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Hazardous scenarios identification for Li-ion secondary batteries

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ABSTRACT

Lithium ion rechargeable batteries represent an energy storage technology already commonly used in a number of applications (mobile cellular phones, laptops, etc.), and will play an even increasingly important role in the next future. However, a number of past accidents have raised concern about their reliability and safety, and thus delayed their introduction in larger and more strategic systems like the main electrical network or large photovoltaic power systems.

With the aim of identifying the largest number of dangerous scenarios associated with the use of these systems, and based on the available information on this technology, Failure Modes and Effects Analysis (FMEA) has been selected for the hazard identification process and applied to a number of common system configurations. The main focus of the analysis has been on the possible negative interactions between the battery system and its surrounding environment (powered system, location of installation, but also modality of use, and so on).

The resulting tables collect data from a wide range of sources of information, thus allowing to identify the most important predictable dangerous scenarios, and to suggest adequate mitigation actions to be implemented in any phase of the battery's life cycle (installation, operation, etc.).

This would allow a safer use of this technology in a wider range of practical applications, enabling more reliable systems operation and reducing the risk to the possibly exposed people and to the environment.

1. Introduction

In the framework of the continuous effort to reduce the emission of greenhouse gases and increase the use of renewable energy sources and energy vectors, rechargeable (also named *secondary*) batteries play a more and more significant key role. They make the availability of the energy derived from these sources more continuous, in contrast with their highly intermittent characteristic (e.g. wind energy), and, at the same time, they allow the adoption of this "green energy" in a much wider range of applications, such as in the case of the automotive industry, where the number of electric (EV) and hybrid electric (HEV) vehicles is constantly increasing. A strong interest is thus present in introducing this efficient energy storage technology also in further strategic systems, such as the main electrical network, in the form of large stationary battery systems, and in the aeronautical and aerospace industries, where high power and energy densities are required. Among the many types of available rechargeable batteries, lithium ion (Li-ion) cells represent a very interesting option, already steadily adopted in a number of applications such as mobile phones, portable computers, and many others. The high energy density (typically up to 230 Wh/kg, 530 Wh/l), high power density (up to 500 W/kg) and long cycle life (more than 1000 cycles) provided by these batteries, as well as other useful characteristics, such as lack of memory effect and low self-discharge rate, make these systems very attractive for a wide range of applications, especially where high loads and small volumes are required.

However, besides a number of operational limitations, such as the gradual loss of capacity and the negative influence of the temperature, a series of accidents occurred even in the very recent past, denote important drawbacks and limitations from the reliability and, above all, from the safety point of view, which hamper their adoption in a wider market. In Table 1, a short list of accidents, along with the assessed causes, is summarized as an example; more comprehensive and up-to-date lists can be found in the literature (FAA, 2017, Barsukov, 2009).

It is apparent even from the short list presented, that the accidents connected with the use of Li-ion cells can be originated by different causes, either linked to the intrinsic structure of the cell, which in turn can be sometimes caused by production defects, to improper use of the batteries, or to external events (RECHARGE, 2013). On average, the currently adopted test methods and quality standards (either IEC, UL, IEEE) actually allow the production of reliable systems, but they still fail in predicting, and thus preventing, failures connected with production defects or generated by some combinations of battery system, service conditions and local environment (location of installation, etc.).

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Table 1
Some accidents associated with the use of Li-ion batteries.

Year	Accident	Cause
2006	Explosion in a laptop PC	Cell internal short-circuit
2006	Explosion in a cellular telephone	Cell internal short-circuit
2007	Explosion in a laptop PC	Cell internal short-circuit
2008	Fire on a hybrid electric vehicle (HEV)	Battery overheating ($LiFePO_4$ cathode)
2008	Fire in a laptop	Battery overheating
2009	Fire on a civil transportation flight	Battery fire
2010	Two electric buses fire (EV)	Battery overheating ($LiFePO_4$ cathode)
2010	Fire on a Boeing B747-400F	Battery overheating
2011	Fire on an electric vehicle (taxi)	Overcharge
2011	Fire on an electric vehicle (bus)	Battery overheating ($LiFePO_4$ cathode)
2012	Fire on an electric vehicle (taxi)	Cell internal short-circuit
2013	Fire on a Boeing 787 Dreamliner aircraft	Battery overheating
2013	Fire on a hybrid electric vehicle (HEV)	Mechanical impact of the battery with a metal object
2015	Fire in a bag containing a *quadcopter* drone connected to a Li-ion battery	Thermal runaway
2015	Electronic cigarette (E-cig) fire	Battery overheating
2015	Mobile phone fire	Battery overheating

Of course, if not identified, the possible consequences of all these unpredicted accident scenarios will not be assessed. Conversely, the knowledge of all the conditions that can give rise to dangerous scenarios, possibly generating harm to people or damage to the environment, would be very useful to undertake proper preventive actions, and allow a more widespread and safer use of this kind of energy storage technology.

General and comprehensive analyses of the hazardous scenarios possibly associated with the use of Li-ion secondary batteries, are not very common in the literature, and they are often focused on specific aspects of the problem.

As a matter of fact, only a few methodical and structured safety analyses of Li-ion batteries have been reported; in most of the cases they make use of Fault Tree Analysis (FTA) (Tabaddor, 2011), Failure Modes and Effects Analysis (FMEA) (or more generally some FMEA-like methodology) (Schlasza et al., 2014, Ashtiani, 2008, Ganesan et al., 2005, IATA, 2016, Soares et al., 2015, Hendricks et al., 2015), or some combinations of FTA and FMEA (Hong and Binbin, 2009, Lanzisero and Fernando, 2009). In some cases the analyses are only theoretical. FTA is an accurate logical representation of the system structure, and for this reason it is generally too specific, requiring any time to be adapted to the particular configuration under analysis; as a consequence, even though it is probably the most powerful and accurate method to identify failure paths for a given configuration, it is not as general as needed for a widespread and direct application to a whole typology of systems. FMEA-like methodologies have been actually rather successfully applied to electrochemical energy storage systems. Soares et al. (2015) have properly analyzed the problem from a global point of view, taking into consideration all the phases making up a whole life cycle of a battery system. Hendricks et al. (2015) highlighted valuable insights into the failure mechanisms by developing a Failure Modes Mechanisms and Effects Analysis (FMMEA) as a preliminary step for a Physics of Failure approach to modeling battery's health and performance.

In the present paper, after a synthetic description of the main issues and components associated with the safety and reliability of Li-ion secondary batteries, FMEA has been selected as the most adequate hazard identification (HAZID) technique and subsequently applied to a group of cells representing a significant portion of those most commonly adopted in practical applications. A preliminary significant effort was carried out by collecting all the available information from a wide range of sources (either experimental investigations and theoretical studies), which has been successively integrated to set up the presented FMEA tables, where the identified dangerous scenarios have been listed along with their possible initiating causes, as well as with some suggested preventive and/or mitigative actions. Rather than addressing specific issues such as structural characteristics or internal reaction mechanisms of these energy storage systems, the present analysis adopted a different point of view, mainly looking at the possible interactions between the energy storage system (cell, module or battery pack) and the external environment (connected equipment, operating personnel, exposed people, etc.), in terms of both consequences and causes of the hazardous scenarios.

The presented results can be of help in the prevention of dangerous situations associated with the use of Li-ion batteries, improving both the reliability of the powered system and the safety levels for the operators at work and for the users.

2. Safety issues of Li-ion cells

Lithium ion batteries are made up of one or more basic elements (cells), which can be combined in series/parallel to get the required characteristics of voltage and capacity, giving rise to modules (a set of cells) or packs (a set of modules). A single cell is composed of a number of basic elements, among which: a positive electrode (often containing $LiCoO_2$ or $LiFePO_4$), a negative electrode (usually made of graphite), a separator and the electrolyte, which allows the movement of the lithium ions ($Li+$) between the electrodes. In most cases, a pack of cells is also provided with an electronic protection system (Battery Management System) to control the charge/discharge phases and to prevent unwanted conditions from occurring (overcharge/overdischarge, imbalance of the cells, etc.). In addition, a variety of mechanical systems can be added to increase the safety of the cells (Balakrishnan et al., 2006). Concerning their architecture, the modules can have different shapes: cylindrical, prismatic, or *pouch*, this latter configuration being usually preferred in terms of weight, space requirements and cost; on the other hand, pouch cells have the disadvantages of being more vulnerable to mechanical damages or to external heat inputs than other cells, and of allowing a higher heat transfer rate among adjacent cells.

Besides other characteristics, Li-ion cells have higher energy densities than traditional non-rechargeable batteries, and, also connected with the use of flammable and toxic electrolytes, this introduces a number of additional concerns from the safety point of view, which must be properly considered and managed. More details about structural characteristics and operational fundamentals of Li-ion batteries can be found in specialized literature (Linden and Reddy, 1995, Kurzweil and Brandt, 2009, Yamaki, 2009, Bresser et al., 2015, Scrosati and Garche, 2010); in the following, the most important issues connected with safety and reliability aspects of Li-ion cells will be addressed.

2.1. Failure modalities

The most common failure modalities of Li-ion cells are briefly summarized below; they are based on past experience and they are fundamental to set up a hazard identification methodology.

Since a number of accidental events have already occurred several times in the past, their mechanisms and causes have been recently examined and understood (Barsukov 2009, Abada et al. 2016, Balakrishnan et al. 2006, Kong et al. 2005, Mikolajczak et al. 2011, Orendorff 2012, Peabody and Arnold 2011, Ravdel et al. 2003, Renganathan et al. 2010, Tobishima 2009, Wang et al. 2012, Zhang and Jow 2002, Zhang et al. 2014, Woodbank Communications, 2017), so that prevention and/or mitigation actions can be taken in advance. Based on their similarities, most of them can be grouped in a number of homogeneous classes which are synthetically described below.

- **Manufacturing defects.** Despite the quality control methods