review of advanced electric machines and control strategies for electric vehicles," *Proceedings of the IEEE*, 2020.

[103] J. De Santiago, H. Bernhoff, B. Ekergård, S. Eriksson, S. Ferhatovic, R. Waters, and M. Leijon, "Electrical motor drivelines in commercial all-electric vehicles: A review," *IEEE Transactions on vehicular technology*, vol. 61, no. 2, pp. 475–484, 2011.

[104] G. Sieklucki, "An investigation into the induction motor of tesla model s vehicle," in *2018 International Symposium on Electrical Machines (SME)*, pp. 1–6, IEEE, 2018.

[105] Z. Yang, F. Shang, I. P. Brown, and M. Krishnamurthy, "Comparative study of interior permanent magnet, induction, and switched reluctance motor drives for ev and hev applications," *IEEE Transactions on Transportation Electrification*, vol. 1, no. 3, pp. 245–254, 2015.

[106] X. Sun, Z. Li, X. Wang, and C. Li, "Technology development of electric vehicles: A review," *Energies*, vol. 13, no. 1, 2020.

[107] A. Chernyshev, T. Lisovskaya, and R. Lisovskiy, "Comparative analysis of different electrical motor types as a traction drive part in electrical transmission," in *2017 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, pp. 1–5, IEEE, 2017.

[108] P. Lumyong and P. Sarikprueck, "A study on induction motor efficiency improvement for implementing in electric vehicle," in *2018 21st International Conference on Electrical Machines and Systems (ICEMS)*, pp. 616–619, IEEE, 2018.

[109] M. Y. Metwly, M. S. Abdel-Majeed, A. S. Abdel-Khalik, R. A. Hamdy, M. S. Hamad, and S. Ahmed, "A review of integrated on-board ev battery chargers: Advanced topologies, recent developments and optimal selection of fscw slot/pole combination," *IEEE Access*, vol. 8, pp. 85216–85242, 2020.

[110] B. Zhang, R. Qu, W. Xu, and J. Li, "A permanent magnet traction machine with wide high efficiency range for ev application," in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, pp. 000457–000463, 2015.

[111] S. Sharifan, S. Ebrahimi, A. Oraee, and H. Oraee, "Performance comparison between brushless pm and induction motors for hybrid electric vehicle applications," in *2015 Intl Aegean Conference on Electrical Machines Power Electronics (ACEMP), 2015 Intl Conference on Optimization of Electrical Electronic Equipment (OPTIM) 2015 Intl Symposium on Advanced Electromechanical Motion Systems (ELECTROMOTION)*, pp. 719–724, 2015.

[112] M. Franko, J. Kuchta, and J. Buday, "Development and performance investigation of permanent magnet synchronous traction motor," in *International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion*, pp. 70–74, IEEE, 2012.

[113] P. Rasilo, A. Salem, A. Abdallh, F. De Belie, L. Dupré, and J. A. Melkebeek, "Effect of multilevel inverter supply on core losses in magnetic materials and electrical machines," *IEEE transactions on Energy Conversion*, vol. 30, no. 2, pp. 736–744, 2014.

[114] X. Sun, Z. Li, X. Wang, and C. Li, "Technology development of electric vehicles: A review," *Energies*, vol. 13, no. 1, p. 90, 2020.

[115] M. Caruso, A. Di Tommaso, R. Miceli, C. Nevoloso, C. Spataro, and F. Viola, "Enhanced loss model algorithm for interior permanent magnet synchronous machines," in *2017 AEIT International Annual Conference*, pp. 1–6, IEEE, 2017.

[116] H. Pairo and A. Shoulaie, "Effective and simplified method in maximum efficiency control of interior permanent magnet synchronous motors," *IET Electric Power Applications*, vol. 11, no. 3, pp. 447–459, 2017.

[117] E. S. Sergaki, "Electric motor efficiency optimization as applied to electric vehicles," in *International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion*, pp. 369–373, IEEE, 2012.

[118] J. Wübbeke, "Rare earth elements in china: Policies and narratives of reinventing an industry," *Resources Policy*, vol. 38, no. 3, pp. 384–394, 2013.