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Advancements and Future Challenges in Core Components of Electric and Hybrid Vehicles: Energy Storage, Power Conversion, Traction Motors, and Charging Systems

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ABSTRACT

Electric and hybrid vehicles (EVs/HEVs) are increasingly recognized as promising solutions to address rising oil costs, environmental concerns, and the global pursuit of sustainable mobility. Alongside, there is still a need for a clear and comprehensive review of the technological advancements and ongoing challenges across the core components that influence their performance, efficiency and sustainability. This review aims to fill this gap by synthesizing recent developments and future challenges in EVs/HEVs systems, with a focus on energy storage technologies, power conversion, traction motors, and charging systems.

The paper adopts a structured and comparative approach, beginning with the classification of electrification levels, covering hybrid, plug-in hybrid, battery, fuel cell, and extended-range EVs. Following this, the paper discusses energy storage systems, including batteries, supercapacitors, fuel cells, and hybrid configurations, highlighting their roles in improving energy density, efficiency, and reliability. Key power electronic converters are analyzed in depth, including DC/DC and DC/AC converters. The review also examines advances in electric traction motors, including induction, switched reluctance, permanent magnet synchronous, and permanent magnet assisted synchronous reluctance motors, each with distinct performance attributes. Finally, advancements in EVs charging systems are discussed, with a focus on both conductive and inductive charging methods. This work highlights recent technological progress, identifies ongoing challenges, and provides insights to support future developments in EVs/HEVs systems.

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التطورات والتحديات المستقبلية في المكونات الأساسية للمركبات الكهربائية والهجينة: تخزين الطاقة، تحويل الطاقة، محركات الجر، وأنظمة الشحن

حمزة الحسوني، عبد العزيز فري.

ملخص: تُعتبر السيارات الكهربائية والهجينة (EVs/HEVs) حلولًا واعدة لمواجهة تحديات ارتفاع أسعار النفط، المخاوف البيئية، والسعي العالمي نحو تنقل مستدام. ومع ذلك، تظل هناك حاجة إلى مراجعة شاملة تُلخّص أحدث التطورات التكنولوجية والتحديات المرتبطة بالمكونات الأساسية التي تحدد أداء هذه المركبات وكفاءتها واستدامتها. تهدف هذه المراجعة إلى سد هذه الفجوة من خلال تحليل مُنظّم للتطورات الحديثة والتحديات المستقبلية في أنظمة السيارات الكهربائية والهجينة، مع تركيز خاص على تقنيات تخزين الطاقة، أنظمة تحويل الطاقة، محركات الجر، وأنظمة الشحن. تعتمد الدراسة منهجية المقارنة تبدأ بتصنيف مستويات التكهرب، بما في ذلك السيارات الهجينة (HEVs)، الهجينة القابلة للشحن (PHEVs)، الكهربائية بالكامل (BEVs)، الكهربائية التي تعمل بخلايا الوقود (FCEVs)، والكهربائية ذات المدى الممتد (EREVs). ثم تناقش أنظمة تخزين الطاقة، بما في ذلك البطاريات، المكثفات الفائقة، خلايا الوقود، والتكوينات الهجينة، مع تسليط الضوء على دورها في تحسين كثافة الطاقة، الكفاءة، والموثوقية. كما تُحلّل بدقة محولات الطاقة الإلكترونية، بما في ذلك محولات DC/DC و DC/AC . إضافة إلى ذلك، تستعرض الدراسة التطورات في تقنيات محركات الجر الكهربائية، مثل المحركات الحثية، المحركات ذات الممانعة المتغيرة، المحركات المتزامنة ذات المغناطيس الدائم، والمحركات المتزامنة ذات المغناطيس الدائم المساعد، مع بيان خصائص أداء كل منها. أخيرًا، تناقش التطورات في أنظمة شحن السيارات الكهربائية، سواءً الشحن التلامسي أو الشحن اللاسلكي. تساهم هذه الدراسة في إبراز أحدث التقدمات التكنولوجية، وتحديد التحديات القائمة، وتقديم رؤىً قيّمة لدعم التطوير المستقبلي لأنظمة السيارات الكهربائية والهجينة.

الكلمات المفتاحية – بالمركبات الكهربائية/الهجينة، أنظمة تخزين الطاقة، محركات الجر، محوّلات الطاقة الإلكترونية، أنظمة الشحن.

1. INTRODUCTION

The increase in greenhouse gas (GHG) emissions has become a significant global issue, drawing concern from both environmental advocates and policymakers alike. This trend, marked by a steady overall increase, is fueling urgent discussions on sustainable solutions and long-term strategies to address its widespread impact on the environment[1].

The transportation field is one of the leading contributors to global GHG emissions, significantly influencing climate change and its associated environmental effects.

Data from the International Energy Agency (IEA) shows that in 2023, the sector released about 8 gigatonnes of CO_2, including emissions from road transport, aviation, shipping, and rail. Among these, road transport is the largest contributor. Notably, cars and vans contributed roughly 3.8 gigatonnes of CO_2 in 2023, representing more than 60% of total road transport emissions, as presented in Figure 1.

This growing concern has driven modern initiatives to promote the shift from internal combustion engine (ICE) vehicles to more sustainable and environmentally conscious alternatives[3]. Moving toward electric-driven transportation offers a promising path to addressing these environmental and health challenges.

Consequently, EVs are increasingly seen as a viable replacement for traditional ICE vehicles, providing a cleaner and more eco-friendly solution[4], [5], [6], [7].

EVs offer promising benefits such as zero tailpipe emissions, lower long-term expenses, and enhanced safety features. Nevertheless, their broader adoption continues to face challenges due to limited driving range, extended charging durations, high upfront costs, and a lack of adequate charging networks[8].

While battery electric vehicles (BEVs) eliminate tailpipe emissions, they are constrained by range limitations, whereas hybrid electric vehicles (HEVs) provide a balance by combining an ICE with an electric motor, extending driving distance while still relying on fossil fuels[4], [9].

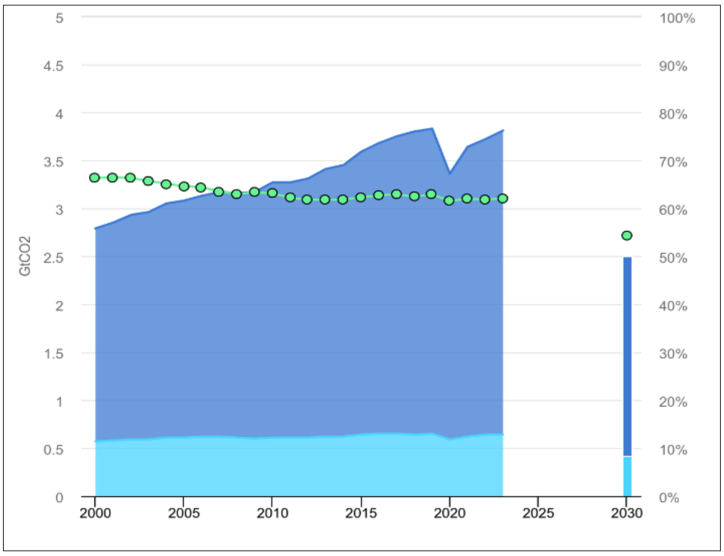

Figure 1. CO_2 emissions from cars (blue) and vans (light blue) as a share of total transport emissions. Green points represent their percentage compared to overall road transport emissions [2].

Despite the environmental benefits of EVs, producing them presents new challenges, especially in the supply chain stages involving crucial materials for manufacturing lithium-ion batteries. The transition to BEVs has led to significant demand for key materials like lithium, cobalt, and nickel, causing concerns about price volatility and resource availability. A 2023 World Economic Forum report highlights the risks of supply-demand imbalances, which could lead to market dislocation and cost fluctuations. In 2024, lithium prices stabilized following their extreme volatility in 2023, while cobalt prices decreased as battery manufacturers transitioned to cobalt-free chemistries, reducing reliance on scarce resources[10].

Recognizing these economic pressures, governments worldwide have introduced regulations to promote EV adoption while ensuring stable supply chains for battery materials. In 2023, the European Union, China, and the U.S. introduced standards for battery recycling and material efficiency, with the objective of reducing the need for newly mined resources. While 2024 saw changes in EV subsidies, some governments, including Germany, Sweden, and New Zealand, adjusted financial incentives as manufacturing costs decreased [11],[12],[13]. These policy changes are part of a continuous effort to harmonize economic viability with environmental objectives, ensuring that EVs remain a practical option for lowering GHG emissions while also considering long-term material sustainability and cost-effectiveness.

As governments continue refining EV incentives and sustainability policies, advancement of EV technology has resulted in a variety of vehicle types adapted to different customer needs, including HEVs, BEVs, fuel cell EVs (FCEVs), and extended-range EVs (EREVs). Each type offers specific advantages in power source management, energy efficiency, and emission reduction. Energy storage systems (ESSs), such as lithium-ion batteries and hybrid setups, play a crucial role in improving the efficiency of EVs. Although lithium-ion batteries are preferred for their high energy density, supercapacitors (SCs) excel in power delivery, making them particularly useful for functions like regenerative braking[14].

Furthermore, power converters, such as DC/DC and DC/AC converters, are critical for controlling energy flow and transferring power across vehicle components. Emerging bidirectional converters also enable vehicle-to-grid (V2G) integration, enhancing grid stability and supporting renewable energy use[15], [16]. Similarly, a variety of electric motors (EMs), including induction motors and permanent magnet synchronous motors, provide different trade-offs in terms of efficiency, torque, and speed, influencing the overall design and performance of EVs. In parallel, advancements in

both conductive and inductive charging technologies aim to meet the increasing need for quicker and more convenient charging solutions.
With rapid developments in battery technology, power converters, and charging systems, there is a growing need to assess their impact on EV adoption and performance. This paper presents a comprehensive analysis of recent advancements in EV components, highlighting their role in promoting sustainable transportation. This review enhances current comprehension by combining both technical and non-technical aspects, including component-level innovations in economic, policy, and regional adoption factors, thereby giving a more holistic and multidisciplinary perspective than current reviews. Unlike previous reviews that focus on individual EV components([17], [18], [19], [20], [21], [22], [23]), this paper compares powertrains, ESSs, power converters, EMs, and charging systems, identifying key research trends and future challenges. In addition to technical aspects, this paper also examines economic and policy issues, including high initial costs, restrictive regulations, and the role of government incentives, which continue to hinder widespread adoption of EVs. A deeper analysis of regional market trends, like BEV dominance in China and FCEV adoption in Japan, is also given, giving a more comprehensive perspective on EV growth in diverse markets. Despite significant progress, challenges such as improving battery lifespan, enhancing bidirectional DC/DC converter efficiency, and expanding high-power fast-charging infrastructure remain critical areas for further research. Furthermore, the discussion highlights sustainability problems like the need for rare-earth materials in PMSMs and infrastructure constraints, such as hydrogen refueling stations for FCEVs and charging deserts in rural areas, to bring attention to broader environmental and logistical concerns.
The paper continues by exploring different levels of EV electrification in the next section. section 3 reviews ESSs, section 4 examines power converters, section 5 focuses on EMs, section 6 discusses charging systems, and section 7 presents the conclusions.

2. EVS ELECTRIFICATION LEVELS

EVs can be divided into four main categories, such as HEV, where we can find three types: mild hybrid EV (MHEV), full hybrid EV (FHEV), and PHEV, in addition to BEV, FCEV, and EREV as shown in Figure 2[24], [25], [26]. In the next subsection, we will explore the configurations of each type of EV and provide an overview of all of them.

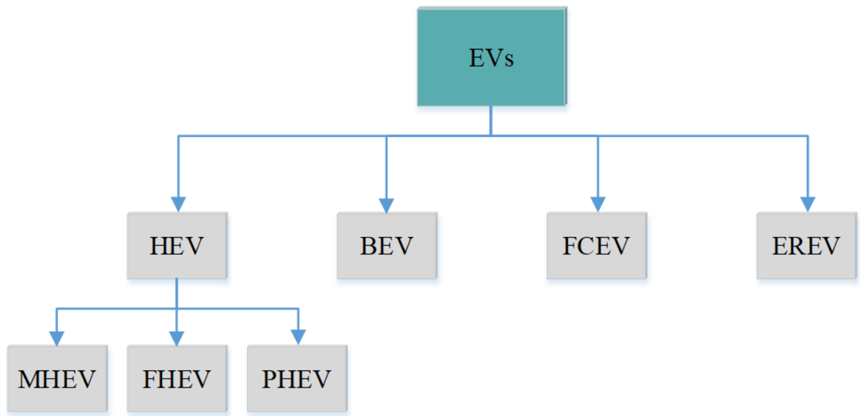

Figure 2. EVs classification.

2.1. Mild hybrid electric vehicle (MHEV)

MHEV has a small EM which assists the ICE during acceleration and other high-load conditions, enhancing fuel efficiency by regenerative braking, and enabling features like start-stop functionality to decrease idling emissions[27]. In real-world driving situations, mild HEV typically achieve fuel efficiency increases of 20%–30% compared to non-hybrids[28].

2.2. Full hybrid electric vehicle (FHEV)

FHEV is composed of two or more power plants, with a primary focus on an ICE and an EM. The ICE serves as the primary energy source, supplying the majority of the vehicle's propulsion energy, it enables extended driving range. Meanwhile, the EM serves as a secondary source to handle peak power demands and improve fuel efficiency[29]. It helps recharge the ESS using excess power from the ICE and energy recovered during braking[30]. Figure 3 illustrates the typical classification of FHEVs into three main types: series, parallel, and a combination of both (series-parallel)[31].

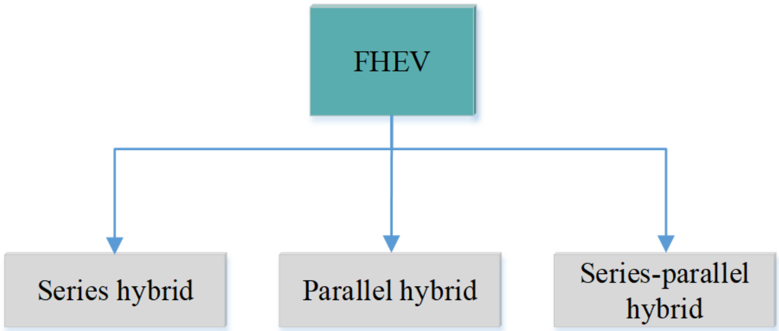

Figure 3. FHEV classification.

2.2.1. Series HEV

In a series powertrain configuration, the EM is the primary vehicle propeller. The ICE provides power to a generator that charges the ESS[32]. Furthermore, the ICE-generator pair is capable of driving the traction EM without the need for an ESS [30]. The series' configuration is depicted in Figure 4.

Below is an overview of the operating modes in a series configuration:

- Starting: the power for propulsion is provided by both the ICE and the EM.
- Reduced load: When the ICE generates excess power beyond what is needed for propulsion, the additional energy is directed toward charging the ESS.
- Braking phase: the EM is used as a regenerative generator to recharge the ESS during deceleration.
- Standstill: the ICE can be utilized to charge the ESS through the generator.

2.2.2. Parallel HEV

In a parallel powertrain configuration, the ICE and EM can work together to power the wheels [29]. Both are connected to the driveshaft via two clutches, allowing either the ICE, the EM, or both to deliver traction simultaneously. Additionally, the EM works as a generator, capturing energy during vehicle deceleration or being driven by the ICE when excess power is produced beyond what's needed for propulsion[33].

The parallel configuration benefits from smaller power ratings for its components, particularly the EM, compared to the series configuration, which can lead to reduced electromechanical power losses. However, within urban areas where traffic flow is often interrupted, the parallel HEV generally exhibits lower efficiency[30]. Figure 5 illustrates the parallel HEV setup.

Below is an overview of the operating modes in a parallel configuration:

- EM only: The vehicle is driven solely by the EM.
- ICE only: The vehicle operates solely under ICE propulsion.
- Combined ICE and EM: The ICE and EM work together to propel the vehicle.

- Power split: The ICE output is split between propelling the vehicle and charging the battery, while the EM functions as a generator.
- Stationary charging: the ICE is used to charge the battery when the vehicle is stationary.
- During braking: the EM recovers energy to recharge the battery through regenerative braking.

2.2.3. Series–parallel HEV

The series-parallel powertrain configuration, or power-split HEV, merges advantages from both series and parallel HEVs. This design enables the use of a smaller ESS and EM than in the series setup, and a smaller ICE than in the parallel setup[29], [34]. Figure 6 shows the configuration of series-parallel HEV.

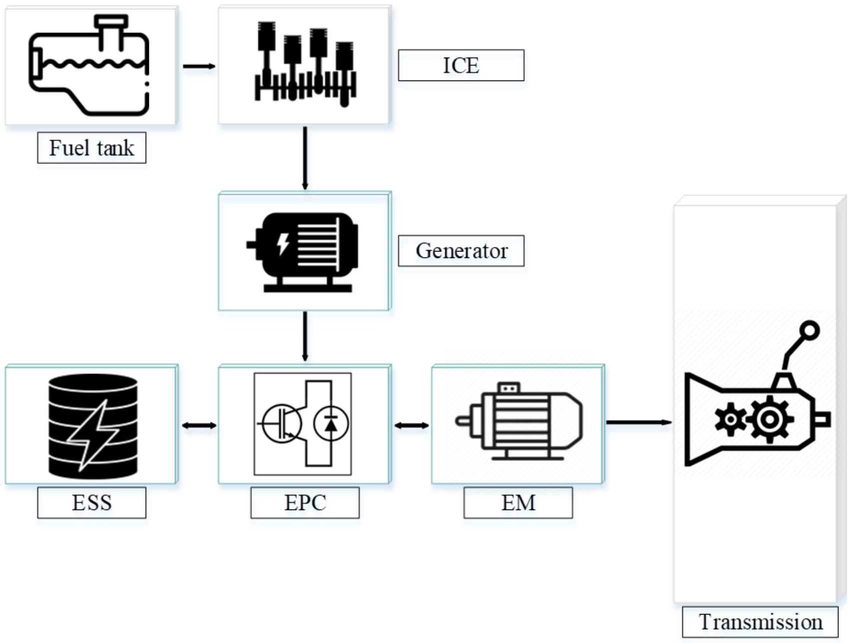

Figure 4. Series HEV powertrain block diagram.

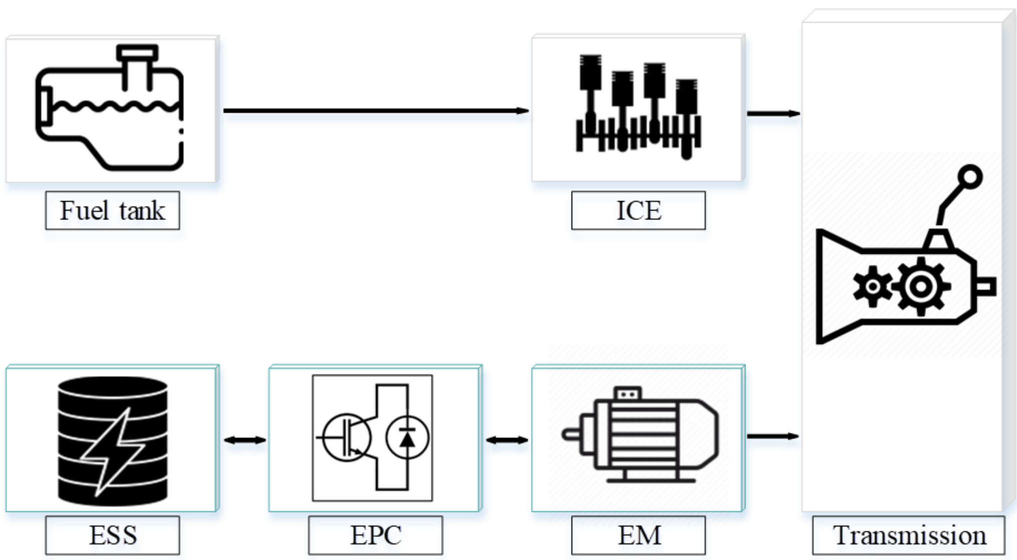

Figure 5. Parallel HEV powertrain block diagram.

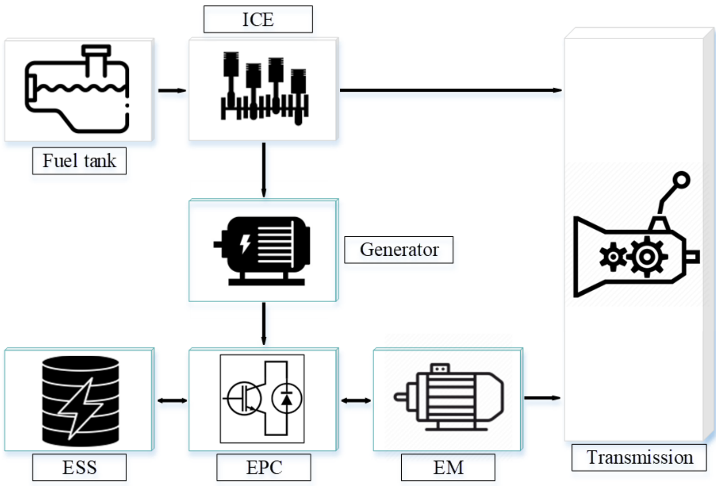

Figure 6. Series-parallel HEV powertrain block diagram.

2.3. Plug-in hybrid electric vehicle (PHEV)

PHEV combines both an ICE and an EM. Unlike conventional hybrid vehicles, PHEVs can be recharged by connecting to an external power supply, allowing them to run on electric energy for a certain range before switching to the ICE. A typical example is the BMW 320e/330e with a battery pack of 12kWh, and it offers a driving range between 59 and 61km using just the EM. As described in Figure 7, the PHEV shares the same components as the BEV, including an EM, PEC, an ESS, and a charger. The key differences are the addition of a fuel tank and an ICE.

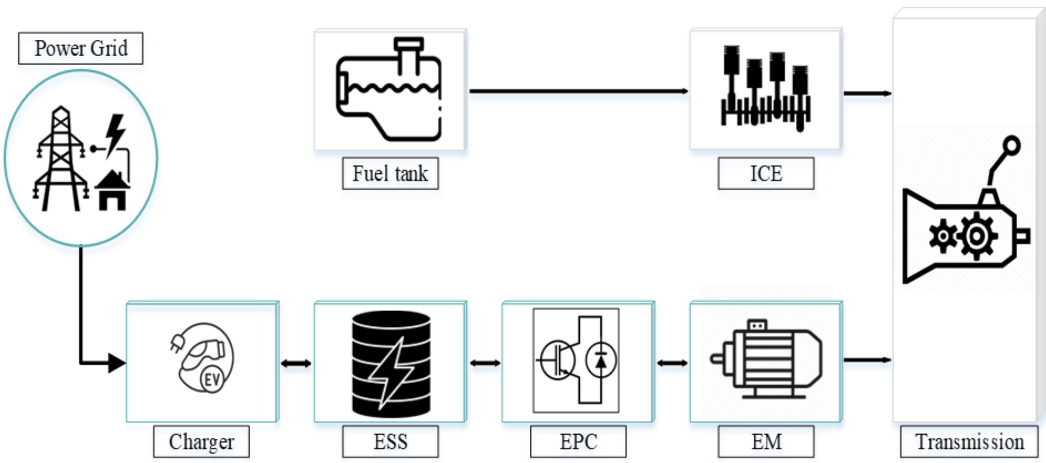

Figure 7. PHEV configuration.

As previously mentioned, there are three main categories of HEVs: MHEV, FHEV, and PHEV. Table 1 provides a comparison of these categories.

Table 1. Comparison of different types of HEVs[35].

Key Parameters	MHEV	FHEV	PHEV
Idle Stop/Start	x	x	x
Electric Torque Assistance	x	x	x
Energy Recuperation	x	x	x
Electric Drive		x	x
Ability to Charge During Driving		x	x
Ability to Charge From the Grid			x

Voltage of the Battery (V)	48–160	200–300	200–300
Electric Machine Power (kW)	10–15	30–50	60–100
Electric-Only Driving Distance (km)	0	5–10	> 10
CO_2 Estimated Benefit	7–12%	15–20%	> 20%

2.4. Battery electric vehicle (BEV)

A BEV is powered solely by electricity stored in rechargeable batteries, with no ICE. It uses EMs energized by battery packs, which are recharged via electrical outlets or charging stations. BEVs generate no tailpipe emissions, positioning them as a sustainable and eco-friendly alternative to conventional vehicles. Tesla Model S, Tesla Model 3, Toyota bZ4X, BMW i4, BMW iX, and Nissan Leaf are examples of this type of vehicle[9]. Taking the example of the Nissan Leaf, it is a fully EV equipped with a 62 kWh battery, offering a driving range of up to approximately 360 km on a single charge[36]. As illustrated in Figure 8, the BEV powertrain generally consists of a traction EM, its associated EPC, an ESS, and a charger.

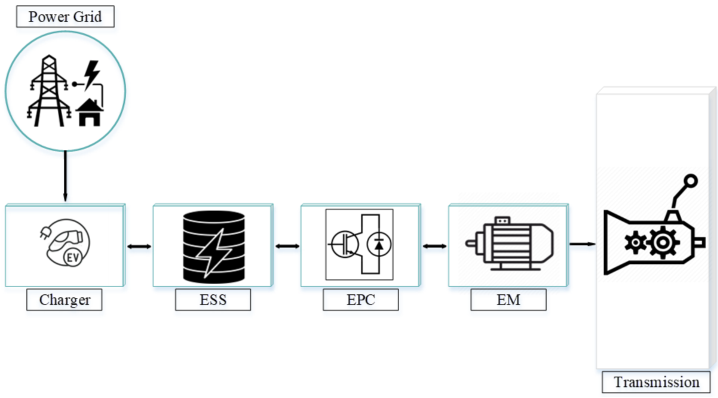

Figure 8. BEV configuration.

2.5. Fuel cell electric vehicle (FCEV)

In FCEV, hydrogen serves as the primary fuel. Its powertrain architecture closely resembles that of a BEV, with the fuel cell functioning like a battery by delivering power to propel the motor [37]. The fuel cell stack generates electricity by combining hydrogen with oxygen from the air. These vehicles do not produce any harmful emissions, making them environmentally friendly[38],[39]. The Toyota Mirai and Hyundai Nexo are examples of FCEVs, which use hydrogen fuel cells to power their traction motor.

According to [40] FCEV configuration can be illustrated in Figure 9, where the electricity produced by the fuel cell stack passes through a converter to supply the EM. To make high-speed vehicles, there are a variety of modifications that can be made to the basic powertrain. By modifying the FCEV powertrain, a new vehicle configuration is created called a fuel cell hybrid EV (FCHEV).

According to [41] FCHEV powertrains can be categorized into three types: fuel cell and battery (FC + B), fuel cell and supercapacitor (FC + SC), in addition to fuel cell, battery, and supercapacitor (FC + B + SC) [42]. Due to the complexity of the FC + B + SC configuration and the low energy density of supercapacitors, the FC + B configuration is primarily used and applied in most FCHEV [43]. Figure 10 shows the FCHEV powertrain configuration.

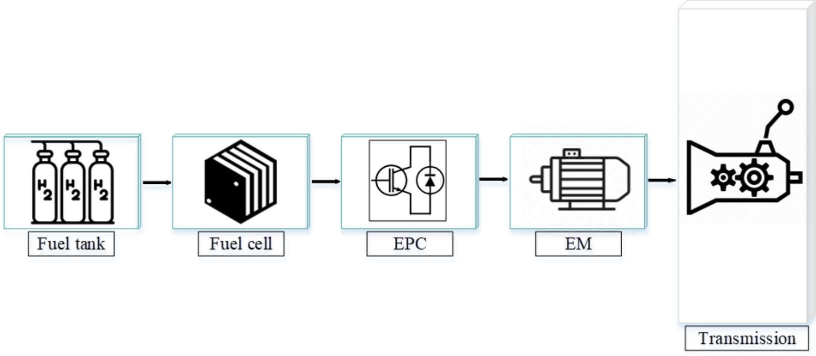

Figure 9. FCEV configuration.

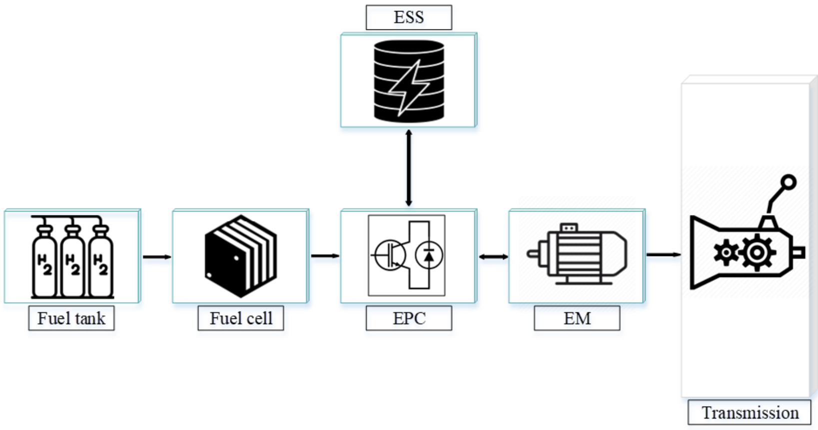

Figure 10. FCHEV configuration.

2.6. Extended-range electric vehicle (EREV)

An EREV is primarily a vehicle that runs solely on electricity, with an EM providing all the power. However, it has a small ICE that generates extra electric power. Once the battery is discharged enough, the ICE activates and runs a generator that provides power to the EM and/or recharges the ESS[44]. Figure 11 shows the EREV configuration based on the ref.[45]. The ICE, along with an integrated starter generator (ISG) and an AC/DC converter, is part of the auxiliary power unit (APU), it generates electrical power.

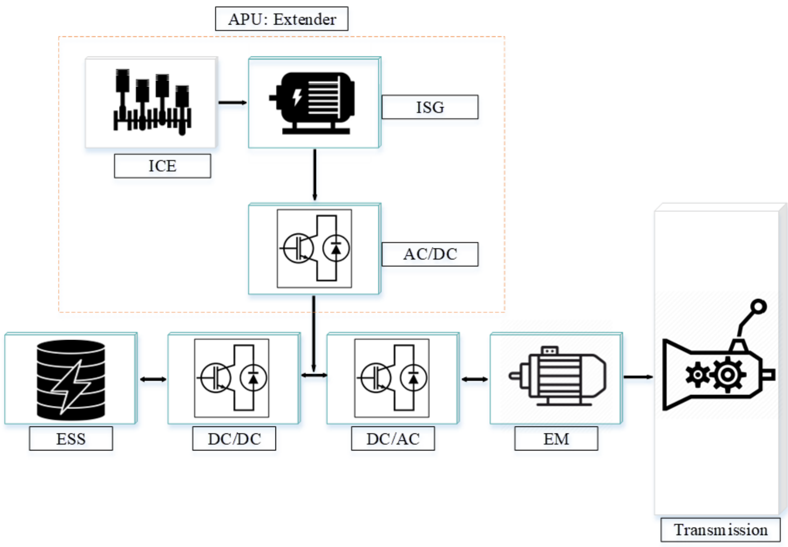

Figure 11. EREV configuration.

This power can either drive the EM directly or charge the ESS through a DC/DC converter. By using a DC/AC converter, the stored energy in the ESS can be utilized to power the EM and drive the vehicle's transmission. By using this dual setup, the vehicle can either operate in full-electric mode for short distances or use the ICE for generating electricity over extended ranges.

2.7. Discussion

As seen previously the main type of EVs are BEV, HEV, PHEV, and FCEV, Each configuration offers unique properties in terms of in terms of emissions, energy efficiency, driving range, infrastructure requirements, and charging or refueling times. To better understand the differences and make informed decisions, Table 2 provides a detailed comparison of these vehicle types. The following discussion explores the key aspects highlighted in the table, helping to identify the strengths and limitations of each option based on individual needs and priorities.

Table 2. Aspect of selecting an EV

Aspect	BEV	PHEV	HEV	FCEV	Ref.
Emissions	Zero	Low	moderate	Zero	[46], [47], [48]
Energy efficiency	Very High	High	moderate	Low	[49], [50], [51], [52]
Driving range	250-500km	500-700km	500-800km	>800km	[53], [54], [55], [56], [57], [58], [59]
Cost	High	Medium-High	Medium	Very High	[60], [61], [62], [63], [64]
Infrastructure	Under development	Under Available	Not required	Limited	[17], [65], [66], [67], [68]
Charging time	30 minutes-8hours	1- 4 hours	Not needed	3-5minutes	[69], [70], [71], [72]

BEVs are marketed as the perfect choice for environmentally conscious consumers due to their zero emissions and high energy efficiency. Nevertheless, they usually have a medium driving range of 250–500 km and a slow charging time (30 minutes to 8 hours), which can be inconvenient for certain users. These limitations are particularly problematic in rural areas, where charging stations are few or even nonexistent. Charging deserts make it difficult for people to own and use an EV. According to the IEA, BEVs are most widely adopted in China, supported by large-scale government subsidies and aggressive infrastructure deployment. Similarly, European countries such as Norway, Germany, and the Netherlands are rapidly expanding their BEV fleets due to stringent emissions regulations and urban clean air policies. In contrast, BEV adoption in the U.S. is concentrated in specific regions, with significant adoption in states like California but failing in rural and midwestern regions due to infrastructure gaps.

PHEVs offer a trade-off between convenience and emissions, with low emissions, high energy efficiency, and modest 1- 4 hours charging times. They also offer the benefit of existing infrastructure, making them suitable for a wide range of drivers. In Europe and North America, PHEVs remain popular among consumers transitioning from ICE vehicles due to their flexibility. However, their growth is more modest in China, where national policy now strongly favors BEVs over PHEVs.

HEVs require no charging infrastructure and have an extended 500–800 km range, but their emissions are currently higher than the other types. HEVs remain popular in regions where EV infrastructure is limited, such as Southeast Asia, India, parts of Latin America, and the majority of nations in Africa, where charging stations are limited and expense remains a major concern.

FCEVs stand out for their very long range of over 800 km and fast refilling times of 3–5 minutes

but are hampered by limited infrastructure and the lack of hydrogen refueling infrastructure. Japan is proactively working to expand the use of FCEVs, with the assistance of government-led initiatives to construct hydrogen infrastructure. South Korea is also making similar efforts. However, in many regions of Europe and North America, hydrogen stations are still scarce, and the high cost of producing, transporting, and storing hydrogen remains a significant obstacle.
Each category of EV comes with distinct strengths and weaknesses. Choosing the optimal option has a significant impact on regional infrastructure availability, government policy incentives, and consumer needs related to driving range, environmental concerns, and fueling/charging convenience.

3. ENERGY STORAGE SYSTEMS (ESSS)

ESSs play a vital role in EV applications. Besides storing energy, these systems also regulate and control its flow to guarantee efficient and reliable operation. Devices used in these systems must have the ability to manage energy supply to meet the vehicle's demands, optimize performance, and maintain stability. To guarantee reliable EV operation in a variety of scenarios, sophisticated technologies and precise control mechanisms are necessary to balance energy input and output. As reported by [9], several factors must be considered when selecting the most appropriate energy storage devices, such as capacity, state of charge, energy density, power density, lifespan, and efficacy.
According to a review on EV energy storage and management systems [73], ESSs can be classified into three main categories: electrochemical storage (batteries and SCs), chemical storage (fuel cells), and hybrid storage systems. The hybrid systems include configurations such as battery + SC, battery + fuel cell, fuel cell + SC, and a combination of all three. All of that can be seen in Figure 12. An overview of every storage system used in EVs will be provided in the following section.

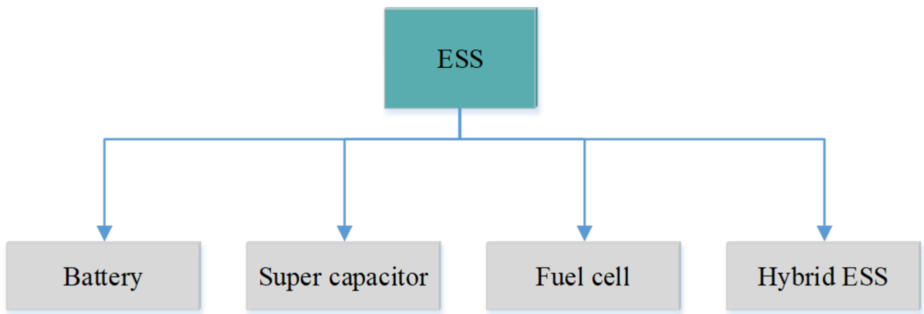

Figure 12. ESS classification.

3.1. Batteries

This section reviews the different types of traction batteries used in EVs, exploring the characteristics, advantages, and limitations of each type. It provides insights into how various battery technologies influence the performance and efficiency of EVs. Various types of rechargeable batteries utilized in EVs are shown in Figure 13, such as lead-acid, sodium–sulfur, sodium–chloride, nickel-based, zinc–bromine, and lithium-ion batteries, as well as other emerging technologies including solid-state and lithium–sulfur batteries[9], [73], [74], [75].

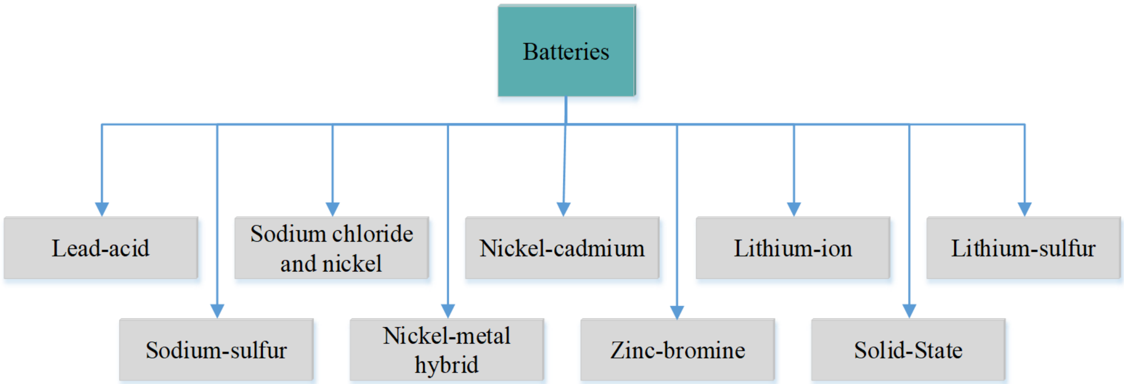

Figure 13. Batteries types used in EVs.

3.1.1. Lead-acid batteries

Lead-acid batteries have become the most widely adopted power source for EVs in the late 19th century. These batteries generate electricity by converting chemical energy through a reaction where lead dioxide serves as the positive plate, sponge lead acts as the negative plate, and sulfuric acid functions as the electrolyte[76]. They were instrumental in various applications during the early days of EVs.

However, early EVs were significantly constrained by the technological limitations of their era. The low energy density and limited range of these batteries have made them impractical for long-distance or cross-city travel. Additionally, the absence of a widespread charging network made recharging slow and inconvenient, which further reduced the usability of early EVs. Even with their difficulties, lead-acid batteries are still in use today and are commonly found in various applications, particularly as low-voltage batteries for automotive starting systems. [77].

3.1.2. Sodium-sulfur (Na-S) batteries

Na-S batteries are high-temperature rechargeable batteries and rely on sodium and sulfur as their active materials, with sodium serving as the anode and sulfur as the cathode[78], [79]. They are known for their high energy and power capabilities, as well as a relatively high energy density and a lifespan of 2,000 to 3,000 cycles. However, their high production costs and safety concerns currently limit their commercial viability.

3.1.3. Sodium-nickel chloride (NaNiCl) batteries

NaNiCl batteries have been in use since the mid-1990s as high-temperature storage systems, typically operating at around 300 °C and are recognized as both reliable and environmentally sustainable in comparison to other battery types. They are advantageous for their high cell voltage, safety, and ability to withstand limited overcharge and deep discharge conditions. They are particularly suitable for applications that require stability in diverse temperature conditions ranging from -30 to 50 °C [80].

3.1.4. Nickel-cadmium (Ni-Cd) battery

Ni-Cd battery, a rechargeable technology developed by Waldemar Jungner in 1899, is recognized for its relatively high energy density, extended lifespan, and reliable performance in low temperatures[81]. Ni-Cd batteries are a reliable alternative to lead-acid batteries in terms of size and ratings, and they demonstrate similar maturity. Nickel oxide-hydroxide is the main ingredient used in these batteries, followed by cadmium for the negative electrode, and potassium hydroxide acts as an electrolyte [82].

3.1.5. Nickel-metal hybrid batteries (NiMH)

NiMH batteries replace the cadmium used in Ni-Cd batteries with a hydrogen-absorbing alloy at the negative electrode [83]. Although they have a higher self-discharge rate than Ni-Cd batteries, NiMH batteries remain widely used in HEVs, such as the Toyota Prius and the second-generation GM EV1[84]. Additionally, the Toyota RAV4 EV was available with either lead-acid or NiMH battery options [9].

3.1.6. Zinc-bromine batteries

Zinc-bromine batteries are recognized for their high energy storage capacity and long-lasting cycle life, which enables them to be charged and discharged many times without a significant drop in performance. They have advantages including high energy density, electrochemical reversibility, and the use of abundant and low-cost materials. Zinc and bromine are used as active materials in the Zn-Br battery, and an electrolyte solution facilitates the processes of energy storage and release [85].

While Zn-Br batteries are primarily being explored for grid-scale energy storage, their potential for use in EVs is being examined due to their energy density and long cycle life, which could provide reliable and sustainable power for EVs [86].

3.1.7. Lithium batteries (LiBs)

LiBs are considered the most suitable ESS for automotive applications due to several key advantages: They have a lightweight design, deliver high specific energy, offer specific power levels up to 4000 W/kg, and achieve energy densities as high as 300 Wh/kg [75], [87]. These characteristics make them ideal for use in EVs, as they offer a combination of lightweight, powerful, and efficient energy storage capabilities that enhance vehicle performance and range. LiBs operate by shuttling lithium ions between the anode and cathode during charge and discharge cycles, as illustrated in Figure 14.

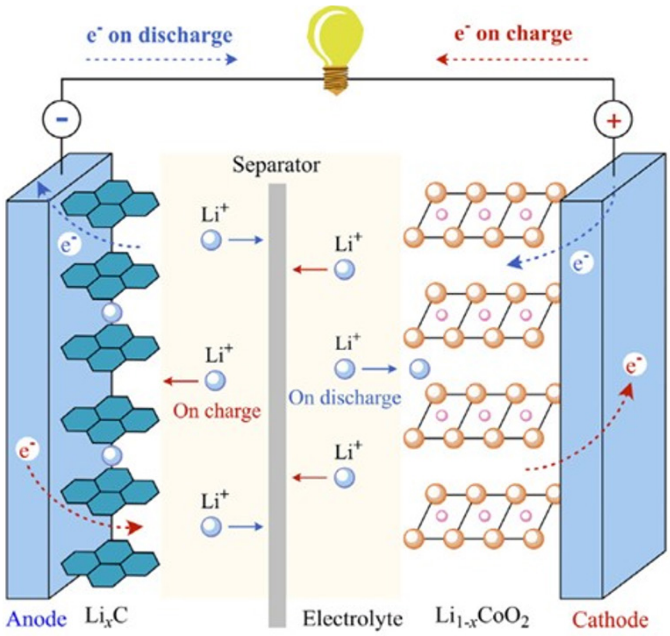

Figure 14. Structure of a typical lithium-ion battery cell [20].

3.1.8. Solid-state batteries (SSBs)

SSBs are becoming an attractive alternative to conventional lithium-ion batteries, allowing for significant safety and energy density improvements [88], [89], [90]. A key safety benefit of SSBs is the use of solid-state electrolytes (SSEs), which replace the flammable liquid electrolytes found in conventional batteries. The properties of SSEs, including garnet-type and sulfide-based materials, are non-flammable and have higher thermal stability, which prevents thermal runaway and fire hazards[91].

The use of lithium metal anodes with high theoretical capacities is the main reason why SSBs provide higher energy densities than traditional lithium-ion batteries. Recent developments have shown that SSBs can achieve energy densities exceeding 450 Wh/kg, which is significantly higher than the typical 250–300 Wh/kg range of conventional batteries. This improvement leads to longer driving ranges for EVs and better energy storage solutions [92].

3.1.9. Lithium-sulfur batteries (Li–S)

Li-S batteries are gaining attention as a potential ESS solution because of their high theoretical energy density and affordability[93], [94], [95]. They have a theoretical energy density of approximately 2600 Wh/kg [96], which is much higher than the average range of 250–300 Wh/kg in conventional Li-ion batteries. This high energy density is primarily attributed to the use of sulfur cathodes and lithium metal anodes. Recent research has shown that Li-S batteries can have energy densities that exceed 500 Wh/kg, which is a step closer to commercial viability[94], [97].

A real-world example of a vehicle that uses a battery pack as its main ESS is the Tesla Model Y, which currently exists in two distinct variants depending on the battery technology used.

- An earlier version utilizing 2170 cylindrical lithium-ion cells.
- A newer version employing 4680 tabless cylindrical cells in a structural pack design.

The earlier Tesla Model Y variants, produced in Fremont and Giga Shanghai, are equipped with a traction battery pack composed of 2170 cylindrical cells (21 mm diameter × 70 mm length). These cells are arranged into four or five modular sub-packages, with a traditional pack enclosure mounted under the vehicle floor. The pack employs Nickel Cobalt Aluminum (NCA) chemistry and aluminum serpentine cooling tubes to effectively handle heat. This design is reliable and has been proven, but the presence of multiple modules and additional structural casing elements leads to structural redundancies and an increase in vehicle mass. Despite these limitations, the 2170 packs are still capable of delivering reliable performance with a nominal system voltage of approximately 350–360 V and are widely utilized in long-range Model Y configurations, offering up to 525 km of driving range[98].

In contrast, the Tesla Model Y vehicles that were made in Giga Texas have a structural battery pack that is assembled from larger-format 4680 cells (46 mm diameter × 80 mm length). These tabless cells are embedded directly into the vehicle's chassis, eliminating the need for conventional module assemblies, allowing the battery to serve as a load-bearing structural element. The cells are arranged in a dense grid pattern and encapsulated in polyurethane foam, which provides both thermal insulation and mechanical rigidity. The structural battery is bonded directly between the front and rear mega-castings, which results in a significant increase in chassis stiffness, a reduction in overall vehicle mass, and a simplified assembly process. This design is able to operate at an estimated nominal voltage of 400–450 V and has a driving range of about 449 km[99], [100].

The Model Y's dual-architecture approach explains how battery design has progressed, ranging from the modular, serviceable 2170 packs to the highly integrated, mass-manufacturing-optimized 4680 structural pack, which embodies a cell-to-vehicle (CTV) philosophy.

3.2. Supercapacitor (SC)

A SC, which is also called an ultracapacitor (UC) or electrochemical capacitor (EC), has the ability to discharge and recharge power in a brief period of time. SCs store electrical energy directly through the electric double-layer (EDL) effect, unlike batteries that convert chemical energy to electrical energy. This design enables rapid storage and release of electrical energy, making them highly effective for uses that demand fast power output and quick charging. [101]. A SC is capable of charging and discharging at extremely high specific current values (A/kg), up to 100 times higher than those of a battery, without causing harm to the unit. They serve as supplementary devices, capturing energy from braking and supplying additional power for quick acceleration, which ultimately improves the vehicle's efficiency [102]. There are three types of SCs used in EVs [103],[104], including electric double-layer capacitors (EDLCs), pseudocapacitors, and hybrid SCs as illustrated in Figure 15.

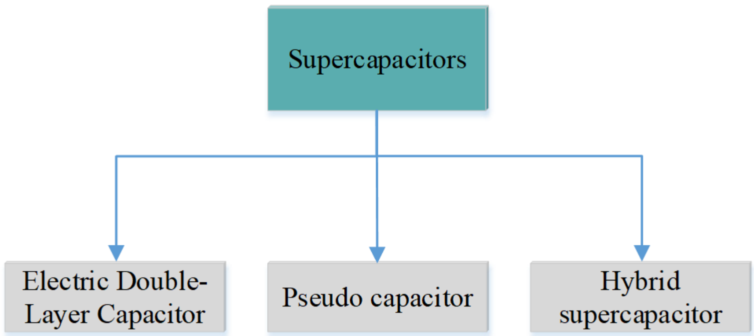

Figure 15. SCs classification.

3.2.1. Electric double-layer capacitor (EDLC)

EDLC offers enhanced cyclic stability compared to rechargeable lithium-ion batteries. They operate by distributing charges at the double-layer interfaces between the electrode and electrolyte, with charges separated by only a few angstroms and remaining static, as shown in Figure 16-a. EDLCs have gained popularity over other capacitor types because of their high energy density, long-term reliable performance, fast charging and discharging capabilities, and environmentally friendly materials. [101].

3.2.2. Pseudo capacitor

In this category of charge storage, charge transfer occurs through faradaic processes between the electrodes and electrolytes. Pseudo capacitors rely significantly on these redox charge transfers, where reversible oxidation and reduction reactions at the electrode surfaces contribute to energy storage. This mechanism is depicted in Figure 16-b.

3.2.3. Hybrid supercapacitor

This represents an important type of energy storage, where the word "hybrid" refers to the blend of EDLC and pseudocapacitive materials. This integration aims to blend the benefits of both types, leveraging the high-power density of EDLCs and the higher energy density of pseudo capacitors, the mechanism of hybrid DC is depicted in Figure 16-c.

As examples of vehicles in the market that utilize SC technology as their main ESS, the Toyota Yaris Hybrid-R and Lamborghini Sián FKP 37. The Yaris Hybrid-R uses a series-parallel hybrid configuration, which integrates a 1.6L turbocharged ICE with three EMs, allowing flexible operation in both parallel and series modes. It utilizes a standard SC instead of conventional batteries, providing rapid charge-discharge cycles for dynamic power boosts. In addition, the Lamborghini Sián FKP 37 employs a lithium-ion SC as its primary 48V MHEV ESS, providing rapid power delivery to boost acceleration and recuperate braking energy, even though it cannot support all-electric driving [105]. Both systems enhance overall efficiency and performance without requiring external charging, demonstrating the potential of SC-based energy recovery in high-performance hybrid vehicles.

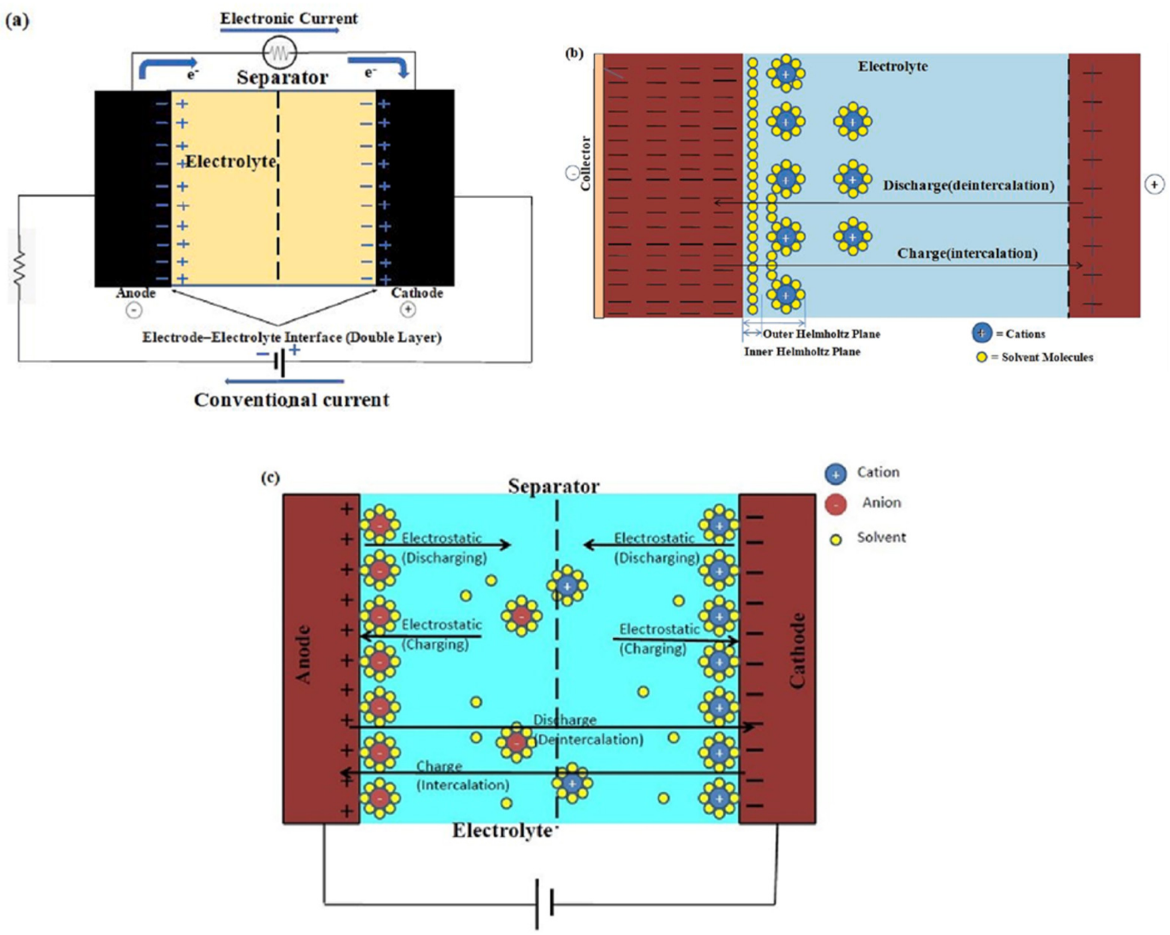

Figure 16. Classification of SCs. EDLC, Pseudo capacitor, and hybrid SC [106].

3.3. Fuel cell (FC)

A fuel cell is an electrochemical system that generates electrical power by converting the chemical energy of hydrogen and oxygen into electricity, heat, and water through redox reactions. It is composed of two electrodes, the anode and the cathode, separated by an electrolyte. Hydrogen is supplied to the anode, while oxygen is fed to the cathode, resulting in the production of electricity along with water and heat as the sole byproducts [107]. Its working mechanism can be shown in Figure 17.

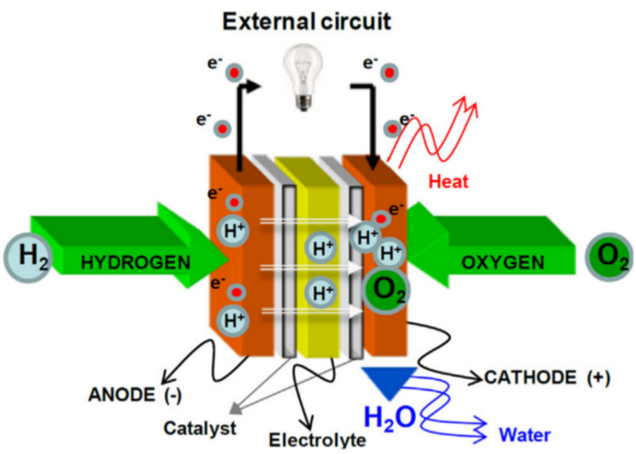

Figure 17. Mechanism of fuel cell power generation [112].

Due to their mechanism, fuel cells are exceptionally clean and entirely carbon-free. These qualities make them highly attractive for power generation and various other applications, especially in FCEVs. Fuel cells are available in multiple forms, including solid oxide FCs, molten carbonate FCs, phosphoric acid FCs, polymer electrolyte FCs, proton exchange membrane FCs, and direct methanol FCs[108], [109], [110], [111].

3.4. Hybrid energy storage system (HESS)

A hybrid storage system combines two or more energy storage systems, such as a battery and SC, battery and fuel cell, SC and FC, or a combination of battery, SC, and FC[113]. Each configuration offers distinct advantages, such as high capacity, high specific power, and high power density, while others provide long life, high-temperature tolerance, and low discharge rates [114]. SC and battery are the most commonly used as HESS. HESS offers several advantages, including high storage capacity, affordability, extended lifespan, and enhanced overall system performance [115].

3.5. Discussion

ESS devices are an integral part of EVs/HEVs today, influencing driving range, efficiency, and overall system performance. Each ESS having its own advantages and limitations. Evaluating these technologies means looking at a number of performance metrics such as energy density, power density, lifetime, efficiency, and cost. Understanding these characteristics allows researchers to choose the most suitable energy storage solution for specific applications, whether for traction, auxiliary power, or regenerative braking.

Figure 18 illustrates a comparative overview of leading energy storage technologies, identifying their strengths and weaknesses. Lithium-ion batteries possess a good balance profile with high energy density and efficiency and also moderate cost and lifetime, making them the first preference for EVs. SCs, on the other hand, have the highest power density and are optimal for fast charge/discharge cycle applications but with much lower energy storage capacity. Lead-acid and nickel-cadmium (NiCd) batteries have relatively poor energy and power density but are inexpensive solutions for low-performance applications. Sodium and zinc batteries, although not as widespread as Li-ion, are under consideration as potential alternatives due to their moderate energy density level and lower costs. Fuel cells, being distinct from conventional batteries, offer high efficiency and extended operational life but suffer from their prohibitive cost and infrastructural complexities.

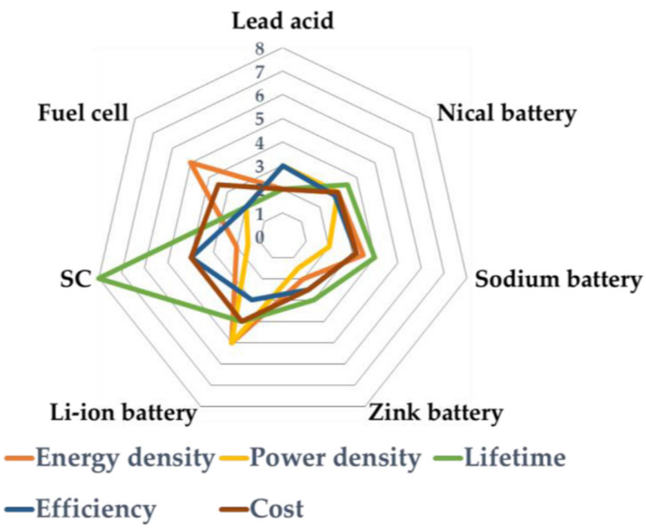

Figure 18. Comparison among the ESSs[73].

The trade-offs among energy storage technologies significantly influence their applications in EVs/HEVs. Lithium-ion batteries dominate due to their high energy storage and efficiency, but concerns about cost and resource availability persist. SCs, though unsuitable for primary energy storage, enhance efficiency in hybrid systems by managing peak power demands during regenerative braking and acceleration. Fuel cells offer high efficiency but require advancements in hydrogen production and refueling infrastructure for widespread adoption. A multi-technology approach, integrating batteries, SCs, and fuel cells, is essential to optimize performance, efficiency, and cost, ensuring sustainable and effective solutions for future electric mobility.

4. ELECTRONIC POWER CONVERTERS – DC/DC

In HEVs and EVs, DC/DC converters have a crucial role in converting and managing electrical energy between different voltages. These converters take the DC voltage from the propulsion battery and scale it down or up to a different DC voltage required by various systems, such as the auxiliary battery and traction motor.

The energy flow between the propulsion battery, SC, and other components is managed by DC/DC converters, which optimize power distribution and improve vehicle efficiency. They play a vital role in regenerative braking in converting the captured energy into a usable form for storage or immediate use. In short, DC/DC converters ensure that every part of the vehicle's electrical system operates at the correct voltage, supporting overall vehicle performance and safety.

DC/DC converters can be divided into two categories, isolated and non-isolated [21], [116], and according to the same references, the DC/DC converters commonly employed in EVs include the boost converter, interleaved 4-phase boost converter, resonant boost converter, full-bridge boost converter, isolated ZVS converters, dual active bridge (DAB), multiport isolated converter, and multi-device interleaved converter. These topologies are classified in Figure 19.

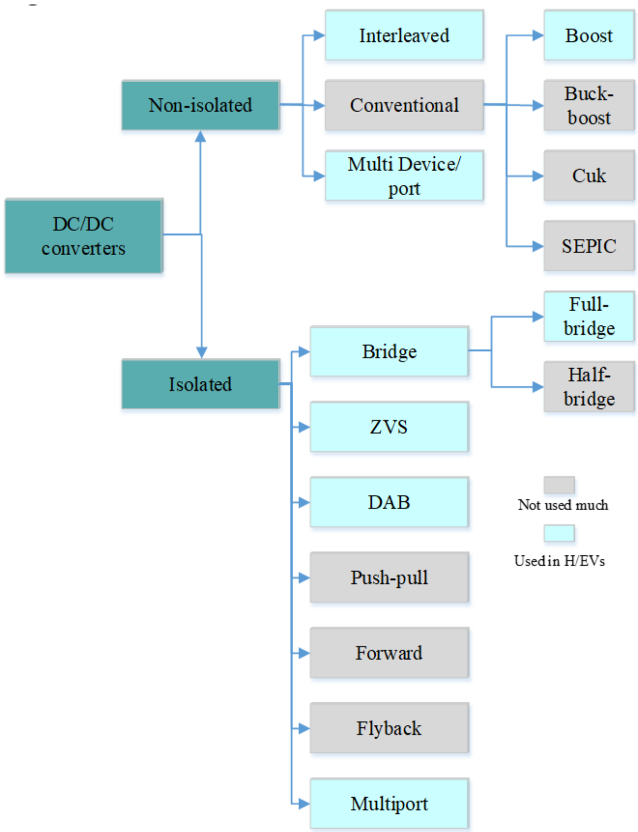

Figure 19. DC/DC classification.

4.1. Non-isolated DC/DC converters

Non-isolated DC/DC converters are devices that convert electrical energy between different voltage levels without isolating the input from the output. In this configuration, the input and output are directly connected, sharing a common ground or electrical pathway. These converters are favored in EVs especially in medium and high-power applications because they are lighter, smaller, and more efficient, which is crucial for optimizing vehicle performance and energy use[21]. Among these, conventional boost and interleaved boost converters are commonly used in EVs. For vehicles, the voltage level of the battery, typically ranging from 180 to 360 V, is generally lower than that required by the EM, which operates around 400 to 750 V. [117]. This voltage difference necessitates the use of step-up DC/DC converters. In the following section, we will explore the converter topologies presented in Figure 19, with a particular focus on those operating in boost mode.

4.1.1. Boost DC/DC converter

A boost converter is a standard type of converter that steps up the input voltage to a higher output voltage, resulting in a decrease in the current drawn from the power source. It typically comprises at least two semiconductor components, a diode and a MOSFET, as well as at least one passive element, such as an inductor, a capacitor, or a combination of both, as illustrated in Figure 20 [118].

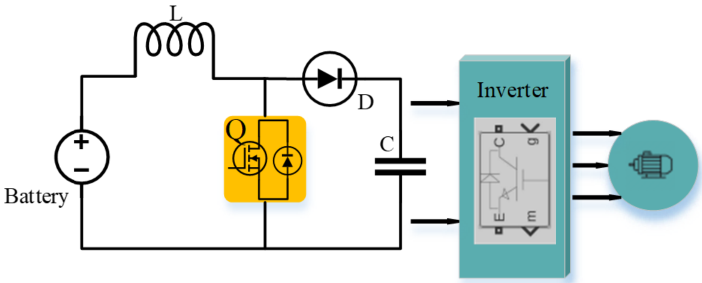

Figure 20. DC/DC boost converter.

4.1.2. Interleaved 4-phase boost DC/DC converter

Interleaved 4-phase boost DC/DC converter utilizes four phase-shifted parallel boost circuits to minimize input current ripple and enhance efficiency. This design, illustrated in Figure 21, distributes the current load across multiple phases, reducing the size of input inductors and output capacitors. It is commonly used in high-power applications requiring low input current ripple for optimal performance and reliability[119].

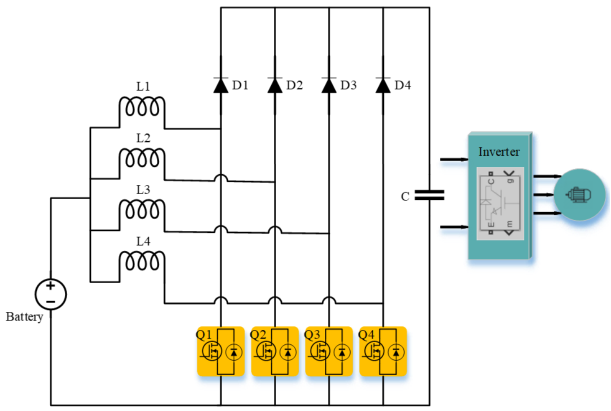

Figure 21. Interleaved 4-phase DC/DC boost converter.

4.1.3. Boost DC/DC converter with resonant circuit

Boost DC/DC converter with resonant circuit is a DC/DC converter that combines the conventional boost topology with a resonant circuit to reduce switching losses, as shown in Figure 22. By incorporating resonance components, the converter can achieve zero-voltage or zero-current switching, significantly decreasing power dissipation during switching events. Nevertheless, this type of converter is restricted to systems with less than 5 kW, does not permit significant output voltage gain, and is incapable of supporting bidirectional power flow[120], [121].

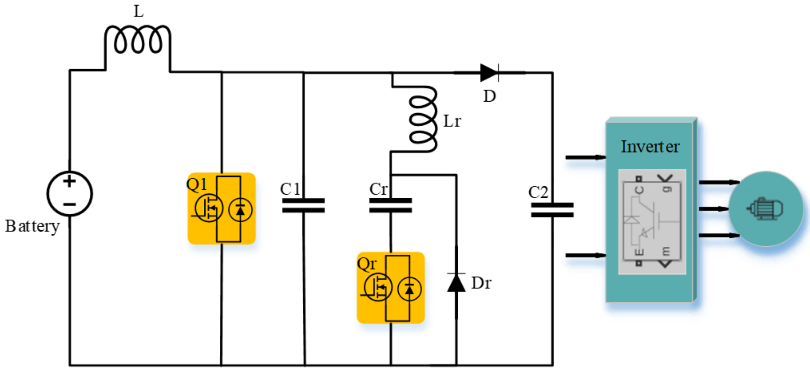

Figure 22: Boost DC/DC converter with resonant circuit.

4.1.4. Multidevice interleaved DC/DC converter (MDIC)

MDIC has many advantages that make it particularly suitable for EVs and PHEVs. The MDIC allows for effective energy transfer between the battery and other components, such as the motor and the regenerative braking system [122]. It minimizes input current and output voltage ripples, contributing to the stability and extending the lifespan of the vehicle's electronic systems. By reducing ripples, the operation can be smoother, and electronic components can be stressed less, which enhances reliability and durability. For applications such as regenerative braking, its bidirectional power flow feature is essential, as it allows energy to be captured and fed back into the battery for storage. This capability enables efficient energy recovery and utilization, which improves overall vehicle performance and energy efficiency. The MDIC's design can be seen in Figure 23 and guarantees high reliability, making it a reliable choice for high-power applications[21].

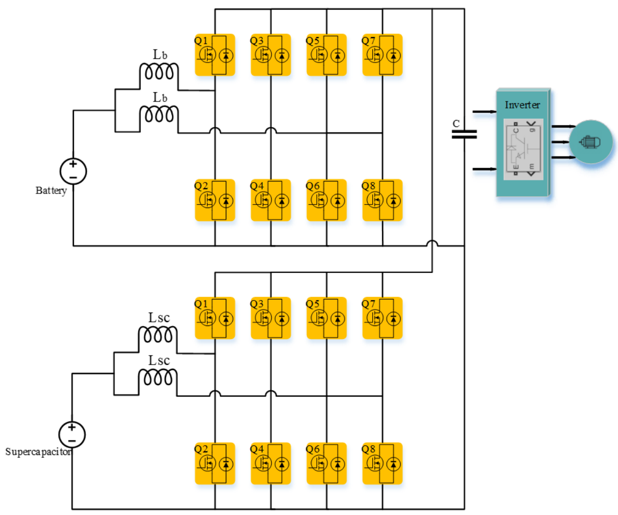

Figure 23. Multidevice interleaved bidirectional DC/DC converter.

4.2. Isolated DC/DC converter

For DC/DC converters, isolation refers to galvanic isolation, which ensures that no direct electrical path exists between different sections of the circuit. The isolation serves as a barrier between the input and output stages, which can be crucial for safety, preventing electrical defects from transferring and safeguarding sensitive components. Isolation is often achieved using transformers or optocouplers, depending on the design requirements and application needs. In the next subsections, we will take a look on all isolated DC/DC highlighted in Figure 19.

4.2.1. Full-bridge boost converter

Full-bridge boost converter generally includes four switches organized in a bridge layout as shown in Figure 24. This configuration efficiently boosts DC voltage for applications requiring higher levels. Its usage is common in renewable energy systems, EVs, and battery chargers [123]. This DC/DC converter charges batteries and supplies voltage to the load in three stages: DC/AC inversion, voltage adjustment via a high-frequency transformer (HFT), and AC/DC rectification [124].

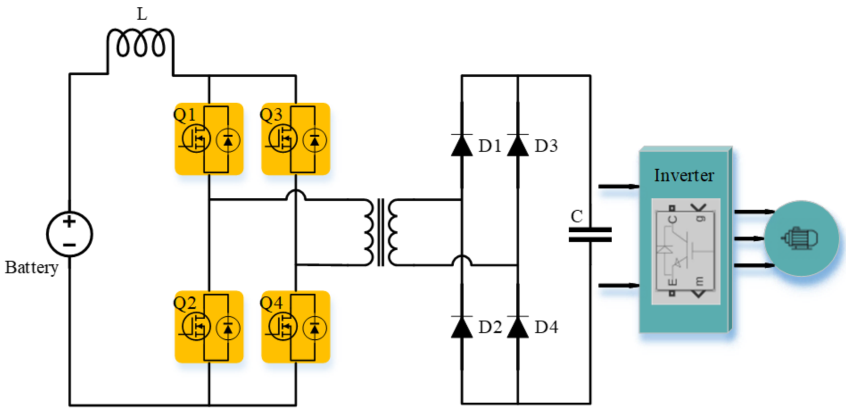

Figure 24. Full-bridge boost DC/DC Converter.

4.2.2. Multiport DC/DC converter

Isolated multiport DC/DC converter is designed to manage multiple input and output ports while ensuring electrical isolation between these ports. These converters are capable of connecting different energy sources, like solar panels, batteries, and supercapacitors, to either one load or multiple loads. Their versatility makes them perfect for applications that require different voltage levels. They are commonly used in renewable energy systems, EVs, and microgrids. In EVs, these converters have the ability to handle power from multiple sources, such as batteries and SC[125].

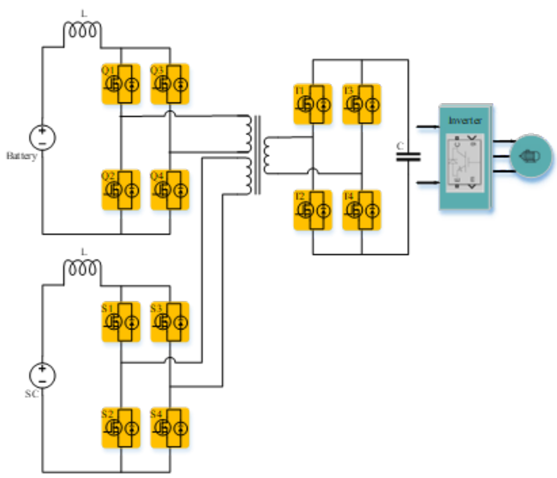

Figure 25. Isolated multiport DC/DC converter.

These converters come in various topologies, including bidirectional and unidirectional types. Bidirectional converters are advantageous in applications that involve battery charging and discharging due to their ability to transfer power in both directions[126]. Isolated multiport DC/DC converter is shown in Figure 25.

4.2.3. Dual active bridge (DAB)

DAB DC/DC converter is regarded as a highly promising topology for modern power electronics, offering bidirectional power transfer, galvanic isolation, and high efficiency in power conversion [127]. DAB converters are commonly used in EV onboard chargers due to their numerous advantages, including high power density, reduced voltage stress on power semiconductor devices, smaller filter component requirements, and low sensitivity to component variations [128]. DAB converter consists of two full-bridge DC/AC converters connected by a series inductor and a HFT as shown in Figure 26. This configuration enables efficient power transfer while providing galvanic isolation, making it ideal for applications that demand secure, high-frequency bidirectional power exchange [129].

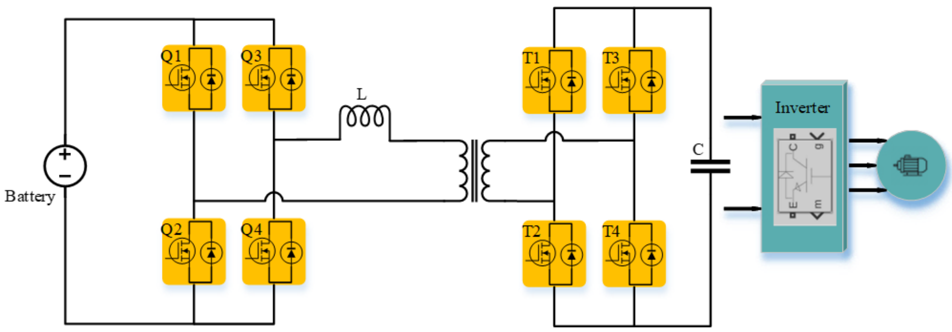

Figure 26. Dual active bridge.

4.2.4. Zero-voltage switching (ZVS) DC/DC

ZVS DC/DC converter offers key advantages for applications requiring cold starting, soft switching, and electrical isolation. Unlike traditional full-bridge step-up DC/DC converters, this ZVS topology requires fewer components and simplifies control, achieving soft switching without the need for additional circuitry. The isolated ZVS converter is designed with a dual half-bridge topology, featuring half-bridge configurations on both sides of the primary transformer. This arrangement, as shown in Figure 27, enhances the converter's efficiency and reduces circuit complexity [21], [130].

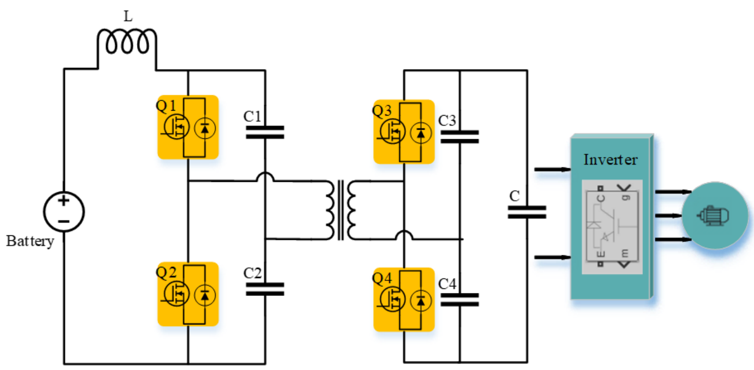

Figure 27. Isolated zero voltage switching.

Bidirectional DC/DC converters are essential in modern EVs, and they are commonly found in two major subsystems. Their primary purpose is to be used in the traction system, alongside an inverter and EM, to both propel the vehicle and recover energy during regenerative braking. Secondly, they are embedded within the onboard charger (OBC), enabling the vehicle not only to charge from the grid but also to discharge stored energy back to external loads, homes, or the grid, in the context of V2G and V2H applications. In both scenarios, bidirectional operation is necessary for managing energy flow, system efficiency, and grid integration.

A real-world implementation of this concept is found in Tesla's upcoming bidirectional charging architecture, announced for rollout across its full EV lineup, including the Model 3, Model Y, Model S, Model X, and Cybertruck by 2025. Tesla's approach utilizes a two-stage architecture, with an AC/DC rectifier followed by a bidirectional DC/DC converter as shown in Figure 28, likely based on the DAB topology due to its ability to handle power flow in both directions with high efficiency and galvanic isolation[131], [132]. This converter has the ability to charge the high-voltage traction battery, as well as export energy during peak demand or outages. In addition, Tesla is reportedly moving toward power electronics integration, combining the OBC, DC/DC converter, and traction inverter into a compact system to reduce volume, cost, and thermal load. This advanced integration enables Tesla vehicles to act as dynamic energy assets in the smart grid ecosystem, supporting distributed energy balancing and home backup power, establishing a benchmark for industrial deployment of bidirectional DC/DC converters in electric mobility.

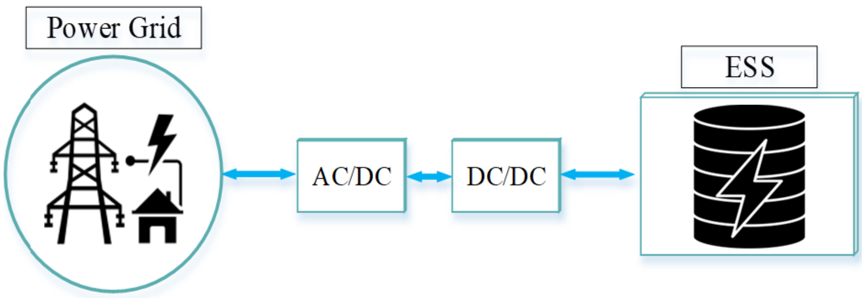

Figure 28. Two stage bidirectional OBC block diagram.

5. ELECTRONIC POWER CONVERTERS – DC/AC

DC-AC converters significantly enhance the controllability, overall performance, and efficiency of EVs. These converters facilitate the bidirectional power flow, enabling energy transfer from the battery to drive the wheels during acceleration, and allowing energy to flow back to the battery during regenerative braking. This dual functionality maximizes energy recovery, optimizes battery usage, increases fuel efficiency, and extends vehicle range.

According to many studies of EVs and power converters used to convert energy from the battery to the EM, traction inverters can be grouped into two basic categories: two-level inverters and multilevel inverters[22], [30], [124], [133].

The fundamental difference between two-level and multilevel inverters lies in the number of output voltage levels. A two-level inverter generates only two voltage levels, whereas a multilevel inverter produces multiple voltage levels in the output waveform. As a result, multilevel inverters offer improved performance compared to two-level inverters at the same power rating.

According to recent studies, two-level inverters (TLIs) can be categorized into voltage-source inverters (VSI), current-source inverters (CSI), impedance-source converters (ZSC), and two-boost inverters (TBI)[29],[22], [30], [124], [133]. Multilevel inverters (MLIs), on the other hand, are categorized into diode-clamped, flying-capacitor, cascaded H-bridge, and hybrid configurations[134]. These classifications are illustrated in Figure 29.

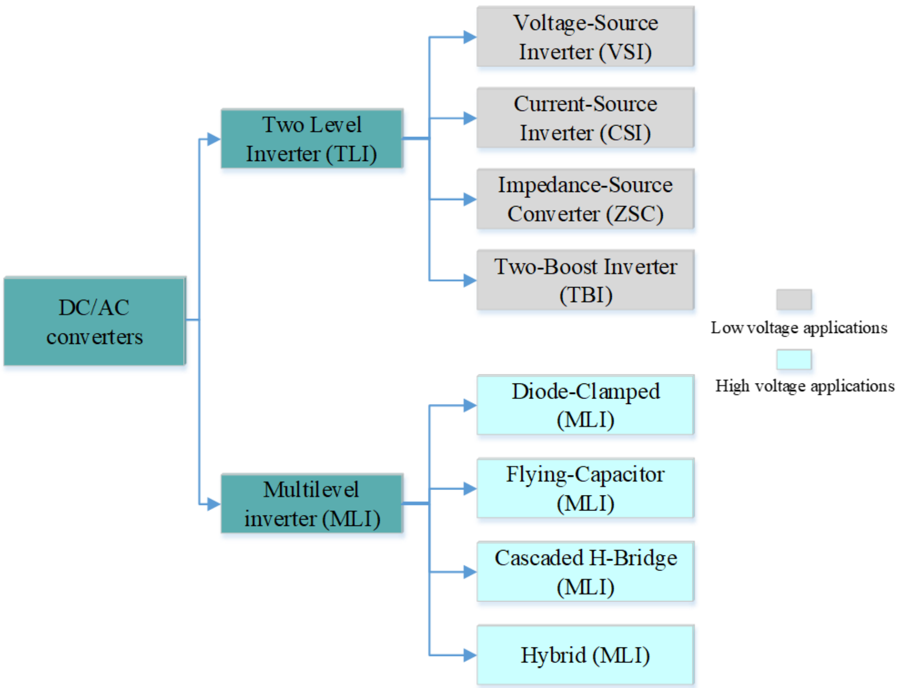

Figure 29. Classification of DC/AC converters (inverters).

5.1. Two level inverters (TLIs)

5.1.1. Voltage source inverter (VSI)

VSI typically includes a DC power source and semiconductor switching devices such as IGBTs, MOSFETs, or thyristors, which generate rectangular voltage pulses to each output phase. VSIs are known for their straightforward design, making them easier to develop and implement than current-source inverters. Additionally, they tend to be more cost-effective since they require fewer components and simpler control strategies. However, they also have disadvantages, such as higher harmonic content in the output waveform, which can impact power quality, and lower efficiency compared to more complex inverter designs due to increased switching losses [135], [136]. VSI configuration is shown in Figure 30.

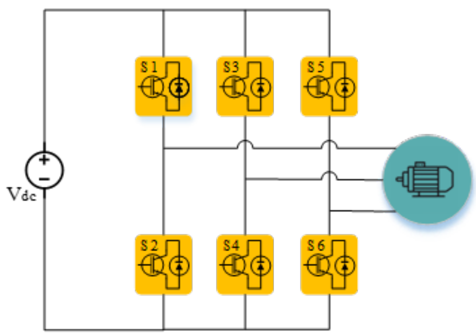

Figure 30. Three-phase voltage-source inverter VSI.

5.1.2. Current source inverter (CSI)

CSI configuration is shown in Figure 31. Among its components we have the inductor maintains a constant current during the switching operation, while the switches (S1 to S6) control the current flow to convert DC into AC. Diodes ensure that current flows in the correct direction when switches are off, and capacitor smooth out voltage fluctuations and spikes caused by the switching, stabilizing the AC output. The advantages of these converters include their ability to handle overloads and short circuits effectively, their high efficiency, and their capability to maintain a constant current. However, they can be complex to design and often necessitate a large inductor, which may be a drawback in some applications [137], [138].

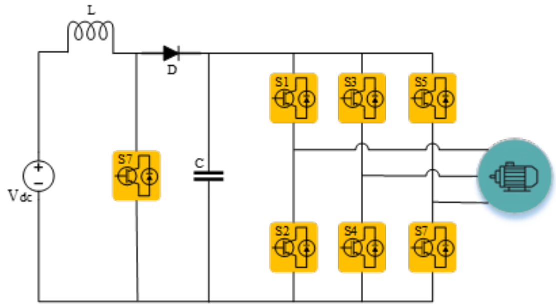

Figure 31. Three-phase current-source inverter VSI.

5.1.3. Z-source inverter

Z-source inverter is an advanced type of inverter that combines features of traditional VSIs and CSIs. They are notable for their ability to perform both buck and boost operations [139]. This capability is achieved through its unique impedance (Z) network, which efficiently converts power between the source and the load. The Z-network, comprising an inductor and a capacitor, forms a bridge that allows the inverter to perform both buck and boost operations. The configuration is illustrated in Figure 32.

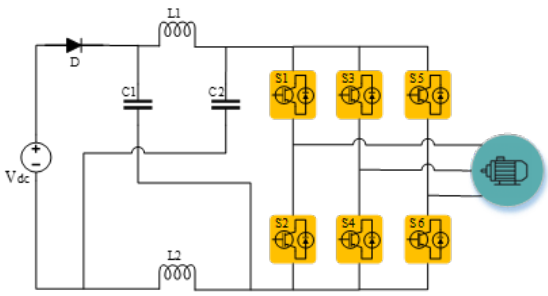

Figure 32. Three-phase Z-source inverter VSI.

5.1.4. Two-boost inverter

Two-boost inverter configuration as shown in Figure 33, the system consists of two separate boost converters connected in parallel to a DC supply. This configuration allows to achieve higher efficiency and better performance in terms of voltage regulation and power handling [22].

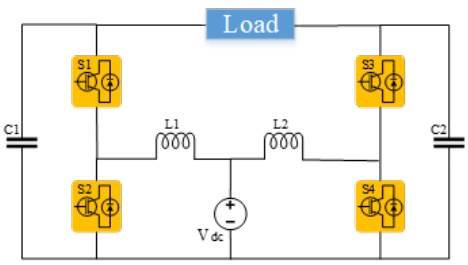

Figure 33. Single phase Two-Boost Inverter TBI.

5.2. Multilevel inverters (MLIs)

5.2.1. Diode-clamped multilevel inverter (DCMLI)
DCMLI is a multilevel inverter that utilizes diodes to restrict voltage stress on power components. This inverter configuration is commonly employed in high-power and medium-voltage applications because it can generate multiple voltage levels, enhancing the quality of the output waveform and minimizing total harmonic distortion (THD) [140]. The DCMLI produces several voltage levels by linking the phases through a series of capacitors. For example, as illustrated in Figure 34, a three-level inverter uses two capacitors to split the DC bus voltage into three separate levels: (0), (Vdc/2), and (Vdc). The diodes limit the voltage across each switch to a portion of the DC bus voltage, which helps to lower the voltage stress on the switches[141]. Capacitors are utilized to divide the input DC voltage into multiple levels. For an M-level inverter, (M−1) capacitors are needed. Each leg of the inverter is made up of multiple switching devices and clamping diodes. Specifically, For an N-level inverter, each leg needs 2 × (N − 1) switching devices and (N − 1) × (N − 2) clamping diodes[140], [141].

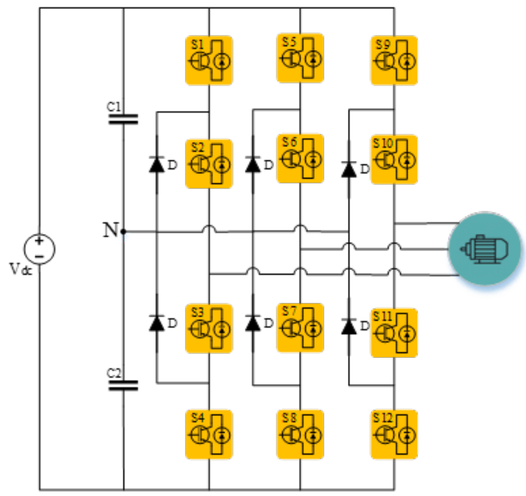

Figure 34: Three-phase three-level diode-clamped MLI.

5.2.1. Flying capacitor multilevel inverter (FCMLI)

FCMLI is similar to the diode-clamped MLI, with the primary difference being that capacitors are used for clamping purposes instead of clamping diodes[140]. The statistics of the topology illustrated in Figure 35 are given below:
The number of switches for N-level is 2(N-1).
The number of DC-link capacitors for N-level is N-1.
The number of auxiliary capacitors is ((N-1)(N-2))/2.
The main advantages and disadvantages of the FC-MLI topology include the following[22]:
- It requires only a single DC source.
- The voltage produced by FCMLI is more robust compared to DCMLI.
- It can control both active and reactive power, aiding in capacitor balancing.
- A large number of clamping capacitors can function as a capacitor bank, offering short-term backup power during brief interruptions or outages.
- There are challenges with capacitor balancing.
- As the number of voltage levels increases, managing the proper charging and discharging of capacitors becomes increasingly complex.
- An increased number of capacitors results in a larger physical size and higher cost of the inverter.

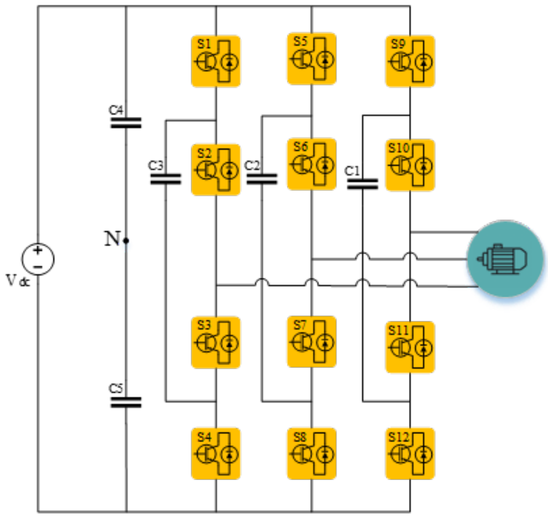

Figure 35. Three-phase three-level flying-capacitor multilevel inverter.

5.2.2. Cascaded H-bridge multilevel inverter (CHB-MLI)

CHB-MLI is composed of multiple H-bridge inverters connected in series. Each H-bridge can generate three voltage levels: positive, zero, and negative. By combining these H-bridges, the inverter creates a staircase waveform that closely approximates a sinusoidal output[140], [142]. CHB-MLI configuration is shown in Figure 36. According to[142], [143], the cascaded H-bridge multilevel inverter offers several key advantages. A staircase waveform provides lower THD, which reduces harmonic content and enhances power quality. Additionally, it minimizes switching losses because each H-bridge operates at a lower voltage. The system also features fault tolerance, allowing it to continue operating with reduced performance even if one H-bridge fails.

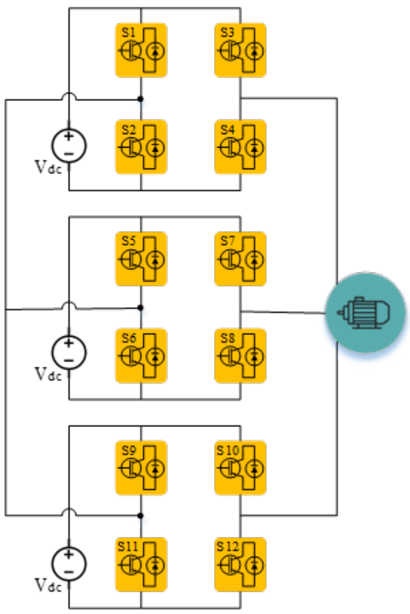

Figure 36. Three-phase three-level cascaded H-bridge MLI.

5.2.3. Hybrid multilevel inverter

Hybrid multilevel inverter is a type of power converter that combines different inverter topologies such as DCMLI, FCMLI, and CHB-MLI converters. The proposed topology is a three-phase hybrid inverter based on a switched capacitor, shown in Figure 37. This inverter topology consists of a multi-stage switched-capacitor auxiliary circuit integrated with a conventional cascaded three-phase inverter bridge. Each switched-capacitor stage is controlled to charge all capacitors fully in parallel with the DC source, then discharge them in series to the EV load through the power switches[22], [144].

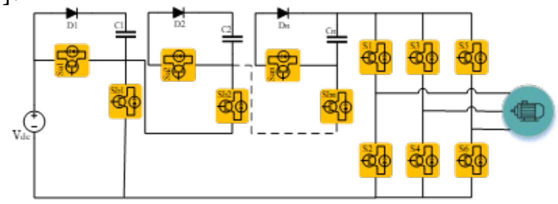

Figure 37. Three-phase hybrid MLI using switched capacitor.

Based on the reference[145], table 3 shows a comparative overview of different inverters used in EV models, with a focus on key powertrain metrics such as DC-link voltage, maximum fundamental frequency, power output, power density, and specific power. Models such as the Nissan Leaf (2012), Tesla Model S 70D (2015), and Toyota Prius (2016) demonstrate the advancements in EV technology through these characteristics, which have a direct impact on the vehicles' efficiency and performance. Power density and specific power, in particular, show advances in energy efficiency and lightweight design in EV powertrains, as these metrics measure power output relative to component volume and weight, respectively.
The Toyota Prius (2016) is notable for its 600 V DC-link and 1133 Hz maximum fundamental frequency, which highlight a highly effective inverter system. Toyota's inverter is equipped with a boost converter to raise the battery voltage to 600 V, resulting in improved motor performance. The inverter has a compact power module with dual-sided cooling and custom-designed IGBTs (later replaced by SiC devices in newer versions) that allow for high power density and efficient thermal management [146].
Toyota is currently using advanced two-level inverters in the existing Prius models, but they are considering using multi-level inverter topologies, such as three-level diode-clamped or flying capacitor inverters. The aim of these architectures is to reduce switching losses, improve efficiency, and support higher voltage scalability [146]. Figure 38 shows an example of Toyota Prius inverter.

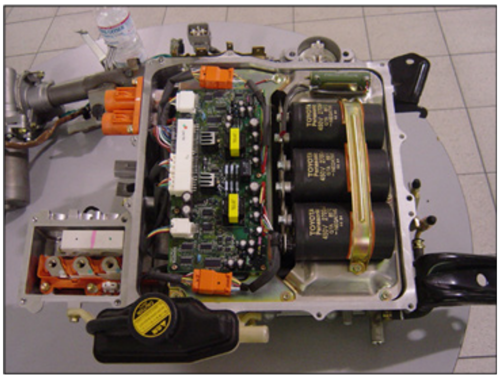

Figure 38. Toyota Prius inverter[147].

Table 3. Traction Inverters specification used in commercially available EVs/HEVs.

	Type	DC-link (V)	Max f1 (Hz)	Power (kW)	Power density (kW/L)	Specific power (kW)
Nissan Leaf (2012)	BEV	345	693	80	7.1	4.7
Tesla Model S 70D (2015)	BEV	375	493	193	30.1	33.
Chevy Volt (2016)	PHEV	430	800	180	17.3	21.7

Cadillac CT6 (2016)	PHEV	360/430	667	215	22.6	16
Toyota Prius (2016)	HEV	600	1133	162	23.7	13.6
Audi A3 e-Tron (2016)	PHEV	396	_	75	9.4	7.4
Tesla Model 3 (2017)	BEV	375/400	900	200	_	_

6. EV MOTORS

EVs have progressed quickly and play a vital role in the worldwide transition to sustainable mobility. At the heart of every EV lies its motor, which significantly influences the vehicle's efficiency, performance, and driving range. This motor transforms electrical energy into mechanical power to propel the vehicle. With the rising demand for EVs, different types of EMs have been developed and improved to suit various requirements and applications.
According to [145], modern BEVs and HEVs generally use three types of machines: AC induction machines, internal permanent magnet (IPM) machines, and permanent magnet synchronous motors.
According to [148], advanced EM technologies used in EVs include induction machines (IMs), switched reluctance machines (SRMs), permanent magnet synchronous machines (PMSMs), and permanent magnet-assisted synchronous reluctance machines (PMa-SynRMs)[149]. The reference also highlights other emerging machine types that could be applied in EVs. Additionally, according to [150], the primary types of machines used are IMs, PMSMs, SRMs, SynRMs, and direct current machines(DCMs). Figure 39 illustrates various common types of machines. It includes IM, which can be categorized into squirrel cage and wound-rotor types. Additionally, the figure features SRMs, and PMSMs, which are further divided into surface-mounted PM (SPM) and interior PM (IPM), as well as PMa-synRMs.

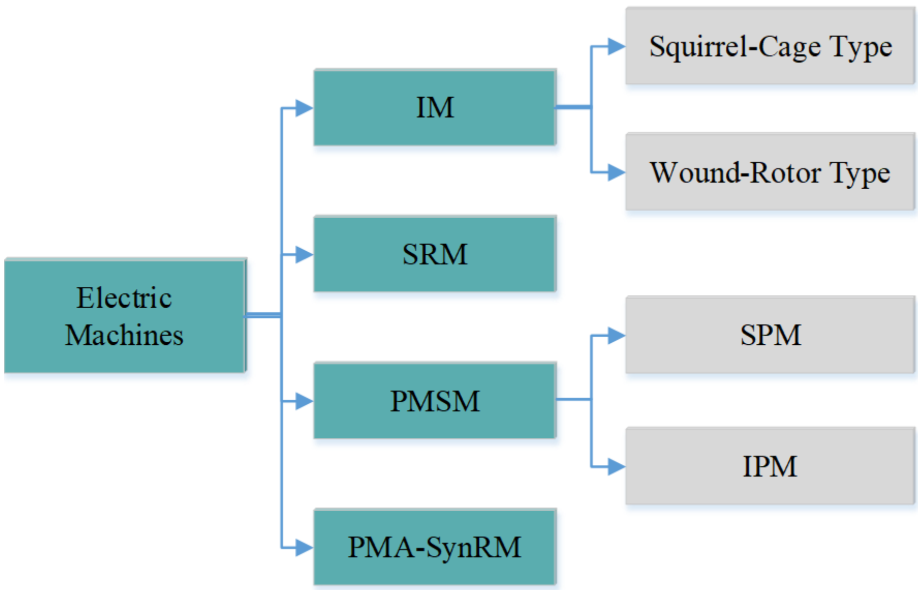

Figure 39. Classification of EMs for EVs.

6.1. Induction machine

An induction machine, or asynchronous machine, is an AC EM in which the current needed to generate torque is induced by the magnetic field of the stator winding through electromagnetic induction. IMs are widely employed in numerous commercial EVs, such as the Tesla Model 3 and

Model S, BMW i3, Mercedes-Benz B-Class Electric, Toyota RAV4, and Nissan Leaf[151], [152]. The advantages and disadvantages of this machine are proposed by [150] as follows :

Advantages:

High Efficiency: Induction motors with high efficiency are specifically engineered to minimize energy losses, leading to greater operational efficiency and lower running costs.

Variable frequency drives: VFDs regulate the speed of IMs, enabling them to operate at varying speeds based on the application. This results in considerable energy savings, along with enhanced control and precision.

Direct torque control: This technique controls the torque of an IM by directly measuring the stator flux and rotor position, which enhances dynamic performance and boosts overall efficiency.

Disadvantages:

Complex control systems: Advanced control methods such as DTC and VFDs necessitate intricate control systems, which can raise the motor's complexity and cost

High inrush currents: Induction motors require substantial magnetizing currents during startup, leading to high inrush currents.

Power factor issues: Induction motors may exhibit a low power factor at light loads, potentially impacting the system's efficiency.

IM can be categorized into squirrel cage and wound rotor as shown in Figure 40, a sample comparison between both types is provided in Table 4.

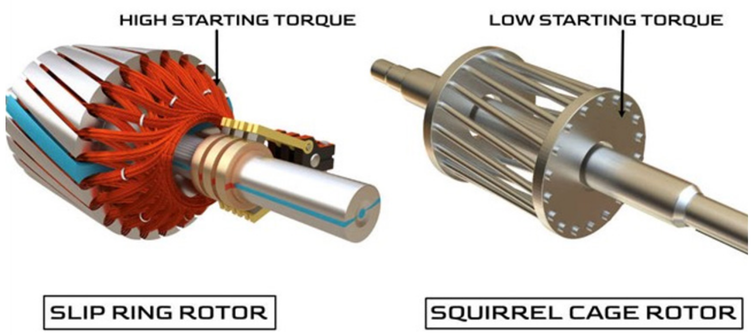

Figure 40. Squirrel case and wound rotor of induction machine (Adapted from [153], [154]).

Table 4. Comparison of squirrel cage and wound rotor induction motors.

Feature	Squirrel Cage Motor	Wound Rotor Motor
Design	Utilizes conductive bars in a cage-like arrangement within the rotor.	Features a wound rotor with external connections via slip rings.
Starting Torque	Provides relatively lower starting torque.	Offers higher starting torque due to external resistance control.
Speed Control	Limited speed control since rotor resistance is fixed.	Allows improved speed adjustment by modifying external resistance.
Starting Current	Requires a high initial current.	Draws lower starting current due to external resistance management.
Efficiency	Generally more efficient in continuous operation.	Slightly less efficient due to energy losses in external components.
Maintenance	Low maintenance; no brushes or slip rings.	Requires periodic maintenance of slip rings and brushes.
Cost	More economical due to simpler design.	Higher cost due to additional components and maintenance needs.

6.2. Switched reluctance machine (SRM)

SRMs feature a salient pole construction, as shown in Figure 41. The stator of a SRM is also salient and features concentrated windings around each pole, which is a defining characteristic of this motor type. SRMs have been increasingly considered for automotive applications due to their simplicity and robustness. Significant efforts are ongoing to enhance their performance, making them more competitive in various industries [155]. While SRMs offer several advantages, such as a high constant power speed range (CPSR) and excellent efficiency, there are still some challenges to overcome. Noise and torque ripple remain significant barriers to their wider adoption, particularly in automotive and other precision-demanding applications [151].

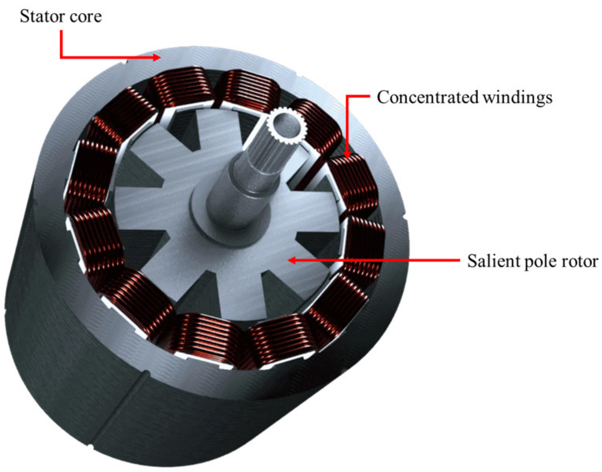

Figure 41. Switched Reluctance Motor (SRM) (Adapted from [156]).

6.3. Permanent magnet synchronous machine (PMSM)

With the rapid advancement in permanent magnet (PM) materials, PMSMs are becoming increasingly favored in electric drive systems for EVs and HEVs [157]. Several commercially available passenger EVs, including the Chevrolet Bolt, Ford Focus Electric, Hyundai Ioniq, and Jaguar I-Pace, utilize PMSMs as their primary propulsion component [151], [157].
PM machines can be categorized into various topologies and classifications. However, the rotor design is a fundamental factor in distinguishing these machines into two primary categories: SPM machines and IPM machines [155]. The distinction between these categories is based on the placement of the permanent magnets relative to the rotor (as shown in Figure 42), which significantly influences their performance and application characteristics.

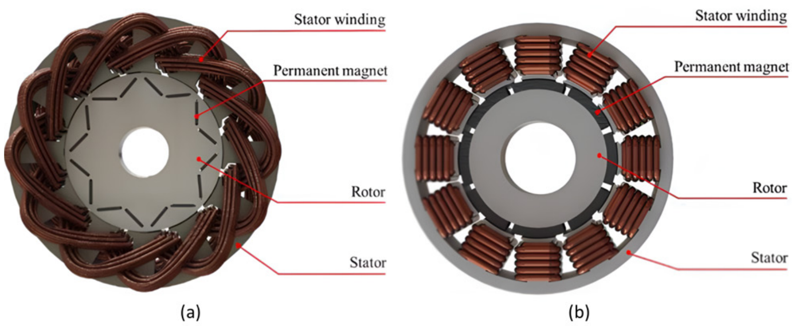

Figure 42. PMSM, (a) Interior PM V-shaped, (b) Surface PM (Adapted from [158]).

IPM machines generally offer better performance, especially at high speeds and under varying load conditions, compared to SPM machines. This is due to the embedded magnets, which allow for greater control and efficiency. However, IPM machines are more complex to design and manufacture because of their internal magnet placement. On the other hand, SPM machines are typically easier and less expensive to produce since the magnets are mounted on the surface, resulting in a simpler design.

6.4. Permanent magnet-assisted synchronous reluctance machine (PMa-synRM)

PMa-synRM combines the benefits of PMSM and SynRM, the stator is similar to that of a PMSM, while the rotor has flux barriers where permanent magnets are embedded. This design boosts magnetic saliency and enhances torque generation. Embedding permanent magnets in the rotor minimizes reluctance torque ripple, leading to improved overall efficiency and higher power density [159].

PMa-synRM delivers high efficiency by leveraging both reluctance torque and magnet torque. The incorporation of permanent magnets enables greater power density compared to conventional SynRMs. Additionally, these machines maintain efficient performance across a wide speed range, making them ideal for a variety of applications [160].

The topology of the PMa-synRM is depicted in Figure 43, where a U-shaped configuration is presented. Besides the U-shaped arrangement, there are also V-shaped and W-shaped configurations available for PMa-synRM.

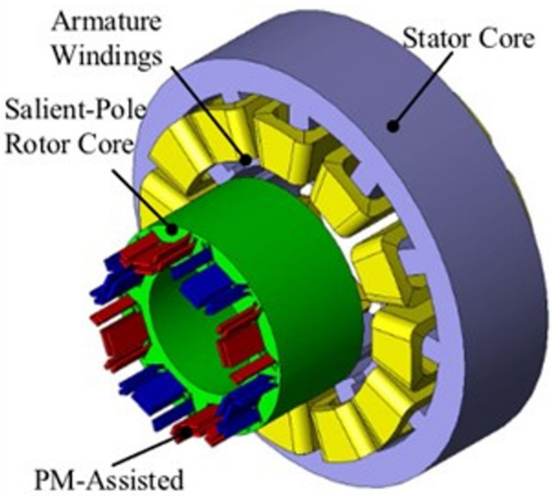

Figure 43. PMa-synRM topology [151].

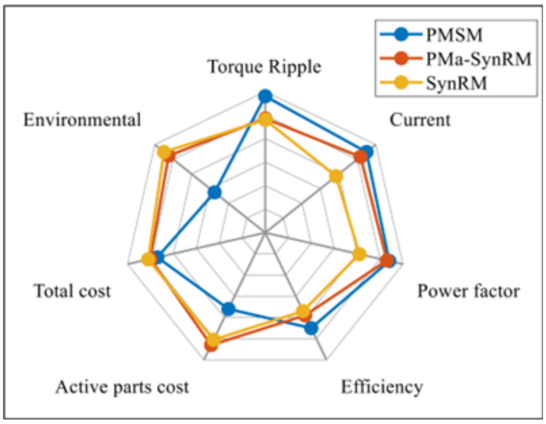

Figure 44. PMSM, PMa-synRM, and SynRM performance comparison [161].

Figure 44 provides a comparison between PMSM, SynRM, and PMa-synRM. PMSM demonstrates superior performance in terms of torque ripple and current, while SynRM excels in total cost and environmental impact. PMa-synRM shows balanced performance across most categories, combining the strengths of both PMSM and SynRM. This visualization emphasizes the trade-offs between these motor technologies in key performance aspects, offering insights into their suitability for various applications.

6.5. Discussion

Table 5 compares the key EMs types, IM, SRM, PMSM, both surface and interior magnets, and PMa-SynRM motors, in terms of efficiency, cost, and application. The table shows that IMs are straightforward and well-known, achieving moderate efficiency (92%) and a wide range of speeds. But lower torque density and power factor than magnet-based motors. PMSMs, on the other hand, offer the highest efficiency (94–95%) and torque density, but they are prone to saturation at high temperatures and rely on expensive rare-earth magnets. SynRM has the potential to be both low-cost and highly efficient, but they suffer from a narrow constant-power speed range and low power factor[162]. SRMs eliminate magnets and are mechanically robust, but they have severe torque ripple, noise, and vibration, which requires complex control. Hybrid designs such as permanent‑ magnet‑ assisted SynRMs use fewer rare-earths and approach PMSM torque density, with substantially lower material cost than a full-PM motor, but still do not fully match the peak performance (power factor, flux density) of pure PMSMs. A major concern with PMSMs and PMa SynRMs is their dependence on rare-earth magnets. NdFeB magnets contain critical elements (Nd, Pr, Dy) that are highly concentrated (the top three producers account for >75% of output) and have geopolitical implications[163]. The demand for minerals is expected to rise under aggressive EV deployment scenarios. For instance, an EV will require roughly six times the mineral inputs of a conventional vehicle[163], [164]. This means that the megatrend growth in EV production could spike Nd/Dy usage many times by 2040[163]. These changes increase the risks of cost and supply: NdFeB prices have already been extremely volatile, and any export restrictions (such as China's market share) would have an impact on the EV industry. Environmentally, rare earth mining/refining is energy intensive and polluting. Leaching and smelting processes generate vast amounts of toxic waste and greenhouse gases. In brief, the use of NdFeB brings with it both economic and environmental challenges[165]. In order to mitigate the sustainability risks, automakers and researchers are examining magnet recycling and developing magnet-reduced or magnet-free motor topologies[165]. Several EV traction designs are now free of permanent magnets altogether. Wound‑ rotor synchronous motors use a rotor excited by DC field windings or flux links. Such motors have been adopted by OEMs. For example, Nidec's mass-produced E-Axle and Renault's new Megane E-TECH powertrain use electrically-excited synchronous rotors[165]. These machines are capable of delivering high torque and a wide constant power speed range without the use of NdFeB magnets. Recent research indicates that a well-designed wound rotor synchronous motor can almost match the efficiency of a comparable PMSM throughout most of the drive cycle, even beating PMSM at light loads[166]. Tesla's initial EVs used three phase induction motors that were magnet free to achieve good high speed performance, although they had lower speed torque density because of slip. Another option for magnetless motors is SRMs, which have a simple, rugged construction and high theoretical efficiency, but require very sophisticated control to compensate for their inherently discontinuous torque [165]. In conclusion, magnet-free solutions such as induction, wound-rotor, and SRM resolve rare-earth supply issues, but usually lead to greater volumes, copper losses, or increased control complexity. Their future relevance will depend on the improvement of materials and control algorithms to minimize trade-offs [165], [166]

Table 5. Comparison of EMs for EVs in terms of efficiency, cost, and application suitability.

Motor type	Efficiency	Cost	Application suitability	Ref.
IM	~92 %	Low (no rare-earth magnets; simple rotor)	Used in some EVs (e.g. early Tesla Model S/X)	[167], [168]
SRM	High (~90–95 %)	Very low (magnet-free, simple construction)	Under research for EVs but not widely used in production cars.	[150], [167]
SPM	Very high (~95–96 %)	High (expensive rare-earth magnets)	Widely used in EVs (e.g. Tesla Model 3 front motor)	[150], [167], [168]
IPM	Very high (~96–97 %)	Highest (complex rotor with lots of rare-earth)	Very common in modern EVs (e.g. Toyota, Nissan)	[150], [167], [168]
PMa-SynRM	High (~94–95 %)	Moderate (uses less or non-rare-earth PM material)	Emerging in EVs (e.g. some Hyundai designs)	[150], [167], [168]

7. EVS CHARGING SYSTEMS

EVs are classified into four types: BEV, HEV, FCEV, and EREV. Both BEVs and PHEVs require charging at designated stations, making the availability of charging infrastructure essential for their functionality and widespread use. EV charging stations operate with two main types of charging systems: the conductive charging system and the inductive charging system [128], [169], [170]. The conductive charging system transfers power through a physical connection between the vehicle and the charger, typically using a cable and plug. This method is widely used for most current EVs due to its efficiency and simplicity. In contrast, the inductive charging system, also known as wireless charging[171], transfers power without direct contact by using electromagnetic fields. The conductive charging system can be divided into level 1, level 2, and level 3[172]. The inductive charging system is also divided into three sections, static wireless charging, dynamic charging, and quasi-dynamic charging [173]. The classification is provided in Figure 45.

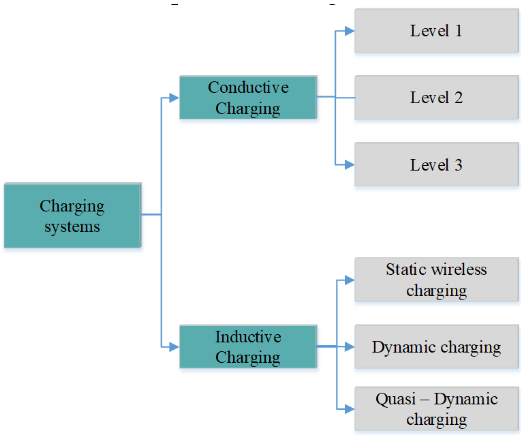

Figure 45. Charging systems classification.

7.1. Conductive charging

Conductive charging, the most common method for powering EVs, relies on a physical cable connection between the EV and the charging station. It includes two main setups: onboard AC chargers, built into the vehicle for slower, alternating current charging, and offboard DC chargers, located externally and designed for rapid charging by supplying direct current directly to the battery. This method is employed by various EV models, including the Tesla Roadster, Nissan Leaf, and Chevrolet Volt [128].

7.1.1. Level 1

Level 1 charging operates at 120V and is classified as a slow charging method. It typically uses a standard SAE J1772 connector (in North America) to connect the EV to a household power outlet. Commonly found in residential settings, Level 1 chargers offer a convenient option for overnight charging or for drivers with modest daily commuting needs, despite their slower charging speed [128]. Although Level 1 chargers typically require no special installation, optional upgrades such as adding a dedicated outlet or enhancing electrical safety can cost between $500 and $880. Charging an EV via Level 1 usually takes between 11 and 36 hours for a full charge, depending on the battery's size and capacity [174]. The concept of Level 1 and Level 2 AC charging systems is illustrated in Figure 46.

7.1.2. Level 2

Level 2 charging stations typically operate at 240 volts in single-phase systems and are commonly used in residential and commercial settings. In North America, they use SAE J1772 connectors for AC charging. With power delivery ranging from 3.3 kW to 22 kW, these chargers can fully recharge most EV batteries within 2 to 8 hours. Although installation involves higher costs due to the need for a dedicated electrical circuit and specialized equipment, Level 2 chargers are more energy-efficient and significantly reduce charging time compared to Level 1. They are ideal for everyday use at home, in workplaces, and at public charging locations [128], [174].

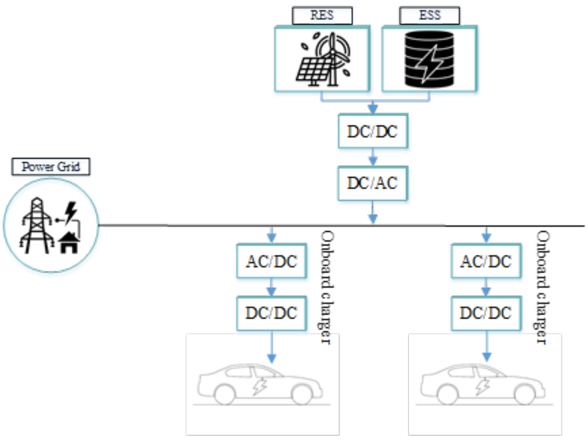

Figure 46. AC charging system.

7.1.3. Level 3 - DC Fast

Level 3 chargers, or DC fast chargers, rely on external isolated power converters to supply high-voltage direct current directly to the vehicle's battery, as shown in Figure 47.

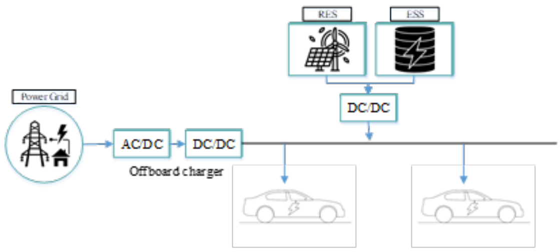

Figure 47. Level 3 charging system.

Unlike Level 1 and Level 2 systems, where AC to DC conversion happens inside the vehicle, DC fast chargers perform this conversion externally, enabling much faster charging speeds.

Depending on the vehicle and charger, an EV battery can typically be recharged to 80% in about 30 minutes. However, the infrastructure cost is substantially higher, with installation expenses generally ranging from $30,000 to $160,000. Several connector standards are used in DC fast charging and DC Ultra-fast charging, including CCS Combo 1, primarily in North America, and CCS Combo 2, commonly used in Europe. Tesla's NACS is gaining widespread adoption in North America due to recent manufacturer support. Other standards include CHAdeMO, mainly used by older Japanese EV models, and ChaoJi, a next-generation high-power charging standard being developed for broader international compatibility [128], [174].

7.1.4. Level 3 – DC Ultra-Fast

Recently, DC fast-charging networks have been deployed Ultra-fast (350 kW) CCS stations along major routes, which significantly reduce full-charge times, often in less than 30 minutes. To take full advantage of these power levels, modern EVs are adopting 800V battery architectures to achieve exceptional charging speeds[175]. To efficiently handle such high power, chargers use advanced CC/CV (Constant Current/Constant Voltage) control, which optimizes charging while protecting battery health. Several locations incorporate local energy storage or renewables, like co-located PV panels and batteries, to reduce grid impact[176]. Table 6 compares conductive charging types based on their normal power outputs, voltage levels, anticipated charging periods, and typical applications. As illustrated, charging time lowers substantially as power level increases, with ultra-fast DC chargers delivering up to 350 kW and achieving an 80% charge in as little as 10-20 minutes, making them ideal for long-distance travel and fleet operations.

Table 6. Comparison of Conductive Charging Types.

Charging Level	Typical Power Output	Voltage	Estimated Charging Time	Use Case	Source
Level 1 (AC)	~1.4–2 kW	120 V (US)	11–36 hours (for ~60 kWh)	Home charging, overnight use	[177]
Level 2 (AC)	3.3–22 kW	208–240 V	2–6 hours	Residential and public chargers	[177]
Level 3 - (DC Fast)	50–150 kW	400–800 V	20–60 minutes	Highway corridors, rapid top-ups	[178]
Level 3 - DC Ultra-Fast	250–350+ kW	800–1000+ V	10–20 minutes	Long-distance travel, fleet operations	[178]

Adding DC Ultra-Fast chargers can strain distribution networks. Studies report that fast charging introduces significant power loss, voltage dips, harmonic distortion, and transformer overloading when large loads are connected to a feeder [179], [180]. In order to avoid this, system designs are increasingly incorporating on-site energy storage, intelligent power electronics, and demand-response controls [176], [181]. For example, V2G and stationary storage allow bidirectional power flow, using batteries to smooth out peaks during charging sessions. In practice, planners observe that upstream grid reinforcement is often necessary, particularly in rural corridors, to maintain voltage quality when ultra-fast chargers are densely placed[181].

7.1.5. Standards and Compatibility

EV charging standards are crucial in shaping global infrastructure, interoperability, and accessibility for consumers. Various standards, such as CCS, CHAdeMO, Tesla's NACS, GB/T, and Type 2 as shown in table 7, cater to different regions, each with unique technical specifications and charging capabilities. While CCS has become prominent in Europe and North America because of its combined AC/DC functionality, CHAdeMO still dominates Japan due to its early adoption and bidirectional charging support. Similarly, Tesla's proprietary supercharger network provides high-speed charging, but its integration with wider industry standards is evolving. In China, GB/T keeps defining the charging ecosystem, making sure it is compatible with all domestic EV models. The growing adoption of ChaoJi, developed by Japan and China, suggests a push towards global unification, enabling higher charging speeds and improved efficiency.

Table 7. Comparison of EV Charging Standards.

Charging Level	Standard / Connector	Power Output	Voltage Range	Typical Use Case	Region	Source
Level 1 (AC)	SAE J1772 (Type 1)	Up to 1.92 kW	120 V	Home charging	North America	[182]
Level 2 (AC)	SAE J1772 (Type 1)	Up to 19.2 kW	208–240 V	Residential and public charging	North America	[183]
	IEC 62196-2 (Type 2)	Up to 43 kW	230–400 V	Residential and public charging	Europe, South Africa, North Africa	[184]
	GB/T 20234.2	Up to 27.7 kW	220–380 V	Residential and public charging	China	[182]
Level 3 (DC Fast Charging)	CCS Combo 1 (Type 1)	Up to 350 kW	200–1000 V	Public fast charging	North America	[185], [186]
	CCS Combo 2 (Type 2)	Up to 350 kW	200–1000 V	Public fast charging	Europe, South Africa, North Africa	[185], [186]
	Tesla NACS	Up to 250 kW	300–500 V	Tesla Supercharging network	North America	[185], [187]
	CHAdeMO	Up to 400 kW	50–1000 V	Public fast charging	Japan, North Africa (limited)	[185]
	ChaoJi (CHAdeMO 3.0)	Up to 900 kW	200–1500 V	Emerging global standard	China, Japan	[188]

Despite technological advances, charger compatibility remains a major challenge that impacts EV owners, manufacturers, and infrastructure providers. The absence of universal connector standards results in regional fragmentation, necessitating drivers to acquire adapters or specific stations for their cars. In addition to physical connectors, communication protocols like ISO 15118 and OCPP dictate how EVs and charging networks interact, which affects efficiency, security, and authentication processes. Compatibility issues are also a result of differences in power delivery, as different charging standards operate at distinct voltage and current levels. While CCS and Tesla's NACS aim for high-power charging at 350 kW, CHAdeMO's architecture limits expansion beyond 400 kW without redesign. Additionally, bidirectional charging is essential for V2G applications, but it faces hurdles due to differing implementations across standards, which slows the adoption of energy-sharing solutions.

In the future, it will be essential to have more industry collaboration and regulatory efforts to bridge compatibility gaps and improve charging accessibility. The evolution of open-access networks, as demonstrated by Tesla's decision to share Supercharger infrastructure, hints at a shift towards universal compatibility. By standardizing connectors and protocols, such as ChaoJi's advancement and ISO adoption, charges can be simplified for both users and infrastructure providers. Sustainability also remains a key concern, as the deployment of charging stations must balance environmental impacts, grid stability, and accessibility for underserved regions. Addressing compatibility challenges will be essential for creating a seamless and efficient global charging network as EV adoption accelerates.

7.2. Inductive charging

Inductive charging, often called wireless power transfer (WPT), has become a promising substitute for conventional conductive charging methods in electric vehicles. This approach enables EV charging without physical plug-in connectors. Charging can occur either while the vehicle is moving, termed dynamic or quasi-dynamic charging, or when the vehicle is parked, known as static charging[189].

Unlike conductive charging, inductive charging operates without a direct physical connection between the vehicle and the charger. While bidirectional power flow, which enables energy to be transferred both to and from the vehicle, is not yet a standard feature in WPT, the technology shows potential for future integration. Wireless charging relies on electromagnetic induction, which uses two coils: a primary coil embedded in the road or surface of a charging station and a secondary coil installed within the vehicle. This setup enables the transfer of power through an electromagnetic field, providing a convenient, contactless charging solution [169], [189], [190]. The inductive charging system is shown in Figure 48.

Static charging can be installed in suitable areas like parking lots or residential garages, providing a convenient charging option when the vehicle is stationary.

Dynamic charging continuously powers the vehicle while it is moving, using designated charging tracks along its driving route. Dynamic WPT is currently being tested in several countries. Numerous demonstration projects (PATH, FABRIC, UNPLUGGED, etc.) have been noted by academic reviews that demonstrated the feasibility of in-motion charging[191]. For example, in 2022, Utah State's ASPIRE wirelessly charged a heavy-duty electric truck on a short roadway segment[192]. In Europe, Sweden's public road pilot (Smartroad Gotland) used embedded coils to charge buses/trucks, which proved to have 100 kW power delivery at highway speeds. These trials demonstrate the technical feasibility of DWPT, but its full-scale deployment is limited by cost and infrastructure complexity.

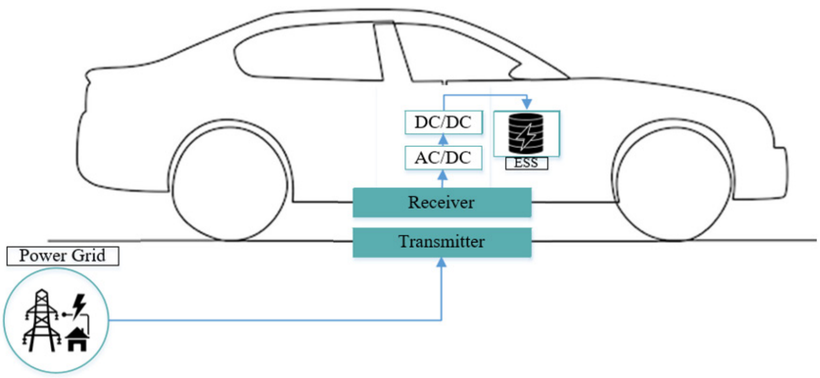

Figure 48. Inductive charging system.

Quasi-dynamic charging operates by charging the vehicle during brief stops, such as at traffic lights or intersections. In quasi-dynamic system, EVs, commonly buses or trucks, charge during short stops. An optimal layout for urban electric buses was determined by an optimization study, which involved placing 300 m of roadway transmitter across several bus stops and equipping buses with 13 kWh batteries, resulting in a reduction in overall cost and losses[193]. In practice, this involves installing inductive pads at specific stops to ensure that buses can consistently top off power. These quasi-dynamic setups combine the use of larger installed infrastructure (coils at stops) with smaller battery size and continuous charging. Initial projects, such as pilots at bus depots or select stops, are investigating these trade-offs, demonstrating that strategically positioning coils and utilizing local storage can increase range with minimal driver disruption [193].

Even though there is potential, inductive charging systems have several limitations that include loss of energy transfer efficiency, electromagnetic interference concerns, misalignment issues, and high installation and maintenance costs. Furthermore, the absence of international standards for coil designs and communication protocols hinders interoperability between vehicles and infrastructure[194].

The focus of future research should be to enhance coil alignment systems, enhance energy transfer efficiency, reduce costs through scalable manufacturing, and develop universal standards. Additionally, techno-economic studies are necessary to assess the viability of massive deployment in both urban and highway situations[195].

8. CONCLUSIONS

EVs and HEVs are critical to the advancement of sustainable transportation, as evidenced by this paper's thorough evaluation of over 190 research papers. This study analyzed the important components that support EV functionality and efficiency, including ESS, power electronic converters, traction motor, and charging infrastructure.

The exploration of electrification levels revealed a variety of EV categories, including HEVs such as MHEV, FHEV, and PHEV, as well as BEVs, FCEVs, and EREVs. Each category has distinct configurations that balance internal combustion engines with electric propulsion, catering to a variety of consumer needs while also contributing to lower greenhouse gas emissions.

Energy storage technologies were thoroughly examined, underlining the critical role of batteries, particularly lithium-ion batteries, in providing the energy density and dependability required for expanded vehicle ranges. Furthermore, the use of SCs and HESS was highlighted as critical for increasing charge and discharge rates, hence boosting total energy management and driving performance.

Power electronic converters, including both DC/DC and DC/AC, were assessed for their role in regulating and converting electrical energy in EVs. The review underlined the impact of different converter topologies on energy efficiency, power distribution, and the smooth integration of various vehicle components, all of which influence the overall operational efficacy of EV systems.

The traction motor technologies that were examined included IM, SRM, PMSM, and PMa-synRM. Each motor type was assessed for its efficiency, torque characteristics, and suitability for specific EV applications, demonstrating how motor selection impacts vehicle performance and energy consumption.

Lastly, the examination of charging systems emphasized the significance of both wireless and wired charging methods in facilitating the extensive adoption of EVs. The review highlighted the advancements in charging infrastructure, which are crucial for reducing range anxiety and ensuring that charging solutions are both convenient and accessible to users.

However, challenges such as grid stability and charger compatibility still persist. Towards supporting large-scale electric deployment and avoiding electrical grid overload, future research should focus on smart charging algorithms, V2G integration, and global standardization of charging interfaces.

In this context, the integration of V2G and G2V systems plays a vital role in future energy ecosystems. These bidirectional energy flows allow EVs to not only charge from the grid but also discharge energy back into the grid, supporting load balancing and renewable energy integration. To achieve such functionality, bidirectional chargers must be created with advanced control strategies that can manage power quality, grid synchronization, battery health, and cybersecurity. Research should prioritize the development of cost-effective, reliable, and standards-compliant bidirectional charging solutions.

Overall, this review synthesizes advancements in EVs/HEVs components, offering a comprehensive overview of the most recent technologies and their applications. The synthesis of data from numerous studies offers valuable insights into the strengths and limitations of various EV components, paving the way for future research aimed at enhancing vehicle performance, efficiency, and sustainability. By addressing the challenges identified in this review, stakeholders can better support the continued growth and integration of EVs into the global transportation landscape, contributing significantly to environmental sustainability and the reduction of fossil fuel dependency.

In order to advance the field, future research should address sustainability challenges, such as the reliance on rare-earth materials in permanent magnet motors (e.g., PMSMs). Exploring alternative motor designs such as SRM or magnet-free motors, as well as recycling methods for rare-earth elements, is essential.

Furthermore, developing and evaluating new emerging energy storage solutions such as solid-state batteries and lithium-sulfur batteries is essential to enhance safety, energy density, and lifecycle while minimizing dependence on scarce materials such as lithium and cobalt. Investigating sodium-ion batteries is a promising way to address critical mineral supply constraints.

Infrastructure limitations also require urgent attention, particularly hydrogen refueling networks for FCEVs and the lack of charging stations in rural or underserved areas (charging deserts). Research should investigate the cost-effective deployment models, mobile charging units, and incentives that can promote infrastructure expansion in these regions.

In conclusion, to accelerate the global transition to sustainable electric mobility, it is essential to address the identified gaps through targeted, actionable research and practical implementation strategies.

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