Electric Vehicles Maintenance: Recommendations for a Safe Work

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***Abstract*—The surge in Electric Vehicle (EV) adoption marks a crucial shift towards sustainable transportation solutions driven by environmental concerns. EVs offer various advantages, including reduced emissions, enhanced energy efficiency, and quieter operation. However, also the EVs are affected by faults and crashes, and therefore require personnel to repair them. Currently, there is not an International or European Standard dedicated to work activities on EVs. This paper addresses the regulatory gap by examining the properties of the EVs, the risk sources, and the available standards related to generic electrical installations, or EV emergency scenarios. The study proposes suggestions for workshop setup, organizational procedures, and operational protocols to ensure safety during EV maintenance activities.**

***Index Terms*—electrical vehicle, risk management, maintenance, electrical works**

I. Introduction

In recent years, the automotive industry has witnessed a notable surge in the diffusion of Electric Vehicles (EVs), marking a significant transition towards sustainable transportation solutions [1]. This transition stems from growing concerns over environmental sustainability and the imperative to mitigate the adverse effects of traditional fossil fuel-dependent vehicles on the ecosystem. The proliferation of EVs represents a pivotal step towards achieving cleaner and greener mobility solutions, thereby addressing pressing global challenges such as climate change and air pollution [2].

Electric vehicles offer some advantages over their conventional counterparts, ranging from reduced greenhouse gas emissions to enhanced energy efficiency. The general benefits of EVs encompass lower operating costs, decreased reliance on finite fossil fuels, and quieter operation, contributing to a more sustainable urban landscape [3]. Moreover, EVs boast advanced technological features and innovations, including regenerative braking systems and seamless integration with renewable energy sources, further enhancing their appeal to consumers and policymakers alike.

Despite the evident advantages of electric vehicles, it is imperative to acknowledge that like any other automotive technology, they are not immune to malfunctions or accidents. As with traditional vehicles, EVs can experience breakdowns and collisions, necessitating preparedness to effectively manage associated risks and mitigate potential hazards. The Standard ISO 6469 provides the safety specifications that the manufacturers of EVs shall adopt [4]–[6]. These precautions increase the people safety in case of crash. Given the unique characteristics of electric propulsion systems and high-voltage components, addressing safety concerns and implementing proper risk management strategies are paramount to ensuring the widespread adoption and safe operation of EVs.

Moreover, several international and national agencies, such as the American NFPA and the Italian "Corpo Nazionale dei Vigili del Fuoco," have provided operational procedures for managing emergency scenarios involving crashed electric vehicles [7], [8].

Unfortunately, there is currently no international or European standard specifically dedicated to electrical work on vehicles in non-emergency conditions. In fact, the European Standard BS EN 50110-1, which provides reference guidelines for electrical works, explicitly exclude onboard systems [9]. As a result, maintenance personnel solely rely on BS EN 50110-1 and emergency response guidelines as their primary references, even when these documents do not cover the scope of their activities. A regulatory framework to address this gap is crucial due to the growing number of EVs. This article aims to contribute to this mission by discussing the risks and mitigation strategies of non-emergency electrical work on vehicles.

II. Battery Electric Vehicles

EVs are usually fed by on-board batteries. For this reason, they are referred to as Battery Electric Vehicles (BEVs). More in detail, BEVs can be grouped into two main categories: Full Electric Vehicles (FEVs) and Hybrid Electric Vehicles (HEVs). In the following subsections, the main characteristics of these vehicles will be provided.

A. Full Electric

FEVs are automobiles powered solely by rechargeable battery packs. They rely entirely on electric propulsion for locomotion. FEVs can be particularly effective in reducing the CO_2 emissions if adopted in scenarios characterized by high penetration of Renewable Energy Sources. Additionally, FEVs typically require low maintenance due to their simpler mechanical design and fewer moving parts. The power-train architecture of a FEVs refers to the arrangement of components responsible for generating and transmitting power to the wheels. Common configurations include:

- single motor with transmission, where a single electric motor drives the wheels through a transmission system;
- dual motor with all-wheel drive, where separate electric motors power the front and rear axles, providing enhanced traction and performance;
- motor at each wheel, where individual electric motors are mounted directly at each wheel, offering precise control and potentially improved efficiency [10].

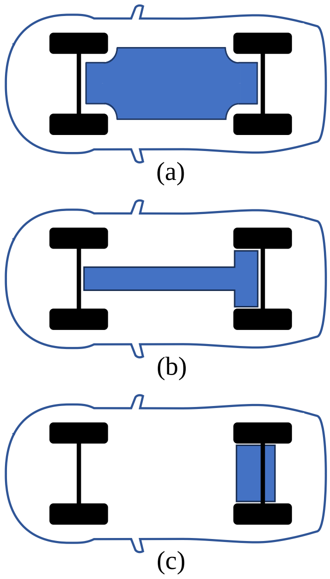

Fig. 1. BP configurations: (a) “Floor”, (b) “T”, (c) “Rear”

Electric motors used in FEVs are typically three-phase alternating current motors [11], [12]. They can be categorized based on their construction, including synchronous motors with permanent magnets and asynchronous motors.

The Battery Pack (BP) is a critical component of FEVs, storing and supplying electrical energy to power the vehicle. Typically, key properties of the battery pack include:

- energy density, which is the amount of energy stored per unit volume or weight, impacting the vehicle’s range and performance [13];
- rated voltage, which is the electrical potential difference provided by the battery pack, typically ranging from 300 V to over 1000 V [14];
- rated capacity, which is the total amount of energy the battery pack can store, typically expressed in kWh (up to 100 kWh) [14].

The geometry of the BP, along with its placement and the structural design of the vehicle, are also important properties for its characterization. In fact, the BPs can also be categorized considering the installation strategies, which impact its shape. The main configurations are depicted in figure 1, and include [15]:

- “Floor”, where the batteries form a slab positioned between the two axles;
- “T”, where the batteries are placed between the two axles in two directions;
- “Rear”, which is rare and typically adopted when small capacity is required.

B. *Hybrid*

Hybrid Electric Vehicles HEVs are vehicles that utilize a combination of two or more power sources for propulsion, typically comprising an Internal Combustion Engine (ICE) and an electric motor. The integration of these power sources allows HEVs to achieve improved fuel efficiency and reduced emissions compared to traditional vehicles solely powered by ICEs. Considering their power-train architectures, they can be classified into two groups: Series and Parallel HEVs.

Series HEVs feature an architecture where the ICE is used solely to generate electricity to power the electric motor. The ICE does not directly drive the wheels but serves as a generator to charge the vehicle’s battery pack. In this way, the ICE is kinetically released from the wheels, can operate at maximum efficiency and provides the average power needed for motion, while the instantaneous part is provided by the battery, which is smaller in size (thus less expensive) than a FEV.

Parallel HEVs feature an architecture where both the ICE and the electric motor are mechanically connected to the wheels, allowing for different combinations of power from both sources. They can operate using either the ICE, the electric motor, or a combination of both, depending on driving conditions and power demands. Many parallel HEVs offer plug-in capability, allowing users to charge the battery pack from an external power source, further reducing reliance on the ICE and improving overall efficiency.

III. Risk sources

In this section, the risk sources associated with work activities involving EVs are discussed. In this paper, the risk in the scenario where an EV is interconnected to a charging station is not considered [16].

A. *Electric shock*

An electric shock is defined as the “physiological effect resulting from an electric current passing through a human body or livestock” [17]. The effects are more severe by increasing the current and the exposure time.

An electric shock can occur in case of direct and indirect contact. In the first one, the person touches one or more live parts. In the second, the electric contact of human beings is established with exposed conductive parts that have become live under fault conditions [17].

In normal operation mode, the manufactures of EVs have adopted measures to guarantee the protection against direct and indirect contacts.

In working on EVs, or after a crash, these measures could be removed or damaged. Moreover, where a BP is installed and therefore only some part of the circuit can be disconnected, specific analysis and precautions should be adopted.

If a direct contact occurs, the current flowing through the human body can have different paths and amplitude, based on the involved number of poles and parts of the body.

Fig. 2 depicts the most frequent and significant direct contacts.

Fig. 2-a represents the contact between a person (one hand) and a live part of the electrical wiring. Both the person and the vehicle are in contact with the soil through high impedance. The current flows through the natural resistance of the human body to earth (R_{BE}) and the stray capacitance of the electrical wiring (C_{CE}). The flowing current amplitude depends on the value of the path impedance, which is function of the electrical cable lengths and the soil properties.

Fig. 2-b shows the contact between the person (through two metallic tools) and both the poles of the electrical wiring. In this case, the current flows between the two hands of the worker. Considering the contact analyzed in Fig. 2-a as a reference, the impedance of the current path is lower causing a more dangerous scenario. The eventual interconnection of the negative pole of the BP with the metallic chassis of the

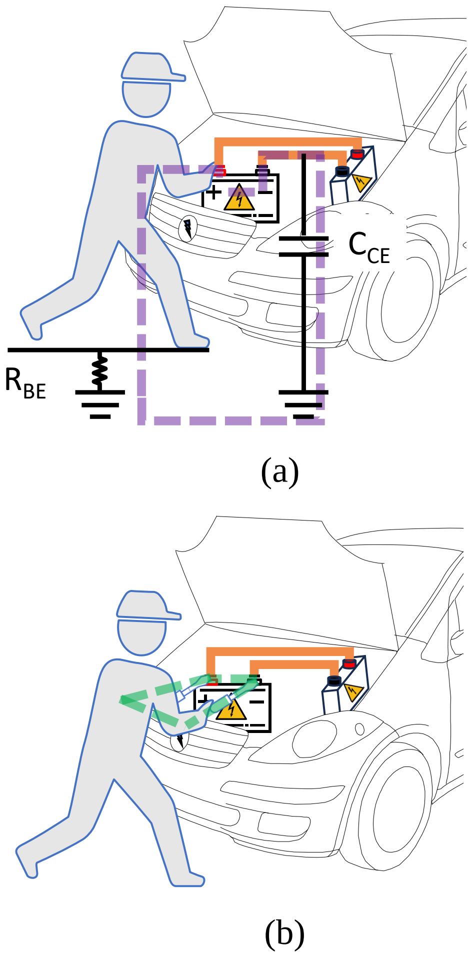

Fig. 2. Direct contacts: a) single pole; b) double poles.

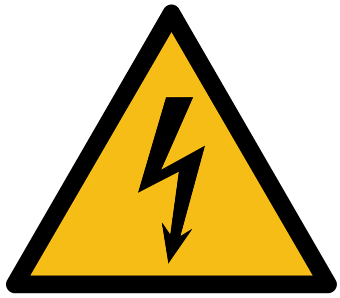

Fig. 3. Symbol ISO 7010-W012 [6]. It identifies Class B electric components.

EV impacts the probability of having this event, since in this case, the probability of having a contact is higher.

The placement of dangerous live parts can be identified thanks to the safety specifications provided by the standard ISO 6469-3, which are usually adopted by the manufacturers [6]. The standard classifies the on-board electrical circuits considered their maximum working voltage, as reported in Table I. ISO 6469-3 specifies that the symbol ISO 7010-W012 reported in Fig. 3 shall be visible on protective barriers and enclosures which, when removed, expose hazardous live parts of voltage class B electric circuits. The insulation surrounding cables and harnesses used in voltage class B2 electrical circuits, when not contained within protective enclosures or shielded by protective barriers, must be visibly distinguished by an orange color marking. For voltage class B1 cables and harnesses, they should be identified by a two-color combination of orange and purple, or solely by an orange color marking.

TABLE I
VOLTAGE CLASSES ACCORDING TO ISO 6469-3 [6]

Voltage class	Maximum working voltage [V]	
	DC	AC
A	$0 < U \leq 60$	$0 < U \leq 30$
B	$60 < U \leq 1500$	$30 < U \leq 1000$
B1	$60 < U \leq 75$	$30 < U \leq 50$
B2	$75 < U \leq 1500$	$50 < U \leq 1000$

B. Arc flash

The arch flash is defined as a "self-maintained gas conduction for which most of the charge carriers are electrons supplied by primary electron emission" [18]. The Standard IEC 60050-651 specifies in the notes that during live working, the electric arc is generated by gas ionization arising from an unintentional electrical conducting connection or electric breakdown between live parts or a live part and the earth path of an electrical installation or an electric device [18].

A European standard to properly manage the arc flash risk is still missing. BS EN 50110-1 simply mentions in Annex B.6.3 some examples of guidelines for assessing the arc flash hazard, such as the American NFPA 70 E and the German DGUV 203-077 [19], [20]. Even if the approaches are different, both the Standards consider the probability of occurrence of an arc flash and its electrical properties to identify dangerous situations and choose the right Personal Protective Equipment (PPE).

Usually, manufacturers cover the live parts with insulation or enclosures, reducing the probability of accidental short circuits that can cause arc flashes. Moreover, protection against over-currents (e.g. fuses) reduces the time of the arc flash event, with a great reduction of the incident energy [19]. Typically, a fuse is installed downstream the terminals of the BP and sometimes, a fuse could be connected in series to each cell of the BP. If the probability of having an arc flash is not negligible, and its energy could injure workers, PPEs shall be adopted.

C. Fire and explosion on battery packs

Thermal Runaway (TR) is defined as an unstable condition arising during constant voltage charge in which the rate of heat dissipation capability, causing a continuous temperature increase with resulting further charge current increase, which can lead to the destruction of the battery [21].

TR can occur within a battery cell when increased temperature initiates a series of exothermic reactions, leading to a further rise in temperature and the onset of more harmful reactions. This elevated temperature can result from a gradual buildup of heat that isn't effectively dissipated in a timely manner or from sudden, externally induced reactions within a brief time frame [22]. The TR can widespread from a cell to the entire BP, as in a chain effect, producing fires and explosions. It is typically caused by internal short-circuit, which can be caused by battery manufacturing defects, as well as mechanical, electrical and thermal abuses [23]–[25].

D. Chemical burns and poisoning

Maintenance of EVs introduces unique chemical hazards that technicians must manage. In particular, lithium-ion batteries contain flammable electrolytes, such as lithium hexafluorophosphate (LiPF6) in organic solvents, which pose fire and explosion hazards if mishandled or damaged [26]. Additionally, exposure to electrolyte components, including lithium salts and organic solvents, can cause skin irritation, respiratory problems, or other health issues.

IV. Works on electric vehicles - state of the art

The works on electric vehicles can be classified into two categories:

1) workshop works, which are necessary to maintain the functioning of the vehicle over time. During these activities, the people exposed to the risks are the workshop employers. As already discussed, there is no dedicated International or European Standards specifically focused on these activities. Currently, in Europe, the reference standard is the BS EN 50110, which provides recommendations to safely carry out works on electrical installations [9]. In the scope of the standard it is specified that this document has not been specifically developed for vehicles, but the principles of this document could be applied also to these systems if there are no other rules or procedures. In subsection IV-A, the main principles of the BS EN 50110 are presented, as they can inspire specific guidelines for work on electrical vehicles.
2) emergency works, which are after a crash carried out by firefighters to secure the vehicles. In this case, the people exposed to the risk are the firefighters themselves, the driver and the passengers of the vehicle, and the citizens in the proximity of the accident site. Even if the aims are different, some analogies between the two work types can be found. For example, in both cases, people are exposed to the same risk sources (presented in section III) and the risks depend on the status of the vehicle. In section IV-B, an analysis of the guidelines provided by the American Fire Protection Research Foundation is presented [7]. The aim is to identify the measurements that can increase safety for workers, also in non-emergency scenarios.

A. BS EN 50110 principles: operation of electrical installations

The BS EN 50110 describes the requirements for general work on or close to an electrical installation. Its main principles can be summarized as follows.

- The works can be classified into three categories: works in Live Working Zone (LWZ), which is the space around live parts in which the insulation level to prevent electrical danger is not assured when reaching into or entering it without protective measures; works within a Vicinity Zone (VZ), which is a limited space outside the LWZ; works ouside of the VZ.
  The LWZ and VZ are delimited by the distances D_L and D_V, respectively. These borders are a function of the rated voltage. For AC and DC systems characterized by a rated voltage lower than 3 kV, which is a voltage close the the maximum voltage classes reported in Table I for EVs, $D_L = 60\,\mathrm{mm}$ and $D_V = 1120\,\mathrm{mm}$;
- the procedures for works in the LWZ are two:
  1) dead working, which requires:
     a) the disconnection of the part of the electrical installation on which work is to be carried out;
     b) to secure against re-connection, locking the operating mechanism of switches or doing equivalent preventative actions;
     c) to verify the absence of operating voltage, using voltage detectors that have been previously tested;
     d) earthing and short-circuiting all parts that are to be worked on. This is always required for systems characterized by a rated voltage $>1\,\mathrm{kV}$ in AC or $1.5\,\mathrm{kV}$ in DC. For the others, it is required if there is the risk that the electrical installation is being made live (e.g. by a battery storage).
     e) to adopt protection against adjacent live parts.

     This procedure shall be adopted if technically feasible.
  2) live working, for which collective or personal protective equipment is required. In case of maintenance on EVs, workers shall use insulating gloves and possibly arm sleeves, insulated and insulating hand tools.
- the procedures for works within the VZ requires to adopt safety measures to be sure that live parts cannot be touched or the LWZ cannot be reached. For example, an effective measure is the installation of a screen, barrier, enclosure or insulating covering. The same approach is proposed for working outside the VZ, after a risk assessment.
- the personnel shall have practical and theoretical skills to properly identify and manage dangerous situations.

B. Emergency scenarios that involve EVs

The best practices proposed by the American Fire Protection Research Foundation can be summarized with the following steps [7]:

1) identify the presence of an EV, recognizing labels of the brand and model. If the electrical wiring is visible, the presence of symbols associated with an electric risk (e.g. the one reported in Fig. 3 and the "orange cables" described in subsection III-A can also be useful for this activity, as suggested by the Italian Guidelines [8];
2) immobilize the vehicle, placing chocks to the front and rear of one of the wheels;
3) disable the vehicle, switching off and disconnecting all the power sources (such as the high voltage BP or the battery that often powers the auxiliary circuits). If the vehicle can be turned on/off by a proximity key, after the power-off, place the key beyond the range of the vehicle. To prevent the vehicle from powering up, after the power-off, the American guidelines require the severing of the auxiliary battery's negative ground cable and, eventually, the pulling fuses to disable the high-voltage system. Only if the previous action cannot be exploited, the main disconnect should be removed or switched off.

In case of fire, a large and sustained volume of water is required [7], [8].

V. Proposed recommendations to work on EVs

The proposed suggestions can be grouped into two categories: the first ones are related to the properties of the workshop; the second ones are related to the organization of the work and operational procedures.

A. Workshop set-up

The following are the actions required to properly set up the workshop on which the activity under consideration will be carried out:

- while performing the activities, cordon off the area using barriers or obstacles. Barriers can be tapes, ropes, chains, or bars that must be fixed between 1000 mm and 1400 mm away from the floor. The minimum distance from the ground must not be less than 800 mm;
- hang warning signs to indicate the presence of live parts;
- ensure that the room is sufficiently illuminated even following an interruption of the power supply;
- adopt measures to mitigate the risk of fire and explosion. For example, evaluate the adequacy of the ventilation in the room to avoid over-temperatures and explosive atmospheres;
- adopt measures to prevent a fire in the room could propagating to other parts of the buildings;
- design escape routes to guarantee an effective and timely evacuation.

B. Organization of the work and operational procedures

Considering the EV properties (section II), the risk sources (section III), and the suggestions provided (section IV), the following recommendations to properly manage the risk associated with working on EVs are presented:

- identify the risk sources for the specific activity under analysis;
- instruct and train the personnel, who shall have theoretical and practical skills before carrying out the work. The level of ability should be confirmed by a live working certificate, delivered by the employer;
- the role of each person during the work shall be clear to everybody, and specified in writing, to avoid misunderstanding and for a clear acceptance of responsibility;
- for all the complex works and the most frequent ones, written instructions shall be made available for each model of EV, so that they can be consulted by the involved operators before starting activities;
- identify BP over temperatures using thermal sensors (such as a thermal camera). If a temperature greater than the environmental one is detected, wait until the BP has completely cooled down;
- if possible, disconnect all the power sources (such as the high voltage BP or the auxiliary battery), following the dead working procedure provided by [9]. This can be carried out effectively for all the works where it is not required that the EV could be powered on;
- in certain circumstances, such as the identification of a fault, it is not possible to disconnect the power sources. In this case, the live working procedure shall be adopted. Considering the typical rated voltage of the EV wiring reported in Table I, Class 0 insulating electrical gloves, which are designed to protect against 1kV in AC and 1.5 kV in DC systems, shall be used. It is good to remember that dielectric gloves are often not cut-resistant. In this case, an over glove offering mechanical protection is necessary. Moreover, insulating or isolated tools shall be used to increase the protection against both electric shock and arc flash. For the other risks, a dedicated assessment shall be evaluated to identify the need for PPE, and their properties.

VI. Conclusion

This paper underscores the significant transition towards sustainable transportation solutions witnessed in recent years, exemplified by the growing adoption of Electric Vehicles (EVs). Recognizing the environmental imperative and the need to address issues such as climate change and air pollution, EVs offer numerous advantages including reduced greenhouse gas emissions, enhanced energy efficiency, lower operating costs, and quieter operation. Moreover, advancements in technology such as regenerative braking systems and integration with renewable energy sources further enhance the appeal of EVs to consumers and policymakers.

However, it is crucial to acknowledge that EVs, like any automotive technology, are not without their challenges. Safety concerns, particularly regarding the unique characteristics of electric propulsion systems and high-voltage components, necessitate proper risk management strategies and adherence to safety standards. This includes the development of specific regulations addressing electrical works on vehicles, which are currently lacking at the International or European level.

The paper identifies various risk sources associated with working on EVs, such as electric shock, arc flash, fire, explosion on battery packs, and chemical burns and poisoning.

To address these risks, the paper proposes suggestions for maintenance works on EVs, encompassing workshop set-up considerations and organizational procedures. These recommendations emphasize the importance of proper training for personnel, identification of risk sources, and adoption of appropriate Personal Protective Equipment (PPE) and operational procedures. Overall, the paper provides valuable insights into mitigating risks and ensuring the safe operation of EVs, contributing to the ongoing discourse on sustainable mobility solutions.

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