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RELAZIONE PER IL CONSEGUIMENTO DELLA
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Maintenance program for Electric Vehicles power train by Reliability Centred Maintenance

RELATORI

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LIST OF NOTATIONS

AC	Alternating Current
DC	Direct Current
PdM	Predictive Maintenance
PM	Preventive maintenance
CM	Corrective Maintenance
EV	Pure-Electric Vehicle
FCEV	Fuel-Cell Electric Vehicles
HEV	Hybrid Electric Vehicles
PHEV	Plug-In Hybrid Electric Vehicles
ICEV	Internal Combustion Engines vehicle
Li-Ion	Lithium-ion
Ni-Cd	Nickel-Cadmium
Ni-MH	Nickel-Metal Hydride
PMSM	Permanent Magnet Synchronous Motor
PMBM	Permanent Magnet Brushless Motor
DSP	Digital Signal Processor
OEM	Original Equipment Manufacturers
RCM	Reliability centred Maintenance
RBD	Reliability Block Diagram
FMECA	Failure Mode, Effects and Criticality Analysis
COFA	Consequence of Failure Analysis
RTF	Run-to-failure component
ARC	Asset Reliability Criteria

ABSTRACT

The reduction of environmental pollution is one of the greatest challenges for humanity, today and for the immediate future. Air quality is one of the most critical aspects in determining people's health, particularly in big cities, and transportation emissions are currently considered accountable for almost 32% of total air contamination.
The more widespread use of green vehicles could have important effects both on the environment and the economy, and this thesis work intends to focus on reliability and maintainability of pure-electric vehicles (EVs).

The main objectives of this paper are:

- To conduct research into state-of -art of pure-electric car powertrain technology, describing the functions and operations of its various components: mechanical, electrical and the control links between those components are all carefully considered.
- To identify and define a long term maintenance plan for the power train system, utilising the RCM method.

In order to achieve these targets and objectives, a wide literature review will be conducted on existing electric vehicle technology, taking already published and available information from similar technologies which are more mature than EVs one, but with comparable run conditions and operations.

The method adopted for this maintenance study is Reliability Centred Maintenance (RCM): this logic will be reviewed and applied to the powertrain system, designing and completing proper worksheets (*COFA worksheet* and *PM task worksheet*) which will form the suggested maintenance plan. This proposed plan consists of various elements including: failure modes identification, failure effects on the vehicle, criticality classification of the components, failure causes identification and suggested preventive maintenance tasks with proper periodicity.

In the final part of the paper, the results and outcomes of the analysis will be discussed, and possible future developments will be identified.

Chapter 1

1. INTRODUCTION

1.1 BACKGROUND

The large number of automobiles currently in use around the world is one of the major causes of environmental pollution and energy problems: air pollution, global warming and consumption of Earth's petroleum resources are the main consequences and contributing effects of the rapid development and expansion of the conventional automotive industry.

In an internal combustion engine, the energy is supplied by the combustion of hydrocarbon fuels and the reaction products are released into the atmosphere. The more toxic molecules to human health are nitrogen oxides (NO_x), carbon monoxides (CO), and unburned hydrocarbons. [1] [2]
Global warming is the result of the "greenhouse effect" induced by high concentrations of carbon dioxide and other gases in the atmosphere. Many human activities contribute towards this phenomenon, and transportation accounts for a large share (32% from 1980 to 1999) of carbon dioxide emissions.

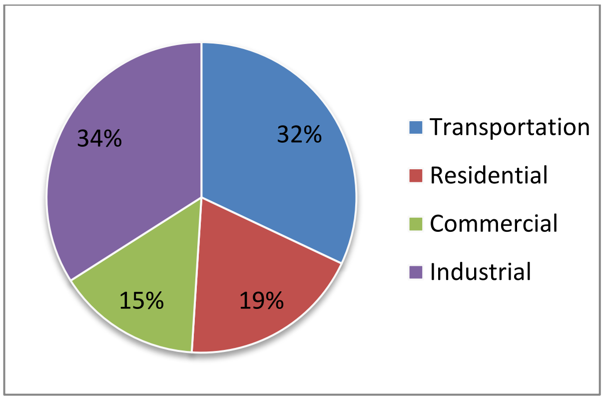
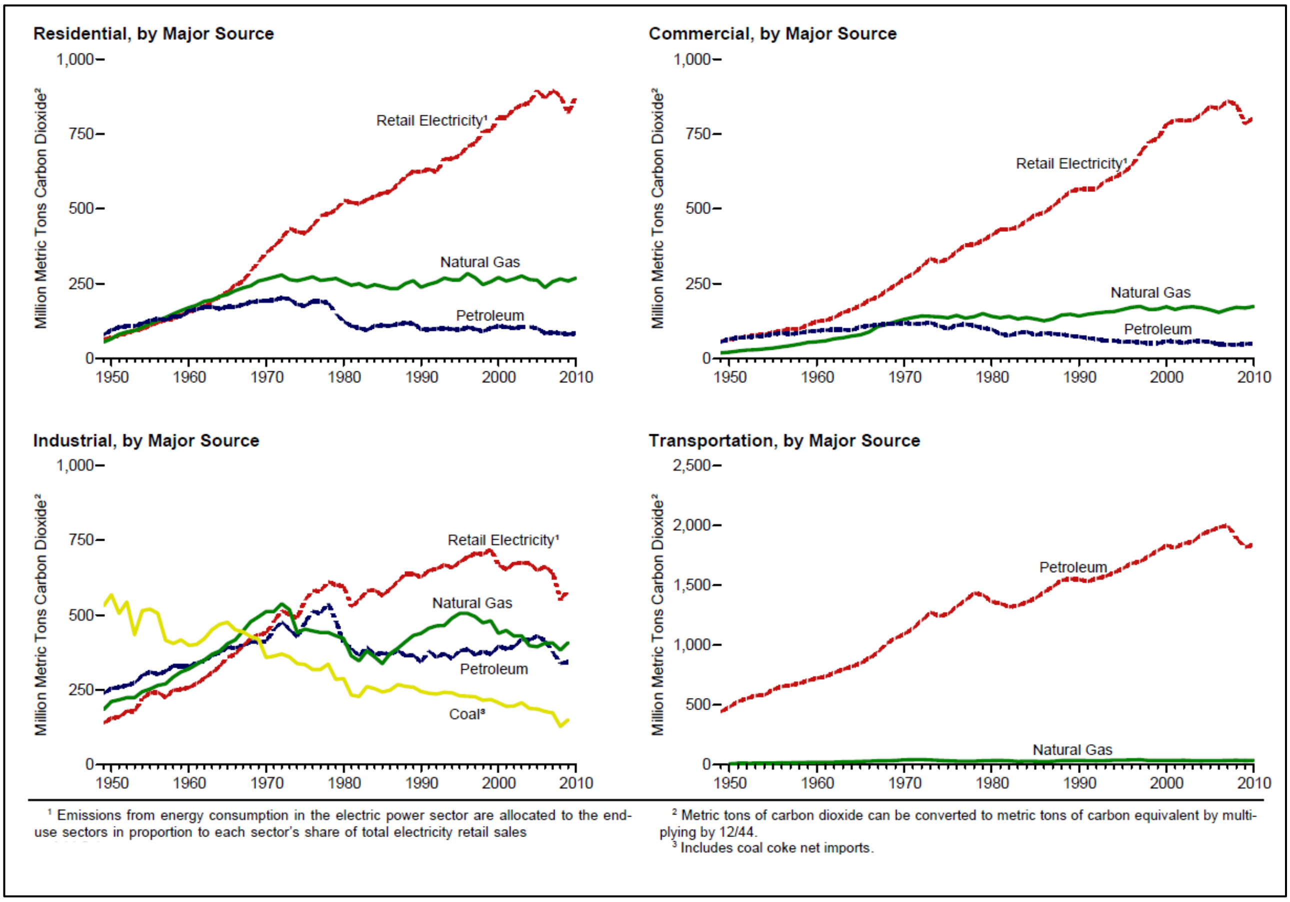


FIGURE 1.1
Carbon dioxide emission distribution 1980 – 1999 [3]

In recent decades, research activity has focused on the development of alternative transportations, with qualities like high efficiency, reduction of emission, and use of unconventional energy sources.



[1] Emissions from energy consumption in the electric power sector are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales

[2] Metric tons of carbon dioxide can be converted to metric tons of carbon equivalent by multiplying by 12/44.

[3] Includes coal coke net imports.

FIGURE 1.2
Carbon dioxide emissions from energy consumption by End-Use sector, 1949-2010 [4]

As shown in the above figure, the production of CO_2 in the environment tends to increase year on year in all the considered human circumstances, such as industrial activity, residential, commercial and transportation. Furthermore, the system of transportation is particularly critical in effecting human health because it produces air pollution directly in the place where people live, which can result in serious effects upon the quality of life.

Considering pure-electric vehicles (EVs), even if the production of electricity is still mostly supplied by fossil fuels, there are several advantages among the utilization of petrol as vehicle fuel:

- The power plants are usually located far from cities and urban centers;
- The efficiency of power plants is higher than transportation vehicles, which is a base condition to save energy sources;
- Power plants are equipped with systems for the reduction of pollution which are more effective than vehicles, in particular, old vehicles and trucks. Only coal plants utilization could increase the emission of NO_x, SO_x and particulates, with some potential negative consequences for air acidification. These impacts would reduce over time if greater

proportions of renewable power were introduced and the amounts of cold generation were reduced.

Electric vehicles have zero emissions at the point of use, so-called *‘tank-to-wheel’*, when powered solely by the battery. The *‘well-to-wheel’* concept includes the CO_2 emissions during electricity generation, which depends on the current mixture of fuels used to make the electricity for the grid.
To make a correct comparison with emissions from all cars, you have to use the ‘well to wheel’ concept, which includes the CO_2 emissions during production, refining and distribution of petrol/diesel.
On a comparable basis taking into account both electricity generation and the processes necessary to deliver petrol and diesel to the vehicle, emission factors and lifetime carbon use have been calculated for vehicles manufactured in 2010, 2020 and 2030. For ICEVs, the addition of pre-combustion emissions (extraction, refining, transport, etc.) typically adds another 10-18% to the ‘tank to wheel’ figure. The table below presents these ‘well to wheel’ figures.

Vehicle manufactured in 2010			
	EV	ICEV	
	GaBi 4 factors grid mix[1]	Petrol	Diesel
Emission factor well to wheel gCO_2/km	*106*	*172*	*156*
Lifetime vehicle carbon use kg CO_2 - equiv	*19,161*	*30,916*	*28,012*
Vehicle manufactured in 2020			
Emission factor well to wheel gCO_2/km	*56*	*144*	*130*
Lifetime vehicle carbon use kg CO_2 - equiv	*10,132*	*25,864*	*23,435*
Vehicle manufactured in 2030			
Emission factor well to wheel gCO_2/km	*41*	*120*	*109*
Lifetime vehicle carbon use kg CO_2 - equiv	*7,390*	*21,639*	*19,606*

TAB. 1.1

Comparison of an EV and an ICEV over the Vehicle Life (defined as 180,000 km) [5]

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[1] GaBi 4 is a Life Cycle Assessment tool conforming to the ISO 14040 Life Cycle Assessment (LCA) standards. It is designed to allow the user to model the whole life cycle (or part) of a product or service, and provides a quantitative output on a range of environmental impacts.

As electricity production decarbonises through an increase in low carbon generation, the overall emission figure for running an EV will drop further. The current lowest emitting ICEV produces tailpipe (tank to wheel) emissions of 86g CO_2/km [6]. Adding the average ‘well to tank’ proportion (which starts at 10% and equates to 8.6g CO_2/km) means ICEVs can achieve ‘well to wheel’ emissions as low as 94.6g CO_2/km and ICE vehicles are being refined to further reduce the ‘tank to wheel’ emissions.

It is worth noting that the standard industry metrics only consider CO_2 emissions. However, tailpipe emissions include oxides of nitrogen (NOx) and particulate matter (tiny particles of solid or liquid matter suspended in a gas or liquid) which furthermore contribute to air pollution. This is why vehicle manufacturers are striving to reduce tailpipe emissions and why any vehicle operating solely on battery power can play a significant role in improving local air quality. [6]

In a world where environmental protection and energy conservation are ever more critical, the development of green transportation technology has taken on an accelerated pace and Electric Vehicles, Hybrid electric vehicles (HEVs) and Fuel cell vehicles are typically proposed to replace the ICE vehicles in the near future [7].

1.2 WORK OBJECTIVES

The main objective of this thesis work is to produce a maintenance program for the modern EVs power train, consisting in both the traction system and the energy source system. The focus of this program is on electronic control units, communication units and traction power units. The auxiliary system and cooling system analysis is not within the scope of this paper: the purpose is to produce an applicable and effective maintenance program, and the research strategy has been to concentrate the resources in the traction-power subsystem, instead of the whole system.

The maintenance study is based on the Reliability Centred Maintenance (RCM) method: in the chapter 3 *Methodology*, the principals of this method are further described and discussed.

The objectives proposed to be achieved on this thesis are:

1. Analysis and understanding of the typical architecture of the electric car powertrain.
   1.1. Description and schematic drawing of the structure of a typical electric car power train representing mechanical, electrical and control links between components;
   1.2. Description of structure and operations of each system component;
   1.3. Reliability Block Diagram for general reliability considerations on the whole system.
2. Identification of the best maintenance strategy for the power train system, employing the RCM method. Definition of a long-term maintenance plan.
   2.1. Identification of functions, functional failures, failure modes, and criticality classification of each powertrain component;
   2.2. For each component (except for run-to-failure[2] ones), identification of failure causes, definition of the proper Preventive Maintenance tasks and related periodicity.

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[2] Run-to-failure are those components which can be replaced after the occurrence of their failure, without preventive maintenance activities.

1.3 THESIS STRUCTURE

The Chapter 2 will focus on a literature review of the technology related to electric traction, electronic control system and energy storage system, and it refers to the first macro-objective. Different configurations will be compared through a pros-and-cons analysis and the complete scheme of the power train system will be drawn.

The methodology of the research will be reported in Chapter 3, and in this section the Reliability Centred Maintenance logic will be described: it is the method applied to the power train to produce a maintenance program (ref. Appendix A and B). The RCM principles will be defined, the reliability analysis process will be planned and the maintenance worksheets (*COFA worksheet* and *PM task worksheet*) will be designed.

The core section of the thesis work forms Chapter 4, in which the overall results and findings are described. In this part, the second objective of the research, the identification of the best maintenance strategy for the powertrain and definition of a long-term maintenance plan, is reviewed and presented. In particular, the outcomes of six interesting components will be widely described.

Finally, in Chapter 5, the results and outcomes of the analysis and possible future developments will be discussed.

Chapter 2

2. LITERATURE REVIEW

2.1 STRUCTURE OF A TYPICAL EV POWER TRAIN

2.1.1 INTRODUCTION

The conventional vehicles employ a combustion engine for propulsion and the energy source is either liquid petrol or diesel. In contrast, pure-electric vehicles (EVs) use an electric motor for traction, and chemical batteries, fuel cells, ultracapacitors, or flywheels as energy sources[3]. These vehicle types have different advantages over the internal combustion engine vehicles (ICEVs), such as an absence of emissions, high efficiency, flexible structure, independence from petroleum[4] and quiet operation.

This chapter investigates the state of the art of the modern EVs power train structure: describing the operational and fundamental principles, the multiple drive train configurations and the typical system composition by detailed diagrams.

2.1.2 ICE VEHICLES POWER TRAIN

An automotive *power train*, or *drive train*, is the electromechanical system that allows the flow of power from the energy source to the road.

Basically, any vehicle power train has four main assignments:

I. Develop sufficient power to match the requirements of the load;
II. Carry sufficient energy to support vehicle driving on a target range;

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[3] Presently achievable energy of ultracapacitors and flywheels can’t be the sole energy sources for EVs.
[4] Without considering the process of electricity generation, tank to wheel figure.

III. Demonstrate high efficiency;
IV. Emit limited environmental pollution.

A usual drive train consists of a power plant (engine or electric motor), a clutch in manual transmission or a torque converter in automatic transmission, a gearbox (transmission), final drive, differential, drive shaft, and driven wheels.

In Figure 2.1 represents a schematic drive train of an ICE vehicle.

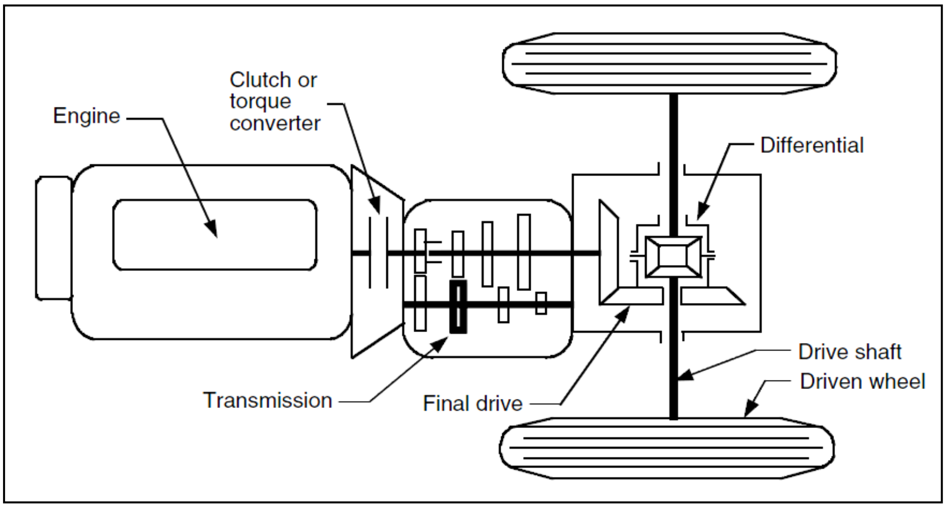


FIGURE 2.1

Conceptual illustration of an automobile power train [3]

The clutch is used in manual transmission to couple to or decouple the gearbox from the power plant. The torque converter replaces the clutch in automatic transmission: it consists in a hydrodynamic device with a continuously variable gear ratio. The gearbox supply a few gear ratios from its input shaft to its output shaft for the power plant torque-speed profile to meet the demand of vehicle performance: by incorporating both clutch and gearbox, the driver can shift the gear ratio and hence the torque going to wheels. The final drive is usually a pair of gears that reduce further the speed and distribute the torque to each wheel through the differential. Differential is a mechanical device that allows the wheels to have different speed along a curved path, where the outer wheel rotates faster than inner one.

In ICEVs, all the links between these devices are mechanical links and this is why the drive train configuration is not so flexible.

Nowadays more and more significance is given to the environmental impact of the vehicles, emphasizing the development of high efficiency, clean, and safe transportation, able to take place of conventional ICEVs.

2.1.3 ELECTRIC VEHICLES POWER TRAIN

Previously, the EV was mainly converted from the existing ICEV by replacing some components with new devices that have the same function, like internal combustion engine with electric motor drive and fuel tank with battery pack, while retaining all the other components, as in following Figure 2.2.

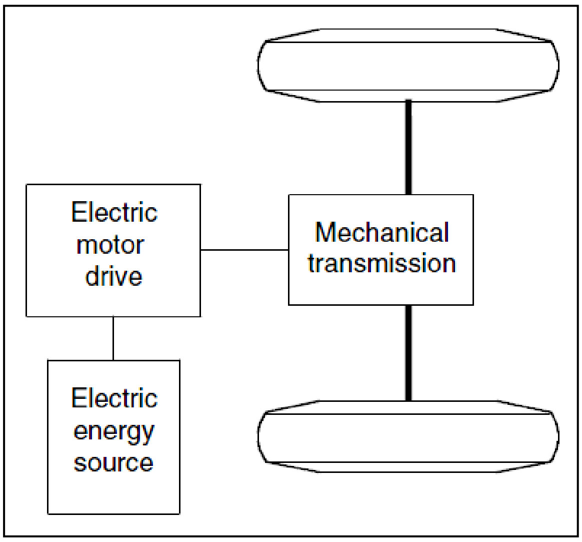


FIGURE 2.2

Primary electric vehicle power train [3]

The lower flexibility, performance degradation, and the heavy weight have caused the use of this type of EV to fade out. To solve this negative aspect, the modern EV is built based on original body and frame design. This solution takes the significant advantage over the "converted" one because it provides the engineer with the flexibility to coordinate and integrate various subsystems so that they can work together efficiently.

Compared with an ICE vehicle, the configuration of an EV is particularly flexible. This is due to several factors. Firstly, the energy flows in the EV is mainly via flexible electrical wires rather than bolted flanges and rigid shafts. Secondly, since the torque-speed characteristic of an engine covers only a narrow range, the required performances of the vehicle have to be achieved through gear changing. On the other side, the electric vehicle propulsion design can be more flexible, namely single or multiple motors, with or without reduction gearing, with or without differential gearing, and axel or wheel motors. Furthermore, EV gives the possibility to choose different energy sources (such as battery and fuel cell) that have different weights, sizes and shapes. The corresponding refuelling system also involves different hardware and mechanism: for example, the battery can be recharged both via conductive or inductive means.

2.1.3.1 STRUCTURE AND BEHAVIOUR

Figure 2.3 shows the general configuration of an EV, consisting of three major subsystems: [8]

- Electric motor propulsion;
- Energy source system;
- Auxiliary system.

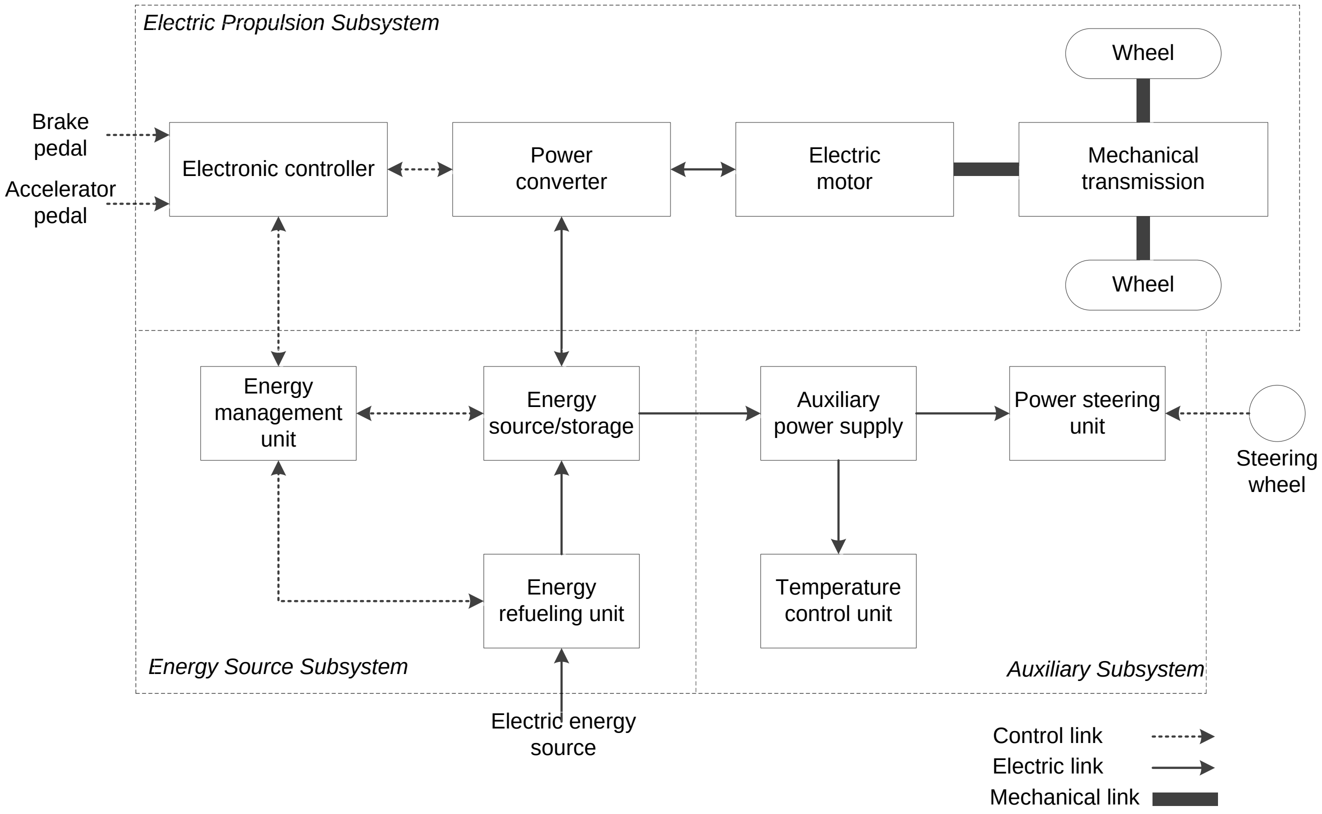


FIGURE 2.3

General EV configuration

The electric propulsion subsystem consists of the motor drive, transmission device and wheels. The heart of this system is motor drive, comprising of the electric motor, power converter and electronic controller, and the major requirements of the EV motor drive are summarized as follow:

- High instant power and high power density;
- High torque at low speed for starting and climbing as well as high speed and low torque for cruising;
- High efficiency over wide speed and torque ranges;
- High reliability and robustness for various vehicle operating conditions;
- Reasonable cost.

The energy source subsystem consists of energy source, energy management unit and energy refuelling unit.
The auxiliary subsystem involves the power steering unit, temperature control unit and auxiliary power supply.

Based on the control inputs from the accelerator and brake pedals, the electronic controller provides proper control signals to switch on or off the electronic power converter, which functions to regulate the power flow between the energy source and electric motor. The backward power flow is due to the regenerative braking of the EV and this regenerated energy can be restored to the energy source, provided the energy source is receptive. Notice that most EV batteries as well as ultracapacitors and flywheels readily possess the ability to accept regenerated energy. The energy management unit cooperates with the vehicle controller to control the regenerative braking and its energy recovery. It also works with the energy refueling unit to control the refueling unit, and to monitor the usability of the energy source. The auxiliary power supply provides the necessary power at different voltage levels for all the EV auxiliaries, especially the temperature control and power steering units. [8]
Typically, a Permanent Magnet Synchronous brushless motor is selected for a modern EV and the corresponding power converter is a three-phase PWM inverter. In general a Lithium-based (Li-Ion) battery pack is used as energy source, and consequently the refueling unit becomes a battery charger. The temperature control unit consists of a cooler and/or a heater. [3]

This typical configuration is shown in Figure 2.4.

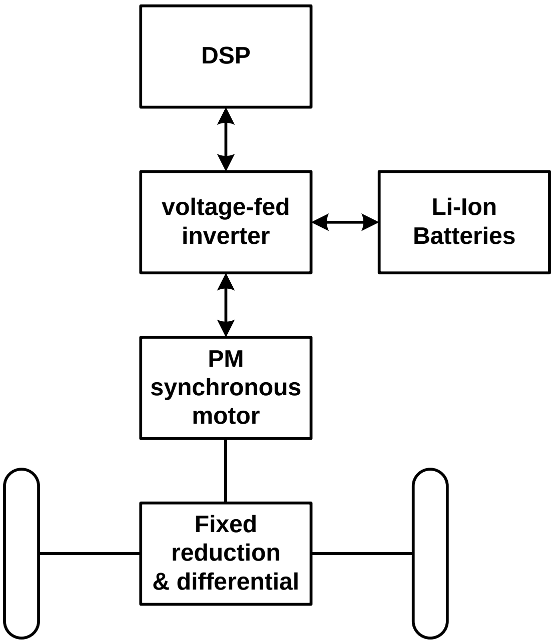


FIGURE 2.4

Typical EV drive train configuration

2.1.3.2 DRIVE TRAIN CONFIGURATIONS

As mentioned above, there is a variety of possible EV configurations, due to the multiple types of propulsion devices and energy sources, and due to the flexibility of electric links. Focusing on the power train shape, in Figure 2.5 are shown six typical alternatives.

- 2.5.a. Figure 2.5.a shows the configuration of the first alternative, in which an electric motor replaces the IC engine of a conventional vehicle power train. It consists of an electric motor, a clutch, a gearbox and a differential.
- 2.5.b. With an electric motor, which has constant power in a long speed range, a fixed gearing can replace the multispeed gearbox and reduce the need for a clutch. This configuration not only reduces the weight and size of the mechanical transmission, but also simplifies the drive train control because gear shifting is not required.
- 2.5.c. The electric motor, the fixed gearing, and the differential device are further integrated into a single assembly, while both axles point at both driving wheels.

2.5.d. In this configuration the mechanical action of differential is electronically replaced by two electric motors operating a different speed, each of them drives one side wheel.

2.5.e. In order to further shorten the drive train from the electric motor to the driving wheels, the traction motors can be placed inside a wheel (*in-wheel drive*). A thin planetary gear set can be used to reduce the motor speed and enhance the motor torque.

2.5.f. By fully abandoning any mechanical gearing, the out-rotor of a low-speed electric motor can be directly connected to the driving wheel. Figure 2.5.f shows a gearless arrangement in which the speed control of motor is equivalent to the control of the wheel and hence the vehicle speed. However, this configuration requires the electric motor to have a higher torque to start and accelerate the vehicle.

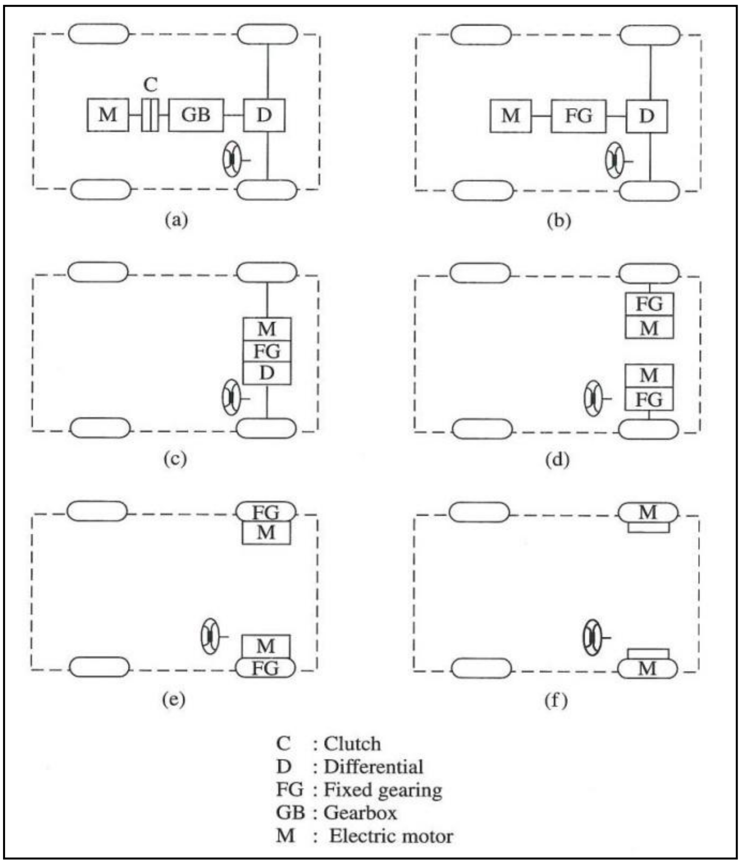


FIGURE 2.5

Possible EV configuration [8]

As mentioned before, the system configuration of EV propulsion can adopt a single motor or multiple motors, as shown in the following Figure 2.6 and 2.7.

Since these two configurations have their individual merits, both of them are adopted in modern EVs but the use of single-motor configuration is still the majority today, for example the new Nissan Leaf and Renault Z.E. fleet. [3] [9] [10]

That choice is explained especially by several reasons:

- Costs: the multiple-motor is a completely new configuration and requires a complete redesign of OEMs production plants and consequently very high investments, not justified by the current market demand;
- Maintenance benefits: the number of components is inversely related with the reliability of the system, even if in the multiple-motor configuration there is not a differential unit, affected by wear and ageing;
- Total weight reduction: the single-motor structure is lighter, even if the multiple-motor one allows a better distribution of the mass of the vehicle. [3] [7]

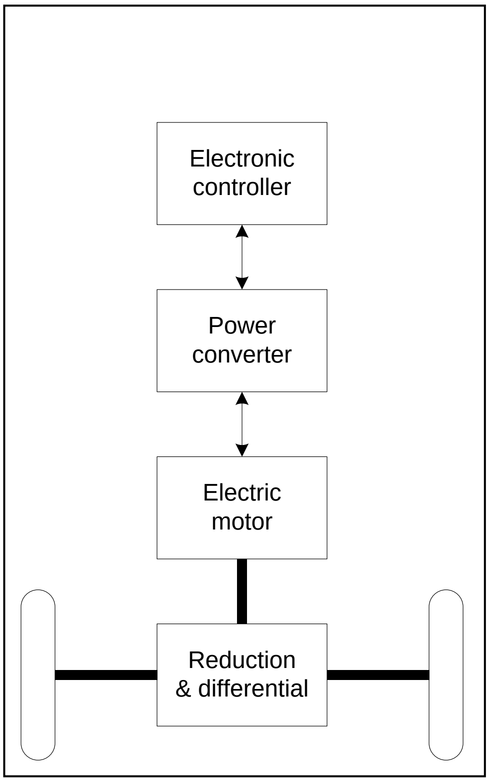


FIGURE 2.6

Single-motor configuration

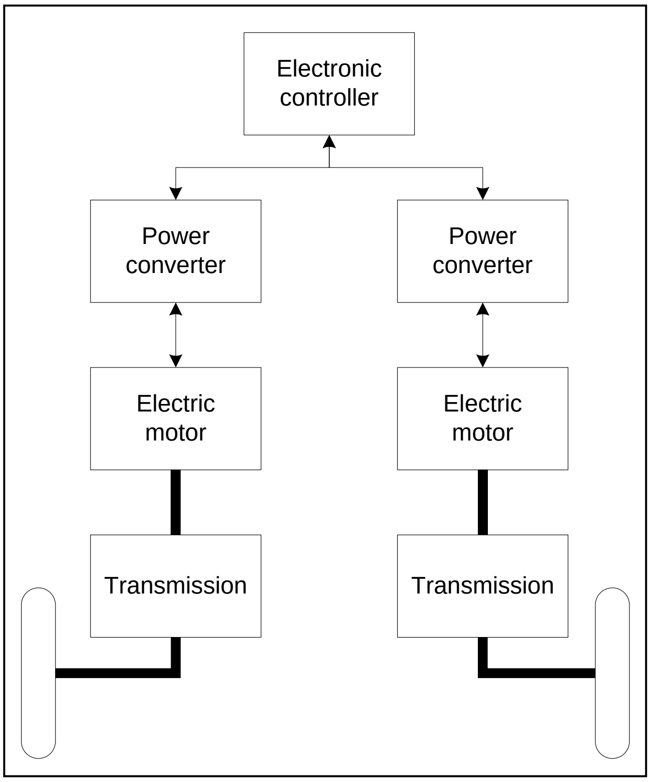


FIGURE 2.7

Multiple-motor configuration

2.1.3.3 ULTIMATE SYSTEM SOLUTIONS

Analysing the configurations showed in Figure 2.5, it is possible to notice a strong evolution from "conventional structures" toward very innovative structures. The major changes are in gearbox and differential concepts.

For ICEVs, there is no alternative to the use of variable gearing, because the torque-speed characteristics of the engine cannot offer the desired performances in a complete driving cycle, such as high torque for hill climbing and high speed for cruising. So primarily, were applied the same concepts to the first electric vehicles. However, the concept of converted electric vehicle is almost obsolete, as it cannot fully utilize the flexibility and potentiality of EVs. Some obsolete theory claimed that variable gearing could also improve the regenerative braking efficacy and the motor efficiency operation over a wide speed range. The modern EVs, with the advances of power electronics and control algorithms, can achieve that aims by electronic means rather than mechanical means. Electric motors can supply the requested vehicle performances and so fixed gearing transmission can replace variable gearing, reducing the overall complexity, size, weight, cost of the transmission and costs of maintenance.

A more controversial aspect is the possibility in EV to replace the differential device, Figures 2.8 and 2.9, with two or even four electric motor coupled to the driving wheels (as anticipated in Figures 2.5.d, 2.5.e and 2.5.f).

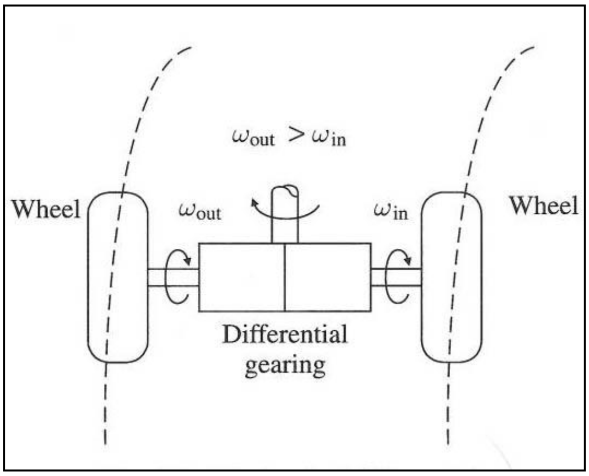


FIGURE 2.8

Mechanical differential [8]

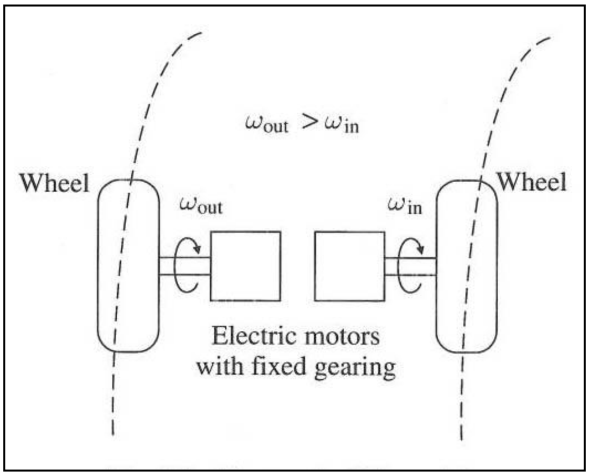


FIGURE 2.9

Electronic differential [8]

The differential action can be supplied by several motors, controlling the speed of each wheel independently with an electronic control rather than a mechanical device, as in Figure 2.9.

In this arrangement, the weight is better distributed than in the conventional one, but negatively, the use of double motor and power converter causes an increase of initial costs and an increase of number of components, with critical consequences in reliability. Nowadays thanks to the low-cost electronic technology, it is possible to find solutions that increase the reliability level, for example using redundant microprocessor in the electronic controller.

The ultimate solution in EVs configurations is the in-wheel drives, as shown in the relative configurations in Figure 2.5.e and 2.5.f. By placing the motor inside the wheel, there is the advantage of minimizing or even removing any mechanical transmission path between motor and wheel.

If using a high-speed inner-rotor motor (represented in the following Figure 2.10.a), a high-speed reduction becomes necessary to attain a realistic wheel speed. On the other hand, the transmission can be totally removed when a low-speed outer-rotor motor is used: in this case, the outer rotor itself is the wheel rim, and no gears are required (Figure 2.10.b).

Both these solutions could be applied to modern EVs: the high-speed inner-rotor motor has the advantage of smaller size, lighter weight and lower cost, but needs an additional planetary gear set; the low-speed outer-rotor motor has the great advantage of gearless and simplicity but it is heavier, bigger in size and more expensive.

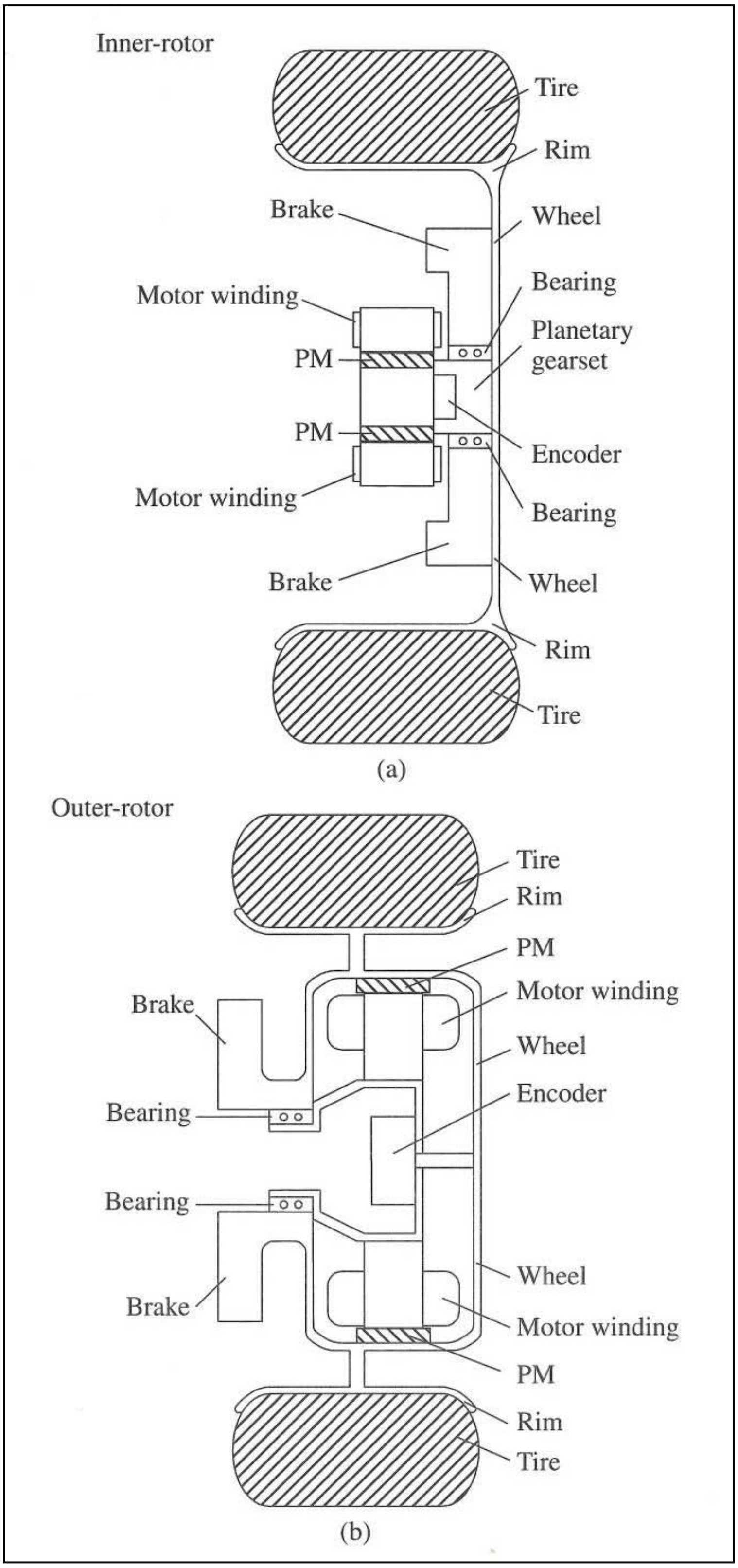


FIGURE 2.10

In-wheel drives [8]

2.2 EV POWER TRAIN: COMPONENTS OPERATIONS, FUNCTIONS AND RBD

2.2.1 INTRODUCTION

This section consists in an overview on the modern electric cars propulsion system configurations: several combinations of units offer different possibilities of power train structure. The most proper electric motor drives are compared and described in their operations and main characteristics. The technologies of power converter and energy source are overviewed, as well as the modern possibilities of electronic control systems. A base evaluation of the reliability of the entire power train is made by the Reliability Block Diagram (RBD).

The electric propulsion subsystem is the heart of EVs. Its role is to link energy source to wheels, converting electric energy in vehicle motion with high efficiency and matching the required performances.
It consists of:

- electric motor;
- electronic controller;
- power converter.

Electric motor supplies mechanical energy converting electric one from batteries to wheels, and can generate electricity during the braking phase to recharge energy storage. Regenerative braking is a key process for EV appeal because it enhances vehicle efficiency of between 20 - 25 %.

The power converter supplies the electric motor with the appropriate current and voltage.

Electronic controller provides control signals to power converter and so it controls the electric motor behaviour in order to achieve the requested torque and speed, according to commands from the driver. [8] [11]

In the following Figure 2.11, the functional block diagram of electric propulsion system is shown, listing some possible devices used for each unit.

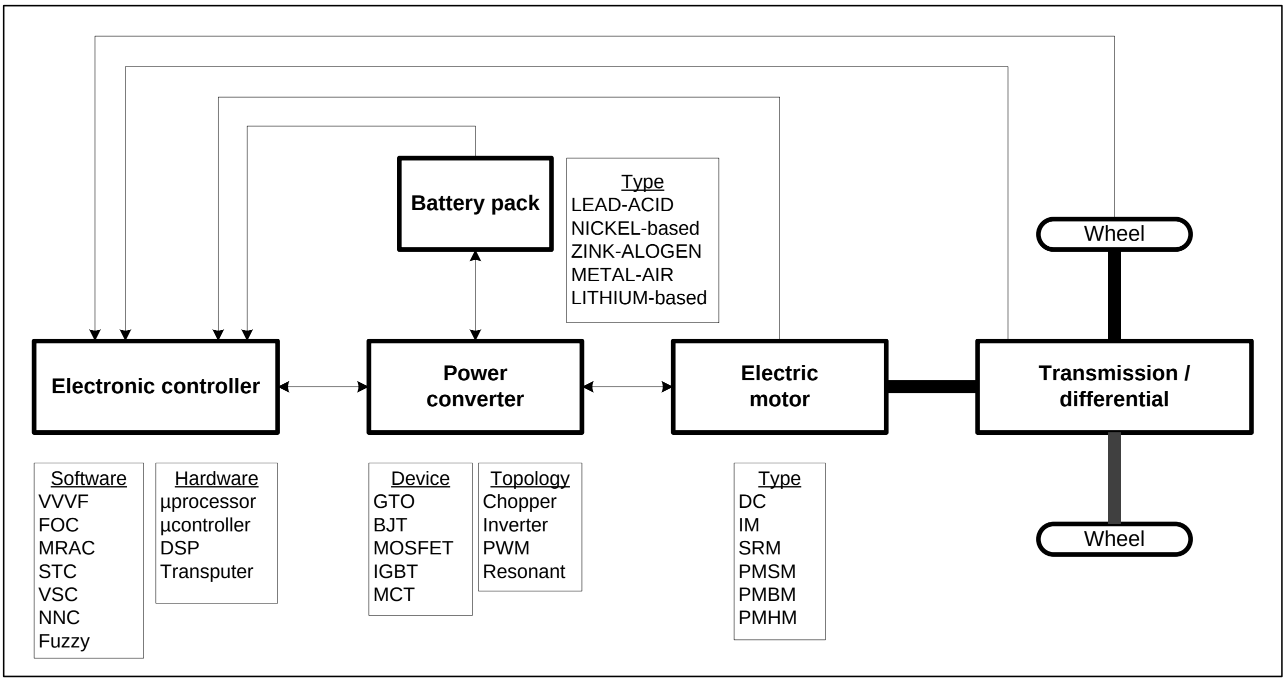


FIGURE 2.11

Functional block diagram of an EV propulsion system: technical options for each function.

The choice of components and shape mainly depends on three factors: user driver expectation, vehicle constraints and energy source.

Driver expectation depends on performance and driving cycle: automobile manufacturers have to take into account that customers will compare ICEVs performances with EVs ones.

Vehicle constraints are linked with vehicle type, vehicle weight and payload.

Electric propulsion subsystem depends on what kind of source is adopted, such as batteries, ultracapacitors, flywheels, fuel cells and various hybrid sources.

2.2.2 ELECTRIC MOTOR

The operations requested to the vehicle motor vary widely during a normal drive cycle: frequent start/stop, high rate of acceleration/deceleration (overcoming or braking phase), high torque at slow speed (hill climbing), high speed at low torque (cruising highways).

For these reasons, motors for EV form an individual class, quite different from industrial devices, which operate on a narrow range of conditions.

Industrial motors are generally optimized at rated torque and speed; while EVs need to match four/five times the nominal torque and speed for temporary acceleration and for cruising. Furthermore, industrial motors work usually in fixed place instead of mobile vehicles with harsh operating conditions such as high temperature, frequent vibrations and bad weather.

The motor drives for EVs can be classified as two main groups, namely the *commutator* motors and *commutatorless motors*, as shown in Figure 2.12.

The former refer mainly to the classical DC (direct current) motors, which need commutators and brushes to feed current into the armature, making them less reliable and suitable for maintenance-free and high speed. Nevertheless, in recent past DC motors have been prominent thanks to their mature technology and simple control.

With technological progress, commutatorless motors are now more attractive than the conventional. Advantages include higher efficiency, higher power density, lower operating costs, greater reliability and maintenance-free. In fact, the absence of brushes and commutator increases widely the reliability of the motors and reduces failure probability. [8]

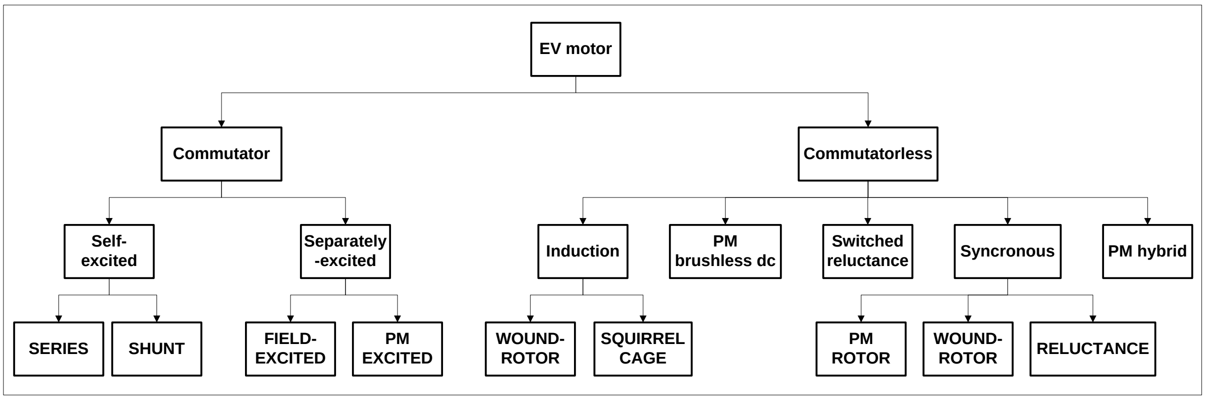


FIGURE 2.12

Classification of EV motors

2.2.2.1 ELECTRIC MOTORS: PROS AND CONS ANALYSIS

The most proper motors in modern EVs are Induction motors, PM Synchronous motors, Switched Reluctance motors and PM Hybrid motors.

Induction motor

It is a widely accepted type of device for EV propulsion thanks to its low cost, high reliability and maintenance free, and at present, it is one of the most mature technologies among various commutatorless motor drives. The main advantages of this type of device are: [12]

- Light weight
- Small volume
- Low initial cost
- High efficiency
- Low maintenance

These strengths can outweigh the major weakness of induction motors, namely the control complexity.

Permanent Magnet synchronous motors

By simply replacing the field winding of a DC motor with permanent magnets, PM synchronous motors can eliminate conventional brushes, slip-rings and field copper losses. The major advantages of this kind of motor are: [3] [12]

- High efficiency
- Compactness
- Ease of control
- Low maintenance

However, it presents also several drawbacks:

- High initial cost
- Limited constant power range

- Magnet demagnetization
- Small speed range

Switched reluctance motors

SR motors have been recognized to have big potential for EV propulsion. They have the definite merits of: [3]

- Simple structure
- Low initial cost
- Proper torque-speed characteristics

Although they hold these advantages, there are also some weaknesses:

- Design complexity
- Control complexity
- Acoustic noises

PM Hybrid motor

There are different kinds of hybridization, namely the PM and reluctance hybrid, the PM and hysteresis hybrid, and the PM and field-winding hybrid. Each type has particular advantages that are summarised as: [3]

- High efficiency
- High power density
- Wide speed range
- Ease of control
- Low maintenance
- Quiet operation

The most important disadvantages are linked to the lack of technological maturity and costs.

In Tab.1, the results of a comparative analysis by a grading system are depicted: each type of motor is evaluated for six major characteristics from 1 to 5 points. At the end of each column, there is the final rating: induction motor and PM brushless motors are the most relatively acceptable for EV driving. On the other hand, conventional DC motors are leaving their leadership to the modern solutions. [3][12]

	DC motor	**Induction motor**	**PM brushless motor**	**SR motor**	**PM hybrid motor**
Power density	2.5	3.5	5	3.5	4
Efficiency	2.5	3.5	5	3.5	5
Controllability	5	3	4	3	4
Reliability	3	5	4	5	4
Maturity	5	5	4	4	3
Cost	4	5	3	4	3
Total	22	25	25	23	23

TAB. 2.1
Evaluation of EV motors [8]

2.2.2.2 DIRECT CURRENT (DC) MOTOR

The DC motors are classified in two categories: wound-field motor and PM motor. In the former, magnetic field is produced by a set of winding and it can be controlled by the dc current, in the latter magnetic field is made by permanent magnets and it is uncontrollable.

Traditionally this type of motor has been widely adopted in cases requiring adjustable speed, frequent start/stop, braking and reversing.

The torque is produced by the Lorentz principle, which states that any current-carrying conductor placed within an external magnetic field (B) generates a force (F). If the conductor is a coil, than there is a torque, as shown in Figure 2.13.

In order to keep the same direction of rotation, DC motors need commutators and brushes, which periodically reverse current direction between rotor and stator. These components cause the principal drawbacks of this kind of motor: commutators limit the motor speed and generate torque ripples; brushes are responsible for friction and wear, so that periodic maintenance is definitely required. Nevertheless, DC motor has been the most used device for vehicle propulsion for years, especially thanks to its controllability.

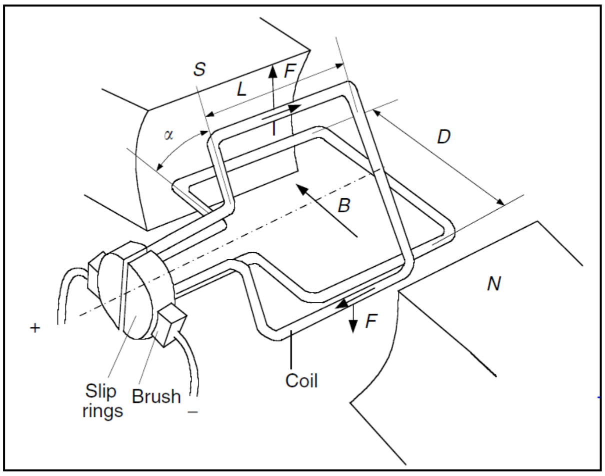


FIGURE 2.13

Operation principle of a DC motor [3]

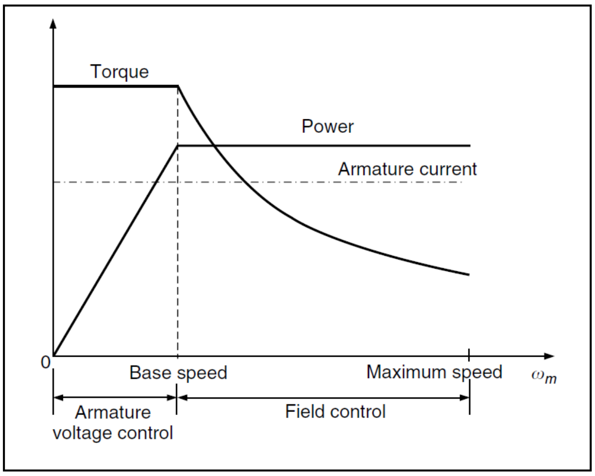


FIGURE 2.14

Combined armature and field control of DC motor [3]

In EV starting operation, from zero to base speed, rotor coil voltage must be increased proportionally with the increase of speed (Armature Control). At the base speed, the armature voltage reaches the rated value and cannot be further increased. In order to reach higher speed it is possible to weaken the magnetic field (Field Control), keeping constant armature current. The torque produced drops parabolically with the increase of speed and the output power remains constant, as shown in Figure 2.14. [12]

2.2.2.3 INDUCTION MOTOR DRIVES

In order to overcome the weaknesses of conventional DC motors, one of the most mature alternatives available is the induction motor drive (IM). It is a type of AC motor (alternative current) where power is supplied to the rotor by electromagnetic induction. There are two typology of IMs namely *wound-rotor* and *squirrel cage*. Because of high cost and high maintenance, the former is less attractive than the latter, especially for EV drive train. [3]

Induction motor has some important advantages as low cost, ruggedness, easy maintenance, lightweight and high efficiency. On the other hand, the principal problem is the complexity of speed control, which can be solved only with advanced electronic technology and modern control solutions, increasing the total cost of propulsion system.

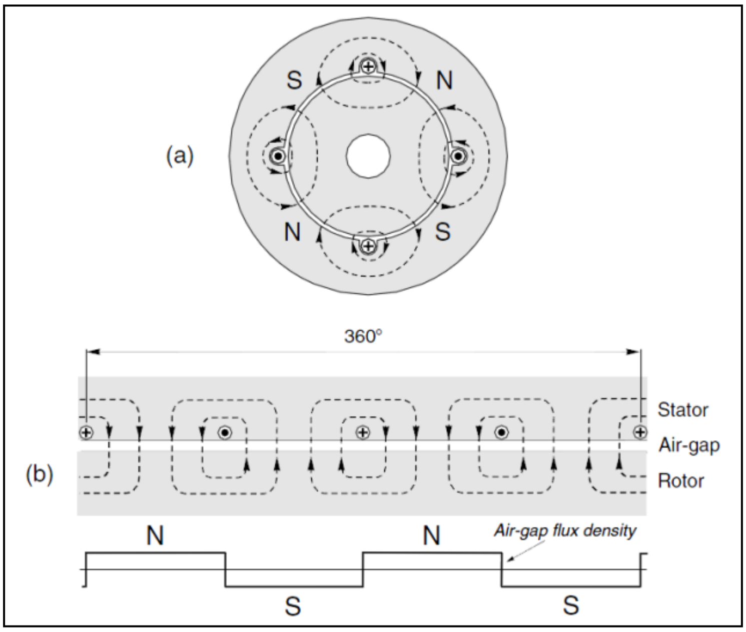


FIGURE 2.15

Operation principle of an Induction Motor [12]

2.2.2.4 PM SYNCHRONOUS MOTOR DRIVES

Considering the waveform feeding into the PM motors, they can be classified into two categories:

- PM DC motor drive;
- PM AC motor drive.

Because of the absence of brushes and commutators, the latter is usually named PM brushless motor drive. This kind of drives is the most capable to compete with induction motor drives for electric propulsion. Their advantages are summarized as following: [12]

- Since the magnetic field is excited by high-energy PMs, the weight and volume can be reduced for a given output power (higher power density);
- Greater efficiency than induction motor, thanks to the absence of rotor copper losses;
- Since the heat mainly originates in the stator, it can be more easily dissipated;
- Higher reliability, since PM excitation presents low risks of manufacturing defects, overheating or mechanical damage.

The system configuration of PM brushless motor drives is similar to that of induction motors, such as single or multiple motors configuration. Basically, the single-motor configuration consists of a PM brushless motor, a voltage-fed inverter, an electronic controller and reduction & differential gears.

Compared with the induction motor solution, there is a further difference: the PM brushless motor is not restricted to be three-phase. In fact, a higher number of phases allows reducing phase current and current rating of power devices.

PM AC motor drives can be further classified in three categories:

- PM synchronous motor (PMSM);
- PM brushless dc motor (PMBM);
- PM hybrid motors (PMHM).

The first two typologies are much more mature for electric propulsion utilization.

The Motor control system

PMSMs are fed by sinusoidal ac waves and use continuous rotor-position feedback signal to control the commutation, whereas PMBMs are fed by rectangular ac wave and use discreet rotor position feedback signals to control the commutation.

Because of the rectangular interaction between flux and current, the PMBM has the ability to produce larger torque and, by specially arranging the stator winding and flux path, it has superior dynamic performance and flexible controllability. In particular, the easier control system is one of the principal reasons to choice a PM AC motor drive instead of an induction one. [3] [8]

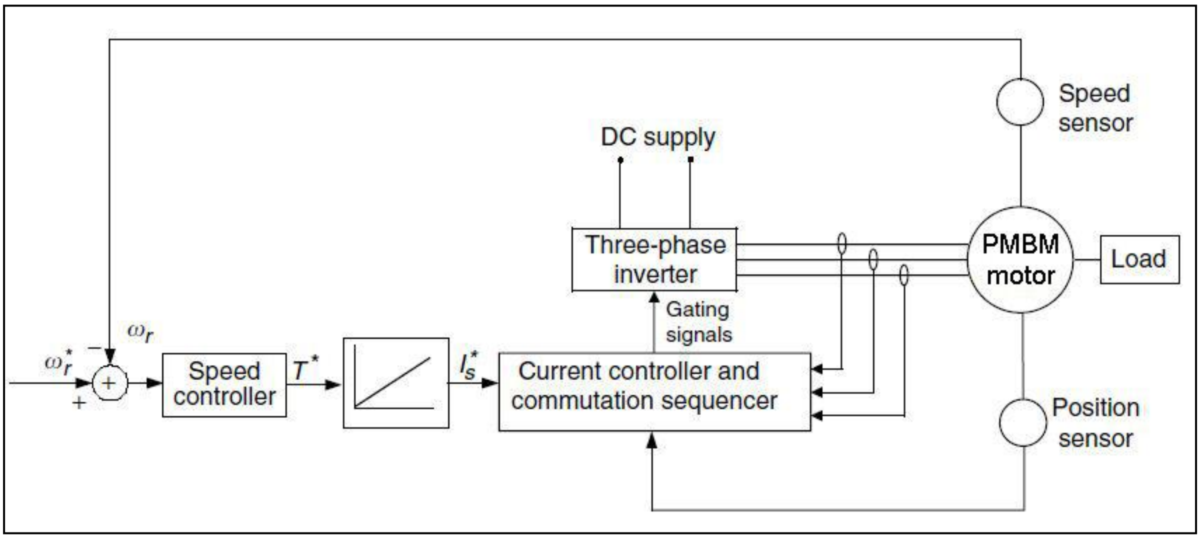


FIGURE 2.16

Block diagram of the torque and speed control of the PM brushless motor [3]

In Figure 2.16 a torque and speed control scheme is shown for a PM brushless motor drive. Torque, speed and current controller functions are embedded in the Electronic Controller module of EV (DSP). The desired speed ω_r^* is compared with the motor speed ω_r, identified by a sensor, then $\Delta\omega$ is processed by the speed controller producing the commanded torque T^*. The desired current I_s^* is the result of a simple equation that relates current and torque. The current controller receives I_s^* and the motor position information from a position sensor, and then produces gating signal to control the inverter. By this gate signal, the inverter can produce the required phase current to properly control the electric motor torque. The current controller provides the properly sequenced gating signals to the three-phase inverter while comparing sensed currents to a reference to maintain a constant peak current control: using position information, the commutation sequencer causes the inverter to electronically commutate, acting as the mechanical commutator of a conventional DC machine.

Many high-performance applications include current feedback for torque control. At the minimum, a DC bus current feedback is required to protect the drive and machine from overcurrent. [3]

Early permanent magnet motors suffered from the tendency for the magnets to be demagnetized by the high stator currents during starting, and from a restricted maximum allowable temperature. Much improved versions using high coercivity rare-earth magnets were developed to overcome these problems. [12]

A stumbling block to the actual spread of PM brushless motors is the cost of this kind of rare-earth magnets, but currently, the principal automotive manufacturers are adopting PM Synchronous motors for their electric vehicles traction, as in the cases of Nissan Leaf and Renault Z.E. fleet [9] [10]. For this reason, the maintenance analysis in the following sections of this paper will consider only the PMSM.

2.2.3 EV POWER CONVERTERS

A power converter is an electrical device that links energy source with motor, feeding current with the proper characteristics (AC/DC, voltage and frequency). The evolution of power converter topologies normally follows that of power devices, aiming to achieve high power density, high efficiency, high controllability and high reliability (Bose, 1992).

There are several types of power converters, namely ac-dc, ac-ac at the same frequency, ac-ac at different frequencies, dc-dc and dc-ac.

Dc-dc converter are usually named **dc choppers**, dc-ac are named **inverters**, which are respectively used for dc motor and ac motor drives.

Inverters are classified into two categories: voltage-fed and current-fed. The former is almost exclusively used for EV propulsion because it has a very simple construction and allows power flow in either direction: the inverter converts direct current (dc) from the car's batteries to alternating current (ac) to drive the electric motor that provides power to the wheels. The inverter also converts ac to dc when it takes power from the motor-generator to recharge the batteries (regenerative braking). [8]

A typical inverter adopted with induction motor or PM brushless motors is a 3-phase voltage-fed PWM inverter. PWM refers to the output waveform.

The electronic scheme of this device is shown in Figure 2.17. This inverter has three legs (*S*1 and *S*4, *S*3 and *S*6, and *S*5 and *S*2) which feed phase *a*, phase *b*, and phase *c* of the induction motor. When the switches *S*1, *S*3, and *S*5 are closed, *S*4, *S*6, and *S*2 are opened, and phases *a, b,* and *c* are supplied with a positive voltage (*Vd*/2). Similarly, when *S*1, *S*3, and *S*5 are opened and *S*4, *S*6, and *S*2 are closed, phases *a, b,* and *c* are supplied with a negative voltage. All the diodes provide a path for the reverse current of each phase. [3]

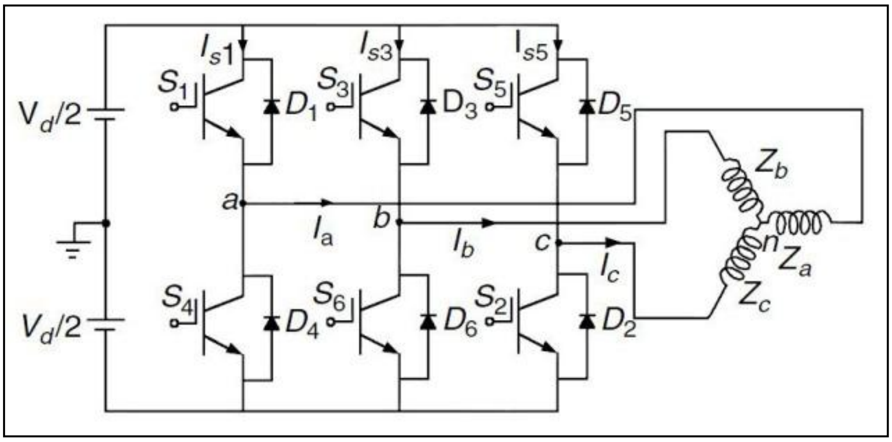


FIGURE 2.17

DC/AC three-phase Voltage-fed inverter [3]

2.2.4 ELECTRONIC CONTROLLER

The Electronic controller provides control signals to power converter: in this way it's possible to control the electric motor operations and supply the request torque and speed according to command from the driver. The controller receives feedback signals from the vehicle about load parameters and conditions (actual speed driver request speed, battery status, etc.), it analyzes them and sends output to control behavior and matches the proper performances. The control system is divided into three functional units: sensors, interface circuitry and processor.

Sensors translate physical parameters (such as speed, current level, temperature) into electric signals through the interface circuitry. These signals, after being conditionate, are fed into the microprocessor, which processes them and produces the proper outputs to control the vehicle. Sensors are very critical components from the reliability point of view, because they have to work in contact with stressed devices often at high temperature, increasing the fault probability.

Microelectronics technology has gone through an intense evolution in last thirty years. Modern microelectronic devices can be classified in three categories:

- Microprocessors;
- Digital signals processors (DSPs);
- Microcontrollers.

Microprocessor is the calculator (CPU) of the electronic system, which decodes instructions and controls operations.

DSPs are specialized processors for the fast operational needs of digital signal processing to implement sophisticated control algorithms for high performances motors for electric propulsion [13]. It is a very common solution and a functional scheme of a DSP is shown in Figure 2.18. Further reliability considerations will be discussed in the following Chapter 4.

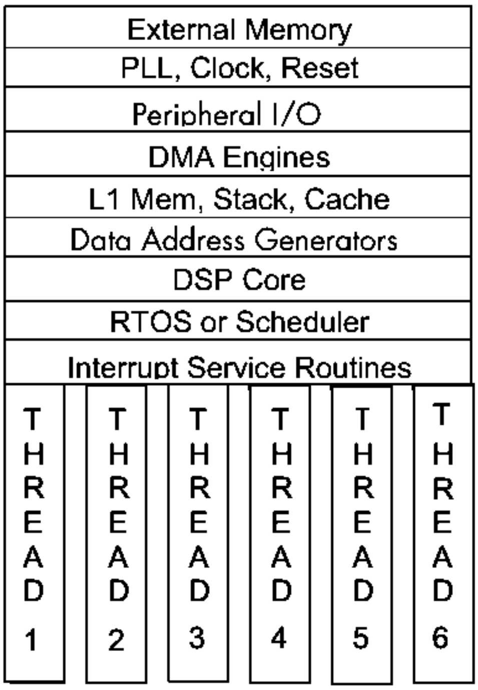


FIGURE 2.18

Digital sugnal processor - block diagram [14]

Microcontroller includes all resources to control the system (CPU, ROM or EPROM, RAM, DMA, timers, A/D and D/A converters and I/O signal ports). This control solution has the definite advantage of compact hardware and smooth software.

A modern example of microcontroller is the Fujitsu MB91580: it offers a 3-phase inverter motor control and an embedded resolver interface for electric and hybrid electric vehicles. The device offers a 12-bit Analog to Digital Converter (ADC) and a 12-bit Resolver to Digital Converter (RDC) to detect motor current and position at high speed and with high resolution. The electric angle of the revolver, which is calculated by the RDC, is latched into dedicated registers and synchronized with the three-phase current detected by the ADC. [15]

2.2.5 ENERGY SOURCE: BATTERIES

There is no doubt that the energy source device is the most critical element in the development and spread of modern EVs. In order to compete with ICEVs, energy sources have to offer:

- High specific energy: the key parameter related to the driving range;
- High specific power: the key parameter related to the acceleration and climbing capability;
- Long cycle life: defined as the number of deep-discharge cycles before failure;
- High efficiency: defined as the ratio between output energy and input energy;
- Low total cost: it consists of initial cost (manufacturing) and running cost (maintenance) and the former is generally dominant the latter. It’s a very sensitive parameter to compete with ICEVs. [8] [16]

There are different kinds of technical solutions, namely rechargeable electrochemical batteries, fuel cells, ultracapacitors, ultrahigh-speed flywheels, and each one presents specific strengths.

At present and in the near future, batteries have been identified as the best solution, thanks to the mature technology and reasonable cost. [17]
Batteries are electrochemical devices which convert chemical energy into electric energy (discharging) and vice versa (charging), so they have both functions of source and storage. Several types of batteries are available in the market, classified into lead-acid battery, nickel-based battery, zinc-halogen battery, metal-air battery, sodium-β battery, and ambient-temperature lithium battery [3].

The US Advanced Battery Consortium (USABC) is a R&D organization composed by US Department of Energy, Ford, Chrysler, General Motors and battery manufacturers, with the objective of fund research on advanced battery technology. This organization has set the long-term performance goals for EV batteries, as shown in Tab. 2.2. [18]

Parameter (units) of fully burdened system	Minimum goals for long term commercialization	Long term goal
Power density (W/L)	460	600
Specific power – discharge 80% DOD/30sec[5] (W/kg)	300	400
Specific power – regen 20% DOD/20sec (W/kg)	150	200
Energy density – C/3 discharge rate[6] (Wh/L)	230	300
Specific energy – C/3 discharge rate (Wh/kg)	150	200
Specific power / specific energy	2 / 1	2 / 1
Total pack size (kWh)	40	40
Life (years)	10	10
Life 80% DOD (Cycles)	1,000	1,000
Power & capacity degradation (% of rated spec)	20	20
Selling price 25,000 units @ 40 kWh ($/kWh)	<150	100
Operating environment (°C)	-40 to +50 20% performance loss (10% desired)	-40 to +85
Normal recharge time	6 hours (4 hours desired)	3 to 6 hours
High rate charge	20% - 70% SOC[7] in <30min @ 150 W/kg (<20 min @ 270W/kg desired)	40% - 80% SOC in 15 minutes
Continuous discharge in 1 hour – no failure (% of rated energy capacity)	75	75

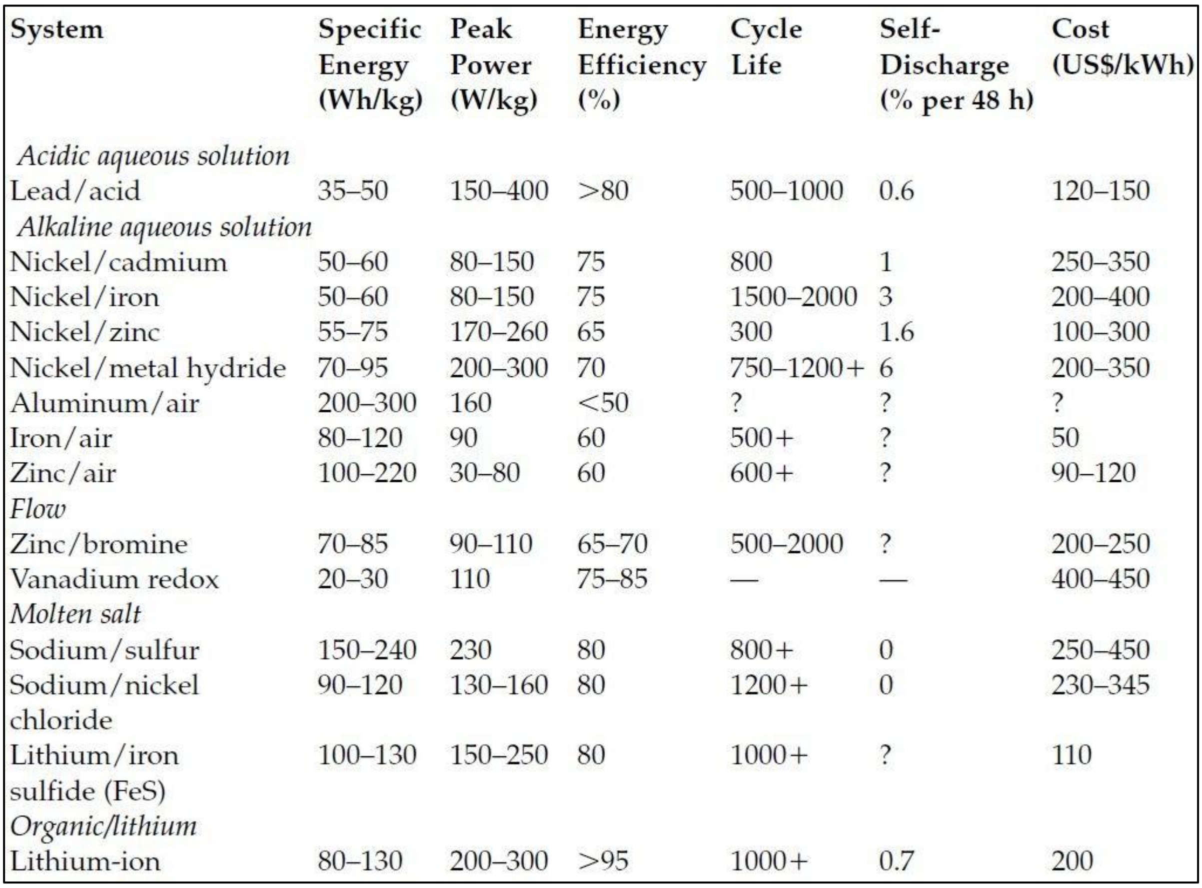
TAB. 2.2

USABC goals for advanced EVs batteries [19]

---

[5] DOD = Depth of Discharge, is the percentage of battery energy spent in the load. [40]
[6] C-rate is the charge/discharge rate of a battery [41]
[7] SOC = State of charge

USABC aims to make EVs as close in performance to ICEVs as possible and there is no a unique energy device able to completely satisfy these requests. The status of the art of batteries performances is explained in the following Table 2.3.



System	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy Efficiency (%)	Cycle Life	Self-Discharge (% per 48 h)	Cost (US$/kWh)
Acidic aqueous solution						
Lead/acid	35–50	150–400	>80	500–1000	0.6	120–150
Alkaline aqueous solution						
Nickel/cadmium	50–60	80–150	75	800	1	250–350
Nickel/iron	50–60	80–150	75	1500–2000	3	200–400
Nickel/zinc	55–75	170–260	65	300	1.6	100–300
Nickel/metal hydride	70–95	200–300	70	750–1200+	6	200–350
Aluminum/air	200–300	160	<50	?	?	?
Iron/air	80–120	90	60	500+	?	50
Zinc/air	100–220	30–80	60	600+	?	90–120
Flow						
Zinc/bromine	70–85	90–110	65–70	500–2000	?	200–250
Vanadium redox	20–30	110	75–85	—	—	400–450
Molten salt						
Sodium/sulfur	150–240	230	80	800+	0	250–450
Sodium/nickel chloride	90–120	130–160	80	1200+	0	230–345
Lithium/iron sulfide (FeS)	100–130	150–250	80	1000+	?	110
Organic/lithium						
Lithium-ion	80–130	200–300	>95	1000+	0.7	200

TAB. 2.3

Status of batteries performances for automotive applications [3]

Lithium is the metal with the lightest atomic weight and the highest negative potential, so it presents very interesting characteristics from an electrochemical point of view. Lithium-based battery allows a high electrochemical potential and provides the largest energy density for weight, providing to EVs the greatest performance characteristics in terms of acceleration and range. Two different technologies are available for lithium-based battery:

- Lithium-Polymer (Li-P) Battery
- Lithium-Ion (Li-Ion) Battery

The Li-Ion has been identified by many battery manufacturers to be the most promising EV battery: as shown in Tab. 2.3 this energy device presents the higher efficiency rate (>95%), one of the major power density range (200-300 W/Kg), a very high specific energy (80-130 Wh/Kg) and wide life duration (more than 1000 deep-discharge cycles).

During discharging phase, Lithium ions (Li^+) are released from the anode and travel through an organic electrolyte toward the cathode. [16]

When the Lithium ions reach the cathode they are quickly incorporated into this material. This process is easily reversible and, thanks to this, lithium-ion batteries can charge and discharge faster than others typologies. In addition, Li-ion batteries produce the same amount of energy of NiMH cell, but they are 40% smaller and half lighter: this is one of the most important aspects considering that energy storage is the heaviest subsystem of the vehicle. Moreover, this allows using twice as many batteries, doubling the amount of energy stored and widely increasing the drive range. [16] [17]

The fast development in battery technology is helping to build EVs increasingly similar for performances to the conventional ICEVs.

2.2.6 MAINTENANCE CONCEPTS: RELIABILITY BLOCK DIAGRAM

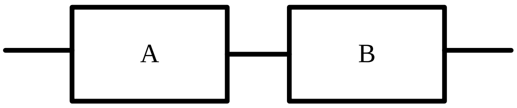
The Reliability Block Diagram (RBD) is a useful analysis tool to evaluate the reliability of complex systems. By RBD method, the analyst represents by simple blocks the functional components of the system, linking them in serial path or in parallel path respectively if the fault of a single unit affects directly the working of the entire system, or if this fault can be bypassed through an alternative path. The RBD has nothing to do with the functional block diagram of the system behavior: the aim is to represent the reliability relations between components and system.

Each component can reside in one of two mutually exclusive operational states: functioning adequately or failed.

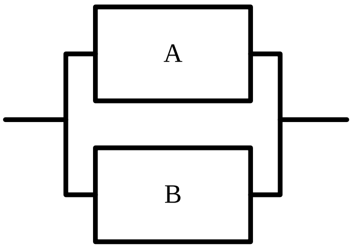
There are some simple rules to produce a Reliability Block Diagram:

1. Each block can represent a subsystem of components, whose reliability could be calculated;
2. Blocks are represented in a serial path if all of them are required to allows entire system to run;
3. Several series of blocks are represented in parallel paths if is enough that one of them is working properly;
4. A failed block can be replaced by a “open circuit”;
5. A block with a 100% reliability can be replaced by a “short circuit”;
6. RBD method refers to a maintenance strategy without repair activities: a failed block is not repaired if the system still works;
7. Blocks failures are independent each other.

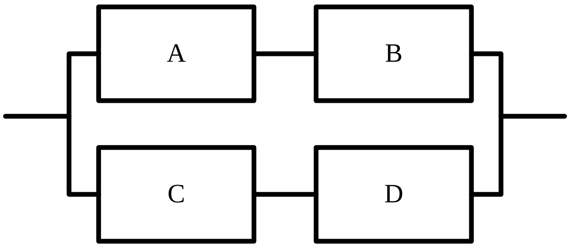
Some examples of block diagrams are shown in the following Figure 2.19.



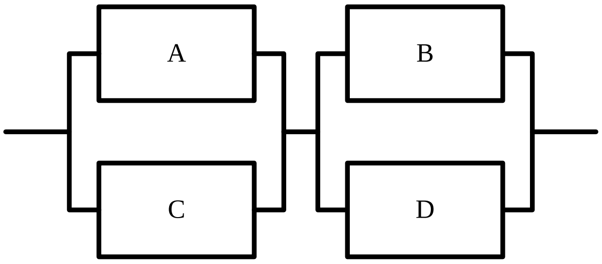
System requires both subsystems,
A and B



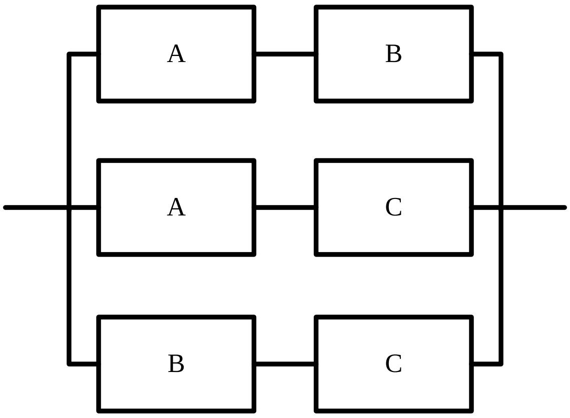
System requires A or B



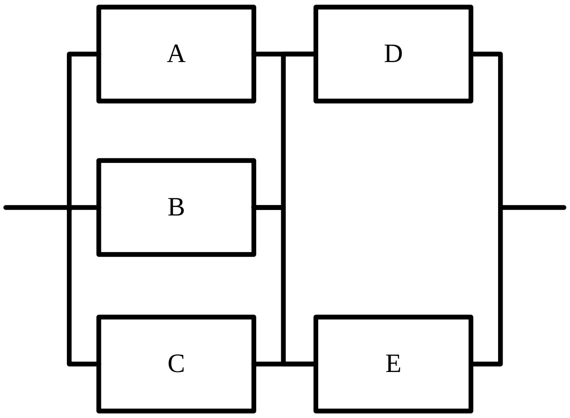
System requires A and B, or C and D



System requires A or C, and also B
or D

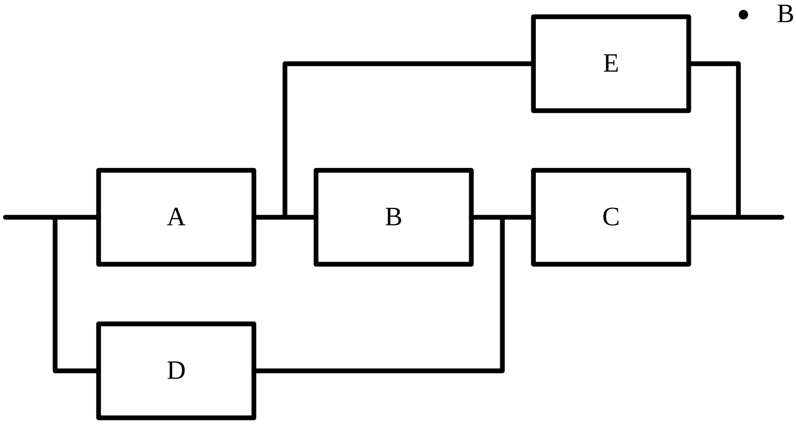


System consists of 3 subsystems A, B, C,
and requires at least any two of these to
perform correctly



System is sutisfied by any of the following:

- A and D perform correctly
- C and E perform correctly
- B and either D or E permorm correctly



System is sutisfied by any of the following:

- A and B and C perform correctly
- D and C perform correctly
- A and E permorm correctly

FIGURE 2.19

Examples of basic RBD structures [20]

There are some rules to calculate the reliability of the whole system, assembling single blocks of the RBD: [20]

- The reliability of a serial path of blocks is the product of all blocks reliability;

$$\boldsymbol{R_s(t) = \prod_i R_i(t)} \tag{1}$$

R_s (t) = system reliability
R_i (t) = component reliability

- Reliability of several blocks in different parallel paths is calculated according to the following equation:

$$\boldsymbol{R_s(t) = 1 - \prod_i (1 - R_i(t))} \tag{2}$$

The units in parallel systems are referred to as redundant units, since at least one of the units must succeed for the system to succeed. That’s why adding redundancy is one of several methods of improving system reliability.

In general, reliability of a serial path is lower than that of any of its members; whereas reliability of a parallel system is higher than that of the most reliable block. [20]

Estimation of system reliability is a very critical and complex activity; it’s strictly linked to the *failure rate* λ(t) of each component and a wide number of failure data is necessary to calculate it with good approximation.

The general equation which connects reliability and failure rate of a component is the following:

$$\boldsymbol{R_s(t) = e^{-\int_0^t \lambda(\tau)d\tau}} \tag{3}$$

This equation can be easily simplified if component has a constant failure rate in the time: this is the case of electronic units which are not affected by wear and so failure probability does not increase over time.

$$\boldsymbol{R_s(t) = e^{-\lambda t}} \tag{4}$$

Electric cars power train consists in major part of electric and electronic units, so maintenance strategy has to consider failure behavior of this kind of components.

Considering electric vehicle configuration from a reliability point of view it’s possible to understand the relationship between components and system, to produce the RBD and evaluate the reliability of the entire structure.
The components of the system are the following:

- Digital Signal Processor;
- Propulsion battery pack (Li-Ion);
- 12V auxiliary battery;
- Power inverter;
- Electric motor drive;
- Fixed reduction gearing.

Digital Signal Processor (DSP) is the “brain” of the vehicle; it receives and sends signals to each unit in order to obtain the request performances.
Battery pack is the energy source and energy storage which supplies power to the electric motor.
Auxiliary battery is the energy provider of the auxiliary subsystem (cooler ad heater, steering unit, radio, etc.).

Power inverter is the electronic device that links energy source with motor, feeding current with the proper characteristics (AC/DC, voltage and frequency).
Electric motor supplies mechanical energy converting electric one from batteries to wheels.
Fixed reduction gearing plays the role of connect electric motor to the wheels shaft.

Considering the behavior of the vehicle, each component is necessary to allow the system to work: without any of these units it’s impossible to have the correct operation. The proper way to show this kind of system is a serial path, as described in the following RBD (Figure 2.20).

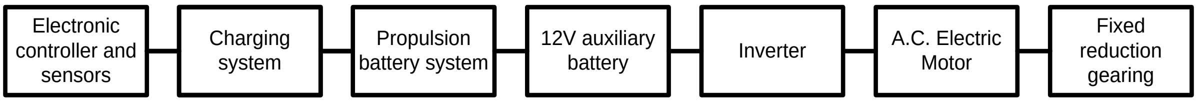


FIGURE 2.20
EV power train: Reliability Block Diagram

The main weakness is the serial structure: this configuration, with absence of redundancies, underlines a criticality from the reliability point of view: the proper operation of each component is absolutely required to allow the whole system to run. For this reason the reliability of the system is strongly related to the less reliable component of the structure, and consequently, the manufacturing quality of each components and an effective preventive maintenance program are very important.

Considering that great part of the system is composed by electronic and electric components, marked by a constant failure rate, it’s very important to predict the *main time between failures* of each of them, in order to apply a preventive maintenance strategy to avoid system breakdown.

2.3 CHAPTER CONCLUSIONS

In this chapter, the structure of a normal ICE car has been shortly introduced in order to explain the first idea of electric vehicles, replacing conventional components with electric ones. Then, several configurations of EVs have been described, with pros and cons analysis of functions and operations. Particular considerations have been reserved to the differential unit and mechanical transmission, identifying the potentiality offered by the new electric propulsion (in-wheel drive and electronic differential).

The scheme of the power train is reported with the main links between components, distinguishing for control, electric and mechanical links, in order to understand clearly the role of each component in relation with the others.

In the second subsection, the components of an EV power train have been described; and different configurations and technical solutions have been compared on their specific features.

In particular, have been analyzed the following parts of a power train:

- electric motor;
- electronic controller;
- power converter;
- energy source.

Finally, prime maintenance aspects have been considered and discussed through the Reliability Block Diagram: the system is a serial path and its reliability is strongly related to the less reliable component, according to equation (1).

As result of this literature review, a typical power train configuration (Figure 2.21), currently adopted by OEMs, is so described: a single-motor drive train, mainly consisting in a ≈60-80 kW Permanent Magnets synchronous motor drive, with fixed reduction gearing and differential to transmit power to the wheels; the propulsion energy source and storage consists in a ≈22-24 kWh Li-Ion battery pack [9] [10]. The power converter unit is generally a voltage-fed inverter, controlled by a Digital Signal Processor. Finally, a conventional 12V battery is required to supply the auxiliary subsystem of the vehicle, taking energy from the Li-Ion battery through the DC/DC converter.

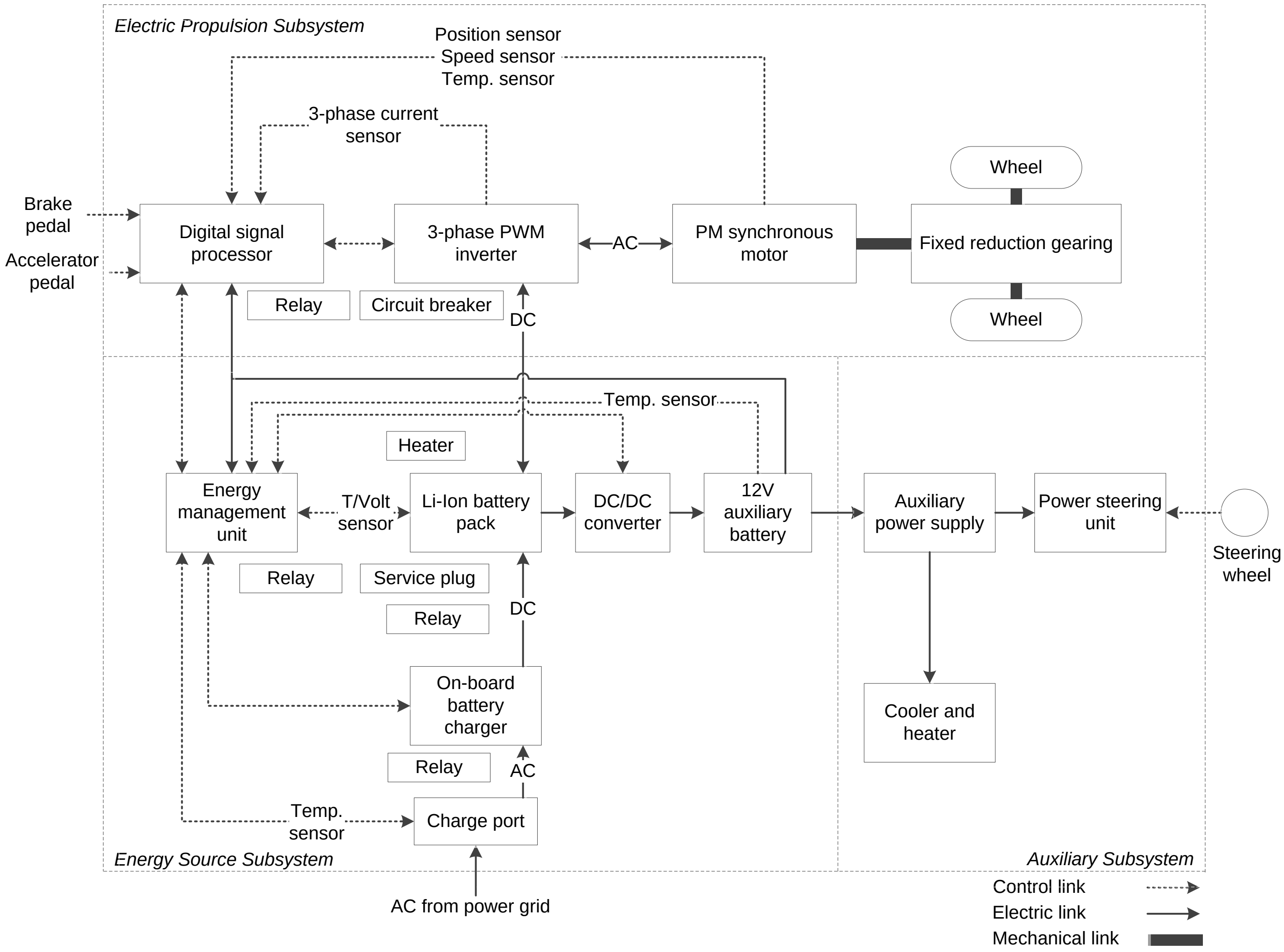


FIGURE 2.21

Typical EV configuration. Illustration of control, electric and mechanical links.

Chapter 3

3. METHODOLOGY

3.1 INTRODUCTION

This thesis work started with a literature review of the technology related to electric traction, electronic control system and energy storage system. Different configurations have been considered and compared through a pros-and-cons analysis. Latest academic papers, reference books, industrial publications and individual theses have been studied for understanding the typical failure modes and proper PM tasks of an electric vehicle power train.

Reliability Centred Maintenance (RCM) is the approach used in this analysis to produce a long period maintenance program for electric cars power train. In this section the major reasons for the choice of this method will be explained, its base principles, the logic steps and phases.

3.2 RCM APPROACH

RCM is a logical method to identify and prevent plant failures, according to the formal definition: *a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context.* [21]

Over the past twenty years, maintenance has changed a lot, jointly with the huge increase of number and variety of physical assets (such as plants, equipment and buildings), with the increase of complex structures, new maintenance techniques and new ways of organizing maintenance. Moreover, the growing attention and sensitivity to the safety and environmental effects of equipment failures, trying to keep costs down, is leading maintenance towards a systematic and integrated approach: RCM seems to be the most effective method to face with these challenges.

There are several ways to apply the RCM method: different start points of the logical path (i.e. system level or component level) and different analysis tools (i.e. FMECA or COFA), but the common principles of the method are clear. *RCM is focused on preserving system functions,* classifying components in categories in order to find the right maintenance tasks to keep the system available, as close as possible to the 100% threshold.
Furthermore, each RCM approach adopts as its own guideline seven basic questions about the asset or system under review, [21] as follows:

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfil its functions?
3. What causes its functional failure?
4. What happen when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

In this chapter is presented the logic path, which will be used in the following analysis of the electric cars power train, paying attention to each phase of the method, each single decision step and the structure of the worksheets produced.

3.3 RCM METHOD: FUNDAMENTAL CONCEPTS

The RCM method consists in three macro-phases, each one made by a set of steps: [22]

- Phase 1: ***identify*** equipment, which are important for the plant’s safety, production and asset protection. These are the parts of the system, which require a preventive maintenance strategy to prevent failure, in order to preserve critical equipment functions.
- Phase 2: ***specify*** the type of preventive maintenance tasks and the periodicities that should be prescribed to the equipment identified in phase 1.
- Phase 3: ***execute*** the activities specified in the previous phase and ***control*** if the planned scheduling is observed.

A first output of the method is the classification of the system components, at the end of the first macro-phase, in order of priority as following: [22]

- ***Critical component***: when the occurrence of the component failure is evident and causes an immediate unwanted consequence at the plant level, from a safety, operational and environmental point of view. For these reasons, this kind of failure has to be avoided before its occurrence by Preventive Maintenance (PM) tasks.
- ***Potentially critical component***: this is probably the most subtle concept in RCM approach and is strictly correlated to the meaning of *hidden failure*.

  Firstly, a failure is hidden if there is no indication of failure and there are no operational consequences to the facility when it happens (i.e. the failure in one or more component in a parallel design without indication of failure for each individual component). So, a component should be classified as potentially critical if its failure is hidden but has the potential to become critical just with an additional failure, or with the duration of time. That is why a multiple-failure analysis is required when this kind of situation is detected. A potentially critical component refers to the potential consequence of failure to the plant, after the hidden failure of that component has already occurred, and there is no evidence of this event.

  The difference between critical and potentially critical components is that the former manifest themselves immediately and the latter are hidden without consequence until a second failure occurs (in most cases) or certain time duration occurs.
- ***Commitment component***: this definition is related with those components which have regulatory, environmental, occupational, safety, health and administration (OHSA) commitments that must be fulfilled, requiring a PM strategy to preclude components from failing and causing a commitment to be missed.
- ***Economic component***: the failure of this type of component has economic consequence only and has no effect on system safety and operability.
- ***Run-to-failure (RTF) component***: to be classified as RTF, a component must have no safety, operational, commitment or economic consequence as the result of a single failure. Moreover, the occurrence of the failure has to be evident to operations personnel. A common mistake is to consider equipment as run-to-failure just because it has no unwanted consequences to the facility: the difference between RTF and potentially critical component is that the former’s failure has to be evident, while the latter’s one is hidden.

RTF components do not require preventive maintenance prior to failure, but then corrective maintenance is required in a timely manner after failure.

Quite often it occurs that several failure modes are detected for a single component, and those failure modes are classified in different categories each other (i.e. a critical failure mode and a RTF one): also, the final classification of that component is the most limiting and precautionary (i.e. critical).

A typical misunderstanding of meaning, and also of maintenance analysis, concerns the concepts of ***standby/backup function*** and ***redundant function***. [22]

- When a component performs a standby (or backup) function in a facility, it usually does not operate and is called to run only in case of failure of the normally operating component. Thus, if the backup should fail, an unwanted consequence at plant level could occur and the component is considered *critical* and PM task is required.
- Redundant components usually operate simultaneously. If individual indication of failure is evident, the components are identified as *RTF*, otherwise as *potentially critical*.

Later in the chapter will be exposed the logic tree used in the analysis to classify each component of the electric vehicle drive train system, with the final aim to specify the appropriate PM tasks.

3.3.1 PHASE 1: RCM IMPLEMENTATION PROCESS

In this paragraph will be briefly described steps and tools, which will be used in the RCM application of EV power train. The implementation process is built in a sequence of elements, beginning from the Asset Reliability Criteria. [22]

Define the Asset Reliability Criteria (ARC)

Defining ARC means identifying all the unwanted consequences of failure, concerning safety and operability, that can occur in the analysed plant and that must be prevented. Economic criteria are separate from safety and operability criteria and will be discussed later, as well as commitment components that are determined by the commitment requirements.

Component functional failures that can trigger one or more asset reliability criteria will lead in a component classification of either critical or potentially critical. Also, components will be classified as following:

- Critical for safety or operability concern;
- Potentially critical for safety or operability concern;
- Commitment;
- Economic.

Any component with one of these classifications should have a PM strategy to prevent its failure, or a design change should be implemented if an effective PM task cannot be specified.

The asset reliability criteria specified for safety and operability concerns, related with EV power train are as following:

Asset Reliability Criteria for Electric Vehicle power train

Safety concerns

- No personnel safety or public safety concerns (mandatory)
- No facility safety concern (mandatory)

Operability concerns

- No unplanned facility shutdowns
- No power reduction
- No technical specification violations
- No range reduction over 50%

RCM COFA logic tree, Potentially critical guideline and Economically significant guideline

The classification of components follows a simple logic path, that begins by identifying critical components, than potentially critical, than commitment, than economical components and finally run-to-failure components, in order of importance. [22]

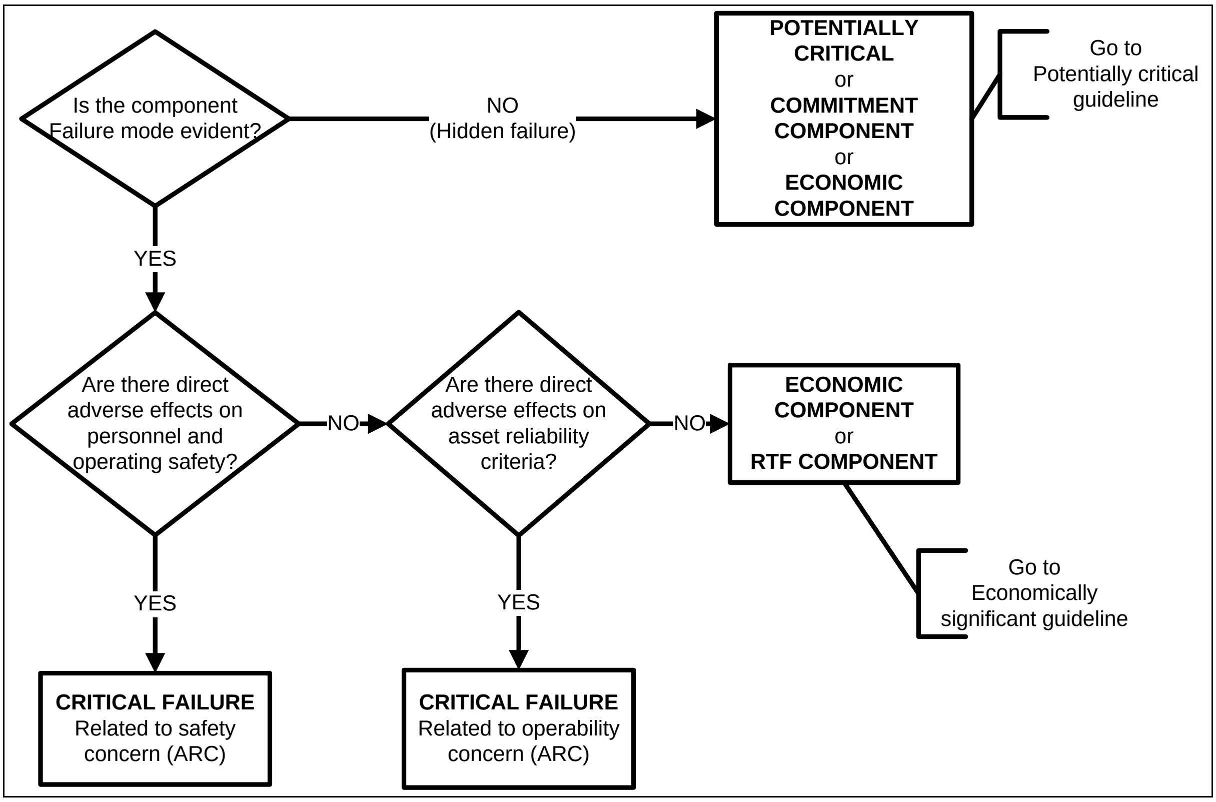


FIGURE 3.1

RCM COFA Logic Tree

Potentially critical guideline

Can the component failure, in combination with an additional failure or initiating event, or over time, result in an unwanted consequence that has a direct adverse effect on one or more of the asset reliability criteria?

If ***YES***, this is a ***potentially critical*** component. It could be potentially critical for *safety* or for *operability* concerns depending on its consequence of failure.

If ***NO***, is the component associated with a commitment? If it is, this is a ***commitment*** component. If it is not associated with a commitment, proceed to the following Economically Significant Guideline.

Economically significant guideline

Will the component failure result in a high cost of restoration?

Will the component failure result in a high cost of related corrective maintenance (CM)?

Will the component failure result in significant downtime?

Will the component failure result in a long lead-time for replacement parts? Are the parts obsolete or in short supply?

If ***YES*** to any of the above questions and a PM is further justified by the Economic Evaluation, this is an ***economic*** *component.*

If ***NO*** to all of the above, this is a ***run-to-failure*** *component (RTF)*.

This logic consists in a system of filters, through which all component failure modes have to pass. The critical components are identified by the COFA logic tree, the first filter. Potentially critical components are detected by the second filter, Potentially Critical Guideline. Those components making it through the first two filters then must pass through the commitment filter, included in the Potentially Critical Guideline. Fourth filter consists in the Economically Significant Guideline. If a component passes through all filters, it is classified as RTF.

The Consequence of Failure Analysis (COFA) Worksheet

The COFA worksheet is the main document produced in the phase 1 of RCM process, regarding the identification and classification of failure modes for each component. This worksheet integrates the COFA Logic Tree and the two guidelines, and its structure runs the RCM logic, as following: [22]

- **COLUMN A: Specification of component I.D. and description**;
- **COLUMN B: Description of all function of the component**;
  there are several functions for each component, the functions are the explanation for why the component is installed and preserving these functions is the main objective of the maintenance program.

- **COLUMN C: Description of the ways each function can fail**;
  typically functional failures are the opposite of functions.
- **COLUMN D: Description of the dominant component failure mode for each functional failure**;
  the failure modes are the several ways a component can fail to provide a specified function.
- **COLUMN E: Is the occurrence of the failure evident?**
  the answer to this question comes directly from COFA Logic Tree. The failure must be evident during normal activities, and it can happen thanks to indication alarm, or by routinely performed rounds or by the unwanted consequence at facility level.
- **COLUMN F: Description of the system effect for each failure mode**;
  the ultimate aim of the analysis is to identify the consequences of failure at facility level, note that hidden failures have not system effects.
- **COLUMN G: Description of the consequence of failure based on the Asset Reliability Criteria**;
  these consequences are at plant level and they are identified for each failure mode.
- **COLUMN H: Criticality classification of each failure mode**;
- **COLUMN I: Criticality classification of the component**;
  there could be different classification for the same component: the final one defaults to the highest level, according to the classification ranking.

At the end of the COFA Worksheet, the first phase of RCM process can be considered complete.

C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		Component functions		Component functional failures	Dominant component failure mode for each functional failure	Evident failure?	Vehicle effect for each failure mode	Consequence of failure, based on the ARC	Failure Classific.	Component Classification

TAB. 3.1

Structure of the COFA worksheet

3.3.2 PHASE 2: PM TASKS SELECTION PROCESS

In this phase of RCM process, preventive maintenance activities are specified to *address the causes of failure* identified in the previous phase. [22]

There are three main categories of PM task:

- **Condition directed**: this kind of task is addressed to know the real condition of the equipment by measuring, monitoring or analysing activities. Predictive maintenance (PdM) tasks, such as vibration analysis, oil analysis, thermography, etc., refer all to condition directed maintenance.
- **Time directed** tasks include usually replacements, overhauls, or restoration of component at planned periodicity.
- **Failure finding** is a strategy to ascertain, at a periodic interval, whether a component is already failed or not, before it results in a plant level consequence. That is why it is a proper activity only for hidden failures.

The PM task selection logic tree

The first tool used to approach the phase 2 of RCM process is the following logic tree, used to identify what kind of PM activity is required for each failure cause identified in the COFA Logic Tree.

The preferable task is a nonintrusive one, so it is firstly evaluated if a predictive maintenance is applicable. The second choice is a time-directed task, which usually is intrusive and could require downtime. A failure-finding task can be applicable only to potentially critical components, and it is the choice if a task to prevent the failure cannot be found. Finally, if no PM task is selected for the component, the alternative solutions could be a design change or accept the risk of the failure.

The condition-based maintenance is preferred to the time-based because, when a component is replaced or overhauled, its lifetime is restored but its failure probability increases highly for two reasons: premature failure and infant mortality, according to the common rule described by the “bathtub” curve, Figure 3.3.

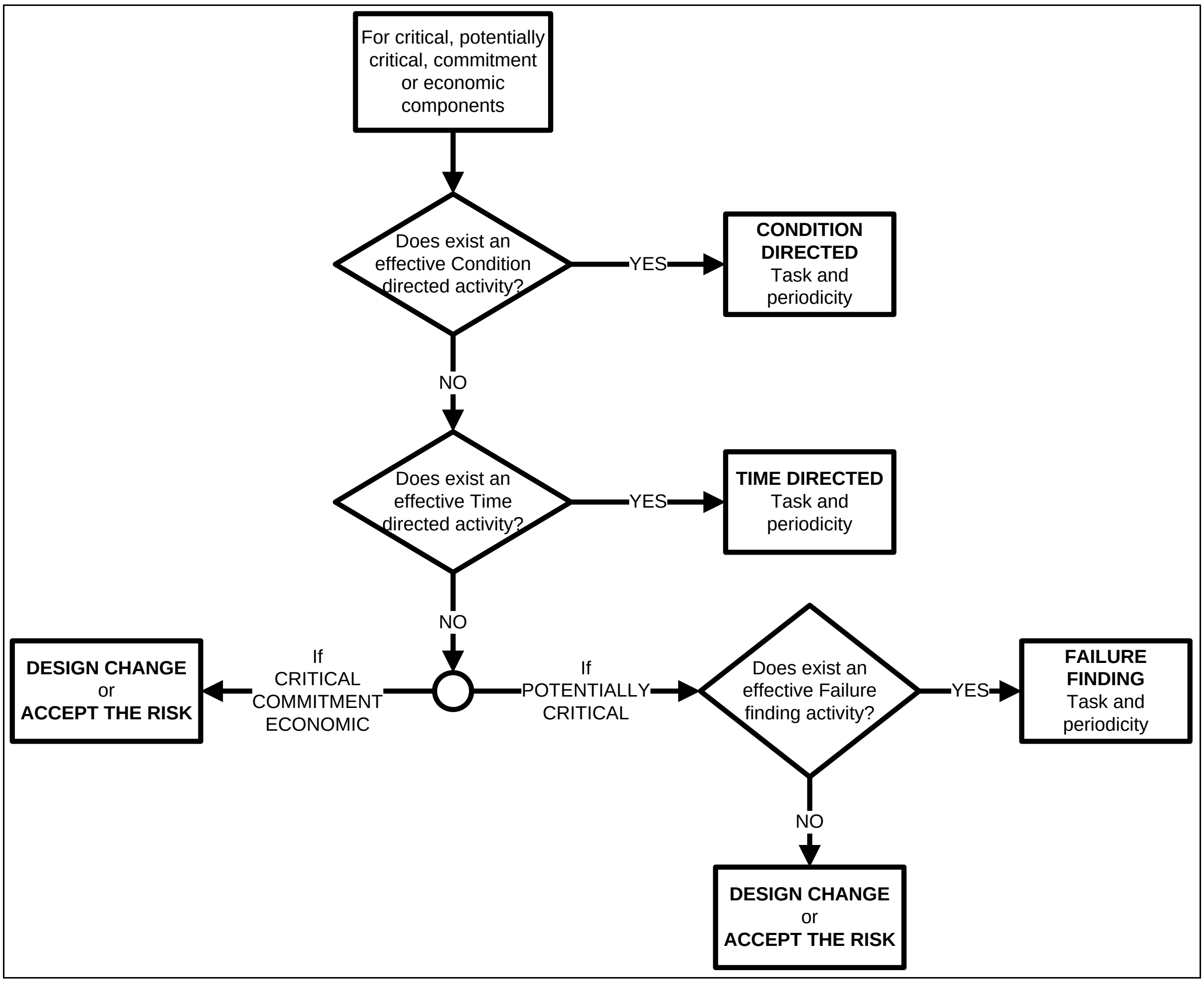


FIGURE 3.2

PM Task selection Logic Tree

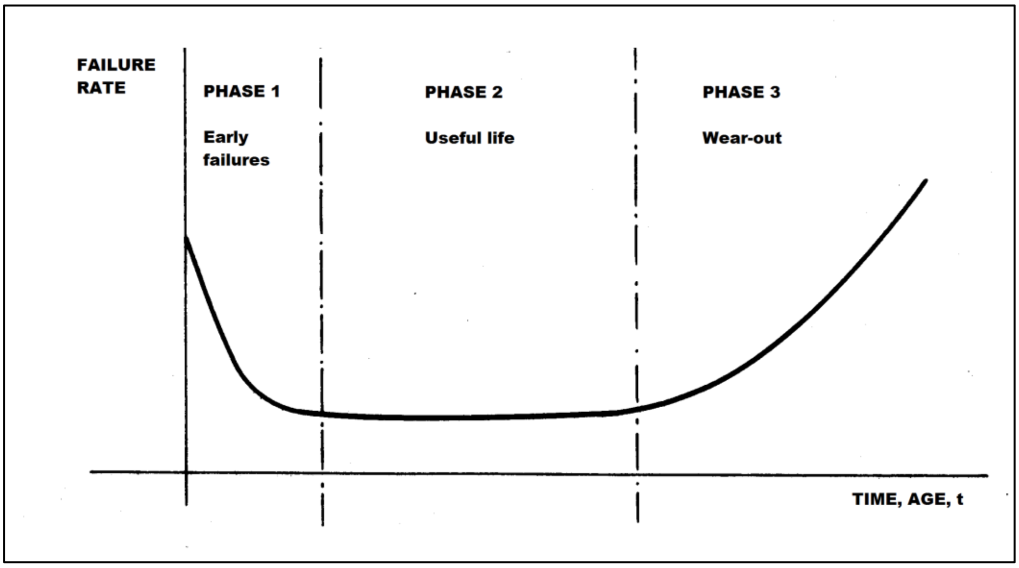


FIGURE 3.3

The “bathtub” curve [20]

The PM task worksheet

After COFA Worksheet and PM Task Logic Tree, it is possible to issue the last document of the phase 2 of RCM process, the PM Task Worksheet that takes results from the previous analysis, as following: [22]

- **COLUMN A: component I.D. and description** (from COFA Worksheet);
- **COLUMN B: what were the consequences of failure?** (from COFA Worksheet);
- **COLUMN C: describe each dominant component failure mode** (from COFA Worksheet);
- **COLUMN D: describe the vehicle effects for each failure mode** (from COFA Worksheet);
- **COLUMN E: criticality classification of the component** (from COFA Worksheet);
- **COLUMN F: describe the credible failure cause for each dominant failure mode**;
- **COLUMN G: describe the applicable and effective PM task for each failure cause** (from PM Task Logic Tree);
- **COLUMN H: define frequency and interval for each pm task** (from PM Task Logic Tree);
- **COLUMN I: is a design change recommended?**

C.#	Column A	#.#	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I
Component I.D. and description		Component functions		Dominant failure mode for each functional failure	Vehicle effect for each failure mode	Component Classification	Failure causes for each function	PM tasks for each failure cause	Frequency and interval for each PM task	Design change?

TAB. 3.2

Structure of the PM Task worksheet

Each failure mode has one or more PM tasks to address it. Therefore, a single component may have several different PM activities associated with it. The PM Worksheet is where the piece of parts (or subassemblies) of the components are introduced: these parts are the credible causes of failure, such as bearing failures, motor winding failure, plug-in failure.

The Economic evaluation worksheet

The evaluation of PM activities for economic component needs further analysis. This kind of component results only in a monetary cost of labour and/or material, so a break-even point analysis is required between the cost of failure and the cost for performing a PM to prevent the failure. To allow this equation every cost must be calculated on an annualized basis.

3.4 RCM ANALYSIS FORMAT: FMECA versus COFA

The common analysis format in RCM method is FMECA (failure modes, effects and criticality analysis), which leads the analyst in the identification of components criticality, beginning from the functions of equipment at system level in a top-down way. An alternative format is the COFA (consequence of failure analysis): it includes all the same attribute of FMECA as well as additional attributes, but the analysis begins at the component level that is the final destination for detect consequences of failures. Furthermore, COFA includes the decision process for determining the consequence of failure based on asset reliability criteria specified. COFA maintains clear separation among phase 1, *identification of equipment*, and phase 2, *specification of PM tasks*, resulting in a simpler format than FMECA.

Concerning the phase 1, a *COFA worksheet* will be developed, defining the *Asset Reliability Criteria* and following the *COFA Logic Tree with Guidelines*; regarding to the phase 2, will be developed the *PM task worksheet* and the *Economic evaluation worksheet.* All these tools will be described later in the document. [21] [22]

3.5 COMPONENTS LABELLING

The very first stage of RCM analysis is the classification and labelling of the systems components. Labelling components is a basic activity because it allows, thanks to modern IT facility, to link efficiently under a unique code a lot of different information, using CMMS software, ERP software, database, etc.
Multiple data can be associated to a component label, such as component functions, risk classification, PM tasks, and even warehouse location of replacement parts, supplier, price, date of warehousing and so on.

Is very important to define a method to produce standard labels for each component: in this paper, the entire structure has been divided in three subsystems, as shown in the previous Figure 2.21, Electric Propulsion Subsystem, Energy Source Subsystem and Auxiliary Subsystem; only the first two of these are considered in the RCM analysis.
The structure of a label consists in several sections, to define each component uniquely:

- The subsystem in which the component is placed;
- The general function of the component (i.e. motor, battery, controller);
- The particular typology of the component (i.e. PM motor, Li-Ion battery)

In the following table, the labelling of each component analysed is shown.

Electric propulsion subsystem (EP)		**Energy source subsystem (ES)**	
LABEL	*DESCRIPTION*	*LABEL*	*DESCRIPTION*
EP-CTRL-DSP	Electronic controller, digital signal processor	**ES-CTRL**	Energy management unit
EP-INV-3PH	Traction motor inverter, 3phase voltage-fed PWM	**ES-BAT-LIP**	Li-Ion Battery Pack
EP-EMOT-PMSM	Permanent Magnet Synchronous traction motor	**ES-CH-OB**	Battery on-board charging unit
EP-GR-PLAN	Planetary reduction gear	**ES-CH-PT**	Charge port
EP-SNS-M-P	Motor position sensor	**ES-BAT-HT**	Li-Ion battery heater unit
EP-SNS-M-S	Motor speed sensor	**ES-BAT-12V**	Auxiliary 12 V battery
EP-SNS-M-T	Motor temperature sensor	**ES-SNS-12V**	Voltage and temperature sensor of 12V battery
EP-SNS-ACC	Accelerator pedal sensor	**ES-SNS-LIP-C**	Li-Ion Battery current sensor
EP-SNS-BRK	Brake pedal sensor	**ES-SNS-LIP-T**	Li-Ion Battery temperature sensor
EP-SNS-INVPH	Inverter phases sensor	**ES-PLUG-LIP**	Li-Ion battery service plug
EP-CIR BRK	Fail-safe circuit breaker	**ES-SNS-CHPT**	Charge port temperature sensor
EP-REL-DSP	DSP relay	**ES-CON-DCDC**	DC/DC converter
		ES-REL-LIP	Li-Ion battery relay
		ES-REL-CHOB	Charging relays
		ES-REL-EMU	Energy management unit relay

TAB. 3.3

Table of components labelling

3.6 CHAPTER CONCLUSIONS

In this chapter the research process has been described, starting from the literature review of the vehicle power train system. The RCM analysis method has been presented, with particular attention to the logical steps of the process, which will be followed in the application to EVs.

In this study, only the first two phases of RCM are applied, in order to produce a preventive maintenance program, and all the needed tools, such as logic trees, guidelines and Asset Reliability Criteria, have been described.

Finally, all the components of the analyzed system have been labeled, in order to better refer to them during the application of the RCM method.

Chapter 4

4. RESULTS AND FINDINGS

4.1 INTRODUCTION

In the COFA worksheet and PM task worksheet, shown in the Appendices, each component of the Traction Subsystem and Energy Source Subsystem is analyzed. In this chapter of the paper the principal findings of the analysis will be reported, describing the main failure modes of those components, their criticality level and the Preventive Maintenance tasks identified to address these failure modes.

4.2 COMPONENTS CLASSIFICATION AND EFFECTS OF FAILURES

The first step of the Reliability Centered Maintenance method is to identify the likely *failure modes* of components and classify them from the *criticality* point of view. The COFA worksheet is at the same time a report template and a guide for the analysis, and has been filled following the COFA logic tree and the Guidelines, as explained in the *Methodology* chapter.

As expected from the Reliability Block Diagram in Figure 2.20 at page 40, the great majority of the components are classified as *CRITICAL*, meaning that a lot of components have direct impact on the car's principal functions and behavior. On 26 components, 22 are classified as CRITICAL (85%), 3 are classified as POTENTIALLY CRITICAL (11%), and only one is considered as RUN TO FAILURE (4%).

From a reliability point of view, this situation could appear very risky and, indeed, it's enough that one of those components fails to have the vehicle shut-down. According to the theory explained in the Paragraph 2.2.6, the reliability of a serial path structure is given by the product of all components reliability, as in the following equation: [22]

$$\boldsymbol{R_s(t) = \prod_i R_i(t)} \qquad \textbf{(1)}$$

For this reason each component must have a very high reliability to keep the system risk acceptable, and this is the goal of the proposed Preventive Maintenance program.

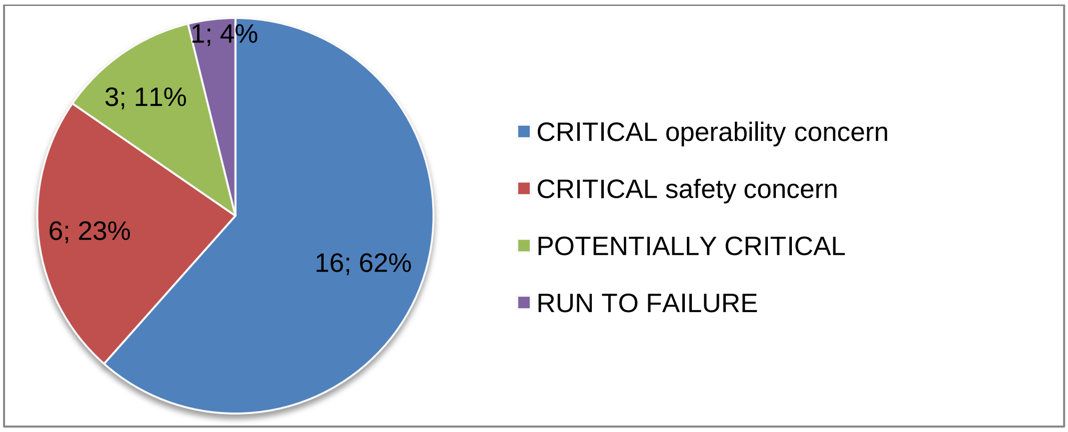


FIGURE 4.1
Components criticality classification

In some cases, a component has different classifications for different failure modes, so the final classification defaults in the most critical according to the ranking: Critical (safety concern), Critical (operability concern), Potentially critical, Commitment, Economic and Run to Failure.

From the above diagram it is immediately obvious that 85% of components, the Critical components, require a *Single-failure analysis* because the failures are evident and cause immediate unwanted consequences. Only the 11% of devices are Potentially critical and therefore requiring a *Multiple-failure analysis*, because of their hidden failures to address. This has a double meaning: the system needs a very effective PM program to be reliable, but it is quite easy to identify failure modes and failure causes of the majority of components. Potentially critical components are, indeed, the most dangerous components for the system, because their failure modes are *hidden* and because they have the potential to be critical in conjunction with an additional failure. In these cases the analysis has to be very careful because is important to identify every failure-links between components, in order to address the root-causes with proper PM tasks applied on several components (Multiple-failure analysis).

It is important to notice that it has not been identified any Economic or Commitment component across the classification: as explained in the Chapter 3 *Methodology*, there is a standard process, explained in the COFA logic tree (Figure 3.1), to classify the components of the vehicles traction system, according to the RCM principles. From a reliability point of view it's important to make decisions with caution and, indeed, for all the components considered in this study, except for one RTF, each failure mode has been classified as more critical than commitment and economical.

In the COFA worksheet, Appendix A, the likely effects of each failure mode have been identified, and the consequences have been categorized according to the Asset Reliability Criteria. These consequences at system level have been divided into 4 classes:

- Vehicle shutdown;
- Power reduction;
- Range reduction;
- Safety risks for users or maintenance operators.

In the following diagram the percentage of consequence for all the failure modes is shown: the most likely effect is the breakdown of the vehicle, which is the effect of almost half of the identified failure cases. This is an important outcome that addresses considerations on the criticality of the whole system and the importance of preventive maintenance.
Power reduction and Range reduction are, respectively the 21% and 24% of all consequences of failure, and Safety risk is the 6%.

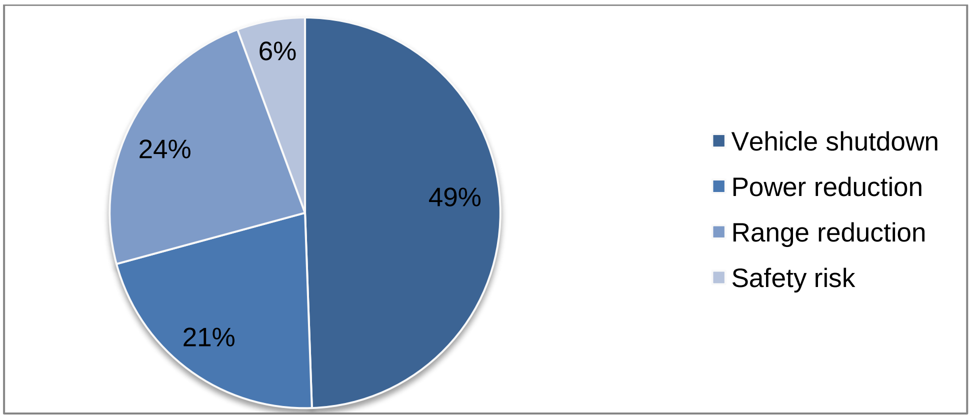


FIGURE 4.2

Consequences of failures, according to the ARC

4.3 THE MOST IMPORTANT RESULTS

In the Appendices it is possible to see the analysis divided in two worksheets, COFA worksheet and PM task worksheet, in which all the 26 component are processed.

In the COFA, 60 likely failure modes of the powertrain components have been identified and, in the PM task worksheet, 100 failure causes linked with those failure modes have been detected. Thanks to academic papers, technical articles and industrial publications, has been possible to produce a maintenance program, with Preventive Maintenance activities and relative periodicities, in order to address the failure causes of each component.

In this section of the paper the most important and interesting units of the vehicle powertrain will be described, for further details refer to the Appendices.

- ***Li-Ion battery pack***
  Code: ES-BAT-LIP
  Classification: CRITICAL operability concern

The battery pack is probably the most critical component of an electric car power train for cost, performances and weight, and, already for this, it needs particular attention. Modern batteries hold more and more power density and capacity, but the drive range is still the most important lack for the spreading of electric vehicles.

The basic functions of this unit are:

- Provide energy to the PM electric motor through the inverter device;
- Provide energy to the auxiliary system (i.e. heather/air conditioned, radio, steering unit, etc.) through the 12V battery and the DC/DC converter;
- Store energy generated by the PM electric motor during regenerative braking.

The likely failure modes identified for the battery system are: [23] [24] [25]

- Short circuit;
- Overheating;
- Internal resistance increasing;

- Over-charge;
- Over/under-current.

These failure modes and effects on the vehicle have been evaluated, according with the COFA logic tree, the Asset Reliability Criteria, Potentially Critical guideline and Economically critical guideline in order to identify their criticality level.

The battery pack is finally classified as CRITICAL for safety concerns, and electronic system is vital to provide safe operations of this important unit. In the following table are reported detection and protection devices for each safety related failure mode. [23]

Abnormal/abusive condition	**Detection device**	**Protection device**
Over temperature	*Temperature sensor*	*Power switch is opened and insulates battery from load and rectifier*
Over charge	*Permanent screening of charging unit*	*Power switch*
Over current	*Charge current sensor*	*Power switch*
Short circuit	*Fuse status detector*	*Electrical fuse*

TAB. 4.1

Safety system of the battery pack: detection and protection

The *detection* functions ensure that all the physical data are accurately measured. It seems obvious that, without reliable acquisition of data at intervals relevant with the application, electronics will not be able to protect the lithium cells or to optimize their performances.

The data to be measured in a lithium-based battery may vary with the electrochemistry, but the following values are usually acquired by sensors: [23]

- each individual cell voltage;
- overall battery voltage;
- charge current;
- temperature of the cells;
- temperature of the electronics;
- ambient temperature inside the battery.

Protection is the most critical type of action, since safety depends on it. A common type of protection is the fast opening of a reversible power switch, which isolates the battery system from the rectifier and the load. This isolation prevents a number of abusive conditions being applied to the battery. Over-charge is one example of an abusive condition imposed by the charger; a short circuit would be an example of a condition imposed by the load. When conditions come back to normal, the power switch closes. For all these reasons is evident that apply preventive maintenance activity to the electronic control system is as necessary as to the battery itself.

During the study, proper Preventive Maintenance tasks have been identified for the Li-Ion battery pack, with the aim to address the root failure causes linked with each failure mode. The following PM activities are extracted from the PM task worksheet in Appendix B: [24] [26]

Failure causes	**PM tasks for each failure cause**	**Frequency and interval for each PM task [months / miles]**
Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	12 / 15,000
Failure of battery heater	Check the heater device operability	12 / 15,000
Failure of battery sensor	Check the sensor operability	12 / 15,000
Mechanical stress, ageing wear	Check the battery charge controller to verify the correct voltage settings	12 / 15,000
Failure of Battery Control Module	Check the battery charge controller to verify the correct voltage settings	12 / 15,000
	Check and compare the voltage readings at the battery connections and at the controller	12 / 15,000
Failure of Battery Charger	Check all charging subsystems	12 / 15,000

TAB. 4.2

Failure causes and PM tasks for the Li-Ion battery pack

- ***Vehicle control unit - Digital signal processor (DSP)***

  Code: EP-CTRL-DSP

  Classification: CRITICAL operability concern

The Digital signal processor is the unit that receives signals from other vehicle's components through sensors, analyzes these signals according to preinstalled algorithms, and sends feedback to control the vehicle's functions and behavior.

Due to advances in semiconductor technology, ever more complex DSP algorithms and applications are now feasible, which, in the same time, increase the complexity of the systems and products. As the complexity increases, the system reliability is no longer solely defined by the hardware reliability: system reliability is increasingly determined by both hardware and software architecture and the level of design maintainability. [14] [25]

The basic functions of this unit are:

- Provide control signals to power converter;
- Monitor vehicle status analyzing signals from sensors;
- Process inputs from driver (accelerator and brake pedals signals);
- Calculate range considering battery state of charge.

The likely failure modes identified for the DSP are:

- Device cannot initialize;
- Device cannot provide proper output;
- Device cannot analyze input signals.

During the research, proper Preventive Maintenance tasks have been identified for the Digital Signal Processor, with the aim to address the root failure causes linked with each failure mode. The following table shows the PM activities with suggested frequency. The most critical cause of failure is about the software ability to communicate with vehicle's different units: as a new technology, the control algorithm could have some lacks and bugs, and a careful updating of the software is vital.

A few of the more common causes of DSP software bugs are due to: [14]

- Failure of interrupts to completely restore processor state upon completion;
- Failing to properly initialize or disable circular buffering addressing modes;
- Memory leaks, the gradual consumption of available volatile memory due to failure of a thread to release all memory when finished;
- Dependency of DSP routines on specific memory arrangements of variables;
- Conflict or excessive latency between peripheral accesses;
- Subroutine execution times dependent on input data or configuration.

These failure modes and effects on the vehicle have been evaluated, according with the COFA logic tree, the Asset Reliability Criteria, Potentially Critical guideline and Economically critical guideline in order to identify their criticality level.
The Digital Signal Processor is finally classified as CRITICAL for operability concerns. [14] [27]

Failure causes	**PM tasks for each failure cause**	**Frequency and interval for each PM task [months / miles]**
Over/under power voltage	Check relay EP-REL-DSP	12 / -
Software bugs	Update software and report known bugs to supplier, by internet access	If available
Incorrect installation	Check list of standard installation procedure	-
Abnormal output signal	Check I/O peripherals	12 / -

TAB. 4.3

Failure causes and PM tasks for the Digital Signal Processor

- ***Permanent Magnet Synchronous traction motor (PMSM)***
  Code: EP-EMOT-PMSM

  Classification: CRITICAL operability concern

The electric motor has the main role of providing the traction power to the wheels and moving the vehicle but, in the case of pure-electric transportation, the range limitation induced manufacturers to research in solutions able to increase the efficiency.
The idea of *Regenerative Braking* goes on this direction, and it consists of the ability to generate electric energy during the braking phase of the car: the motor works as a generator charging the battery and increases the driving range of almost 20 - 25%.
The main functions of the electric motor are:

- Convert electric energy to mechanical energy;
- Convert kinetic energy to electric energy.

The likely failure modes identified for this component are: [28] [29]

- Winding failure;
- Bearings failure;
- Rotor and shaft failure.

Each of these principal failure modes has several failure causes that could generate the unwonted effect, and in the PM worksheet the proper maintenance activities have been planned. [26] [28] [29]

Failure causes	PM tasks for each failure cause	Frequency and interval for each PM task [months / miles]
Windings failure for Insulation breakdown	Keep motor clean with good air flow	-
Windings failure for electrical fault	Store motor correctly away from moisture and chemical	-
Windings failure for AC drive stress	Perform regular inspection	24 / 30,000
Windings failure for cycling/flexing due to frequent start/stop	Keep motor clean with good air flow	-
Bearings failure for mechanical breakage	Replace bearings	Corrective task
Bearings failure for start/stop loss of lube film	Replace bearings	Corrective task
Bearings failure for improper lubricant	Replace bearings	Corrective task
Bearings failure for improper handling/storage	Replace bearings	Corrective task
	Store motor correctly away from moisture and chemical	-
Rotor failure for physical damage and corrosion	Check list of standard installation procedure	-

TAB. 4.4

Failure causes and PM tasks for the PMSM

Major part of maintenance tasks relate to keep the motor away from moisture, pollution, dust and chemical, both during the storing and the running, because these are the main root causes of failure.

Indeed an electric motor has a very few components moving inside the housing, unlike a classic internal combustion engine, so friction is not a big problem and the reliability is much more high. On the other hand, the strong magnetic field generated by the rotor permanent magnets has an ageing effect on the bearings, which besides continue to have a long life cycle and assure duration.

According to Terry Harris in the web seminar for UE system Inc [29], the failures of an electric motor can be divided into 6 main classes:

- Bearings;
- Stator winding (i.e. overload, water);
- External (i.e. environment, voltage, load);

- Rotor bar;
- Shaft or coupling.

In the following diagram are shown the average percentage of occurrence for these classes.

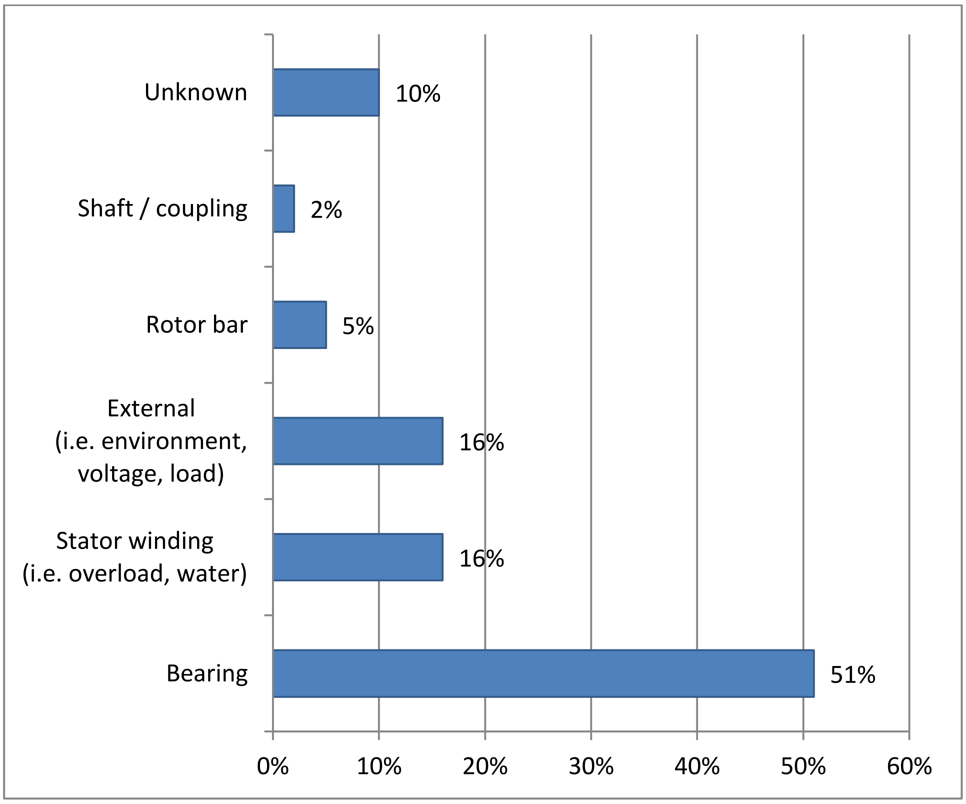


FIGURE 4.3

Percentage of occurrence of each failure cause of the PMSM electric motor

In the following table, the main failure causes are summarized for each constituent of the motor structure. [28]

MOTOR COMPONENT	FAILURE CAUSE
Housing	- improper installation - physical damage - corrosion - material build-up
Stator	- physical damage - contamination - corrosion - voltage imbalance - high temperature - broken support
Rotor	- thermal stress - imbalance - physical damage - contamination
Bearings	- improper handling/storage - improper installation - misalignment - improper lubricant - start/stop loss of lube film - contamination
Fan	- physical damage - ice build-up - corrosion
Winding / insulation	- contamination - overheating - improper storage - moisture - thermal stress - AC drive stress
Shaft	- physical damage - improper installation - improper manufacturing - corrosion

TAB. 4.5

Failure causes for each component of the Electric Motor

Breakdown maintenance and overhaul jobs are handled at maintenance service provider facilities. However, breakdown maintenance for electric traction motors is not common due to their low failure rates, almost $4.0x10^{-5}$ (failure/hour). [25] [28]

- ***Power converter – 3 phase Inverter***

  Code: EP-INV-3PH

  Classification: CRITICAL operability concern

The Inverter has the role of connection between the battery and the motor, addressing two main functions:

- Control the electric traction motor converting current at the required voltage;
- Charge the battery during regenerative braking, converting energy generated by the motor.

The basis failure modes identified for this device are mainly three:

- Device cannot initialize;
- Abnormal output to the motor;
- Abnormal output to the battery.

In the following table are shown the failure causes and proper maintenance tasks to address these causes, with suggested frequency of application. [26] [28]

Failure causes	**PM tasks for each failure cause**	**Frequency and interval for each PM task [months / miles]**
Winding insulation breakdown	Check winding insulation condition	24 / 30,000
Insulation bushing breakdown	Check insulation bushing	24 / 30,000
Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts	Keep device clean	24 / 30,000
Malfunction of protective relay	Check protective relay operability	12 / -
Normal deterioration from age and corrosion phenomenon	Keep device clean	24 / 30,000
Overheating	Temperature monitoring, by DSP unit	-
Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	Switchgear inspection	24 / 30,000

TAB. 4.6

Failure causes and PM tasks for the Inverter device

- ***Fail-safe circuit breaker***

  Code: EP-CIR BRK

  Classification: CRITICAL safety concern

Circuit breakers are used in a power system to break or make current flow through power system apparatus, in order to protect an electrical circuit from damage caused by overload or short circuit. Its basic function is to detect a fault condition and, by interrupting continuity, to immediately discontinue electrical flow. Unlike a fuse, which operates once and then has to be replaced, a circuit breaker can be reset to resume normal operation.

Reliable operation of circuit breakers is critical to the ability to reconfigure a power system and can be assured by regular inspection and maintenance. [26] [28] [30] [31]

The likely failure modes identified for this critical component are:

- Stuck switch in *on position*;
- Stuck switch in *off position*.

The first failure has no evident effects on the vehicle, because the current is able to flow through the circuit, but in the case of electrical malfunction, the switch could not work. It is a typical example of hidden failure, impossible to detect without a proper preventive maintenance program, and in this particular case very dangerous for safety reasons. This failure mode is classified as potentially critical for the vehicle.

Obviously, the second failure brings evident consequences on the system because electricity cannot flow through the power system, and it results in the breakdown of the vehicle, with possible consequences on safety. For this second failure mode, the component is finally classified as CRITICAL for safety concerns.

As the majority of electrical devices, the circuit breaker is often replaced in case of failure, but is vital to replace it before the occurrence of the failure: this is the reason for apply a preventive maintenance program, as shown in the following table.

Failure causes	**PM tasks for each failure cause**	**Frequency and interval for each PM task [months / miles]**
Normal deterioration from age	Inspect breaker-operating mechanism for loose hardware and missing or broken cotter pins, etc. Examine latch and roller surfaces	12 / -
Loss or deficiency of oil or cooling medium	Clean and relubricate operating mechanism with a light machine oil	12 / -
Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -
Exposure to abnormal moisture, chemicals or dust	Wipe and clean the insulating parts, including bushings	12 / -
Misoperations or testing error	Check list of standard operation and test procedure	-

TAB. 4.7

Failure causes and PM tasks for Circuit Breaker

- ***Temperature sensor of 12V battery***

  Code: ES-SNS-12V

  Classification: POTENTIALLY CRITICAL operability concern

This sensor has the role of detecting and communicating to the Battery Control unit the thermal status of the auxiliary 12 V battery. The processor analyzes these data and controls the flux of energy through DC/DC converter, in order to avoid a failure of the battery.

This component is classified as POTENTIALLY CRITICAL, because its failure is hidden, and only with the addition of another failure, as the failure of the battery, there is a consequence at the vehicle level.

If this failure is made evident by the Vehicle Control System (DSP), then the Temperature sensor could be classified as a *Run to Failure* component, and replaced after its breakdown.

In the following table are shown the PM tasks planned for this component and relative periodicity. [26] [28] [32]

Failure causes	PM tasks for each failure cause	Frequency and interval for each PM task [months / miles]
Incorrect installation	Check list of standard installation procedure	-
Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000

TAB. 4.8

Failure causes and PM tasks for Circuit Breaker

All the sensors of the system require similar maintenance activities, being part of the same technology family and being subjected to similar work conditions.

4.4 DISCUSSION

Other than the Li-Ion battery and the final gearing, EVs are much less likely to suffer from ageing wear compared to conventional ICE vehicles. The majority of failures are originated from electric circuit problems and defective manufacturing. [25]
A first reason for that is the lower number of components by which the power train is made up. As explained in the section 4.1 of this chapter, the reliability of a serial system is inversely proportional to the number of its constituents. Moreover, thanks to the nature of electric propulsion, there are few components in mutual contact with each other, so reducing friction cases and the need of replace lubrication oil and failed parts. On the contrary, ICEVs have numerous moving parts such as valves and cams, which increase the failure occurrence and the costs for spare parts.

In general, maintenance for electric cars is supposed to cost almost 25 – 50% less than for conventional vehicles [33], but a proper evaluation of this aspect could be done only after a wide commercialization and utilization of this new transportation.

The future development, that likely will have the ability to increase the reliability of electric vehicles, relates with *Predictive maintenance* with on-board failures self-detection systems.

Prognostic methods, with the capability of predicting system degradation before breakdown, are very promising and more affordable on electronics systems than mechanical systems:

thanks to the modern digital technology, the ability of self-detection and anticipation of failures are much increased. Early detection of the likely critical failures relies on capabilities of the Electronic controller, both of the algorithm and the hardware structure. Further investigation and testing are important for electric cars development.

The on-board predictive maintenance (PdM) application needs a system composed by sensors, which detect the conditions of the single components and then communicate with a processor. The calculator unit has to translate the signals in readable data and compare them with threshold values.

In general, on-board and off-board PdM for electric motor systems mainly refers to vibration analysis, thermal analysis and ultrasound analysis. However, in the case of a vehicle, the operative conditions have to be considered very carefully and the real affordability must be evaluated by a cost/benefit analysis.

A very important development suggested for EVs refers to the capability to communicate real-time relevant vehicle health data to OEMs. Communication systems are, at the present time, mature and reliable to provide an effective feedback to the manufacturers, creating the conditions for a real continuous improvement of the product and the service to the customers.

Indeed, the final objective of the maintenance strategy is to increase the customer satisfaction, and reliability is one of the most important factors influencing cars purchases, as underlined in the following Table 4.9. [34]

Factors influencing car purchase		
Most important	***Medium importance***	***Least important***
- Vehicle price - Size - Reliability - Comfort - Safety - Running costs - Fuel consumption - Appearance	- Performance - Power - Image - Brand name - Insurance costs - Engine size - Equipment	- Depreciation - Sales package - Personal experience - Dealership - Recommendation - Road tax - Environment - Vehicle emission - Alternative fuel

TAB. 4.9

Factors influencing car purchase (as in King Review 2007)

4.5 CHAPTER CONCLUSIONS

In this chapter, some general considerations on the reliability of the EVs power train have been presented, underlining the below concepts:

- Electric traction systems are much more reliable than ICEVs drive train, thanks to the lower number of components and to the lower number of moving components in contact with each other;
- The most critical component is the battery system, which suffers from wear and ageing, and is the most expensive to replace;
- From a reliability point of view the power train has a serial structure, see RBD in Figure 4.20, and it is the reason of a wide number of component classified as *critical* (85%);
- An effective Preventive Maintenance program is indispensable to keep the functions of the system;
- The most likely vehicle effect in case of failure is the shutdown of the entire system (49%). This is an important outcome that addresses considerations on the criticality of the vehicle and the importance of preventive maintenance. Power reduction and range reduction represent respectively the 21% and 24% of all consequences of failure, and Safety risk the 6%.

Furthermore, six relevant components are described in detail, explaining their main functions, likely failure modes, failure causes, suggested PM tasks and periodicity. These components are the Li-Ion Battery pack, the PMSM electric motor, the 3phase Inverter, the DSP vehicle controller, the Fail-safe Circuit Breaker and the Thermal sensor of 12V battery.

The outcomes for all the 26 components of the EVs power train are reported in the COFA and PM tasks worksheets, in the Appendices of this paper: 60 different failure modes and 100 failure causes have been identified, and for each failure cause, the proper PM activities have been planned. These documents together represent the maintenance program based on RCM principles.

Chapter 5

5. CONCLUSIONS AND FUTURE DEVELOPMENT

The objectives of this thesis work, as stated in the introduction section, have been:

1. Analysis and understanding of the typical architecture of the electric car powertrain.
    1.1. Description and schematic drawing of the structure of a typical electric car power train representing the mechanical, electrical and control links between components;
    1.2. Description of structure and operations of each system component;
    1.3. Reliability Block Diagram for general considerations on the whole system.
2. Identification of the best maintenance strategy for the power train system employing the RCM method and definition of a long-term maintenance plan.
    2.1. Identification of functions, functional failures, failure modes, and criticality classification of each powertrain component;
    2.2. For each component (except run-to-failure ones), identification of failure causes, definition of the proper Preventive Maintenance tasks and relative periodicity.

The first section of this thesis work, Chapter 1, consists of a general consideration and overview about the important role that EVs could play in the near future, specifically regarding environmental issues and their reduction of air pollution in metropolitan areas. Transportation has a big impact on the air quality, equating to 32% of human pollution, and a comparative analysis between ICEVs and EVs has therefore been reported with associated numerical data in order to demonstrate the great potential of green vehicles.
The availability of accurate data regarding environmental topics has proven to be very useful in laying the foundations for further research and development.

The Chapter 2 is focused on a literature review of the technology related to electric traction, electronic control system and energy storage system, and it is referred to as the first macro-objective. Different configurations have been compared through a pros-and-cons analysis. The EV models, currently produced by OEMs, have been considered and the complete scheme of the power train system has been drawn.

Latest academic papers, reference books, industrial publications and individual theses were studied for a more detailed understanding of the state of the art of this technology.
This part of the work has been quite complex because of the relative youth and continuous nature of development of this technology: in this situation, a reference written a few years ago could already be obsolete, but, at the same time, finding very recent sources has been quite difficult. A great source has been the on-line archives of IEEE, where it has been possible to locate and have access to the most recently available research publications.

The methodology of the research is reported in Chapter 3, and in this section the Reliability Centred Maintenance logic, which is the method applied to produce a maintenance program (ref. Appendix A and B), is reported and discussed. Additionally, other major reasons for the choice of this method have been explained.
Authoritative references have been utilized in this review: the principles and logic of the method are very intelligible, but the application on a real case, such as the powertrain of EVs, requires much attention and care.

Finally, the core section of the thesis work forms Chapter 4, in which the overall results and findings are described. In this part, the second objective of the research, the identification of the best maintenance strategy for the powertrain and definition of a long-term maintenance plan, is reviewed and presented. General considerations on the reliability of the EV power system are reported and the outcomes of six interesting components are widely described. For each component, the functions, the typical failure modes, the causes of malfunctions and the proper PM tasks and relative periodicity are reported and discussed. The reliability results and maintenance suggestions for all the powertrain system units are reported in the Appendix A and B, at the end of this paper.
The most serious issue in this part of the research has been the lack of reliability and maintenance information. The youth of the technology and the reluctance of manufacturers to divulge and share sensitive data, for image reasons and in order to retain competitive advantage, have been the main cause for the scarcity of this information. This issue has been resolved by researching information from similar technologies, more mature than EVs one, but which have comparable run condition and operations.

Some maintenance findings of this thesis work, i.e. preventive tasks and periodicity, are based on general data from academic articles papers, technical books, industrial publications and individual theses. These sources are absolutely accurate and authoritative, but often based on simulations, laboratory studies and statistical outcomes, instead of field experience. [35]

The data about failures are very sensitive for manufacturers: they are afraid to publish information that could provide a negative impact on the customers and affect their competitive advantages. Furthermore, in the particular case of a new technology, such as electric vehicles, OEMs probably do not hold so much data from the field: the car equipped with an on-line communication system could definitely help to fill this lack of information.

Some European projects are working to increase the number of electric vehicles in the cities, attracting early adopters. People interested in the new mobility solutions and available to test cars and charging infrastructure takes part to these projects providing feedback to the manufacturers: a recent example is E-mobility project in Italy that is a partnership between Smart of Daimler group and Enel s.p.a. (the first electricity provider in the country). In some Italian cities, as Roma, Milano, Bologna and Pisa, this collaboration has begun to provide results both for the manufacturer and customers, bringing new clean vehicles on the streets.

Throughout this paper, a maintenance program for EVs power train has been planned by Reliability Centred Maintenance principles. RCM is an effective method that considers maintenance as the means to maintain the functions a user may require of machinery, but good quality records are necessary: the lack of actual failure data is a major constraint on early studies regarding electric car reliability. Future works on this subject could have the possibility to take advantage from more updated references.

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Appendix A – COFA worksheet

C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		Component functions		Component functional failures	Dominant component failure mode for each functional failure	Evident failure?	Vehicle effect for each failure mode	Consequence of failure, based on the ARC	Failure Classification	Component Classification
1.	EP-CTRL-DSP Electronic controller, digital signal processor [14] [25] [27]	1.1	Provide control signals to power converter	Fail to provide control signals to power converter	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
					Device cannot provide proper output		Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
		1.2	Monitor vehicle status analyzing signals from sensors	Fail to monitor vehicle status analyzing signals from sensors	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Device cannot analyze input signals		Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
		1.3	Process inputs from driver (accelerator and brake pedals signals)	Fail to process inputs from driver (accelerator and brake pedals signals)	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Device cannot analyze input signals		Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
		1.4	Calculate range considering battery state of charge	Fail to calculate range considering battery level	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Device cannot analyze input signals		Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
2.	EP-INV-3PH Traction motor inverter, 3phase voltage-fed PWM [26] [28]	2.1	Control the electric traction motor converting current at the required voltage	Fail to control the electric traction motor converting current at the required voltage	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
					Abnormal output to the motor		Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
		2.2	Charge the battery during regenerative braking, converting energy generated by the motor	Fail to charge the battery during regenerative braking	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Abnormal output to the battery		Battery cannot be charged	Range reduction	Critical failure (operability concern)	

Appendix A – COFA worksheet

C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
3.	EP-EMOT-PMSM Permanent Magnet Synchronous traction motor [25] [26] [28] [29]	3.1	Convert electric energy to mechanical energy	Fail to convert electric energy to mechanical energy	Winding failure	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
					Bearing failure		EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Rotor and shaft failure		EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
		3.2	Convert kinetic energy to electric energy	Fail to convert kinetic energy to electric energy	Winding failure	no	Battery cannot be charged	Range reduction	Critical failure (operability concern)	
					Bearing failure		Battery cannot be charged	Range reduction	Critical failure (operability concern)	
					Rotor and shaft failure		Battery cannot be charged	Range reduction	Critical failure (operability concern)	
4.	EP-GR-PLAN Planetary reduction gear [36]	4.1	Reduce electric motor speed and increase torque	Fail to reduce electric motor speed and increase torque	Gear seizing	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
					Gear breaking		EV cannot move	Vehicle shutdown	Critical failure (operability concern)	

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C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
5.	ES-CTRL Energy management unit [14] [25] [27] [38] [39]	5.1	Optimize voltage and current output according to load and battery state of charge	Fail to optimize voltage and current output	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
					Device cannot analyze input signals		Reduction of range	Range reduction	Critical failure (operability concern)	
					Device cannot provide proper output		Reduction of power	Power reduction	Critical failure (operability concern)	
		5.2	Detect battery state of charge	Fail to detect battery state of charge	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Device cannot analyze input signals		Reduction of charging	Range reduction	Critical failure (operability concern)	
		5.3	Detect battery temperature	Fail to detect battery temperature	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Device cannot analyze input signals		Reduction of range	Range reduction	Critical failure (operability concern)	
		5.4	Control energy refuelling unit	Fail to control energy refuelling unit	Device cannot initialize	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Device cannot analyze input signals		Battery cannot be charged	Range reduction	Critical failure (operability concern)	
					Device cannot provide proper output		Reduction of power	Power reduction	Critical failure (operability concern)	

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C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
6.	ES-BAT-LIP Li-Ion Battery Pack [23] [24] [25] [26]	6.1	Provide energy to the PMSM through the 3P-PWM-INV	Fail to provide energy to the PMSM through the 3P-PWM-INV	Short circuit	yes	EV cannot move	Vehicle shutdown	Critical failure (safety concern)	CRITICAL safety concern
					Overheating		EV cannot move	Vehicle shutdown	Critical failure (safety concern)	
					Internal resistance increasing		Reduction of power	Power reduction	Critical failure (operability concern)	
					Over-charge		Reduction of power	Power reduction or Vehicle shutdown	Critical failure (safety concern)	
					Over/under-current		Reduction of power	Power reduction or Vehicle shutdown	Critical failure (safety concern)	
		6.2	Provide energy to the 12V battery through the DC/DC converter	Fail to provide energy to the 12V battery through the DC/DC converter	Short circuit	yes	EV cannot move	Vehicle shutdown	Critical failure (safety concern)	
					Overheating		EV cannot move	Vehicle shutdown	Critical failure (safety concern)	
					Internal resistance increasing		Reduction of power	Power reduction	Critical failure (operability concern)	
					Over-charge		Reduction of power	Vehicle shutdown	Critical failure (safety concern)	
					Over/under-current		Reduction of power	Vehicle shutdown	Critical failure (safety concern)	
		6.3	Store energy from the PMSM during regenerative braking	Fail to store energy from the PMSM during regenerative braking	Short circuit	yes	Battery cannot be charged	Vehicle shutdown	Critical failure (safety concern)	
					Overheating		EV cannot move	Vehicle shutdown	Critical failure (safety concern)	
					Over-discharge		Reduction of range	Range reduction	Critical failure (operability concern)	
					Internal resistance increasing		Battery cannot be charged	Range reduction	Critical failure (operability concern)	

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C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
7.	ES-CH-OB Battery on-board charging unit [26] [28]	7.1	Provide the proper energy refuelling from external power grid, converting AC power to DC power, according to the signals from BAT-CTRL unit	Fail to provide the proper energy refuelling from external power grid	Device cannot initialize	yes	Battery cannot be charged	Range reduction	Critical failure (operability concern)	CRITICAL operability concern
					Overheating		Battery cannot be charged	Range reduction	Critical failure (operability concern)	
					Under-voltage output		Reduction of charging	Range reduction	Critical failure (operability concern)	
					Under-current output		Reduction of charging	Range reduction	Critical failure (operability concern)	
					Communication error with BAT-CTRL unit		Reduction of charging	Range reduction	Critical failure (operability concern)	
8.	ES-CH-PT Charge port [26] [28]	8.1	Connect vehicle on-board charging unit to the external power grid	Fail to connect vehicle on-board charging unit to the external power grid	Communication error with BAT-CTRL unit	yes	Battery cannot be charged	Range reduction	Critical failure (operability concern)	CRITICAL operability concern
					Over/under-voltage to BAT-OB-CHARG		Reduction of charging	Range reduction	Critical failure (operability concern)	
					Over/under-current to BAT-OB-CHARG		Reduction of charging	Range reduction	Critical failure (operability concern)	
9.	ES-BAT-HT Li-Ion battery heater unit [26] [28]	9.1	Heat the Li-Ion battery to the standard operating temperature	Fail to heat the Li-Ion battery to the standard operating temperature	Device cannot initialize	no	EV cannot move at very low temperature	-	Potentially critical failure	POTENTIALLY CRITICAL operability concern
10.	ES-BAT-12V Auxiliary 12 V battery [32] [37]	10.1	Provide 12V DC power to the DSP and BAT-CTRL unit	Fail to provide 12V DC power to the DSP and BAT-CTRL unit	Cell failure	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
					Overcharging		Loss of battery capacity	-	Potentially critical failure	
					Undercharging		Loss of battery capacity	-	Potentially critical failure	
		10.2	Provide 12V DC power to accessories and gauges	Fail to provide 12V DC power to accessories and gauges	Cell failure	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
					Overcharging		Loss of battery capacity	-	Potentially critical failure	
					Undercharging		Loss of battery capacity	-	Potentially critical failure	

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C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
11.	EP-SNS-M-P Motor position sensor [26] [28]	11.1	Detect rotation angle of traction electric motor	Fail to detect rotation angle of traction electric motor	Abnormal values reading	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
		11.2	Report signals output to the DSP	Fail to send signals output to the DSP	Abnormal signal output	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
12.	EP-SNS-M-S Motor speed sensor [26] [28]	12.1	Detect rotation speed of traction electric motor	Fail to detect rotation speed of traction electric motor	Abnormal values reading	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
		12.2	Report signals output to the DSP	Fail to send signals output to the DSP	Abnormal signal output	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
13.	EP-SNS-M-T Motor temperature sensor [26] [28]	13.1	Detect electric motor operating temperature	Fail to detect electric motor operating temperature	Abnormal values reading	yes	-	-	Run to failure component	RUN TO FAILURE
			Report signal output to the DSP	Fail to report signal output to the DSP	Abnormal signal output		-	-	Run to failure component	

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C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
14.	EP-SNS-ACC Accelerator pedal sensor [26] [28]	14.1	Convert accelerator pedal position in signals to the DSP unit, in order to control motor acceleration	Fail to convert accelerator pedal position in signals to the DSP unit	Abnormal values reading	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
					Abnormal signal output		EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
15.	EP-SNS-BRK Brake pedal sensor [26] [28]	15.1	Convert brake pedal position in signals to the DSP unit, in order to control motor acceleration	Fail to convert brake pedal position in signals to the DSP unit	Abnormal values reading	yes	EV cannot brake	Safety risks for user	Critical failure (safety concern)	CRITICAL safety concern
					Abnormal signal output		EV cannot brake	Safety risks for user	Critical failure (safety concern)	
16.	ES-SNS-12V Temperature sensor of 12V battery [26] [28] [32]	16.1	Detect operating temperature of the 12V auxiliary battery	Fail to detect operating temperature of the 12V auxiliary battery	Abnormal values reading	no	No effects until failure of the 12V battery	-	Potentially critical failure	POTENTIALLY CRITICAL operability concern
		16.2	Report signals output to the BAT-CTRL unit	Report signals output to the BAT-CTRL unit	Abnormal signal output	no	No effects until failure of the 12V battery	-	Potentially critical failure	
17.	ES-SNS-LIP-C Li-Ion Battery current sensor [26] [28]	17.1	Detect state of charge and charge/discharge current of battery pack	Fail to detect state of charge and charge/discharge current of battery pack	Abnormal values reading	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
		17.2	Report signals output to the BAT-CTRL unit	Fail to report signals output to the BAT-CTRL unit	Abnormal signal output	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
18.	ES-SNS-LIP-T Li-Ion Battery temperature sensor [26] [28]	18.1	Detect operating temperature of battery pack	Fail to detect operating temperature of battery pack	Abnormal values reading	yes	EV cannot move	Vehicle shutdown	Critical failure (safety concern)	CRITICAL safety concern
		18.2	Report signals output to the BAT-CTRL unit	Fail to report signals output to the BAT-CTRL unit	Abnormal signal output	yes	EV cannot move	Vehicle shutdown	Critical failure (safety concern)	

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C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
19.	ES-PLUG-LIP Li-Ion battery service plug [26] [28] [30] [31]	19.1	Turn off/on the high voltage current for EV maintenance tasks	Fail to turn off/on the high voltage current for EV maintenance tasks	Stuck switch in *off position*	yes	EV cannot move	Vehicle shutdown	Critical failure (safety concern)	CRITICAL safety concern
					Stuck switch in *on position*	yes	Electric power cannot be turned off	Safety risks for user and maintenance operator		
20.	ES-SNS-CHPT Charge port temperature sensor [26] [28]	20.1	Detect operating temperature of charge port	Fail to detect operating temperature of charge port	Abnormal values reading	yes	Battery cannot be charged	Range reduction	Critical failure (operability concern)	CRITICAL operability concern
		20.2	Report signals output to the BAT-CTRL unit	Fail to report signals output to the BAT-CTRL unit	Abnormal signal output	yes	Battery cannot be charged	Range reduction	Critical failure (operability concern)	
21.	EP-SNS-INVPH Inverter phases sensor [26] [28]	21.1	Detect the 3-phases current supplied to traction motor by inverter	Fail to detect the 3-phases current supplied to traction motor by inverter	Abnormal values reading	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	CRITICAL operability concern
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
		21.2	Report output values to the DSP	Fail to report output values to the DSP	Abnormal signal output	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
							Traction power uncontrollable	Power reduction	Critical failure (operability concern)	
22.	ES-CON-DCDC DC/DC converter [26] [28]	22.1	Step down the high voltage DC current from the Li-Ion battery to a 12V DC current	Fail to step down the high voltage DC current from the Li-Ion battery to a 12V DC current	Device cannot initialize	no	No effects until failure/discharge of the 12V battery	-	Potentially critical failure	POTENTIALLY CRITICAL operability concern
					Abnormal output					

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C.#	Column A	#.#	Column B	Column C	Column D	Col. E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component functional failures**	**Dominant component failure mode for each functional failure**	**Evident failure?**	**Vehicle effect for each failure mode**	**Consequence of failure, based on the ARC**	**Failure Classification**	**Component Classification**
23.	EP-CIR BRK Fail-safe circuit breaker [26] [28] [30] [31]	23.1	Turn off the main power in case of a dangerous malfunction	Fail to turn off the main power in case of a dangerous malfunction	Stuck switch in *on position*	no	-	Safety risks for user and maintenance operator	Potentially critical failure (safety concern)	CRITICAL safety concern
					Stuck switch in *off position*	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
24.	ES-REL-LIP Li-Ion battery relay [26] [28] [30] [31]	24.1	Turn off/on the high voltage current at the EV	Fail to turn off/on the high voltage current at the EV	Stuck switch in *on position*	no	-	Safety risks for user	Potentially critical failure (safety concern)	CRITICAL safety concern
					Stuck switch in *off position*	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
25.	EP-REL-DSP DSP relay [26] [28] [30] [31]	25.1	Turn off/on the power to the electronic controller DSP in case of over-voltage	Fail to turn off/on the power to the electronic controller DSP in case of over-voltage	Stuck switch in *on position*	no	DSP failure in case of over-voltage	-	Potentially critical failure	CRITICAL operability concern
					Stuck switch in *off position*	yes	EV cannot move	Vehicle shutdown	Critical failure (operability concern)	
26.	ES-REL-CHOB Charging relay [26] [28] [30] [31]	26.1	Turn off/on the charging power to the Li-Ion battery	Fail to turn off/on the charging power to the Li-Ion battery	Stuck switch in *on position*	no	On-board charger failure in case of over-voltage	-	Potentially critical failure	CRITICAL operability concern
					Stuck switch in *off position*	yes	Battery cannot be charged	Range reduction	Critical failure (operability concern)	

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C.#	Column A	#.#	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I
Component I.D. and description		Component functions		Component failure mode	Vehicle effect for each failure mode	Comp. Classif.	Failure causes for each function	PM tasks for each failure cause	Frequency months/miles	Design change?
1.	EP-CTRL-DSP Electronic controller, digital signal processor [14] [25] [27]	1.1	Provide control signals to power converter	Device cannot initialise	EV cannot move	CRITICAL operability concern	Over/under power voltage	Check relay EP-REL-DSP	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot provide proper output	EV cannot match the driver request		Abnormal output signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
		1.2	Monitor vehicle status analyzing signals from sensors	Device cannot initialise	EV cannot move		Over/under power voltage	Check relay EP-REL-DSP	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot analyze input signals	EV cannot match the driver request		Abnormal input signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
		1.3	Process inputs from driver (accelerator and brake pedals signals)	Device cannot initialise	EV cannot move		Over/under power voltage	Check relay EP-REL-DSP	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot analyze input signals	EV cannot match the driver request		Abnormal input signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
		1.4	Calculate range considering battery state of charge	Device cannot initialise	EV cannot move		Over/under power voltage	Check relay EP-REL-DSP	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot analyze input signals	EV cannot match the driver request		Abnormal input signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No

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C.#	Column A	#.#	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component failure mode**	**Vehicle effect for each failure mode**	**Comp. Classif.**	**Failure causes for each function**	**PM tasks for each failure cause**	**Frequency months/miles**	**Design change?**
2.	EP-INV-3PH Traction motor inverter, 3phase voltage-fed PWM [26] [28]	2.1	Control the electric traction motor converting current at the required voltage	Device cannot initialise	EV cannot move	CRITICAL operability concern	Winding insulation breakdown	Check winding insulation condition	24 / 30,000	No
							Insulation bushing breakdown	Check insulation bushing	24 / 30,000	No
							Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts	Keep device clean	24 / 30,000	No
							Malfunction of protective relay	Check protective relay operability	12 / -	No
							Normal deterioration from age and corrosion phenomenon	Keep device clean	24 / 30,000	No
				Abnormal output to the motor	Abnormal power output		Overheating	Temperature monitoring, by DSP unit	-	No
							Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	Switchgear inspection	24 / 30,000	No
		2.2	Charge the battery during regenerative braking, converting energy generated by the motor	Device cannot initialise	EV cannot move		Winding insulation breakdown	Check winding insulation condition	24 / 30,000	No
							Insulation bushing breakdown	Check insulation bushing	24 / 30,000	No
							Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts	Keep device clean	24 / 30,000	No
							Malfunction of protective relay	Check protective relay operability	12 / -	No
							Normal deterioration from age and corrosion phenomenon	Keep device clean	24 / 30,000	No
				Abnormal output to the battery	Battery cannot be charged		Overheating	Temperature monitoring, by DSP unit	-	No
							Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	Switchgear inspection	24 / 30,000	No

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Component I.D. and description		Component functions		Component failure mode	Vehicle effect for each failure mode	Comp. Classif.	Failure causes for each function	PM tasks for each failure cause	Frequency months/miles	Design change?
3.	EP-EMOT-PMSM Permanent Magnet Synchronous traction motor [25] [26] [28] [29]	3.1	Convert electric energy to mechanical energy	Winding failure	EV cannot move	CRITICAL operability concern	Windings failure for Insulation breakdown	Keep motor clean with good air flow	-	No
							Windings failure for electrical fault	Store motor correctly away from moisture and chemical	-	No
							Windings failure for AC drive stress	Perform regular inspection	24 / 30,000	No
							Windings failure for cycling/flexing due to frequent start/stop	Keep motor clean with good air flow	-	No
				Bearing failure	EV cannot move		Bearings failure for mechanical breakage	Replace bearings	Corrective task	No
							Bearings failure for start/stop loss of lube film	Replace bearings	Corrective task	No
							Bearings failure for improper lubricant	Replace bearings	Corrective task	No
							Bearings failure for improper handling/storage	Replace bearings	Corrective task	No
								Store motor correctly away from moisture and chemical	-	No
				Rotor and shaft failure	EV cannot move		Rotor failure for physical damage and corrosion	Check list of standard installation procedure	-	No
		3.2	Convert kinetic energy to electric energy	Winding failure	Battery cannot be charged		Windings failure for Insulation breakdown	Keep motor clean with good air flow	-	No
							Windings failure for electrical fault	Store motor correctly away from moisture and chemical	-	No
							Windings failure for AC drive stress	Perform regular inspection	24 / 30,000	No
							Windings failure for cycling/flexing due to frequent start/stop	Keep motor clean with good air flow	-	No
				Bearing failure	Battery cannot be charged		Bearings failure for mechanical breakage	Replace bearings	Corrective task	No
							Bearings failure for start/stop loss of lube film	Replace bearings	Corrective task	No
							Bearings failure for improper lubricant	Replace bearings	Corrective task	No
							Bearings failure for improper handling/storage	Replace bearings	Corrective task	No
								Store motor correctly away from moisture and chemical	-	No
				Rotor and shaft failure	Battery cannot be charged		Rotor failure for physical damage and corrosion	Check list of standard installation procedure	-	No

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Component I.D. and description		Component functions		Component failure mode	Vehicle effect for each failure mode	Comp. Classif.	Failure causes for each function	PM tasks for each failure cause	Frequency months/miles	Design change?
4.	EP-GR-PLAN Planetary reduction gear [36]	4.1	Reduce electric motor speed and increase torque	Gear seizing	EV cannot move	CRITICAL operability concern	Bearings failure for mechanical breakage	Replace bearings	Corrective task	No
							Bearings failure for start/stop loss of lube film	Replace bearings	Corrective task	No
							Bearings failure for improper lubricant	Replace bearings	Corrective task	No
							Bearings failure for improper handling/storage	Replace bearings	Corrective task	No
								Store motor correctly away from moisture and chemical	-	No
				Gear breaking	EV cannot move		Fatigue	Check the wear condition of the gear surface	12 / 15,000	No
							Friction between teeth	Keep gear clean and correctly lubricated	12 / 15,000	No
							Torsional and lateral vibration	Check the wear condition of the gear surface	12 / 15,000	No
							Misalignment	Check the wear condition of the gear surface	12 / 15,000	No
5.	ES-CTRL Energy management unit [14] [25] [27] [38] [39]	5.1	Optimize voltage and current output according to load and battery state of charge	Device cannot initialise	EV cannot move	CRITICAL operability concern	Over/under power voltage	Check relay EP-REL-EMU	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot analyze input signals	Range reduction		Abnormal input signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot provide proper output	Reduction of power		Abnormal output signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No

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Component I.D. and description		**Component functions**		**Component failure mode**	**Vehicle effect for each failure mode**	**Comp. Classif.**	**Failure causes for each function**	**PM tasks for each failure cause**	**Frequency months/miles**	**Design change?**
		5.2	Detect battery state of charge	Device cannot initialise	EV cannot move		Over/under power voltage	Check relay EP-REL-EMU	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot analyze input signals	Reduction of charging		Abnormal input signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
		5.3	Detect battery temperature	Device cannot initialise	EV cannot move		Over/under power voltage	Check relay EP-REL-EMU	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot analyze input signals	Range reduction		Abnormal input signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
		5.4	Control energy refuelling unit	Device cannot initialise	EV cannot move		Over/under power voltage	Check relay EP-REL-EMU	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot analyze input signals	Battery cannot be charged		Abnormal input signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No
				Device cannot provide proper output	Reduction of power		Abnormal output signal	Check I/O peripherals	12 / -	No
							Software bugs	Update software and report known bugs to supplier, by internet access	If available	No
							Incorrect installation	Check list of standard installation procedure	-	No

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C.#	Column A	#.#	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I
Component I.D. and description		**Component functions**		**Component failure mode**	**Vehicle effect for each failure mode**	**Comp. Classif.**	**Failure causes for each function**	**PM tasks for each failure cause**	**Frequency months/miles**	**Design change?**
6.	ES-BAT-LIP Li-Ion Battery Pack [23] [24] [25] [26]	6.1	Provide energy to the PMSM through the 3P-PWM-INV	Short circuit	EV cannot move	CRITICAL safety concern	Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	12 / 15,000	No
				Overheating	EV cannot move		Failure of battery heater	Check the heater device operability	12 / 15,000	No
							Failure of battery sensor	Check the sensor operability	12 / 15,000	No
				Internal resistance increasing	Reduction of power		Mechanical stress, ageing wear	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
				Over-charge	Abnormal power output		Failure of Battery Control Module	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
								Check and compare the voltage readings at the battery connections and at the controller	12 / 15,000	No
							Failure of Battery Charger	Check all charging subsystems	12 / 15,000	No
				Over/under-current	Abnormal power output		Failure of Battery Control Module	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
								Check and compare the voltage readings at the battery connections and at the controller	12 / 15,000	No
		6.2	Provide energy to the 12V battery through the DC/DC converter	Short circuit	EV cannot move		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	12 / 15,000	No
				Overheating	EV cannot move		Failure of battery heater	Check the heater device operability	12 / 15,000	No
							Failure of battery sensor	Check the sensor operability	12 / 15,000	No
				Internal resistance increasing	Reduction of power		Mechanical stress, ageing wear	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
				Over-charge	Abnormal power output		Failure of Battery Control Module	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
								Check and compare the voltage readings at the battery connections and at the controller	12 / 15,000	No
							Failure of Battery Charger	Check all charging subsystems	12 / 15,000	No
				Over/under-current	Abnormal power output		Failure of Battery Control Module	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
								Check and compare the voltage readings at the battery connections and at the controller	12 / 15,000	No

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Component I.D. and description		**Component functions**		**Component failure mode**	**Vehicle effect for each failure mode**	**Comp. Classif.**	**Failure causes for each function**	**PM tasks for each failure cause**	**Frequency months/miles**	**Design change?**
		6.3	Store energy from the PMSM during regenerative braking	Short circuit	Battery cannot be charged		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	12 / 15,000	No
				Overheating	EV cannot move		Failure of battery heater	Check the heater device operability	12 / 15,000	No
							Failure of battery sensor	Check the sensor operability	12 / 15,000	No
				Over-discharge	Reduction of range		Mechanical stress, ageing wear	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
				Internal resistance increasing	Battery cannot be charged		Failure of Battery Control Module	Check the battery charge controller to verify the correct voltage settings	12 / 15,000	No
								Check and compare the voltage readings at the battery connections and at the controller	12 / 15,000	No
7.	ES-CH-OB Battery on-board charging unit [26] [28]	7.1	Provide the proper energy refuelling from external power grid, converting AC power to DC power, according to the signals from BAT-CTRL unit	Device cannot initialise	Battery cannot be charged	CRITICAL operability concern	Winding insulation breakdown	Check winding insulation condition	24 / 30,000	No
							Insulation bushing breakdown	Check insulation bushing	24 / 30,000	No
							Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts	Keep device clean	24 / 30,000	No
							Malfunction of protective relay	Check protective relay operability	12 / -	No
							Normal deterioration from age and corrosion phenomenon	Keep device clean	24 / 30,000	No
				Under-voltage output	Reduction of charging		Overheating	Temperature monitoring, by DSP unit	-	No
							Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	Switchgear inspection	24 / 30,000	No
				Under-current output	Reduction of charging		Overheating	Temperature monitoring, by DSP unit	-	No
							Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	Switchgear inspection	24 / 30,000	No
				Communication error with BAT-CTRL unit	Reduction of charging		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	24 / 30,000	No

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Component I.D. and description		Component functions		Component failure mode	Vehicle effect for each failure mode	Comp. Classif.	Failure causes for each function	PM tasks for each failure cause	Frequency months/miles	Design change?
8.	ES-CH-PT Charge port [26] [28]	8.1	Connect vehicle on-board charging unit to the external power grid	Communication error with BAT-CTRL unit	Battery cannot be charged	CRITICAL operability concern	Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	6 / 7,500	No
				Over/under-voltage to BAT-OB-CHARG	Reduction of charging		Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	Relay inspection	6 / 7,500	No
							Normal deterioration from age and corrosion phenomenon	Check device condition	6 / 7,500	No
				Over/under-current to BAT-OB-CHARG	Reduction of charging		Transient overvoltage disturbance (switching surges, arcing ground fault, etc.)	Relay inspection	6 / 7,500	No
							Normal deterioration from age and corrosion phenomenon	Check device condition	6 / 7,500	No
9.	ES-BAT-HT Li-Ion battery heater unit [26] [28]	9.1	Heat the Li-Ion battery to the standard operating temperature	Device cannot initialise	EV cannot move at very low temperature	POTENTIALLY CRITICAL operability concern	Heater element failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
							Short circuit	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
10.	ES-BAT-12V Auxiliary 12 V battery [32] [37]	10.1	Provide 12V DC power to the DSP and BAT-CTRL unit	Cell failure	EV cannot move	CRITICAL operability concern	Phenomenon of sulfation	Inspection and monitoring individual cell voltages	12 / -	No
							Grid corrosion			
				Overcharging	Loss of battery capacity		Incorrect charge regulation	Check the battery charge controller to verify the correct voltage settings	12 / -	No
								Faulty charge regulation can be detected by monitoring the system voltage	12 / -	No
							High series resistance path in the controller sense circuit causing the controller to receive a lower battery voltage than is correct	Check and compare the voltage readings at the battery connections and at the controller	12 / -	No
				Undercharging	Loss of battery capacity		Improper controller charging set points	Check all charging subsystems before considering adjustment of charge controller set points	12 / -	No
							Higher than anticipated load use	Inspection and monitoring individual cell voltages	12 / -	No

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Component I.D. and description		**Component functions**		**Component failure mode**	**Vehicle effect for each failure mode**	**Comp. Classif.**	**Failure causes for each function**	**PM tasks for each failure cause**	**Frequency months/miles**	**Design change?**
		10.2	Provide 12V DC power to accessories and gauges	Cell failure	EV cannot move		Phenomenon of sulfation	Inspection and monitoring individual cell voltages	12 / -	No
							Grid corrosion			
				Overcharging	Loss of battery capacity		Incorrect charge regulation	Check the battery charge controller to verify the correct voltage settings	12 / -	No
								Faulty charge regulation can be detected by monitoring the system voltage	12 / -	No
							High series resistance path in the controller sense circuit causing the controller to receive a lower battery voltage than is correct	Check and compare the voltage readings at the battery connections and at the controller	12 / -	No
				Undercharging	Loss of battery capacity		Improper controller charging set points	Check all charging subsystems before considering adjustment of charge controller set points	12 / -	No
							Higher than anticipated load use	Inspection and monitoring individual cell voltages	12 / -	No
11.	EP-SNS-M-P Motor position sensor [26] [28]	11.1	Detect rotation angle of traction electric motor	Abnormal values reading	EV cannot move	CRITICAL operability concern	Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
		11.2	Report signals output to the DSP	Abnormal signal output	EV cannot move		Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
12.	EP-SNS-M-S Motor speed sensor [26] [28]	12.1	Detect rotation speed of traction electric motor	Abnormal values reading	EV cannot move	CRITICAL operability concern	Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
		12.2	Report signals output to the DSP	Abnormal signal output	EV cannot move		Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
13.	EP-SNS-M-T Motor temperature sensor [26] [28]	13.1	Detect electric motor operating temperature	Abnormal values reading	-	RUN TO FAILURE	-	-	-	No
				Abnormal signal output	-		-	-	-	No

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Component I.D. and description		**Component functions**		**Component failure mode**	**Vehicle effect for each failure mode**	**Comp. Classif.**	**Failure causes for each function**	**PM tasks for each failure cause**	**Frequency months/miles**	**Design change?**
14.	EP-SNS-ACC Accelerator pedal sensor [26] [28]	14.1	Convert accelerator pedal position in signals to the DSP unit, in order to control motor acceleration	Abnormal values reading	EV cannot move	CRITICAL operability concern	Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
				Abnormal signal output	EV cannot move		Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
15.	EP-SNS-BRK Brake pedal sensor [26] [28]	15.1	Convert brake pedal position in signals to the DSP unit, in order to control motor acceleration	Abnormal values reading	EV cannot brake	CRITICAL safety concern	Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
				Abnormal signal output	EV cannot brake		Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
16.	ES-SNS-12VTemperature sensor of 12V battery [26] [28] [32]	16.1	Detect operating temperature of the 12V auxiliary battery	Abnormal values reading	No effects until failure of the 12V battery	POTENTIALLY CRITICAL operability concern	Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
		16.2	Report signals to the BAT-CTRL unit	Abnormal signal output	No effects until failure of the 12V battery		Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
17.	ES-SNS-LIP-C Li-Ion Battery current sensor [26] [28]	17.1	Detect state of charge and charge/discharge current of battery pack	Abnormal values reading	EV cannot move	CRITICAL operability concern	Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
		17.2	Report signals output to the BAT-CTRL unit	Abnormal signal output	EV cannot move		Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No

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Component I.D. and description		Component functions		Component failure mode	Vehicle effect for each failure mode	Comp. Classif.	Failure causes for each function	PM tasks for each failure cause	Frequency months/miles	Design change?
18.	ES-SNS-LIP-T Li-Ion Battery temperature sensor [26] [28]	18.1	Detect operating temperature of battery pack	Abnormal values reading	EV cannot move	CRITICAL safety concern	Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
		18.2	Report signals output to the BAT-CTRL unit	Abnormal signal output	EV cannot move		Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
19.	ES-PLUG-LIP Li-Ion battery service plug [26] [28] [30] [31]	19.1	Turn off/on the high voltage current for EV maintenance tasks	Stuck switch in *off position*	EV cannot move	CRITICAL safety concern	Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No
				Stuck switch in *on position*	Electric power cannot be turned off		Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No
20.	ES-SNS-CHPT Charge port temperature sensor [26] [28]	20.1	Detect operating temperature of charge port	Abnormal values reading	Battery cannot be charged	CRITICAL operability concern	Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
		20.2	Report signals output to the BAT-CTRL unit	Abnormal signal output	Battery cannot be charged		Incorrect installation	Check list of standard installation procedure	-	No
							Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No

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21.	EP-SNS-INVPH Inverter phases sensor [26] [28]	21.1	Detect the 3-phases current supplied to traction motor by inverter	Abnormal values reading	EV cannot move	CRITICAL operability concern	Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
		21.2	Report output values to the DSP	Abnormal signal output	EV cannot move		Incorrect installation	Check list of standard installation procedure	-	No
					Traction power uncontrollable		Connector/terminal failure	Check connector conditions and keep clean from moisture and chemical	36 / 45,000	No
22.	ES-CON-DCDC DC/DC converter [26] [28]	22.1	Step down the high voltage DC current from the Li-Ion battery to a 12V DC current	Device cannot initialise	No effects until failure/discharge of the 12V battery	POTENTIALLY CRITICAL operability concern	Winding insulation breakdown	Check winding insulation condition	24 / 30,000	No
							Insulation bushing breakdown	Check insulation bushing	24 / 30,000	No
							Mechanical breaking, cracking, abrading, deforming of structural parts	Keep device clean	24 / 30,000	No
							Malfunction of protective relay	Check protective relay operability	12 / -	No
							Normal deterioration from age and corrosion	Keep device clean	24 / 30,000	No
							Overheating	Temperature monitoring, by DSP unit	-	No
							Transient overvoltage disturbance (switching surges, arcing ground faulted.)	Switchgear inspection	24 / 30,000	No
				Abnormal output	No effects until failure/discharge of the 12V battery		Winding insulation breakdown	Check winding insulation condition	24 / 30,000	No
							Insulation bushing breakdown	Check insulation bushing	24 / 30,000	No
							Mechanical breaking, cracking, abrading, or deforming of structural parts	Keep device clean	24 / 30,000	No
							Malfunction of protective relay	Check protective relay operability	12 / -	No
							Normal deterioration from age and corrosion	Keep device clean	24 / 30,000	No
							Overheating	Temperature monitoring, by DSP unit	-	No
							Transient overvoltage disturbance (switching surges, arcing ground faulted.)	Switchgear inspection	24 / 30,000	No

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23.	EP-CIR BRK Fail-safe circuit breaker [26] [28] [30] [31]	23.1	Turn off the main power in case of a dangerous malfunction	Stuck switch in *on position*	-	CRITICAL safety concern	Normal deterioration from age	Inspect breaker-operating mechanism for loose hardware and missing or broken cotter pins, etc. Examine latch and roller surfaces	12 / -	No
							Loss or deficiency of oil or cooling medium	Clean and relubricate operating mechanism with a light machine oil	12 / -	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Exposure to abnormal moisture, chemicals or dust	Wipe and clean the insulating parts, including bushings	12 / -	No
							Misoperation or testing error	Check list of standard operation and test procedure	-	No
				Stuck switch in *off position*	EV cannot move		Normal deterioration from age	Inspect breaker-operating mechanism for loose hardware and missing or broken cotter pins, etc. Examine latch and roller surfaces	12 / -	No
							Loss or deficiency of oil or cooling medium	Clean and relubricate operating mechanism with a light machine oil	12 / -	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Exposure to abnormal moisture or chemicals	Wipe and clean the insulating parts, including bushings	12 / -	No
							Misoperation or testing error	Check list of standard operation and test procedure	-	No

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24.	ES-REL-LIP Li-Ion battery relay [26] [28] [30] [31]	24.1	Turn off/on the high voltage current at the EV	Stuck switch in *on position*	-	CRITICAL safety concern	Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No
				Stuck switch in *off position*	EV cannot move		Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No
25.	EP-REL-DSP DSP relay [26] [28] [30] [31]	25.1	Turn off/on the power to the electronic controller DSP in case of over-voltage	Stuck switch in *on position*	-	CRITICAL operability concern	Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No
				Stuck switch in *off position*	EV cannot move		Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No

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26.	ES-REL-CHOB Charging relay [26] [28] [30] [31]	26.1	Turn off/on the charging power to the Li-Ion battery	Stuck switch in *on position*	-	CRITICAL operability concern	Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No
				Stuck switch in *off position*	Battery cannot be charged		Misoperation or testing error	Check list of standard operation and test procedure	-	No
							Persistent overloading	Replace component if contacts are badly worn or burned and check control device for freedom of operation	12 / -	No
							Normal deterioration from age	Inspect relays for physical damage and deterioration	12 / -	No