Chapter

Overview of Main Electric Subsystems of Zero-Emission Vehicles

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Abstract

The rapid growth of the electric vehicle market has stimulated the attention of power electronics and electric machine experts in order to find increasingly efficient solutions to the demands of this application. The constraints of space, weight, reliability, performance, and autonomy for the power train of the electric vehicle (EV) have increased the attention of scientific research in order to find more and more appropriate technological solutions. In this chapter, it proposes a focus on the main subsystems that make a zero-emission vehicle (ZEV), examining current features and topological configurations proposed in the literature. This analysis is preliminary to the various electric vehicle architectures proposed in the final paragraph. In particular, the electric drive represents the core of the electric vehicle propulsion. It is realized by different subsystems that have a single mission: ensure the requested power/energy based on the operating condition. Particular attention will be devoted to power subsystems, which are the fundamental elements to improving the performance of the ZEV.

Keywords: electric vehicle (EV), zero-emission vehicles (ZEV), battery electric vehicles (BEV), pure electric vehicles (PEV), vehicle to grid (V2G), electric drive, power train, energy storage system (ESS), battery management system (BMS), DC/AC converter, permanent magnet synchronous motor (PMSM), induction motor (IM), charging interface, EV architecture

1. Introduction

Until recently, electric cars were only small vehicles often designed with unusual shapes, able to move almost exclusively in the city area [1, 2]. Nowadays, electric cars are available in every size and style, often derived from the corresponding petrol models, so leading to the same internal and external fittings, load capacity, and passenger transport. Over the past few years, several legislative provisions aimed at encouraging electric mobility, pushing above all the administrations to create the boundary conditions so that the switch from a traditional vehicle to a *zero-emission vehicle* (*ZEV*) occurs with reduced discomfort [3]. Indeed, regarding the environmental impact, for assigning an optimal fuel/combustion ratio, about 85% of the combustion products in *internal combustion engines* (*ICE*) is represented by: carbon dioxide (CO_2), nontoxic but responsible for the greenhouse effect, carbon monoxide (CO), toxic and now constituting 2% of the air breathed, unburned hydrocarbons

(*HC*) and nitrogen oxides (*NOx*), toxic and responsible for acid rain. Therefore, the emissions of pollutants produced by traditional propulsion, multiplied by the number of vehicles in circulation, have a significant impact on our survival and life quality [4, 5]. As a consequence, the e-mobility role becomes crucial in the "green revolution," at least as much as that of the energy production from renewable sources. The transition to this new era of mobility is gradually increasing, passing through an intermediate phase, where there is also a fair presence of hybrid solutions that are progressively accustoming the user to the electric technology. After the transition period, the full electric propulsion will be destined to establish itself exclusively.

This revolution is accompanied by the parallel innovation in other sectors. The electric grid, for instance, is one of the fundamental elements to promote the development of electric cars; through a capillary presence of the charging stations to compensate the weak capacity of the onboard energy storage. The future is made of renewable sources and smart grids that manage power while taking into account both consumption and distributed generation, and electric cars can become a tool to strengthen efficiency and stability of the electric grid [6]. Several countries are already going down that route, with the so-called *vehicle to grid* (*V2G*) service: an innovative service, which allows electric vehicles to return energy to the grid when they are not in use, thus generating income for their owners [7]. Moreover, the spread of electric goes well with the sharing economy: electric car sharing is becoming increasingly common in all of the world's major cities.

Designing an electric car does not just mean replacing the *ICE* with an electric motor. Generally, electric car has no traditional transmission, no gear, and the engine size changes significantly (it can even be fitted in the wheels), but it needs space for the batteries, which are very heavy: the frame requires a new design; also materials change, shifting from aluminum to composite materials that are resistant but lighter, in order to increase battery capacity. The electric revolution thus opens up new opportunities regarding the areas of the design and manufacturing [8].

The *electric drive (ED)* represents the core of the electric vehicle propulsion. It is realized by different subsystems that have a single mission: to ensure the requested power/energy based on the operating condition. This chapter will show the characteristics of the individual subsystems that carry out a generic electric drive and the main architectures of electric drives suitable for *ZEVs*. Particular attention will be dedicated to state-of-the-art of the architectures and topologies employed for each power-subsystem in order to obtain the best performance on the market. This approach is fundamental to obtain an improving efficiency; nowadays, according to well-to-wheel (W2W) analysis [9], thermal engines have 17–19% efficiency scores, whereas the electric engine scores are at least equal to 36%.

2. Classification of electric vehicles

In recent years, hybrid and electric vehicles have always gained more market share [10]. These cars are equipped with an *energy storage system* (*ESS*, typically batteries), also integrating an *ICE* in the case of hybrid vehicle [11]. Despite the presence of an electric motor/generator and a battery, it is not possible to define a hybrid car a zero-emission vehicle. Therefore, before addressing the main issues of our topic, it is important to better define the different topologies of hybrid/electric cars, as briefly shown in **Figure 1**:

- *Plug-in hybrid electric vehicles (PHEVs)*: they are hybrid vehicles, that is, with double power source for propulsion, an electric and a combustion engine whose battery, normally designed for a range of a few tens of kilometers, and can be recharged from the electric grid [12]. Once the battery is discharged or as soon as it reaches a minimum charge level (20–40% of its energy), the vehicle, according to the type of system management, enters in "normal" hybrid operation, similar to that of hybrid vehicles not rechargeable. With a battery sizing suitable for delivering a range of 30 km, it may meet to "zero emissions" most of the vehicles in the city. Several cars of this type have autonomy in electric operation even over 50 km.

- *Range-extended electric vehicles (REEVs)*: they have a plug-in battery pack and electric motor, as well as an internal combustion engine. The battery, normally sized for a range around hundred kilometers or more, can be recharged from the electric grid; once discharged, comes into action an electric generator powered by the onboard internal combustion engine which provides the battery charging [13]. The difference from a plug-in hybrid is that the electric motor always drives the wheels, with the internal combustion engine acting as a generator to recharge the battery when it is depleted. The *ICE* of a *REEV* works at an optimized regime and this allows to obtain better efficiency compared to a traditional vehicle.

- *Bimodal vehicles*: they are vehicles equipped with two completely independent engines, respectively, electric powered by a rechargeable battery from the electric grid and endothermic that can be used as an alternative to the electric

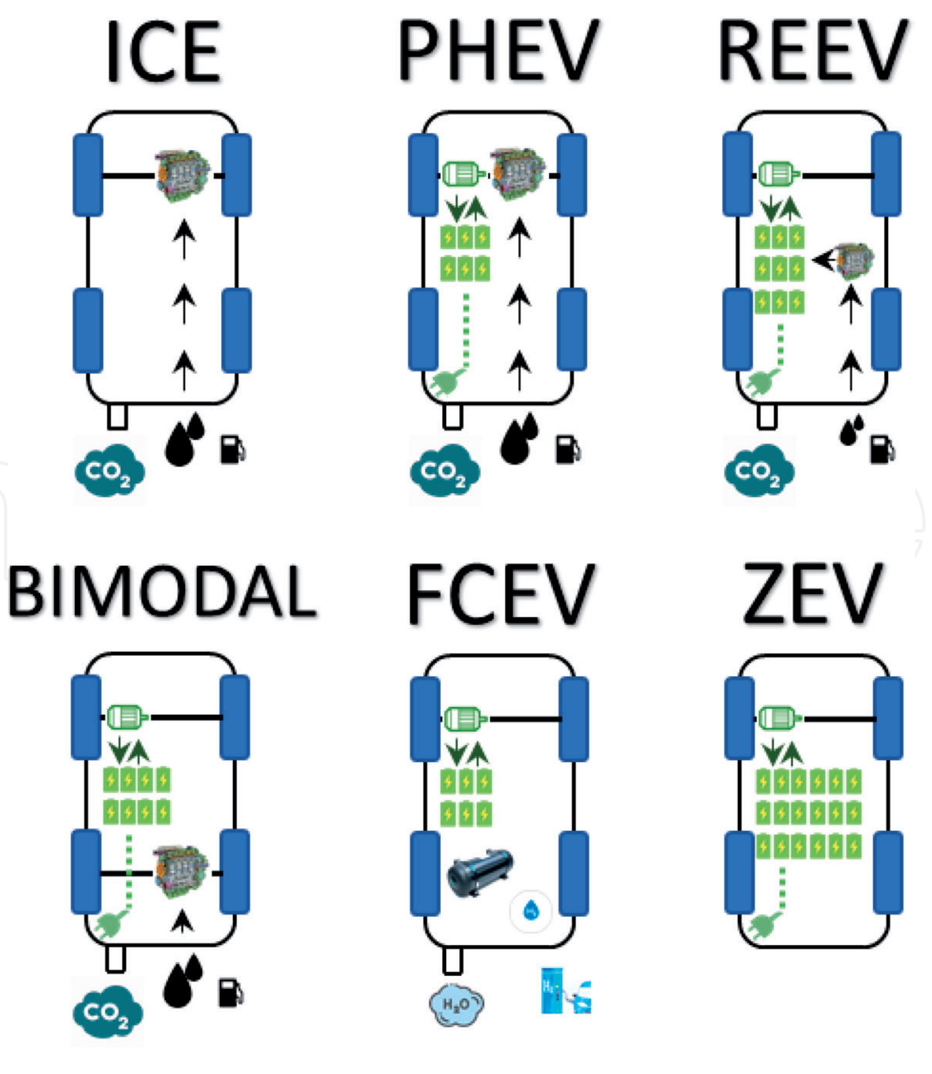

Figure 1.
Classification of the hybrid and electric vehicles.

one for long distances. Often, each of the engines is connected to an axis of the vehicle, which then operates with front or rear wheel drive depending on the activated motor.

- *Fuel cell electric vehicles (FCEVs)*: hydrogen fuel cell vehicles are a different topology of electric car and they have a fuel cell stack which uses hydrogen to produce energy that then powers the wheels of the vehicle [14]. The main difference between a fuel cell and a battery is the manner for supplying the source of energy. In the fuel cell, the production of the energy carries out thanks to hydrogen supply; in this way, it is not necessary to recharge in order to generate power. The products of the chemical reaction that occurs in a fuel cell are substantially heat and water; in particular, the latter is disposed of through the tailpipe. Differently from what happens for battery-powered vehicles, vehicles equipped with fuel cell can be recharged to appropriate filling stations in the same way as conventional vehicles. Charging times are comprised between 3 and 6 min. Typically, these vehicles have autonomy of about 500 km.

- *Zero-emission vehicles (ZEVs)*: full electric vehicles, otherwise known as *battery electric vehicles* (*BEV*) or *pure electric vehicles* (*PEV*), are wholly driven by an electric motor, powered by a battery that can be plugged to the grid [15]. There is no combustion engine.

Then, it will be evaluated and analyzed only the several solutions to realize the power train of a ZEV.

3. Basic ZEV architecture

The main elements on which ZEV architecture is built on are shown in **Figure 2**.

Indeed, several subsystems can be identified and each of these performs a specific mission also interacting with one or more other subsystems. The main macroblocks identified are:

- *The energy storage system*: usually the battery pack with its management system (*battery management system* also called *BMS*), which is designed to accumulate and supply energy.

- *DC/AC converter*: it is the power interface between the storage and the electric motor. It not only has the task of adapting the power supply but it also play important control functions, as will be fully described later.

- *Motor*: the electric motor, which can also be operated as a generator in case of the adoption of the regenerative braking, has the task of carrying out the conversion of electric energy coming from the *ESS* into mechanical energy to be supplied to the mechanical transmission to allow the car motion.

- *Charging interface*: the charging interface is essential for a ZEV, as it must allow the batteries to be recharged onboard. The charging interface includes different kinds, depending on the type/types of recharge that it wants to adopt (even more types on the same vehicle).

- *Control layer*: the supervisor and data acquisition system is dedicated to processing driving information and transforming it into references for the aforementioned power subsystems.

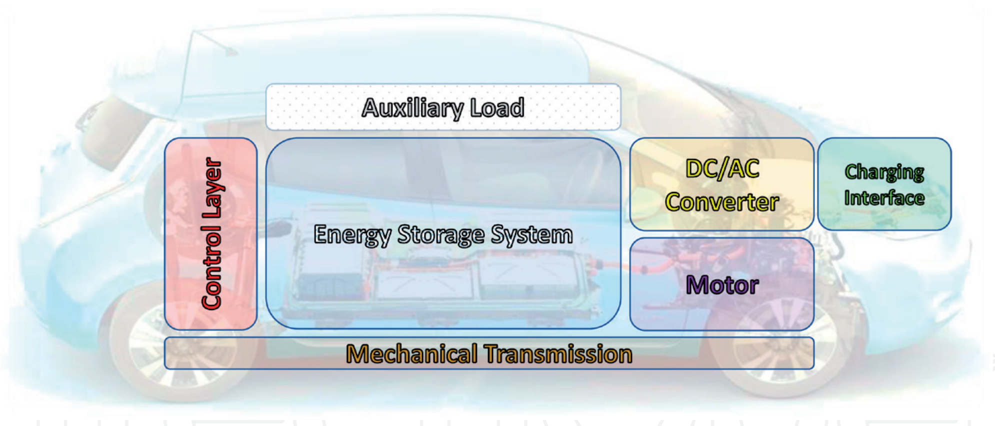

Figure 2.
Main subsystems of the basic ZEV architecture.

- *Auxiliary load*: the auxiliary loads, which will not be analyzed in this chapter, represent all the utilities onboard that need a power supply. Typically, the power of these loads occurs at a much lower voltage of the main voltage of the DC-bus, for example, 12 V, and must be galvanically insulated, for safety reasons, since this last. The power supply of the auxiliary load, therefore, is derived from the DC-bus through a DC/DC converter with electronic transformer (e.g., *flying bridge converter* or *isolated switch mode power supply*) which ensures the request insulation condition [16].

- *Mechanical transmission*: the mechanical transmission of an electric vehicle takes care of converting the energy coming from the electric motor into mechanical energy of movement, distributing it directly to the wheels of the car. This element has been borrowed from traditional vehicles and therefore has poor interest in carrying out its analysis here.

Next paragraphs are dedicated to the analysis of the technological solutions used and the technical characteristics regarding the main power subsystems of the power train previously indicated. In particular, we will provide the characteristics of the individual subsystems, identifying the performances achieved by the research in progress and their use/integration into the different proposed architectures.

4. Energy storage system

The storage system is becoming a key component in the electric vehicle. The panorama of energy storage devices can be divided into two main families: on one side *electromechanical* storage devices and on the other *electrochemical/electrostatic* devices. The first set fundamentally includes flywheels, while for the characteristics and the performances required of an electric vehicle, electrochemical systems are employed exclusively in order to guarantee the main propulsion; the classification is broader and more detailed [17], in particular, the main categories identified are:

- *Fuel cells*: it is an electrochemical system in which electric energy is produced through an oxidation–reduction chemical reaction. The storage difficulties are the main obstacle to the diffusion of systems based on hydrogen technologies, even if at the theoretical level, there are about several types of storage systems [18].

- *Electrochemical batteries*:

1. *Lead-acid batteries*: they are commercially mature rechargeable batteries. Generally, they are made up of lead metal and lead dioxide electrodes immersed in a sulfuric acid electrolyte (in the charged state). Lead-acid batteries generally are used in stationary energy storage applications, especially as a DC auxiliary. The energy density of lead-acid batteries is 35–40 Wh/kg, whereas the power density is 250 W/kg; the cost is (battery system only) 150–200 $/kWh [19].

2. *Nickel metal hydride batteries*: With reference to the positive electrode (cathode) of the nickel metal hydride (NiMH) batteries, it is made by nickel hydroxide ($Ni(OH)^2$). On the other hand, the anode uses the hydrogen as absorbing negative electrode. This latter is composed by metal hydrides, typically alloys of lanthanum and rare earths that work as a solid source of reduced hydrogen, which becomes oxidized to provide protons. As a rule, the electrolyte is alkaline (e.g., potassium hydroxide). These batteries have an energy density of 70–80 Wh/kg and a typical power density of 150–200 W/kg. The cost is around 400–450 $/kWh. Their main disadvantages are high self-discharge rates and a relatively low cycling capacity. Moreover, NiMH battery deteriorates during long time storage. This problem can be solved by charging and discharging the battery several times before reuse. This reconditioning also serves to overcome the problems of the "memory" effect [20].

3. *Sodium/metal chloride batteries*: the sodium-nickel chloride battery is better known as *zero-emission battery research activities* (ZEBRA) battery. These batteries work at high temperature, about 300 °C; it is very similar to the sodium sulfur battery. The energy density of the considered battery is around 100–120 Wh/kg and the specific power is about 150 W/kg. The negative electrode is composed of molten sodium, while the positive electrode is nickel in the discharged state and nickel chloride in the charged state. The molten sodium salt is employed as electrolyte. Lately, there has been a growing attention in the sodium-nickel chloride batteries for EV application. These batteries are substantially being developed and manufactured by General Electric and Fiamm SoNick. $NaNiCl_2$ batteries have a much lower self-discharge rate and better cycling capabilities than the other nickel battery variants. Like lead-acid batteries, sodium-sulfur batteries have a limited cycle life; they are able to charge and discharge a limited number of times before significantly degrading. The cost is about 600–700 $/kWh [21].

4. *Metal-air batteries*: metal-air batteries have a hypothetical energy density much higher than lithium-ion batteries and they are commonly sponsored as a solution toward next generation of ESS for electric vehicles or grid energy applications. This type of battery has a very high specific energy density; the reason is that these batteries are very performant because one of the reactants (the air) does not have to be stored in the battery. The metal-air battery is made by an exposed porous carbon electrode (called the air cathode) separated from the metal anode by an electrolyte. The exposed carbon electrode traps oxygen atoms from the air, which react with the positive metal ions from the anode. The scientific literature is investigating to substitute the nonaqueous electrolyte with solid, liquid, aqueous, and organic electrolytes but truth of facts demonstrate that the nonaqueous electrolyte is the most developed. The main advantage of this type of battery is the huge increase

in energy density over more conventional batteries; it is supposed that an energy density of up to 3 kWh/kg may be achievable although the actual maximum is 350 Wh/kg [22] in lab test. This is a developing technology that promises excellent results in the near future. It promises that the cost can reach 130–160 $/kW.

5. *Lithium polymer*: lithium polymer batteries use lithium metal and a transition metal intercalation oxide (MyOz) for the negative and positive electrodes, respectively. It has a specific energy of 155 Wh/kg and operates at a nominal voltage of 3 V with specific power of the 315 W/kg. A very low self-discharge rate, equal to 0.5% per month, is the main advantages together with capability of fabrication in a variety of sizes and shapes, and safe operation thanks to reduced activity of lithium with solid electrolyte. However, it has the low performance when works at a low temperature; this aspect is linked to the temperature dependence of ionic conductivity. The cost is about 200 $/kWh, a reduction to 100 $/kWh in 2025 is expected [23].

6. *Lithium ion batteries*: lithium ion batteries are now the leading type of batteries found in electric vehicles due to their high energy density, high efficiencies, and lightweight. The positive electrode is made by graphitic carbon with a layered structure, while the negative electrode in these batteries is a lithiated metal oxide. Typically, the electrolytes consist of lithium salts dissolved in organic carbonates. Lithium ion batteries are set to be the dominant battery for the electric vehicle market, and their development for this market is driving their costs down. The lithium-ion batteries are at the heart of technological development as it is currently the most promising technology. The current trend is to develop batteries in nanoscale and with vastly increased electrode surface areas. This approach provides significant improvements in terms of power, capacity, cost, materials, and sustainability. One other issue with Li-ion batteries is the lack of a viable recycling process. This is another topic of current research. There are many types of lithium-ion batteries. Those that have commercial relevance are lithium cobalt, lithium manganese, lithium nickel manganese cobalt, and lithium iron phosphate batteries. The energy density of actual L-ION batteries is 150–190 Wh/kg, whereas the power density is 500 W/kg; the cost is (battery system only) 150–200 $/kWh [24, 25].

- *Supercaps*: known as *electric double-layer capacitor* (*EDLC*); they are devices with a very high specific capacity when compared to the most common electrostatic capacitors. The electrochemical capacitor is characterized by a very similar construction to that of a battery; it has substantially two electrodes and an ion permeable separator, placed between the electrodes, which contains the electrolyte. The porous electrodes are immersed in an electrolytic solution and the area in which the charges are concentrated at the electrode/electrolyte interface is also called double-layer or "double layer." The electrochemical capacitors thus store energy in the double layer, or Helmholtz layer. The use of supercap in electric vehicles is linked to a demand for power rather than energy storage, indeed the frequent stop/go operation of EVs, the discharging/charging profile of the energy storage is vastly varied. The average power that the energy storage has to provide is very lower than the peak power; indeed, the peak power is required only for short time, for example, for fast acceleration and hill climbing. The ratio between peak power and average power can overcome 10:1. The energy involved in the acceleration and deceleration transients is roughly two-thirds of the total amount of energy over the whole vehicle mission in urban driving. Since it is difficult to obtain at the same time an energy storage with high values of specific energy, specific power, and cycle life, a hybridization solution can be chased for EV/HEV applications. In particular, the energy storage can be fulfilled with combination of the high specific energy system together to high specific power system. The power source system can be recharged from the energy system during less demanding driving or regenerative braking [26].

In order to have a general overview, in **Figure 3**, the characteristics of the main storage technologies that can be used for the purpose are summarized.

Although there are different types of batteries, those with lithium ion dominate the most recent group of developing electric vehicles. This type of batteries, as known, has a high energy density and they have a low memory effect. Furthermore, in the technical comparison of the different systems, an element that plays a crucial role is certainly the stability of the system and the expected life both in terms of system availability over time and life cycles. The effective life of lithium-ion batteries can be carried out with two different criteria: calendar life and cycle life. The first one allows the estimation of the useful life span without considering the cyclical model of the battery. The other one, instead, allows evaluation of the number of charge/discharge cycles that the battery can undertake before its usable capacity falls below 80% of its nominal capacity [27]. Several research studies have investigated the degradation process of lithium-ion batteries, identifying the different factors contributing to it and parameterizing the de-rate according to the characteristics of battery use, such as charge/discharge cycles, discharge depth (*DOD*), state of charge (*SOC*), operating temperature, charge/discharge rate, end-of-charge voltage (*EOCV*), etc. [28]. The loss of the cell capacity depends on a nonlinear way by the retention time, with a tendency to slow down while the aging process evolves. Conversely, the reduction of the power of the cell follows a linear dependence.

Table 1 shows the characteristics of the main accumulators examined previously, with particular attention to the energy density and power density.

4.1 Battery management system

The battery represents a time-varying system with a heavy nonlinear behavior due to the complex electrochemical process and to its inherent parameters: equivalent

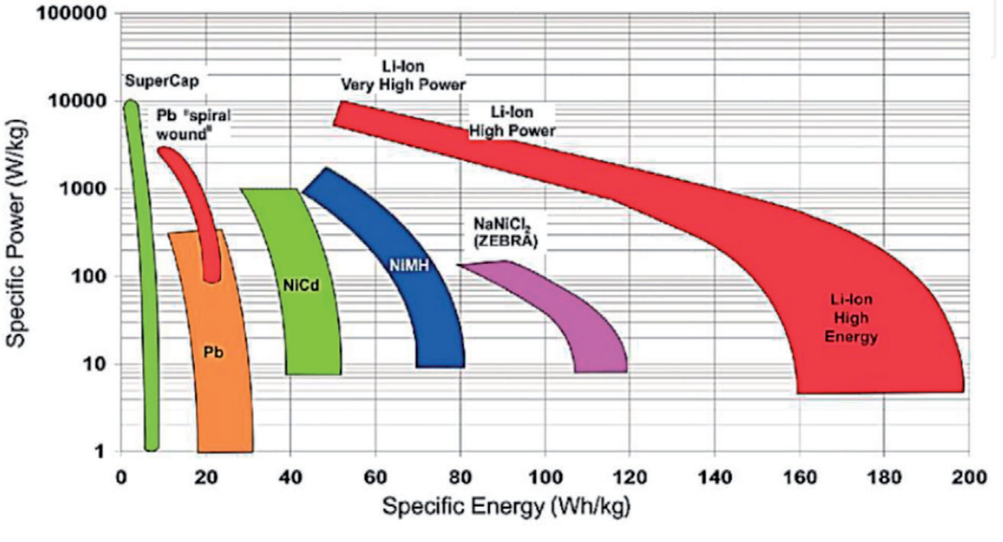

Figure 3.
Ragone diagram for the main storage technologies.

Type	Energy density (Wh/kg)	Power density (W/kg)	Efficiency (%)	Cost ($/kWh)	Cycling capacity
Fuel cell	1850[1]	—	50–55	—	—
Pb-A	35–40	250	75–90	150–200	500–2000 cycles
NiMH	70–80	150–200	72–78	400–450	1500–3000 cycles
$NaNiCl_2$	100–120	150	75–85	600–700	300–500 cycles
Metal-air	350	—	50	130–160	100–300 cycles
Lithium polymer	155	315		200	300–2000 cycles
Li-ion	150–190	500	75–90	150–200	3000 cycles at 80% D.O.D.
EDLC	5–15	up to 20.000	90–95	up to 10.000	up to 20.000.000 cycles

[1]*Hydrogen tank at 700 Bar and 10 kg of H_2.*

Table 1.
Energy and power density for ESS.

series resistance, open circuit voltage (OCV), and available capacity. The stable battery behavior in harsh environments represents a relevant issue regarding the safety and the utilization efficiency. Moreover, another objective is to increase the lifetime of the battery by suitably controlling the charging/discharging process. The latter means that it is recommended to avoid wide temperature excursion as well as a high frequency of charging cycles and/or deep discharging. Therefore, a *battery management system* (BMS) becomes an essential component to properly supervise the battery state [29]. The BMS represents a separate part, with its own hardware and firmware, which can usually be adapted to different battery categories by also allowing a safe battery operation. The battery state of charge (SOC) is the ratio between the available and the maximum capacity and its estimation is not very simple, because of the nonlinear nature of the battery itself. Nevertheless, a careful SOC evaluation is useful to prevent a battery fault, while also avoiding a premature aging, due to undesired undercharging/overcharging [30]. The above discussion highlights that an accurate battery model is crucial to guarantee an adequate dynamic behavior and to improve performance in terms of lifetime [31–33]. In fact, an accurate battery modeling should allow predicting the battery behavior in steady-state condition as well as during transient operation. Therefore, the main goal is to provide an accurate SOC estimation method, able to precisely track the SOC also during the charge/discharge transient operation, so that the residual vehicle autonomy is properly evaluated. In the current literature [34, 35], different approaches are proposed to model the battery behavior. The obtained models can be divided in three main categories: experimental, mathematical, and electrochemical equivalent circuit-based. The mathematical modeling is based on the evaluation of the battery voltage as a function of SOC, current and dc gain, while the equivalent circuit-based one neglects the internal electrochemical processes. The aforementioned models endorse good results in terms of accuracy and can be implemented in BMS for battery voltage prediction. Indeed, the model implementation inside the BMS is mandatory to suitably manage the energy flow both in case of charge and discharge process. Usually, in underperforming applications, one of the most used models is the simplified circuit model, which does not take into account the SOC as well as the battery dynamics: it consists of an ideal voltage source with a series resistance (i.e., internal resistance). On the other hand, an equivalent circuit, which also considers the battery dynamic behavior, consists of an OCV with voltage depending on SOC, an internal resistance and a number n of RC branches that take into account the effects of hysteresis and polarization, which occur inside the cells [36]. The model parameters are not constant but their behaviors vary with the SOC, the temperature, the lifetime, and the history (i.e., number and depth of cycles) of the cells. In order to evaluate the model parameters, it is possible to implement several series of charge/discharge cycles, monitoring the terminal voltages and currents at controlled temperature. The evaluation of the model parameters is a difficult task, since, either at the time of manufacturing or during their operation, a slightly variation of capacity occurs. In order to minimize the effects caused by cell parameter differences, it is very important to keep the cells at the same SOC. Thus, the equalization of the cell voltage and relative capacity is mandatory. Passive and active cell balancing action allows to maintain a suitable battery SOCs by monitoring individual cells in the stack. Consequently, the battery lifetime increases [37], while also assuring an extra protection against possible damage arising from deep discharging and/or overcharging. The passive balancing acts in a simple manner by dissipating the surplus of charge in a bleed resistor, so maintaining balanced SOCs. Nevertheless, this method does not extend the system run time. On the contrary, the active balancing represents a more effective method, able to equally distribute the energy among the cells both during charge and discharge cycles. This allows an increase of the available charge in the battery stack, so resulting in higher run time, while reducing the charging time and the heat generation, with respect to passive balancing.

5. DC/AC converter

In the architecture of an EV, the presence of the DC/AC converter is fundamental both for storage management and for the operation of the electric motor. Its main goal is to promote the transfer of energy from the batteries to the engine. Compared to the first versions of electric cars, currently, the best technological solution employs as a traction motor an AC type: *permanent magnet synchronous machine* (PMSM) or alternatively an induction motor (IM), for the relative details, see next section. This choice requires the adoption of a converter that must convert from DC to AC to supply the traction motor. Torque and speed of the motors can be controlled accurately by converter's control, improving the handling of the EV and maximizing the traction effort. Variable-speed, variable-frequency operations are essential features of traction drives and, therefore, electric motors and power converters are intimately connected in terms of design and performances [38, 39]. Future electric drives can improve the present state-of-the-art with an optimization of all the subsystems. Therefore, it is evident how the topology of this converter affects all the power train of an EV. It is possible to discriminate three topological configurations for the considered converter:

1. a single-stage DC/AC converter

2. a double-stage DC/AC converter

3. an integrated DC/AC converter

Each of the previously mentioned types has advantages and disadvantages and can be implemented with different circuit topologies, extending the realization possibilities and the achievable performances.

5.1 Single-stage DC/AC converter

The direct conversion from DC to AC current can be realized with converters as H-bridge and neutral point clamped (NPC) [40, 41]. The aim is to obtain an output

AC, which appropriately performs the motor control consistent with the assigned reference, starting from DC in output from the batteries. However, given the dependence of the voltage of the battery pack from the SOC, it is appropriate to balance the operation just as the DC input voltage changes. This can be achieved by acting appropriately on the modulation index of the traction control. However, the performance of this solution might be affected by their state of charge. Therefore, compared to a simple construction, a reduction in weight and dimensions, the solution examined certainly has significant performance limitations and in any case variable with the SOC. For example, the classic diagram of a three-level NPC inverter is shown in **Figure 4** with the correspondent voltage space vectors (18 active and 1 zero-voltage vectors). Large, medium, and small voltage magnitudes are identified by subscripts "*L*," "*M*," and "*S*" while with "*Z*" refers to zero-voltage vectors. The complex plane can be split in six sectors each of which up into two regions (region 1, region 2), in order to accurately modulate the reference to be followed.

The most high-performance converters are those multilevel, who provide a large number of voltage space vectors. In fact, this allows to follow with a good degree of accuracy the reference imposed by the control logic. However, in multilevel converters, the problem of capacitor voltage balancing leads to limitations in selecting the converter output voltage vector, and suitable corrections are introduced in the control technique. The voltage balancing method is strongly linked to the converter topology used. In the literature, it is possible to find different solutions that propose complex algorithms based on analytical methods, coordinate transformation, pulse width (PWM), or space vector (SVM) modulation, among others [42]. The issue of balancing becomes even more critical when there is a direct connection to the storage system.

5.2 Double-stage DC/AC converter

In this case, as can be seen from the architecture shown later (**Figure 12**), the battery pack must be interfaced with the DC-bus through a DC/DC converter that can manage the flow of power both during charging (regenerative break) and during the discharge phase. The type of converter is bidirectional for the flow of energy [43, 44]. Its characteristics are closely linked to the voltage levels chosen for the DC-bus and the battery string. Typically, this is a buck-boost chopper that can also accommodate the option of interfacing with a fast and/or ultrafast charging system for charging the whole battery pack. Many topologies of this converter are proposed in the literature, borrowing the configuration by the application of steady

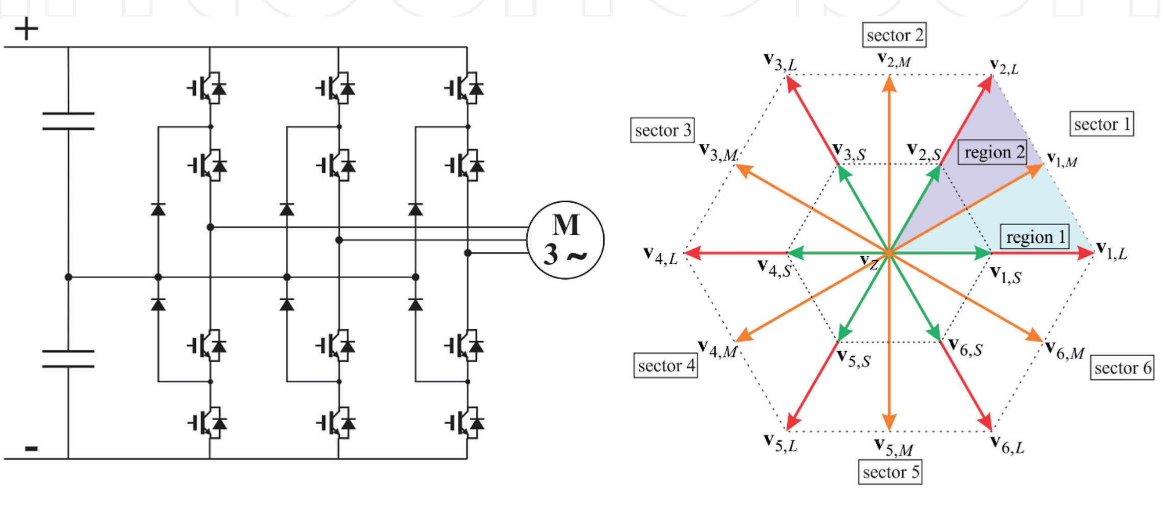

Figure 4.
Neutral point clamped topology with correspondent voltage vectors.

storage that is already established, for example, in order to highlight the differences compared to abovementioned converter, one of the double-stage topologies consists of the interleaved DC/DC chopper [45] before the NPC, as shown in **Figure 5**.

5.3 Integrated DC/AC converter

Solutions worthy of note, instead, refer to the DC/AC topologies that are trying to integrate, in a single converter, both the battery management system and the interface toward the DC-bus [46]. Indeed, as it is shown in **Figure 6**, the onboard storage systems must be managed very carefully, ensuring constant balancing, in different operation conditions, in order to preserve the declared performances for lifetime. The lifetime of the batteries is strictly dependent on the use of the batteries and the management capacity. In a traditional method, all the battery cells are connected in series/parallel to reach the desired DC-bus voltage and to obtain required energy. The charge/discharge phase is carried out with the same current but, due to the different

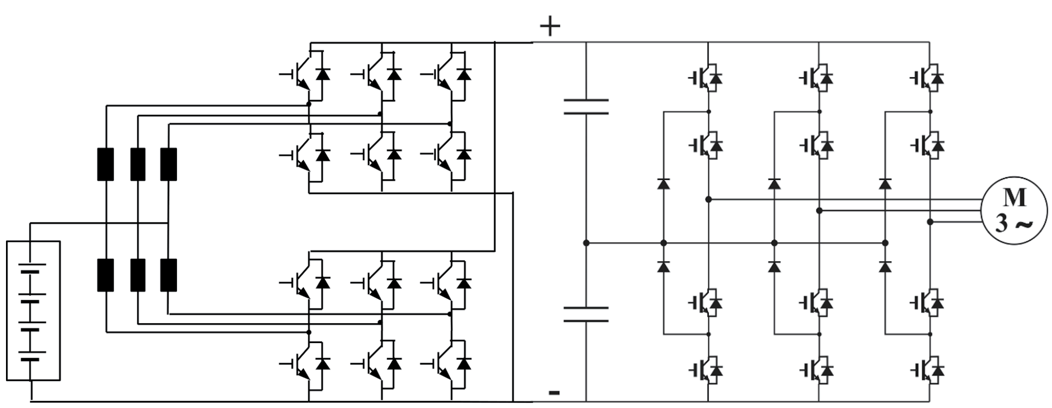

Figure 5.
Double-stage converter topology: interleaved DC/DC chopper with NPC inverter.

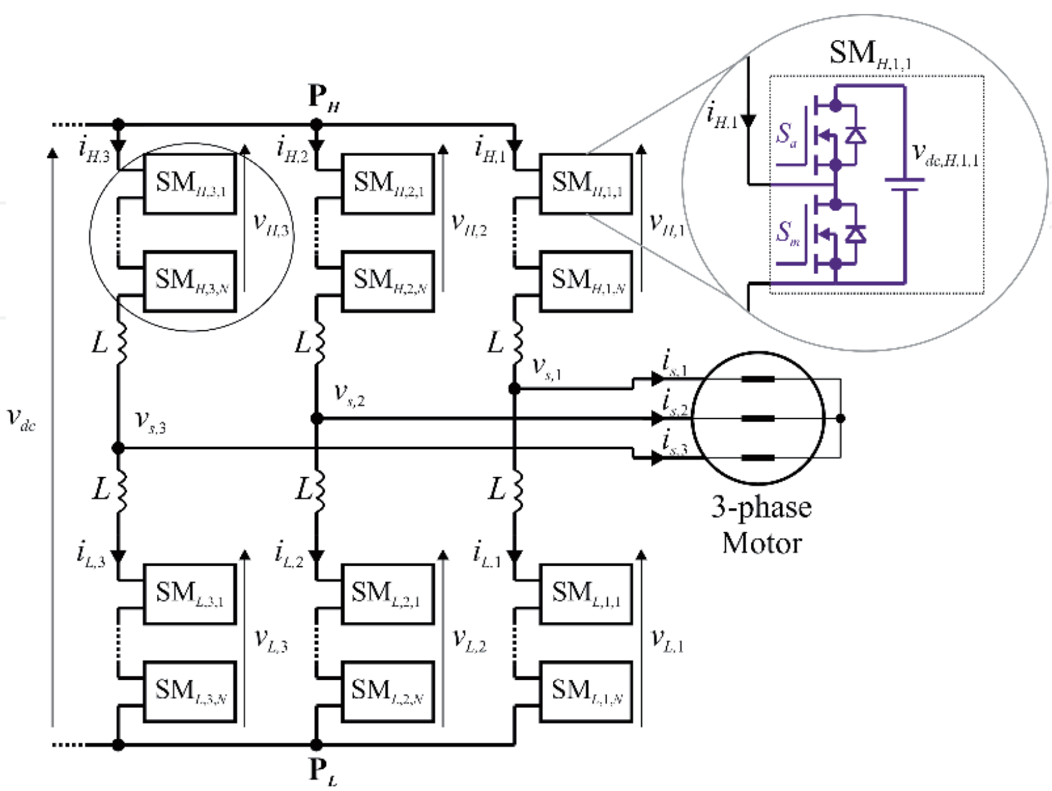

Figure 6.
Modular multilevel converters power topology.

electrochemical characteristics of the batteries, different voltages and different SOCs will be obtained for each cell. Therefore, the charge/discharge phase must be stopped as soon as even one of the cells reaches its cutoff voltage. The inequality of chemical characteristics among the cells affects load current and determines an unbalanced power contribution. Unbalancing of the cells can cause premature failure of the pack over extended cycling due to the overhanging/undercharging of cells. This aspect introduces a progressive damage of battery cells and consequently reduction of their service lifetime. For this reasons, passive or active battery management systems (BMSs), as described above, are usually added to the battery pack. The BMS has the main purpose of dynamically minimizing the imbalance of the battery pack during normal operations in order to preserve the cells' lifetime. In this traditional approach, the traction power unit is equipped with an AC converter that allows the connection with AC-motor and/or AC-grid for recharge. In some cases, it is possible to find ZEVs that host onboard another converter, which has the task of allowing the charging of the battery from the grid. More and more widespread are the solutions that integrate in one *integrated DC/AC converter* the features that individual converters offer separately. Different converter solutions have been considered to obtain high performance, especially from the point of view of the conversion efficiency. Among them, multilevel converter is one of the most accredited topologies to achieve good performance. The most promising one is definitely the modular multilevel converter (MMC), where each individual submodule (SM), in half- or full-bridge configuration, is directly fed by an elementary cell. Generally, this converter topology is used for high-voltage application, where the main advantages over conventional ones and the most significant features are: simple realization of redundancy, low device ratings, easy scalability and a possibility of common DC-bus configuration for multidrive applications, low THD of the output voltage, good fault-tolerance capability, and enhanced motor efficiency/performance in comparison with the traditional two-level voltage source inverter (VSI). The converter plays a double role: in fact, it can work as traction converter as well as a charger, which increases the power density and reduces the cost by combining the traction and charger converters. This solution allows to obtain both the BMS functionality and the power interface to AC utilities. However, this type of converter has also some drawbacks. The main disadvantage is substantially linked to the conversion efficiency: the presence of a high number of switching devices generates power losses that penalize the overall efficiency of the power train. Moreover, each cell delivers a current waveform not only dependent on the load active power request. The difference between the RMS and DC value of the current increases the losses of the battery cells [47].

6. Motor

The quick growth of road electric traction applications (i.e., zero-emission electric vehicle, hybrid electric vehicle, E-motorcycle, E-bike, aerospace taxing driving, and so on) drew the attention of the world of electric machines exposing several critical issues, so far ignored for industrial applications. This aspect is strictly related to the different needs that characterize the traction chain of a road electric vehicle. Therefore, the design of an electrical drive for such applications requires an adaptation of the external characteristics of the system, especially in terms of torque vs. speed ratio in the whole speed range. In fact, the performance of the drive system (motors + power converter) is strongly limited by the current rating of the ESS. Consequently, the effective torque output of the system is heavily reduced in low-speed range with respect to the potentially available torque by the electric motor. Actually, in order to follow the constraints that a road electrical traction system has to satisfy, three-phase brushless/induction motors are generally used. These solutions require high-frequency switched power converters and suitable control strategy, in order to ensure dynamic performance in line with the expectations of the end user. In a conventional traction drive, the motor current limit vs. the motor speed is practically constant until the nominal motor speed. As a consequence, in order to increase the torque-speed ratio of the drive in the low speed range, two solutions are generally adopted:

1. The motor current limit is increased in the low speed range;

2. A different gear ratio is used in low-speed range.

In the first case, an oversizing of the power converter is needed. Of course, the employed converter will never be used at its full power capability, resulting in a worst cost/benefits ratio. In the second case, additional mechanics are required resulting in a worst system efficiency in the low speed range. Different solutions in order to overcome the previous limits are being investigated by the scientific world [48–50]. Such studies, although different in the substance, try to increase the torque-speed ratio of a given motor by *modifying the stator-winding configuration* of the motor in order to obtain a different behavior of the torque/speed ratio for a fixed motor current. This approach allows avoiding the oversize of the power converter and/or the need of a variable gear ratio [51, 52]. In EV automotive applications, the torque/weight ratio value for PM machines is typically less than 10 Nm/kg (Nissan Leaf 6.52 Nm/kg; Toyota Prius 7.84 Nm/kg) [53], while for induction machine, it is problematic to reach 5 Nm/kg (TeslaS).

In the last few years, the use of permanent rare earth magnets has made feasible use of *permanent magnet synchronous motors* (PMSM) in all those applications where it was customary to use direct current or induction machines [54]. One of the fundamental characteristics of the synchronous realized with permanent magnets is that of having a high specific torque; this makes them particularly suitable in EV applications where compactness, lightness, and high mechanical shaft power are requests. The permanent rare earth magnets have a high residual induction value and a high coercive field value, in addition to the possibility of being able to work at very high temperatures (up to 350°). Compared to the induction machine, the permanent magnet synchronous loses reliability due to the magnets that can be subject to demagnetization, but it has the possibility of being built with a high number of pole pairs and it works well with single-layer and concentrated-type windings, which are preferred in traction applications as they ensure a longer lifetime. With regard to the magnets, the types of rare earth magnets used are mainly two [55]:

- *Neodymium-iron-boron (NdFeB) magnets*: characterized by a high residual induction field (1.2–1.4 T), high value of the coercive field (higher than 1000 kA/m), maximum operating temperature without undergoing a strong decay of the magnetic characteristic of 150 °C;

- *Samarium-cobalt magnets (SmCo)*: characterized by a high residual induction field (1.0–1.2 T), high value of the coercive field (greater than 850 kA/m), maximum operating temperature without undergoing a strong decay of the magnetic characteristic, about 350 °C.

In view of the moldability of the rare earth magnets (they are generally made using powder metallurgy techniques), different types and geometric configurations of permanent magnet motors have been developed, see **Figure 7**.

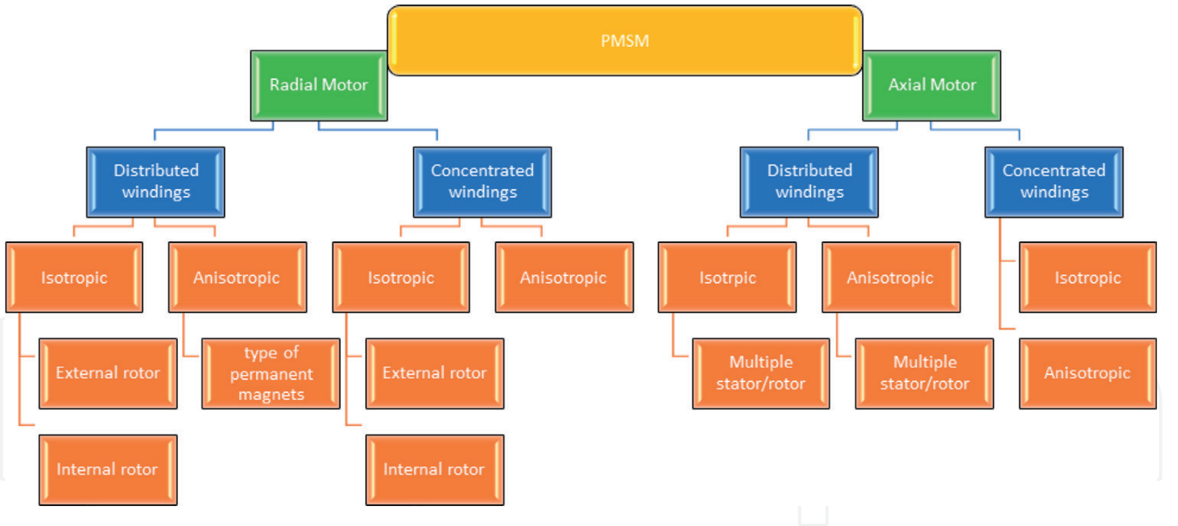

Figure 7.
Classification of permanent magnet electric motors.

As can be seen from the figure, the main classification of PMSM is made according to the direction of the magnetic flux with respect to the rotation axis: the distinction between *axial motors* and *radial motors*. In the first type of motor, the flux lines of the magnetic field to the air gap generated by the permanent magnets are parallel to the axis of the motor, while in the second case, the magnetic flux is parallel to the radial direction of the machine. Constructively, the axial flow motors have a greater radial development (they are sometimes also referred to as pancake motors), they are composed of multiple stacks (i.e., repeated parts composed of stator and rotor, or several stators and rotors assembled together) and it can be used in those applications in which the motor is thought to be integrated directly into the drive (e.g., motor wheel, or in general, for gearless applications) [56]. The axial motors are used for low-speed applications, and therefore, they are built with a high number of pole pairs (also because the high radial extension would cause problems of mechanical stress at high speeds). The radial motors are characterized by a greater axial length and they can be used both for standard applications and for special applications [57]. The two types of motors can be built with windings concentrated at the tooth or with distributed windings. For each of the types of winding, it is can think of realizing the motor with a magnetic configuration isotropic or anisotropic, that is characterized by an inductance constant magnetization in all directions or variable.

The isotropic and anisotropic motors have different magnetic and constructive characteristics, which affect their operation. The isotropic motors are made with the magnets arranged on the rotor surface (the rotor can be internal or external), and can be characterized by the use of magnets of different shapes adapted to optimize the field of magnetic induction provided by the magnets themselves. The anisotropic motor consists of magnets, partially or totally, drowned in the iron, arranged perpendicular to the radial direction or rotated by a certain angle with respect to the main machine axes; the isotropic and anisotropic motors allow to obtain high specific power density with also high torque or speed. In particular, the anisotropic motor can reach higher specific power density thanks to contribution of reluctance torque component; it is usually employed in lower speed performance when the asymmetric rotor configuration is adopted or rather, when drowned magnets are used, it is generally preferred for operation in field weakening. The main electrical faults that may affect the electrical machines are divided into three main categories:

- opening of a winding;
- short circuit between phase and ground or between phase and phase;
- short circuit at the motor terminals.

In order to minimize the occurrence of faults and their effect on mechanical performance, constructive measures are used to make the motor fault tolerant [58]. The fault tolerant characteristics of an electric machine are obtained by suitably modifying the winding [59]. Normally, in most electric machines in alternating current, a distributed multilayer winding is used, capable of generating an almost sinusoidal air gap induction field. From the constructive point of view, a multilayer winding can submit within a slot of the coil sides belonging to different phases, and therefore between the insulators of the two sides would impose a potential difference capable of creating discharges inside the insulating. Moreover, a possible short circuit that would affect a phase, besides damaging the insulator of the phase itself, could cause the failure to propagate also to the insulation of the other phase present in the same slot. To avoid this, a first fault tolerant feature is obtained by using the single-layer windings concentrated on the tooth: in this way, it is possible to avoid the overlapping of the coils of the various phases, and in each slot, there will be a single winding relative to a determined phase. The use of single-layer winding concentrated on the tooth allows to reduce the length of the heads, also bringing a considerable advantage for the machine's overall dimensions [60–63]. An innovative solution to extend the drive operating range in EV would be to use *multiphase motor* and to dynamically modify its torque-speed ratio by changing the stator-winding configuration. This approach would give also the multiphase motor advantages: *greater fault tolerance*, *smaller torque ripple*, *less phase power rating,* and so on.

6.1 Control strategy

Since many years, field-oriented control (FOC) and direct torque control (DTC) are the most popular control methodologies for AC motor drives. The FOC strategy, see **Figure 8**, is strictly dependent on the motor electrical parameters, requires long computation time and high switching frequency of the inverter. Instead, the DTC strategy (see **Figure 9**) is a more robust technique that needs very low computation time and ensures acceptable results even at low switching frequency [64]. A fast torque response can be obtained by means of DTC, due to "direct" interaction of machine electromagnetic quantities (torque and flux) and selected voltage space-vector [65]. Despite these important benefits, DTC has several drawbacks as variable switching frequency (strongly dependent on hysteresis band and motor speed) and large torque ripple in the low-speed region.

The rapid development of multilevel converters for drive systems has strongly improved DTC performance with regards to the torque ripple especially when a high number of levels are used [66]. Applying the DTC for converters with more levels, a larger number of voltage vectors can be exploited in order to better control stator flux and torque in induction motors. In this case, the identification of the proper voltage space-vector to be applied has a number of solutions increasing with the number of inverter levels, and consequently, a more complex voltage selection criterion is needed. On the contrary, the increased freedom degrees can be exploited by minimizing the switching frequency, while keeping uniform both the conduction and switching losses of the electronic devices. These methods allow to solve problems of torque ripples, difficulty to control torque at very low speed, variable switching frequency, high values of total harmonic distortion (THD) contents in

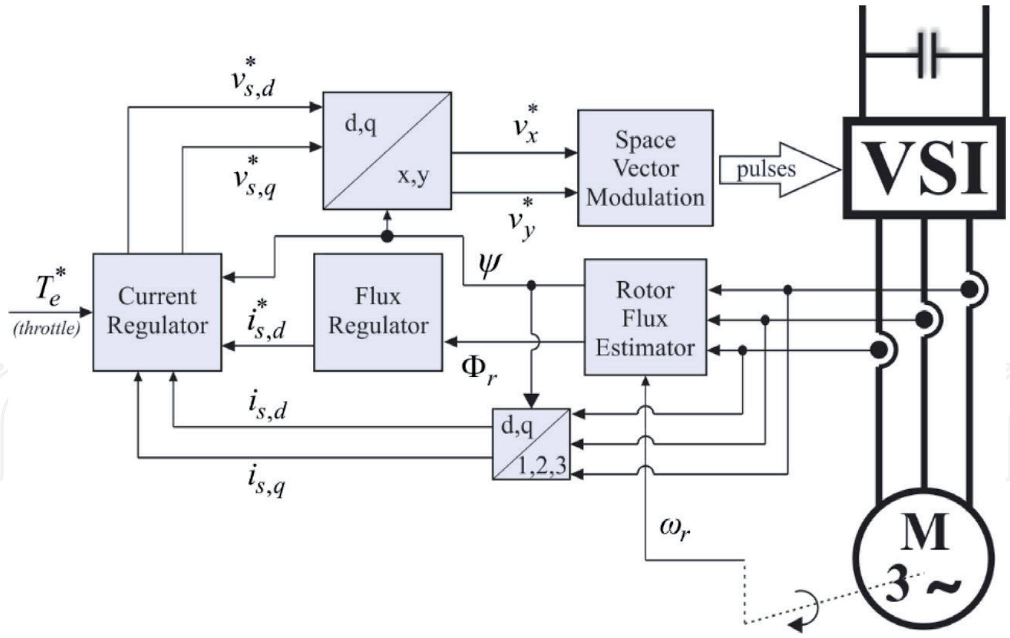

Figure 8.
General block diagram of the field oriented control (FOC).

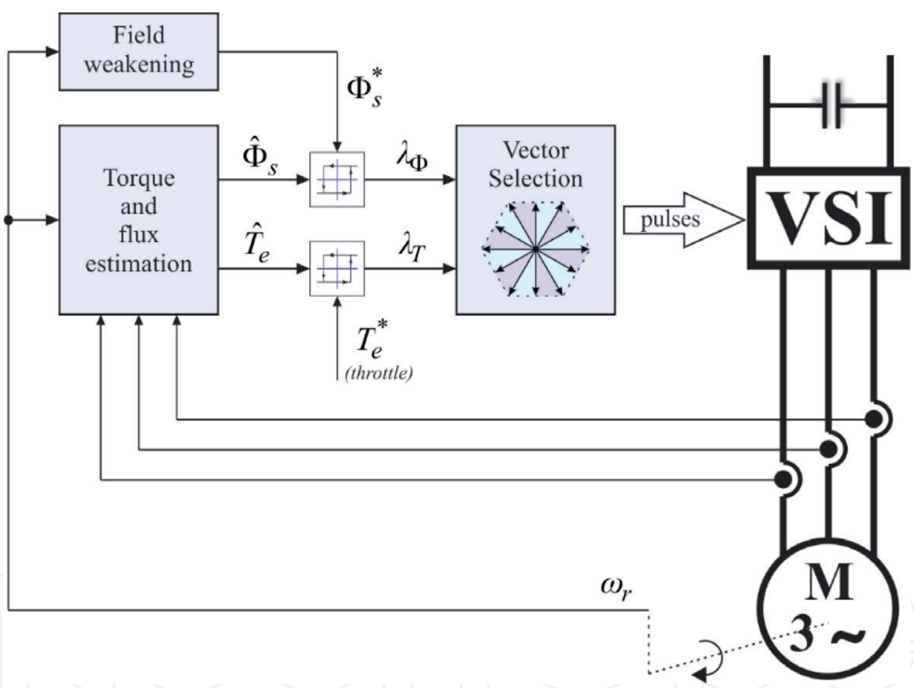

Figure 9.
General block diagram of the direct torque control (DTC).

armature currents. In DTC induction drives supplied by multilevel inverters, usually not all the available converter voltage vectors are used by the selection criterion, due to the aforementioned freedom degrees. This could negatively influence steady-state and/or dynamic drive behavior.

7. Charging interface

The charging infrastructure is essential to "refuel" the ESS of an electric vehicle. They are classified and configured according to the type of power supply, whether in alternating current (AC) or in direct current (DC), of the operating power and of the charging time, of the type of connection by cable (plug) between the fixed part (station) and moving part (vehicle) both for the power and signal part [67–69].

A first distinction between the alternating current and direct current infrastructures as well as the type of power supply is based on the position of the battery charger, i.e., the converter that manages the charge profiles required by the battery pack. The alternating ones in most cases have the battery charger onboard the vehicle. In the case of direct current charging, however, the converter is integrated into the charging station. Obviously, the management of the recharging process in the case of AC recharges is simplified compared to the DC case, because the charging infrastructure is limited to providing energy to the vehicle and to guarantee the safety requirements prescribed by the IEC 61851 standard.

In the case of DC recharges, the infrastructure is called to check the current and voltage profiles supplied to the vehicle that may vary according to the battery packs onboard. Therefore, they are exchanged during the connection of the vehicle, and during the charging phase, a whole series of information with the battery management system (BMS) onboard the vehicle. The main advantage of DC charging regards to lighten the vehicle of a conversion unit, and therefore, to reduce the weights, the overall dimensions, and the costs. Furthermore, since the external converter to the vehicle, it is easy to increase the power when charging the battery if pack so permits. The charging time is strictly dependent on the energy of the battery pack and the power of the charging station. In an electric car, a "full" of energy is of the order of 20/30 kWh and requires 20–30 min to 100 kW (80% of the SOC).

The possibility of reducing the charging time is therefore linked, on the one hand, to the increase in the maximum power of supply of the charging point, and on the other hand to the increase in the maximum charging current of the battery without reducing the useful life cycles [70, 71]. However, the excessive increase of the installed power in a charging point leads to an unjustified increase in the installation and maintenance costs of the plant as a function of the reduction in recharge time. Based on these preliminary remarks, the IEC 61851 classifies charging points accessible to the users:

- *standard power recharge point "Normal Power" (≤22 kW)*: this is a recharging point that allows the transfer of electric energy to an electric vehicle with a power rating of 22 kW or less, excluding devices with a power rating of less than or equal to 3.7 kW, which are installed in private homes or whose main purpose is not to recharge electric vehicles, and which are not accessible to the public. The standard power recharge is detailed in the following types:

    1. *slow* = equal to or less than 7.4 kW;

    2. *quick* = more than 7.4 kW and equal to or less than 22 kW;

- *high power recharge point "High Power" (> 22 kW):* this is a recharging point that allows the transfer of electric energy to an electric vehicle with a power greater than 22 kW. The high power recharge is detailed in the following types:

    1. *fast*: more than 22 kW and equal to or less than 50 kW;

    2. *ultrafast*: more than 50 kW.

The standards EN 62196-2 and EN 62196-3 define the types of connectors and the "mode" to allow the charging of the vehicle from the mentioned charging stations:

- *Mode 1*: the vehicle is connected to the AC grid with domestic connectors up to 16 A and with 30 mA differential protection type A.
- *Mode 2*: the connection of the electric vehicle to the power supply is carried out with household or industrial connectors up to 32 A, with 30 mA differential protection type A and a control test on the cable.
- *Mode 3*: the connection of the electric vehicle to the power supply is carried out with dedicated connectors, with 30 mA differential protection type A. The connection must also have a connecting cable with some extra conductors suitable for a maximum current of 250 A or a cable compatible with the Mode 2 suitable for a maximum current of 32 A.
- *Mode 4*: it is a direct current (DC) connection for fast recharging. Practically, the connection of the electric vehicle to the power supply is made via an external charger to the vehicle. Control and protection functions and the vehicle charging cable are installed always in the charging station.

The sockets and plugs, for charging electric vehicles in AC, are defined and regulated by IEC 62196-2, while accessories for DC charging are regulated by the IEC 62196-3 standard.

In particular, the standard defines the following types for AC charging:

- *Type 1*: single-phase plug socket with two pilot contacts. Maximum current up to 32 A, maximum voltage 250 V, and IPXXB protection degree.
- *Type 2*: single-phase or three-phase plug socket up to 63 A 500 V. Required degree of protection IPXXB with interlocking requirement to avoid disconnection under load.
- *Type 3A*: *for light vehicles*: single-phase plug socket up to 16 A 250 V. Required degree of protection IPXXD. This standard requires that the plug can be disconnected under load.
- *Type 3C: for all vehicles*: both three-phase and single-phase plug socket with two pilot contacts up to 63 A 500 V and IPXXD protection degree with the option of disconnecting the plug even under load up to 32 A.

With reference to the four types of charging, the standard IEC 62196-2 specifies four types of electrical connectors:

i. *Type 1—SAE J1772-2009 (Yazaki)*: it is a single-phase connector with two power contacts + PE and two pilot contacts for the control, max 32 A 230 V (7.4 kW), is adopted by Japanese and American vehicles. The specifications of the connector, referred to by the previous standard. The connector is equipped with mechanical interlock.

ii. *Type 2—VDE-AR-E 2623-2-2 (Mennekes)*: it is a single/three-phase connector, with two pilot contacts for control, max 32 A—7.4 kW (63 A—43.5 kW), 230/400 V, is adopted on European vehicles. Initially, there was no mechanical interlocking that was introduced only from 2012.

iii. *Type 3A—EV Plug Alliance (Scame)*: single-phase, two power contacts + PE and one pilot contact for the control, max 16A, 230 V, is used only for light vehicles (scooters and quadricycles) and refills up to 3.7 kW.

iv. *Type 3C—EV Plug Alliance (Scame)*: single/three-phase, two/three power contacts + PE and two pilot contacts for control, max 32A—230/400 V, 7.4 kW/21 kW, it is scarcely widespread.

For direct current charging, the standard defines two types of connectors:

- *CHAdeMO*: it's connector for DC charging with additional pins for communication with the vehicle;

- *Combo combined charging system (CCS)*: it's connector for DC charging that integrates also the Type 2 AC inside to allow both AC and DC charge through a single connector;

The CHAdeMO standard is the standard for fast charging in direct current (DC) [72]. This standard is adopted for Nissan, Mitsubishi, Peugeot, Citroen vehicles. Vehicles equipped with this standard have two connectors:

- CHAdeMO for fast DC charging

- Connector for AC charging (normally Type 1)

Its specifications are defined by the Japan Automobile Research Institute (JARI) G105-1993 standard and use a CAN-BUS communication protocol. With reference to the combined charging system (CCS), however, it provides a unique charging connector on the electric vehicle, which allows both the fast charge current (DC) and the slow charging alternating current (AC). The CCS is made from Type 2 connector, so the system is called Combo2. This system is now adopted by some European car manufacturers (for example, BMW and Volkswagen). **Figure 10** shows the previously defined connectors.

With reference to the previous power classification, the "normal power" charging systems must be equipped with a Type 2 socket compliant with the IEC 62196-2 standard for each charging point dedicated to passenger cars and four-wheel commercial vehicles; a socket type 3A conforms to the IEC 62196-2 standard for each charging point dedicated to mopeds, motorcycles, and quads. The "high-power" charging systems, on the other hand, must be equipped with at least one connector of the CCS Combo 2 type and of the CHAdeMO type, according to the IEC 62196-3 standard for direct current charging; and finally, a charging connector/socket with standard Type 2, according to the IEC 62196-2 standard, for charging in alternating current. Finally, the charging systems must be connected to a control system that allows carrying out at least the following functions in real time:

- verification of correct operation (availability);

- verification of the employment status;

- user recognition;

- enabling/inhibition of the charge;

- reading of the electrical parameters during charging.

In conclusion, it is possible to synthesize the main characteristics of the different charging points in **Table 2**.

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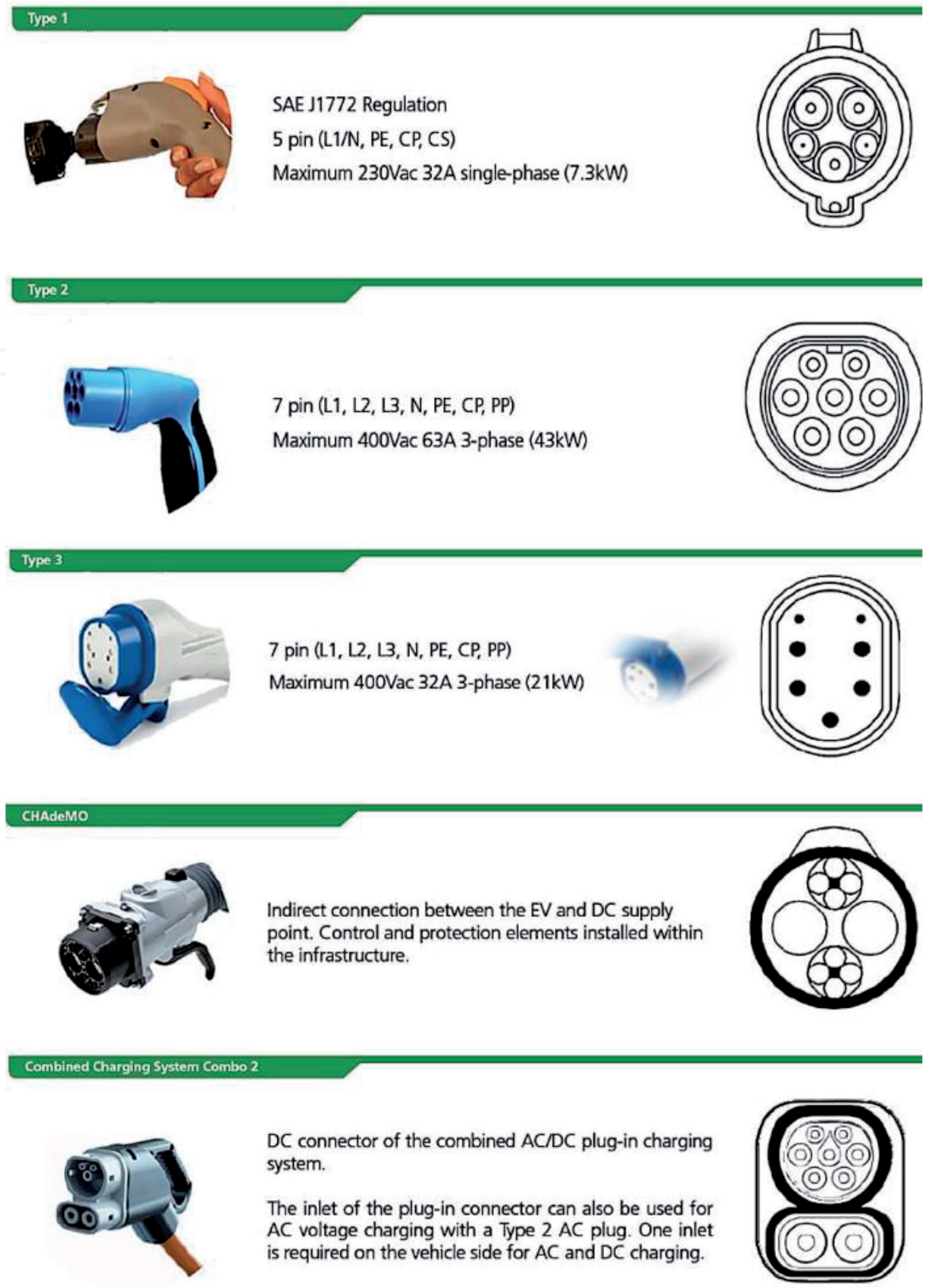

Figure 10.
Standard connectors for AC and DC charging.

Classification	Normal power (slow)	Normal power (quick)	High power (fast)	High power (ultrafast)
Categories	1	2	3	4
Supply	Single-phase AC	Single-phase or three-phase AC	three-phase AC	DC
Power	<3.7 kW	3.7–22 kW	>22 kW	>50 kW
Charging time	>6 h	1–3 h	20–60 min	20–30 min
Connector	Type 1	Type 2/Type 3	Type 2/Type 3	ChadeMO Combo
Standard communication protocol	—	IEC 81851-1 PWM	IEC 81851-1 PWM	Digital communication

Table 2.
Main characteristics of the different charging points.

However, charging via a physical connection to a charging station is not the only possibility that can be used to supply the ESS. In fact, the research is very hot to allow an inductive or wireless charging [73, 74]. The latter allows to recharge an electric vehicle without connecting it to the charging station via cables, but by exploiting the magnetic field for transferring power from a transmitter toward a receiver coil. This solution currently involves high manufacturing costs, and therefore, not to make it competitive on the market.

8. State of art ZEV architectures

Based on the considerations made previously, it is possible to identify different architectures for a ZEV. Each of the proposed architectures differs, substantially,

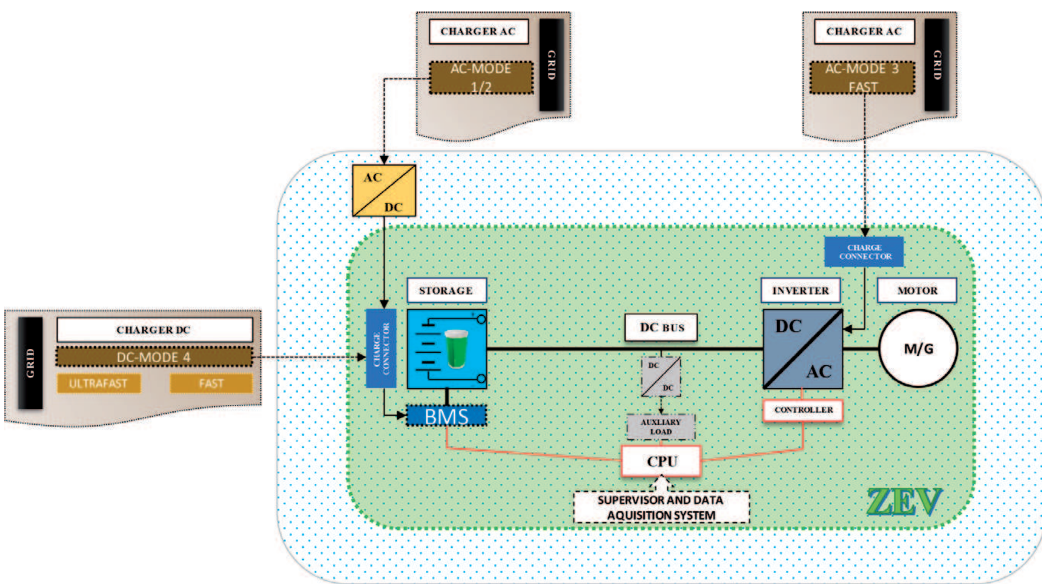

Figure 11.
Electric drive architecture for ZEV: single-stage converter/single motor.

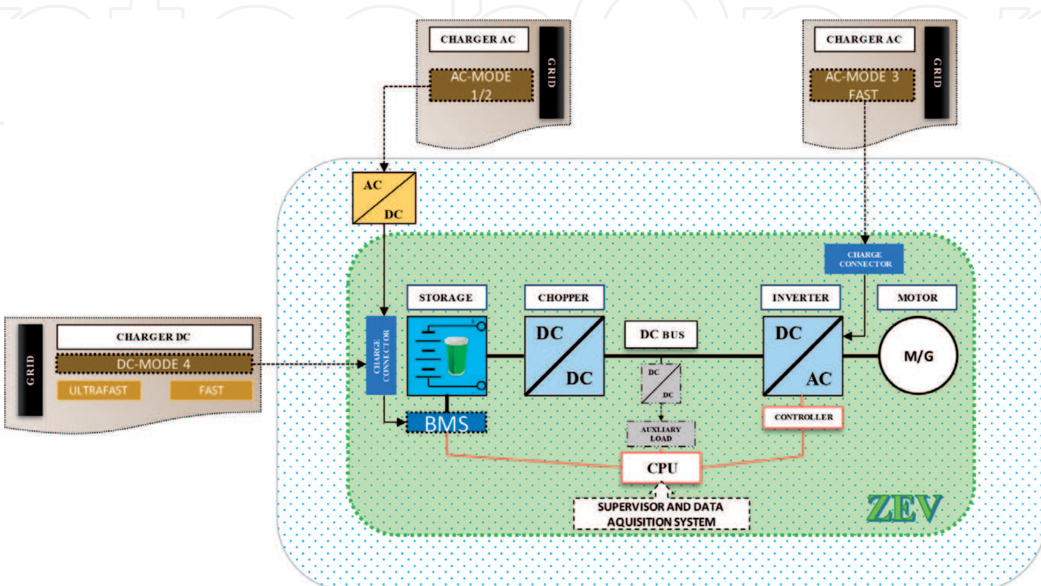

Figure 12.
Electric drive architecture for ZEV: double-stage converter/single motor.

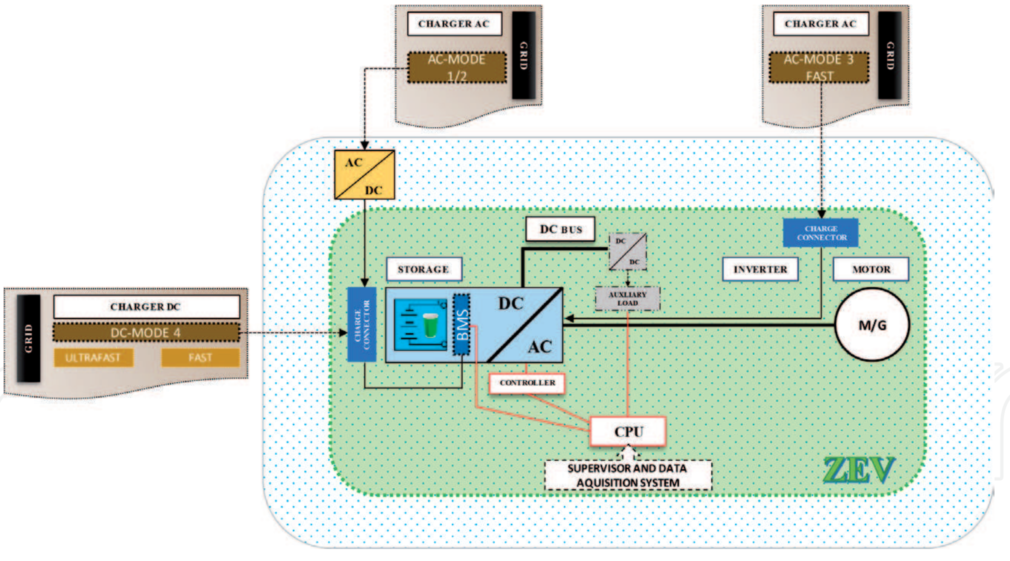

Figure 13.
Electric drive architecture for ZEV: integrate converter/single motor.

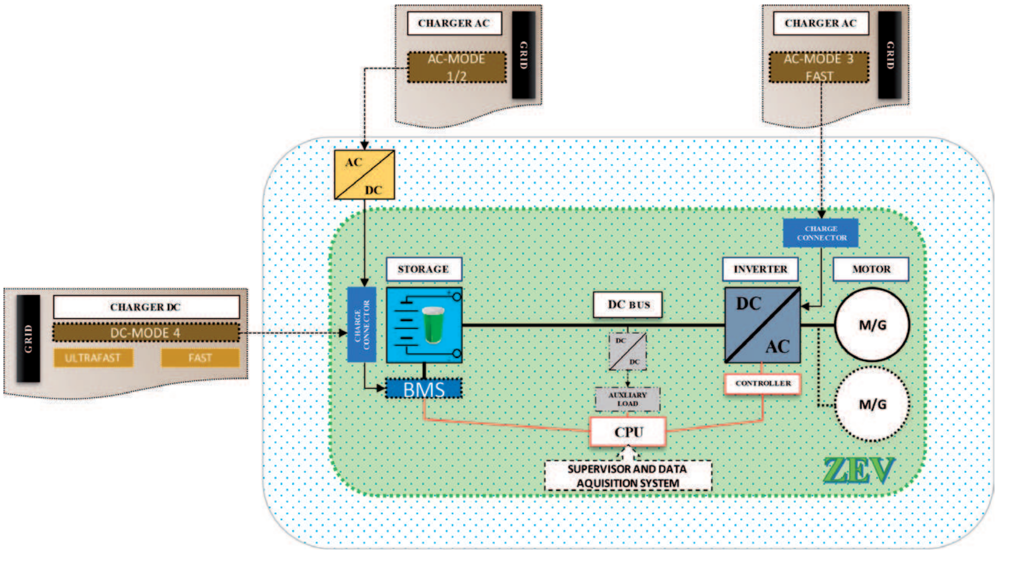

Figure 14.
Electric drive architecture for ZEV: single-stage converter/multiple motor.

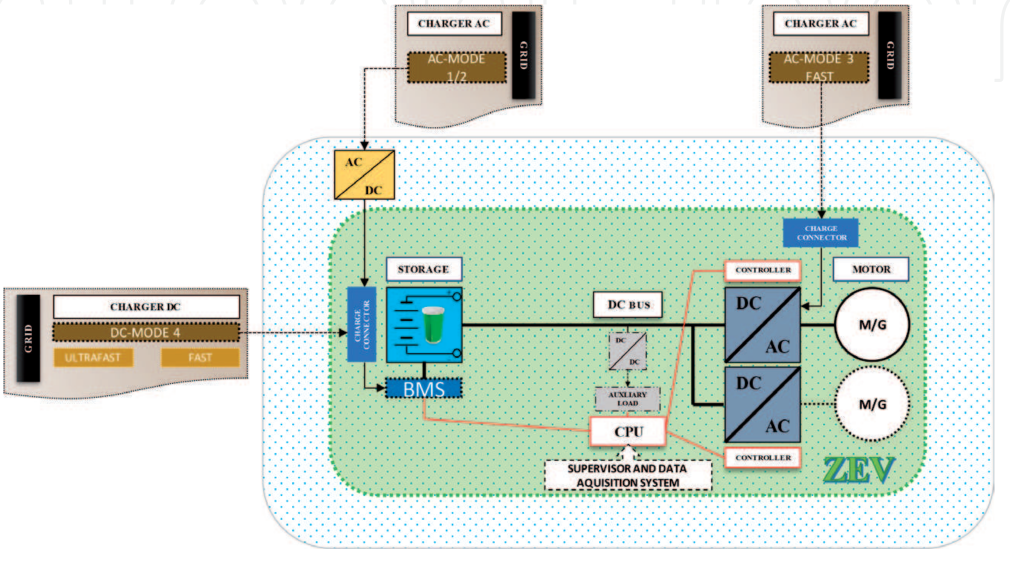

Figure 15.
Electric drive architecture for ZEV: multiple-stage converter/multiple motor.

by the choice of the DC/AC conversion stage and by the number of motors that constitute the electric drive. In each of the proposed configurations, the adoption of any of the charging modes was assumed. It is clear that every embodiment may implement one or more of the charging modes indicated. **Figure 11** shows the configuration with a single-stage converter and a single electric motor for traction. By replacing the previously described double-stage solution to the DC/AC converter, the architecture shown in **Figure 12** can be obtained. An innovative solution, on the other hand, can be achieved by using a DC/AC converter that interfaces directly with the batteries; in this case, the converter can also perform the BMS function, managing the charge and discharge of the battery pack, see **Figure 13**.

Alongside the proposed solutions, it is possible to derive new configurations depending on the use of several traction motors. The presence of multiple motors determines a change once again in the AC side converter. In this case, it is possible to adopt "dual motor" solutions where only one converter is used to supply two motors or solutions where each converter supplies its motor, see **Figures 14** and **15**.

9. Conclusions

In this chapter, it has been presented the main subsystems that making up the electric drives for a ZEV. In particular, analyzing each of one, it is evident that there are different solutions to carry out the assigned task in the whole system. Matching all possible alternatives for the realization of each subsystem, different architectures for the power train are obtained. In each of the architectures, the substantial difference is linked to the DC/AC converter, thanks to which it is possible to transfer energy from and/or toward the battery pack. Indeed, the identified configurations differ precisely in function of the choice of the latter: single-stage, double-stage, or integrated DC/AC converters generate the respective solutions examined. A further difference is related to employ one or more traction motors coupled with one or more inverters to produce the respective last two configurations.

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References

[1] Rajashekara K. History of electric vehicles in general motors. IEEE Transactions on Industry Applications. 1994;**30**(4):897-904

[2] Chan CC. The rise & fall of electric vehicles in 1828-1930: Lessons learned [scanning our past]. Proceedings of the IEEE. 2013;**101**(1):206-212

[3] Explaining Road Transport Emissions, European Environment Agency. ISBN: 978-92-9213-723-6, ORDER ID (Catalogue Number): TH-04-16-016-EN-N

[4] Energy, Transport and Environment Indicators - 2014 edition, Product Code: KS-DK-14-001, ISBN: 978-92-79-41256-1, ISSN: 2363-2372, the Eurostat website at http://ec.europa.eu/eurostat

[5] Lorf C, Martínez-Botas RF, Howey DA, Lytton L, Cussons B. Comparative analysis of the energy consumption and CO_2 emissions of 40 electric plug-in hybrid electric hybrid electric and internal combustion engine vehicles. Transportation Research Part D: Transport and Environment. 2013;**23**:12-19

[6] Khan A, Memon S, Sattar TP. Analyzing integrated renewable energy and smart-grid systems to improve voltage quality and harmonic distortion losses at electric-vehicle charging stations. IEEE Access. 2018;**6**:26404-26415

[7] Monteiro V, Pinto JG, Afonso JL. Operation modes for the electric vehicle in smart grids and smart homes: Present and proposed modes. IEEE Transactions on Vehicular Technology. 2016;**65**(3):1007-1020

[8] Saju C, Lydia M. A comprehensive review on hybrid electic vehicles: Power train configurations, modelling approaches, control techniques. In: 2018 Second International Conference on Inventive Communication and Computational Technologies (ICICCT), Coimbatore. 2018. pp. 925-930

[9] Karimi H, Ansari J, Gholami A, Kazemi A. A comprehensive well to wheel analysis of plug-in vehicles and renewable energy resources from cost an emission viewpoints. In: 2014 Smart Grid Conference (SGC), Tehran. 2014. pp. 1-6

[10] Global EV OUTLOOK 2018 – IEA WEBSTORE: https://webstore.iea.org/

[11] Chan CC. The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE. 2007;**95**(4):704-718

[12] Millner A, Judson N, Ren B, Johnson E, Ross W. Enhanced plug-in hybrid electric vehicles. In: 2010 IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply, Waltham, MA. 2010. pp. 333-340

[13] Liu D, Wang Y, Zhou X, Lv Z. Extended range electric vehicle control strategy design and muti-objective optimization by genetic algorithm. In: 2013 Chinese Automation Congress, Changsha. 2013. pp. 11-16

[14] Bauman J, Kazerani M. A comparative study of fuel-cell-battery, fuel-cell-ultracapacitor, and fuel-cell-battery-ultracapacitor vehicles. IEEE Transactions on Vehicular Technology. 2008;**57**(2):760-769

[15] Yong JY, Ramachandaramurthy VK, Tan KM, Mithulananthan N. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. Renewable and Sustainable Energy Reviews. 2015;**49**:365-385. ISSN 1364-0321

[16] Gallo CA, Tofoli FL, Correa Pinto JA. Two-stage isolated switch-mode power supply with high efficiency and high input power factor. IEEE Transactions on Industrial Electronics. 2010;**57**(11):3754-3766

[17] Gerssen-Gondelach SJ, Faaij APC. Performance of batteries for electric vehicles on short and longer term. Journal of Power Sources. 2012;**212**:111-129. ISSN 0378-7753

[18] Guaitolini SVM, Yahyaoui I, Fardin JF, Encarnação LF, Tadeo F. A review of fuel cell and energy cogeneration technologies. In: 2018 9th International Renewable Energy Congress (IREC), Hammamet. 2018. pp. 1-6

[19] May GJ, Davidson A, Monahov B. Lead batteries for utility energy storage: A review. Journal of Energy Storage. 2018;**15**:145-157. ISSN 2352-152X

[20] Fotouhi A, Auger DJ, Propp K, Longo S. Electric vehicle battery parameter identification and SOC observability analysis: NiMH and Li-S case studies. IET Power Electronics. 2017;**10**(11):1289-1297

[21] TM O'Sullivan, CM Bingham, RE Clark. Zebra battery technologies for all electric smart car. In: International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2006. SPEEDAM 2006, Taormina; 2006. pp. 243-249

[22] Kraytsberg A, Ein-Eli Y. Review on Li-air batteries—Opportunities, limitations and perspective. Journal of Power Sources. 2011;**196**(3):886-893. ISSN 0378-7753

[23] Scrosati B, Croce F, Panero S. Progress in lithium polymer battery R&D. Journal of Power Sources. 2001;**100**(1-2):93-100. ISSN 0378-7753

[24] Silva FA. Lithium-ion batteries: Fundamentals and applications [Book News]. IEEE Industrial Electronics Magazine. 2016;**10**(1):58-59

[25] Divya KC, Østergaard J. Battery energy storage technology for power systems—An overview. Electric Power Systems Research. 2009;**79**(4):511-520. ISSN 0378-7796

[26] Kouchachvili L, Yaïci W, Entchev E. Hybrid battery/supercapacitor energy storage system for the electric vehicles. Journal of Power Sources. 2018;**374**: 237-248. ISSN 0378-7753

[27] Farzin H, Fotuhi-Firuzabad M, Moeini-Aghtaie M. A practical scheme to involve degradation cost of lithium-ion batteries in vehicle-to-grid applications. IEEE Transactions on Sustainable Energy. 2016;**7**(4):1730-1738

[28] Millner A. Modeling lithium Ion battery degradation in electric vehicles. In: 2010 IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply, Waltham, MA. 2010. pp. 349-356

[29] Lu L, Han X, Li J, Hua J, Ouyang M. A review on the key issues for lithium-ion battery management in electric vehicles. Journal of Power Sources. 2013;**226**:272-288. ISSN 0378-7753

[30] Cheng KWE, Divakar BP, Wu H, Ding K, Ho HF. Battery-management system (BMS) and SOC development for electrical vehicles. IEEE Transactions on Vehicular Technology. 2011;**60**(1):76-88

[31] Peterson SB, Apt J, Whitacre JF. Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. Journal of Power Sources. 2010;**195**(8):2385-2392

[32] Majeau-Bettez G, Hawkins TR, Strømman AH. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in

hybrid and battery electric vehicles. Environmental Science and Technology. 2011;**45**(10):4548-4554

[33] Ager-Wick Ellingsen L, Majeau-Bettez G, Singh B, Kumar Srivastava A, Ole Valøen L, Strømman AH. Life cycle assessment of a lithium-ion battery vehicle pack. Journal of Industrial Ecology. 2014;**18**(1):113-124

[34] Hussein AA, Batarseh I. An overview of generic battery models. In: Power and Energy Society General Meeting, 2011. IEEE; 2011. pp. 1-6

[35] Tremblay O, Dessaint L. Experimental validation of a battery dynamic model for EV applications. World Vehicle Journal. 2009;**3**. ISSN 2032-6653

[36] Dannier A, Ferraro L, Miceli R, Piegari L, Rizzo R. Numerical and experimental validation of a LiFePO battery model at steady state and transient operations. In: 2013 Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER), Monte Carlo. 2013. pp. 1-6

[37] Daowd M, Omar N, Van Den Bossche P, Van Mierlo J. Passive and active battery balancing comparison based on MATLAB simulation. In: 2011 IEEE Vehicle Power and Propulsion Conference, Chicago, IL. 2011. pp. 1-7

[38] Rind SJ, Ren Y, Hu Y, Wang J, Jiang L. Configurations and control of traction motors for electric vehicles: A review. Chinese Journal of Electrical Engineering. 2017;**3**(3):1-17

[39] Çağatay Bayindir K, Gözüküçük MA, Teke A. A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units. Energy Conversion and Management. 2011;**52**(2):1305-1313

[40] Brando G, Dannier A, Del Pizzo A, Rizzo R. A generalized modulation technique for multilevel converters. In: 2007 International Conference on Power Engineering, Energy and Electrical Drives, Setubal, Portugal. 2007. pp. 624-629

[41] Brando G, Dannier A, Del Pizzo A. An optimized control of PWM-rectifiers with predicted variable duty-cycles. In: 2008 IEEE International Symposium on Industrial Electronics. Cambridge; 2008. pp. 68-73

[42] Brando G, Dannier A, Del Pizzo A, Rizzo R. Power quality problems in unbalanced operations of fault tolerant H-bridge multilevel active front-ends. In: 2007 9th International Conference on Electrical Power Quality and Utilisation, Barcelona. 2007. pp. 1-6

[43] Karimi R, Koeneke T, Kaczorowski D, Werner T, Mertens A. Low voltage and high power DC-AC inverter topologies for electric vehicles. In: 2013 IEEE Energy Conversion Congress and Exposition, Denver, CO. 2013. pp. 2805-2812

[44] Chen CH, Cheng MY. Design and implementation of a high-performance bidirectional DC/AC converter for advanced EVs/HEVs. IEE Proceedings - Electric Power Applications. 2006;**153**(1):140-148

[45] Dannier A, Guerriero P, Coppola M, Brando G. Interleaved converter for fast charge of battery system. In: 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi. 2018. pp. 425-430

[46] Brando G, Dannier A, Spina I, Tricoli P. Integrated BMS-MMC balancing technique highlighted by a novel space-vector based approach for BEVs application. Energies. 2017;**10**(10). art. no. 1628

[47] Dannier A, Brando G, Spina I, Iannuzzi D. Battery Losses In a MMC for BEVS Application. The Open Electrical & Electronic Engineering Journal. 2018;**12**:98-109

[48] Miller JM, Ostovic V. Pole phase modulated toroidal winding for an induction machine. U.S. Patent 5977679, Nov 2, 1999

[49] Gautam A, Ojo JO. Variable speed multiphase induction machine using pole phase modulation principle. In: IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society. pp. 3659-3665

[50] Sun D, Ge B, Bi D. Winding design for pole-phase modulation of induction machines. In: 2010 IEEE Energy Conversion Congress and Exposition (ECCE). pp. 278-283

[51] Edelson JS, Cox IW, Magdych JS. The Chorus Meshcon solution for starter-generators Electric Machines and Drives. In: IEEE International Conference on IEMDC. 2005. pp. 1720-1724

[52] Miller JM, Stefanovic V, Ostovic V, Kelly J. Design considerations for an automotive integrated starter-generator with pole-phase modulation. In: Conference Record of the 2001 IEEE Thirty-Sixth lAS Annual Meeting. Vol. 4. pp. 2366-2373

[53] Hayes JG, Davis K. Simplified electric vehicle power-train model for range and energy consumption based on EPA coast-down parameters and test validation by argonne national lab data on the Nissan Leaf. In: 2014 IEEE Transportation Elec-trification Conference and Expo (ITEC). IEEE; 2014

[54] Yang Y, Castano SM, Yang R, Kasprzak M, Bilgin B, Sathyan A, et al. Design and comparison of interior permanent magnet motor topologies for traction applications. IEEE Transactions on Transportation Electrification. 2017;**3**(1):86-97

[55] https://www.stanfordmagnets.com/samarium-cobalt-magnet-motor-vs-ndfeb-magnet-motor.html

[56] Profumo F, Zheng Z, Tenconi A. Axial flux machines drives: A new viable solution for electric cars. IEEE Transactions on Industrial Electronics. 1997;**44**(1):39-45

[57] Sitapati K, Krishnan R. Performance comparisons of radial and axial field, permanent-magnet, brushless machines. IEEE Transactions on Industry Applications. 2001;**37**(5):1219-1226

[58] Mecrow BC, Jack AG, Haylock JA, Coles J. Fault-tolerant permanent magnet machine drives. IEE Proceedings Power Applications. 1996;**143**(6)

[59] Tong C, Wu F, Zheng P, Sui Y, Cheng L. Analysis and design of a fault-tolerant six-phase permanent-magnet synchronous machine for electric vehicles. In: 2014 17th International Conference on Electrical Machines and Systems (ICEMS), Hangzhou. 2014. pp. 1629-1632

[60] Dajaku G, Gerling D. A novel tooth concentrated winding with low space harmonic contents. In: 2013 International Electric Machines & Drives Conference, Chicago, IL. 2013. pp. 755-760

[61] Dajaku G, Xie W, Gerling D. Reduction of low space harmonics for the fractional slot concentrated windings using a novel stator design. IEEE Transactions on Magnetics. 2014;**50**(5):1-12

[62] Dajaku G, Hofmann H, Hetemi F, Dajaku X, Xie W, Gerling D. Comparison of two different IPM traction machines with concentrated winding. IEEE

Transactions on Industrial Electronics. 2016;**63**(7):4137-4149

[63] Le Besnerais J et al. Analysis of noise reduction in a low speed and high torque PMSM with tooth concentrated windings. In: 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), Monte Carlo. 2016. pp. 1-6

[64] Abassi M, Khlaief A, Saadaoui O, Chaari A, Boussak M. Performance analysis of FOC and DTC for PMSM drives using SVPWM technique. In: 2015 16th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), Monastir. 2015. pp. 228-233

[65] Martins CA, Roboam X, Meynard TA, Carvalho AS. Switching frequency imposition and ripple reduction in DTC drives by using a multilevel converter. IEEE Transactions on Power Electronics. 2002;**17**(2):286-297

[66] Brando G, Dannier A, Del Pizzo A, Rizzo R, Spina I. Torque derivative control in induction motor drives supplied by multilevel inverters. IET Power Electronics. 2016;**9**(11):2249-2261

[67] Shareef H, Islam MM, Mohamed A. A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles. Renewable and Sustainable Energy Reviews. 2016;**64**:403-420

[68] Veneri O. Technologies and Applications for Smart Charging of Electric and Plug-in Hybrid Vehicles. Springer; 2016. pp. 1-307. DOI: 10.1007/978-3-319-43651-7

[69] Rubino L, Capasso C, Veneri O. Review on plug-in electric vehicle charging architectures integrated with distributed energy sources for sustainable mobility. Applied Energy. 2017;**207**:438-464

[70] Vasiladiotis M, Bahrani B, Burger N, Rufer A. Modular converter architecture for medium voltage ultra fast EV charging stations: Dual half-bridge-based isolation stage. In: 2014 International Power Electronics Conference, IPEC-Hiroshima - ECCE Asia 2014, art. no. 6869766. pp. 1386-1393

[71] Tsirinomeny M, Hõimoja H, Rufer A, Dziechciaruk G, Vezzini A. Optimizing EV driving-recharge time ratio a under limited grid connection, 7th IET International Conference on Power Electronics, Machines and Drives (PEMD 2014), Manchester. 2014. pp. 1-6

[72] Jampeethong P, Khomfoi S. An EV quick charger based on CHAdeMO standard with grid-support function. In: 2015 18th International Conference on Electrical Machines and Systems (ICEMS), Pattaya. 2015. pp. 531-536

[73] Madawala UK, Thrimawithana DJ. A bidirectional inductive power interface for electric vehicles in V2G systems. IEEE Transactions on Industrial Electronics. 2011;**58**(10):4789-4796

[74] Li S, Mi CC. Wireless power transfer for electric vehicle applications. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2015;**3**(1):4-17