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# POTENTIAL OF PEV TO PROVIDE ANCILLARY SERVICES IN A SMART GRID CONTEXT – THE PORTUGUESE CASE

Dissertation submitted to the University of Coimbra in partial fulfilment of the requirements for the Degree of Master Science in Energy for Sustainability – Energy Systems and Policies

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January 2012

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UNIVERSIDADE DE COIMBRA

*To my wife, Patrícia, and my lovely daughter, Beatriz, my energy sources!*

*"Everyone needs to think differently about the future, a future that is riddled with change, challenge, and risk."*

James Canton

## Acknowledgement

First of all, I would like to thank to my supervisors at ISR – Institute of Systems and Robotics, Prof. Aníbal T. de Almeida and Prof. Joaquim Delgado, for their availability and support to develop this work.

I would also like to thank to Eng. Francisco Mira and Eng. Garcia Monteiro, from EDP Distribuição, Prof. Carlos Henggeler Antunes, from INESC Coimbra, and Eng. Rui Pestana, from REN, for their precious technical support.

I wish to thank to colleagues at ISR, Anabela Carvalho, Ana Cristina Lopes, Luis Conde, Pedro Moura and Ricardo Faria, to colleagues of the Energy for Sustainability Initiative, Ana Soares, Andreia Carreiro, Fernando Rodrigues and Marta Lopes, and to colleagues of work, António Lebre, Flávio Cação, Pedro Veloso and Teresa Couceiro for their collaboration and friendliness.

I would also like to thank to my close family, António, Letícia, Alda, José Carlos and Diogo for their permanent support.

And, I am thankful to Patrícia and Beatriz for their warmth and unconditional support.

## Abstract

Regarding challenges of modern society on energy and climate fields, the increasing adoption of renewable energy sources seems to be the best approach to achieve a sustainable energy generation in a framework of increasing demand. On the other hand, the electric mobility is promising a new paradigm towards a more efficient and clean transportation sector. However, the intermittent renewable generation is challenging the operation of electric power systems, namely in terms of generation forecasting, system stability and quality of service, requiring the development of smarter grids and controllable loads. At this level, the charging process of Plug-in Electric Vehicles (PEV), associated to optimum control strategies, represents a new potential resource to provide ancillary services, contributing to the accommodation of higher shares of renewable generation on the electric power system.

This work aims to contribute to the development of a cost-effective control system for efficient integration of PEV in the electric power system, taking the synergies between them. Therefore, the potential of PEV to contribute to the primary regulation, secondary regulation and regulation reserve in the Portuguese power system is analysed, regarding the commute profile by car in Portugal and the typical demand of PEV. On the other hand, in order to identify possible distribution network constraints to be considered on the development of the control system, the impact of PEV charging on Power Quality (PQ) is also analysed based on some field measurements.

This work shows that a universe of 280 000 PEV has potential to provide an average secondary regulation reserve of 123 MW for up-regulation and 63 MW for down-regulation, during the night-time charging period, if supported in a dedicated control system. On the other hand, if energy required by PEV every night was used to provide regulation reserve for down-regulation, PEV would contribute with a share between 13% and 100% of the required regulation reserves by the electric power system during weeknights of January 2011, and with a share between 38% and 100% of the required reserves in September 2011. Regarding PQ, the monitoring results show maximum 3$^{rd}$ harmonic currents around 12% and Total Harmonic Distortion ($THD_I$) between 12% and 16%, which can contribute to increase the harmonic distortion in Low Voltage (LV) public distribution networks, despite recorded harmonic current emissions being significantly below the limits established by current standards.

## Keywords

PEV; secondary regulation, regulation reserve; renewable generation; smart grids

## Resumo

Tendo em consideração os desafios da sociedade moderna nas áreas da energia e do clima, tudo indica que a melhor abordagem para garantir geração sustentável de energia, num contexto de aumento da procura, passa pela adoção crescente de fontes renováveis de energia. Por outro lado, a mobilidade elétrica promete um novo paradigma para o setor dos transportes, através de soluções mais limpas e eficientes. No entanto, a geração renovável intermitente está a lançar alguns desafios na exploração dos sistemas elétricos, nomeadamente na previsão de geração, na estabilidade do sistema e na qualidade de serviço, exigindo o desenvolvimento de redes mais inteligentes e de cargas controláveis. A este nível, o processo de carregamento dos veículos *plug-in*, associado a estratégias de controlo ótimo, apresenta-se como um novo recurso potencial para o fornecimento de serviços de sistema, contribuindo assim para a acomodação, no sistema elétrico, de maiores percentagens de geração renovável.

Este trabalho pretende contribuir para o desenvolvimento de um sistema de controlo, técnico/economicamente viável, para integração eficiente de veículos *plug-in* no sistema elétrico, aproveitando as sinergias entre ambos os sistemas. Neste sentido, é analisado o potencial dos veículos *plug-in* para contribuírem para regulação primária, regulação secundária e reserva de regulação no sistema elétrico Português, tendo em consideração o perfil de mobilidade pendular, em automóvel, em Portugal e os consumos típicos de um veículo *plug-in*. Por outro lado, de modo a identificar possíveis constrangimentos ao nível da rede de distribuição, que devem ser considerados no desenvolvimento do sistema de controlo, é analisado o impacto na qualidade de energia do carregamento de veículos *plug-in*, através de algumas monitorizações no terreno.

Este trabalho mostra que um universo de 280 000 veículos *plug-in* tem potencial para fornecer uma banda de regulação secundária de 123 MW para regulação a subir e de 63 MW para regulação a descer, durante o período de carregamento noturno, caso sejam implementados os necessários mecanismos de controlo. Se a energia necessária, todas as noites, para carregamento dos veículos *plug-in* fosse utilizada para fornecer reserva de regulação a descer, estes veículos contribuiriam com uma percentagem entre 13% e 100% das necessidades de reserva de regulação mobilizada a descer, no sistema elétrico, durante a noite, nos dias úteis do mês janeiro de 2011 e com uma percentagem entre 38% e 100% das necessidades de reserva de regulação mobilizada a descer, durante a noite, nos dias úteis do mês de setembro de 2011. No que se refere à qualidade de energia, os resultados de monitorização apresentam correntes harmónicas de 3.ª ordem com cerca de 12% e uma distorção harmónica total da corrente entre 12% e 16%, que podem contribuir para aumentar a distorção harmónica das redes de distribuição pública em baixa tensão, apesar dos valores de correntes harmónicas registados se situarem significativamente abaixo dos limites definidos nas normas atuais.

## Palavras Chave

Veículos elétricos *plug-in*; regulação secundária; reserva de regulação; geração renovável; redes inteligentes

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# List of abbreviations and acronyms

AC - Alternating Current

ACE - Area Control Error

ACS - Aggregation Control System

AGC - Automatic Generation Control

BMS - Battery Management Systems

CAN - Control Area Network

CAU - Central Aggregation Unit

CESA - Continental Europe Synchronous Area

CPO - Charging Points Operators

CVC - Cluster of Vehicle Controller

DC - Direct Current

DFC - Distribution Feeder Controller

DL - Decree-Law

DoD - Depth of Discharge

DSO - Distribution System Operator

DTC - Distribution Transformer Controller

EB - Energy Box

EC - European Commission

EMN - Electric Mobility Network

ENTSO - European Network for Transmission System Operators for Electricity

EPC - European Parliament and Council

EREV - Extended Range Electric Vehicles

ESP - Energy Service Providers

EU - European Union

EV - Electric Vehicle

EVSE - Electric Vehicle Supply Equipment

FCEV - Fuel Cell Electric Vehicles

FEV - Full Electric Vehicles

GENCO - Generation Companies

GHG - GreenHouse Gases

HEV - Hybrid Electric Vehicles

HV - High Voltage

ICCB - In-Cable Control Box

ICE - Internal Combustion Engine

ICT - Information and Communication Technologies

ICV - Internal Combustion Vehicle

IGBT - Isolated Gate Bipolar Transistors

LFC - Load-Frequency Control

LV - Low Voltage

MES - Electric Mobility Energy Suppliers

MGAU - Microgrid Aggregation Unit

Mobi.E - Portuguese Electric Mobility Program

MOM - Mobility Operation Managers

MV - Medium Voltage

PEV - Plug-in Electric Vehicles

PF - Power Factor

PHEV - Plug-in Hybrid Electric Vehicles

PQ - Power Quality

PWM - Pulse Width Modulated

RES - Renewable Energy Sources

SGC - Smart Grid Controllers

SO - System Operator

SoC - State of Charge

SoH - State of Health

T&D - Transmission and Distribution

THD - Total Harmonic Distortion

TSO - Transmission System Operators

UCTE - Union for the Coordination of the Transmission of Electricity

US - United States

V2G - Vehicle-to-Grid

VC - Vehicle Controller

# 1. Introduction

Regarding worldwide requirements for the reduction of GreenHouse Gases (GHG) emissions and the recent oil market instability, associated to the increasing demand, potential depletion of fossil resources and geopolitical instability, technological developments have been noticed in renewable energies and electrical storage technologies. Recent progresses on power and energy density of electrochemical batteries have been sprung up again the old dream of the electric mobility.

On the other hand, electric power systems have been developed for more than one century ago in a top-down perspective, based on highly predictable centralized generation and power flowing from transmission to distribution networks. The recent advent of large-scale intermittent renewable generation is challenging the operation of electric power systems, namely in terms of generation forecasting, system stability and quality of service. This new generation paradigm is requiring the development of smarter grids and controllable loads.

In this framework, it is very important to answer the following question: How Plug-in Electric Vehicles (PEV) can be integrated in electric power systems, supporting an increasing penetration of intermittent renewable generation and simultaneously ensuring a reliable and efficient operation of the distribution network? Therefore, by analysis of the potential of PEV to provide ancillary services, this work aims to contribute to support the Distribution System Operator (DSO) and electric Mobility Operation Managers (MOM) to design and implement a cost-effective control system and advanced control charging strategies for efficient integration of PEV in the electric power system and to take the expected synergies between them.

Although PEV demand would not initially lead to a strong increase in electricity generation, their impact on the distribution network load diagram shall require a new approach in load control. On the other hand, the charging process of PEV, associated to optimum control strategies, represents a new potential resource to provide ancillary services, such as secondary regulation range and regulation reserve, contributing to the accommodation of higher shares of renewable generation in the electric power system.

Nevertheless, the integration of PEV in electric power systems has to be developed in such a way that ensures the reliability, efficiency and Power Quality (PQ) in the distribution network. Indeed, the increase of intermittent Renewable Energy Sources (RES) and the expected integration of PEV on electric power systems suggest a new approach based on smart grids.

Aware about forthcoming challenges and opportunities, the automotive industry, electric utilities and other potential stakeholders are performing large investments on development of PEV and their control systems, with organizations such as Google spending US$10 million for PEV research and testing [1]. Several governments are supporting the implementation of charging infrastructures and stimulating the adoption of PEV, being the United States (US) government committed with a goal of 1 million PEV by the next 5 years [1], Portuguese government aiming to achieve 160 000 Full Electric Vehicles (FEV) by 2020, through the programme Mobi.E [2], as well as some predictions suggesting that by the year 2020 would be as much as 500 000 PEV in Portugal [3], 600 000 in Sweden [4] and 6.7 million in Germany [5].

## 1.1. Electric mobility framework

### 1.1.1. European Union policies

Regarding the requirements for reduction of GHG emissions, the needs for reduction the external energy dependency of fossil fuel and the importance of ensure the security of supply, the European Union (EU) has been leading the adoption of energy sustainable policies. According to the Climate-Energy Package, proposed by the European Commission (EC) and approved by the European Parliament and Council (EPC), EU has established ambitious goals to be achieved by 2020, also known as the “20-20-20” targets [6], characterized by 3 main goals:

- Reduction of GHG emissions by 20%, below the levels of 1990;

- Increase the energy efficiency, by 20% reduction of the primary energy consumption compared to the projected levels;
- Achieve a 20% share of RES in the overall EU energy consumption and a 34% share in electricity generation.

These targets have been transposed to the Portuguese policies by the Resolution of Council of Ministers n. 29/2010 [7], known as National Strategy for Energy 2020, with the following main objectives:

- Promote the sustainable development, in order to achieve the targets assumed by Portugal on the EU framework;
- Reduce 20% of the primary energy consumption according to the EU Climate-Energy Package;
- Achieve a 31% share of RES in the overall energy consumption and a 60% share on electricity generation.

These global strategic targets will require a significant reduction of GHG emissions in the EU electric generation sector and, as consequence, an increased share of RES in the electricity consumption, from today's 18% to about 34% [8].

On the other hand, it is expected that the development of electric mobility can contribute to an effective reduction of GHG emissions. As stated in the White Paper on Transport [9], the EU ten goals for a competitive and resource-efficient transport system have targets of 50% reduction of conventionally fuelled vehicles in cities by 2030 and 100% reduction by 2050. Therefore, a strong investment on electric mobility is expected during the next few decades. To achieve a significant deployment of PEV by 2050, Europe has to target a 10% share of PEV by 2020 [8].

### 1.1.2. The Portuguese electric mobility program

The Portuguese government has been promoting the development of electric mobility solutions and the adoption of FEV. The Portuguese Electric Mobility Program (Mobi.E) includes a consortium of companies and a network of municipalities for implementation and operation of a pilot Electric Mobility Network (EMN), in order to stimulate electric mobility across all country. This program defines a market model to be implemented in a pilot phase and developed in two subsequent phases. With this program, Portuguese authorities aim to achieve a 25% global reduction in $CO_2$ emissions by 2020. The Decree-Law (DL) n. 39/2010, of April 26th, has the following 3 main targets:

- Incentive the purchase and utilization of FEV;
- Ensure that battery charging is done by an integrated charging network;
- Establish a regime of universality and equity on access to electric mobility services.

This DL enacts the organization, access and framework to electric mobility activities, establishes a pilot EMN and regulates the incentives to utilization of FEV. Based on this DL, a pilot EMN has been implemented in the 25 main cities across the country. According to the initial planning, this infrastructure includes 1300 normal charging points[1] and 50 fast charging points[2] by the end of 2011.

Regarding market organization, main activities to support the electric mobility in Portugal include:

- Management of EMN operations – Management of financial and power flows associated to charging operations;
- Operation of charging points of the EMN – Installation, operation and maintenance of charging points integrated in the EMN;
- Electricity commercialization for electric mobility – Buy energy in the wholesale market and sell energy to electric drivers, in charging points of the EMN.

Also based on this DL, the following market agents have been established:

- Electric MOM[3], participated by the main Portuguese DSO[4] with a minimum share of 51%, being responsible by: management of the EMN for all Charging Points Operators (CPO) and Electric Mobility Energy Suppliers (MES); management of charging sessions and validation of electric drivers; issue Mobi.E identification cards on behalf of MES; certification of charging equipment; provision of information about the EMN through a website[5] and a call center.
- CPO are companies responsible by: installation, operation and maintenance of normal and fast charging points in open market; make available the infrastructure to MES, being remunerated by the amount of energy supplied to each electric driver. These

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[1] Power lower than 40 kVA or 40 kW.
[2] Power higher or equal to 40 kVA or 40 kW.
[3] SGORME – Sociedade Gestão de Operações de Mobilidade Eléctrica
[4] EDP Distribuição Energia
[5] www.mobie.pt

market agents are independent from MES and they have no direct relation with electric drivers.

- MES are typical Energy Service Providers (ESP), operating in open market, responsible by energy supply for battery charging and other services. According to their commercial strategies, energy might be supplied in pre-paid or pos-paid arrangements, by previous configuration of Mobi.E identification cards.

## 1.2. Motivation

Regarding forthcoming challenges on GHG emissions, system stability and distribution network reliability, and following recent technological developments on fields of RES, Information and Communication Technologies (ICT) and PEV, research for integration of these technologies in electric power systems has became one of the most exciting innovation areas. This is definitely an opportunity to develop a systems strategy approach, maximizing synergies between 2 fundamental systems: electric power system and transportation system. Indeed, research on this area is a single opportunity to contribute to a more sustainable and friendly world.

In this framework, a more precise research question can be identified to limit the scope of this work – What is the potential of PEV to provide ancillary services to the electric power system, supporting an increasing penetration of intermittent RES and simultaneously ensuring a reliable and efficient operation of the distribution network?

This work would contribute to support DSO, System Operator (SO) and forthcoming electric MOM to develop a cost-effective control system for an efficient integration of PEV in the electric power system, taking the synergies between them.

## 1.3. Objectives

To answer the highlighted research question and to derive the expected benefits and synergies between the electric power system and electric mobility, the main contribution is intended on analysis of the potential of PEV to provide ancillary services in the Portuguese power system and on assessment of the charging impact on PQ of distribution network.

This work aims to analyse the potential of PEV to contribute to the primary regulation, secondary regulation and regulation reserve in the Portuguese power system, in order to support the future development of a cost-effective control system to place bids on the operation market. Therefore, ancillary services in the Portuguese power system will be reviewed, as well as the commute profile by car in Portugal and typical PEV demand will be also characterized.

On the other hand, in order to identify possible distribution network constraints to be considered on the development of the mentioned control system, the potential impact of PEV charging on PQ will be analysed by some field measurements, namely in terms of harmonic current emissions.

## 1.4. Research methodology

In order to achieve the proposed objectives, based on available resources in the Institute of Systems and Robotics (ISR) – Department of Electrical Engineering and Computers – University of Coimbra, an analytical methodology supported by some field measurements is developed. This methodology includes 3 main components:

- Data collection and characterization of the Portuguese scenario regarding the operation market of ancillary services, commute profile by car and available methods and modes of PEV charging.
- Analysis of the impact of PEV charging on PQ of the distribution network, with focus on harmonic current emissions by onboard chargers.
- Analysis of the potential of PEV to provide ancillary services in Portugal, based on real data available from the operation market, such as secondary regulation range and regulation reserve, and real data from the commuting behaviour of a community with potential to adopt PEV.

## 1.5. Structure of the dissertation

In order to guide the reader in the next Chapters of the work, this section describes the main structure of the document and highlights the main topics addressed in each Chapter.

The first part of the dissertation starts with a detailed literature review on technological developments about PEV, smart grids and advanced control charging strategies. Chapter 2 presents the state of the art of PEV, namely in terms of powertrain topologies, electric driving machines, promising battery systems, chemistry challenges and management systems, as well as onboard charger topologies and charging methods and modes. In order to address the integration of PEV in the electric power system, this Chapter also approaches the concept of smart grids and reviews some works about provision of ancillary services by PEV and advanced control charging strategies.

Chapter 3 presents the results of analysis carried out in order to characterize the impact of PEV on the distribution network, regarding harmonic current emissions in normal power charging. The first section introduces the harmonic theory and the second section presents the results of field measurements with a Nissan Leaf in a charging operation.

The approach to ancillary services starts in Chapter 4 with an extensive review about requirements of primary regulation, secondary regulation and regulation reserve in the Portuguese operation market. To analyse the potential of PEV to provide these ancillary services, presented in Chapter 6, a previous characterization of the commute profile by car in Portugal is presented in Chapter 5. This characterization includes driving distances and parking duration profiles during weekdays.

Chapters 7 and 8 highlight the main conclusions of the developed work during this phase of the project and feature proposals for future development of a cost-effective control system, including architecture and optimization algorithms.

# 2. State of the art

With focus on proposed objectives, this chapter includes a literature review about work developed in Europe, US and Japan on the field of PEV integration in electric power systems, in order to provide ancillary services and to deal with distribution network constraints. At this level, a comprehensive state of the art review is presented on topics such as PEV and battery systems technology, smart grids, potential of PEV to provide ancillary services, control architecture and advanced charging strategies, as well as impact of PEV on the distribution network.

## 2.1. Plug-in electric vehicles

In overall perspective, an Electric Vehicle (EV) is any vehicle with an electric-drive motor powered by onboard batteries, fuel cells or hybrid powertrain. In this broad group of vehicles, there are included FEV, also called “pure” EV, Fuel Cell Electric Vehicles (FCEV), Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV) and Extended Range Electric Vehicles (EREV). The subgroup of PEV is characterized by its capability to charge onboard batteries from the distribution network, directly by plug into a typical socket outlet or by a dedicated Electric Vehicle Supply Equipment (EVSE). Due to that characteristic and to potential synergies with the electric power system, only PEV, which include FEV, PHEV and EREV, are considered in the scope of this work.

The new paradigm supported in electric motors and more efficient powertrains, with better performance, has been developing since 90’s decade, with the success of HEV, like Toyota Prius. The main powertrain components of PEV include electric driving machines, power electronic drives, Alternating Current (AC) / Direct Current (DC) and DC/DC converters, electromechanical devices, batteries, Battery Management Systems (BMS), and auxiliary power units [10].

The charging efficiency of a FEV utilizing an onboard AC/DC charger, with an output power of 3.5 kW, is about 83.5% [11], as presented in Figure 1.

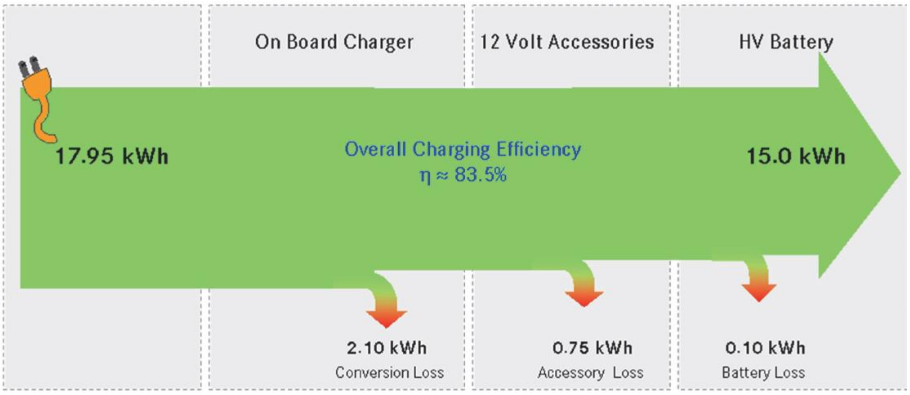

Figure 1 – Diagram of charging efficiency in a FEV [11]

On the other hand, the overall operation efficiency of a typical FEV is about 81.3% [11], as presented in Figure 2.

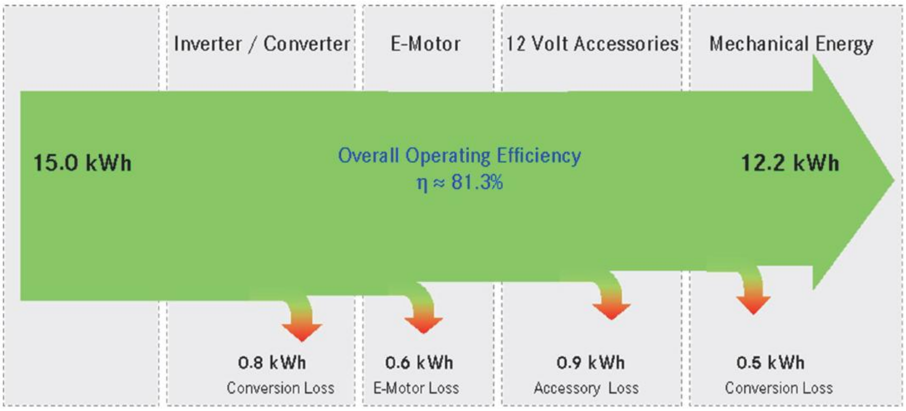

Figure 2 – Diagram of operation efficiency in a FEV [11]

Combining the charging efficiency and the operation efficiency, it is expected that a typical FEV achieve an overall efficiency around 68%, which presents a large potential compared to the overall efficiency, from tank-to-wheels, around 13% - 14% in a conventional Internal Combustion Vehicle (ICV) [11] [12].

### 2.1.1. Powertrain topologies

This section describes the mostly adopted powertrain topologies in PEV, regarding range capability, design considerations and costs.

#### *2.1.1.1. Plug-in hybrid electric vehicles*

Overall, PHEV are similar to current HEV with higher energy storage capacity and ability to charge from an external electric source, such as typical socket out, by onboard normal power chargers or external fast chargers. On opposition to HEV, PHEV are designed to use the battery as the primary power source for short and medium range travels. Typically, PHEV are designed around 3 main powertrain architectures:

- <u>Series hybrid powertrain</u> – The traction power is only delivered by the main electric machine, which operates as motor to drive wheels and as generator during regenerative braking. The Internal Combustion Engine (ICE) is used to drive an auxiliary generator, which supplies extra power to charge the battery and to support the main electric machine. Battery charging is complemented by the auxiliary generator and by regenerative braking. This powertrain is easier to design, control and implement, but it is typically more expensive [10].
- <u>Parallel hybrid powertrain</u> – The traction power is shared by the ICE and the electric machine, which operates as motor to drive wheels and as generator during regenerative braking. Battery charging is only complemented by regenerative braking. This powertrain architecture does not typically allow operation in all-electric mode at high speeds [10].
- <u>Series-parallel hybrid powertrain</u> – The traction power is shared by the ICE and the main electric machine, which operates as motor to drive wheels and as generator during regenerative braking. A secondary electric machine is used to supply extra power to the battery and to start and support the ICE. Battery charging is complemented by the secondary electric machine, operating as generator, and by regenerative braking.

Figure 3 depicts the series-parallel hybrid powertrain of a Toyota Prius PHEV[6], which can provide traction power from the ICE alone, from the main electric machine alone, or from any mix of both.

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[6] Hybrid Synergy Drive system

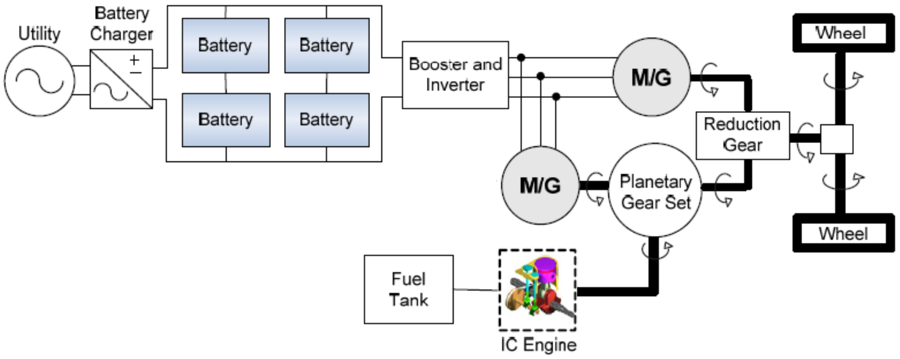

Figure 3 – Toyota Prius PHEV topology [13]

Operation of the Toyota Prius PHEV is based on the current Prius HEV, with extended all-electric range and plug-in charging from an external electric source. This new model maintains the Hybrid Synergy Drive system of the Prius HEV and it seamlessly switch into hybrid operation at a pre-determined State of Charge (SoC) [14]. This PHEV has the following main characteristics [15]:

- Powertrain:
    - Hybrid system with electronically controlled continuously variable transmission, with 100 kW.
- ICE:
    - 4-cylinder, 16-valve VVT-i;
    - Displacement: 1798 cc;
    - Power: 73 kW at 5200 rpm.
- Main electric driving machine:
    - Type: Permanent magnet AC synchronous machine;
    - Power: 60 kW;
    - Maximum motor-drive voltage: 650 $V_{DC}$;
    - Operation as motor and as generator.
- Battery system:
    - Lithium-based battery technology;
    - Capacity: 4.4 kWh;
    - Weight: 80 kg.

- Performance:
    - All-electric range: 24 km at speeds up to 100 km/h;
    - Charging time at 240 V: 1.5 hours.

#### *2.1.1.2. Extended range electric vehicles*

The EREV has a configuration similar to PHEV series powertrain. GM has developed 2 models based on this powertrain architecture, called Voltec – the Chevrolet Volt to the US market and the Opel Ampera to the European market. The Voltec technology ensures that traction power is always delivered by the main electric machine. The Opel Ampera was designed to travel between 40 km and 80 km in all-electric mode, as the European driver profile corresponds to less than 50 km per day[7] [16]. When the battery reaches a low SoC, a compact gasoline engine/generator automatically starts in order to extend the range, being this ICE configured to operate in optimized regime for maximum efficiency. This EREV has the following main characteristics [17]:

- Powertrain:
    - EREV with Voltec electric drive system.
- ICE:
    - Type: 1.4 l DOHC gasoline;
    - Displacement: 1398 cc;
    - Power: 63 kW at 4800 rpm.
- Main electric driving machine:
    - Type: Three-phase induction motor [18];
    - Power: 111 kW;
    - Torque: 368 Nm;
    - Operation as motor and generator.
- Range extender electric generator:
    - Type: Tree-phase induction motor;
    - Power: 54 kW.

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[7] As presented in section 5.1, in Portugal 77% of commuters travel less than 50 km per day.

- Battery System:
    - Type: Lithium-based battery technology – Lithium Manganese Spinel polymer, prismatic cells [19];
    - Capacity: 16 kWh, configured to a 50% Depth of Discharge (DoD) that corresponds to an usable capacity of 8 kWh [18];
    - Weight: 198 kg.
- Performance:
    - All-electric range: Between 40 km and 80 km;
    - Charging time at 240 V: about 4 hours.

#### *2.1.1.3. Full electric vehicles*

The typical configuration of a FEV is characterized by a main electric machine that delivers all traction power to drive wheels and charges the battery in regenerative braking. FEV does not require any ICE, to deliver traction or to drive any auxiliary generator, on opposition to PHEV and EREV. FEV include a larger battery pack, which can be charged from the distribution network, by an onboard normal power charger or by an external fast charger.

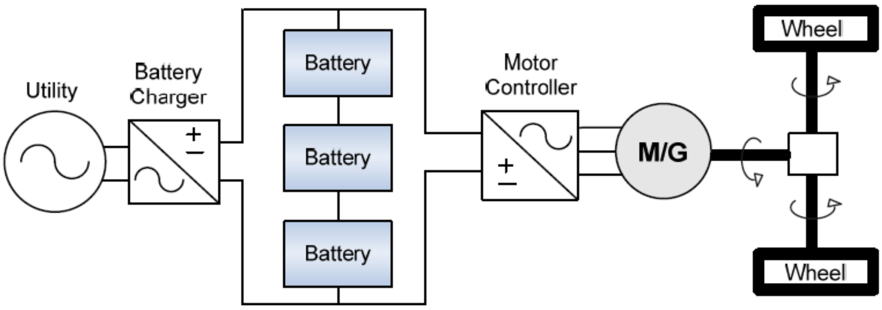

Figure 4 – Typical configuration of a FEV [13]

A very promising FEV is the Nissan Leaf that is powered by a new generation of laminated Lithium-ion battery. This FEV has a range of 160 km, in US LA4 mode, enough to the requirements of the large majority of commuters. An extensive consumer survey has shown that 80% of daily driving is below to 100 km per day[8], with 80% of drivers in Japan and UK driving less than 50 km per day [20]. The Nissan Leaf presents the following main characteristics [21]:

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[8] As presented in section 5.1, in Portugal 93% of commuters travel less than 100 km per day.

- Powertrain:
    - FEV.
- Main electric machine:
    - Type: Permanent magnet AC synchronous machine;
    - Power: 80 kW;
    - Torque: 280 Nm;
    - Operation as motor and as generator.
- Battery system
    - Type: Lithium-based battery technology – Lithium Nickel Manganese polymer, laminated cells [19];
    - Capacity: 24 kWh, in 48 modules, with 4 cells per module [20].
    - Weight: 171 kg.
- Performance:
    - All-electric range: 160 km, by US LA4 mode;
    - Maximum speed: 145 km/h;
    - Charging time at 240 V: about 6 hours.

### 2.1.2. Electric driving machines

The majority of automotive manufacturers are currently using permanent magnet electric machines. However, due to the high price of rare-earths required for permanent magnets, as well as environmental and supply concerns, some alternatives are being studied [10]. Electric machines with higher potential as driving motors and regenerative braking in PEV belong to 3 main brushless technologies, regarding their efficiency, reliability, control and costs:

- Asynchronous machine:
    - Advantages – Technology widely used in industrial applications, with low maintenance requirements, high reliability, high efficiency and low cost, only requiring design optimization and weight reduction for automotive applications.

    - Disadvantages – Poor power factor at low load regimes and high inrush currents.

- Permanent magnet synchronous machine:
    - Advantages – High power density, high efficiency, with low noise and reduced vibration.
    - Disadvantages – High cost and supply concerns about permanent magnets raw materials.
- Switched reluctance synchronous machine:
    - Advantages – High power density, high speed operation and wide constant power regimes, high starting torque and high ratio torque/inertia.
    - Disadvantages – Noise at low speed, complex design and control.

### 2.1.3. Battery systems

Nowadays, the main challenge to a massive deployment of PEV remains on the traction batteries. Batteries must be sized in order to store enough energy and to deliver adequate peak power to meet the driving cycles and acceleration requirements of PEV [22], which may involve large and heavy battery packs, representing the most expensive component of PEV. Other important challenge of batteries remains on the number of equivalent charging cycles achieved during their lifetime. Figure 5 shows the capacity and power requirements to battery systems for automotive applications, with PEV requiring typically more than 8 kWh storage capacity and power above 50 kW.

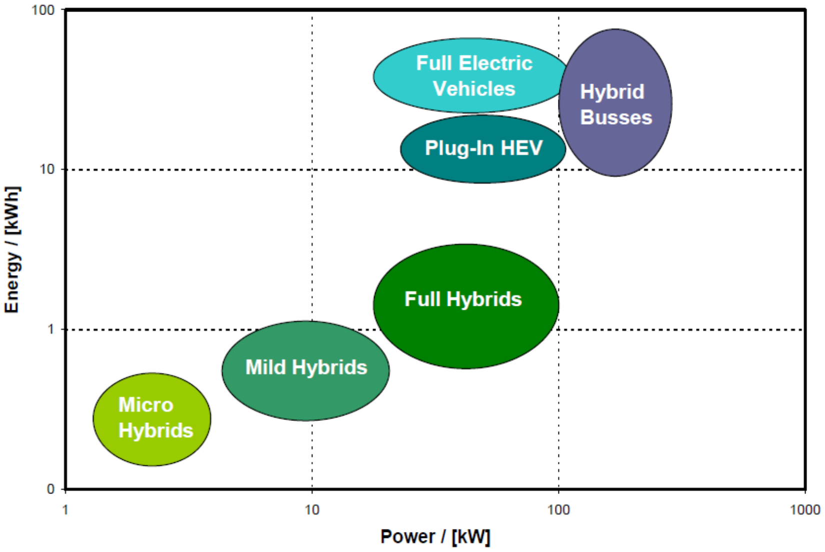

Figure 5 – Battery capacity and power requirements by automotive applications [23]

Regarding the state of the art of battery technology, the Table 1 presents a more detailed approach regarding the minimum storage capacity, performance and maximum admissible costs required by PEV with the following characteristics:

- PHEV – Midsize passenger vehicles with 32 km and 64 km all-electric range, respectively;
- FEV – Small and midsize vehicles, respectively, with weight, performance and accommodation comparable to similar sized ICV.

Table 1 – Storage capacity, performance and costs required by PEV [24]

| | **Max. weight (kg)** | **Min. peak power (kW)** | **Min. power density (W/kg)** | **Min. energy storage (kWh)** | **Min. energy density (Wh/kg)** | **Min. n.º cycles[9] @ 80% DoD** | **Max. specific cost ($/kWh)** |
|---|---|---|---|---|---|---|---|
| **PHEV[10]** | 120 | 50 - 65 | 400 - 540 | 6 - 12 | 50 - 75 | 2400-2300 | 300 |
| **FEV** | 250 | 50 - 100 | 200 - 400 | 25 - 40 | 100 - 160 | 1000 | 150 |

For PHEV the battery capacity is designed regarding the all-electric range. In charge-depletion mode, the battery is discharged continuously to reach a predefined SoC, typically 20% to prevent deep discharges that reduce the battery lifetime [24]. The control system switches to charge-sustaining mode when that SoC is reached. On the other hand, FEV require larger battery storage capacities to ensure typical driving requirements and higher gravimetric and volumetric energy densities, in order to reduce the weigh and volume [24]. Battery systems for PEV must be designed in order to store enough energy and to deliver the required peak power for each kind of vehicle. Nowadays, the Lithium-based battery is the most promising technology to ensure the energy and power requirements of PEV, as presented in Figure 6.

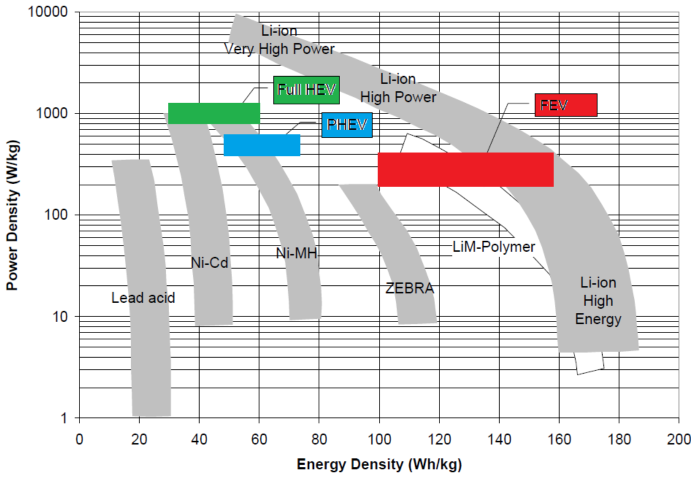

Figure 6 – Potential of battery technologies for PEV application (adapted from [24])

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[9] Number of equivalent 80% DoD cycles to be delivered by battery over a 10 years lifetime.

[10] PHEV data derived from Duvall (2001) are considered preliminary.

Due to the high energy density and design flexibility, Lithium-based batteries currently outperform other battery technologies [25]. As demonstrated in [26], it would be possible to design Lithium-ion battery packs, with acceptable size, to ensure 30 km – 60 km all-electric range for PHEV and 240 km for FEV, with acceleration performance equivalent to ICV.

### *2.1.3.1. Lithium-based battery technology*

As Lithium is the most electronegative element and the lightest metal, it holds unique advantages to the anode[11] of batteries. The most conventional structure of a Lithium-ion battery includes an anode, supported on graphite and/or coke deposited on thin copper sheets, a cathode[12] of Lithium Metal Oxide and an electrolyte of Lithium salt in a mixed organic solvent imbedded in a separator felt [27]. Figure 7 presents the operating scheme of a conventional Lithium-ion battery.

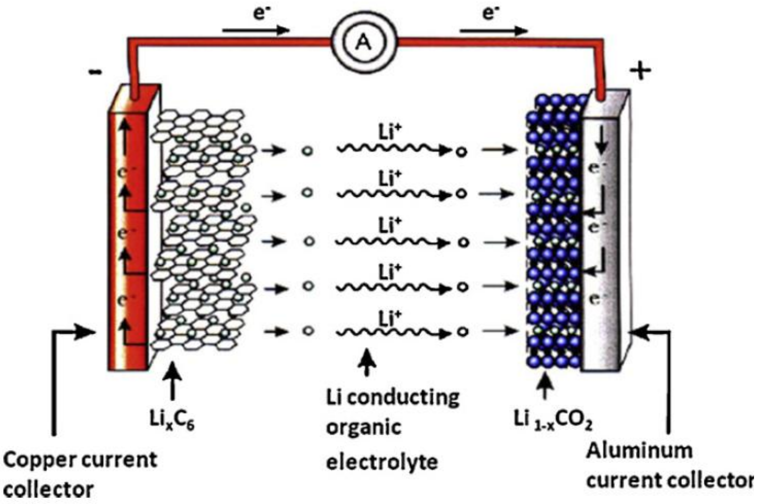

Figure 7 – Operating scheme of the most conventional Lithium-ion battery [27]

The cathode may be formed by several materials, such as Lithium Manganese Spinelor or Lithiated ion Phosphate, mixed with carbon to increase the conductivity, deposited on thin aluminium sheets to operate as conducting plates [24].

As result of the high electronegative properties of Lithium, it is possible to design cells with higher voltages comparing to other materials, being achieved operating voltage ranges between 2.75 V and 4.2 V [24].

Other important characteristic of the Lithium-based technology is its flexibility to build batteries in several shapes and configurations, such as cylindrical, coin, prismatic and flat, as presented in Figure 8.

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[11] Negative electrode

[12] Positive electrode

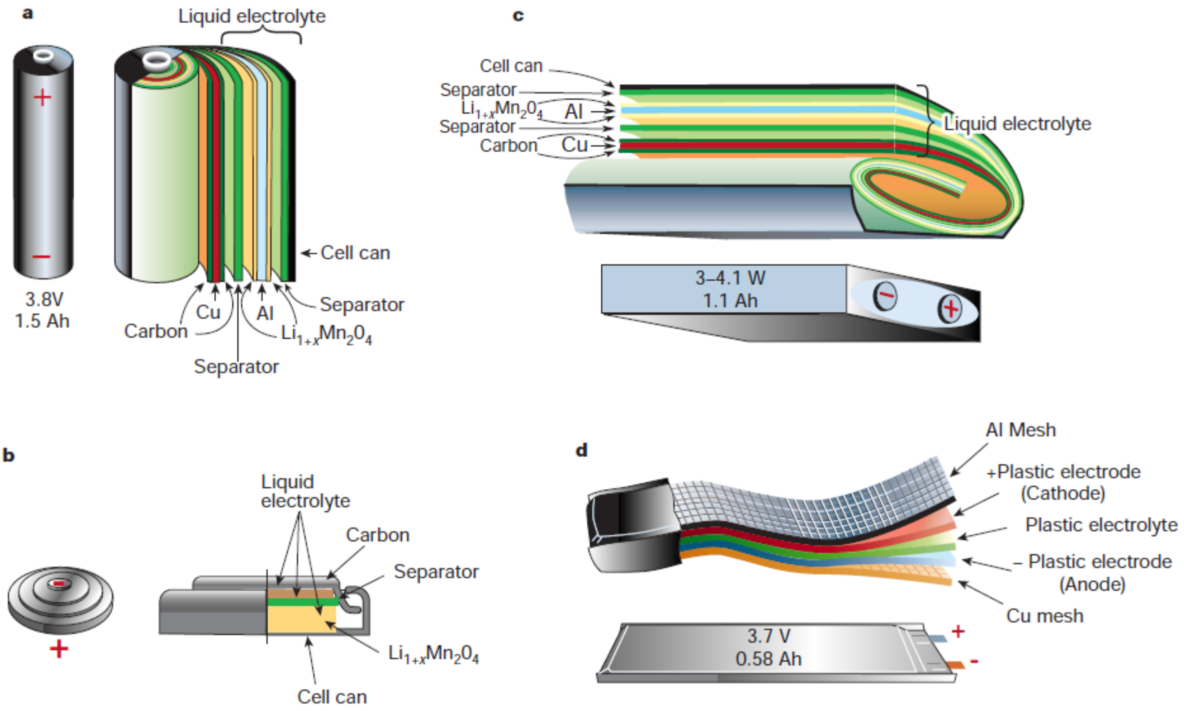

Figure 8 – Schematic drawing of shapes and components of several Lithium-ion battery configurations: a – Cylindrical; b – Coin; c – Prismatic; d – Thin and flat [25]

### *2.1.3.2. Main challenges of Lithium-based battery technologies*

The Lithium-ion battery technology still faces some challenges regarding the requirements of PEV. Main issues are related to safety, impact of cycling on the lifetime, costs and performance at low operating temperatures. Despite unique properties of the Lithium-based technology, its main challenge is also related with the high electronegative properties of Lithium, which accelerate the chemical reactivity within the cells. Other important challenge of Lithium-ion technology is its sensitiveness to overcharging, which can cause chemical decomposition of cathode materials, electrolyte and/or metallic Lithium of the anode, requiring an accurate voltage control at the cell level [24].

The following subsections address two important practical aspects that definitely determine the performance and lifetime of the battery – cycling and thermal effects.

#### 2.1.3.2.1. Cycling effects

The DoD has a significant impact on the number of cycles a cell will be able to perform during its lifetime. Figure 9 presents an interesting characterization of the cycle life achieved by SAFT, as result of the DoD [24].

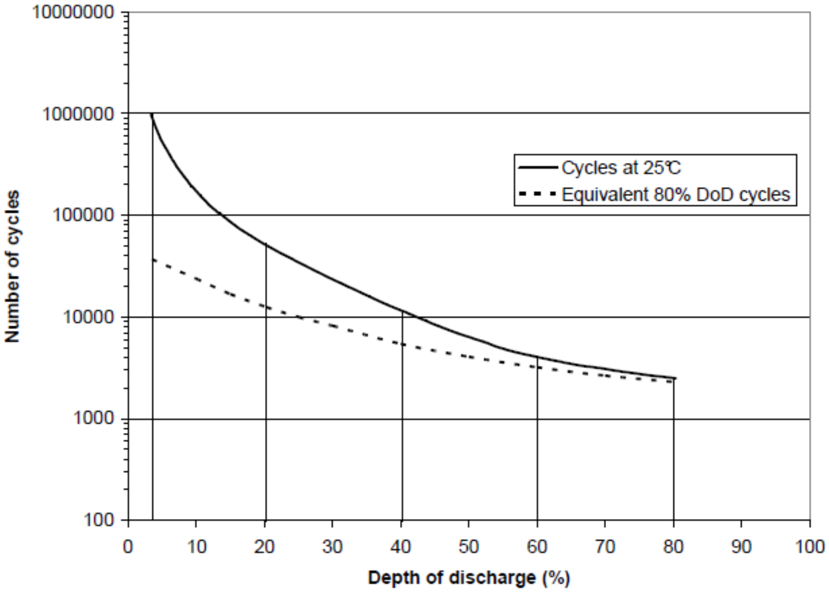

Figure 9 – Deep discharge cycle life of Lithium-ion high energy cell technology [24]

Regarding this profile, the black line shows the number of cycles achieved by a cell during its lifetime as consequence of the DoD. The number of cycles supported by a cell during the lifetime decreases exponentially with the DoD. Although this cell be able to perform about 50 000 cycles with 20% DoD, it only performs around 3000 cycles if submitted to cycles of 80% DoD.

The dotted line represents the number of equivalent cycles with 80% DoD achieved by the cell, during its lifetime, for cycling at lower DoD. For example, if the battery is cycled at 80% DoD, it will reach about 3000 cycles. However, if the battery was routinely cycled at 40% DoD, it would support 12000 cycles, that corresponds to 6000 cycles at 80% DoD. Thus, the energy delivered by the battery during its lifetime cycling at 40% DoD is twice the energy delivered cycling at 80% DoD [24].

This behaviour of Lithium-based technology suggests that batteries should be submitted to low DoD, in order to extend their lifetime and the amount of energy storage. Thus, it is recommended that PEV be charged whenever possible and at least in a daily-base timeframe, every night.

Other interesting study [28] shows the degradation of a battery of prismatic $LiFePO_4$ cells, resulting from the accelerated cycling in a typical PEV, in terms of capacity and power fade, as well as efficiency degradation. The tests on the scope of this study were performed under the following conditions:

- Nominal capacity of the battery pack: 16.4 Ah;
- Weight: 500 g;
- Cell charged and discharged at 3 C[13] rate, between 3.6 V and 2 V at 50 ºC;
- Cycling interrupted every 300 cycles for characterization tests at temperatures of 45 ºC, 25 ºC, 0 ºC and -10 ºC.

As presented in Figure 10, this study shows that capacity slowly fades with the number of cycles, but it significantly reduces near to 600 cycles, with 74.4% capacity retention.

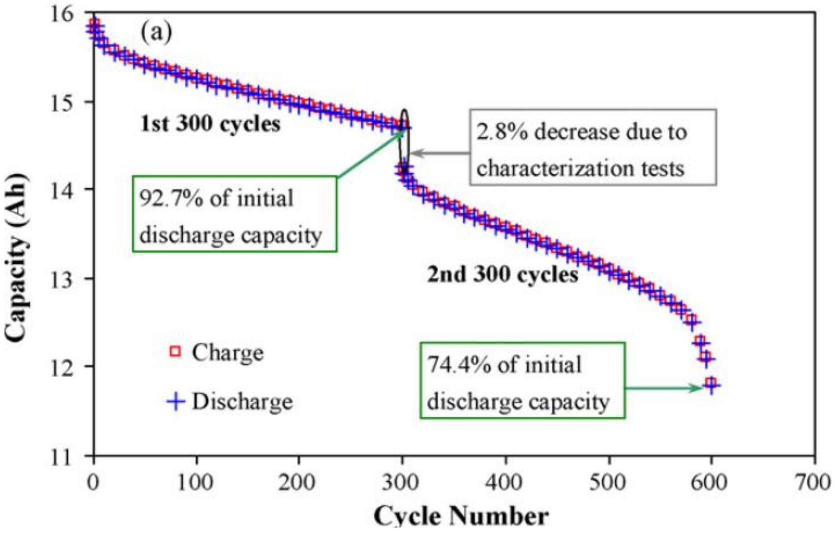

Figure 10 – Cycling performance at 3 C rate between 3.6 V and 2 V at 50 ºC[14] [28]

Regarding the cycling efficiency, Figure 11 shows the charge/discharge loops in cycling tests for the 1st, 300th, 301st and 600th cycles. The results show that the discharge capacity in cycling tests is very close to the charge capacity, being the energy efficiency reduced in 4.5%, from 94.1% to 89.6%, with the 600 cycles.

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[13] C is the capacity rating (in Ah) of the battery – Theoretical current that the battery delivers/draws when discharged/charged in 1 hour to the point of 100% of discharge/charge.

[14] The 2.8% capacity lost between 300th and 301st cycles was due to some characterization testes performed between them.

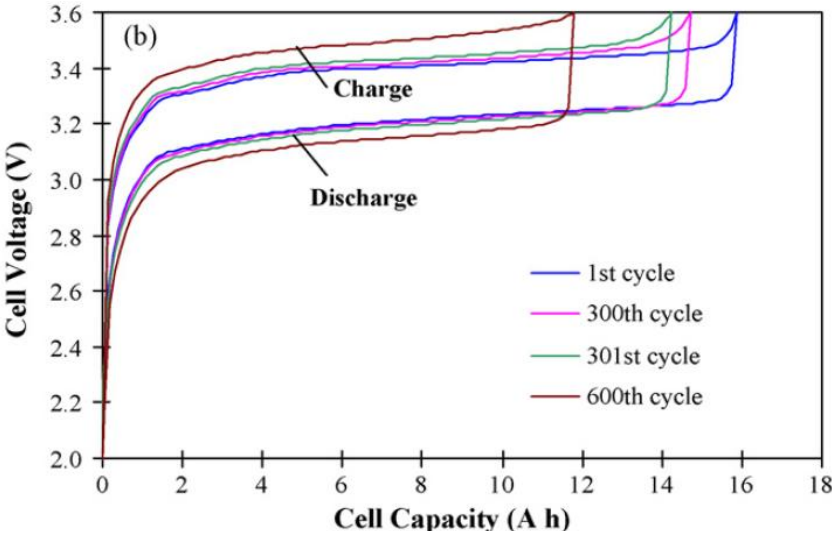

Figure 11 – Cycling performance at 3 C rate between 3.6 V and 2 V at 50 ºC [28]

Regarding the power fade, it can be evaluated by the discharge Pulse Power Capacity ($PPC_{discharge}$), given by [28]:

$$PPC_{discharge} = \frac{V_{min}(V_0 - V_{min})}{R_{discharge}}$$

with:

- $V_{min}$ – Low cut-off voltage for the discharge current pulse;
- $V_0$ – Open-circuit voltage right before the discharge pulse;
- $R_{discharge}$ – Discharge resistance:

$$R_{discharge} = \frac{\Delta V}{\Delta I} = \frac{V_{t_0} - V_{t_1}}{I_{t_0} - I_{t_1}}$$

  - where:
    - $t_0$ – Time point just before each discharge pulse;
    - $t_1$ – Time point at the end of each discharge pulse.

The cell has a limited maximum discharge current at each temperature, since serious degradation and even damage may occur above the maximum discharge current. The discharge pulse power capacity is limited by:

$$P_{lim} = V_{min} \times I_{max}$$

with:

- $I_{max}$ – High current limit.

According this study, the $R_{discharge}$ for a 30 s pulse at 45 ºC increases with cycling, but such resistance increase does not reduce the pulse power capability, as it is restricted by the $PPC_{limit}$ from 0 to 600 cycles. Similarly, at 25 ºC, the $R_{discharge}$ increases after 300 cycles, and it does not reduce the pulse power capability. However, the $R_{discharge}$ increases much more after 600 cycles and leads to 16.2% power fade from 300 to 600 cycles. The $PPC_{discharge}$ obtained at 0 ºC and -10 ºC is seen to significantly decrease with cycling. The power fade at 0 ºC is 42.1% and 61.6%, respectively, after 300 and 600 cycles in comparison with the initial pulse. The power fade at -10 ºC is 49.6% and 77.2% after 300 and 600 cycles.

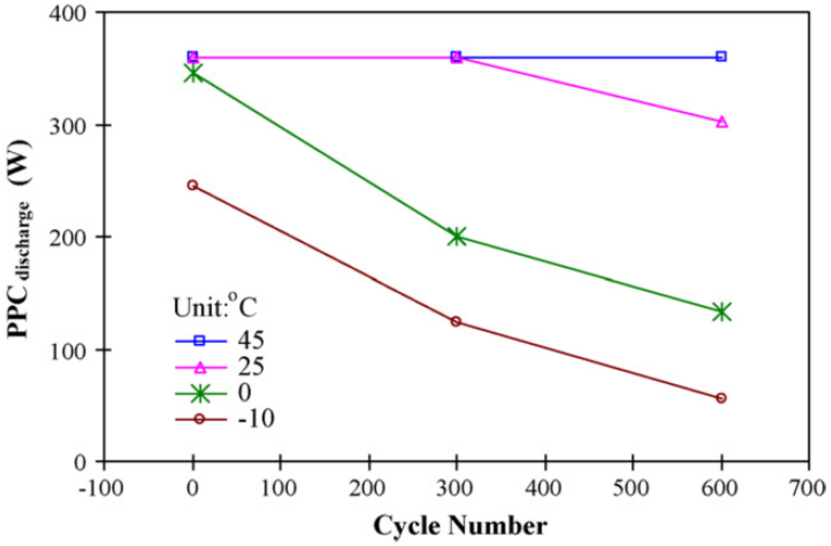

Figure 12 – Discharge pulse power capability for 30 s pulse as a function of cycle number at different temperatures [28]

As demonstrated on this work, as the discharge resistance increases significantly with temperature and the number of cycles, by consequence the discharge pulse power capacity is severely affected by the operating temperature.

Authors of the work have concluded that the capacity fade of a high capacity $LiFePO_4$ cell after 600 cycles is 14.3% at 45 ºC and 25.8% at -10 ºC. The discharge pulse power capability at 45 ºC does not decrease with cycling from 0 to 600 cycles, but the power fade after 600 cycles is 61.6% and 77.2% at 0 ºC and -10 ºC, respectively.

#### *2.1.3.2.2. Thermal effects*

Although the high energy efficiency of battery cycling, around 90%, losses generated by Joule effect due to high charging and discharging currents must be dissipated. In fact, operation and storage temperatures are key aspects to ensure a good performance and battery lifetime. Operating or storage temperatures above 40 ºC – 60 ºC reduce significantly its power and capacity [29] [30]. The battery capacity may also be reduced if cycled at temperatures significantly below -5 ºC – -10 ºC [29] [30].

Due to these thermal effects, thermal management systems are required in practical applications to reduce the operation temperature and to warm the battery in cold environments. As result of major improvements, the design of battery systems with 10 years lifetime is currently possible for PEV applications [23], as presented in Figure 13.

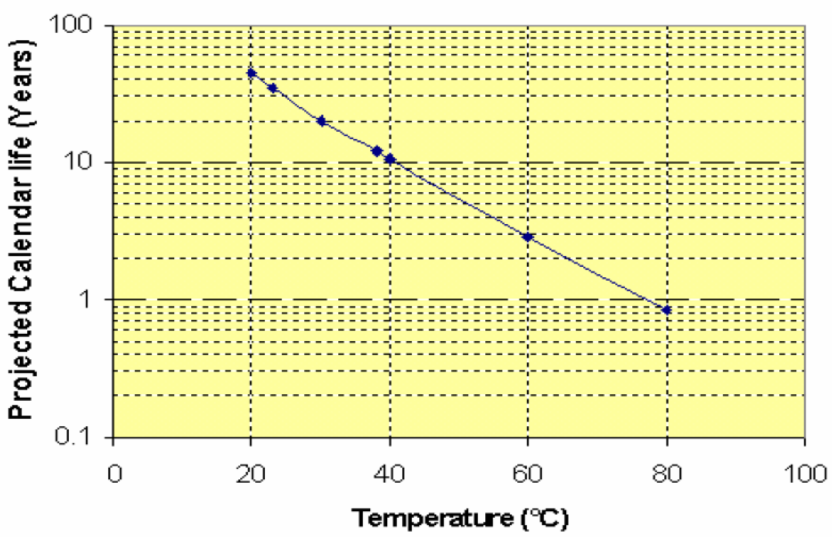

Figure 13 – Lifetime of Lithium-ion cells as a function of the storage temperature, with 60% SoC [23]

Capacity and power fade – The capacity is reduced due to the transformation of the active material into inactive phases. As presented in the previous study, the power or rate capacity is reduced when the internal impedance of the cell increases, which reduces the operating voltage at each discharge rate [29]. Based on [29], the capacity decreases if the operating temperature increases beyond ~50 ºC, besides discharge rate or cell chemistry. Furthermore, the capacity and power fade can happen even when batteries are not cycled, namely when stored at higher SoC and temperature.

Self-discharge – According to the review in [29], at ambient temperatures are expected very low self-discharge of batteries, and if they are stored at 60 ºC the capacity reduces only 0.44% per day, which is not significant for PEV application, which are supposed to be frequently charged.

Thermal runaway – This phenomenon occurs when higher temperatures trigger heat-generating exothermic reactions, increasing the temperature and potentially enabling more dangerous reactions [29]. Thermal runaway is triggered by portions of the battery reaching critical temperatures that start exothermic reactions, with consequent extra heat-production.

The research to improve the Lithium-ion battery safety is focused on current-limiting or pressure releasing devices, safer electrolytes and cathode materials, special additives and coating, as well as appropriate thermal management strategies for limitation of thermal runaway [29]. This phenomenon can occur especially in situations of overcharging or due to internal short-circuits.

Electrical balance – In practical applications, battery cells must be connected in series, in order to reach useful voltages. The operation of batteries with different capacities in series is a critical factor to battery packs. The weakest cell limits the overall performance of the battery pack, being the weaker cells exposed to overcharging, causing potential thermal runaway [29]. By this reason the voltage of each cell, or group of cells connected in parallel, in Lithium-ion battery packs must be monitored individually to ensure safe operation [29]. Electrical balance among multiple Lithium cells in a single pack is a critical factor for retrieving maximum energy and reducing the possibility of individual cells overdischarging or overcharging. Hotter cells will discharge or charge faster than colder cells [29].

Low temperature performance – Based on the review presented in [29], the performance of Lithium-ion batteries is reduced at lower temperatures for all cell materials, being the charge performance even substantially below the discharge performance at the same temperature. Some authors, on this review [29], recommend that high charge rates at low temperatures should be avoided, even at short pulses, to limit capacity fade. Based on this review [29], important highlights should be taken for PEV applications. To mitigate the self-discharge and capacity/power fade, Lithium-ion batteries must be cooled to nominal ambient temperatures or lower (about 20 ºC) in operation and during storage periods. In cold environments, batteries must be heated rapidly to improve both cycle life and energy extraction [29].

#### *2.1.3.3. Promising Lithium-based battery technologies*

##### *2.1.3.3.1. Thin-film Lithium-based technology*

Thin-film Lithium battery is currently considered one of the most promising technologies due to advantages related to power capability, volumetric energy density, gravimetric energy density and shape flexibility. Figure 14 shows the advantages of the Thin-film Lithium-ion technology in comparison to several other battery technologies regarding the gravimetric and volumetric energy densities.

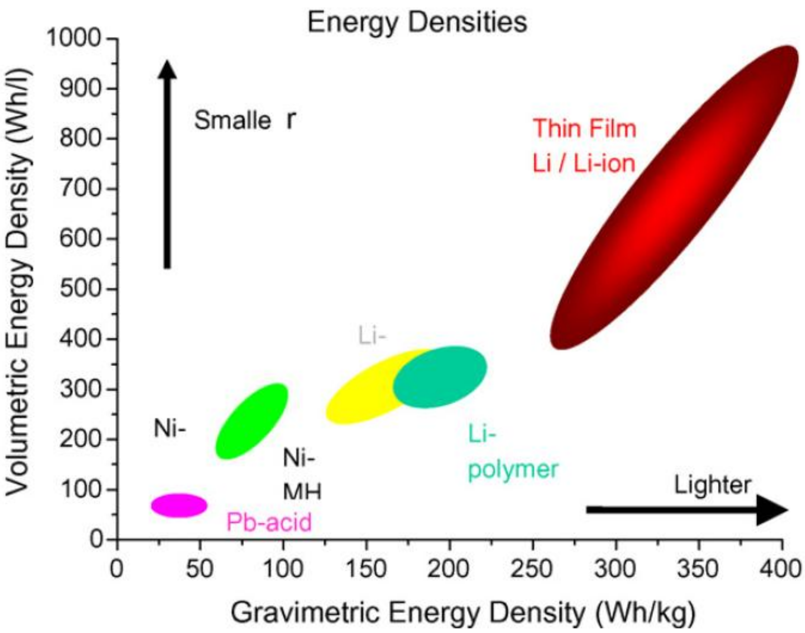

Figure 14 – Comparison between several Lithium-ion batteries regarding volumetric and gravimetric energy density [31]

This comparative analysis shows the large potential of this technology, achieving values of 400 Wh/kg and 1000 Wh/l.

This technology is already used in several portable electronic devices, such as laptops, video cameras and phones, and its adoption for PEV applications is soon expected [31]. This technology concept is very simple, as it only requires the deposition of solid films for anode, electrolyte and cathode over a substrate, as depicted in Figure 15.

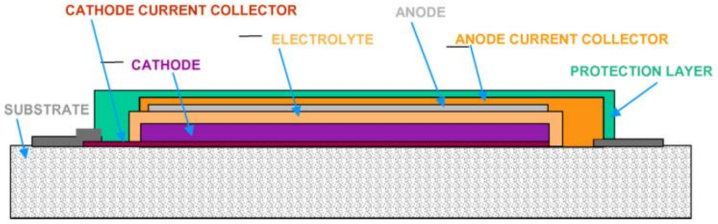

Figure 15 – Cross-section of a thin-film-Lithium battery [31]

The thin-film technology represents the transition from the traditional electrochemistry to solid-state physics. The ideal thin-film battery should have the following main characteristics [31]:

- Compact and light weight;
- No heavy metal housing;
- Made in variety of designs and sizes;

- Excellent reliability and safety;
- High cycle time and high energy capacity;
- Low cost and wide temperature range;
- High power density and high discharge voltage;
- No memory effect;
- Do not use poisonous metals, such as lead, mercury and cadmium.

#### *2.1.3.3.2. Lithium-sulfur technology*

According to [24], the Lithium-sulfur (Li-S) electrochemical pair shows a high theoretical energy density among other battery systems. The theoretical gravimetric energy density of the Lithium-sulful materials is greater than 2500 Wh/kg and the volumetric energy density greater than 2600 Wh/l [32]. However, only a small part of this energy density can be achieved in practical PEV applications, due to the weight of other materials required to the battery, being really good to achieve values between 350 Wh/kg and 400Wh/kg in practical applications [24].

Based on this technology, the Sion Power company has developed thin-film rechargeable cells with gravimetric energy density over 350 Wh/kg and volumetric energy density greater than 320 Wh/l, and this company claims to achieve cells with 600 Wh/kg and 600 Wh/l in the near future [32].

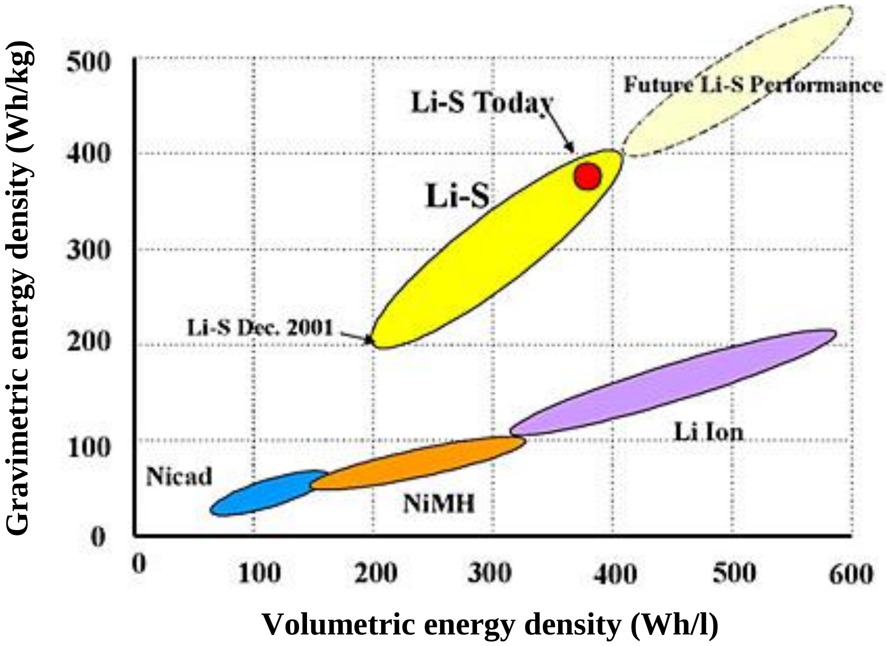

Figure 16 – Lithium-sulfur versus other cell chemistries (adapted from [32])

Also based on [24], this technology still faces several challenges. The anode of metallic Lithium is more expensive to process, more difficult to assure safety due to its reactivity with moisture and air, and it is more difficult to recharge by organic electrolytes [24]. On the other hand, on [32] is claimed that Lithium-sulful technology starts with a lower material cost than Lithium-ion or Lithium-polymer batteries, as sulphur is much less expensive than the typical components of other battery systems, having similar manufacturing techniques.

#### *2.1.3.3.3. Lithium-air technology*

The electrochemical batteries based on anode of metal, electrolyte and cathode of oxygen presents the highest energy density potential, because the active material of cathode, the oxygen, is not stored in the battery and can be easily accessed from the environment [33].

Figure 17 presents a comparison of theoretical and practical gravimetric energy densities between several rechargeable battery technologies and the gasoline. The gravimetric energy density of the gasoline is 13 000 Wh/kg. However, considering the average tank-to-wheels efficiency of 12.6% in ICV, the usable energy density of the gasoline in automotive applications can be approximated by 1700 Wh/kg [12].

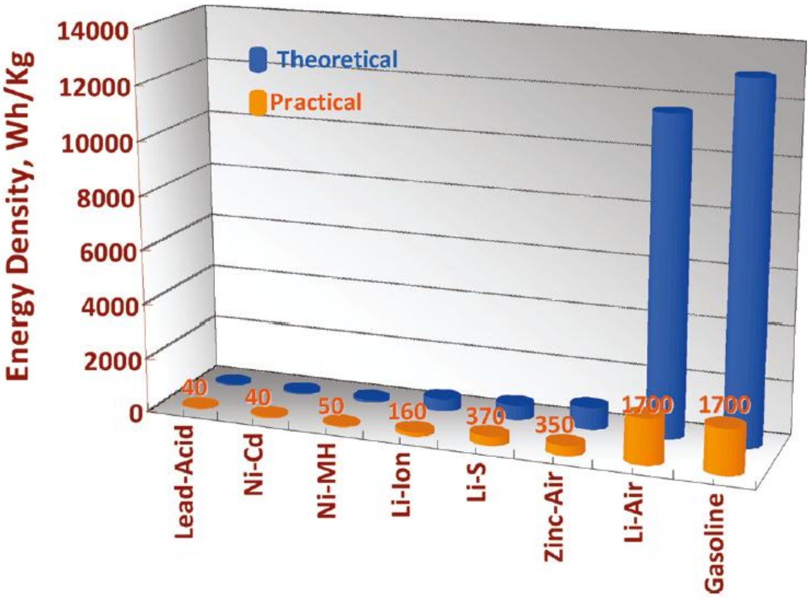

Figure 17 – Comparison of gravimetric energy densities between rechargeable batteries and gasoline [12]

As presented in the graph, even with very high efficiency of grid-battery-wheels in PEV, the Lithium-ion battery technology is far to achieve the practical energy density of gasoline and it is not expected it will ever reach a similar range, being required new chemistries [12]. However, regarding that oxidation of Lithium metal releases 11 680 Wh/kg, it is expected that

Lithium-air battery technology can achieve practical energy densities similar to gasoline range achieved in ICV, after long-term development [12].

One challenge of this chemistry for PEV application is related to its very low power density. For an effective reaction of oxygen with Lithium in discharging and charging processes very large cathode surfaces are required, both in microscopic and macroscopic senses [12]. A battery with 100 kW power output at a cell voltage of 2.5 V and a current density of 25 $mA/cm^2$ will require a total internal surface of 160 $m^2$, equivalent to the internal surface of the human lung [12]. One possibility of overcome this limitation in PEV applications could be the combination of Lithium-air batteries with other technologies with lower capacity but with higher power density, such as supercapacitors to support the acceleration demands.

The current cycling energy efficiency ranges between 60% and 70% [12], which is quite low compared to Lithium-ion technology, which is typically above 90% [28] in PEV applications.

As Lithium-air batteries support a very low number of cycles, the future development should be focused on improving the capacity retention during cycling. However, due to the large energy capacity of Lithium-air cells, it is not required a very high number of charging cycles on large propulsion batteries. For example, a battery with lifetime to drive 250 000 km and 800 km range will only need to be recharged about 312 times (full cycle equivalent) [12].

Typical safety issues of Lithium-ion batteries due to overcharging or internal short-circuits are not a problem in Lithium-air batteries, as the reactant $O_2$ is not stored in the battery [12]. However, the use of Lithium metal anodes has some safety concerns due to the development of dendrites, which can short-circuit the battery and react aggressively with many contaminants. On the other hand, the dominant reaction product of the cells, which is a string oxidizer, combined with an organic electrolyte, can lead to safety issues in case of accident [12].

Currently, 4 chemical architectures of Lithium-air batteries are being researched over the world, 3 versions include liquid electrolytes and 1 solid electrolyte. A typical design for aprotic Lithium-air batteries is shown in Figure 18, including an electrolyte comprising dissolved Lithium salt in an aprotic solvent, and a porous $O_2$-breating cathode composed by large surface area carbon particles and catalyst particles, both bound to a metal mesh using a bind [12].

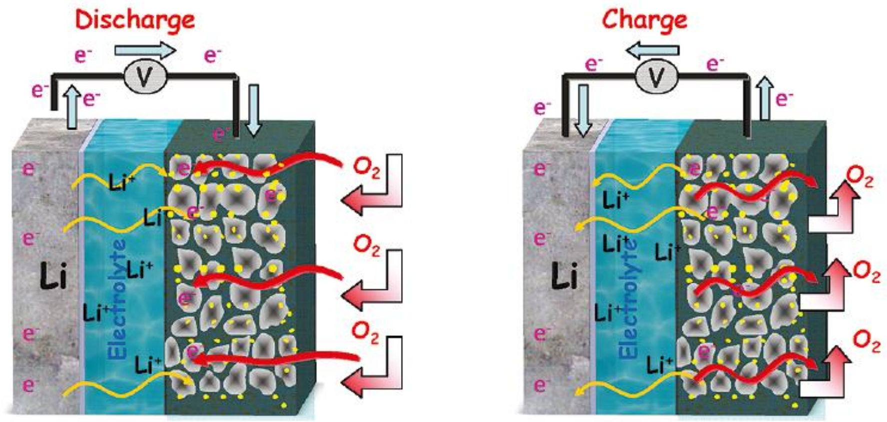

Figure 18 – Schematic operation proposed for the rechargeable aprotic Lithium-air battery [12]

### 2.1.4. Battery management systems

To achieve required voltages in battery packs several cells must be connected in series. On this configuration, different internal resistances, degradation and temperature variations may cause capacity imbalance between cells, resulting in overcharge of some cells and undercharge of others. On the other hand, charge/discharge cycles increase the cell voltage imbalance, which is an important issue in PEV, due to their operation dynamics [34].

Regarding the safety concerns about operation of batteries, a BMS to ensure a safe and reliable operation of battery systems is required, namely by monitoring and control of battery cycling. In PEV, BMS are used in order to prevent dangerous uncontrolled energy releases, that can be caused by severe physical abuse, as crushing, puncturing or burning or by internal faults, like cells short-circuits, abnormal high discharge or overcharging [35].

Typically, battery packs consist of several battery modules, each one with many cells, which incorporate cooling mechanisms and monitoring systems for temperature, voltage and current [35]. Battery packs also include mechanisms to control the power flow to the output terminals [35]. The BMS ensures the collection of data from sensors and the activation of relays to optimize the operation of the battery pack. This system is also responsible by communications with the other onboard systems and charging points, if applicable.

The paper [34] presents an innovative BMS for PEV applications based on a concept of redundant cells. This work proposes a BMS for linear packs with maximum 10 Lithium-ion cells for low-medium power applications, from 100 W to 500 W. The operation strategy is based on the availability of an additional cell that can be continuously disconnected from the load, allowing the insulation of bypassed cell for optimal balancing with remaining cells in operation – charging or discharging. On the other hand, the BMS is able to identify a cell in severe fault and bypass it permanently. The architecture of the proposed BMS includes 3 main modules: switch network; data acquisition block; control unit, as presented in Figure 19.

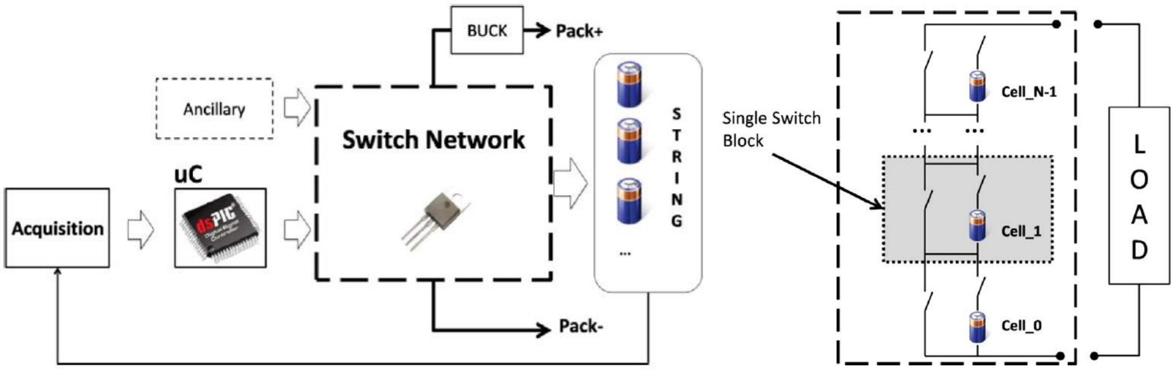

Figure 19 – Diagram of BMS architecture and diagram of switch network [34]

According to this work, the development of the switch network has presented the following challenges:

- As switches are series connected in the load circuit, their resistance reduces the global efficiency of the system;
- Being required balancing in charging and discharging modes, switches must have bidirectional operation, opening the current flow in both directions;
- Minimization of the number of components and required safety in every operative condition.

The microcontroller ensures signal acquisition, processes signals, controls all switches and evaluates the SoC of each cell, based on a predefined method. The balancing algorithm, which defines the connection or bypass of the cell, is a key component of the system, directly impacting the balance effectiveness and efficiency of the system. The main task of this algorithm is to manage the cell to be disconnected.

#### *2.1.4.1. Main characteristics and functions of BMS*

BMS Topology – The standard topology of BMS ensures that temperature and voltage monitoring of individual cells is performed by a sub-module or slave circuit board, which is directly installed in each battery module [35]. Functions such as computing SoC and actions based on processed data from sub-modules are performed by the main module of the BMS [35].

BMS SoC Calculation – SoC information is critical to estimate and to extend the battery lifetime and to determine the end of charging cycles. As the SoC is not measured directly, the

BMS is responsible by computation of this variable based on monitoring data of voltage, temperature, current and other parameters [35].

BMS Cell Balancing Functions – The BMS should compensate weaker cells in a module, by monitoring and balancing the SoC of each cell. Small differences between cells tend to increase with each charging cycle and the BMS should minimize this effect [35]. Considering a cell with reduced capacity in a battery pack, during the recharging process this cell can be submitted to overcharging until other cells, in the chain, reach their full charge, resulting in high temperature and pressure with possible damage of the cell. During the discharging process, this cell would be discharged before others, reaching deeper discharges, increasing its degradation [35]. The voltage on weaker cells could even invert when they become fully discharged before the rest of the cells [35]. The cell balancing mechanism aims to compensate weaker cells, by equalizing the SoC on every cell in the chain, in order to extend the battery lifetime. In this process, charge is transferred from neighbouring cells to undercharged cells detected in a module [35]. To ensure the efficiency of this process, cells must be equipped with an active balancing circuit and the BMS must receive voltage data from each single cell [35].

State of Health and Diagnostics – The State of Health (SoH) indicates the capability of the battery to safely deliver its nominal output power. This variable can be computed by monitoring and analysis of historical operation data such as number of cycles, maximum and minimum voltages and temperatures and maximum charging and discharging currents [35]. More advanced measures of SoH can be performed by automated measurement of the pack's insulation resistance, which requires dedicated circuits inside the battery pack to measure the electrical insulation and the high current path from ground planes of the battery pack [35].

BMS Communications – In PEV applications, communications between the BMS and peripheral systems is typically implemented over a Control Area Network (CAN), but options such as serial RS232, RS485 and TCP/IP and other protocols are also possible [35].

### 2.1.5. Onboard chargers

In order to ensure Power Factor (PF) near to 1, onboard chargers are typically designed with two main stages, a first module to convert the AC voltage in DC voltage and to ensure PF correction, and a second module that ensures DC/DC conversion and controls voltage and current to supply the battery. These chargers also include an input filter to mitigate conduced harmonics and noise from the distribution network.

By safety reasons, the output of the battery charger should have a galvanic insulation from the distribution network, which requires an insulation transformer. On the other hand, to ensure high power density, reducing the volume and weight, and low costs, this transformer operates at high frequencies, typically from 20 kHz to 100 kHz [36].

As mentioned before, the battery performance and lifetime are strongly influenced by cycling profile, which imposes some requirements on chargers design, such as:

- Prevent overcharging and overdischarge;
- Reduce charging time without impact on the battery lifetime;
- Ensure good PQ to the battery.

Regarding the requirements of PEV, the normal power chargers would have the following main features:

- Connection to the distribution network, in AC single phase;
- High efficiency;
- Low harmonic emissions;
- Good PF;
- Reduced volume and weight.

The work [37] presents the design and some experimental results of a 3.3 kW onboard charger for PEV. This charger is design based on a series-loaded resonant full-bridge DC/DC converter. On the other hand, a dual-mode battery charging algorithm Constant Current – Constant Voltage (CC-CV) was implemented by frequency control methods using resonant characteristics. This design, as presented in Figure 20, has been proposed in order to maximize the efficiency and to reduce the volume and weight. A boost converter is used to improve the PF and to regulate the output voltage.

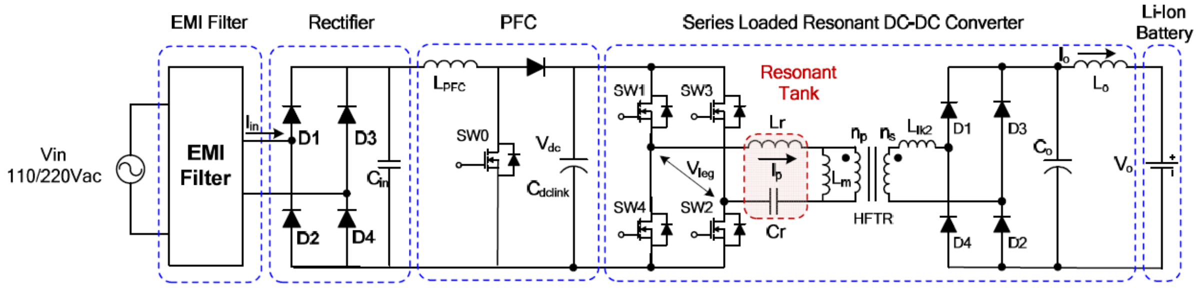

Figure 20 – Battery charger configuration based on series-loaded resonant DC/DC converter [37]

In order to reduce the size of passive components, the system was designed with increased frequency. On the other hand, to reduce additional switching losses due to the increased frequency, the authors have adopted a series-loaded resonant DC/DC converter.

The system is controlled based on a dual-mode charging strategy CC-CV, to obtain a more efficient charging process, as presented in Figure 21.

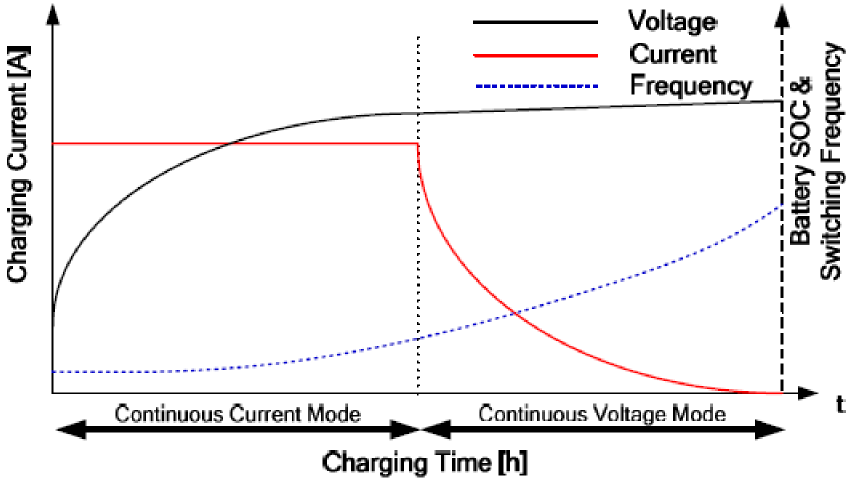

Figure 21 – Battery charging profile with frequency control [37]

According to experimental tests with an electronic load, the proposed system allows a sine wave input current with PF 0.995 and output voltage of 380 V [37]. The experimental tests also show very good results in terms of efficiency, with a minimum efficiency of 84% at 300 W and a maximum efficiency of 93% at 2.7 kW, as presented in Figure 22.

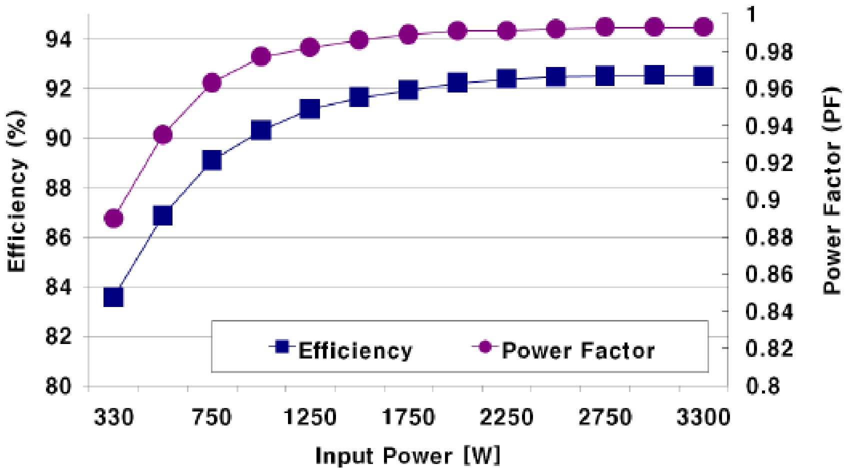

Figure 22 – Efficiency and PF with a control strategy for battery charging [37]

Regarding several research projects on design and test of onboard battery chargers [37] [38] [39] [40], there are expected the following performance for onboard chargers with 3.68 kW, 230 V input voltage:

- Average efficiency: Between 92.5% and 94%;
- PF: Around 0.99;
- Input current Total Harmonic Distortion ($THD_I$): below to 5%.

### 2.1.6. Charging methods and modes

According to the Eurelectric position paper [41], to express the charging process in terms of power is more accurate than in time-related terms. Thus, the Table 2 suggested classification will be used from now, in this work.

Table 2 – Classification of PEV charging methods [41]

| | *Mains connection* | *Power (kW)* | *Current (A)* | *Range[15] (km)* |
|---|---|---|---|---|
| **Normal Power** | 1-phase AC | ≤ 3.7 | 10 – 16 | < 20[16] |
| **Medium Power** | 1-phase or 3-phase AC | 3.7 – 22 | 16 – 32 | 20 – 110 |
| **High Power AC** | 3-phase AC | > 22 | > 32 | > 110 |
| **High Power DC** | DC | > 22 | > 32 | > 110 |

#### *2.1.6.1. Normal power charging*

This charging method shall be typically used in applications such as residential and office buildings, as well as in some public locations as curb-side charging points and parking lots. As mentioned previously, Mobi.E includes the installation of 1300 Normal Power charging points.

The Normal Power charging method is characterized by an onboard charger with 1-phase connection to the supply network. The charger draws AC power from the distribution network and converts it into DC power for battery charging. This charging method can be implemented according to charging Mode 1 or charging Mode 2 of the standard IEC 61851-1 [42].

##### *2.1.6.1.1. Charging Mode 1*

Non-dedicated socket outlet – PEV is connected to the mains AC supply network through a standard socket outlet (rated current: 16 A) at the supply side, with 1-phase or 3-phase, neutral and protective earth conductors. The adoption of this mode depends on the

---

[15] Assuming an average demand of 20 kWh/100km.

[16] Normal power method may be used to charge PEV when ranges higher than 20 km are required. Moreover, this charging method is even recommended in order to extend the battery lifetime. The [41] suggests this method for ranges up to 20 km in a context of reduced time (less than 1 hour) for charging the energy required to prosecute the travel.

availability of a residual current device at the supply side. This mode is not allowed where residual current devices are not required by national standards.

#### *2.1.6.1.2. Charging Mode 2*

Non-dedicated socket outlet with cable-incorporated protective device – PEV is connected to the mains AC supply network through a standard socket outlet (rated current: 16 A) at the supply side, with 1-phase or 3-phase, neutral and protective earth conductors and a control pilot-conductor between the vehicle and an In-Cable Control Box (ICCB), at the cable supply side ending, or a control connector.

### *2.1.6.2. Medium and high power AC charging*

These charging methods, with 1-phase or 3-phase AC connections to the supply network, shall be mainly used by end-users in shopping centers or in parking lots in city areas.

In Medium and High Power AC charging configurations, a high power onboard charger can be used for currents higher than 16 A, or the powertrain inverter can operate as AC/DC converter to charge the battery. On this last option, the charging power will be equivalent to power of the motor.

These charging methods can be implemented according to Mode 3 of the standard IEC 61851-1 [42]. This charging mode requires a dedicated socket outlet – PEV is connected to the mains AC supply network through a dedicated EVSE, with a control pilot-conductor between the vehicle and the EVSE.

### *2.1.6.3. High power DC charging*

This charging method shall be mainly used to ensure longer journeys with short charging periods, namely in highways. It is probably the most suitable solution for installation in typical gas stations, as already available in some main Portuguese gas station[17] and in the city of Gaia[18].

The High Power DC charging method is characterized by an external 3-phase AC/DC converter. The output of the charger is directly connected to the battery input and the DC power is controlled by onboard BMS.

This charging method can be implemented according to Mode 4 of the standard IEC 61851-1 [42]. This charging mode is based on a DC connection – PEV is indirectly connected

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[17] Galp’s A1-Aveiras, A1-Pombal and A5-Oeiras.

[18] EDP Mop’s fast charging point.

to the mains AC supply network through an external DC charger, with a control pilot-conductor between the vehicle and the DC charger.

## 2.2. Smart grids

In a broad sense, a smart grid is an electric power system that integrates behaviours and actions of all its users by an intelligent way in order to ensure a sustainable, economic and secure electricity supply [8]. Actually, it includes monitoring, protection and automatic operation optimization of all interconnected elements, from centralized and distributed generation, through Transmission and Distribution (T&D) systems, to industrial and commercial users, as well as energy storage installations and residential users and their thermostats, PEV, appliances and other household devices [43]. Supported by ICT, the intelligent control of loads, generation and storage resources would increase the overall sustainability and reliability with potential benefits to the entire value-chain (Generation Companies (GENCO), Transmission System Operators (TSO), DSO, energy suppliers and end-users).

According to the Eurelectric suggestion [8], functionalities and services of smart grids can be split up in 3 main categories:

- Smart grid management:
  - Conventional network development combined with new resources;
  - Network automation with PQ monitoring, fast fault location and self-healing capabilities;
  - Advanced network operation and control;
  - Smart metering;
- Smart integrated generation:
  - Balancing with a large penetration of RES, with variable and intermittent profile, and distributed generation;
  - Integrating PEV and heating and cooling systems;
  - Intelligent storage solutions;
- Smart markets and customers:
  - Developing demand response;
  - Aggregating distributed energy sources, including PEV.

As depicted in Figure 23, these functionalities would be implemented with active participation of end-users, being the load control one of the main goals to achieve with smart grids, for which PEV can have a huge contribution, due to their singular characteristics.

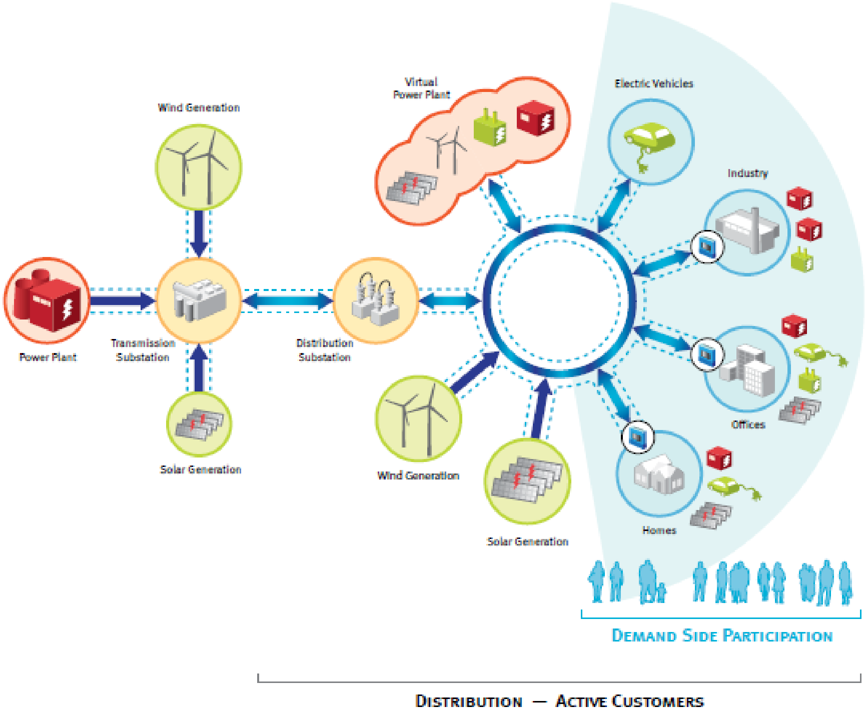

Figure 23 – Power system of tomorrow [8]

## 2.3. Provision of ancillary services by PEV

To approach the capability of PEV to provide ancillary services to electric power systems, it is important to introduce the concept of Vehicle-to-Grid (V2G), that was initially proposed by Willett Kempton, and to establish the main differences between two sub-concepts that are used in this work. The basic concept of V2G is that PEV provides power to the distribution network while parked and plugged-in [44]. PEV absorbs and stores energy, being able to supply electricity to the distribution network and provide ancillary services. In this work, V2G is approached as a capability of PEV to provide ancillary services and to support electric power systems, by two main configurations:

- V2G with bidirectional power flow – It corresponds to the basic concept proposed by Willett Kempton, where power can flow from the distribution network to PEV or vice-versa, to provide ancillary services;
- V2G with unidirectional power flow – Ancillary services are provided only based on control charging strategies, preventing battery degradation and extra energy losses in charging cycles.

In order to determine the impact of the V2G on the load curve, [3] it was assumed a scenario of 500 000 PEV in Portugal by 2020 and an average charging power of 3.5 kW, which can leads to a “theoretical” charging peak power of 1750 MW. In this scenario, Figure 24 shows that forecasted consumption of PEV will not represent a strong demand increasing on the Portuguese daily load diagram, by 2020. These conclusions are in line with [45], that suggests an additional demand between 10% and 15% for a complete electrification of the European fleet, concluding that European generation capacity will be able to supply the additional PEV demand, at least in short to medium-term, if suitable control charging strategies be adopted.

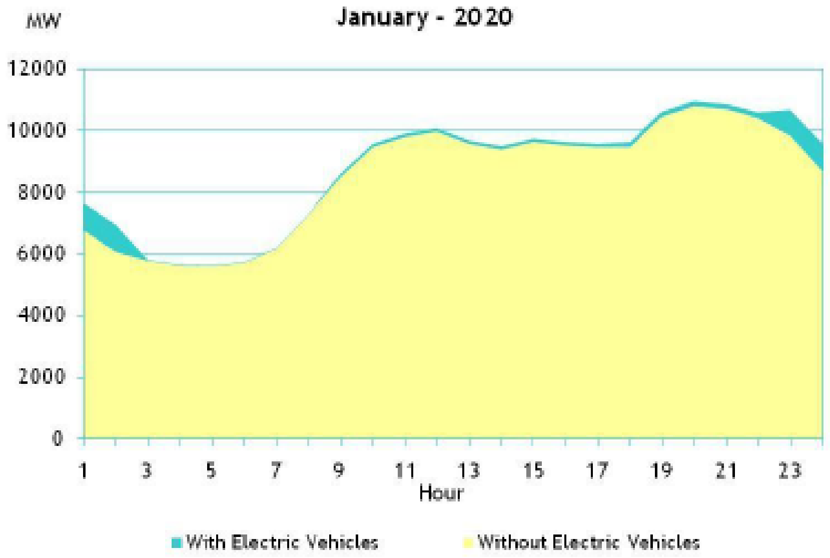

Figure 24 – Forecasted consumption to January of 2020 with and without PEV [3]

To avoid the impact of uncontrolled charging on electric power systems may be adopted smart interfaces, which by price-signalling can shift the growing charging demand to night periods. On the other hand, [3] also suggests that PEV can operate in V2G, with bidirectional power flow, with technical and economical benefits, due to different energy rates between charging and injection periods, and to associated retribution of ancillary services.

Based on several studies [44], it has been demonstrated that PEV would not supply base-load power at a competitive price, mainly due to reduced energy storage capacity, short battery lifetime, relatively high energy costs per kWh of charging and the efficiency of the charging cycle, as presented in the previous section. Nevertheless, they seem to have a large potential to provide ancillary services, such as primary and secondary regulation. Typically to provide these services are not mobilized large amounts of energy, being users compensated only by their availability. However, regarding current rules of European Network for Transmission System Operators for Electricity (ENTSO), the implementation of primary-frequency regulation would be quite difficult on the Continental Europe Synchronous Area (CESA), as very high reliability levels are required to provide this first level of control, being this task restricted to large power plants.

Regarding the potential of PEV demonstrated by Willett Kempton, [46] presents an analysis of the incentives to a PEV owner by charging control, in the Danish power system, by price-signalling from the day-ahead market, and by participation in ancillary services. As described in this work, the Danish power system is characterized by a very high penetration of wind power, with about 20% yearly average wind power penetration. As verified in Portugal, during certain night periods, the wind power exceeds the total consumption within Denmark and this surplus is exported to the neighbouring countries at low price or even at zero price, in some hours. This framework implies high prices for regulation/balancing wind power. The Danish electricity market is a liberalized market and a part of the Nord Pool market[19]. As in MIBEL, in Nord Pool's day-ahead market[20] the electricity is traded hourly one day before the production/consumption, being about 75% of all the electricity traded on this market.

The authors of this work expect that in near-term it will be available hourly prices to end-users, through smart meter, allowing a better consumption planning and charging of PEV by price-signalling. However, the same authors think that PEV are not expected to participate in primary regulation or blackstart capacity due to rather slow V2G communication and activation systems.

According to this study in the Danish power market, V2G, with bidirectional power flow, controlled by price-signalling, with power charged during the night and discharged during the day time, causing energy losses of 15%, will be compensated by a price differential 150 – 200 DDK/MWh (about 20 – 27 €/MWh). On the other hand, the authors conclude that electric drivers may earn large amounts for rendering PEV for frequency regulation and manual reserve services in V2G, with unidirectional power flow. Assuming the most conservative scenario analysed in the study[21], the annual revenue of a PEV can reach the following values, including the payment for availability and energy:

- Frequency regulation service – 1440 DKK (about 192 €);
- Manual reserve service – 1530 DKK (about 204 €) for up-regulation and 508 DKK (68 €) for down-regulation.

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[19] Scandinavia

[20] ElSpot

[21] Maximum energy available: 5 kWh; Maximum connection power: 2 kW

A similar study [47] has investigated the potential of PEV as providers of primary, secondary and tertiary frequency regulation, based on real data from Sweden and Germany during 4 months of 2008. In order to estimate profits that could be generated by PEV in Sweden and Germany, authors have developed a model that simulates the behaviour of 500 individual PEV during January, April, July and October of 2008. In this model, PEV were assumed to drive 35 min, 2 times per day, being parked, plugged-in by a 3.5 kW connection, and available to participate in the regulation market during the remaining time of the day.

The results of this simulation show that, in the Swedish regulation market the PEV do not give any profit, and that in the German market PEV may only provide down-regulation, preventing possible economic losses from providing up-regulation. In the German market, the following incomes would be achieved by providing down-regulation:

- 60 €/month in primary regulation services;
- 40 €/month in secondary regulation services;
- 10 €/month in tertiary regulation services.

These works developed in Europe and US show that PEV have a huge potential to provide frequency regulation, with evident benefits to power system, and interesting revenues to electric drivers. The contribution of PEV for frequency regulation would contribute to ensure the system stability in a framework of large penetration of intermittent RES. However, to release these benefits, analysed works suggest that would be implemented smart control systems, including price-signalling technologies, to ensure the charging control of PEV. Other important remark is that authors do not typically have doubts about potential of V2G, with unidirectional power flow, but they show several concerns about V2G, with bidirectional power flow, being achieved reduced or zero profit in some markets by this approach.

## 2.4. Architecture and advanced control charging strategies

### 2.4.1. Aggregative approach

Regarding architecture and control strategies, [48] proposes that PEV can operate as controllable loads, contributing to demand management, or as generation/storage devices to provide capacity and ancillary services to the electric power system. This is supported by the concept of the aggregation entity, which concentrates all small storage capacity of PEV to act as a single provider in the operation market. This entity would have the following main roles:

- Concentration of PEV power in MV packages capacity to be allowed to participate on the operation market;
- Provide aggregated capacity and energy services to SO, from all PEV;
- Allow each PEV to benefit from better purchasing conditions in energy, batteries and other services in large-scale.

According to that author, the aggregation entity can support the SO to ensure a balanced system operation between demand and generation, providing down-regulation and up-regulation. As controllable loads, PEV can provide symmetrical control power increasing or decreasing the load on the system. The PEV start-charging action increases the load and delivers down-regulation. The PEV stop-charging action decreases the load and delivers up-regulation. Furthermore, as dispatched generation, PEV can discharge their batteries and supply energy to the grid providing up-regulation.

These authors are mainly focused on a V2G concept, with bidirectional power flow, and they do not consider the possibility of down and up-regulation, operating PEV as simple controllable loads, with evident benefits in terms of investment in infrastructures, battery lifetime and efficiency.

The aggregator interfaces with PEV, SO and energy suppliers. Figure 25 displays the interrelationships among these stakeholders.

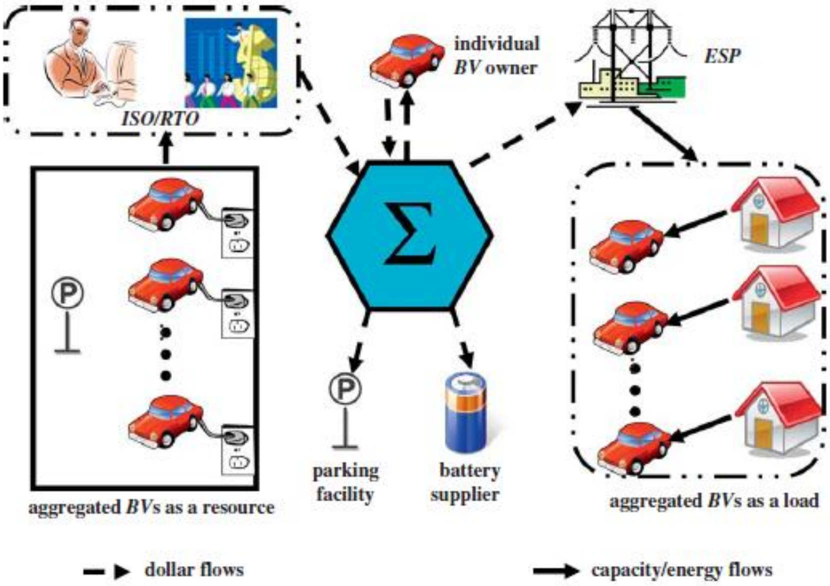

Figure 25 – Aggregator in a concept of V2G, with bidirectional power flow [48]

This approach is characterized by a physical layer of power and energy flows and battery and parking services, supported by an information layer with control commands, monitoring data, billing information and other required communication services.

Based on this work, the main challenges for implementation of this approach include the construction of the information layer[22] and the scheme to attract and retain PEV owners with appropriate incentives. The information layer must have capability to ensure the required information transfers between the aggregator and each PEV, SO and ESP. The aggregator needs to have information about the battery status of each PEV, to collect data for services provided to PEV and SO, to follow the services provided by PEV, and to maintain the required data on the battery purchase and maintenance and on the parking services.

The network must provide the appropriate interfaces for metering electrical power flows to and from each PEV, for storage all the data collected including those for billing purposes, and for transmitting the control signals to PEV from SO and ESP. Based on this framework, [48] also includes simulations of the usable storage as a function of time and provision of reliable up and down-regulation services and load shaving energy with aggregation of PEV. Results indicate that the ability of the aggregator to provide services grows as the size of the PEV aggregation increases.

As approached by the previous work, despite the amount of studies that have been developed on the field of V2G, according to [49] the main challenge remains on the technical feasibility of aggregation of thousands PEV, providing ancillary services with the availability, reliability and security levels required by SO. The scope of this work suggests a possible V2G system based on economically existing technologies and it tests the applicability of the system concepts on two markets with different rules and regulations – Sweden and Germany.

This work proposes a reference architecture to deliver symmetric regulation by operation of PEV in V2G, with bidirectional or unidirectional power flow – As controllable loads or as generation.

As proposed in the previous work, this approach introduces a new entity which aggregates PEV in order to overcome some market constraints and to correspond to the rules of the SO. A typical cross country SO rule is the minimum bid capacity – Typically 1 MW. Even the lowest bids are too large to be handled by a single PEV. Therefore, a minimum number of PEV has to be aggregated to be able to participate on the operation market. The

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[22] Computer, communication and control network

aggregator will be the entity that ensures the promised control power, but the physical power is delivered by each PEV. This requires bi-directional communication between the aggregator and PEV, as depicted in Figure 26, which shows the proposed reference architecture.

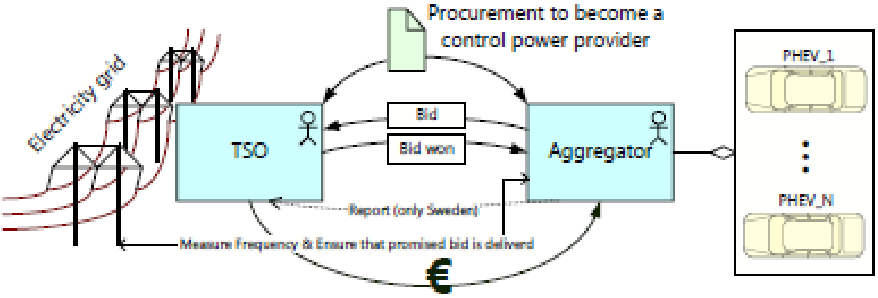

Figure 26 – Interaction between the TSO, aggregator and PEV [49]

Overall, this work has concluded that through a central aggregator, PEV can provide symmetric control power, in V2G configurations with bidirectional or unidirectional power flow, in operation markets of Sweden and Germany. For V2G, with bidirectional power follow, it was concluded that the system requires intelligence both in PEV and at the charging point, being more expensive than systems based on unidirectional power flow. V2G, with unidirectional power flow, would be considered the cheapest for implementation, if PEV were V2G compatible, being more probable its implementation to provide regulation services in the near-term future.

Other work [50] compares a direct deterministic PEV control architecture with an aggregative PEV control architecture regarding the availability, reliability and value of services provided by PEV. Authors suggest that V2G must satisfy the requirements of two important stakeholders, SO and electric driver, to achieve wide-spread near-term participation in the operation market. This study assumes that in direct deterministic architecture exists a direct communication line between the SO and each PEV, allowing its command. In this architecture the PEV is allowed to bid and perform services during the charging period. This architecture is conceptually simple but it has recognized problems in terms of near-term feasibility and long-term scalability.

On the other hand, the study proposes a new command and contracting architecture to provide ancillary services, which aggregates PEV to make a single controllable power resource. In this aggregative architecture, the aggregator receives ancillary service calls from the SO and it issues commands to contracted PEV that are available and willing to perform the required services. The aggregator bids into the hourly operation market and compensates

PEV, under its control, for each minute that they are available to perform regulation. This architecture attempts to address 2 main problems of the direct deterministic architecture:

- Large-scale aggregation and improved reliability allow the aggregator to be seen by SO as a conventional ancillary services provider.
- Communications between aggregator and PEV in a more manageable scale. This architecture is therefore more scalable in PEV and aggregators.

Globally, the study concludes that the aggregative architecture is more feasible and scalable for implementation of V2G ancillary services from the perspective of the SO. On the other hand, the direct deterministic architecture is preferred from the electric driver perspective. However, the authors conclude that the different requirements of stakeholders make only the aggregative architecture acceptable to both parties. The direct deterministic architecture appears to be unacceptably complex, unreliable and unscalable for utilities and SO. The aggregative architecture reduces the revenue of electric drivers, but it still allows positive revenue. The authors suggest that only the aggregative architecture is mutually acceptable for all stakeholders and can provide a more feasible implementation of a MMS.

In the work [51] a conceptual framework for integration of PEV into electric power systems is also presented, covering in detail the network operation and electricity markets. This work also presents several simulations in order to illustrate the potential impacts and benefits from the integration of PEV according this framework, but at this level only the proposed framework will be analysed.

From [51], a large deployment of PEV will involve: evaluation of battery charging impacts may have on the system operation; identification of adequate management and control strategies regarding battery charging periods and use of RES; assessment of the PEV potential to participate in the operation market, in order to provide ancillary services, regulation reserves and deliver power, within a V2G concept.

The proposed control architecture and market framework is based on the combination of a centralized hierarchical management and control structure with a local control at the PEV interface. To ensure the participation of PEV on the electricity markets, more than smart grid interfacing devices are required. In this case, a hierarchical management and control structure is required for the entire network operation, including PEV management.

From [51], in normal operating conditions, PEV will be managed and controlled by an aggregation entity, which concentrates electric drivers according to their preferences. Proposed technical and management structures are described in Figure 27.

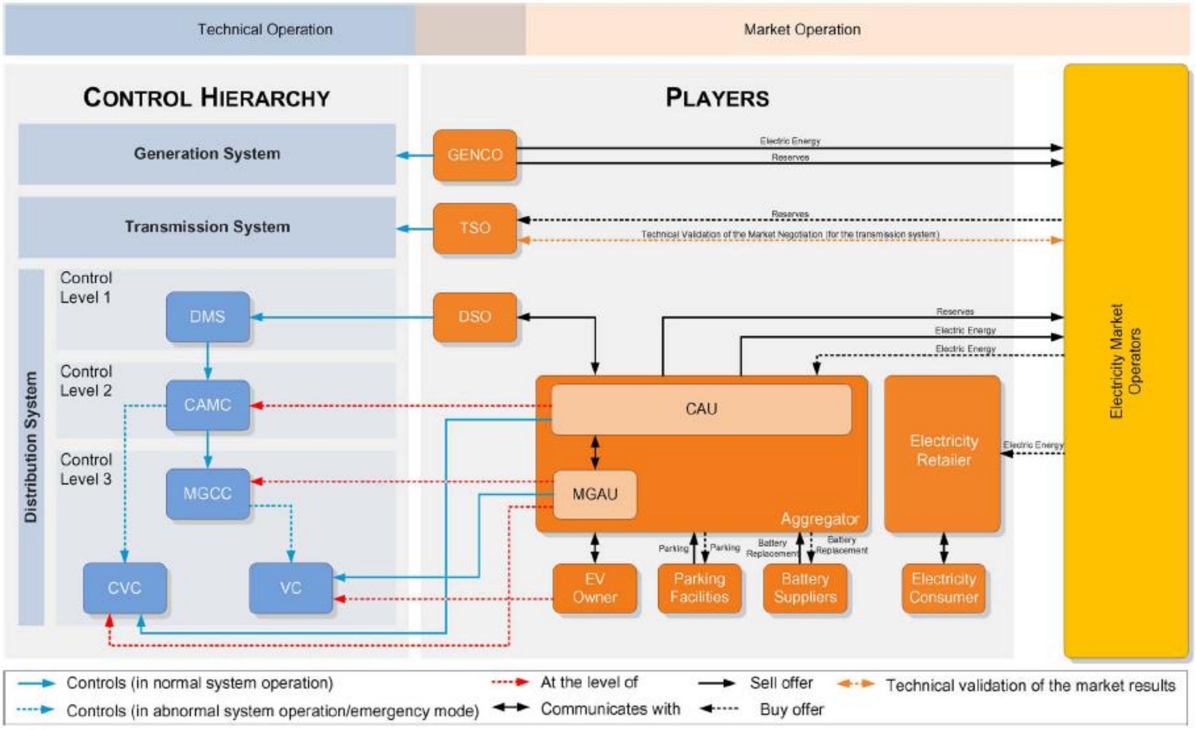

Figure 27 – Framework for PEV integration into electric power systems [51]

Given the complexity of the information that an aggregator has to collect and process, authors suggest a hierarchical management structure independent from the DSO. Being the aggregator responsible by management of a large geographic area, it will be composed by two different entities: Central Aggregation Unit (CAU) and Microgrid Aggregation Unit (MGAU). CAU manages up to a maximum of 20 000 customers, typically supplied by a High Voltage (HV) / Medium Voltage (MV) substation, communicates with several downstream MGAU, located in MV/LV substations, with an expected maximum of about 400 customers.

Each PEV must have a Vehicle Controller (VC) to support bidirectional communications with the upstream charging management system. On the other hand, it would be also implemented a Cluster of Vehicle Controller (CVC) to control the charging of large parking lots (e.g. shopping centres) supplied in MV.

Aggregators will forecast the market behaviour for the day-ahead and prepare their bids. However, a prior negotiation with the DSO must take place to prevent the occurrence of congestion and voltage drops in distribution networks. Aggregators will present their day-ahead proposals to the DSO, which will evaluate its technical feasibility. If valid, the aggregator can proceed to the market negotiation. If not, the aggregator has to make the required changes to guarantee a safe operation of the distribution network on the day-ahead.

The work [52] also presents a PEV control strategy based on the concept of aggregation entity, but only focused on the load management potential of PEV. Aggregators acquire data from PEV in each area and build a consolidated model that describes overall load availability.

The control structure of power systems based on current Automatic Generation Control (AGC) is not likely change in the foreseeable future, even though the challenges associated to the intermittency of renewable generation. Any strategy for incorporating load control into the power system operations have to be compatible with existing control systems. On the other hand, the effectiveness of load control is very much dependent upon participation of large number of devices and its direct interaction with AGC is impractical. In this context, it is suggested that aggregators can be the most effective load control strategy to satisfy these dual requirements.

Each aggregator has control over a group of PEV and provides an interface between these loads and the AGC. It acquires information from participating loads, regarding their ability and availability to respond to control actions. The aggregator uses the information received from each PEV to build a model of the responsiveness of the entire group.

The aggregator should interact with the AGC, as performed by large generators in power plants, including two-ways information exchange. Aggregators should be able to dispatch their loads to respond to the same up/down signals that are received by large generators. This requires that the aggregator has to process control signals, received from AGC, and pass the right instructions to single PEV.

It is suggested that the central challenge for PEV participation on operation market lies on ensuring adequate end-users performance while delivering ancillary services. To meet this challenge, load models, communications and control frameworks that effectively can balance these objectives are required.

As presented on this section, several studies have suggested that the conceptual control architecture would be based on aggregation entities, in order to meet the reliability requirements of SO, preferences of end-users and technical feasibility. On the other hand, a system based on V2G, with unidirectional power flow, seems to ensure up and down-regulation services with more profitable results and higher efficiency, with lower infrastructure investments and reduced impact on battery lifetime, regarding the current state of the art technology.

### 2.4.2. Non-aggregative approach

Another relevant work [53] has a slightly different approach from previous ones. In this work, a charging control of PEV is proposed in order to ensure frequency regulation capacity during nighttimes, by direct response of PEV to frequency variations.

Typically, SO are responsible for the regional balance between supply and demand. To carry out their responsibility, they control the output of generation units based on the Area Control Error (ACE). The control is implemented by dispatching the ACE to PEV plugged into the control area, keeping the regional balance and then restoring the frequency to nominal value and the tie-line power flow to their desired values.

In this study, the control method is based on ACE and frequency characteristic of PEV ($k_{PEV}$), which corresponds to a change in charging power divided by a change in frequency. With this method, the SO could control the charging power to the desired value by sending the same signal ($f_{LFC}$=-ACE/$k_{PEV}$) to all PEV. According to the authors, sending the same signal to all PEV allows SO to recognize all PEV as a single controlled object, leading to easier control system and reduction of cost in communication infrastructures.

By simulation of this control method in a power system model with two interconnected control areas, results demonstrate that it is possible to suppress the frequency fluctuation caused by wind power, especially during nighttimes, and to ensure the programmed power flow in tie-lines, reducing the requirements of traditional regulation capacity.

# 3. Analysis of PEV charging impact on the distribution network

To support the future development of a control architecture and advanced control charging strategies, this part of the work deals with an overall analysis to the impact of large scale penetration of PEV on the distribution network. This section intends to identify possible constraints at Low Voltage (LV) networks caused by PEV charging. At this level, some analysis regarding PQ disturbances are performed.

As DSO are committed with standards, such as EN 50160 [54] and QoS regulation codes, and regarding they efforts to fit the increasing PQ demand by end-users, the control system should be able to manage the PEV charging, preventing load congestion, voltage drops and high levels of harmonic distortion.

The impact of charging rectifiers on the voltage quality is assessed by PQ monitoring in a normal power charging point. The main focus of this approach intends to characterize the harmonic distortion of the current drawn in normal charging points.

Some studies have been done on the field of PEV integration in electric power systems, namely in terms of load impact and network congestion, during peak and off-peak hours, for large-scale penetration of PEV. On the other hand, some works have been presented regarding the potential impact of PEV chargers on the PQ. This new load is typically characterized by 1-phase[23] or 3-phase[24] rectifiers to convert AC in DC power to charge battery packs, which

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[23] 230 $V_{AC}$

[24] 400 $V_{AC}$

typically store the energy at 300 $V_{DC}$ – 400 $V_{DC}$. As any other non-linear electronic load, based on diodes, thyristors or Isolated Gate Bipolar Transistors (IGBT), these rectifiers may generate some harmonic currents. Actually, harmonic distortion is an important issue that is drawing attention in the field of integration of PEV in power systems. The the [55] presents a simulation study of the impact of PEV charging on the PQ of smart distribution systems, in Australia. The simulations, based on the expansion of the IEEE 30 bus system, conclude that low PEV penetration levels, with normal charging rates, will have acceptable low harmonic levels and voltage variations, but fast charging rates would cause significant voltage harmonics and losses.

Based on the effect analysis of PEV charging on distribution transformers, presented in [56], there is a quadratic relationship between the transformer lifetime fade and the $THD_I$ of battery charging, suggesting that $THD_I$ should be limited to 25% – 30% to have an acceptable transformer lifetime expectancy. Also simulation results for large-scale penetration of PEV are presented in [57], based on a LV residential network, with 19 buses, for assessment of voltage variations, system losses, transformer overloading and harmonic distortion, assuming several charging scenarios over the time of one day. This study concludes that the penetration of PEV, as well as the regime and the period of charging have major impacts on system losses and on voltage distortion, putting in evidence the advantages of coordinated charging, namely by a control system.

In a complementary perspective, considering that some charging technologies tend to cancel or amplify harmonics generated by other loads, [58] presents a comparison between four typical PEV charger designs: Pulse Width Modulated (PWM); square wave; basic 1-phase bridge rectifier; 3-phase bridge rectifier. This study suggests that PWM chargers may be an interesting option to reduce or remove undesirable harmonics from the power system, if properly configured to automatically minimize the sum of preselected harmonic components.

## 3.1. Introduction to the harmonic distortion theory

Voltage systems generated by large synchronous machines are typically symmetrical and balanced, characterized by 3-phase sinusoidal waveforms. In ideal power system, supplying linear loads, which draw sinusoidal currents, proportional to the voltage waveform, like resistance heaters and incandescent lamps, the voltage waveform would remain sinusoidal across all T&D networks. However, current power systems are no longer supplying only linear loads. Non-linear loads, like switched mode power supplies, which draw non-sinusoidal currents, are proliferating in domestic and industrial appliances, generating harmonic currents and inducing voltage distortion in distribution networks.

According to the Fourier theorem, any periodic function can be expressed by a series composed by: a sinusoidal component at the fundamental frequency; plus a series of sinusoidal components, which are integral multipliers of the fundamental frequency; and a constant – the continuous component. Therefore, the instantaneous value of current, drawn by a non-linear load, may be expressed by:

$$i(t) = I_0 + I_{p1}\sin(wt + \varphi_1) + \mathrm{I}_{\mathrm{p2}}\sin(2wt + \varphi_2) + \cdots$$

$$\ldots + \mathrm{I}_{\mathrm{ph}}\sin(hwt + \varphi_h)$$

with:

- $i(t)$ – instantaneous value of current on t;
- $I_0$ – mean value of current (DC component);
- $I_{ph}$ – peak value of the harmonic component *h*;
- $\varphi_h$ – lag of the harmonic component *h* on t=0;
- *w – 2πf* , with *f* – frequency of the fundamental component.

Ignoring the DC component:

$$i(t) = \sum_{h=1}^{\infty} I_{ph} sin(hwt + \varphi_h)$$

$$i(t) = \sum_{h=1}^{\infty} \sqrt{2} I_h sin(hwt + \varphi_h)$$

where:

- $I_h$ – RMS value of the harmonic component *h*.

The RMS current can be expressed by:

$$I = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt}$$

$$I = \sqrt{\sum_{h=1}^{\infty} I_h^2} = \sqrt{I_1^2 + I_2^2 + I_3^2 + \cdots + I_h^2}$$

The RMS current THD can be also expressed by:

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100\%$$

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + \cdots + I_h^2}}{I_1} \times 100\%$$

In ideal conditions, power conversion with full wave rectifiers generates harmonic currents with the following components:

$$h = np \pm 1$$

where:

- $h$ – harmonic order;
- $n$ – integer 1, 2, 3, 4…;
- $p$ – number of current pulses per cycle.

Theoretically, a 1-phase full wave diode rectifier generates harmonic currents, based on 2 rectified current pulses per cycle[25] converted to DC, with the following main components: 3, 5, 7, 9, 11, 13… On the other hand, a 3-phase full wave diode rectifier generates harmonic currents, based on 6 rectified current pulses per cycle[26] converted to DC load, with the following main components: 5, 7, 11, 13…

As this kind of non-linear loads have symmetrical waveforms[27], only odd harmonics components are generated. Loads with asymmetrical waveforms generate odd and even harmonic components, as well as possibly DC components.

The harmonic distortion of supply voltage typically is a direct consequence of harmonic current flows by impedances of T&D lines and transformers, causing harmonic voltage drops on each related component.

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[25] 1 pulse per half cycle.

[26] 1 pulse per half cycle, per phase.

[27] The positive half cycle is identical to the negative half cycle.

## 3.2. Harmonic current emissions in normal power charging

The analysis and characterization of the impact of normal power charging method on the supply network are based on voltage and current monitoring of the onboard 1-phase charger, during a charging operation, by Mode 2, in a standard non-dedicated socket outlet in an office-building.

Measurements were carried out with the ISR's Nissan Leaf, with a battery pack of 24 kWh, during a charging operation of 14.4 kWh, as presented in Figure 28, from onboard displayed 64 km range to 166 km range. Monitoring data were collected by a PQ recording device[28], in accordance to the class A requirements of the standard IEC 61000-4-30.

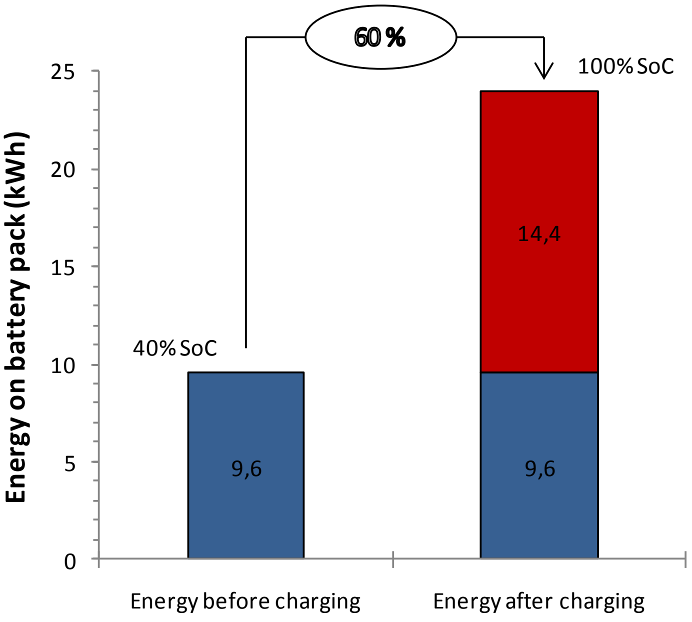

Figure 28 – Energy charged in a normal power charging point

Figure 29 shows the RMS values of current and voltage during the charging period of 4h:10min. Voltage has remained constant (about 225 V) during all charging period. Current has also remained constant (about 16.4 A) during the first 3h:44min. In the last 26 minutes, the current has decreased progressively from 16.4 A to about 6 A, followed by the automatic switch-off.

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[28] Fluke 1760

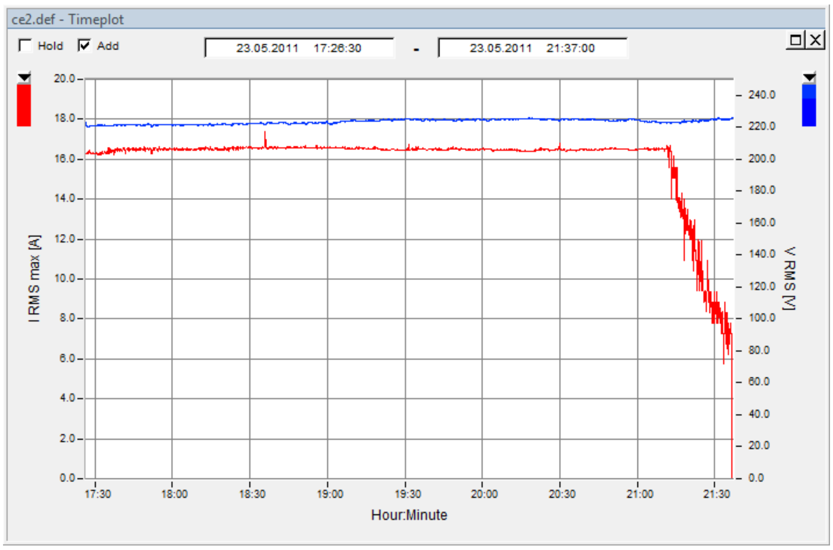

Figure 29 – Maximum RMS values of current and average RMS values of voltage recorded in 10s intervals

Regarding harmonic distortion, Figure 30 shows maximum values of THD of current and voltage during the charging period. The values of $THD_V$ have range among the typical values recorded in office-buildings (2% - 3%), supplied in MV. The values of $THD_I$ have remained constant (12%) during the first 3h:44min and they have reached a maximum of 16% in the last 26 minutes, with lower charging currents.

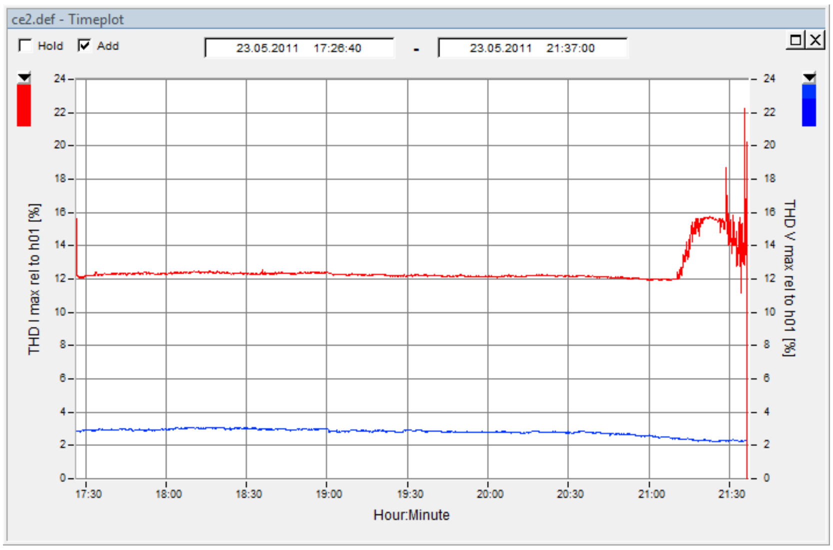

Figure 30 – Maximum values of THD of current and voltage recorded in 10s intervals

The 3rd harmonic current reached maximum RMS values around 1.9 A (11.6%), during the initial period of 3h44min, being by far the most significant harmonic component contributing to the $THD_I$. These significant values of the 3rd harmonic component show that PEV charging can contribute to increase the harmonic distortion in LV networks, supplied typically by public power transformers in delta-star connection, inducing additional losses in neutral conductors and power transformers.

Based on collected data, Figure 31 compares maximum RMS values of the most important harmonic current components with limits defined by the standard IEC 61000-3-2 [59] for class A equipment. Recording data on this field test would not be directly compared with limits of the standard IEC 61000-3-2 [59], because measurements were not carried out in lab environment, as required by the standard. However, this approach allows an outlining of the main expected conclusions.

This comparison shows that all recorded harmonic components have maximum values significantly below to the admissible limits of the standard.

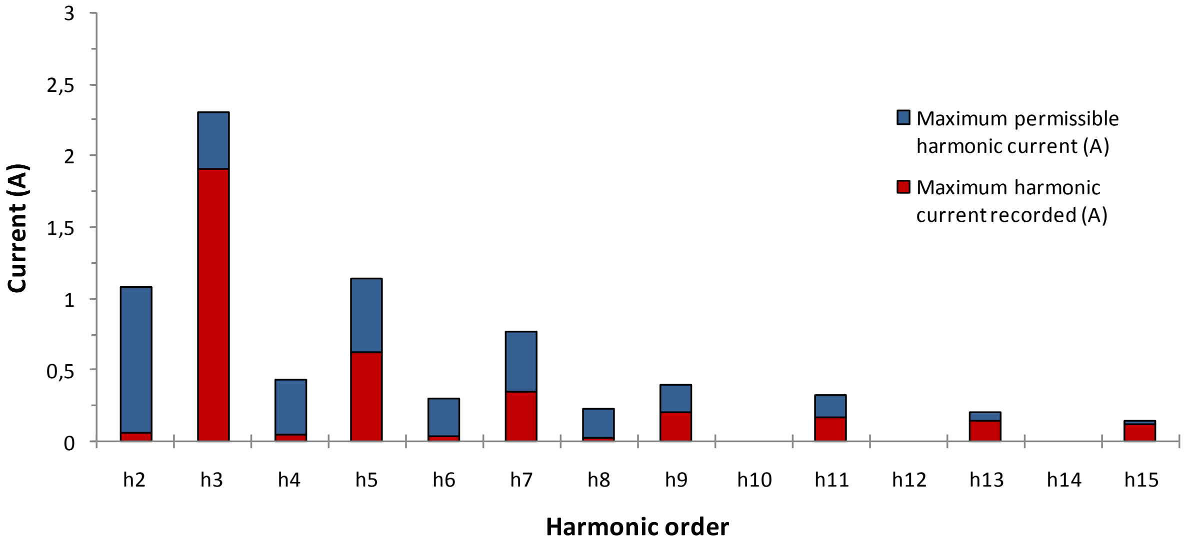

Figure 31 – Harmonic current in normal power charging (up to 16 A) – Comparison between recorded values and admissible values of IEC 61000-3-2 for Class A equipment

Based on field tests carried out in this work, the following main conclusions can be highlighted:

- Normal power charging of PEV can contribute to increase the harmonic distortion in LV public distribution networks, despite expected harmonic current emissions significantly below to limits of the standard IEC 61000-3-2 [59] for class A equipment.
- The simultaneous operation of several 1-phase chargers in the same LV feeder, with maximum 3rd harmonic currents around 12% and $THD_I$ between 12% and 16%, can have a significant impact on distribution networks. In these situations, right technologies should be adopted in order to prevent the potential impact of the 3rd harmonic current on neutral conducts and power transformers.

# 4. Ancillary services in the Portuguese power system

Ancillary services are traditionally provided by large power plants to support fundamental services of generation, transmission and distribution. The main purpose of these services is to ensure good levels of supply security, reliability and QoS. Regarding the system operation requirements, ancillary services may be grouped in two main categories:

- Ancillary services related to active power and Load-Frequency Control (LFC), to ensure the balance between demand and generation;
- Ancillary services related to voltage control, to support the desired voltage profile and optimum reactive power flow in T&D networks.

In deregulated markets, ancillary services are typically separated from the energy generation services, being transacted between agents by market-driven mechanisms [60]. In terms of market organization, these ancillary services may be also included in two main categories [61]:

- Mandatory services – Ancillary services due by generators participating in ordinary regime, not eligible for any additional remuneration:
    - Voltage control;
    - Stability control;
    - Primary regulation.

- Complementary services – Ancillary services eligible for extra remuneration:
    - Secondary regulation;
    - Regulation reserve;
    - Blackstart;
    - Synchronous and static compensation;
    - Fast load-shedding.

Nowadays, in Portugal only secondary regulation and regulation reserve ancillary services are remunerated by competitive market-driven mechanisms on the operation market, being these ancillary services permanently required for a safe and reliable operation of the electric power system. Currently, agents that provide complementary ancillary services on the operation market are EDP, Iberdrola and REN Trading. Remaining complementary ancillary services are provided by bilateral arrangements, being required only in some critical events. This section is only focused on LFC related ancillary services, regarding the expected potential to be provided by PEV.

LFC ancillary services in Portugal have to be analysed in the context of the CESA[29], where the Portuguese power system is integrated. Figure 32 presents the 5 permanent regional groups, or synchronous areas, of the ENTSO: Continental Europe; Nordic; Baltic; UK and Ireland.

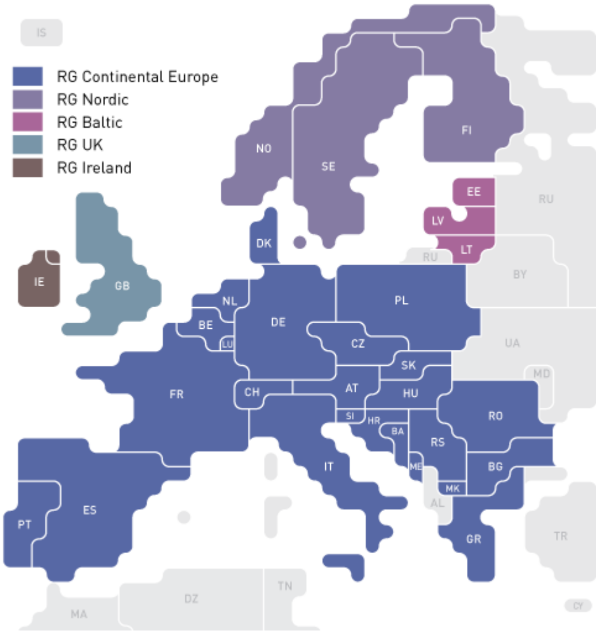

Figure 32 – Permanent Regional Groups of ENTSO [62]

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[29] Former Union for the Coordination of the Transmission of Electricity (UCTE)

In order to ensure the power system stability in a synchronous area, the balance between demand and generation has to be maintained, i.e. the generated active power has to permanently match the demand. Any disturbance to this balance is initially attenuated by the kinetic energy of rotating generators and motors connected to T&D networks.

Regarding current limitations associated to the energy storage, power system must have enough flexibility and LFC to react in real-time to load variations and unpredictable outages of power plants or severe faults in transmission networks.

In the CESA, the control and reserves are organized in a hierarchical structure, composed by 2 coordination centres[30], control blocks and control areas, typically associated to each TSO. [63].

As presented in Figure 33, the LFC is developed in independent and subsequent levels, by primary control, secondary control, tertiary control and time control, in order to support the provision of ancillary services of primary regulation, secondary regulation and regulation reserve.

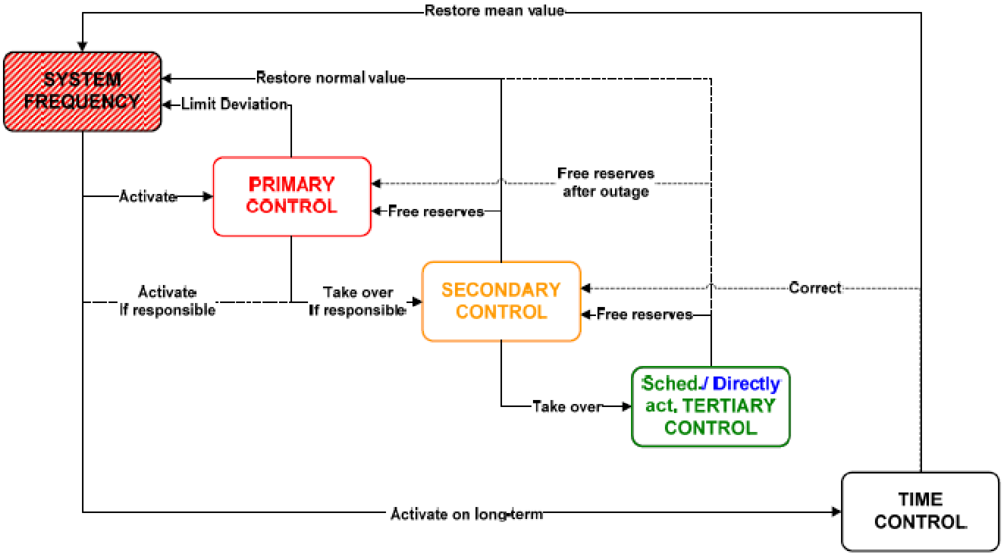

Figure 33 – Control scheme and actions starting with the system frequency [63]

Figure 34 presents an overview of the activation process of different reserves in order to recovery from a large frequency drop caused by an incident. The rose-coloured shaded area corresponds to the frequency deviation, which leads to the activation, in seconds, of the primary control reserve in all CESA, followed by the activation, in minutes, of the local secondary control reserve that is supported and replaced by the tertiary control reserve.

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[30] UCTE South and UCTE North

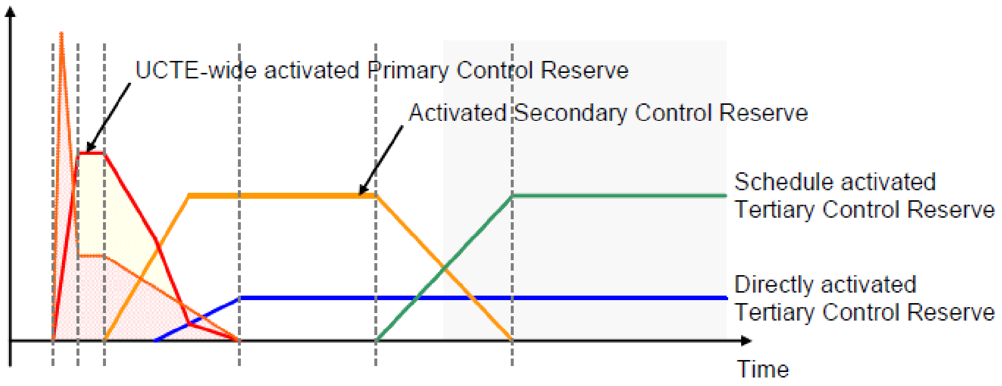

Figure 34 – Progressive activation of reserves as consequence of large frequency deviation [63]

## 4.1. Primary regulation

Primary regulation is the mandatory ancillary service associated to the primary control action, performed automatically by large generators, in ordinary regime, in order to prevent large frequency deviations from 50 Hz, as consequence of any disturbance. The proportional characteristic of the primary control and the global contribution of all control areas in the CESA are such that the balance between demand and generation is restored in few seconds, after a disturbance, ensuring that the frequency is maintained within admissible limits [63]. Primary controllers of generators, participating in this control action, adjust the output power until the balance between demand and generation be re-established. After deployment of primary control action, the frequency remains at a quasi-stationary regime, with an offset to the set-point, as result of the droop characteristic of generators. As consequence, the tie-lines power flow between control areas varies from scheduled values, requiring the action of secondary control in order to restore the frequency set-point and the power flow scheduled values in tie-lines.

The total primary control reserve is defined by the RG Continental Europe, and it should be fully activated in response to quasi-stationary frequency deviations of 200 mHz or more [63]. Every interconnected system has to contribute to the primary control reserve, being this power defined to Portugal every year by [64]:

$$R_{PC} = \frac{E}{E_T} \times R_{PCT}$$

with:

- $R_{PC}$ – Primary control reserve;

- E – Energy generated during the previous year by the national power system, including exportation and energy generated according to programs by participating generators;
- $E_T$ – Total energy generated during the previous year by all power systems included in the CESA;
- $R_{PCT}$ – Minimum primary control reserve established to the CESA.

Generators providing primary regulation should allow a primary control range at least 5% of the rated power around each stable operating point, and they should be fitted with regulators of 10 mHz resolution and no dead-band [64].

According to the rules of the CESA, the required primary control reserve of each control area should be fully activated within the following timeframe [61]:

- Up to 15 seconds, for disturbances that cause frequency deviations below to 100 mHz (1500 MW in the CESA);
- Between 15 and 30 seconds, with linear variation, for disturbances causing frequency deviations between 100 and 200 mHz (between 1500 MW and 3000 MW in the CESA).

## 4.2. Secondary regulation

The primary control prevents any disturbance to result in large frequency deviations, but it does not restore the frequency to the set-point value (50 Hz), leading this first control approach to a sustainable frequency deviation. The main purpose of the secondary control is to restore the system frequency to its set-point and the tie-lines power flow, between adjacent control areas, to their scheduled values, ensuring that activated primary control reserve within adjacent control areas is restored. The secondary control should not disturb the action of primary control, being expected a simultaneous and continuous operation, both in response to minor or larger frequency deviations [63].

By opposition to primary control action, for that all control areas contribute with mutual support, the secondary control action should only be carried out by the control area affected by the unbalance, which consequently should activate the required secondary control reserve from its resources.

Secondary regulation is the complementary ancillary service associated to the secondary control action. In order to understand this complementary ancillary service in Portugal, the following concepts should be addressed:

- Secondary control, or regulation[31], range – Adjustable range of power, where the secondary controller can operate automatically, in both directions – up and down, at any time, from the current operating point. It corresponds to the sum, in absolute value, of individual contributions of all generators participating in secondary regulation.
    - Secondary control, or regulation, reserve – Positive part of the secondary control range, between the current operating point and the maximum value.
    - Secondary control, or regulation, power – Portion of secondary control range already activated at the current operating point.

The required secondary control reserve typically depends on load variations, scheduled changes and generating units. The secondary control reserve is established by each SO to their control areas, for each hour, following the criteria of ENTSO, given by:

$$R_{SC} = \sqrt{aL_{max} + b^2} - b$$

with:

- a = 10 MW and b = 150 MW, empirically established;
- $L_{max}$ – Forecasted maximum demand for each hour.

Based on this expression, Figure 35 presents the minimum secondary control reserve, recommended to a control area with maximum hourly peak power up to 10 000 MW, where the Portuguese control area is included.

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[31] Secondary control – Statement more used in technical contexts; Secondary regulation – Statement more used in market contexts

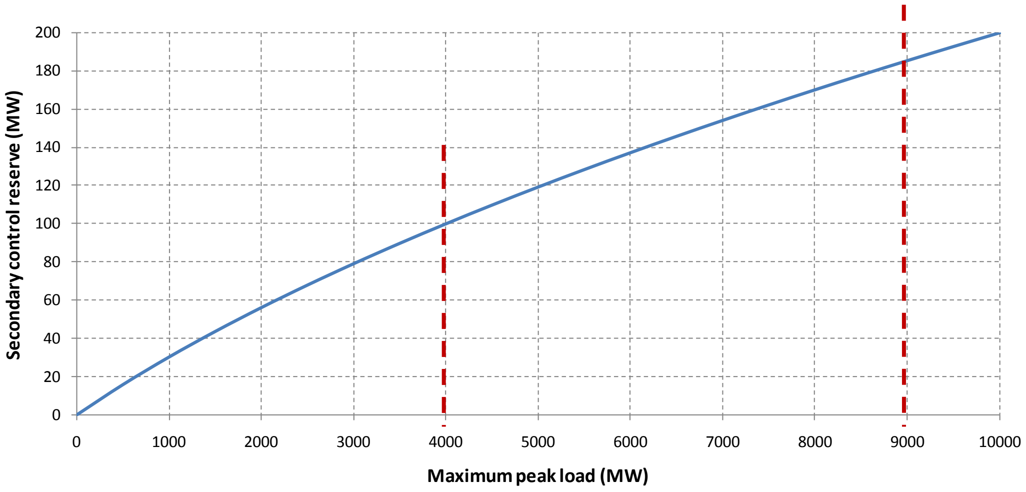

Figure 35 – Minimum recommended secondary control reserve by maximum hourly load

In Portugal, the secondary control reserve for up-regulation has been following this recommend criterion of ENTSO. Regarding the secondary control reserve for down-regulation, the contracted values have been being 50% of the recommend, as it is typically easier and faster to mobilize control reserve for down-regulation than for up-regulation [65].

For optimized operation of the power system, a central controller, the AGC, is required to ensure the LFC, in order to maintain the frequency variation and tie-lines power flow within admissible limits.

After resolution of technical constraints, in the day-ahead market, starts the market of secondary regulation range and regulation reserve, for that each agent bids for installation, with teleregulation capabilities, a specific secondary regulation range with respective price for each hour of the day-ahead. Each bid has to fulfil a pre-established relation between the regulation range for up and down regulation [61].

The SO defines and communicates each day to generation companies the required secondary regulation range for each hour of the day-ahead, establishing the relation between secondary regulation range for up and down regulation [64]. On the other hand, providers bid a secondary regulation range, in MW, with prices to each hour of the day-ahead, in €/MW, being the price limited to a maximum regulated value. The SO assigns the bids based on the lower global over cost criterion. The sum of assigned secondary regulation ranges would be with the interval of +/- 10% around the required secondary regulation range.

This complementary ancillary service is typically provided by large generators, with teleregulation capacity, being their remuneration achieved by market-driven mechanism composed by the following 2 components [61]:

- Secondary regulation range – Value in €/MW for each hour, obtained in the operation market, based on hourly maximum marginal prices[32] of secondary regulation reserves for up and down regulation.
- Secondary regulation energy (if mobilized) – Value in €/MWh for each hour, obtained in the operation market of regulation reserve, remunerated at hourly maximum marginal prices[33] called each hour for up and down regulation.

The secondary regulation range represents a fixed cost to the system, as this range is required besides the occurrence of deviations. By this reason, the cost is supported by all agents. However, the cost of secondary regulation energy is only supported by agents that cause deviations from scheduled values each hour [61].

To perform the secondary regulation, the SO directly controls the regulators of generators, operating as distributor of the regulation signal, informing the regulators about the value of power to provide in each moment [64].

The starting of secondary regulation should not last more than 30 seconds and it should be entirely deployed and eventually complemented by regulation reserve in 15 minutes [61]. The time cycle of the automatic controller should be between 1 and 5 seconds[34], in order to minimize the time between disturbance, reaction and regulation.

## 4.3. Regulation reserve

Following the secondary control, the tertiary control corresponds to the automatic or manual adjustment of operating points of generators or participating loads, in order to:

- Restore the adequate secondary control reserve at the right time;
- Optimize the distribution of secondary control power by generators regarding economic aspects;
- Answer to a maximum predefined generation loss;
- Correction of significant unbalance between demand and generation.

The tertiary control action may be provided by [63]:

---

[32] Last accepted bids
[33] Last bids of energy for regulation reserve
[34] Typically 4 seconds

- Connection or disconnection of power plants (e.g. gas turbines, reservoir, pumped storage power plants, etc.) in order to increase or decrease the output of operating generators;
- Redistribution the output power of generators participating in the secondary control action;
- Adjust the power of interchange programmes between control areas;
- Load telecontrol, by centralised action.

The power connected automatically or manually under tertiary control action, in order to provide or restore an adequate secondary control reserve corresponds to the tertiary control reserve or 15 minutes reserve.

Figure 36 outlines the interaction between secondary and tertiary control actions, based on 3 generators with different actions and operating points.

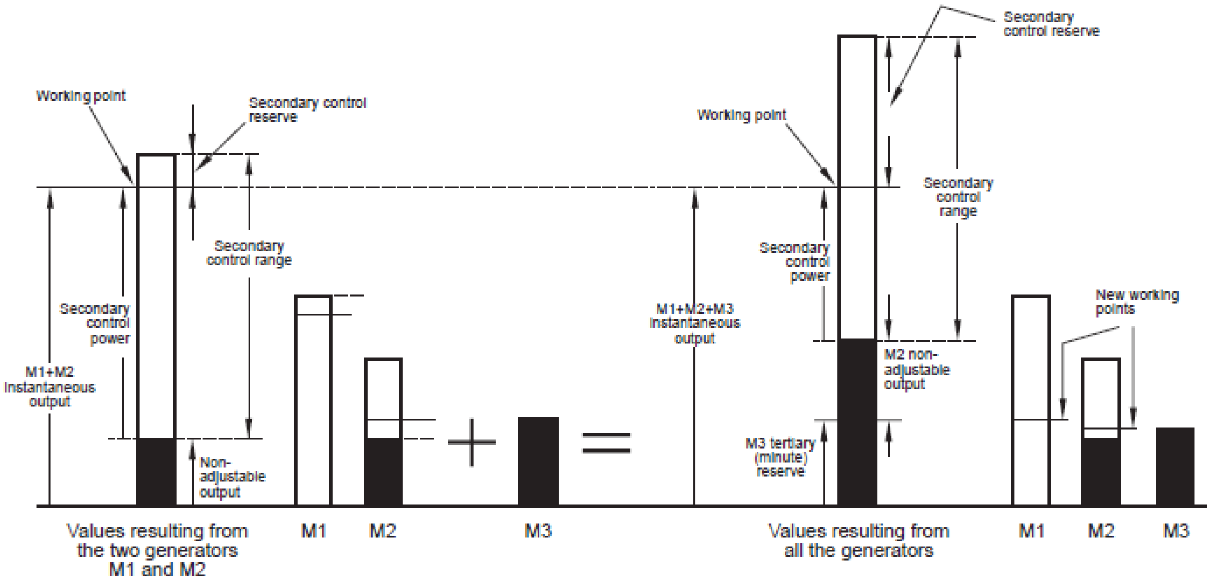

Figure 36 – Diagram of secondary control and tertiary control actions [63]

The tertiary control reserve should start and be available to restore the secondary control reserve in a timeframe of 15 minutes. However, the tertiary control can continue in order to optimise the operation of the transmission network and the generation system.

Figure 37 summarizes the timeframe of primary, secondary and tertiary control actions.

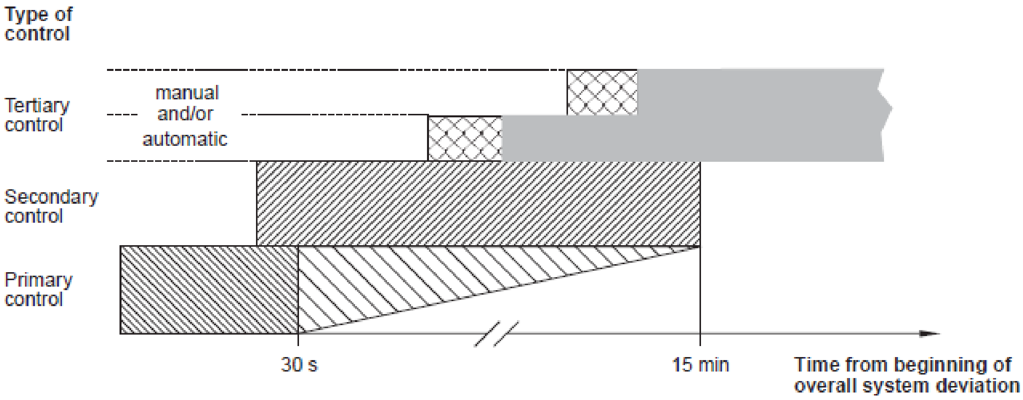

Figure 37 – Timeframe of control actions: primary, secondary and tertiary control [63]

Based on this interaction scheme:

- The range of the primary control action is up to 30 seconds, being progressively replaced by the secondary control action.
- The range of secondary control action is up to 15 min, being complemented or replaced by the range of tertiary control reserve, with manual and/or automatic mobilization.

As mentioned before, the purpose of the tertiary control reserve is to replace the secondary control reserve in use, increasing the available reserve to the initial scheduled values. So, it is typically called and dispatched when the secondary regulation reserve is exhausted.

Regulation reserve is the complementary ancillary service associated to the tertiary control action. This service is also remunerated under market-driven mechanisms, in the Portuguese operation market, and it is composed by the following 2 components [61]:

- Minimum regulation reserve – Defined by the SO for each programmed day-ahead period, based on the potential maximum generation loss caused by the simple outage of an single element of the system[35], plus 2% of the forecasted demand.
- Complementary regulation reserve – It should ensure the operation of the system in the following situations:
    - Hourly demand forecasted by SO is 2% higher than the hourly demand resultant from the generation market;

---

[35] The largest generator

    - Generation losses forecast due to successive failures and/or delays in connection or power increasing of thermal groups.

Agents present bids in the operation market, between 18 and 21 hours, for regulation reserve for up and down regulation for each balance area and for each hour of the day-ahead. In real time, the SO receives the bids, being the market agents remunerated by the price of the last bid mobilized for up or down regulation [61].

The SO manages this regulation reserve based on minimum cost criteria, calling available cheaper bids when the service is required. The regulation energy is remunerated at the marginal price of regulation bids mobilized in each hour, being distinguished the reserve for up-regulation and down-regulation.

Extra costs caused by mobilization of regulation reserve are only distributed by agents that cause the deviation from the scheduled programme.

# 5. Commute profile by car in Portugal

The commute profile by car presented in this Chapter is based on data collected in a survey carried out to employees of EDP, regarding their commuting behaviours. This profile includes the contribution of commuters from 18 cities in Portugal landfield and it aims to characterize the every-weekday round trip between home and offices. In driving distances are also included small travels that commuters have to do in a daily-basis pattern, before and/or after work, for instance to leave and take children in school, go to shopping centres, gym, etc.

In order to build a suitable profile to analyse the potential of PEV, only answers of commuters that use car to travel from home to work and return were considered, corresponding to a universe of 951 drivers. Either cases where the car is used on the complete travel or cases where the car is only used in a part of the distance, for instance to take public transportation means, like train, metro or bus. Therefore, only distances travelled by car were considered to build the commute profile presented in the following sections.

## 5.1. Driving distances during weekdays

Based on this representative survey, the commute profile by car in Portugal is built by extrapolation of the behaviour of 951 drivers, who have contributed to the survey, to a universe of about 300 000 Portuguese commuters. Therefore, Figure 38 shows the daily commute profile of about 300 000 drivers, by car, during weekdays (Monday, Tuesday, Wednesday, Thursday and Friday).

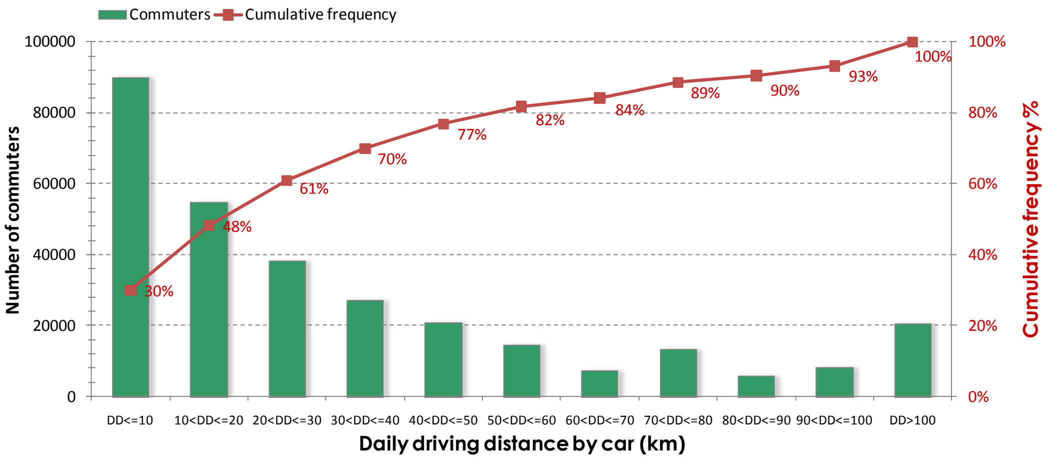

Figure 38 – Histogram of daily Driving Distances (DD) by car during weekdays

Based on this histogram, 77% of the commuters drive, from home to work and return, less than 50 km per day and only 7% of the commuters drive more than 100 km per day.

## 5.2. Parking duration at home during weekdays

In order to build a suitable profile to analyse the potential of PEV to provide ancillary services, when parked at home, only daily driving within the typical ranges of PEV are considered to build the parking duration profile.

Driving distances compatible with typical ranges of PEV are derived from some driving tests performed by researchers at ISR – University of Coimbra with its state of the art FEV - Nissan Leaf. Based on 13 driving tests at average speeds between 30 km/h and 80 km/h and different top speeds, the average energy demand by a FEV will be assumed as 150 Wh/km.

Regarding the results of these driving testes, it will be assumed in this work that a typical commuting PEV has an average demand of 150 Wh/km, a value slightly higher than achieved with the Nissan Leaf in order to consider small extra load or higher sloping profiles in other cities.

On the other hand, assuming that the typical storage capacity of a FEV is around 24 kWh and that 30% of the capacity should not be used, in order to prevent deep discharges and premature battery degradation, a typical FEV would have 16.8 kWh available for everyday travel. Therefore, with an average energy demand of 150 Wh/km, a typical PEV can travel up to 100 km, with an extra safety storage reserve of about 10%. By this reason, the parking duration profile at home is built only based on the behaviour of about 280 000 commuters that travel less than 100 km per day, as presented in Figure 39.

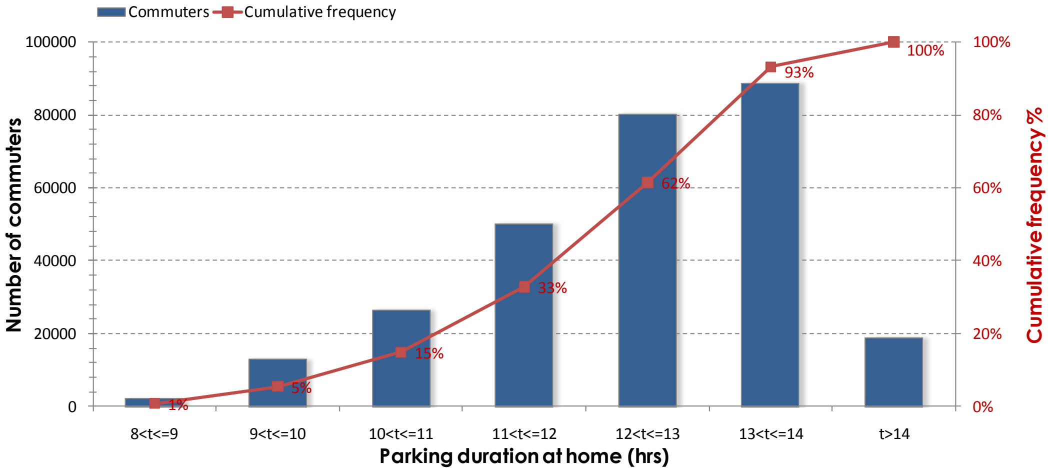

Figure 39 – Histogram of parking duration at home for drivers up to 100 km/day

These data show that all vehicles, which travel up to 100 km per day, are parked at home at least 8 hours per day and that 67% of the vehicles are parked even more than 12 hours per day.

If all these vehicles were replaced by PEV, the parking duration would be enough by far to charge the daily demanded energy. As presented in the section 5.1, 77% of vehicles would require less than 7.5 kWh and 93% less than 15 kWh, which can be charged in about 2 and 4 hours, respectively, in a standard socket outlet of 16 A, at 230 V.

Figure 40 presents the number of vehicles on road, with a 15 minutes resolution, during typical weekday.

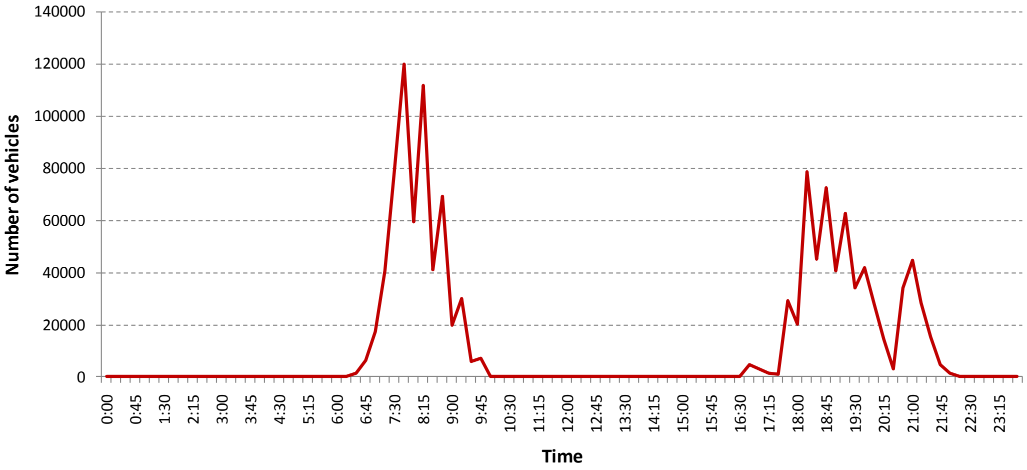

Figure 40 – Number of vehicles on road in typical weekdays

Data show that travels from home to offices of all commuters are performed in a shorter period, between 06:30 and 10:15, than travels from work to home, which are mainly spread from 17:00 to 22:15. As consequence, Figure 41 presents the number of vehicles parked at home during weekdays, being all vehicles parked at home in the period from 22:15 to 06:15, and 90% of the vehicles parked simultaneously at home from 21:00 to 07:00 - During a 10 hours period.

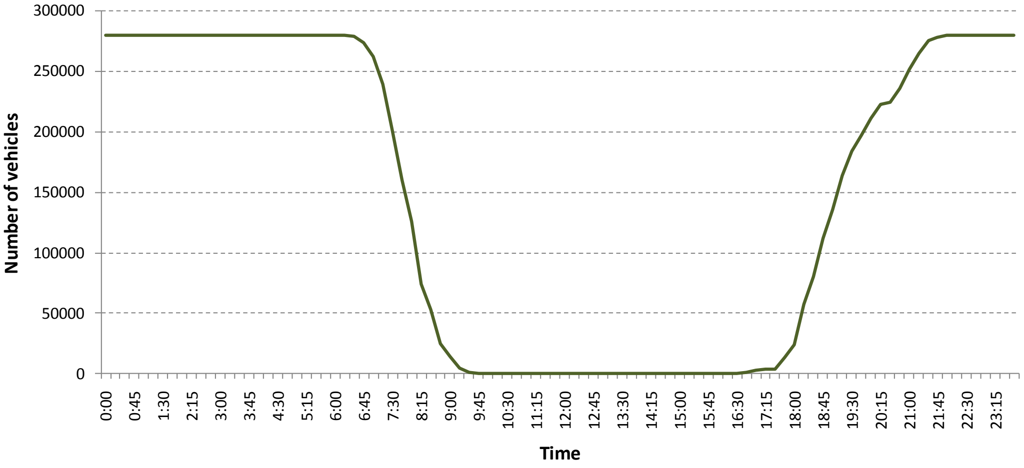

Figure 41 – Number of vehicles parked at home in typical weekdays

# 6. Analysis of PEV potential to provide ancillary services

In this Chapter, the potential contribution of PEV to participate on the operation market and to provide ancillary services in the Portuguese power system, such as primary regulation, secondary regulation and regulation reserve are presented. This approach is based on the commute profile by car presented in the previous Chapter and real operation data, available in the website of the SO [66].

The work is developed only based on PEV in normal power charging (3.68 kW) during parking duration at home. Medium and high power charging methods, with rated power above 3.68 kW, are out of the scope of this analysis. Actually, when electric drivers decide to charge their PEV out of home, it is acceptable to assume whey would not be available to participate in any charging control mechanism, as this option suggests they need to charge PEV as soon as possible. Furthermore, the approach of V2G, with bidirectional power flow, is also out of scope, as it still faces several limitations, regarding costs and cycling reliability, and it would allows a reduced storage capacity compared to large pump hydro plants.

## 6.1. Provision of primary regulation

Conceptually, this ancillary service may be provided by PEV, as the control of charging can be used to attenuate frequency variations, minimizing unbalance between demand and generation. However, the implementation of this ancillary service with PEV would require the integration of expensive monitoring and control systems on PEV and a significant redesign of chargers, as this ancillary service has to be delivered in real-time. On the other hand, SO require that this service must be provided according to very high quality standards that probably would not be possible to achieve considering the dispersion of PEV by the distribution network.

On the other hand, in Portugal, due to measurement and quality assessment limitations, primary regulation is a mandatory ancillary service to generators operating in ordinary regime, not being remunerated today by market-driven mechanisms on the operation market, which also limits the access of controllable loads to this service.

## 6.2. Provision of secondary regulation

To analyse the potential of PEV to provide secondary regulation, the charging duration profile of commuters is derived from the driving distances and parking duration profiles presented on sections 5.1. and 5.2. Figure 42 presents the charging duration profile of about 280 000 PEV, assuming that all commuters driving less than 100 km per day adopt PEV.

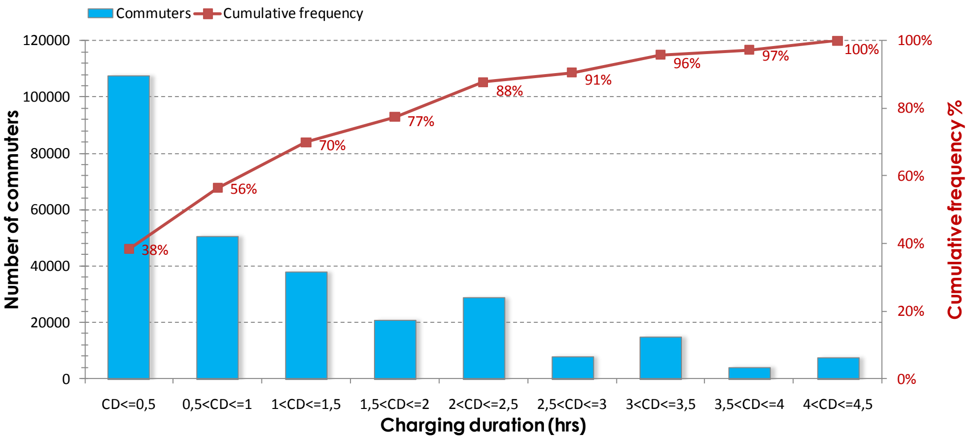

Figure 42 - Histogram of Charging Duration (CD) at home for commuting up to 100 km/day

Assuming that all PEV charge every night, at home, in a standard power outlet of 16 A, at 230 V, with a rated power of 3.68 kW, this profile shows that 77% of PEV require less than 2 hours to charge their batteries and that 100% of PEV require less than 4.5 hours. It is assumed that all PEV are charged every night in order to restore the 100% SoC, even not reaching the minimum admissible SoC (30%), in order to extend the battery lifetime and to increase the number of equivalent full cycles, as suggested by [24] and presented in Figure 9.

Regarding the distance travelled by all 280 000 PEV and the parking duration profile, the total amount of energy[36] (1235 MWh) is charged in 4.5 hours, but it can be efficiently spread and managed during more than 8 hours. This shows a large potential of PEV to provide secondary regulation during parking at home. Assuming the provision of secondary regulation

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[36] Considering that each PEV demand 150 Wh/km.

only when 90% of PEV are parked at home, a regulation period of 10 hours, from 21:00 to 07:00, will be achieved every night.

Spreading the required energy to charge all PEV by the 10 hours period, it corresponds to an average demand power of 123 MW. This shows that PEV have potential to provide an average secondary regulation reserve of 123 MW for up-regulation and 63 MW for down-regulation, at least during a part of the 10 hours period. The value of secondary regulation reserve for down-regulation is established as 50% of the secondary regulation reserve for up-regulation, as currently required by the SO. This contribution of PEV to the secondary regulation range would represent about 62% of the average secondary regulation reserves, for up-regulation and down-regulation, allocated during night-time periods (21:00 – 07:00) in weekdays of January 2011, presented in Figure 43. The month of January is used as reference on this approach because it was the month of 2011 with the largest renewable generation by wind, with 920 GWh, and by hydro, with 212 GWh, in special generation regime.

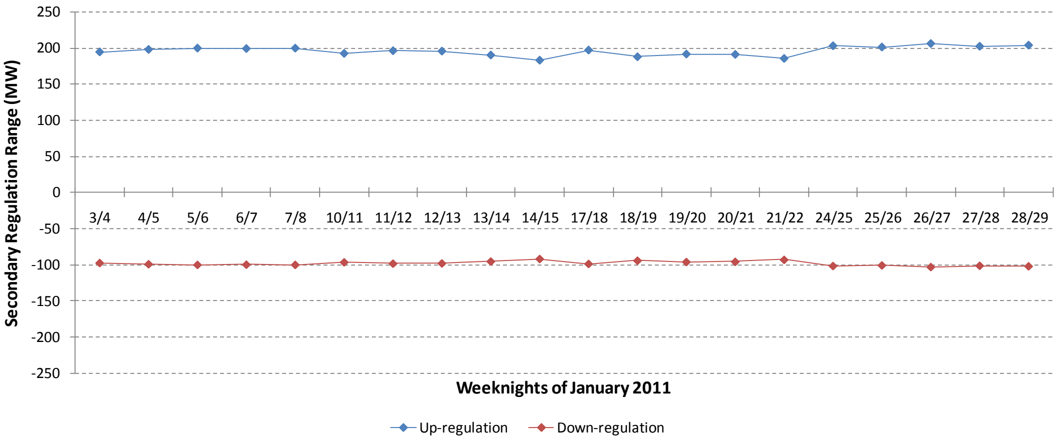

Figure 43 – Average secondary regulation range allocated for up and down in weeknights (21:00 – 07:00) of January 2011

Figure 44 details the secondary regulation range allocated for up and down regulation during the night-time period, from 11 January at 21:00 to 12 January at 07:00. Although the average secondary regulation reserve for up-regulation is around 200 MW, the hourly allocated values vary significantly during the night, from 270 MW at the hour 22 to 119 MW at the hour 6. A similar behaviour is realized, within the same period, with the allocated secondary regulation reserve for down-regulation, with variation between -135 MW at -60 MW.

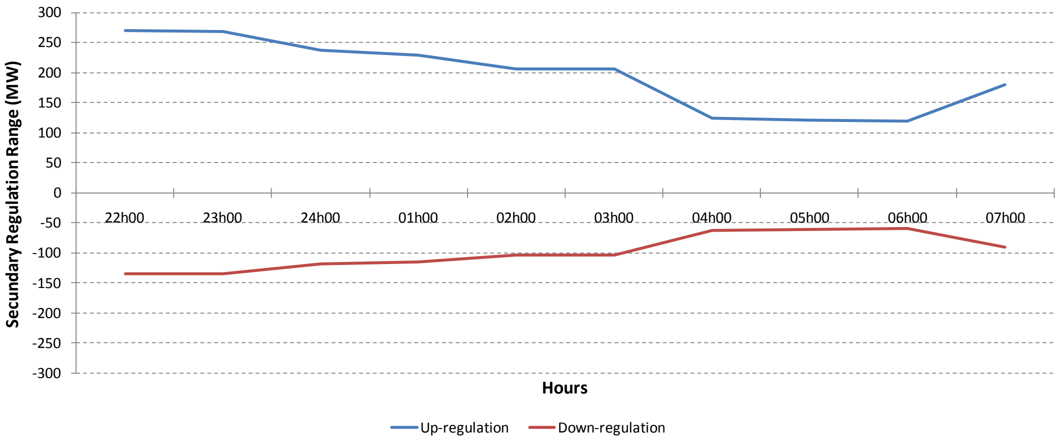

Figure 44 – Secondary regulation range allocated for up and down in the night-time period (21:00 – 07:00) of 11/12 January 2011

The average weighted prices of secondary regulation range during the night-time period in the weeknights of January 2011 was 29 €/MW, in average.

By opposition to January, September was the month of 2011 with the lowest renewable generation by wind, with 459 GWh, and by hydro, with 14 GWh, in special generation regime. Therefore, comparing the potential of PEV with the secondary regulation range allocated in weeknights of September 2011, they would contribute up to 70% of the average secondary regulation reserves, for up and down regulation, allocated in the night-time periods (21:00 – 07:00) in weeknights of September 2011, at least in part of the 10 hours period.

The average weighted prices of secondary regulation range allocated during the night-time period in the weeknights of September 2011 was 30 €/MW, in average, a price quite similar to the price achieved in January. In fact, requirements of secondary regulation range are independent of renewable generation.

## 6.3. Provision of regulation reserve

As mentioned above, the 1235 MWh required for PEV charging every night can be drawn from the electric power system in a controlled and efficient way, during the parking period at night-time, in order to support not only the provision of secondary regulation range, as presented in the previous section, but also regulation reserve.

Figure 45 shows the energy mobilized in secondary regulation and regulation reserve, called for up and down regulation, during night-time period of weeknights during January 2011. As presented to secondary regulation range, this graph quantifies the energy injected or absorbed from the electric power system for up and down regulation, excluding primary regulation, during the night-time period, from 21:00 of one day to 07:00 of the day-ahead.

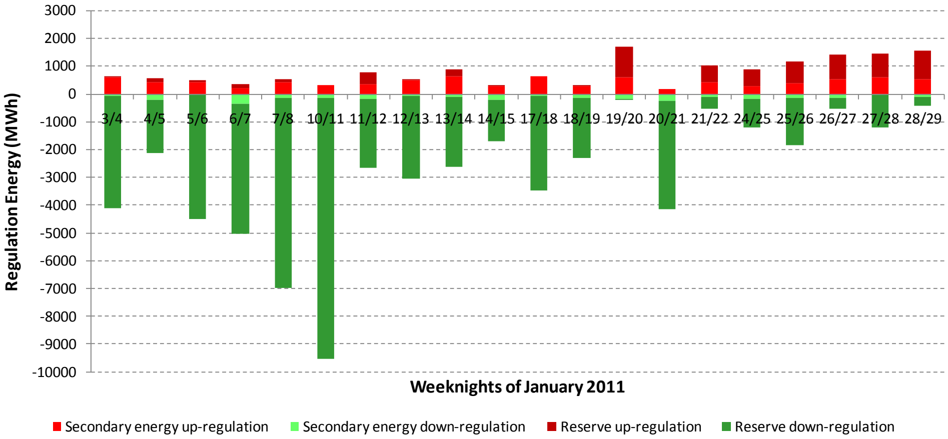

Figure 45 – Energy mobilized for up and down regulation, from 21:00 to 07:00, in weeknights of January 2011

This shows that the electric power system required large amounts of energy, namely for down-regulation, during the night-time of January 2011. This is a direct consequence of the high renewable generation during this winter month of 2011. This also states an important opportunity of PEV to contribute for regulation reserve, acting as controllable loads over a control system in a smart grid context.

If energy required by PEV charging every night was used to provide regulation reserve for down-regulation, this new resource would contribute with a share between 13% and 100% of regulation reserves required by power system in weeknights of January 2011. In 30% of the weeknights the energy required by PEV charging would be enough to provide all required regulation reserves for down-regulation. Figure 46 illustrates the potential contribution of PEV to this ancillary service during January 2011, replacing conventional regulation reserve by energy of PEV charging.

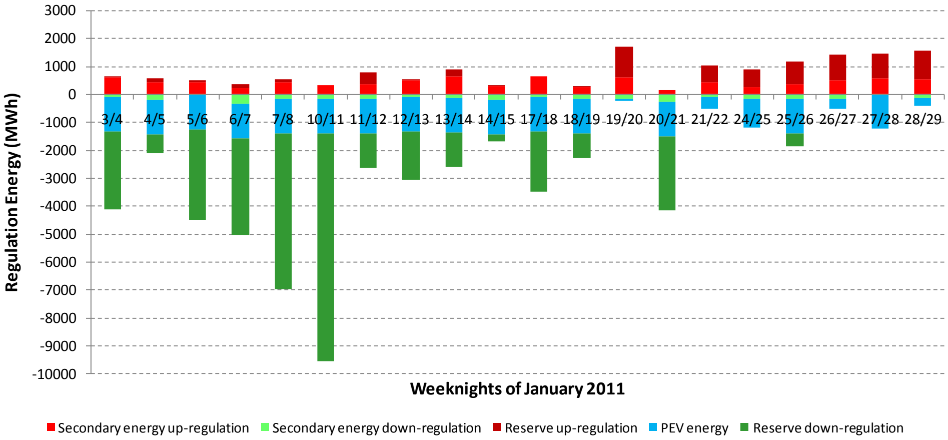

Figure 46 – Potential contribution of PEV for down-regulation in January 2011

Developing the same approach to September, the month of 2011 with the lowest renewable generation, Figure 47 shows the mobilized energy in secondary regulation and regulation reserve during the night-time periods.

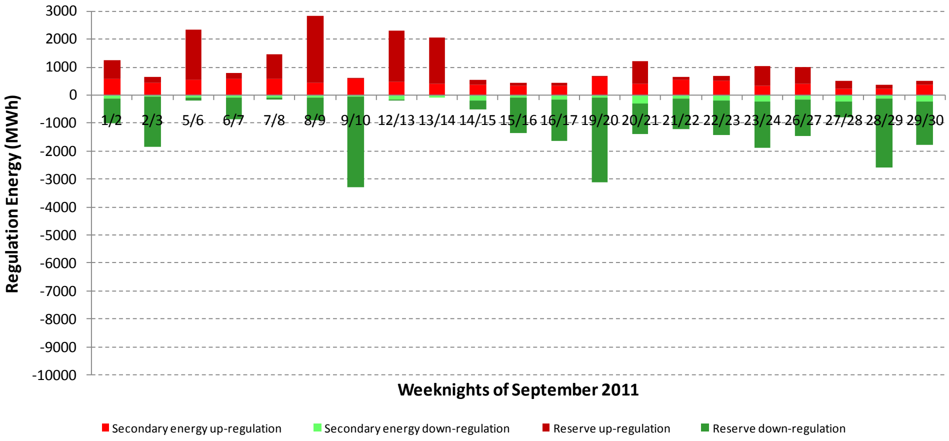

Figure 47 – Energy mobilized for up and down regulation, from 21:00 to 07:00, in weeknights of September 2011

In this month, if energy required by PEV charging every weeknight was used to provide regulation reserve for down-regulation, its contribution would achieve a share between 38% and 100% of the required regulation reserves. Actually, in 52% of the weeknights the energy required by PEV charging would be even enough to provide all required regulation reserves for down-regulation in weeknights of September 2011, as illustrated in Figure 48.

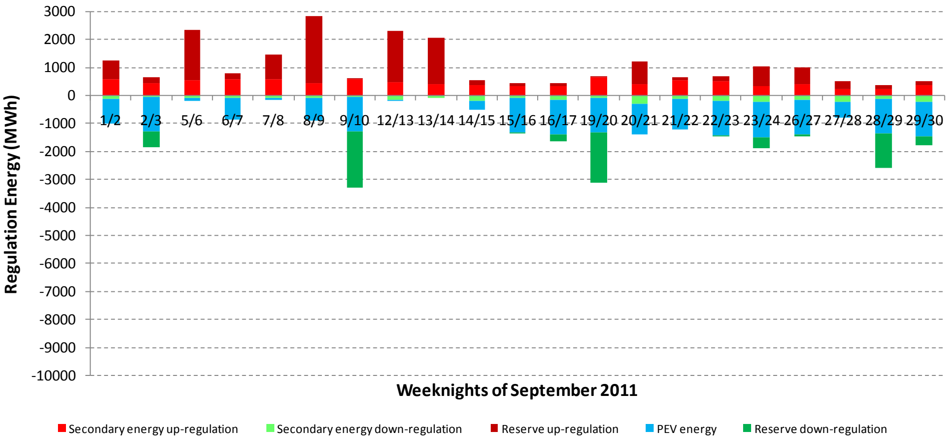

Figure 48 – Potential contribution of PEV for down-regulation in September 2011

Assuming that prices in the operation market would not be influenced by this new resource, important revenues would be expected, especially in months with high wind generation and low hydro generation. The average weighted prices of regulation reserves during the weeknights of September 2011, for down-regulation were around 32 €/MWh. Homologous prices for January 2011 were quite lower, being around 13 €/MWh.

# 7. Main conclusions

In order to contribute to support DSO, SO and forthcoming electric MOM to develop a cost-effective control system for efficient integration of PEV in the electric power system, in the scope of this work, the potential of PEV to provide ancillary services in the Portuguese power system was analysed, namely to compensate the intermittency of renewable generation. The impact of normal power charging of PEV in distribution networks, regarding harmonic current emissions, was also studied.

In order to identify possible distribution network constraints to be considered on the development of the control system, field measurements in normal power charging of a PEV were carried out, characterizing harmonic current emissions by onboard chargers. Monitoring results have shown maximum 3rd harmonic currents around 12% and $THD_I$ between 12% and 16%, which can contribute to increase the harmonic distortion in LV public distribution networks, despite recorded harmonic current emissions being significantly below to admissible limits of the standard IEC 61000-3-2 [59] for class A equipment. Based on this analysis, a paper regarding “Integration of PEV on the Portuguese Distribution Grid – Analysis of harmonic current emissions in charging points” has already been presented in the IEEE Electric Power Quality and Utilisation International Conference – EPQU’11, October, 2011.

The potential analysis of PEV to provide ancillary services in the Portuguese electric power system was developed based on real data available from the operation market, with focus on secondary regulation range and regulation reserve, regarding commute profile of drivers with potential to adopt PEV.

Based on commute profile of about 300 000 drivers in Portugal, about 280 000 drivers were selected (93% of the initial universe, which drive less than 100 km per day) with potential to adopt PEV, in order to characterize their potential to provide primary regulation, secondary regulation and regulation reserve. With an average energy demand of 150 Wh/km, it was estimated that these PEV demand everyday 1235 MWh, being this energy and required power spread by the night-time to derive their potential to provide ancillary services.

Spreading the charging of all PEV by the night-time period (between 21:00 and 07:00), PEV have shown potential to provide an average secondary reserve of 123 MW for up-regulation and 63 MW for down-regulation, at least during a part of the 10 hours period. This contribution of PEV to the secondary regulation range would represent about 62% of the average secondary regulation reserves, for up-regulation and down-regulation, allocated during weeknights of the month with the highest renewable generation in 2011 (January). This share would increase to 70% in the month with the lowest renewable generation in 2011 (September).

On the other hand, if energy required by PEV charging every night was used to provide regulation reserve for down-regulation, this new resource would contribute with a share between 13% and 100% of required regulation reserves by the power system during weeknights of January 2011. In 30% of the weeknights, the energy required by PEV would be enough to provide all required regulation reserves for down-regulation. Following the same approach to September 2011, the contribution of PEV would achieve a share between 38% and 100% of required regulation reserves, being the energy required by PEV enough to provide all required regulation reserves for down-regulation in 52% of the weeknights of September 2011.

Provision of primary regulation by PEV seems to be difficult, as it would require the integration of expensive monitoring and control systems in PEV and a significant redesign of onboard chargers, as this ancillary service has to be provided in real-time and based on very high quality standards.

# 8. Future work

To release the potential of PEV to provide ancillary services, as presented in this work, it is required to design a cost-effective control system, including the architecture and advanced control charging strategies, supported in optimization algorithms, to ensure an efficient integration of PEV in the electric power system.

Therefore, it is recommended to start with the design of a conceptual control architecture to support the large-scale penetration of PEV, providing secondary regulation range and regulation reserve, and ensuring a reliable and efficient operation of the distribution network. The performance of this architecture would aggregate the potential of all PEV and to allow their participation in the operation market, as a single agent. On the other hand, the system would be able to prevent load congestion, especially at LV feeders with higher penetration of PEV.

The original concept of V2G, with bidirectional power flow, is not definitely proven for large deployment. Its impact on the battery lifetime, acceptance by electric drives, TSO and DSO, as well as its economic interest is not demonstrated [43]. Therefore, the system should be developed in order to ensure advanced control charging, as a first natural step to manage large-scale penetration of PEV in a cost-effective way, being desirable reduced control at the PEV level and no impact on batteries lifetime. As suggested in a Google’s project [67], PEV would just receive command signals for start/stop charging at rated power (16 A).

Based on current state of the art, the control architecture would be developed by one of the following alternatives:

- Control of PEV by MOM, only based on a centralized Aggregation Control System (ACS);
- Control of PEV by MOM, with ACS and distributed intelligence by Smart Grid Controllers (SGC):
    - EVSE/Energy Box (EB) and Distribution Transformer Controller (DTC);
    - EVSE/EB, DTC and Distribution Feeder Controller (DFC).

Figure 49 depicts a conceptual architecture stratified in 5 main layers, which include: electric layer; distribution automation layer; aggregation control layer; system control layer; market services layer.

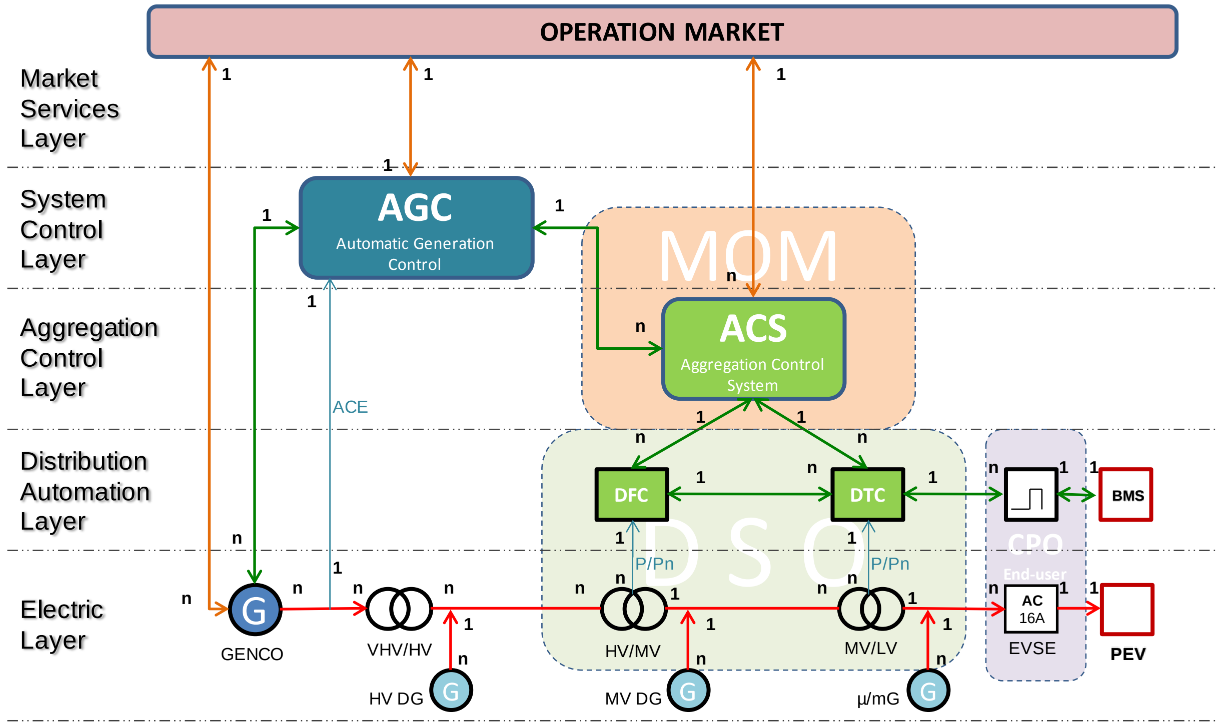

Figure 49 – Outline of a conceptual control architecture[37]

Other really import challenge to release the potential of PEV to provide secondary regulation range and regulation reserve is the development of advanced control charging

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[37] Legend: GENCO – Generation Company; VHV – Very High Voltage; HV – High Voltage; DG – Distributed Generation; MV – Medium Voltage; LV – Low Voltage; μG – Micro Generation; mG – Mini Generation; EVSE – Electric Vehicle Supply Equipment; PEV – Plug-in Electric Vehicle; AC – Alternate Current; P/Pn – Load Factor; DFC – Distribution Feeder Controller; DTC – Distribution Transformer Controller; BMS – Battery Management System; DSO – Distribution System Operator; CPO – Charging Points Operator; ACS – Aggregation Control System; MOM – Electric Mobility Operations Manager; ACE – Area Control Error; AGC – Automatic Generation Control

strategies supported in efficient optimization algorithms, that ensure the answer of multiple PEV, as a single agent, in a near real-time frame. Supported the proposed architecture, the algorithms have to react to the SO calls, as consequence of commitments previously assumed in the operation market, and simultaneously ensure that energy storage requirements of electric drives are fulfilled in a predefined timescale.

In a first approach, this optimization algorithms are foreseen to be implemented by the aggregation entity, which would receive the availability and charging requirements of PEV, place bids of secondary regulation range and regulation reserve on the operation market and delivers ancillary services in near real-time, according to calls of the SO, after assessment and overcoming of distribution constraints. Figure 50 depicts this overview and identifies the main interaction variables.

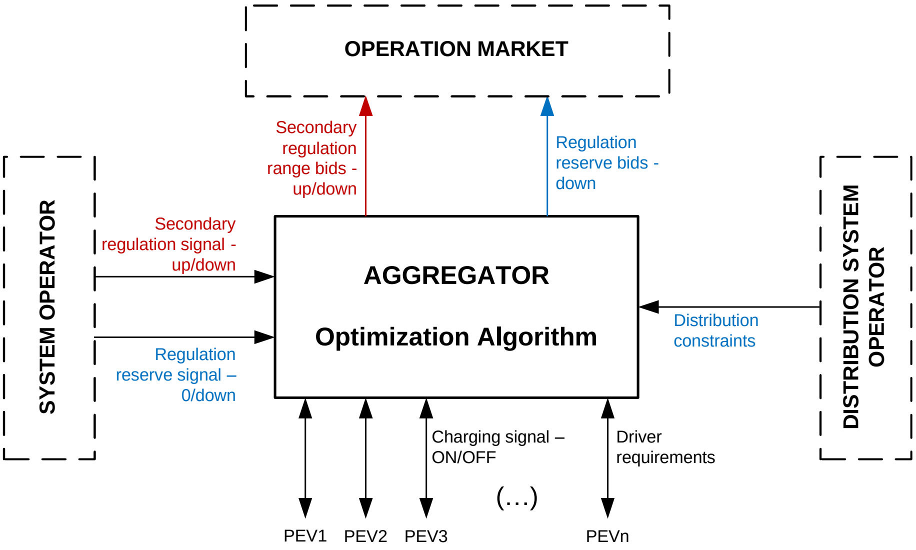

Figure 50 – Overview of agents and interaction variables for an optimization algorithm

This optimization algorithm for advanced control charging has to interact with 4 main agents to achieve the following 3 main objectives, during the parking period of PEV at home:

- Provision of secondary regulation range, for up and down regulation, and PEV charging requirements;
- Provision of regulation reserve, for down-regulation, and PEV charging requirements;
- Provision of secondary regulation range, for up and down regulation, regulation reserve, for down regulation, and PEV charging requirements.

This algorithm requires interaction with the following agents:

- Operation market, placing bids of secondary regulation range, for up and down regulation and its respective price, in €/MW, and regulation reserve, for down-regulation, in €/MWh, for each day-ahead participating interval[38].
- SO, receiving signalling every 4 seconds for secondary regulation range, for up and down regulation, and delivering regulation in a timeframe of 15 – 30 seconds, and regulation reserve, for down-regulation, in a timeframe of 15 minutes.
- DSO, receiving the state of the distribution network and estimating consequences of a specific call of the SO, regarding overload constraints;
- PEV, receiving their availability and timeframe to participate in ancillary services, required energy and possible switching constraints, such as time between ON/OFF commands, etc.

Regarding this combinatorial problem, genetic algorithms are expected to contribute with a suitable and efficient solution. The large combinatorial problem could not be easily solved at a single central location, being require distributed intelligence, namely by implementation of decision capacity at DTC or DFC levels, which would aggregate all PEV in about 65 000 DTC/DFC.

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[38] Participating intervals of 1 hour in the day-ahead operation market

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