TAMPERE UNIVERSITY OF TECHNOLOGY

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TECHNO-ECONOMICAL STUDIES FOR GRID IMPACTS OF ELECTRIC VEHICLE FAST CHARGING

Master of Science Thesis

Examiner: Professor Pertti Järventausta
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ABSTRACT

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Smart grids will bring both opportunities and challenges in the future. Electric vehicles (EVs) will be part of this concept, offering a wide range of opportunities for different parties of power system. When the electric energy charged into EVs is produced using renewable energy, EVs do not affect emissions.

EV is a generic name for the vehicle, where the electric energy fed by a battery is converted with electric motor into mechanical energy that moves the vehicle. There are three main types of EVs. A battery electric vehicle runs solely with electric energy stored into the battery and the battery can be recharged several times. In case of hybrid electric vehicle, the battery cannot be recharged from grid and the electric motor acts as an auxiliary source of power alongside with the internal combustion engine. Plug-in hybrid electric vehicle is like the hybrid electric vehicle, but its battery can be recharged from the grid.

The most important and expensive part of the EV is the battery. The problem of the battery has been the fact that the battery has to have enough high energy density and power density. Improving the other feature will weaken the other. Nowadays, the lithium-ion technology possesses the best combination of these features. In addition, the maximum charging power of a battery depends on the structure of the battery. In this study, the examined chargers are so called fast charging stations, where an external charging point recharges the batteries of EVs up to 50 kW of power. In this case, the batteries will be charged at state of charge of 80 % in about 30 minutes. The duration of a charge depends on the battery capacity, state of the charge at the beginning of the charge, battery conditions, charging power and battery management system.

Medium voltage or low voltage network feeds the required power into the charger. In a case of fast charge, the three phase power will be converted with rectifier into direct voltage and current and the converted power will be fed into the battery of an electric vehicle with charging cable. In case of the slower charging methods, three or one phase power will be fed into EV with a separate charging cable. The power will be converted into direct voltage and current inside the vehicle with on-board rectifier.

At experimental part of the study, the EV fast charging grid impacts will be compared with the standard EN 50160. In the study, five EVs were measured. The vehicles were charged with two fast charging stations, which have similar characteristic values. In addition, the grid impacts were analyzed by simulating new fast charging stations into the three different parts of the present distribution network. The consumption points, where the stations were installed were selected to correspond the conceivable installing points of fast charging stations.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
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Tulevaisuuden älykkäät sähköverkot tuovat tullessaan sekä mahdollisuuksia että haasteita. Sähköautot tulevat olemaan osa tätä kokonaisuutta, tarjoten mahdollisuuden sähköenergian varastointiin sekä kysynnän joustoon. Nämä ominaisuudet voivat tulevaisuudessa tarjota monenlaisia mahdollisuuksia erilaisille sähköverkkojärjestelmässä toimiville tahoille. Sähköautot ovat ympäristöystävällisiä. Kun tarvittava sähköenergia tuotetaan uusiutuvaa energiaa hyödyntäen, sähköautot ovat päästöttömiä.

Sähköauto on yleisnimitys autolle, jossa sähköakun syöttämä sähköenergia muutetaan sähkömoottorin ja voimansiirron avulla autoa liikuttavaksi mekaaniseksi energiaksi. Sähköautotyyppejä on kolmea päätyyppiä. Täyssähköauto kulkee pelkästään akkuun varastoituneen sähköenergian avulla ja sen akkua voidaan ladata useita kertoja. Hybridisähköautossa akkua ei pystytä lataamaan verkosta ja sähkömoottori toimii avustavana voimanlähteenä polttomoottorin rinnalla. Pistokehybridisähköauto on kuten hybridisähköauto, mutta sen akkua pystytään lataamaan verkkovirtaa hyödyntäen.

Sähköautojen tärkein ja kallein komponentti on akku. Akkujen ongelmana on ollut, että varauksen tulee kestää riittävän pitkä ajomatka sekä toisaalta tuottaa joka hetki sähkömoottoriin tarvittava teho. Toisen ominaisuuden parantaminen yleensä heikentää toista ominaisuutta. Nykyisin parhaan näiden ominaisuuksien kombinaation tuottaa litiumioni teknologia. Akun ominaisuuksista riippuu myös akkuun ladattava teho. Tässä työssä tarkasteltavat latauspisteet ovat ns. pikalatauspisteitä, jossa sähköauton akkua ladataan ulkoisella latauspisteellä maksimissaan 50 kW:n teholla. Tällöin autojen akut saadaan ladattua 80 % varaustilaan noin 30 minuutissa. Latausnopeus riippuu auton akun alkutilan varauksesta sekä kokonaiskapasiteetista, akun toimintatilasta, lataustehosta sekä akun hallintajärjestelmästä.

Lataukseen tarvittava teho saadaan keski- tai pienjänniteverkosta. Pikalatauksessa kolmivaiheinen teho muutetaan tasasuuntaajalla tasajännitteeksi ja tasavirraksi, joka syötetään sähköauton akkuun latauspisteessä olevan latauskaapelin avulla. Hitaammissa latauksissa kolmi- tai yksivaiheinen teho syötetään erillisen latauskaapelin avulla sähköautoon, jonka jälkeen auton sisäänrakennettu tasasuuntaaja muuntaa tehon akulle sopivaksi tasajännitteeksi ja -virraksi.

Työn tutkimusosiossa verrataan pikalatauksen verkostovaikutuksia EN 50160 standardin mukaisiin keski- ja pienjännite vaatimuksiin. Työssä mitattiin viittä sähköautoa. Autoja ladattiin kahdessa pikalatauspisteessä, joiden molempien ominaisarvot olivat samankaltaisia. Mittausten perusteella analysoitiin verkostovaikutuksia. Työssä analysoitiin myös pikalatauspisteiden verkostovaikutuksia lisäämällä pikalatauspisteitä kolmeen erilaiseen kulutuspisteeseen. Kulutuspisteet valittiin siten, että ne vastaisivat tulevaisuudessa asennettavia pikalatauksen käyttöpaikkoja.

PREFACE

This Master of Science Thesis was carried out in Fortum Sähkönsiirto Oy as a part of Smart Grids and Energy Markets (SGEM) project. The work was started in August 2011.

First of all, I would want to thank my supervisors from Fortum, Maarit Pihlajaniemi, Kari Koivuranta and Juha Matikainen for giving me this interesting subject as well as for all the support and interesting information that they have given me during the work. I also want to thank all of my other colleagues in Fortum for their friendliness and for many enjoyable conversations during breaks. Special thanks belong to the Espoo city, Eltel Networks, Skanska, Delta auto and Nissan for borrowing their electric vehicles as well as to Juha Matikainen, Kari Koivuranta, Pekka Manner and Jukka Ihamäki for depleting the electric vehicles during the fast charging day. Without you, the measuring day would be impossible to organize.

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I would want to thank my parents Helena and Ari as well as my sister Sanna for all the support that I have had during my whole student time. I also want to thank all of my friends for all the memorable moments during the studies and free time. Finally, I would like to express gratitude to my girlfriend Moona Happonen for understanding my sporty and busy life as well as making my leisure time more relaxed.

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Espoo, Finland
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Tommi Härkönen

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ABBREVIATIONS AND NOTATION

$	Dollar
€	Euro
A	Ampere
A_f	Vehicle frontal area
Ah	Ampere-hour
C_D	Aerodynamic drag coefficient
c_{dis}	Degradation cost factor
CO_2	Carbon dioxide
dV/dt	Acceleration
E_{add}	Additional energy
E_{cars}	Energy required by electric vehicles
f	Frequency
f_r	Rolling resistance
g	Gravity or gram
h	Hour
Hz	Herz
i	Road grade
I	Current
I_{out}	Output current
kWh	Kilowatt-hour
l	Liter
m	Meter
M	Mass of the vehicle
Nm	Newton meter
n_n	Number of customers of a consumption point
P	Active power
P_{b-in}	Regenerative braking power
P_{b-out}	Battery power output
P_{lt}	Long-term severity
P_{max}	Peak power
P_n	Average power
P_{opt}	Optimal active power curve
P_{out}	Output power
P_{st}	Short-term severity
Q	Reactive power
rpm	Revolutions per minute
S	Apparent power
t	Time
u_h	Harmonic voltage related to fundamental voltage
U	Voltage

U_0	Voltage long-term average value
U_c	Supply voltage of public medium voltage network
U_n	Nominal voltage of public low voltage network
U_{out}	Output voltage
v	Velocity
V	Volt
W	Watt
V_1	Positive sequence voltage
V_2	Negative sequence voltage
x	Speed ratio
z_a	Average deviation factor
α	Regenerative braking factor
α_n	Phase angle
δ	Mass factor
ΔP	Active power difference
ε	Safety marginal of a charger
η	Combined efficiency of a charger and a battery
η_m	Efficiency of a motor
η_t	Efficiency of transmission
ρ	Density
σ	Deviation

AC	Alternating current
AMI	Automated metering infrastructure
AMM	Automated meter management
AMR	Automated meter reading
BEV	Battery electric vehicle
BMS	Battery management system
CCCV	Constant current - constant voltage
CCSP	Carbon capture and storage program
CD mode	Charge depleting mode
CEN	European committee for standardization
CENELEC	European committee for electrotechnical standardizardization
CLEEN	Cluster for energy and environment
CNG	Compressed natural gas
C-rate or C	Current rate
CS mode	Charge sustaining mode
CSI	Current source inverter
DC	Direct current
DCM	Direct current motor
DMS	Distribution management system

DOD	Depth-of-discharge
DR	Demand response
DSO	Distribution system operator
E-REV	Extended range electrical vehicle
ESD	Electricity solutions and distribution
ETP	Energy technology perspectives
ETSI	European telecommunications standards institute
EU	European union
EV	Electric vehicle or all-electric vehicle
EVSE	Electric vehicle supply equipment
FCEP	Future combustion engine power plants
FICORA	Finnish communications regulatory authority
FOC	Field-oriented control
FPBEV	Full power battery electric vehicle
G4V	Grid for vehicle
HEV	Hybrid electric vehicle
HV	High voltage
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
ICT	Information and communication technology
IEA	International energy agency
IEC	International electrotechnical commission
IM	Induction motor
IP	Internal protection
IrDA	Infrared data association
ISO	International organization of standardization
ITU	International telecommunication union
LDV	Light-duty vehicle
$LiFePO_4$	Lithium iron-phosphate
Li-ion	Lithium-ion
Li-M-Polymer	Lithium metal polymer
$LiTi_5O_{12}$	Lithium-titanate
LPG	Liquefied petroleum gas
Ltd	Limited company
LV	Low voltage
Max	Maximum
Min	Minimum
MMEA	Measurement monitoring and environmental efficiency assessment
MV	Medium voltage
NA	Not-assessable
$Na\text{-}NiCl_2$	Sodium nickel chloride

Ni-Cd	Nickel-cadmium
Ni-MH	Nickel metal hybrid
NPV	Net present value
PEV	Plug-in electric vehicle
PFC	Power factor correction
PHEV	Plug-in hybrid-electric vehicle
PLC	Programmable logic controller
PM	Permanent magnet
PMBM	Permanent magnet brushless direct current motor
PMHM	Permanent magnet hybrid motor
PMSM	Permanent magnet synchronous motor
PWM	Pulse width modulation
REEV	Range extended electrical vehicle
RMS	Root-mean-square
SEI	Solid-electrolyte interface
SESKO	Finnish electrotechnical standards association
SFS	Finnish standard association
SGEM	Smart grids and energy markets
SLI	Standard-lighting-ignition
SOC	State of the charge
SOS	Start of sales
SRM	Switched reluctance motor
THD	Total harmonic distortion
TSO	Transmission system operator
TtW	Tank to wheel
USD	United states dollar
V2G	Vehicle to grid
V2H	Vehicle to home
WP	Work package
WtW	Well to wheels
ZEBRA	A sodium nickel chloride battery

1 INTRODUCTION

Mobility of people and goods is crucial for today´s society. An increasing trend in oil prices, Kyoto targets and energy use are radically changing the character of transportation. The EU (European Union) has set a target for 20% reduction in greenhouse gases, over 1990 level, by 2020 [1]. In case of transportation, achieving the goal has mainly done by producing more effective vehicles or more sustainable fuels. Electricity is an excellent source for a new fuel of transportation, because electricity can be produced in several different methods. It is predicted that the electric vehicles will substitute the combustion engine powered vehicle fleet in the future because of the fact that the electric vehicles can reduce the amount of CO_2 (Carbon dioxide) emissions and the consumption of fossil fuels. In addition, EVs have much higher energy efficiency and do not produce tailpipe emissions of any kind. Nevertheless, the precise penetration time of electric vehicles remains unknown.

The longtime problem for electric vehicles generalizing has been the battery technology. In the early 1990s, it became clear that electric automobiles could hardly ever compete with gasoline automobiles for range and performance, due to the energy of batteries is stored in the metal of the electrodes, which weigh much more than gasoline for the same content. As a result of intensive researching and investigation all over the world, batteries have developed and several major manufacturers have revealed their plans to launch the electrical vehicle (EV) and the plug-in hybrid-electric vehicle (PHEV) models soon to the markets. In fact, the first models are already in markets. The possible future growth of EVs creates a challenge to the existing distribution infrastructure. Because of a three-phase connection in households and the car preheating system, which are needed in cold winters, the power systems infrastructure is already suitable for low-voltage charging in the Nordic countries. Only small local changes must be made to both distribution network and real estate internal networks before the large-scale implementation of electrical vehicles.

Renewable energy generation produces more fluctuating power to the power network. A new kind of response of load is presumed if the wide-scale renewable energy generation such as wind and solar power is applied. EVs are a fully new load type, which provides possibilities for a demand response. In the future, the batteries of EVs can be used as electricity storage for a power network. The batteries could be charged when the production of wind or solar power is high and use the batteries as a feeder during the peak loads. The battery technology and "smartness" of the power network have to be developed before this kind of Vehicle to Grid (V2G) technologies could be used.

To make buying an EV more attractive than a combustion engine powered vehicle for the customers, driving an EV should be at least as convenient as driving a combustion engine powered vehicle and prices should be somehow comparable. This means that the government has to offer subsidies, privileges and consumer friendly tariffs to the EV users and support to new charging station builders at the beginning of the electrification of transportation. Therefore, co-operation of electrical companies, car manufacturers and government is needed (see Figure 1.1).

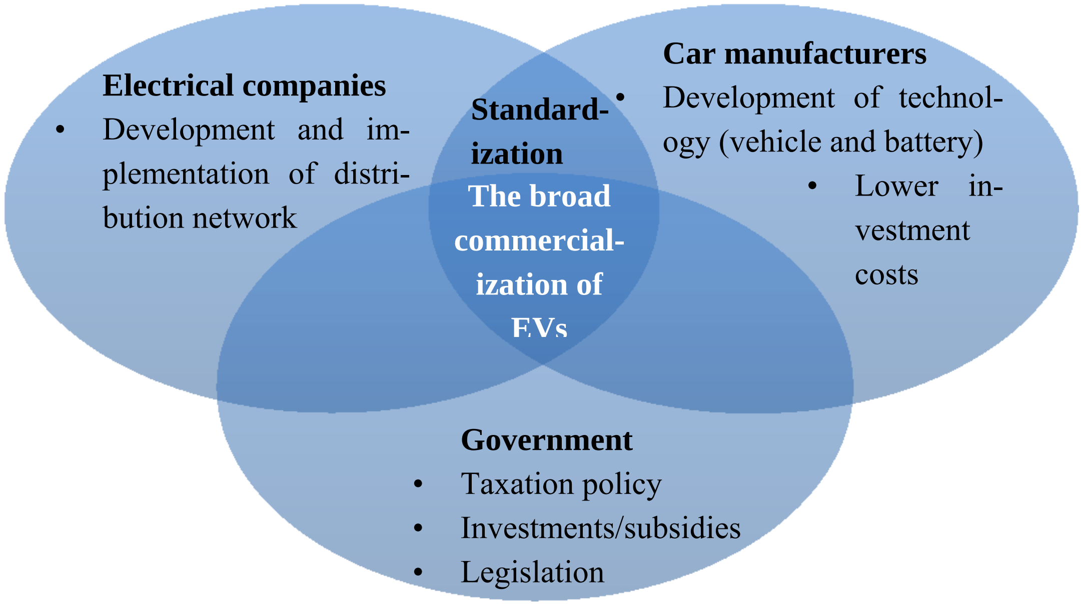

Figure 1.1. *The three main factors that affects to the broad commercialization of electric vehicles [2].*

Constructing fast charging stations is a step towards more convenient driving. Fortum Oyj was the first in Finland, which deployed a fast charging station. The connection power of one of the charger is 50 kW and it uses direct current (120 A). It is capable of charging the battery of an EV from empty to 80% state of the charge (SOC) in 15-30 minutes depending on the capacity of the battery, whereas the slow chargers needs one to eight hours, depending on the capacity of the battery and connection power.

Several analyses have been done on a slow charging of EVs in power distribution networks, but technical and economic questions of the network effects of the fast charging remain open. This Master Thesis is intended to give answers for those questions.

1.1 The objectives and scope of the study

The aim of this Master Thesis is to research electric vehicle grid impacts when using fast charging stations in both customer and network operator perspective. The work will focus on existing fast charging systems and the charging models, which present electric vehicles are using in practice. In addition, it makes account of different fast charging solutions, systems and the technical specifications of those. The option of a fast change of batteries is only shortly taken under consideration and fuel cells and super-capacitors are dropped out of the study.

The goal of the work is also to plan and design the testing (for example measurement and analysis) of systems to be installed in the distribution network. It will give the knowledge how to deploy charging units in the most efficient way and to understand what kind of challenges and benefits it will bring along.

1.2 Structure of the study

This Master Thesis consists of seven chapters. The first chapter, "Introduction", gives general information about the study and Fortum Oyj where this Master Thesis is made. Background overview and future trends as well as objectives, scope and structure of the study are included in the chapter.

Chapter 2 and Chapter 3 are the theory part of the study. Chapter 2 contains all information linked directly to electric vehicles, today's batteries, charging methods and charging models whereas Chapter 3 introduces grid properties, the important parameters and future developments in a general level. Chapter 3 introduces also the power quality requirements of the power system according to European standard EN 50160.

Implementation of measurements is introduced in Chapter 4. First, it takes into account the technical specifications of fast charging stations used in this study. Then, it clarifies how the measurements were organized as well as which devices and electric vehicles were used.

After necessary theory and implementation of measurements are clarified, Chapter 5 will focus on technical effects on the distribution network, which will occur because of the fast charging of an electric vehicle. The goal is to introduce the measurement data gathered from fast charging of electric vehicles. In addition, the chapter analyses the data and compares it to the power quality requirements. As a result of the analysis, the chapter will introduce the grid impacts of fast charging and analyze what kind of costs those would affect on a network operator point of view. At the end of this chapter, a short conclusion of the grid impacts is made.

A fast charging case study is presented in Chapter 6. First, three case grids are defined and all the necessary models and parameters are presented. After models are ready, the cases are simulated and analyzed.

Chapter 7 adds up all the grid impacts of fast charging. In addition, it concludes the challenges and the benefits that fast charging will bring along.

1.3 Fortum Oyj

Fortum Corporation is a leading company in the Nordic countries, Russia and the Baltic Rim area. It was founded in the year 1998 by combining the state owned Imatran Voima (IVO) and the listed company Neste Oyj. At the end of 2010, the shareholding of the Finnish State was 50.76 %. The main business sectors are generation, distribution, the sale of electricity and heat as well as related expert services. In 2010, the sales of the corporation totaled 6296 million euro and operating profit was 1708 million euro. Fortum is divided into four business divisions: Power, Heat, Russia and Electricity Solutions and Distribution as shown in Figure 1.2. [3] Fortum's main intention is to create energy that improves life for present and future generations.

Figure 1.2. *The organizational structure [3].*

The Electricity Solutions and Distribution (ESD) Division is responsible for Fortum's electricity sales and distribution activities. Fortum is the number one company in electricity distribution and the second largest electricity retailer in the Nordic market area. An increased demand for green electricity has become a competitive advantage to Fortum, which is the leading seller of CO_2-free electricity in the Nordic region. ESD has 1.2 million retail customers in Finland, Sweden and Norway and 1.6 million electricity distribution customers in the same above-mentioned three countries and Estonia.

ESD continuously invests in its electricity network in order to maintain and improve the reliability and quality of electricity supply to their customers. In addition, Fortum is researching new solutions and technologies for a carbon-free future. [3]

1.4 Smart Grids and Energy Markets research program

Finnish Cluster for Energy and Environment (CLEEN Ltd) is the strategic centre for science, technology and innovation of the Finnish energy and environment. CLEEN Ltd's is based on the common vision and strategic research agenda defined by owners, for example private companies and research institutes. CLEEN Ltd manages four ongoing research programs: Carbon Capture and Storage Program (CCSP), Future Combustion Engine Power Plants (FCEP), Measurement Monitoring and Environmental Efficiency Assessment (MMEA) and Smart Grids and Energy Markets (SGEM). Fortum is taking part in SGEM research program, which started in September 2009 and will last until 2014. The SGEM program is divided into five work packages (WP), which are:

- WP 1: Drivers and Visions
- WP 2: Future Infrastructure of Power Systems 1: LV&MV
- WP 3: Future Infrastructure of Power Systems 1: HV
- WP 4: Active Resources; active customer, customer interface and ICT

- WP 5: Active Resources; Electrical Vehicles, Energy Storages, Distributed Generation
- WP 6: Intelligent management and operation of smart grids
- WP 7: Energy market

This thesis is part of the second funding period's Work Package 5. The task is WP 5.2 Electrical Vehicles and the deliverable number of this thesis is 5.2.21 Techno-economical studies of EV fast charging grid impacts (Q1/2012). [4]

2 STATE OF ELECTRIC VEHICLE TECHNOLOGY

Manufacturers around the world have been very interested in electric vehicles recently. Many big manufacturers are scheduled to launch rechargeable car models between 2011 to 2013. For example, Renault planned to launch three electric cars to the markets at the end of 2011 [5]. Ford planned to launch one in 2011 and two in 2012 [6]. Companies such as Volvo, Honda, Volkswagen, BMW and Jaguar can continue the list of manufacturers.[7] That is why it is justified to assume that the electrification of transportations has begun.

According to most of the predictions, hybrid electric vehicles (HEVs) and Plug-in Hybrid Electrical Vehicles (PHEVs) are going to be the first of electric vehicles to be generalized. Not until later on, the all-electric vehicles (EVs), which do not have a combustion engine, will generalize. There is still a huge uncertainty of composition, penetration time and rate of EVs, because yet it is impossible to say what the schedule of technically and economically lean EVs is. Today, the EVs are significantly more expensive than the combustion engine powered vehicles because of small manufacturing series of EVs and especially high battery investment costs, as can be seen at Table 2.1. The table shows a comparable data of five different cars in the market. The data shows that EVs are the most expensive, then are the PHEVs and currently the cheapest one is the internal combustion engine (ICE) powered vehicle. The prices of Table 2.1 are based on United States market prices and are converted from United States dollar (USD) to euro (€) at the rate 0.702411 of exchange.

Table 2.1. *Specifications of five existing vehicles in the market [7; 8; 9].*

Made	Car	type	Electric motor	Battery type	Battery	Consumption (1)	All-electric Range	Price
Mitsubishi	i-MiEV(2012)	all-electric	47 kW	(Li-Ion)	16 kWh	2,1 L/ 100 km	120 km	21 480 €
Nissan	Leaf	all-electric	80 kW	(Li-Ion)	24 kWh	2,67 L /100km	76 - 175 km	24 725 €
Honda	Civic 2nd gen.	Hybrid	17 kW	(Ni-MH)	2,6 kWh	6,42 L /100km	11 km	16 893 €
Toyota	Prius III	PHEV	60 kW	(Li-Ion)	5,2 kWh	5,65 L /100km	21 km	17 223 €
Honda	Civic (sedan)	ICEV	NA (2)	NA (2)	NA (2)	9,11 L /100km	0 km	11 102 €
(1) Consumption converted from miles per gallon (mpg) value.								
(2) Honda Civic Sedan (ICEV) do not have an electric motor nor battery that gives power to a traction motor.								

This chapter will introduce EVs, batteries and charging systems of today. It contains all information linked to the electric vehicle. Therefore, the types as well as consumption of EV and a possible composition in the future, are included. Battery is the most important and expensive part of the electric vehicle. It is described in detail. Different technologies, capacities and charging profiles as well as technical specifications and costs are presented and compared. In addition, the chapter introduces different charging methods and models.

2.1 Electric vehicles (EVs)

An electric vehicle is a rechargeable electric vehicle, which is powered by a battery pack. It operates using an electric motor (and its controller) instead of an internal combustion engine (ICE). When generalized as an EV, it can also mean a vehicle, which uses a battery only a part of the time. The rest of the time, it uses the ICE. The electric vehicle like this is also called a hybrid or a plug-in hybrid. The following subchapters will introduce the EV technologies of today.

2.1.1 Parameters and key components

The operational and fundamental principles of EVs and conventional ICE powered vehicles (ICEVs) are similar although the key components of EVs are different in comparison with the components of ICEVs. Parameters, such as acceleration time, maximum speed and gradeability are usually used to evaluate driving performance of a vehicle. The design of the parameters depends mostly on the speed-power (torque) characteristics of the traction motor. For vehicular applications, the ideal performance characteristic is the constant power output over the full speed range and high torque at low speeds.

The typical gasoline engines and variable-speed electric motor drives usually have the characteristics shown in Figure 2.1. At a low-speed region (less than the base speed), the electric motor has a constant torque and in the high-speed region (higher than the base speed) the motor has a constant power. Instead, the characteristics of gasoline engines are far from the ideal performance characteristic required by traction. Therefore, a multigear transmission is needed to multiply its torque at low speed. The tractive efforts of ICEV with four-gear transmission and an EV with single-gear transmission are compared in Figure 2.2. [10]

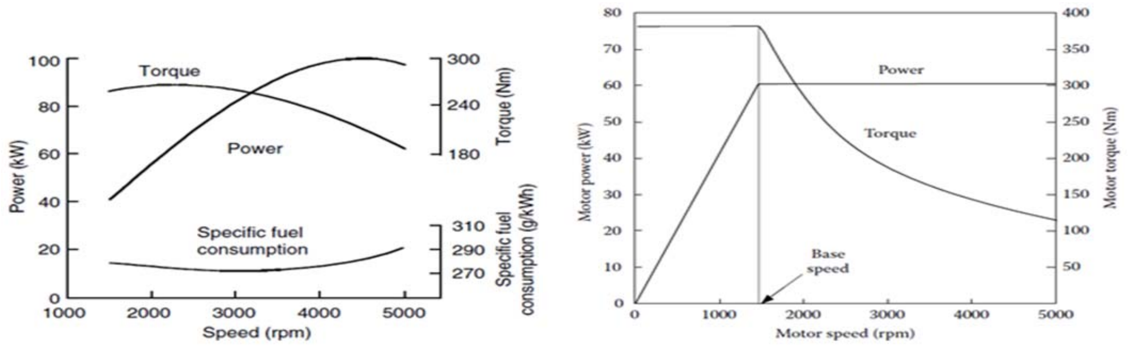

Figure 2.1. *Typical performance characteristics of gasoline engines in full throttle (left chart) and typical variable-speed electric motor characteristics at full load (right chart) [10].*

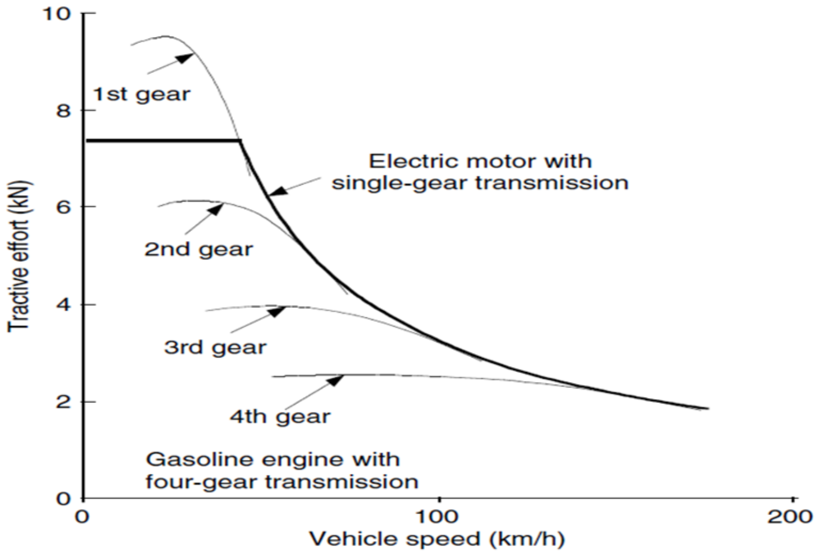

Figure 2.2. *Tractive effort vs. vehicle speed of ICEV with four-gear transmission and an EV with single-gear transmission [10].*

The torque-speed characteristic is often represented by a speed ratio x, defined as the ratio of its maximum speed to its base speed. Figure 2.3 shows the torque-speed profiles of 60 kW motor with different speed rations. With a long constant power region, the maximum torque of the motor can be significantly increased. Therefore, the vehicle acceleration and gradeability performance can be improved and the transmission can be simplified. However, each type of motor has its limited maximum speed ratio due to field weakening abilities. [10]

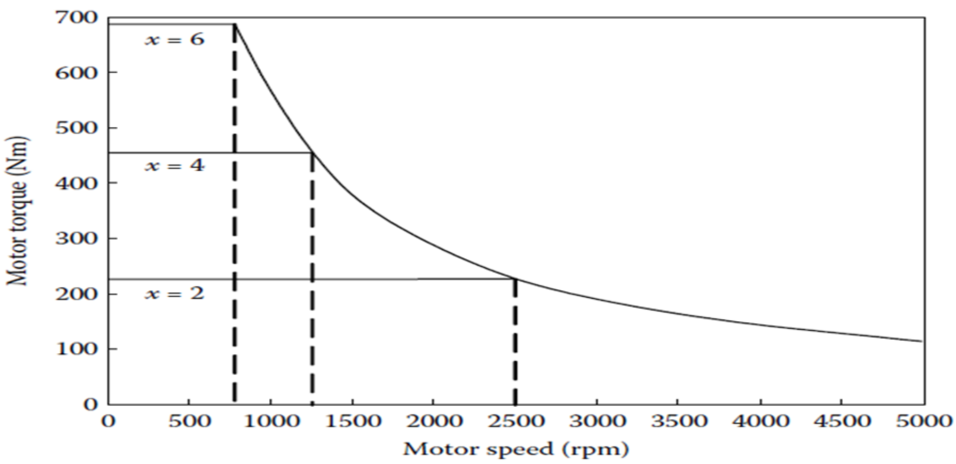

Figure 2.3. *Speed-torque profile of a 60 kW electric motor with speed ratio x = 2, 4, and 6 [10].*

Electric propulsion systems are at the heart of electrically driven vehicles. They consist of electric motors, power converters and electronic controllers. The electric motor converts the electric energy into mechanical energy to move the vehicle. The motor can also enable regenerative braking and/or to generate electricity from energy of ICE for charging the onboard energy storage. The power controller is used to supply the electric motor with proper voltage and current. The electronic controller commands the power converter by providing control signals to it, and then controls the operation of the electric motor to produce needed torque and speed, according to the command from the drive. The functional block diagram of an electric propulsion system is illustrated in Figure 2.4. [10]

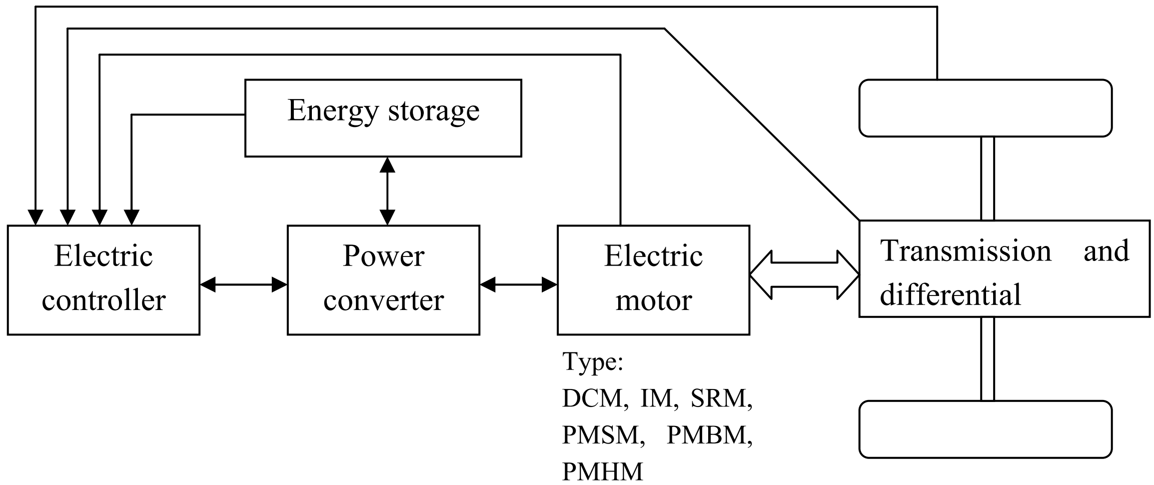

Figure 2.4. *Functional block diagram of a typical electric propulsion system [10].*

The motors used on electrically driven vehicles usually require frequent starts and stops, high rates of acceleration and deceleration, high torque and low-speed hill climbing, low torque and high-speed cruising, and very wide speed range of operation. The motors are often divided by the existence of a commutator. Motors with commutator are mainly the traditional DC motors (DCM), which include a series excited, a shunt excited, a compound excited, separately excited, and a permanent magnet (PM) excited motors. Because of their mature technology and simple control, they have been prominent in an electric propulsion system, but the need of the commutator and brushes makes them less reliable and unsuitable for maintenance-free operation and high speed. On the contrary, electric motors without commutator do not have the maintenance and reliability problems. In addition, advantages include higher efficiency, higher power density and a lower operation costs. Therefore, the commutatorless electric motors have become more attractive.

Induction motors (IM) are widely accepted as a commutatorless motor type for EV, HEV and PHEV propulsion, because of their low cost, high reliability, and maintenance-free operation. However, the complexity of control has been a problem and conventional control methods cannot provide the desired performance. Induction motors using the principle of field-oriented control (FOC) has been accepted to overcome their control complexity, but the motors still suffer from low efficiency at low load and limited constant-power operating range. They may achieve the speed ratio x about four.

Switched reluctance motors (SRM) have been recognized to have considerable potential for EV and HEV applications. Simple construction, low manufacturing cost, and outstanding torque speed characteristics (speed ratio x > 6) for electrically driven vehicle applications have been the advantages of SRM.

Another potential motor type for electrically driven vehicles is a permanent magnet synchronous motor (PMSM). It is a synchronous motor, but the field winding is replaced with PMs. They have inherently high power density, high efficiency, and conventional brushes, slip rings, and field copper losses can be eliminated. A disadvantage of PMS motors is that they inherently have a short constant power range due to their rather limited field weakening capability. The speed ratio is usually less than two. However, when adding the field winding to the PMSM, the speed range can be extended. Due to the presence of both PMs and the field windings, these motors are called permanent magnet hybrid motors (PMHM). PMHM can achieve a speed ratio of around four. Disadvantages of a PMHM are relative complex structure and the speed ratio is still not enough to meet the vehicle performance requirement. Therefore, a multigear transmission is required.

By virtually inverting the stator and rotor of PM DC motors, permanent magnet brushless DC motors (PMBM) are generated. Advantages of these motors are the removal of brushes, ability to produce large torque, the conduction of heat through the frame is improved and therefore an increase in electric loading causes higher power density. Despite the fact that the construction is simple, their design and control are difficult and subtle, because of the heavy saturation of pole tips and the fringe effect of a pole and slots. In addition, the presence of the position sensor reduces the reliability of SRM and constrains some applications. [10]

2.1.2 Types

Currently there are three main types of EVs existing on the roads: Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV) and Plug-in Hybrid Electric Vehicle (PHEV). The types differ from each other in multiple ways.

In a BEV, also be known as an all-electric vehicle, an internal combustion engine (ICE) and a fuel tank is replaced by an electric motor and a battery. Because the BEVs, do not have the ICE or a generator, all the energy is charged and stored to the battery and is from a power network or other external power source. Depending on a size and body, the BEVs are often divided in BEVs and City-BEVs. The BEV has a size and body like a current family or passenger car and it holds higher ranges than a City-BEV. The City-BEV, instead, bears resemblance to current subcompacts and is designed to drive in the city traffic in size, energy consumption and weight. Traditional battery capacities are about 35 kWh in BEV and 16 kWh in City-BEV.

Differently than in case of BEV, HEV has an ICE. It produces all the needed energy from fuel. The idea of HEV is to use the ICE at the maximum possible efficiency by utilizing the battery and the electric motor. The battery of HEV can only be charged with ICE or with regenerative braking, but it is not possible to charge from external power source.

PHEV has the same main components what HEV has, but the battery of a PHEV can be recharged to full charge by connecting the vehicle to the power network or external power source. Therefore, PHEVs have huge operational differences from HEV. When the battery has a high state of the charge (SOC), it can operate like an all-electrical vehicle, without using ICE, or it can operate in "blended" mode, where both the ICE and electric engine are used in a efficient way. When the SOC reduces under a certain level, it starts to operate like a HEV. The capacities of PHEV batteries are not as high as BEVs have, therefore the range when using only the battery as an energy source is not that high either. For example the battery of Toyota Prius 3 has more than three times lower battery capacity than Mitsubishi i-MiEV and almost five times as low as Nissan Leaf. The relation of battery capacities and all-electric ranges can be seen from Table 2.1.

Because of the short ranges of the PHEVs, the manufacturers have pursued to create their own category products such as E-REV (Extended Range Electrical Vehicle) and REEV (Range Extended Electrical Vehicle), which are PHEVs after all. Usually, a PHEV is equipped with a battery capacity about 5 kWh to 18 kWh depending on the size and purpose of the car. Therefore, PHEV does not have the two basic problems that BEV has: a limited range and an expensive battery. The battery capacity is often designed for 20 to 50 kilometers of driving, which usually covers a remarkable part of the daily mileage. Figure 2.5 illustrates the cumulative shares of the driving of Finnish people as a function of length of the trip. The data of the figure is drawn up from the Finnish National Travel Survey 2004-2005 by the authors of [13]. [11; 12; 13]

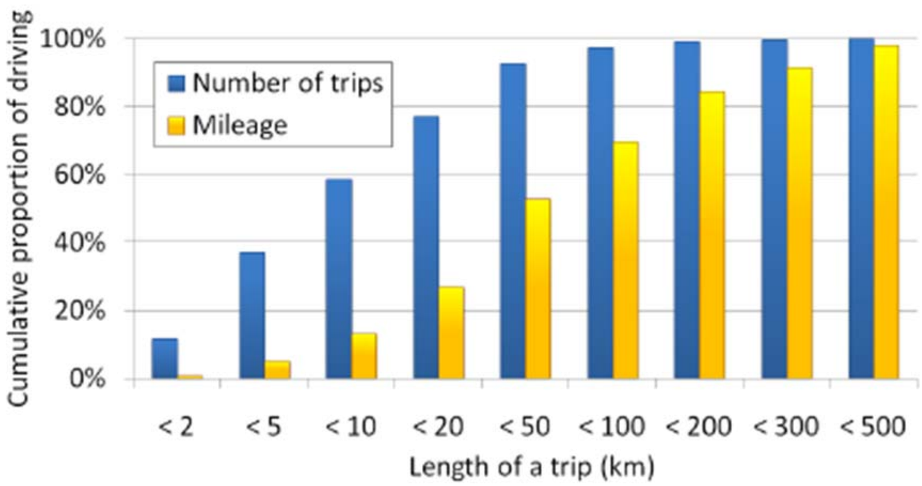

Figure 2.5. *Cumulative share of trips and driven kilometers as a function of a length of a trip [13].*

Currently there are three different decision principles of power transmission of PHEV and HEV: a parallel hybrid, a series hybrid and a series-parallel hybrid. In the parallel hybrid, both an electric engine and an ICE produce traction power. Whereas in the series hybrid, the ICE is used only as a generator and all the energy to the wheels comes from the electric engine. In practice, there have to be minimum two electric engines in the series hybrid. The series-parallel hybrid is a combination of the two previous decisions of principle. The decision principles are illustrated in Figure 2.6.[11]

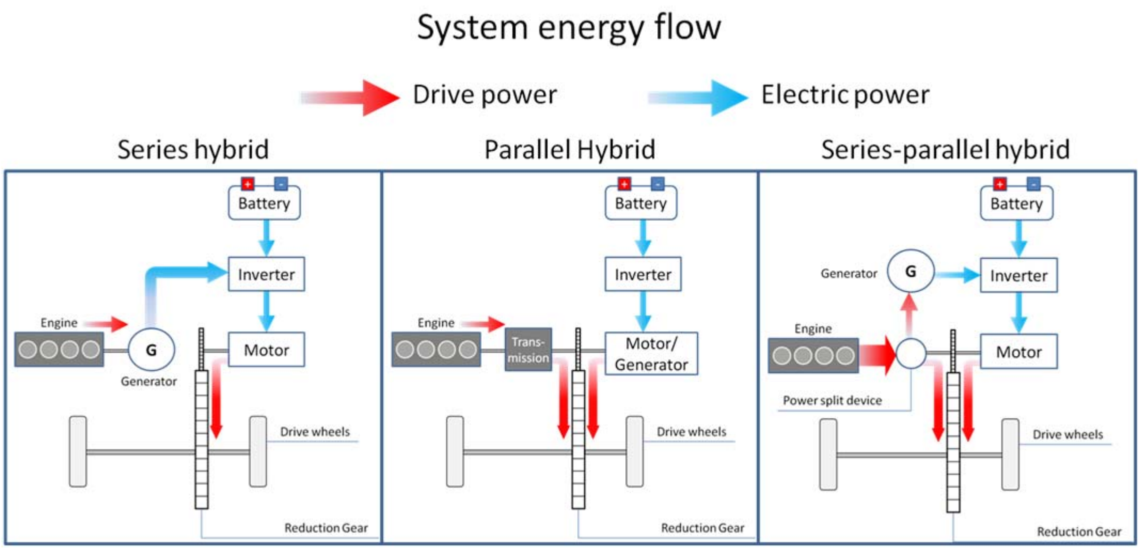

Figure 2.6. *Illustrating figure of three different decision principles of power transmission of PHEV: series hybrid, parallel hybrid and series-parallel hybrid [11].*

It has to be noted that the operational principle chosen and an execution of it will determine the properties of a PHEV. Therefore, the high system-level knowledge is essential, when designing PHEVs.

2.1.3 Consumption and energy efficiency

In a case of EVs, the consumption describes the amount of energy (kWh) an EV needs to drive 1 km (in all-electrical mode in case of PHEV). Manufacturers usually measure their EV consumption with a defined simulative driving cycle, which is measured without the energy use of the heating, cooling or media. Therefore, the real consumption is higher. [12]

Energy consumption is an integration of the power output at the battery terminals. When driving, the battery power output is equal to the resistance power (vehicle resistances opposing its movement) and power losses in the transmission, motor drive and electronics. The battery power output can be expressed as

$$P_{b-out} = \frac{V}{\eta_t \eta_m}\left(Mg(f_r + i) + \frac{1}{2}\rho_a C_D A_f V^2 + M\delta \frac{dV}{dt}\right), \tag{1}$$

where V is vehicle speed and the power losses in transmission and motor drive are represented by their efficiencies η_t and η_m. The first term inside the brackets of Equation *(1)* is called road resistance, where M is the total mass of the vehicle, g is the gravity factor, f_r is the rolling resistance coefficient, i is the road grade. The second term symbolizes aerodynamic drag, which is a function of vehicle speed, vehicle frontal area A_f, shape of the vehicle (characterized by aerodynamic drag coefficient C_D) and air density ρ. The third term represents the dynamic power for acceleration of the vehicle and it is a function of the total mass of the vehicle, the mass factor δ (the equivalent mass increase due to the angular moments of the rotating components) and acceleration dV/dt (vehicle speed derived by time t). In the equation, the nontractional load (auxiliary load) is not included. In some cases, when the auxiliary load is significant, it should be added to the traction load. In addition, a significant amount of energy is consumed by braking. Fuel consumption is especially high, when vehicles are driving with a stop-and-go pattern in urban areas, a significant amount of energy is consumed by frequent braking. When the regenerative braking of an EV is effective, a part of the braking energy can be recovered by operating the motor as a generator and restoring it into the batteries. The regenerative braking power at the battery terminals can be expressed as

$$P_{b-in} = \frac{\alpha V}{\eta_t \eta_m}\left(Mg(f_r + i) + \frac{1}{2}\rho_a C_D A_f V^2 + M\delta \frac{dV}{dt}\right), \quad (2)$$

where road grade (i) or acceleration (dV/dt) or both of them are negative, and α ($0 < \alpha < 1$) is the percentage of the total braking energy that can be applied by the electric motor. It is called the regenerative braking factor. As a result, the net energy consumption from the batteries is

$$E_{b-out} = \int_{traction} P_{b-out} dt + \int_{braking} P_{b-in} dt. \quad (3)$$

It should be noted that the braking power in Equation *(2)* has a negative sign. When the net battery energy consumption reaches the total energy in the batteries (E_{b-out}), the batteries are empty and recharging is needed. The traveling distance (range) is determined by the total energy carried by the batteries, the resistance power, and the effectiveness of the regenerative braking. [10]

The needed energy per kilometer of a single EV depends on various aspects. The factors that affect the specific electricity consumption are:

- the efficiency of the charging-discharging cycle (including the efficiencies of the battery and the charger)
- the efficiency of the regenerative braking system
- the energy needed for heating, air-conditioning and media
- the coefficient of drag
- the rolling resistance
- the total mass of the vehicle
- the driving cycle

When is the case of the total efficiency of energy chain, the terms such as "Well to Wheels" (WtW), "Well to Tank"(WtT) and "Tank to Wheel" (TtW) are often used. WtW means the total energy path from fuel production and supply to consumption of the vehicle. In that case, the oil refining and distribution is taken into account, in addition to the efficiency of the vehicle. The other two terms, are used to compare and analyze the efficiencies of the energy sources of a vehicle. According to the Mitsubishi's survey, the total energy efficiency of an EV is 29 %, containing 43 % WtT and 67 % of the TtW rates. The WtW rate of EV is about three and a half times better than a gasoline engine vehicle (12 %). Table 2.2 shows the results of "Well to Wheel" analysis, which are based on average composition of energy sources for power generation in Japan, but the results can be adapted to Finland.[14] In fact, at the production structure of Finland or Nordic countries, the total energy efficiency is even better [11].

Table 2.2. *Results of the "Well to Wheel" analysis [14].*

Vehicle type	Well to Wheel		
	Well to Tank	Tank to Wheel	(Total energy efficiency)
EV	Refining, power generation, electricity transmission 43 %*	On-the-vehicle efficiency 67 % (including charging efficiency of 83 %)	29 %
Diesel engine vehicle	Refining, transportation 88 %	On-the-vehicle efficiency 18 %	16 %
Gasoline HEV	Refining, transportation 82 %	On-the-vehicle efficiency 30 %	25 %
Gasoline engine vehicle		On-the-vehicle efficiency 15 %	12 %

*: The above figures are based on Japan's average composition of energy sources for power generation.

As illustrated in Table 2.2, the total energy efficiencies of EVs are better than the efficiencies of conventional ICEVs. Therefore, the EVs have a better net present value (NPV) of fuel cost savings. Table 2.3 shows a list of the NPVs of the fuel savings achieved by electric driven vehicles relative to the ICEVs of comparable performance and accommodations [15]. In the table, the vehicle type PHEV-20 is a shorter range PHEV, PHEV-40 is an extended range PHEV and FPBEV is an all-electric vehicle.

Table 2.3. *Net present value (NPV) of fuel cost savings [15].*

Vehicle Type	Annual Mileage		Gasoline Energy		Electric Energy		NPV of Energy Savings[3] $
	Gasoline miles/yr	Electric miles/yr	Cost $/gal	Efficiency[1] miles/gal	Cost $/kWh	Efficiency[2] miles/kWh	
HEV	10,000	0	2.50	30 (40)[4]	n.a.	n.a.	1,573
	10,000	0	3.00	27 (45)	n.a.	n.a.	3,356
	14,000	0	3.50	36 (50)	n.a.	n.a.	2,878
	14,000	0	4.00	33 (50)	n.a.	n.a.	4,356
PHEV-20	7,000	3,000	2.50	30 (40)	0.10	3.0	2,318
	6,000	4,000	3.00	27 (45)	0.06	3.5	4,909
	9,500	4,500	3.50	36 (50)	0.12	3.5	4,221
	8,500	5,500	4.00	33 (55)	0.08	4.0	7,407
PHEV-40	5,500	4,500	2.50	30 (40)	0.10	3.0	2,690
	4,500	5,500	3.00	27 (45)	0.06	3.5	5,491
	8,000	6,000	3.50	36 (50)	0.12	3.5	4,669
	7,000	7,000	4.00	33 (55)	0.08	4.0	8,029
FPBEV	0	10,000	2.50	30	0.10	3.0	4,055
	0	10,000	3.00	27	0.06	3.5	7,239
	0	14,000	3.50	36	0.12	3.5	7,056
	0	14,000	4.00	33	0.08	4.0	10,933

[1] efficiency (gasoline mileage) of baseline conventional ICE vehicle
[2] efficiencies (miles per kWh of AC electricity) used by PHEVs and EVs in EV (electric drive) mode
[3] NPV calculation basis: 10 year battery life, 3% inflation rate, 8% interest rate
[4] in parentheses: efficiencies (gasoline mileage) of HEVs and PHEVs in HEV (hybrid drive) mode

The first two lines for each vehicle type in Table 2.3 can be seen as near-term scenarios and the other two lines as long-term scenarios in terms of annual mileage, the prices of gasoline and electricity, and the efficiencies of ICEVs and EVs. For each set of scenarios, the assumptions used in upper lines are less favorable to EVs in terms of propulsion energy costs and vehicle efficiencies. The lower lines is more favorable. The calculated NPVs for each vehicle type shows that the long-term scenario is about three times the value for a conservative near-term scenario, indicating the large potential for growing fuel cost savings. [15]

Fortum has measured the energy consumption of an electric vehicle in wintertime in Finland. The consumption of the tested EV, Fiat Doplo, was between 0.2 - 0.25 kWh/km. The Fiat Doplo is a big size family car and the heating was also included, therefore the average energy consumption of the vehicle will be the typical 0.15 to 0.2 kWh/km. When assuming that consumption of EV can change from 0.12 to 0.25 kWh/km and consumption of PHEV from 0.15 to 0.25 kWh/km depending on the factors listed before in this chapter, the consumptions of EVs can be listed as showed in Table 2.4.

Table 2.4. *Consumption in different driving cycles [12].*

Vehicle type	Consumption		Battery capacity	Split-up into electricity and conventional propulsion	
	Electrical (kWh/100km)	Conventional (l/100km)	(kWh)	Electrical (%)	Conventional (%)
BEV	13-25	0	25-35	100	0
City-BEV	12-16	0	10-16	100	0
PHEV	15-25	7.5	6-12	33,3	66,6
PHEV(E-REV & REEV)	15-25	7.5	12-18	66,6	33,3

At the end of 2009 in Finland, there were 2 776 644 passenger cars and the cars overall mileage was 46 000 million kilometers [16]. It equals about 16 600 km/a/car. If assumed that the mileage has increased more than the amount of the cars, the average annual driving distance is 17 000 km/a/car and about 47 km/day/car. When the average consumption of EV is 0.20 kWh/km and all the kilometers are driven with BEVs, a single BEV consumes 9.4 kWh/day, which equals 3431 kWh/a. If Fortum's "yleissähkö" price are used, the annual energy cost of an EV would be 315.72 euro. It has to be borne in mind that the calculation includes also the long trips, which are not possible with battery capacities and ranges of present BEVs. [3]

2.1.4 Penetration rate

Electric vehicles have not yet achieved mass commercialization. BEVs and PHEVs are expected to become increasingly available in the near-to-medium term and electrically driven vehicles could achieve considerable market penetration in the future. The estimations of the future development and market penetration of EVs includes great uncertainties and depends on many influencing factors and remaining barriers. The Fortum's prediction for the future development and penetration of EVs is shown in Figure 2.7 [2].

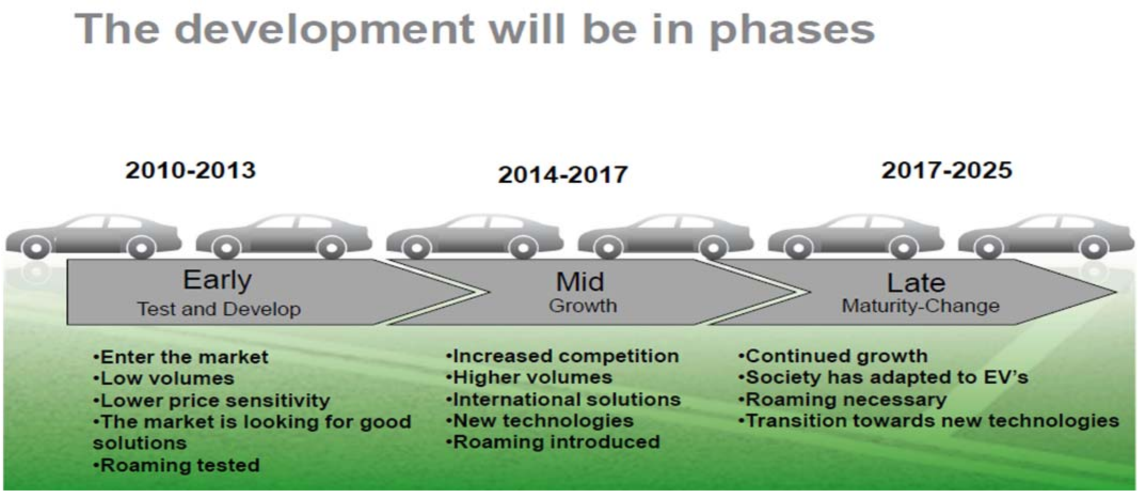

Figure 2.7. *Fortum's prediction for the future development and penetration of EVs [2].*

The electric propulsion system represents an innovative technology that has not yet achieved technology maturity or mass commercialization, because of remaining technological and economic barriers. Besides the battery technology must improve, the commercialization of EVs will particularly be influenced by general framework conditions. The conditions, such as energy prices, regulatory and other governmental measures, can hardly be predicted. Therefore, possible pathways are illustrated in various penetration scenarios that represent different conditions.

According to the baseline scenario of the IEA (International Energy Agency) "Energy Technology Perspectives (ETP) 2010" study, light-duty vehicle sales are mainly conventional ICE vehicles through 2050. The BLUE Map scenario shows (see Figure 2.8.) that PHEVs and EVs reach over 5 million sales by 2020. By 2050, PHEVs and EVs account for more than 100 million sales, which is about 55 % of all sales. [17]

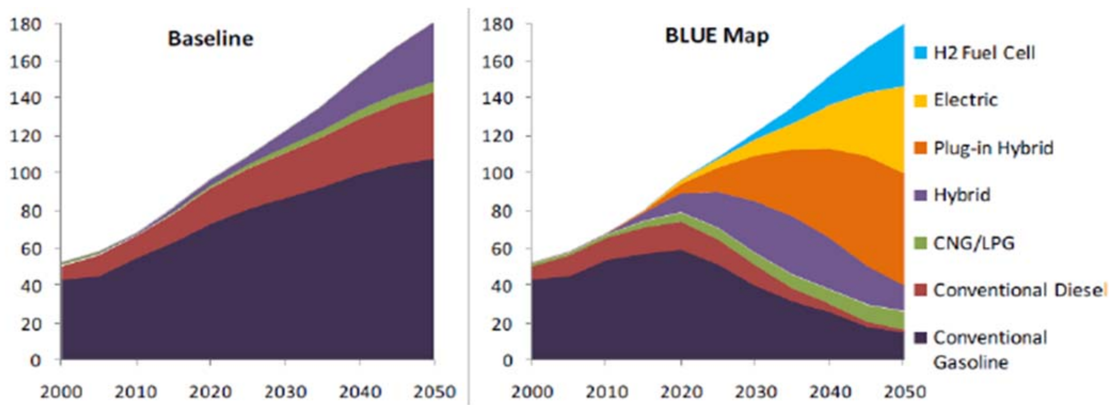

Figure 2.8. *Passenger light-duty vehicle (LDV) sales by technology and scenario (a million sales per year) [17]. CNG means compressed natural gas and LPG means Liquefied petroleum gas.*

In February 2009, the Ministry of Employment and the Economy appointed a working group to clarify the possibilities and actions considered to electric vehicles. The survey introduces three scenarios, which predicts the commercialization of PHEV and EV by 2020 and 2030 in Finland. The scenarios are divided by the quickness of penetration. The overview of the scenarios is showed at Table 2.5. [11]

Table 2.5. *Overview of the scenarios [11].*

Scenario	Year	Share of new vehicles		Cumulative sales volume		Share of passenger car mileage	
		PHEV	EV	PHEV	EV	PHEV	EV
Basic	2020	10 %	3 %	66 000	13 000	3 %	0.6 %
	2030	50 %	20 %	480 000	160 000	19 %	7 %
Fast	2020	40 %	6 %	190 000	26 000	8 %	1 %
	2030	60 %	40 %	960 000	450 000	38 %	19 %
Slow	2020	5 %	2 %	38 000	12 000	2 %	0.5 %
	2030	20 %	10 %	207 000	92 000	8 %	4 %

According to the most optimistic scenario (fast scenario), every new vehicle bought in 2030 is an electricity driven vehicle. Relatively, the slow scenario claims that less than every third is an electricity driven vehicle. However, a lot of assumption has been done and these scenarios are only predictions tools for the future. The truth will most likely to be a mixture of the scenarios.

Generally, it is predicted that it takes 10 to 20 years to a new vehicle technology comprise 5 % of new sales. However, with a combination of competitive technologies and strong policy incentives or governmental regulations, a faster market penetration could be realized. [18]

The good indicator for electric driven vehicles is the availability of vehicles. There has to be several numbers and types of models available to attract a wide range of buyers, and thus enable rapid growth in market share and sales. Figure 2.9 shows the number of EV and PHEV models that have been announced, and planned to be introduced in the future.

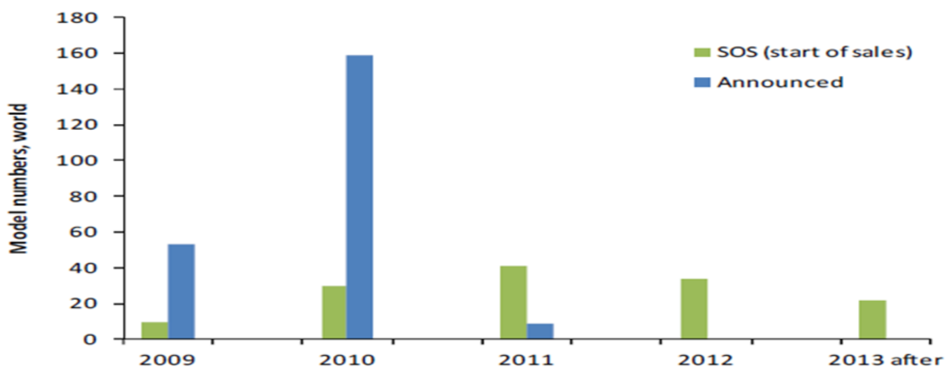

Figure 2.9. *PHEV or EV model introductions [17].*

According to [17], there were only about 30 models actually available on markets around the world at the end of 2010. As can be seen from Figure 2.9, in 2011 there will be about 40 new models in the market and close to 40 more in 2012. The increasing amount of new models in the market indicates that the electrification of transportation has begun.

2.1.5 Composition

Today, many different EV technologies exist, therefore an analysis with only one kind of EV is not reasonable. Because of a non-linear charging profile and variability of battery sizes, the charging behavior for a fleet of vehicles will differ significantly from a charging profile with standard EVs. The composition of different EV types is a necessary analysis to estimate the effects on distribution networks. It describes the percentages of each EV type depending on the penetration rate and the chosen scenario.

Figure 2.10 shows one scenario, how a development of the composition of different vehicles depends on market penetration. When a market penetration is relatively small, City-BEVs and PHEVs are the main types in the market. With a rising market penetration, the percentage of the BEV is increasing and City-BEV is decreasing due to the limited market potential of small vehicles. [12]

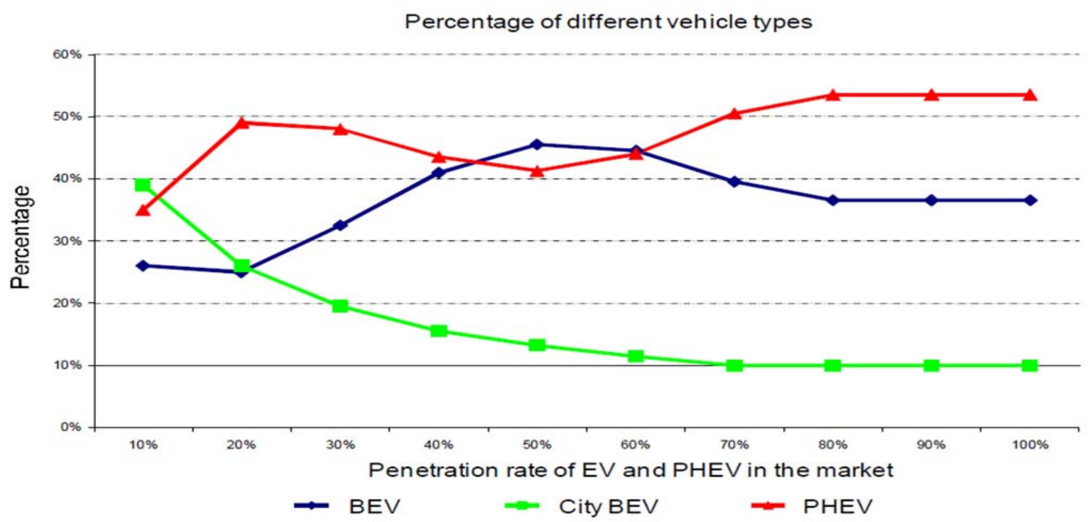

Figure 2.10. *A scenario of a possible development of composition of EV types depending on different market penetrations [12].*

To determine the percentages of different EV types, driving behavior and socioeconomic data in different countries has to be analyzed. A market model that analyses the parking situation and the anticipated vehicle use per type has to be used. When the charging scenario, area and country, driving behavior and socio-economic data have chosen and estimated, the substitution potential has to be analyzed for the regions where the grid data is available. The variation of the market penetration presents the used percentage of the total substation potential. [12]

2.2 Batteries

Batteries are the energy storages of electric drives in PHEV and EV. The battery is composed of individual battery cells, inter-cell connectors, a cooling system, cell monitoring devices and safety circuits. The investment cost and performance of batteries are critical prospects for the performance and commercialization of EVs. Batteries need to offer a considerable electric driving range and appropriate vehicle performance. Therefore, it is the central component in future vehicles. [11]

The battery contains several secondary cells, which are placed in series. Secondary means that cells can be recharged and discharged many times. This is possible because of electrochemical reaction is reversible and the original chemical compounds can be reconstituted by the application of electrical potential between the electrodes injecting energy into the cells. In contrast, primary cells can only be charged and discharged once.

In the charging phase, the cells operate as electrolytic cells, which use current of the charger to strip electrons from the cathode to the anode, leaving the cathode with a net positive charge. The electrons are conducted to the anode giving it a negative charge. When the battery is fully charged, there is a negative charge on the anode and a positive charge on the cathode, resulting in a potential difference across the battery. In case of discharging, the cells in the battery operate like a galvanic cell. When the circuit is completed, the surplus of electrons on the anode flows via the external circuit to the positive charged cathode, which accepts it, neutralizing its positive charge. This action reduces the potential difference across the battery to zero. The circuit is balanced by the flow of the positive ions in the electrolyte from the anode to the cathode. [19]

In electric mobility development, the aim is to develop the energy densities of the batteries. The other important properties are [11; 12]:

- Costs
- Security
- Charging time
- Lifetime (calendar or cycle stability)
- Energy efficiency (Wh/kg or Wh/l)
- Power density (W/kg or W/l)
- Temperature

A difference between batteries depends primarily on the structure used. The major difference comes from the materials of the electrode. Lithium has the highest normal potential of all the elements and it is the strongest deoxidizer. Therefore, it possesses a chance to have a high energy density and to be the best battery material. Almost all the cars, which are launched to the market, are based on the lithium-ion chemistry.[11] The following subchapters will introduce the main technologies, prospects and parameters that are used in the batteries of today.

2.2.1 Available battery technologies

EVs are highly dependent on the availability of a battery technology that allows reliable electric energy storage. Starting from the conventional lead-acid battery, several of battery concepts have been developed during the last decade and already attained considerable progress in storing electric energy.[18] Only a few battery types have potential to meet the combination of power and energy density requirements for EVs[15], as illustrated in Figure 2.11. When deciding the vehicle properties, a high power density of the battery enables vehicle a high performance when accelerating, whereas a high energy density enables a longer range. Figure 2.11 shows that HEVs and PHEVs need a high power density rather than a high energy density and therefore Ni-MH battery is usually suitable. However, when the extended range of PHEV is wanted, the Li-Ion battery is needed. Therefore, almost every PHEV has a Li-Ion battery. BEVs require a suitable mixture of power and energy density, therefore lithium-ion battery chemistry is the best solution of today. The darker gray boxes in Figure 2.11 show energy and power requirements for HEVs, PHEVs as well as city-BEVs (small FPBEV) and BEVs (full FPBEV). FPBEV (Full Power Battery Electric Vehicle) means the same thing as BEV, which is used more often in this thesis. In comparison, the average energy density of gasoline is about 13000 Wh/kg [20], which enables ICE vehicles to drive much longer trips.

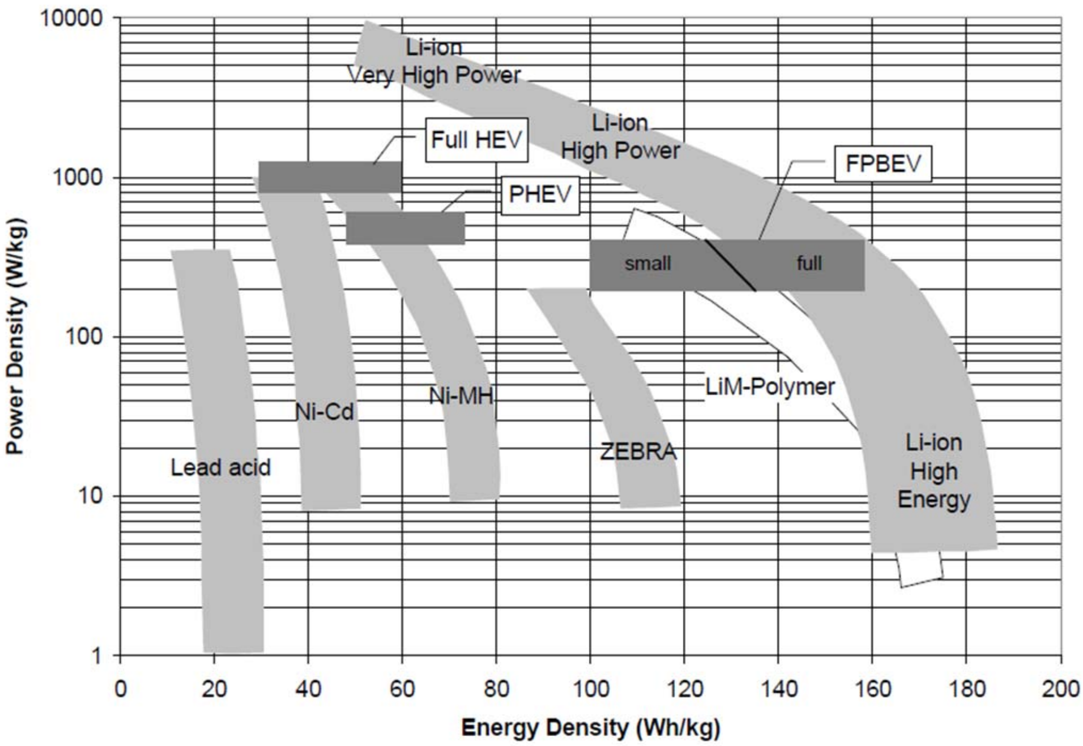

Figure 2.11. *Potential of battery technologies for HEV, PHEV and BEV applications [15].*

Energy density and power density are partly exclusive prospects of themselves. Improving the other might make worse the other. If the battery is wanted to use with high powers (including charging and discharging), wiring gauge have to be increased to reduce losses. That reduces the energy density of the battery, because less reacting subject can be fitted to the battery (to the same amount of kilograms). [11]

In this section, three categories of the battery chemistries of electrically driven vehicles are introduced: nickel-metal hybrid (NiMH) and lithium-ion (Li-Ion) and ZEBRA ($Na\text{-}NiCl_2$). Fuel cells and super-capacitors are dropped out of the study.

The nickel metal hybrid (NiMH) battery uses a hydrogen-absorbing alloy as the negative electrode, nickel oxide as the positive electrode, an alkaline electrolyte, and a separator made from porous polyolefin material. The NiMH cell voltage is a relatively low 1.2 Volt. The batteries have demonstrated high reliability and long life in automotive applications. [15] The energy density is also more than a double compared to a lead acid and 40 % higher than that of NiCds. The NiMH batteries are more expensive than lead-acid and NiCd batteries, but are considered better for the environment. [19]

To enable driving ranges of 120-160 kilometers for typical compact and midsize cars, the NiMH battery capacity of around 30 kWh and more is needed. Weight of the battery would be between 540 to 600 kg, adding 40 % to the weight of a conventional vehicle. [15] Other disadvantages of NiMH are a very high self-discharge rate, vulnerability of overcharging and too low energy density for EVs. Compared with Li-Ion batteries, they are expected to lose their market share in the medium term, due to lower energy density properties although today they are still more mature. [19]

The anode of the lithium ion battery is composed of lithium, dissolved as ions, into a carbon. The cathode is composed of lithium liberating compounds, typically three electro-active oxide materials, for example, Lithium Cobalt dioxide or a Lithium Manganese. The lithium ion cell differs by its electrolyte from the others, because it is not water based but organic solution. An exception is a lithium polymer cell within dry and solid polymer electrolyte.

Lithium is the lightest metal and has the greatest electrochemical potential, which makes it one of the most reactive metals. Therefore, it has a potential to achieve very high energy and power densities and other performance advantages. The other performance advantages are [19]:

- High cell voltage (typically 4.2 Volts)
- Low weight
- Variants of the basic cell chemistry allow the performance to be tuned for specific applications
- Individual cells up to 1000 Ah capacity available
- High discharge rate
- Fast charging possibility
- Can be deep cycled
- Very low self discharge rate

- Very high efficiency
- Long cycle life

These performance advantages of Li-ion batteries make them suitable for automotive applications. Although the high cell voltage is the fundamental reason for the high specific energy of Li-ion cells and batteries, one of the main challenges for practical applications derive from the highly negative potential of lithium. It is a powerful driving force for its chemical reactivity within the cell. Only the formation of a solid-electrolyte interface (SEI) prevents the continued, uncontrolled reaction of lithium with the electrolyte solvent and enables the controlled discharge and recharge of Li-ion cells and batteries. Second key challenge is the sensitivity of Li-ion cells to overcharge. It affects processes that damage the cell and can result in hazardous conditions. To avoid overcharge, the batteries require accurate voltage control in every cell. The accurate and reliable control of cell voltage and temperature are therefore critical requirements for achieving the long life and adequate safety of Li-ion batteries. Third major problem is that the EVs require large batteries, which are expensive. Because of finite lithium resources and high costs, further competitive technologies have to be created. [15]

Although the ZEBRA ($Na\text{-}NiCl_2$) battery does not meet the peak power requirements for electrically driven vehicle applications (see Figure 2.11), the battery has found its way in several hundred City-BEVs as well as in a number of buses and other heavy vehicles. It operates at over 270 °C and therefore preheating system is needed, which prevents significant thermal energy losses. On the other hand, high temperature operation facilitates battery cooling and makes the operation of the insulated ZEBRA battery independent of environmental temperatures. In addition, they have excellent calendar as well as cycle life, because of no corrosion or other side reactions occur within a ZEBRA battery cell. In combination with the modest total weight of the battery active materials, the relatively high cell voltage of 2.58 Volts gives the ZEBRA battery high energy density. They also tolerate substantial amounts of overcharge. Still, the major advantages of ZEBRA batteries are the low material costs and possibility recycle it easily and completely.

The prime drawback of the ZEBRA technology is its low peak power density of approximately 180 W/kg. This characteristic limits the power even of BEV-design ZEBRA batteries and together with high temperature battery operation, this limitation has kept the technology from being accepted as a serious candidate for electrically driven vehicle applications. [15] Table 2.6 summarizes comparative performance, price and safety issues for potential and actual vehicle batteries presented at a 2007-industry forum [21]. The values of column cost are converted from USD to euro at the rate 0.702411 of exchange.

In Table 2.6, Lithium Metal Polymer (Li-M-Polymer) represents one of the prospective technologies especially for automotive applications. There, a more commonly used Lithium Carbon anode is replaced by metallic lithium and a metal oxide cathode. Usually Li-M-Polymer battery need to work at temperatures between 80 to 120 °C for optimum results but can be operated at reduced power at ambient temperature. It is claimed that their cell chemistry is more tolerant to abuse. DOD (depth of discharge) are defined later in the study.

Table 2.6. *Comparison of the battery technologies [22].*

Parameter	Li-ion	Li-M-Polymer	NiMH	Na-NiCl2 (ZEBRA)	Lead-Acid
Energy density (Wh/kg)	75-120	100-120	50-70	100-120	20-30
Power density (W/kg)	1000-3000	200-250	1000-1500	180	200-500
Cost (€/kWh)	693-1386	?	693	416	69-140
Lifetime (cycles, 100 % DOD)	1000-2000	?	2000	1000	300-800 (valve-regulated lead acid battery)
Issues	Safety, cost	No commer-cial product	Temperature limitations	Single sup-plier	

Table 2.6 shows that lithium ion based battery technologies are the most expensive but they meet the energy and power requirements (see Figure 2.11) almost in every prospect. Lead-acid technology has lost their ground completely in automotive applications. ZEBRA batteries are used in heavy working machines and busses, because of high energy density and a low price. NiMH-batteries are only suitable for HEVs and some PHEVs, when high power density, a low price, and long lifetime are required. However, when the range extension as well as good performance when accelerating are needed, Lithium based technologies are the best solution of today. New lithium based technologies, which uses nano-structured cells and novel materials, can offer safer chemistry, high stability, lower price, and better performance capability. Technologies such as Lithium Iron-Phosphate ($LiFePO_4$) with nano-structured cathode made by Finnish European Battery Ltd. and Lithium-Titanate ($LiTi_5O_{12}$) with nano-structured anode are potentially indicative of future trends.

2.2.2 Battery capacity

The battery capacity denotes how much energy the battery can store. The amount of energy that can be extracted from a fully charged battery, for instance, depends on the temperature, the rate of discharge, battery age and battery type. Therefore, it is difficult to specify the capacity of the battery with a single value. The three primary ratings that are used to specify the capacity of a battery are introduced in this chapter.

Battery manufacturers usually specify the battery with coulometric capacity. It is defined as the number of ampere-hours (Ah) gained when discharging the battery from a fully charged state until the terminal voltage drops to its cut-off voltage, as shown in Figure 2.12. The ampere-hour value defines the capacity of a single cell and therefore it cannot be used to define the capacity of full battery pack. Different ampere-hour as well as terminal voltage values will be gained by connecting the cells differently into series or parallel. However, at different discharging current rates, the same battery has a different ampere-hour value. Generally, the ampere-hour value (coulometric capacity) will become smaller with a high discharge current rate, as shown in Figure 2.13. Therefore, battery manufacturers usually add the current rate (C-rate) to a number of ampere-hours when specifying a battery. For example, the standard of SLI (standard-lighting-ignition) batteries is to specify ampere-hours for 20 hours discharge. This standard is denoted by the nomenclature of C/20. For instance, the battery labeled 100 Ah at C/20 rate will produce 100 Ah for a 20-hour discharge. This means that the new and fully charged battery will produce 5 amperes for 20 hours in ideal condition. Thus, the C-rate of a battery is the ability of a battery to be charged and discharged at a certain current. Therefore, coulometric capacity is very important in order to evaluate the ability of a battery to be fast-charged. [10; 12]

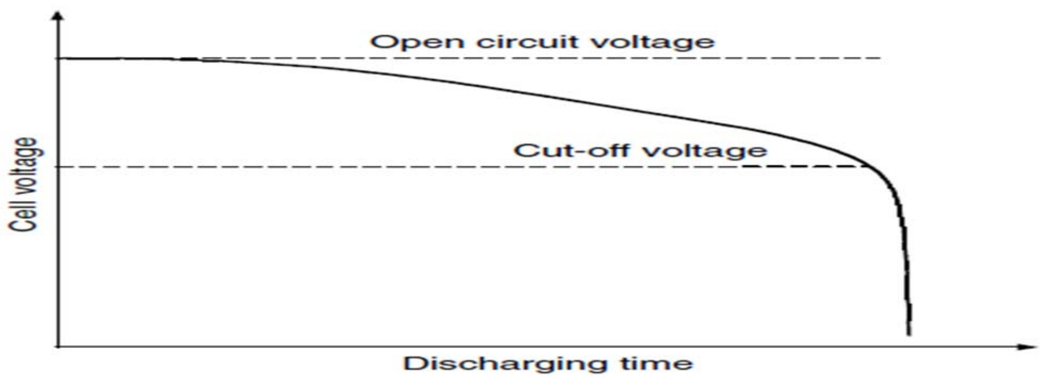

Figure 2.12. *Cut-off voltage of a typical battery [10].*

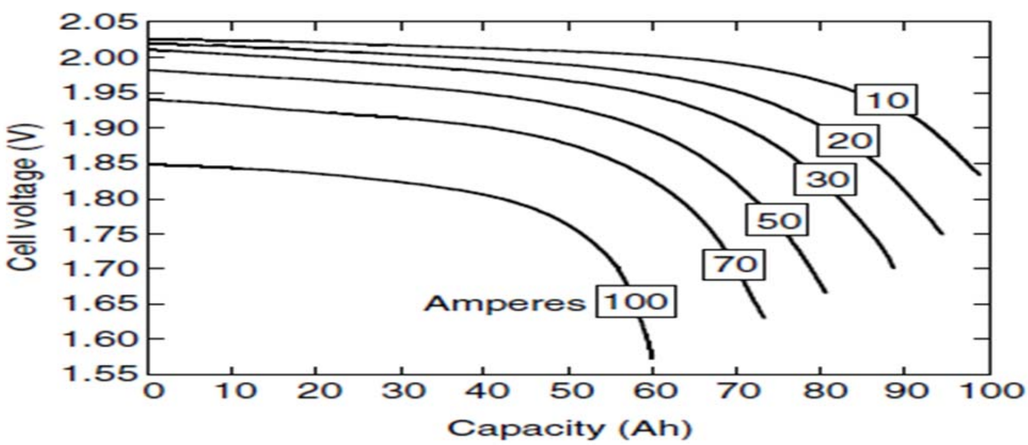

Figure 2.13. *Discharge characteristics of a battery [10].*

A second way to specify the capacity of the battery is energy capacity measured in kilowatt-hours (kWh). It is a product of the terminal voltage and the ampere-hour value of the battery. For EVs, the energy capacity is considered more important than a coulometric capacity, because it is directly associated with vehicle operation. However, it is important to make distinction between total and available energy. While a battery may have 20 kWh of total energy, only a portion of this capacity is available for vehicle operations. Therefore, two important parameters have to be defined: state-of-charge (SOC) and depth-of-discharge (DOD). State-of-charge is defined as the ratio of the remaining capacity to the fully charged capacity, so that fully charged battery has an SOC of 100% and a fully discharged battery has an SOC of 0 %. However, the terms "fully discharged" and "fully charged" sometimes causes confusion because the batteries have different ampere-hour capacities at different discharge rates and different cut-off voltages. In practice, a "fully charged" battery may be less than SOC of 100 %, and the battery may be regarded as "depleted" at something more than SOC of 0 %. This practical range of operation is called the usable depth-of-discharge (DOD). For example, if a battery with 20 kWh of total energy is operating with DOD of 75 %, it would have only 15 kWh of available energy. [10; 23]

A third measure of battery capacity is reserve capacity. It is defined by the length of time that a battery can produce a specific level of discharge. Usually measured in minutes a battery can maintain more than cut-off voltage under 25 amperes discharge. It is used often as a test of battery life. [21]

2.2.3 Charging profile

The standard procedure used when charging a battery is the method of Constant Current - Constant Voltage (CCCV). First, the battery is charged under a constant current with increasing voltage until voltage reaches the set limit, which is usually near SOC of 80 %. Charge can be continued with constant voltage while the current steadily decreases down to zero. The behavior of a charging current, a cell voltage, capacity and power during the charging process depends on battery chemistry. The relations between a charging current, a cell voltage and a capacity of a Li-Ion battery are illustrated in Figure 2.14. In [24], the power behavior of two different lithium-ion battery cells as well as a 1 kWh battery pack with different charging rates are presented according to measured data. The data shows that the power profiles of the battery pack as well as battery cells are fairly flat. [12]

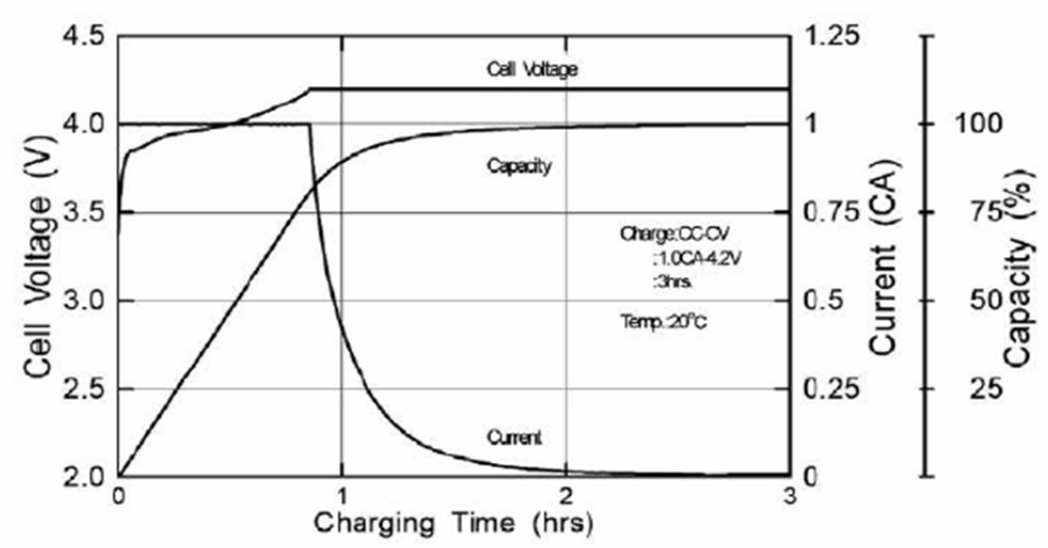

Figure 2.14. *A charging profile of Li-Ion batteries [12].*

Increasing the charging current does not hasten the SOC of 100 % state by much, but high current will quickly fill the battery to about SOC of 80 %. After voltage is peaked, the saturation state, where current decreases steadily, will accordingly take longer.

Most Li-Ion cells can be charged to 4.2 Volts with a tolerance of ± 50 mV/cell. Higher voltages could increase the capacity but the resulting cell oxidation would reduce service life and cause safety issues. The battery life can be prolonged by choosing a lower voltage threshold, or eliminating the saturation charge altogether, but this reduces the range of the vehicle. Adding full saturation at the set voltage, the capacity can be typically boosted by about 10 % but it adds stress because of high voltage. The charge current must be cut off when the SOC of 100 % are reached, or even earlier, because Li-ion cannot absorb overcharge. Once the charge is terminated, the battery voltage begins to drop, which eases the voltage stress. The open-circuit voltage will settle in some lower voltage state. In addition, the lithium ion battery should never be discharged too low. The cell voltages have to be controlled that they are not lower than 3.0 Volts/cell, otherwise equipments will cut-off and if the discharging continues to about 2.7 Volts/cell or lower, the protection circuit of the battery puts it into a sleep mode, which renders the battery pack unserviceable. It has to be borne in mind that the voltage values of this paragraph depend significantly from the used battery chemistry. [19]

2.2.4 Battery lifetime

Lithium-ion cells tend to lose capacity, power and safety as a function of time and use. The degradation of traction batteries can be defined as a measure of time or cycle. Calendar life is the ability of the battery to withstand degradation over time. It may be independent of how much or how hard the battery is used. The typical goal of calendar life of batteries varies between 10 to 15 years at the temperature of 35 °C. The battery cycle life instead, is a measure of a battery's ability to withstand the cumulative changes of the structure and composition of key battery cell components caused by charge-discharge cycling. It defines the number of cycles before battery performance has degraded to a predetermined level. [14; 22; 23]

The cycle life is usually divided into two categories by the measure of DOD. The batteries may require both deep discharge-recharge cycles and frequent shallow-discharge-recharge capability where the variations of SOC are only a few percent. The deep cycle life is the number of discharge-recharge cycles the battery can perform in a charge depleting mode. For example, one complete deep discharge, starting from SOC of 90 % and ending to SOC of 25 % are shown in Figure 2.15. When recharging the battery back to SOC of 90 % would complete one full deep cycle. Smaller variations of SOC are measured by shallow cycle life. It occurs throughout the one deep discharge cycle, as shown in Figure 2.15, because the battery takes in electric energy from regenerative braking and from ICE (in case of PHEV and HEV), and passes energy to the electric motor as needed to power the vehicle. The shallow cycles affect longevity, but cause less degradation than deep cycles. It should be noted that shallow cycles affect more wear on the battery when they occur at a relatively low SOC, for example, in a charge sustaining mode of PHEVs, where SOC are about 25 %. [25]

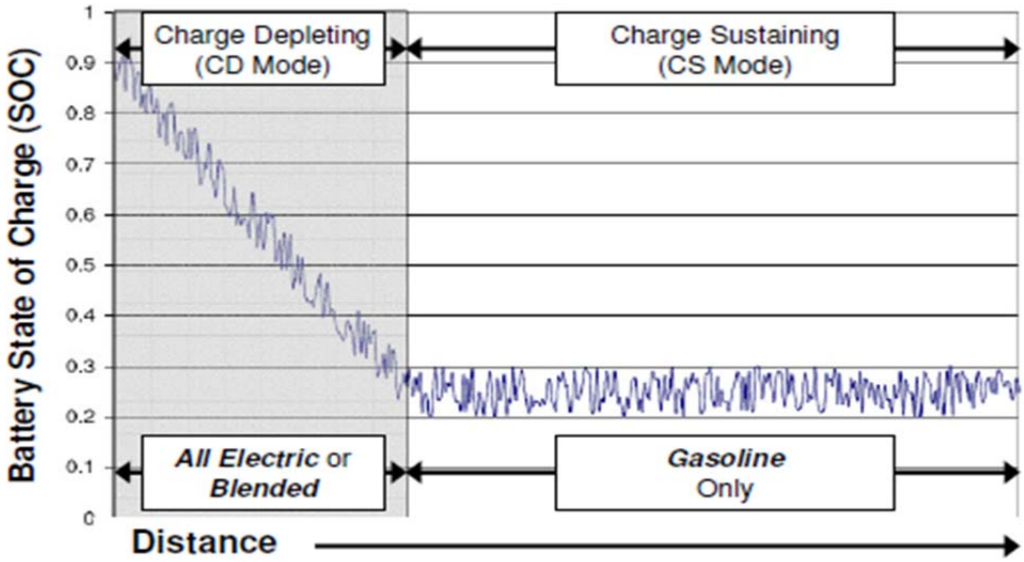

Figure 2.15. *Typical PHEV discharge cycle (DOD of 65 %). [25]*

Comparing the cycle life of different batteries made by different manufacturers are challenging because one manufacturer can define the cycle life differently than the other. In addition, they rarely declare how fast charging will affect the cycle life. The fast charging requires also a high power electricity network connection, and it sets high requirements for battery materials, battery design and heat management system [24]. However, [23] have made a summary of battery goals from different sources. It lists the assumptions of calendar life, deep cycle life and shallow-cycle life made by different sources. According to that list, a new battery would have 10 to 15 year calendar life, it will endure 1,400 to 5,000 deep cycles and from less than 200,000 to 300,000 shallow cycles. These goals are made for PHEVs and have to be reconsidered if different EV type is used. For example, the shallow cycle life of BEVs is not that important due to the inexistence of ICE and HEVs have only shallow cycles because recharging is not possible.

2.2.5 Costs

Costs of the battery are very important for all business aspects. Battery costs include the cost of battery investment, recycling, and degradation. It is defined by the price per kWh.

According to [7], lithium-ion cells usually cost anywhere from 450 USD to 1,000 USD per kWh, which equals approximately from 316 to 702 euro per kWh at the rate 0.702411 of exchange. Therefore, for instance, the battery of Nissan Leaf with capacity of 24 kWh could cost from 7,584 to 16,848 euro, which is a huge share of the overall price of the car (see Table 2.1). Appendix 1 presents a summary of published present, projected and targeted cost targets for high-energy EV batteries. It claims that battery costs will get lower at near future and in 2020 the battery price would be 200 euro per kWh. The long-term target is about 70 €/kWh. If that happens, a 40 kWh battery would only cost 2,800 euro, which is very affordable and competitive price.

Battery recycling costs are usually measured in tonnage. According to [26], the flat cost to recycle a ton of batteries is from 1,000 USD to 2,000 USD, and Europe hopes to achieve a cost per ton of 300 USD, which is about 210 euro per ton. Ideally, this would include transportation. However, moving and handling the goods is expected to double the overall cost in practice.

The battery degradation costs are very hard to estimate, because of the complexity of the battery degradation process and inexperience of new traction batteries. However, when the battery is discharged the degradation costs can be defined as a function c_{dis} in a function of the DOD at the start and at the end of the discharging. The additional parameters of the function are battery-specific parameters, the investment cost of the battery and the usable energy of the battery. Figure 2.16 shows how the discharging costs per kWh differ depending on the investment cost. When the battery is discharged with high DOD rates, the degradation of the battery increases and therefore discharging costs per kWh are higher. The degradation costs also depend from the used battery chemistry. For example, lithium chemistry based on cobalt oxide has poor thermal stability whereas iron phosphate has very good thermal stability [19]. [12]

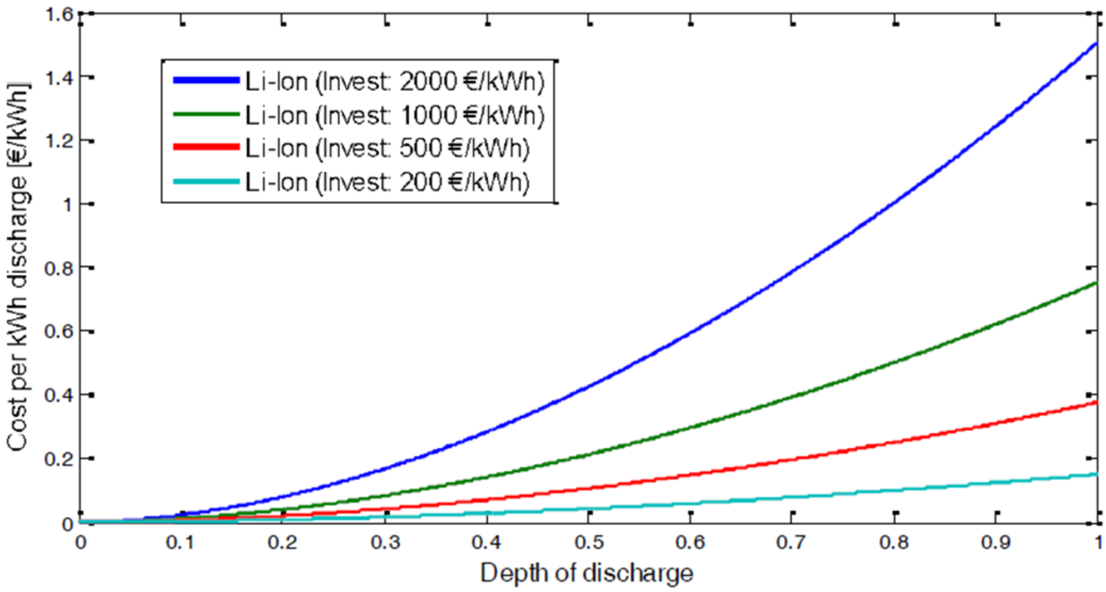

Figure 2.16. *Battery degradation cost curves depending on the DOD for different investment costs [12].*

2.3 Charging infrastructure

Charging infrastructure has an important role in EV commercialization. It is essential that consumers have a possibility to charge their EVs at any time in many different places. In general, where an EV parks and stays for a while, there should be some kind of charging opportunity. Especially the place where a rechargeable vehicle stays longer periods, the existence of charging infrastructure is a major aspect. For example, the parking places of single-dwellings, multi-dwellings, parking houses and working places, where cars usually stay over-night are a good place to locate a charging point. In Finland, this kind of charging infrastructure already exists in the conventional ICEV preheaters. Almost every pre-heater assorts or can be modified as a charging point of an EV. In addition, the Finnish low-voltage (LV) network is planned and equipped for high power loads and therefore the suitable current can be supplied. In these occasions, the EVs can be charged with low power, because of the long time-scale. It is usually called a slow charge or a level 1 charge.

The problem areas of charging infrastructure are in densely populated city-centers that do not have much pre-heater infrastructure and construction of a new charging infrastructure will be very expensive. A significant number of charging points should be placed in connection of parking places of big shopping malls, parking places and houses as well as street-side parking. In this occasion, the parking time is usually something from some minutes to some hours and therefore a slow charge or higher powers could be used. The problem in distribution system operator (DSO) perspective is the unpredictability of the required power. There can be times, when there are no EVs connected with the certain area or every charging place is in use.

Another issue of charging infrastructure is the occasions when the vehicle is needed to charge very fast. This occurs especially in longer trips when the range of the battery is shorter than the needed driving range. The charging is often compared with a normal service station visiting and should take less than 30 minutes. However, this requires a very high power and very developed battery technology that a vehicle could be charged at this time. This charging method is called fast or ultra-fast charge. Second way to solve this problem is so called battery-swapping service, which means changing a fully discharged battery to a fully charged battery at some minutes in a service station. However, it is expected to be impossible in the near-term future, because of batteries are typically very heavy and big-sized. The batteries are also integrated into the manufacture-specific structure of vehicles to increase practicality and safety.

Following subchapters will define the charging process more precisely. The subchapters will introduce mostly used charging techniques including components, parameters and requirements. In addition, the state of standardization and possible charging models are introduced. [11]

2.3.1 Charging system

A charging system of a plug-in electric vehicle (PEV), which can be recharged from the power network, consist of four parts: the battery pack integrated cell electronics, a battery charger, an electric vehicle supply equipment (EVSE) and charging device (or charging "post") with applications. The charging infrastructure is illustrated in Figure 2.17. The charging system is further connected to the grid, which is discussed in Chapter 3.

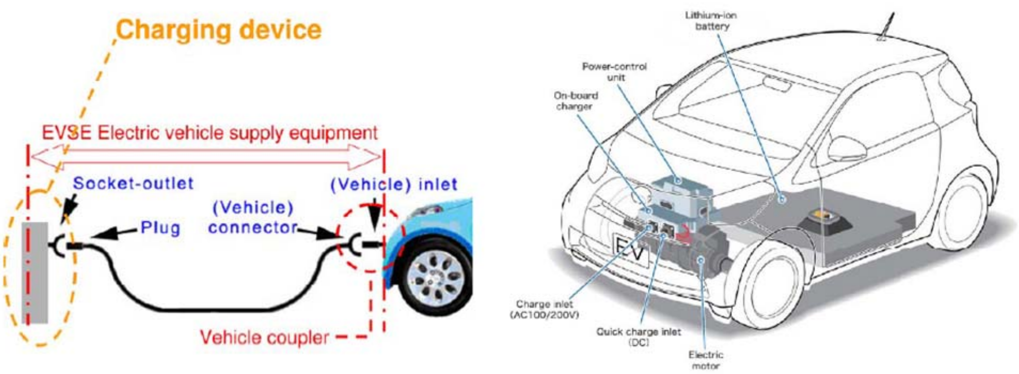

Figure 2.17. *An example of a plug-in electric vehicle charging system [27; 28].*

A cell electronic is necessary because it ensures safety and efficiency of the battery pack. It controls the charging of a lithium-ion battery cell. Therefore, it is a vital part of the battery pack.

Chargers are often divided into two categories depending on location. A charger with less than 20 kW is usually located inside a vehicle and is called an on-board charger (see Figure 2.17). A charger with higher power is forced to install outside of the vehicle because of its size and is therefore called an off-board charger. Another solution is using the power electronics of an electric motor in the charging process, which might decrease the space required and would increase the power. In addition, the type of the battery charger depends strongly on that how effectively the voltage of the battery suits to the power network charging. If the battery voltage is about 400 Volts in one-phase charge or 650 - 750 Volts in three-phase charge, the charging system would become the simplest and the most efficient. If the battery voltage differs a lot from above-mentioned values, there have to be two conversions (a rectification and step-down chopper) instead of one. It will reduce the efficiency value of the charger.

In the one-phase case, the peak value of the AC-voltage is about 325 Volts ($\sqrt{2} \bullet$ 230 V). When the voltage of the battery is somewhat higher (350 - 400 V DC) than that, it is possible to manage with one step-up-type, a voltage lifting full-bridge chopper, in which it is also possible to implement the correction of mains current curve shape near to sinusoidal. The charger could achieve even 94 - 96 percent efficiency.

The voltage of the three-phase diode-rectifier, which is connected to the three-phase 400 Volts AC-network, is about 566 Volts ($\sqrt{2} \bullet$ 400 V). In case the voltage of the battery is somewhat higher (600 - 700 V DC) than that, it is possible charge the battery with the efficiency of 97 - 98 percent with a three-phase step-up active full-bridge rectifier. The mains current curve shape is also nearly sinusoidal. In addition, when the battery voltage is like that, the nominal voltage of the motor is about 400 V AC, which is equal to the network voltage. Thus, it might be possible to use motor-inverter of the vehicle as a battery charger.

All above-mentioned chargers lends also to 4 quadrant use as such, in which case the power transmission and control both from battery to grid and from grid to battery is possible. However, chargers with two conversions could lose this feature. The chargers with low power could contain a simple diode-rectifier and a power electronic chopper. The charger controls the charging current that it is appropriate at the network connection point of view. The efficiency of the diode rectifier is very high (99 %), but it causes plenty of harmonic components and the power inversion is not possible. Therefore, it might not be an acceptable charger in the wide commercialization of PEVs. The harmonic content, caused by the charger, could put too much burden to the power network. [11]

2.3.2 Charging process

For charging an EV, two basic types of energy transmission can be distinguished: Conductive and inductive charging. Conductive charging (plugs and a cable) is probably the simplest solution available. The charging stations of conductive charging are easy to install and the technology is fairly cheap compared with the inductive charging. In addition, the communication between the vehicle and the grid for all purposes can be realized via the same cable that is used in energy transmission. Conductive charging can be achieved by connecting the vehicle charger directly to the grid with an AC connection or using a DC connection. In case of AC connection, the onboard charger converts mains current to direct current to the batteries and in DC connection, an external charger converts AC power from the grid to the requested direct current by the vehicle. The AC connection is cheaper to supply, but the power is limited to the maximum size of the on-board charger that can be fitted in. The DC connections do not have this kind of problem due to the off-board charger. Therefore, higher power can be used. However, the DC connections are more expensive to the infrastructure supplier because they require the off-board charger.

The more convenient solution for users is inductive charging. It enables charging an EV during driving or when parking without having to connect the vehicle. However, inductive charging systems are difficult to install, nowadays have low efficiency and have to be standardized all over Europe, because adapter plugs will not be available.

Charging power is a major factor for overcome range restrictions. Therefore, different charging power levels are required to make driving an EV and charging more convenient. Usually, the levels are named by the quickness of the charging. The charging levels are shown in Table 2.7. In addition, it shows transfer modes (AC or DC), powers as well as possible voltages and currents in Finland. [12]

Table 2.7. *Charging techniques [2].*

Level	Charging power (kW)	Charging time (1)	Name	Current (A)	Voltage (V)	Comment
4	250	6 min	Ultra-fast charging	625	400	Ultra fast DC-charging with external charger
3	50	15-30 min	Fast charging	125	400	DC-charging with external charger
2	10	3 h	Semi-fast charging	16	400	3-phase AC-charging
1	3	10-12 h	Slow charging	16	230	1-phase AC-charging
(1) The progress time when charging a 30 kWh battery from empty to full.						

The apparent power of charging is achieved as a product of current and voltage. The real charging power of slow charging can be calculated as shown in Equation *(4)*. [29]

$$P = U \cdot I \cdot (1 - \varepsilon) \cdot \eta \qquad (4)$$

In Equation *(4)*, the product of phase voltage (U) and phase current (I) is multiplied with the combined efficiency of a charger and a battery (η), and the factor (1 - ε), where ε is a safety marginal of the charger. The same equation can be used, when calculating the active power of semi-fast charging, but the U is now the main voltage or the phase voltage must be multiplied with the factor $\sqrt{3}$, because of three phase charging. In fast and ultra-fast charging methods, the charging is made by DC and the active power can be calculated as presented in Equation *(4)*. In this case, U is a terminal voltage of the battery and I is the current, which flows inside of the battery terminal. [29]

Fortum expects that slow and semi-fast charging will cover about 85 % of customers charging need. [2] They are easy to install into the low voltage network and a lot of charging is done during nighttime or working hours. In addition, the SOC of 100 % can be achieved without reducing safety or a cycle life of the battery, because the battery will not warm up too much in low powers. On the contrary, fast and ultra-fast charging stations have to be in connection with the medium voltage network and the charging times are much more unpredictable. They will probably cover the rest 15 % of the customers charging need. The fast change of batteries is not considered in these predictions, although it could extend the range of certain vehicles.

As mentioned earlier (see Chapter 2.2.3), with fast and ultra-fast charging the battery is only possible to charge up to SOC of 80 % due to the saturation of the current. Although, the share of the high power charging will be small, they have an important role in the mass commercialization of EVs. With the initial growth of EVs in city areas, well-distributed fast and ultra-fast charging stations will make sure that the EV will not leave a nervous potential user on the road. In addition, it would expand the range of EVs and therefore the customers who live in outside city areas could start to consider of buying an EV. [23]

The possible directions of energy transfer to and from the vehicle are important factors if different ancillary services are wanted to offer to the grid. Unidirectional power flow is always from grid to vehicle and it will be available in order to charge the battery. However, if ancillary services (other than load control) are wanted to offer, is a bidirectional power flow required. Different services could enable advantage to both customer and the grid owner. However, more complex power electronic systems are required, which cause additional costs, either to the vehicle manufacturer or to the operator of the charging infrastructure. [12]

2.3.3 System architecture of charger and PEV

Charging system architecture can differ significantly depending on manufacturer, location of the charger and charging technique used. Manufacturers can use their own kind of architecture. The charger can locate inside or outside of the vehicle and charging levels require different components and power electronics. One solution of DC fast charger is introduced in the following paragraphs.

The fast charging system consists of an AC/DC converter, which generates a DC voltage from the AC line. This incoming power need to undergo power factor correction (PFC) to boost the power factor to meet regional regulatory standards. After PFC, a DC/DC converter is needed to create the necessary charging profile for the battery. A microcontroller is programmed to control for all necessary power management functions inside the inverter. A single processor can handle communications in a simple system, but systems that are more elaborate may require a secondary controller, such as a low-frequency narrow-band PLC (programmable logic controller).

The plug-in electric vehicle (PEV) system is built of several modules to form the drive train and energy storage system. The battery block is managed and monitored by the battery management system (BMS) and charged via an AC/DC converter module (on-board or off-board charger) from the grid. A DC/AC inverter uses the voltage of the battery to drive the electric motor and it is used also for storing energy back into the battery (regenerative braking). To connect the high voltage battery to the inverter, a bidirectional reversible DC/DC converter is required in most cases. The connection of the battery block to the conventional 12-V board net also requires a DC/DC converter. A 12-V battery is connected to 12-V board net. The full architecture is shown in Figure 2.18. [30]

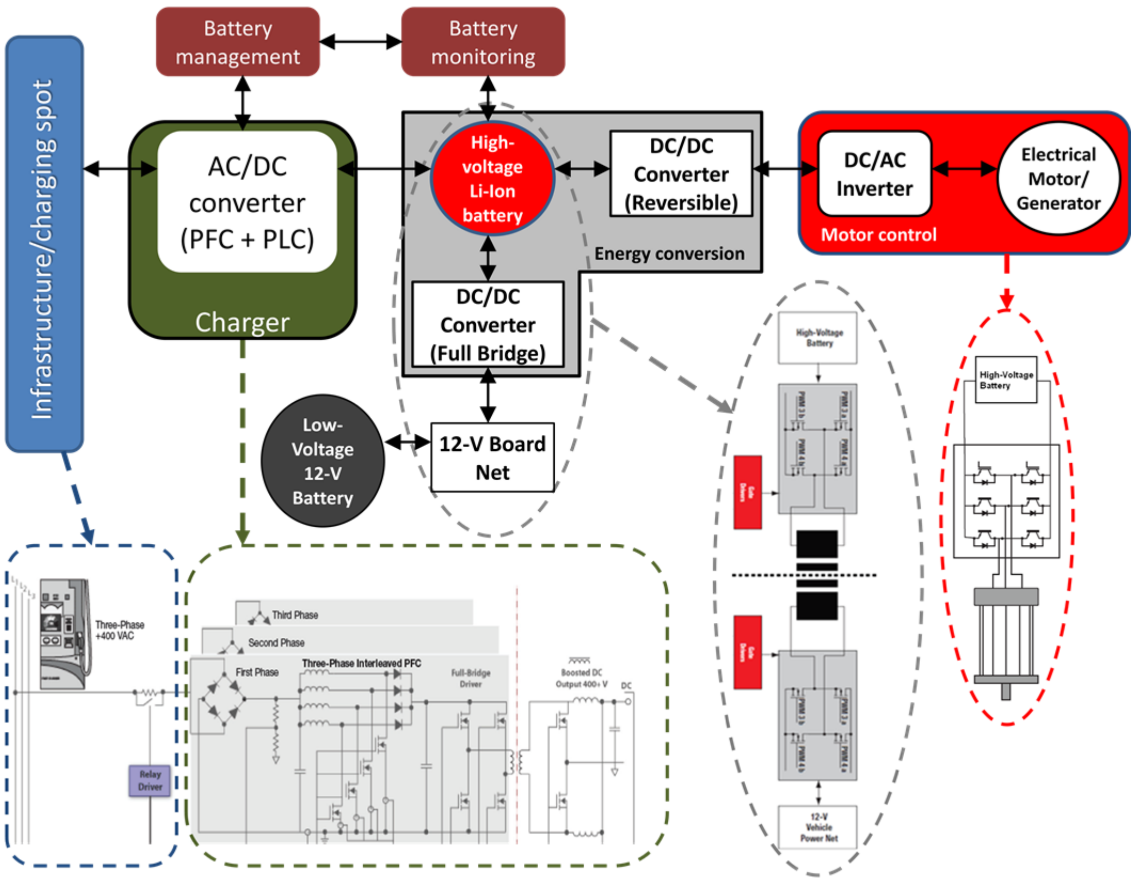

Figure 2.18. *System architecture of a charger and PEV [30].*

2.3.4 Load curve

The load of EVs on the grid is highly dependent on driving behavior and operating schemes. However, many load curves of slow and semi-fast charging has been done and analyzed, but fast and ultra-fast charging are usually ignored in these charging profiles.[12] Figure 2.19, for example, presents a slow charging pattern of household EVs on workdays. The relative power is represented on the vertical axis and time on the horizontal axis.

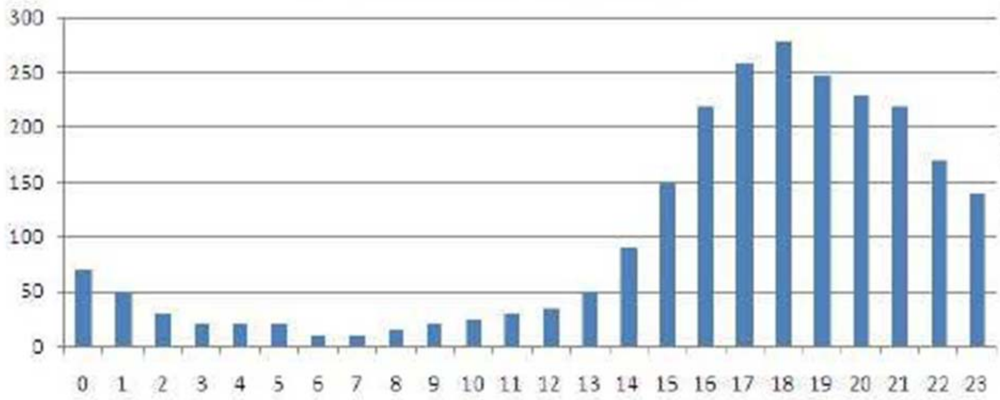

***Figure 2.19.** A hypothetical slow charging pattern of household in workdays. [31]*

The charging profile includes no intelligence at all. It means that the charging of vehicles begins immediately when plugged in. To avoid harmful effects on a power system or even to improve the operation of the power system, intelligent charging concepts have been developed.

Different control methods have different goals, different levels of complexity and different investment costs. The intelligent charging methods can be divided in two groups: control methods based on local control and control methods based on communication. The coordination can be based on time, where charging is shifted to nighttime or to some other time of low loading level of the network. Similarly, the control can be based on the coordination of local loads, the dependency on locally measured frequency or voltage level, or the mitigation of asymmetric load. In the concept based on communication, chargers interact actively with an information system managed by a network company or a service provider. With the information gained, the system can calculate and monitor the state of the power system and the loading level of the different parts and components of the network. Therefore, an efficient operation of a power system and applying different kind of optimizing algorithms are possible. The goals of the control actions and optimization can be minimizing losses, minimizing peak powers in a network or in a part of it, maximizing EV penetration without grid investments or other similar goal. [32]

2.4 State of standardization

Today, there are no single "golden" global standard when it comes to charging. It is typical that every manufacturer has their own solutions depending on the solutions used in their location. Therefore, there are several technologies for charging batteries, which vehicle manufacturers and utility suppliers should discuss to achieve a level of standardization for EVs. [23]

Internationally, the standardization organization of EVs is divided so that ISO (international organization of standardization) investigate an EV as a vehicle, IEC (international electrotechnical commission) concentrates in electrical propulsion and charging of an EV in electrotechnical perspective and ITU (International telecommunication union) is responsible for information and communication technologies. CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical standardizardization) and ETSI (European Telecommunications Standards Institute) are area-organization of above mentioned in Europe and are in tight cooperation with parent companies. In Finland, the corresponding companies are SFS (Finnish Standard Association), SESKO (Finnish Electrotechnical Standards Association) and FICORA (Finnish Communications Regulatory Authority). The standardization system is illustrated in Table 2.8 and the parties related to standardization of EV are combined in Figure 2.20. [33]

Table 2.8. *Standardization system [33].*

	ELECTRO-TECHNOLOGY	TELECOMMUNICATIONS TECHNOLOGY	OTHER TECHNOL-OGY
INTERNATIONAL LEVEL	**IEC** IEC-standards	**ITU** ITU-guideline	**ISO** ISO-standards
EUROPEAN LEVEL	**CENELEC** EN-standards	**ETSI** EN standards	**CEN** EN-standards
NATIONAL LEVEL (FINLAND)	**SESKO** SFS standards	**FICORA** SFS-standards	**SFS** SFS-standards

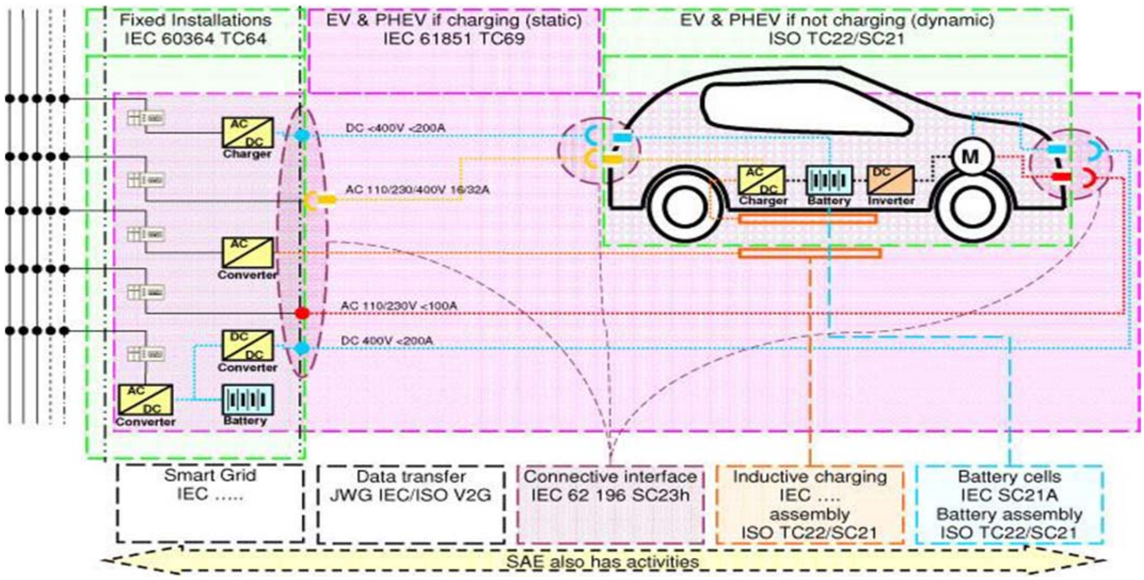

Figure 2.20. *Parties related to standardization of EV [34].*

Two IEC standard series, 61851 and 62196, concern for the charging of a PEV. The first deals with the requirements of a charging infrastructure and the second deals with contact plugs used in chargers. The standard 61851 covers the electrical and mechanical aspects of the connection between a vehicle and the grid. Thus, it includes issues such as protection against electric shocks, specific inlets and connectors' ratings, IP class, permissible temperatures and environmental conditions, and specifications for the charging cables. In addition, there are several other standard series, which relates to the charging of a PEV. The standards concern with the inductive charging (IEC 61980), batteries (IEC 62660 for standardization of battery cells and ISO 12405 for standardization of battery packs), data transmission (IEC 15118, ISO 7816-4 and ISO 14443) and erection requirement of the electrical network, but they are not essential to introduce in this study.

Four charging techniques are defined in the standard 61851-1 (Edition 2.0 Electric vehicle conductive charging system - Part 1: General requirements), which concerns with the general safety requirements of charging infrastructure of EVs. Charging technique 1 (mode 1) means one- or three-phase connection of the EV to the AC supply network utilizing nationally standardized socket-outlets (SFS 5610 accordant plug in Finland), where the current is a maximum of 16 Amperes. Charging technique 2 (mode 2) is the same than the mode 1, except maximum current is 32 Amperes, if the power contact plug is accordant with standard SFS-EN 60309 (in Europe) and there have to be type A residual-current device between the EV and the plug or as a part of the in-cable control box. The in-cable control box shall be located within 0.3 m of the plug or in the EVSE or in the plug. A special plug accordant with standard IEC 62196-2 is used in charging technique 3 (mode 3) when current is 63 Amperes maximum in the three-phase charging. In charging technique 4 (mode 4), the connection of the EV on the AC supply network is done by utilizing an off-board charger where the control pilot function extends to equipment permanently connected to the AC supply. General requirements and structures of the mode 3 and the mode 4 plugs are introduced in IEC standards 62196-1, 62196-2 and will be introduced in IEC standard 62196-3. [27]

In Finland, electrical installations on a low-voltage network should be made according to the standard SFS 6000, which is based on the IEC and CENELEC 60364-series. Existing Finnish outdoor conductive slow charging installations follow the principles and use the same technologies as those encountered in building electrification. Their characteristics are [35]:

- Nominal voltage: 400/230 V
- Nominal current: 3•16 A or 50 A
- Thermal overcurrent rating: 10 kA
- 1-phase outputs: 230 V, 3,6 kW
- 3-phase output: 400 V, 10,8 kW
- Residual current protection: 30 mA
- Overcurrent protection: 16 A
- IP class: 34 and lock on the casing

Today, there are three different plug construction designs. An American-Japanese Yazaki plug, which uses CHAdeMO fast charging design, a German Mennekes design and an Italian Scame Libera design. The Yazaki plug is one-phased and are widely used in America and Japan, but therefore it is not suitable in Europe. The two others are suitable in Europe and they are both vying for European market share.

3 ELECTRICITY NETWORKS AND MARKET

The technical function of an electricity network is electrical energy transfer with adequate voltage quality. Because of the nature of electricity, all the parties connected to the power system (TSO, DSOs, power producers and end-users) have effect on voltage quality. The aim should be to have an electromagnetic environment where electrical equipment and systems function satisfactorily without introducing intolerable electromagnetic disturbances to other equipment. [36]

In this study, one of the main objectives is to investigate the technical effects of the distribution network caused by the fast charging of EVs. To analyze the effects, comprehensive information is required about the distribution network components and actual load flows. In addition, the information such as network topology, customers, feeder and hourly specific actual load curves, network volume and replacement value has to be gathered from numerous sources.

The main question of grid impact investigation is, does the present distribution network require reinforcement operations or is it possible to shift the charging load to the times of low load? The question of how grid losses will change along with EV penetration is also interesting. [11]

Aim of this chapter is to define all the information what should be gathered from the low and medium voltage network. The chapter will introduce the grid parameters, which should be defined that grid effects can be understood and analyzed. Power quality requirements and power system stability is also clarified. In addition, the prospective services of EVs as well as smart meters and ICT (Information and Communication Technology) are introduced. At the end of this chapter, the possible cost of EV grid effects is introduced.

3.1 Power grid

In order to assess the fast charging impact of EVs on the grid it is essential to know the load situation without EVs. This mainly depends on the behavior of customers connected to grids, which are analyzed. For determining the electrical state of the network, information has to be either metered or calculated using load flow calculation. Traditionally, the customer information that have been available were annual energy, tariff, fuse size and type of the load. Additional information has been collected from primary substations or from separate metering points in the grid. Customer load curves are supposed to describe the load situation in detail for any given distribution grid without EVs. The curves have to differ between different types of customers, voltage levels, days of the week and time of the year. In addition, the individual load curve has to be modeled for special customers with high energy demand. [37]

The result based on average load curves is not suitable for evaluating peak demand because results are averages and thereby much smaller than actual peaks. Peak demand can be calculated by the methods of statistical mathematics assuming that it follows normal distribution. Different consumer groups do usually have their peak demand at the same time. Combined peak demand can be calculated using Equation *(5)*.

$$P_{max} = n_1 \cdot \overline{P_1} + \cdots + n_n \cdot \overline{P_n} + z_a\sqrt{n_1\sigma_1^2 + \cdots + n_n\sigma_n^2} \tag{5}$$

In Equation *(5),* n stands for amount of customers, $\bar{P}$ is average power of each customer, σ symbols deviation and z_a is an average deviation factor. The equation can be used only when the annual energies of customers are similar. [37] The factors needed to understand and to describe the grids are listed here [12]:

- Area of supply
- Type and rated current values of the lines
- Grid topology and switch positions
- Geographical information
- Protective devices and protection schemes
- Grid extension and enforcements
- Customer and generator position
- Distributed generation

The area of supply characterizes an analyzed distribution grid without EVs. In other words, it contains all the parameters, which characterizes and gives a detailed view of the supply area. The important characterization values that area of supply should inform are listed here [12]:

- Size of a town and density of population
- Predominant type of buildings
- Size of the electrical distribution grids (length of feeders, rated power of transformers, number of customers per transformer etc.)
- Type of the grid: cable, overhead line, isolated overhead line
- Traffic: typical driving distances, typical frequency of car use, availability of public transportation
- Availability of broadband or other ICT infrastructure
- Penetration of PEVs in different supply areas.

When all the parameters are gathered, the area can be perceived for example as a rural, a suburban or an urban area. After perceiving, the area can be matched to the other data sets via the area of supply.

The type of line does not have any direct influence on the electrical behavior of a grid. This factor is responsible for the electrical parameters of the line and it is important to be taken into account when calculating costs for grid reinforcements. Furthermore, it has significant influence on the reliability of a grid. In addition, as well as knowing the type of the line, it is important to know the maximum current that can be conducted by a given line. Rated current values (short and long-term values) give the information about the maximum load that the system can withstand.

The grid topology is one of the basic characteristics of every electrical grid. Different grid topologies exist in different areas of supply, different voltage levels and in different countries. Four basic topologies are radial, open loop, loop and meshed. They all have their own advantages and different behavior concerning losses, voltage drops, maintenance and repair, costs etc. Therefore, different topologies are used in different purposes. In addition, switch positions strongly refer to the grid topology, because they describe the usual and possible configurations of grids.

For detailed investigations of EV grid impacts, geographical information of the grid structure is also needed. It allows for the combined analysis of grids and transport systems as well as detailed information about customers and location of charging infrastructure.

Distribution networks have been planned on unidirectional load flows. However, grids will contain more and more distributed generation in future. It can change the actual load flows into bidirectional, where distributed generation unit feeds energy into the grid. This is the case also if PEVs have the ability to feed energy back into the grid. Therefore, complex control strategies and the operation schemes of PEV have to be developed. In order to assess additional costs caused by the necessary replacement of protective devices, detail knowledge about the present situation is needed.

When investigating the potential penetration and grid impacts of EVs, the grid extensions and reinforcements that already planned or can be foreseen have to take into account. In addition, typical planning parameters, such as network losses, the quality of supply, costs, expected life duration of components as well as the expected increase rate of demand and statistical distribution of load have to take into consideration.

The positions of customers, PEVs and generators have a large influence on the load flow and the voltage drop along the lines. Besides knowing the current load situation, information about the distributed generation within a grid is required. The information about a day by day generated power curve as well as maximum power, short-circuit power, controllability, potential installations and possible repowering of existing distributed generator units should be given. [12]

3.2 Power Quality requirements

The high quality of the electricity is very important for the customers due to increasing amount of electronics and micro-controlled devices that demand flawless power quality.

A network operator is responsible for voltage quality at the point of the connection. Figure 3.1 shows three stages of power quality as well as the factors affecting to it.

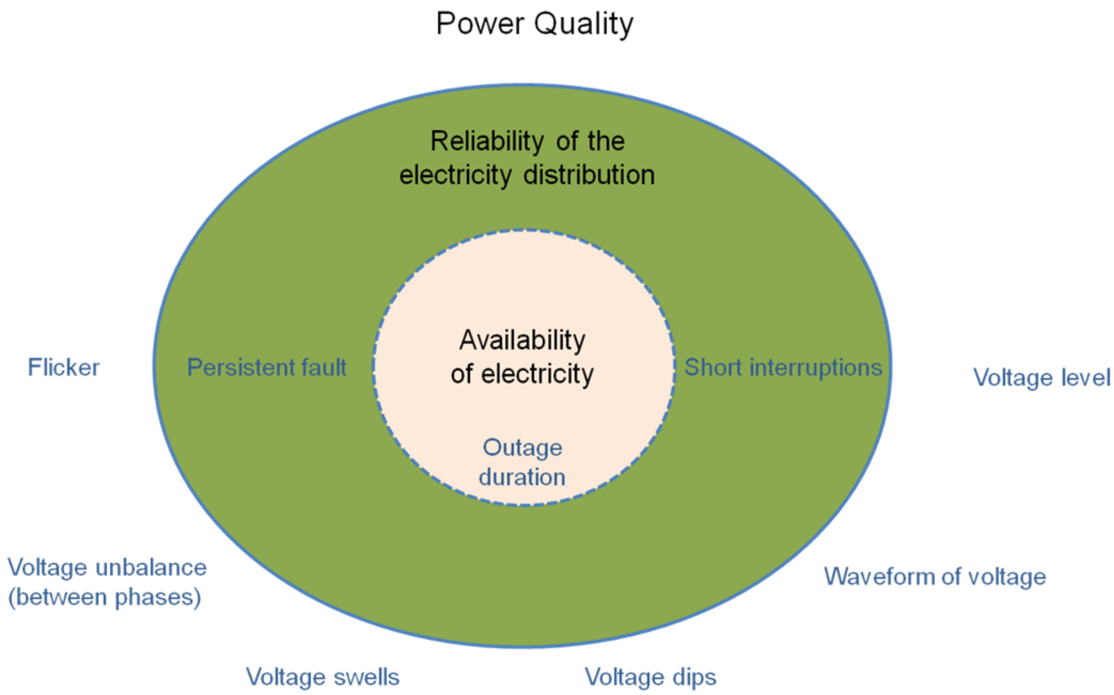

Figure 3.1. *The stages of power quality [38].*

European standard EN 50160 defines minimum demand for the characteristics of the supply voltage concerning frequency, magnitude, waveform and symmetry of the lines under normal operating conditions. [39] Requirements of the standard are often the same for both low voltage (LV) and medium voltage (MV) network, but in a case of exception, the requirements are introduced separately. Only the characteristics and the requirements, which relates to the grid impacts of fast charging are introduced in this chapter.

A fast charging of an EV may have an influence in power quality. It would be useful for DSOs to know the grid impacts of fast charging. For understanding and for analyzing the impacts, several measurements have to be done. The goal of the measurements is to find out the most harmful characteristics.

In this chapter, the main characteristics of power quality are introduced one by one. The quality requirements and grid impacts are introduced in G2V perspective, therefore batteries of the vehicles cannot be discharged into the grid.

3.2.1 Voltage characteristics

Frequency

The nominal frequency of the supply voltage shall be 50 Hz in European network. Under normal operating conditions, the mean value of the fundamental frequency measured over 10 seconds shall be within a range of 49.5 Hz - 50.5 Hz during 99.5 % of a year and a range of 47 Hz - 52 Hz during 100 % of the time for systems with synchronous connection to an interconnected system. The ranges for systems with no synchronous connection to an interconnected system are 49 Hz - 51 Hz during 95 % of a week and 42.5 Hz - 57.5 Hz of the time. [39]

Power frequency is quite stable 50 Hz and deviations are quite rare in European network or in other large networks. Frequency deviations are more common when network is divided into parts and these parts are operated isolated. The reason why power frequency deviation usually occurs is an unbalance between production and consumption. [40]

Voltage

Voltage is a local quantity and its magnitude depends on voltage regulator at the primary substation, network design, customer's point of network connection and load situation. Voltage variation is primarily caused by load changes of network users. Variation can also occur between phases.

Fast charging of EVs will have a huge impact on the customer's load, because of the increasing amount of energy required and randomness of the charging. Therefore, it could affect voltage variations into the distribution network. [37]

Magnitude and variation of the supply voltage

The standard nominal voltage (U_n) for public low voltage (LV) between phase and neutral is 230 V. The network users with demands exceeding the capacity of the LV network are generally connected to medium voltage (MV) network, which magnitude is given by the declared voltage (U_c). The MV network includes the voltages above 1 kV up to and including 36 kV.

According to [39], under normal operation conditions for LV and MV networks the permissible supply voltage variations during each period of one week 95 % of the 10 min mean root-mean-square (RMS) values of the supply voltage in LV network and 99 % of the values in MV network shall be within the range of $U_n \pm 10$ % or $U_c \pm 10$ %. In cases of electricity supplies in networks not interconnected with transmission systems or for special remote network users, voltage variations should not exceed +10 %/ -15 % of the voltage. Network users should be informed of the conditions.

Rapid voltage changes

Rapid voltage change means a single rapid variation of the RMS value of a voltage between two consecutive levels that are sustained for define but unspecified durations. Under normal operation conditions, rapid voltage changes in LV network normally do not exceed the value of ± 5 % U_n, but changes of up to 10 % U_n with a short duration of the sustained level might occur sometimes per a day under some circumstances. Under normal operation conditions, rapid voltage changes in MV network normally do not exceed the value of ± 4 % U_c, but changes of up to 6 % U_c with a short duration of the sustained level might occur sometimes per a day under some circumstances. In general, the frequency and magnitude of rapid voltage changes are related to the load variations by the users and to the short-circuit power level of the network. [39]

A voltage dip is a temporary reduction of the RMS voltage at a point in electrical supply system below a specified start threshold, which is often 90 % (or 95 %) of the reference voltage. Therefore, the voltage dip is a two dimensional electromagnetic disturbance determined by both voltage and time (duration). Typically, the dips occur because of extreme current increase in the system or faults occurring in the system or network user's installations. The duration depends on the protection strategy adopted in network, which may differ from network to network. Often the dips are unexpected and very infrequent incidents.

In normal operation conditions, the expected annual amount of voltage dips could be from few tens to thousand. The duration of the most of the dips is under one second and a residual voltage above 40 %, but voltage dips with longer duration and a smaller residual voltage can occur infrequently.

Opposition phenomenon to voltage dips is voltage swells, where voltage raises. The threshold for swells is equal to the 110 % of the nominal voltage and they are typically caused by switching operations and load disconnections. In LV network overvoltage will generally not exceed 1.5 kV RMS value. In MV network with a solidly or impedance earthed neutral the overvoltage shall not exceed 1.7 U_c and in isolated or resonant earthed systems the overvoltage shall not exceed 2.0 U_c.

Transient overvoltage is a short duration oscillatory or non-oscillatory overvoltage usually highly damped and with a duration of a few milliseconds or less. They are usually caused by lightning, switching or operation of fuses. [39]

Voltage fluctuation in distribution network cause changes of the luminance of lamps, which can create the visual phenomenon called flicker. Above a certain threshold, network users can find it annoying. The annoyance grows rapidly with the amplitude of the fluctuation. Intensity of flicker annoyance is evaluated by two flicker severity quantities, a short term severity (P_{st}) measured over a period of ten minutes and a long term severity (P_{lt}). The long term severity can be calculated from a sequence of twelve P_{st}-values over a two hour interval as expressed in Equation *(6)*. [39]

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{st}^3}{12}} \tag{6}$$

According to [39], under normal operation conditions, during each period of one week the long term flicker severity caused by voltage fluctuation should be less than or equal to 1 for 95 % of the time. In this study, the long term flicker severity rate is hard to evaluate, because of the character of the fast charging load. Therefore, it is not taken into a consideration in measuring.

Voltage interruptions

A supply interruption is a condition in which the voltage at the supply terminals is lower than 5 % of the declared voltage. The interruptions can be prearranged caused by some service work, which have to be done occassionally in the distribution network or accidental, caused by faults, mostly related to external events, equipment failures or interference. Accidental interruptions are very unpredictable and variable from place and from time to time. Therefore, they are further classified as a short interruption and a long interruption, whether the duration of an interruption exceed 3 minutes or not. [39]

Voltage unbalance

Voltage unbalance is a condition in a polyphase system in which the RMS values of the line to line voltages or the phase angles between consecutive line voltages are not equal. Typically, asymmetric loads between phases cause voltage unbalance. Therefore, asymmetric loads affect accelerate aging and declined loading capacity to distribution transformers and cables.

A widely used definition for voltage unbalance in European standards originates from the theory of symmetrical components. It breaks mathematically down an unbalanced system into three balanced systems. These are called positive sequence, negative sequence and zero sequence systems. According to [39], under normal operation conditions, during each period of one week, 95 % of the 10 min RMS values of the negative phase sequence component of the supply voltage shall be within the range 0 % to 2 % of the positive phase sequence component. However, unbalances up to about 3 % at three-phase supply terminals might occur in some areas with partly single phase or two phase connected network users' installations. When the line to line voltages U_{12}, U_{23}, U_{31} are known, the negative sequence voltage unbalance can be calculated by dividing the negative sequence voltage (V_2) by the positive sequence voltage (V_1), as shown in Equation *(7)*. [39; 41]

$$U_{negative\ sequence\ unbalance} = \frac{V_2}{V_1} = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}}, where\ \beta = \frac{(U_{12}^4+U_{23}^4+U_{31}^4)}{(U_{12}^2+U_{23}^2+U_{31}^2)^2} \qquad (7)$$

Harmonic and inter-harmonic voltage

Harmonic voltage is a sinusoidal voltage with frequency equal to an integer multiple of the fundamental frequency of the supply voltage. Inter-harmonic voltages also exist, but their amplitudes are usually very low and are therefore ignored. In literature, harmonic voltages are evaluated either individually by their relative amplitude (u_h) or globally, calculating the total harmonic distortion factor (THD) as expressed in Equation *(8)*. The u_h is the harmonic voltage related to the fundamental voltage, where h is the order of the harmonic. [39]

$$THD = \sqrt{\sum_{h=2}^{40}(u_h)^2} \quad (8)$$

Instantaneous voltage, which contains harmonics, is defined as a sum of all existing voltage components and a DC component (U_0), as shown in Equation *(9)*. In the equation, U_0 is the voltages long-term average value, α_n is a phase angle of the harmonic voltage n and U_n is RMS value of n•f_1-frequency voltage component. [42]

$$u(t) = U_0 + \sum_{n\neq 0}^{\infty}[\sqrt{2}U_n sin(n \cdot 2\pi f_1 t + \alpha_n)] \quad (9)$$

Non-linear loads connected to power distribution system mainly cause harmonic currents and voltages. The current harmonics depend on the drive construction and the voltage harmonics are the current harmonics multiplied by the supply impedances. Overloaded distribution transformers, unsymmetrical loads, power electronics in general, discharge lamps and magnetic circuits are the primary sources of harmonics. Harmonics will cause increase of network losses, overload of transformers, decrease of devices' load capacity, malfunction of protective relays and overload of neutral conductor. In addition, it can affect overheat in transformers, cables, motors, generators and capacitors connected to the same power supply with the devices generating the harmonics. Electronic displays and lighting may flicker, computers can fail and metering can give false readings. Figure 3.2 shows the factors in AC drive system, which has influence on harmonics. In addition, it shows the relationship of cause and effect of the factors. Inverter types presented in the figure are pulse width modulation (PWM) and current source inverter (CSI). [43]

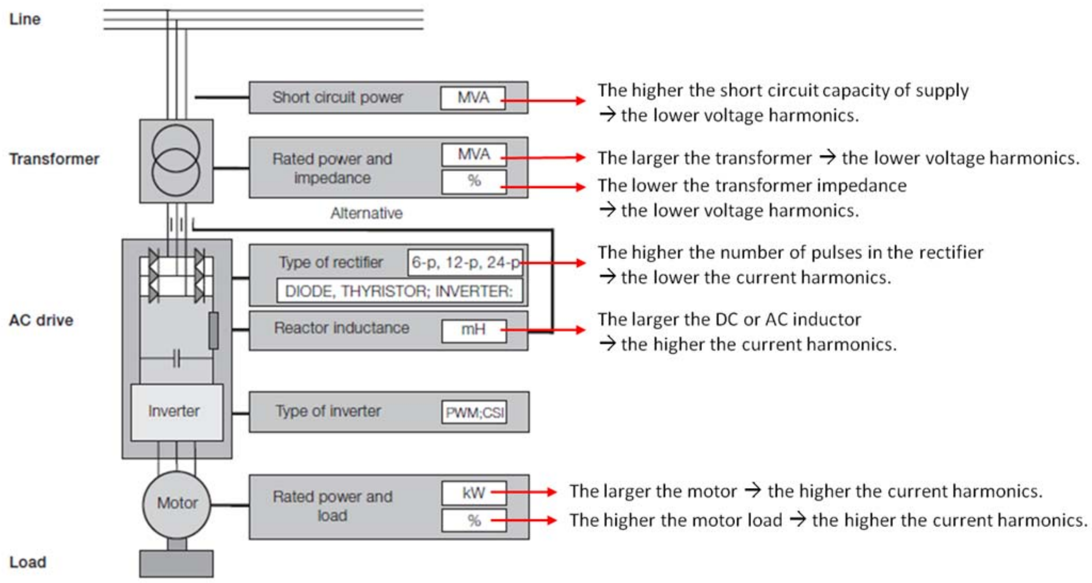

Figure 3.2. *Factors in AC drive having an effect on harmonics [43].*

Under normal operation conditions, during each period of one week, 95 % of the 10 min mean RMS values of each individual harmonic voltage in distribution network shall be less than or equal to the values shown in Table 3.1. Resonances between inductive and capacitive network components may cause higher voltages for an individual harmonic. In addition, the THD of the supply voltage shall be less than or equal to 8 %, when all harmonics up to the order 40 are included. [39]

Table 3.1. *Values of individual harmonic voltages at the supply terminals in distribution network [39].*

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative amplitude u_h	Order h	Relative amplitude u_h	Order h	Relative amplitude u_h
5	6,0 %	3	5,0 %	2	2,0 %
7	5,0 %	9	1,5 %	4	1,0 %
11	3,5 %	15	0,5 %	6...24	0,5 %
13	3,0 %	21	0,5 %		
17	2,0 %				
19	1,5 %				
23	1,5 %				
25	1,5 %				
NOTE: No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.					

The power converters, which function as sources of harmonics, cause occasionally DC component into the load current or into the source voltage. Due to small resistance of transformer windings, even a small DC voltage in a transformer cause high current. If the iron core of a transformer is saturated, magnetization current will increase significantly. The DSO has to consider this aspect when choosing a transformer to the target. When the measured DC component is about 2 % of the rated current in secondary circuit, iron losses will increase about 10 %. In general, the 2 % level of load current is considered as a limit of the current DC component. [42]

Traditional way to control harmonics as well as reactive power has been oversizing the power system. However, it is economically unreasonable. Minimizing the emergence of harmonics and filtering them are more reasonable methods to attain the desired level of harmonics. [43]

Fast charging of an EV will temporarily increase the load of the distribution transformer and it contains power electronics. Therefore, it may degrade waveform and increase losses of the distribution network.

3.2.2 Reactive power and power factor

Reactive electricity is an electrotechnical quantity and reactive power exists in an AC circuit when the voltage and current are not changing at the same time due to electrical devices in AC electricity network. To the function of electricity system, it is important that the phase angle between the voltage and current stay in right value. Transferring the reactive power increases voltage, power and energy losses of lines and transformers. In addition, it reserves a part of the grid's transferring capacity and therefore reduces active power transfer capacity.

Generation of reactive power is not bound to generators of power plants, as is active power, but it can also be produced into the electricity network near the load without power plants. Therefore, for minimizing the negative effects of reactive power transfer, it is reasonable to produce it as close to load as possible. The goal of the TSOs is to reduce the reactive power transfer from the main grid by pricing and control the reactive power compensation of DSOs in the distribution network.

The ratio between active and apparent power in a circuit is called the power factor (PF). In an electric power system, a load with a low power factor (relation between active power and apparent power) draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents require larger wires and increase the energy lost in the distribution network. In the main grid, the surplus of reactive power has to be able to compensate in all situations. [44]

3.3 Stability

When the power network is considered as stable, the synchronous generators run synchronously and voltage and frequency stays in acceptable level in spite of continuous changes in load, production and transfer situation. Otherwise, when the terms of synchronism, voltage or frequency are not realized, it is a case of stability failure, which can affect a network breakdown or breakdown in some part of the power network. Traditionally, stability is divided into three parts: an angle stability, a voltage stability and a frequency stability.

The angle stability means the synchronous generators synchronous running ability. Maintaining the angle stability in the power system depends on the generators ability to maintain a balance between mechanic and electric power after network changes. If the voltage angles between the generators increase over a certain level or the angles start to fluctuate against each other, it is a case of angle stability problem. The angle stability can become a problem after a network fault or due to high power transfer and a weak damping in the network.

Voltage stability means the power systems ability to maintain steady voltage in every node during continuous conditions or after system failures. Traditionally, it has been related to loads and the reactive power consumed or produced by them. Therefore, it has been considered as a stability of loads. In addition, the asynchronous generators has an effect on voltage stability and the grid along with its lines has an effect on voltages because a loaded line both consumes reactive power with its inductance and produce it with its capacitance. Voltage stability as for small disturbances means the system's ability to maintain steady voltage after small changes for example a load change when charging an EV.

Frequency stability means the power system's ability to maintain steady frequency after a change in power generation or a change in load has caused a significant unbalance between the generation and the load. Some generators function as a generation reserve and they change their power generation in relation to frequency changes. After frequency has changed, the power generation has to be increased or reduced or load has to be disconnected to maintain the power balance. In the Nordic interconnected power system, the DC connections that are connected to other AC systems are also used to control the frequency. The frequency stability is usually not a problem when the frequency increases over the nominal frequency because generators can be disconnected from the grid or the power generation of the connected generators can be reduced. The situation when frequency reduces lower than the nominal frequency is more critical than an over frequency situation, if the system do not have resources to generate more power to the system or there are no load that can be disconnected rapidly. The less there are kinetic energy in spinning masses of generators and the less the system have spinning reserves, the faster frequency of the system reduces. [44]

3.4 Smart meter and ICT

Electric energy charged into PEVs must acquire from the electric markets. Therefore, measuring and invoicing of the energy charged is essential part of the charging infrastructure. Different stages of smart metering have to be installed due to different operating schemes of distribution grids. The information gained by smart meters is also useful in different network-planning purposes.

Smart metering can be divided into three different stages of smartness: Automated Meter Reading (AMR), Automated Metering Infrastructure (AMI) and Automated Meter Management (AMM). The stages are illustrated in Figure 3.3.

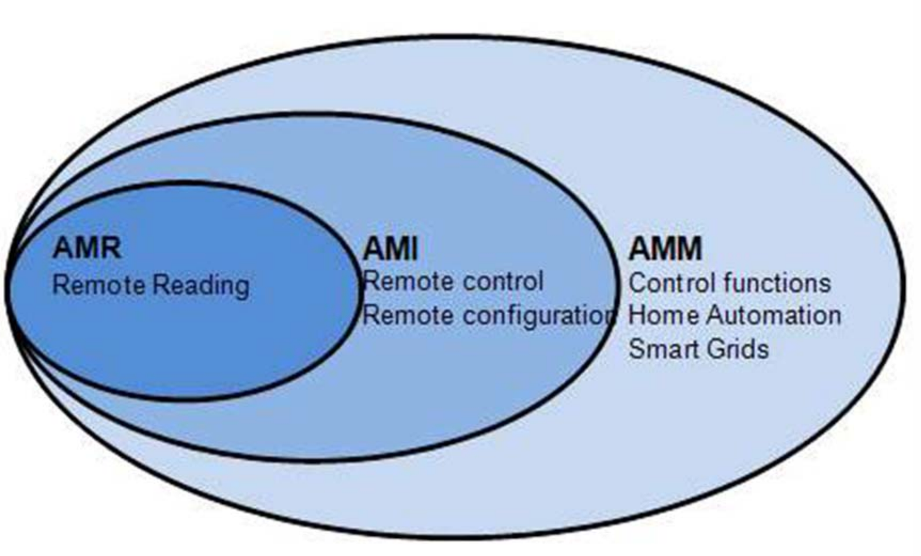

Figure 3.3. *Stages of smart metering [12].*

The AMR system is a remote reading system that permits utilities to read electronic meters over long distances. Consumption and status data are being transmitted to a central system for invoicing and analysis. The gathered data can be further compared with estimated consumption. The AMI system is an extension of the AMR system. It can measure, read and analyze energy consumption. The AMI always communicates bidirectionally and comprises the whole range of metering devices, software, communication media, and data management system. The AMM or smart metering is further extension of the AMI system. It includes the possibility to perform technical measurements and functions and carrying out customer-oriented services via the system.

Basic charging will work without ICT and invoicing can be arranged with household electricity bills or with coin slots in public places. However, the ICT connections have a huge impact on the possibility to offer ancillary services, billing process and business models as well as the convenience of users. The information would include identity, GPS (Global positioning system) location, the battery SOC and power capacity of the interconnection. The range of services becomes wider if the batteries are also discharged into the grid. The implementation of services requires that the vehicle should be able to send and receive information to the service provider, which are discussed more detail in Chapter 3.5.

The internet is used as a medium for data communication. Vehicles can communicate through a wire or without wire with the grid. One approach requires bringing the internet connection to the infrastructure connection point. Then a communication channel is implemented into the cable, which is used for energy transfer. Wireless communication can be implemented through IrDA (Infrared data association) or Bluetooth. This approach has the disadvantage of adding complexity on the infrastructure side. However, mobile-based communications are evolved and there are several systems available and deployed, including bi-directional paging, cellular packet data protocol and general packet radio service or GPRS/3G. The requirements for the interface between the energy management system and a plug-in vehicle are discussed more detailed in [35]. [12; 45; 46]

3.5 Services offered by EVs

Figure 3.4 illustrates prospective services and functionalities a PEV fleet could offer to different parties in the future. Services and functionalities make also the smart charging of an EV possible. As shown in the figure, numerous ICT techniques are required to link different parties. The charging spots are connected to a service provider, which are further linked to four different parties: retailers, power exchange (NordPool in the Nordic countries), transmission system operator (TSO) and distribution system operator (DSO). In addition, if the services are based on communication, the DSO can monitor the state of the network using a distribution management system (DMS) and AMI, and communicate with vehicle chargers. The connection between the charging point and the service provider can vary from a very simple to complex situation allowing interactions and communication in real-time.

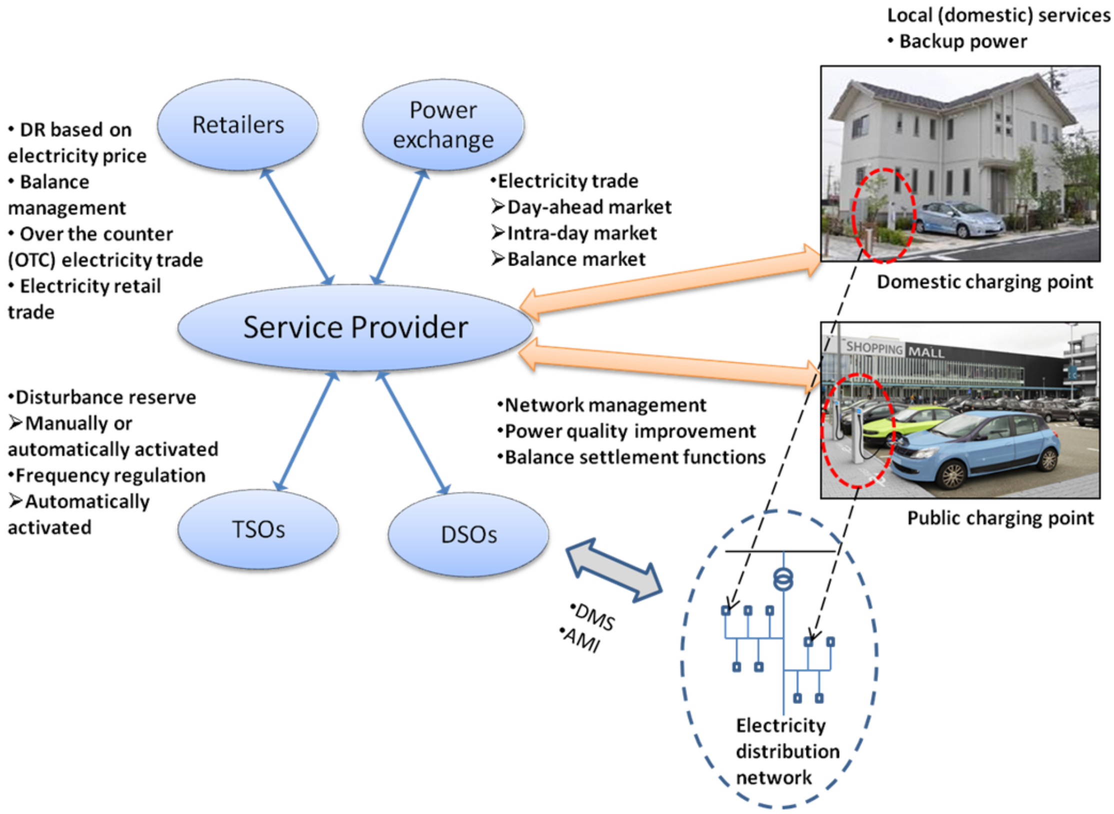

Figure 3.4. Services and functionalities, which PHEV fleet could offer for different parties in Nordic countries [35]. Photos taken from [47] and [48].

The service provider has an essential role in this system. It aggregates numerous vehicles and offers services to different parties. Following subchapters will introduce the important improvements that EVs could provide to different parties through the service provider.

3.5.1 Retailers

Electricity retailing is the final process in the delivery of electricity to the customer after electricity generation, transmission and distribution. In Nordic countries, the electricity market has been opened to competition. It means that anyone can become an electricity retailer and every electricity consumer can freely choose the retailer where to buy one's energy. To safeguard the interests of small electricity users, the retailer having a remarkable market power within area of responsibility of a DSO shall deliver electricity at a reasonable price to the consumers. The energy market authority supervises electricity sales to customers encompassed by the obligation to deliver and the related prices. [49]

In the Nordic electricity market, retailers are responsible for production and consumption balance. Using the aggregated resource a retailer could adjust its realized consumption and production in order to improve its balance position. The principle of this kind of balance management is that the retailer could try to change the real consumption closer to a value bought from the market. [35]

Retailers could use the aggregated resource for a demand response (DR) based on the price of electricity or for balancing purposes by giving electricity price based signals or other signals to customers to modify their energy consumption. In [32], three DR concepts are represented. First is an inconvenient concept, where users reduce their electricity consumption during high prices without changing their consumption habits during other period. In the second concept, the users shift their electricity consumption from a period of the high prices for lower price. Third concept is planned for public charging points or customers, who have onsite distributed generation. This case includes a coordination of the load and local generation. The DR functions like these are used to modify the energy amounts that have to be bought from or sold on the market.

PEVs are mobile electric loads and the possible market mechanisms differ a lot in different charging locations of PEVs. When charging in a public charging point, there are many market mechanisms offering the PEV users a different level of freedom to choose the electricity product. In [32], four market mechanisms are introduced. The first is "Constant payment" mechanism, where payment is done, when parking a PEV, regardless of the amount of electrical energy taken from the grid. The second is called "Fueling principle", which includes the payment in accordance with the amount of electrical energy taken from the grid. These two mechanisms are simple and do not need great infrastructure investments. The third is named as "Multi retailer" mechanism, where vehicle user can choose the electricity retailer or a single product from a certain retailer's product selection. The fourth is the "vehicle electricity" market mechanism. It requires that vehicle has its own AMR. When the vehicle is charging, the energy, which is absorbed from the grid, is measured in the vehicle and the billing is carried out by reading the meter remotely. The two latter are more convenient, but the investments are more expensive and technique used are not as mature as the first two. [35]

3.5.2 Power exchange

NordPool is a Nordic electricity exchange market owned by Nordic TSOs. In NordPool, it is possible to do business in physical hour-level trading with standard products (Elspot) or with financial trading (Eltermin). After the day-ahead trades are final, NordPool offers an alternative to the balancing market for all or some of the imbalances a participant may have. [50]

In Nordic countries, if the service provider is a party operating in the electricity market, it could also make bids directly on NordPool's day-ahead and intraday markets or the TSOs administrating separate balance power markets. All these electricity trade markets are included in the term "power exchange" in Figure 3.4. [35]

3.5.3 TSO

Fingrid Oyj is the electricity TSO in Finland. The company owns the Finnish main grid and is responsible for the functioning of the Finnish power system. The Finnish power system is a part of the European network, which includes systems in other Nordic countries, Baltic region, Continental Europe as well as Ireland and United Kingdom. [40]

Vehicle battery chargers have an impact on the power system, but PEVs are not very big loads when considering the amount of energy absorbed. For example, there are about 2.8 million registered passenger vehicles in Finland today. If all the vehicles would be EVs and the annual consumption of a single EV is 3431 kWh/a (as calculated earlier in Chapter 2.1.3.), the total energy need would be about 9.6 TWh/a. In 2010, the total electricity consumption of Finland was 87.7 TWh [51]. Therefore, the energy need for EVs would be only 10 % of the total energy consumption, which is not a huge increase in TSO point of view. [35]

PEVs can provide some different services for TSOs. By making the charging dependent on local frequency measurement would be an easy way to realize automatically activating disturbance or frequency regulation reserves, or to enhance both of these. The grid code of Fingrid requires that the frequency controlled normal operation reserves have to be activated within two of three minutes after an appropriate frequency change. In addition, 50 % of a frequency controlled disturbance reserve's capacity has to be activated within 5 seconds and 100 % has to be activated within 30 seconds in the case of a sudden 0.5 Hz frequency drop [35]. The simplest way to realize this is to stop the charging of possible PEVs when grid frequency falls under a predetermined level, or in some cases, the charging of possible PEVs can begin if frequency raises to a high enough level. Another way is to control power in continuous manner as a function of frequency. Figure 3.5 illustrates three different appliances of the latter principle: frequency regulation, disturbance reserve and a combination of these two. [52]

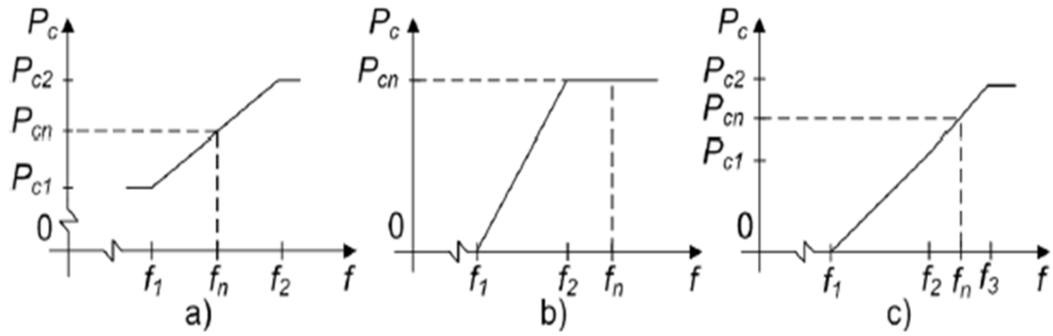

Figure 3.5. *Controlling charging power in accordance of frequency in a) frequency regulation application b) disturbance reserve application c) combination application [52].*

In "frequency regulation application", the charging power from the grid to vehicle varies in accordance of frequency variation between predetermined power limits (P_{c1}…P_{c2}). For example, if the frequency of the grid rises too high, chargers could increase the power to decrease frequency back to the nominal. The charging power should be limited so that charging of the vehicle is not interfered too much and the application causes some uncertainty of charging time of the batteries. This application could support the power balance related to some renewable energy resources that are of intermittent nature, for instance wind power and solar power.

Over-frequency disturbances are rarely a problem in large-scale power systems. Therefore, the "disturbance reserve application" operates only in low frequency area and it does not react on small frequency declines. When frequency falls low enough, which is fairly rare, the charger starts to reduce its power and power can be reduced to zero. The possible operation frequency interval ($f_1 \ldots f_2$ in Figure 3.5.b) of this application could be from 49.5 Hz to 49.9 Hz.

The "combination application" combines the two other applications. During small frequency deviations ($f_2 \ldots f_3$ in Figure 3.5.c) charger changes its power within a limited power interval ($P_2 \ldots P_3$ in Figure 3.5.c), and if frequency falls lower than f_2, power can be cut to zero.

Another option is to control the set point value of the SOC of the battery, in accordance of frequency. When the set point values of SOCs are decreased according to frequency, the vehicle batteries whose SOCs stay below new set point value will continue charging, and the charging of the vehicles whose battery SOCs are above the set point value are stopped. This application would be easier to realize in practice than direct charging power control, but metering of the exact SOCs of individual vehicles could cause some uncertainty for the process. [52]

PEVs could also provide manually activated disturbance reserve, which could be offered directly to the TSO. The time response of Finnish power system requires that the battery reserves have to be able to activate within 15 minutes. The potential of energy-storage capacity from PEVs are significant. Dr. Peter Birkner, the chairman of the Networks Committee of industry association Eurelectric says in [53] that "660,000 vehicles plugged in for charging or discharging with ten kilowatts provide about the same power as all German hydro-pump storage plants combined". According to [53], the hydro-pump storage capacity of Germany amounts to 42 gigawatt-hours, or 7,000 megawatts per six-hour cycle. Birkner notifies that "in principle, this power can support grid balancing for about one hour when 50 percent of the battery capacity is used". However, this hypothesis contains the assumption that the vehicle owners are willing to discharge their vehicles into the grid. In addition, this concept is more of a long-term functionality and it is not possible yet because it requires a high number of electric vehicles. [52; 53]

3.5.4 DSO

PEVs can cause challenges to DSOs when considering instantaneous power. A great penetration level of PEVs and time of charging can increase the peak powers of different parts of an electricity distribution network. The load on the medium-voltage feeder depends significantly on the charging arrangements. The load peaks can be flattened out if the charging system includes some intelligence as discussed in Chapter 2.3.4. These services could be treated as an alternative for network reinforcements. [54]

At DSO point of view, an interesting question is whether it is possible to decrease the present peak load by using vehicles as energy storages on the network. In principle, this could be done by charging the additional energy to the batteries of EVs and discharging the batteries during peak hours. According to [54], a balance can be found by taking into account the basis load curve of the feeder, the energy needed for driving and the capacity of batteries to store and discharge additional energy. Figure 3.6 shows a principle how the peak load can be flattened out by charging additional energy (E_{add}) into EVs and discharging it into the grid during the peak hours. [54]

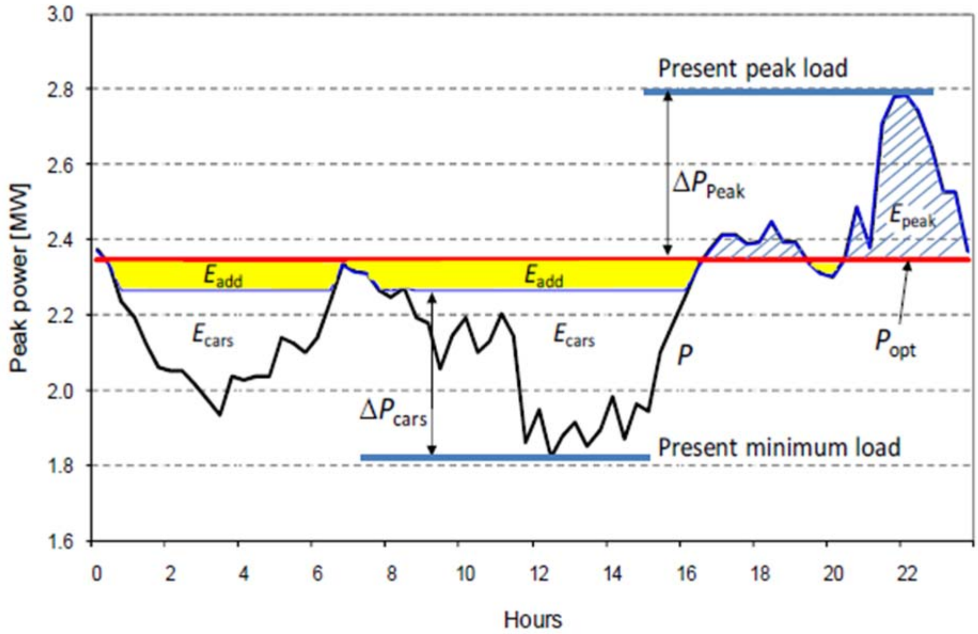

Figure 3.6. *Additional energy (E_{add}) needed to decrease the peak load [54].*

Vehicle chargers could also be used to improve power quality in a local distribution network. It could offer the mitigation of voltage dips, harmonics and asymmetry. In addition, in some market mechanisms, a service provider could offer services for a balance settlement process. [35]

An individual vehicle can also provide local services, such us backup power, at the charging site. During an electricity distribution outage, the batteries of the vehicles could feed a small network island in a network, such as a single household. This interface type is called the vehicle-to-home (V2H) interface. [35]

3.6 Economic aspects

Economic aspects can be measured using several characteristic indicators, which measure the economic performance and market behavior. If different solutions are compared, the level of security and the quality of supply should remain on the same level. The trade-off between quality and cost might lead to the best solution. The number of grid failures can depend on the money spent supporting or upgrading the grid. However, the solutions have to be compared in different aspects. In case of EVs, customer, TSO and DSO points of view as well as dependence on the penetration rate should be taken into account. [12]

The costs for the grid extension or enforcement might vary for different technical solutions or depending on chosen technical parameters, for example the power of the charging connection. Money has to be spent upgrading overloaded or old assets to meet the needs of a massive introduction of EVs. The main questions are when should assets be replaced and upgraded or is there another way to avoid the failure?

According to [55], if the charging of EVs are done without intelligence ("dumb-charging"), the load of EVs would increase the peak load of the power system and shifts the peak-hour to evenings. This would probably increase the peak loads of distribution grids as well, which could require distribution network reinforcements. Increased peak power presumes that transfer and transformer capacity has to be increased to enable power transfer from generation to consumption. An example of load situations with and without the EVs of a medium voltage feeder is shown in Figure 3.7. [11; 55]

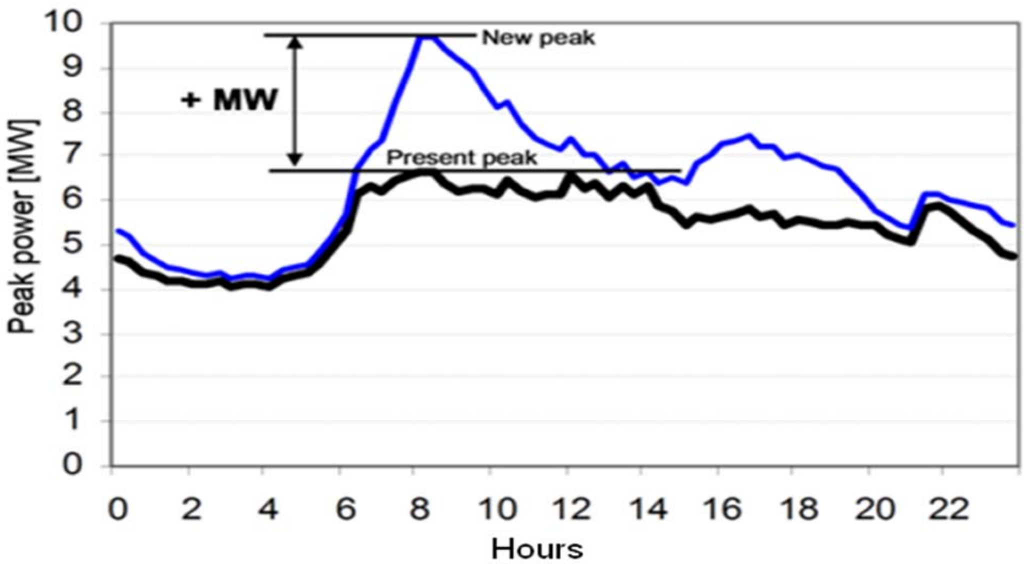

Figure 3.7. *A medium voltage feeder power curve during a day. The black curve represents basic load situation and the blue curve represents load situation of the feeder when EVs are included [11].*

The investment need can be estimated by defining so called "an average investment limit of the grid", which is based on replacement value of the distribution network and the peak load of the grid. It describes the amount of network properties a distribution company forced to provide per every kW transferred. The substation-level average investment limit has been used 100 €/kW, to medium voltage network 300 €/kW and to low voltage network 320 €/kW. When defining the expansion investment, the additional power should be estimated. In Figure 3.7, the additional power is about 3 MW. Therefore the need for expansion investment is about 900,000 € (= 300 €/kW • 3 MW). [11]

On the contrary with "dumb-charging", if the charging would include some intelligence, the EVs could bring cost savings to DSOs and TSOs. The smart charging (with intelligence) of EV can also save some EV owner's money if the electricity is bought from spot-price based hour-tariff and with time based electricity transfer-tariff. For example, according to [55], this could save 10 cents a day or about 35 euro per EV per year. However, that is a negligible sum. Therefore, most consumers would need more incentives to participate. [55]

In general, the use of the electric grid causes unavoidable and therefore negligible costs as well as avoidable costs. The grid loss is one of the costs that are depending on the usage of the grid and therefore avoidable. Because a constant low load will cause lower costs than an oscillating load, the costs for the additional load caused by EV have to be evaluated. An intelligent regulation of EV charging could lead to lower operational expenditure.

The fast charging stations will probably locate nearby current 110 kV power lines and their own connection and substation would have to be constructed. Typical investment would be between 0.5 to 2 million euro. In small volumes, the price of fast charging will not be profitable. According to calculations made in [11], the network cost for fast charging would be about seven euro cents per kWh, which is more than two times more expensive than Fortum's general electricity transfer fee (3.13 c/kWh) [3]. [11]

4 IMPLEMENTATION OF MEASUREMENTS

When new equipment is installed into power network, it is important to be aware of the equipment's electrical characteristics. Two fast charging stations are researched in this chapter. The goal of the chapter is to make account of differences between the fast charging systems and the technical specifications of those. In addition, it will describe how measurements are implemented and what the objectives of measurement are.

4.1 Technical specifications of the used fast charging systems

The two fast charging stations made by Circutor and Epyon (which is now part of ABB) are used in this study. Both of the stations locate in Espoo Keilaniemi, in front of the headquarters of Fortum. This chapter defines the key features and the main components as well as the technical specifications of the stations, which are important when analyzing the measurements.

The fast charging station product of Circutor is called CCL-CP-1. It consists of two parts, a post and a power module. The post is installed to fast charging area of Fortum and it is equipped with a single CHAdeMO charging connection. The charger has communications that allow a permanent connection with remote control stations from which all charging data can be monitored in real time. Therefore, the charger can operate remotely. The power module is the core of the system and it provides direct current for the post. The power module has been designed for its use with a three-phase 400 V (AC) supply with ±10 % tolerance, without neutral. [56]

The fast charging station product of Epyon is called Terra 50.1. It is equipped with a single CHAdeMO charging connection and is compatible with all EVs using the CHAdeMO standard. Unlike the fast charging station of Circutor, the power unit of Terra 50.1 is installed inside to the charging post. Therefore, it can be installed centrally in the fleet yards, or at gas stations. It is also designed for the same input power supply as the Circutor CCL-CP-1. [57]

In Table 4.1, the main parameters of both chargers are presented. The first three parameters illustrate maximum DC parameters that the chargers can produce. The first parameter U_{out} is a maximum output voltage, the second parameter I_{out} is a maximum output current and the third parameter P_{out} informs the maximum output power of the chargers. The last three parameters give information about the input parameters of the chargers. The IP-class of the chargers units are also illustrated in the table.

Table 4.1. *The main parameters of the chargers used in this study [56; 57].*

Parameter	Circutor (CCL-CP-1)	Units	Epyon (Terra 50.1)	Unit
Uout(DC, max)	500 V	Post (IP55)	500 V	Post (IP54)
Iout(DC)	130 A		125 A	
Pout (max)	50 kW		50 kW	
Input power supply	400 Vac (3-phase + PE), +/-10% without neutral	Power module (IP44)	400 Vac (3-phase), +/-10%	
Frequency	50Hz +/- 5%		50Hz	
Input power (max.)	55 kW		55 kVA	

As can be seen from Table 4.1, the chargers are much alike. The chargers are planned to take the required power from the 400 V three-phase AC grid. The power converters inside the chargers convert the input AC to DC and the BMS of the EV, which is plugged into the charger, declares the amplitudes of current and voltage.

4.2 Objective of the measurements

Fast charging stations have been very rare all over the world (except in Japan), but they have started to appear little by little. For example, Estonia is planning to buy 200 fast charging stations to cover their plans to build a proper charging infrastructure for EVs[58]. Therefore, DSOs have to be well prepared for the commercialization of fast charging stations. Many analyses have been done concerning the power balance of the present grid when the fast charging stations are connected, but there are not that much measured data available. This thesis will give an answer to that as well as analysis will be made according to the data.

To understand the grid impacts properly, the measuring has to be planned so that the right parameters will be measured with the right period. In addition, the measuring equipment should be installed equally into both chargers. It is important that the measuring will give information about the waveforms of voltage and current. The measured data should also be comparable with the grid requirements. It helps to analyze the power quality.

The measured data should give information about the charged power during the charging period. In addition, reactive power and the power factor should be possible to analyze. The power information would help to analyze the grid impacts in DSO perspective. Different EV types as well as the chargers might also have different charging power profiles. The profiles should be clarified.

These goals should be taken into account when installing and choosing the measuring devices. In addition, the measuring day should be scheduled and planned so that all the information is possible to gather. The organization of measurements is introduced in the next chapter.

4.3 Organization of measurements

The organization of measurements started at finding all the available EVs with fast charging ability in Finland. Five EVs were available:

- Peugeot i-ON (from Espoo city)
- Peugeot i-ON (from Eltel Networks)
- Citroen C-Zero (co-ownership with Skanska and Fortum)
- Mitsubishi i-MiEV (from Delta auto)
- Nissan Leaf (from Nissan)

The first four EVs introduced above are more or less the same Mitsubishi i-MiEV type vehicle, but with different manufacturers. They are all equipped with fast charging ability with CHAdeMO standard and their nominal battery capacity is 16 kWh. The Nissan Leaf is also equipped with fast charging ability with CHAdeMO standard, but its nominal battery capacity is 24 kWh. All the EVs except Nissan Leaf were available in the same day. Therefore, the first four EVs were measured at 30th November 2011 with both chargers and Nissan Leaf was measured at 5th December 2011, but only with the fast charging station of Circutor.

The measuring device that met the objectives was Dranetz Company's product called Power Xplorer PX5. It complies the Class A requirements of IEC 61000-4-30 standard. It includes high-speed sampling for high frequency transients and data capture of 1 microsecond per channel. It has an 8-channel workhorse, which simultaneously captures and characterizes thousands of parameters. Therefore, it enables measuring the AC voltages and the currents of each phase from the supply as well as DC voltage and direct current from the output. RMS values are computed over one power frequency cycle. The minimum, maximum and average cyclic values are continually updated and saved every user-programmed journal interval. Aggregation time interval of measured RMS values was chosen to be one minute for voltage, current, and power. Snapshot of the voltage and current waveforms were also recorded after every one minute. [59]

When all the devices and EVs were in the offing, the planning of the measuring day started. The plan was to charge the EVs both separately with different chargers and simultaneously with both chargers. In addition, the batteries of the EVs were wanted to be as depleted as possible. Nissan Leaf was forced to charge only with the charger of Circutor and it was only charged once due to practical reasons. In Appendix 2A, the timetable of the measuring day is presented.

The idea was that each of the EVs are charged separately and then the batteries of each EV have to be depleted. When the batteries of the EVs are again depleted, the EVs are charged simultaneously with both chargers. At first, the Peugeot i-ON is charged alone with the charger of Epyon and after that the Mitsubishi i-MiEV alone with the charger of Epyon. When the second charging event has terminated, the Peugeot i-ON is charged alone with the charger of Circutor and after that the Citroen C-Zero with the charger of Circutor. When the EVs are depleted again, the measuring day continues with charging both chargers simultaneously. First, the i-MiEV and i-ON are charged. When the charging events have terminated, the i-ON and C-Zero are charged. Nissan Leaf was charged in 5th December 2011. The plan is to charge it only once.

4.3.1 Realization of measuring day

Realization of the measuring day plan was successful. The EVs were charged as planned and all the data were captured successfully. The record of the measuring day is expressed in Appendix 2B and the principles of the measuring arrangements of both chargers as well as the supply LV network are presented in Figure 4.1. The measured quantities and the used current probes are presented in Appendix 2C.

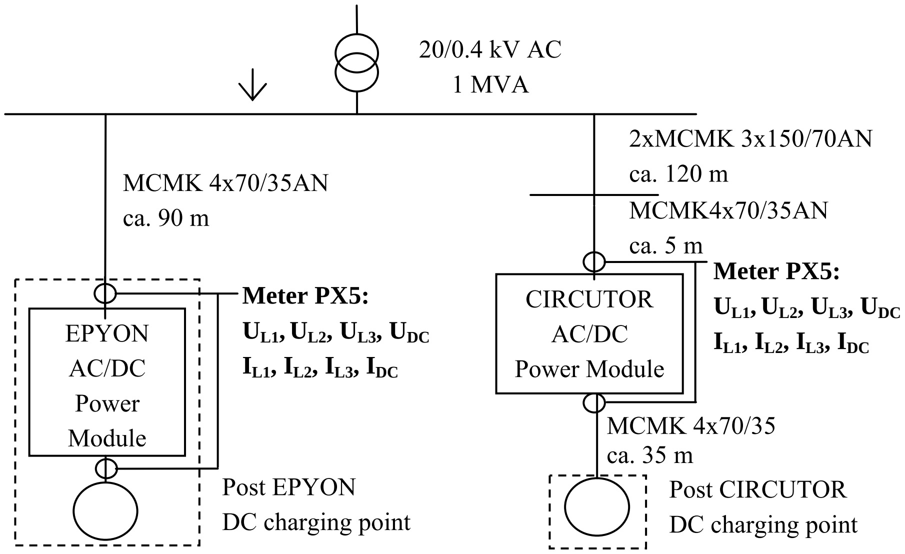

***Figure 4.1**. The arrangement principles of the measuring devices installed into LV network.*

As can be seen from Figure 4.1, the measuring devices were installed near to the power converters of the chargers. In case of Circutor, the DC characteristics were measured from power module. Therefore, the results of Circutor contain the power losses of the cable (MCMK 4x70/35), which connects the power module and the charging post. In case of Epyon, the measuring devices were installed into the charging post. In addition, the short-circuit power of the network has an impact on the results.

As can be seen from Appendix 2B, the starting ranges of the EVs changed from 1 km to 20 km. In addition, the ending ranges of the EVs changed from 66 km to 90 km. It should be noted that the heater volume difference between the EVs causes some uncertainty to the ranges. The range differences occur because of the EVs were gained with different ranges, there were not enough time to deplete them to equal range and the chargers terminated with different SOCs. Therefore, the SOC values changed as well. Some of the SOC values were not documented.

As mentioned earlier in this study, the BMS of the high voltage battery of an EV defines the charging power. Therefore, it was not even possible to get the same SOC values into every EV used in this study. In addition, the battery temperature other conditions might have an impact on the power charged into the battery.

5 REPORTING AND ANALYZING OF THE MEASURED DATA

The goal of this chapter is to introduce and analyze the measured data. Results are compared with power quality requirements. The chapter takes into account of the costs in DSO perspective. At the end, a conclusion of the results is made. As said earlier, the results are mean values over one minute. Therefore, transient peaks cannot be seen from the figures showed in this chapter.

5.1 Analyzing the effects

In this subchapter, the results are introduced. At first, frequency, voltage, and current are introduced and are compared with the standard EN 50160. Then the power profiles and charged energy during charging events is presented. At the end of this subchapter, voltage and current harmonics are analyzed.

Frequency

The frequency of the fast charging day is illustrated in Figure 5.1. As can be seen from the figure, the charging did not cause frequency variations. The deepest dip was during the fourth charging event when Citroen C-Zero was charged with the charger of Circutor between 12:58 and 13:36. The frequency reduced almost 0.1 Hz. However, the frequency increased almost back to nominal value during the charge. This cannot be caused by fast charging, because the reduction of 0.1 Hz would require about 600 MW power reductions in the power system [44]. The figure also shows that the frequency varies between the values 50.1 Hz and 49.9 Hz and therefore it is within the range of the standard.

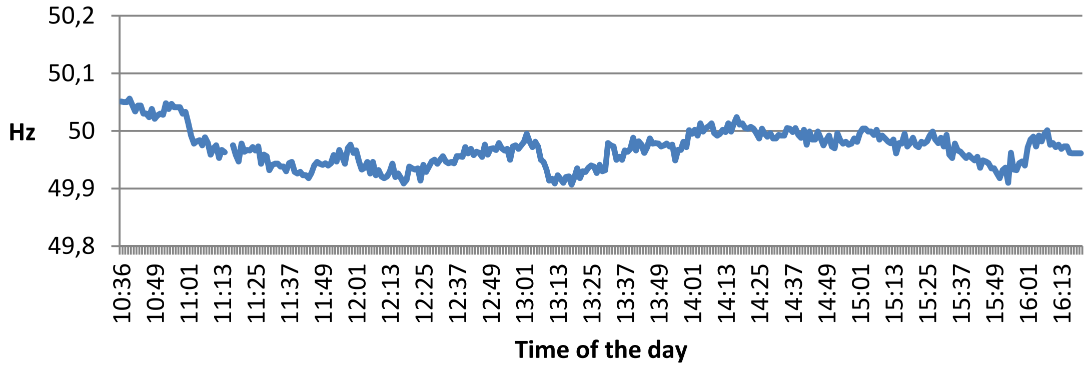

Figure 5.1. *Frequency of the charging day.*

Voltage

Figures 5.2, 5.3, and 5.4 shows the magnitude and variation of the supply voltage as well as the DC voltage, which is used to charge the vehicles. In the figures, CHA, CHB and CHC represent the phase to earth voltages and CHD represents the DC voltage.

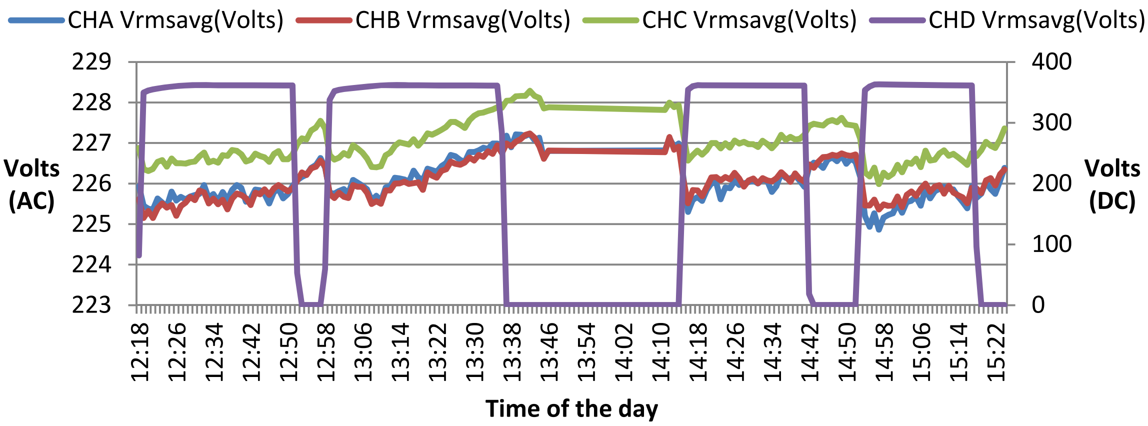

Figure 5.2. *Voltage RMS values during the fast charging day measured from the charger of Circutor.*

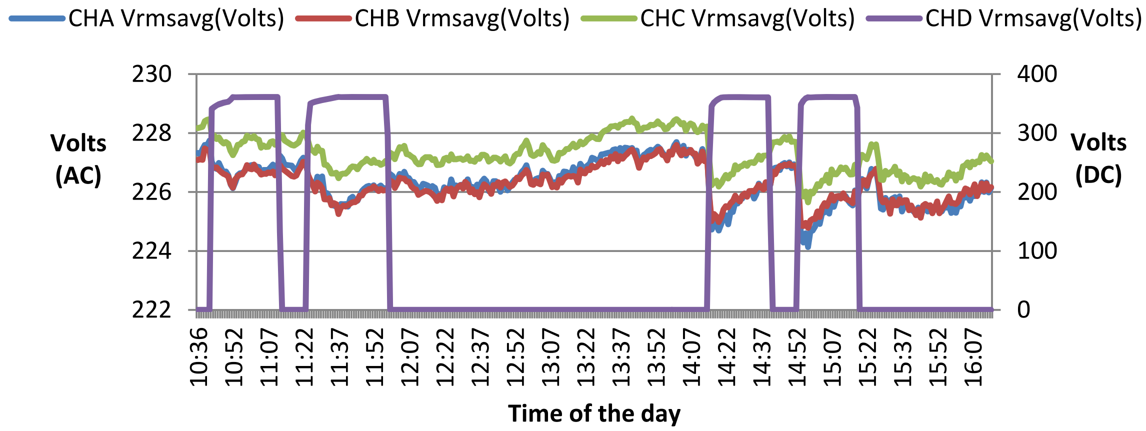

Figure 5.3. *Voltage RMS values during the fast charging day measured from the charger of Epyon.*

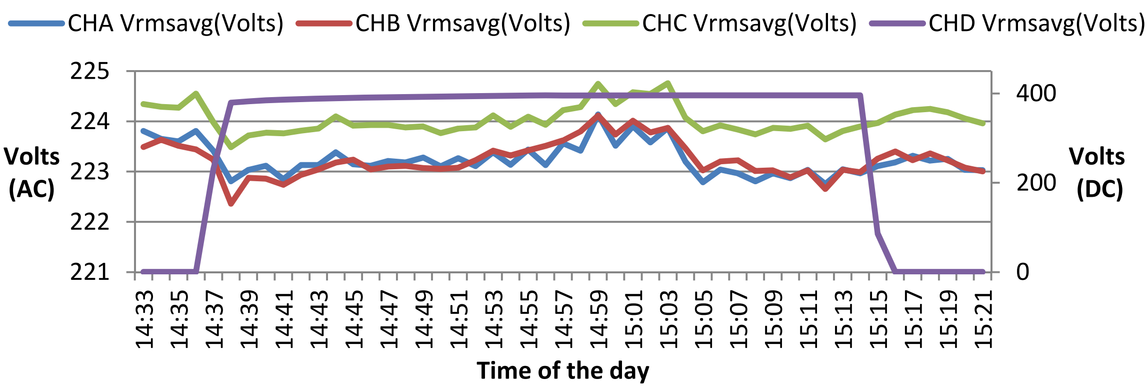

Figure 5.4. *Voltage RMS values, when charging Nissan Leaf, measured from the charger of Circutor.*

As can be seen from Figures 5.2, 5.3, and 5.4, at the beginning of a charge while the DC voltage was increasing, the phase voltages were decreasing. The phase voltages were reduced about 1.4 volts in case of the charger of Circutor and about 2.3 volts in case of the charger of Epyon. When the DC voltage leveled, the phase voltages start to increase. When a charge was ended, the phase voltages shot up making a short peak to the trend curve. However, the changes had small magnitude differences and therefore they do not cause any harm to the grid.

In Figures 5.5 and 5.6, average phase to earth voltage and average line to line voltage are showed as well as 10 minute mean RMS values according to the average voltages. The average voltage value is a voltage RMS mean value calculated every minute during the charging day. Green lines are calculated from the measuring data of Epyon and red lines are from the measuring data of Circutor.

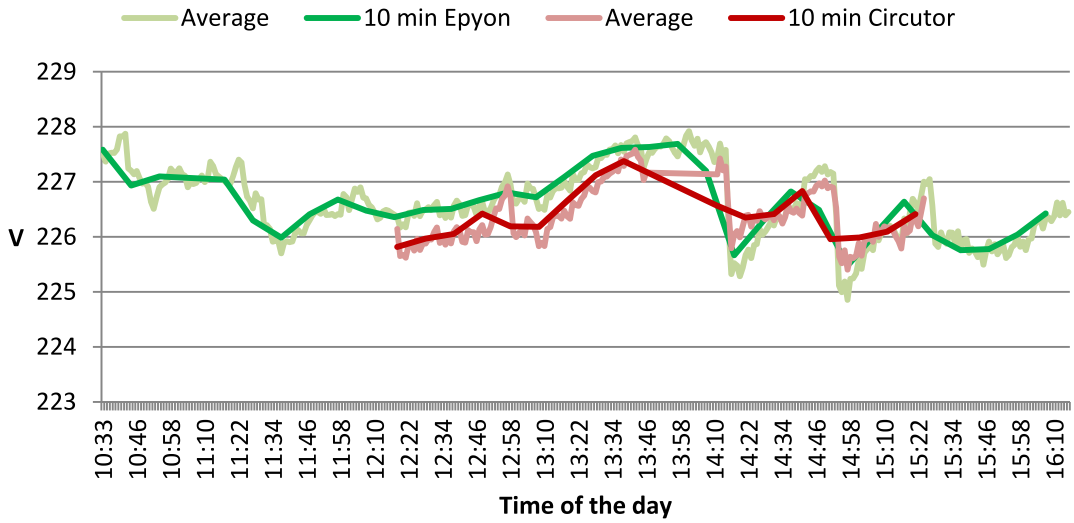

Figure 5.5. *Average phase to earth voltage and 10 minute RMS mean value.*

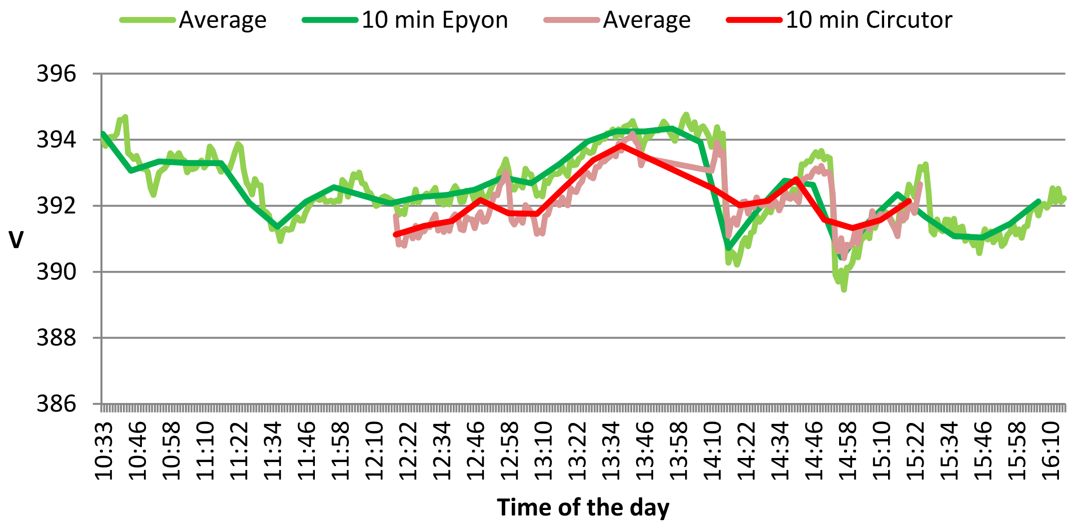

Figure 5.6. *Average line to line voltage and 10 minute RMS mean value.*

As can be seen from the figures showed above, the magnitude of the voltage is stable and the voltage level is easily between the limits of the standard. According to [59], the quality of voltage level variation is high, because the phase voltage is at the range of 220 - 240 volts. The standard 50160 defines that rapid voltage changes in LV network should not exceed the value of ± 5 % U_n. Therefore, higher than 11.5 V of rapid voltage changes are not basically allowable. The highest rapid voltage change was 1 % during the fast charging day, which is far from the limit. The figures also show that there were no voltage dips, voltage swells or voltage interruptions. In addition, flicker, voltage unbalance and DC component were so low that their effect was negligible.

In Figure 5.7, the DC voltage profiles are compared during the charging period. Different charging events are named by the charger's charging event. Nissan Leaf is named differently to make a difference between i-MiEV type vehicles. The x-axis of the figure represents the duration of a charge in minutes.

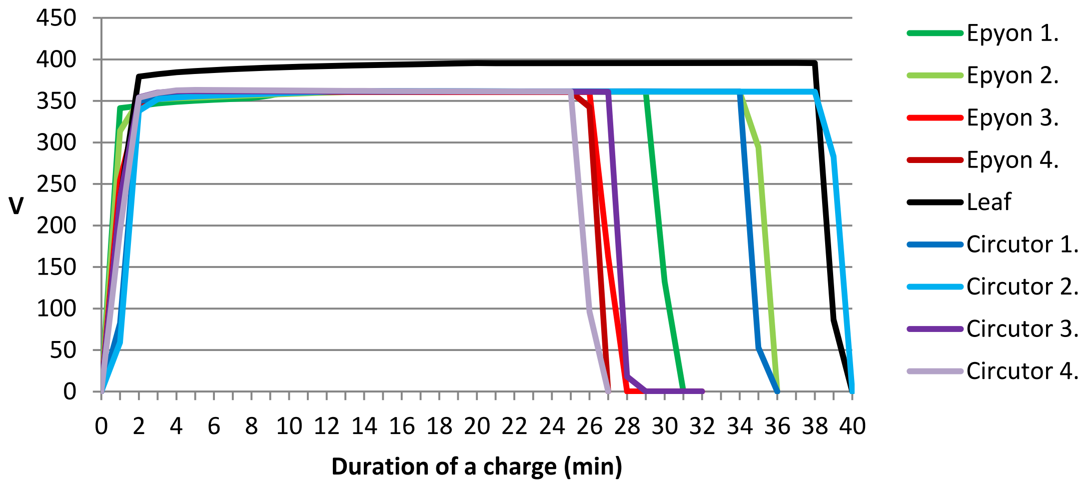

Figure 5.7. *DC voltage profiles during the charging events.*

As can be seen from Figure 5.7, both of the chargers charge i-MiEV type vehicles at the same maximum DC voltage (360 V - 363 V), whereas Nissan Leaf was charged at about 396 V DC voltage at the maximum. However, the profiles seem to have the same shape. First, the voltages shot up to the maximum voltage, and then they leveled. When the battery of an EV is full enough, the voltage reduces rapidly to zero.

Current

Figures 5.8, 5.9, and 5.10 show the magnitude and variation of the supply current as well as the direct current, which is used to charge the vehicles. In the figures, CHA, CHB and CHC represent the phase currents and CHD represents the direct current.

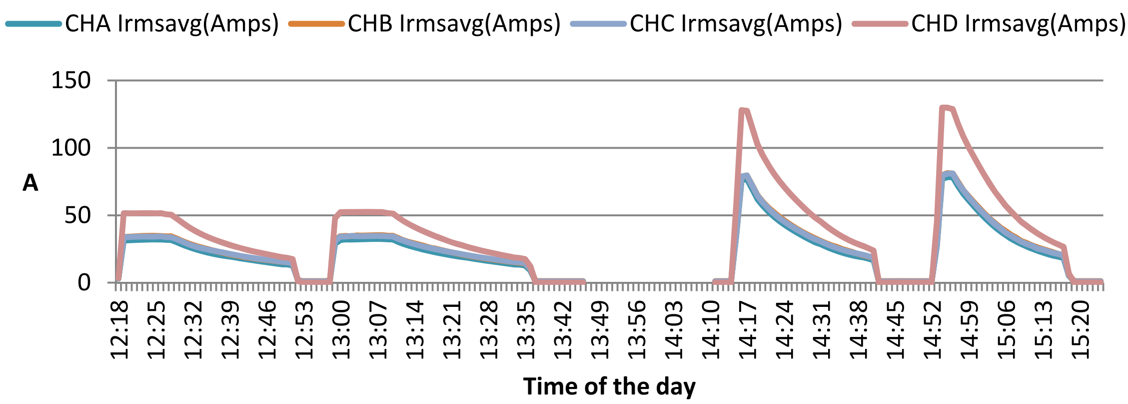

Figure 5.8. *Current RMS values during the fast charging day measured from the charger of Circutor.*

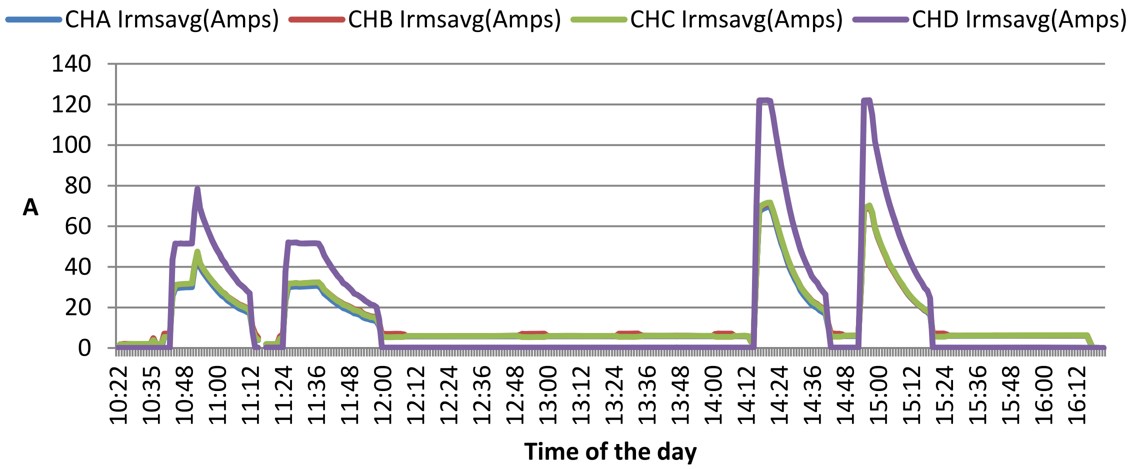

Figure 5.9. *Current RMS values during the fast charging day measured from the charger of Epyon.*

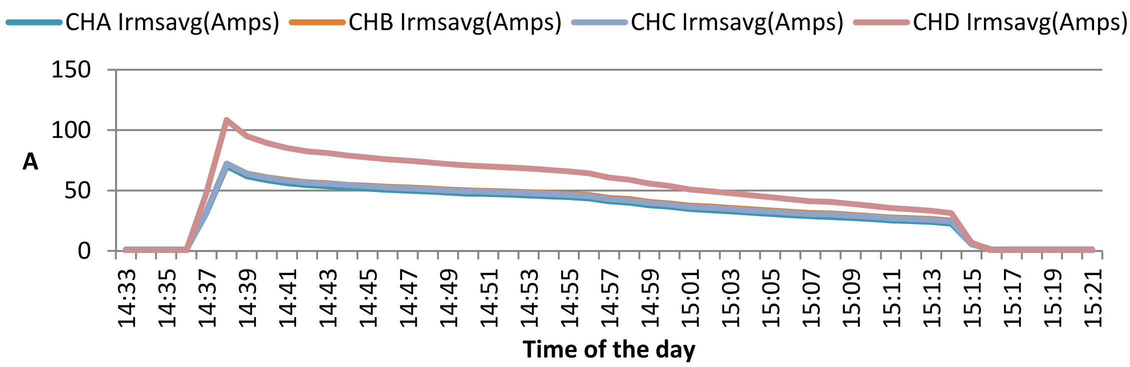

Figure 5.10. *Current RMS values, when charging Nissan Leaf, measured from the charger of Circutor.*

As can be seen from Figures 5.8, 5.9 and 5.10, at the beginning of the charge, the magnitudes of the phase currents start to increase resulting increasing direct current. All the currents follow the shame shape, which is determined by BMS of an EV. In every case, the currents peaked rapidly and were reduced during the charge. In Figure 5.11, the direct current profiles are compared during the charging period. Different charging events are named by the charging event of the charger. Nissan Leaf is named differently to make a difference between i-MiEV type EVs. The x-axis of the figure represents the duration of a charge in minutes.

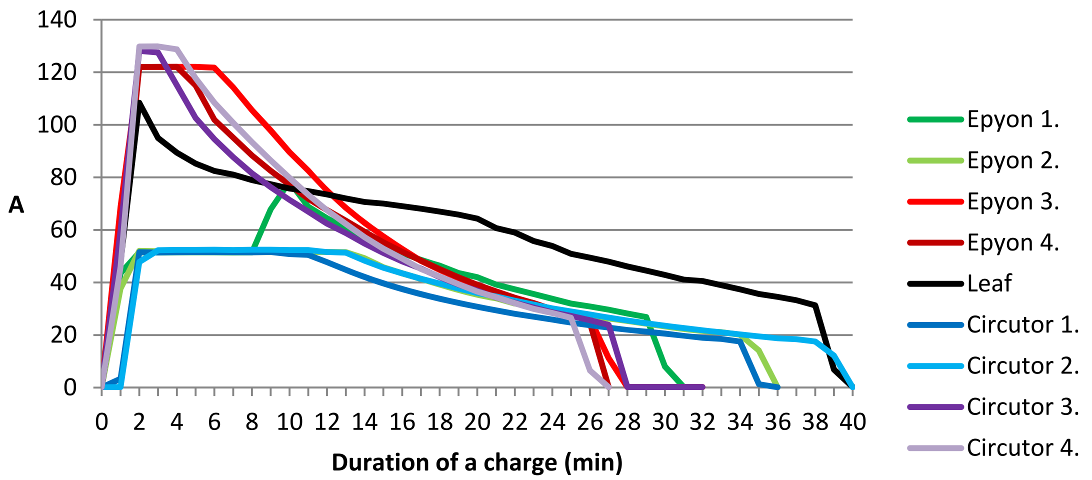

Figure 5.11. *Direct current profiles during the charging events.*

In Figure 5.11, three kinds of profiles can be distinguished. When two EVs were charged at the same time, the current peaked after two or three minutes to the maximum values of the chargers. Then it leveled out for a short while, before it started to reduce. However, when only one EV was charged and the battery was not warmed up yet as well as other battery conditions did not allow maximum charging current, the charging current was limited into about 52 amperes. The current limitation started after 2 minutes and ended after about 12 minutes. After that, it started to reduce. An exception occurred when Peugeot i-ON was charged with the charger of Epyon (Epyon 1. in Figure 5.9). This is because it was the only EV, which was used earlier on the same day. Others were picked up at previous days. Therefore, a battery of the EV was warmed up more than the batteries of other EVs as well as the other battery conditions allowed to increase the charging current. That is why the battery of the EV was able to receive a higher direct current after the conditions were between certain values. This happened after 8 minutes from the beginning of the charge. Before that, it followed the same the limited current profile. After 10 minutes, the current peaked and then it followed the same current profile, where current was not limited. The third profile that can be seen from Figure 5.11 is the charging profile of Nissan Leaf. When the charging began, the current started to shoot up to its peak (about 108 amperes). This was possible, because the Leaf possessed a battery heating and cooling system. After that, it started to reduce, but the reduction took more time than when charging i-MiEV type EVs. In addition, the current lasted longer time at a high current rate. When the current was reduced into about 31 amperes, the current reduced rapidly to zero.

Both chargers seemed to have a similar charging current profile. However, an exception can be distinguished due to different maximum currents. Therefore, the charger of Epyon cannot charge EVs at the same maximum current than the charger of Circutor.

However, it should bear in mind that the batteries of the EVs had different starting SOC and conditions, which causes difference between the charging profiles.

Power

As shown from the voltage and current profiles before, the EVs were charged from different SOCs. Therefore, the power profiles have to be analyzed. Figures 5.12, 5.13, and 5.14 illustrate the total active power, reactive power, and apparent power profiles during the charging events. Different charging events are named by the charging event of the charger. Nissan Leaf is named differently to make a difference between i-MiEV type EVs. The x-axis of the figure represents the duration of a charge in minutes.

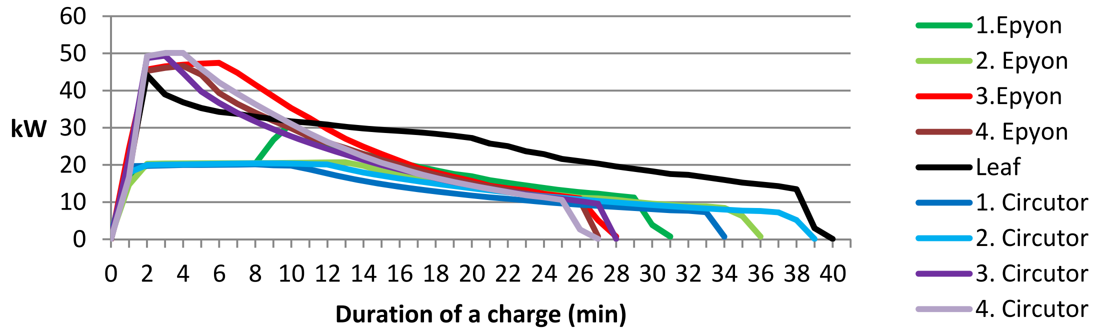

Figure 5.12. *Active power profiles during the charging events.*

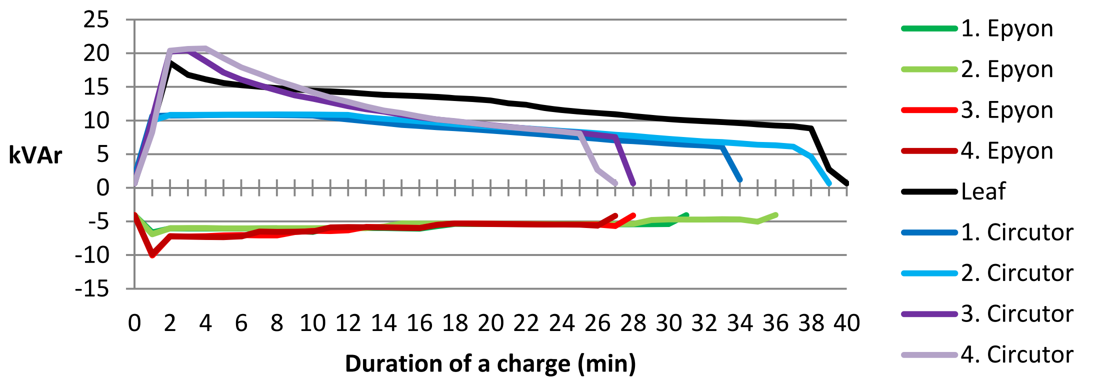

Figure 5.13. *Reactive power profiles during the charging events.*

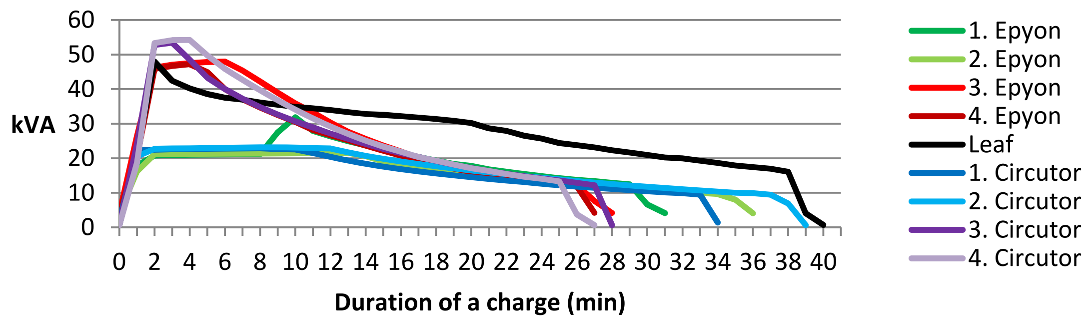

Figure 5.14. *Apparent power profiles during the charging events.*

As can be seen from Figure 5.12 and Figure 5.11, active power follows the profile of current. This is because the DC voltage is leveled almost the whole duration of a charge. Therefore, the same three profiles than before can be distinguished. The figure also shows that the maximum active power of the profile with limited current is about 20 kW, whereas the maximum active power of the profile without limited current as well as the profile of Nissan Leaf is about 50 kW. Therefore, the chargers take significantly higher active power when the battery conditions of an EV are able to receive the maximum current. This causes uncertainty, when planning the network where a charger is connected. If all the EVs would include battery pre-heating system, the battery conditions would be more similar and the EVs could be charged at higher powers.

The voltage level of LV and MV network is dependent from the relation and the absolute values of active and reactive power of loads. Therefore, it is interesting that the charger of Circutor consumes reactive power from the grid, whereas the charger of Epyon feeds reactive power to the grid, as shown in Figure 5.13. In addition, the reactive power profile of Epyon is almost the same at each charging event although the current was higher during the last two charging events. On the contrary, the reactive power profile of Circutor seems to be highly dependent on the current and it follows the profile of current. When buying fast chargers and choosing a location for those, network planners have to take into consideration whether the load of the charger should be inductive or capacitive in order to fit well for the network. Because the charger has to be connected into LV or MV network, the charger has to be chosen in a case-specific way. However, the reactive power of a single fast charger would not cause harm into distribution network.

The apparent power profiles are very similar to the active power profiles, as shown in Figure 5.14. When comparing the profiles, the profiles of Epyon are almost identical whereas the profiles of Circutor differ more because of the higher changes in reactive power. The difference between active power and apparent power can also be seen from Figure 5.15, where the power factor is presented. The power factor (PF) profiles are named by the charger (inside parentheses). The PF profile of Nissan Leaf (green line) is added at the end of the horizontal axis with its own time of the day.

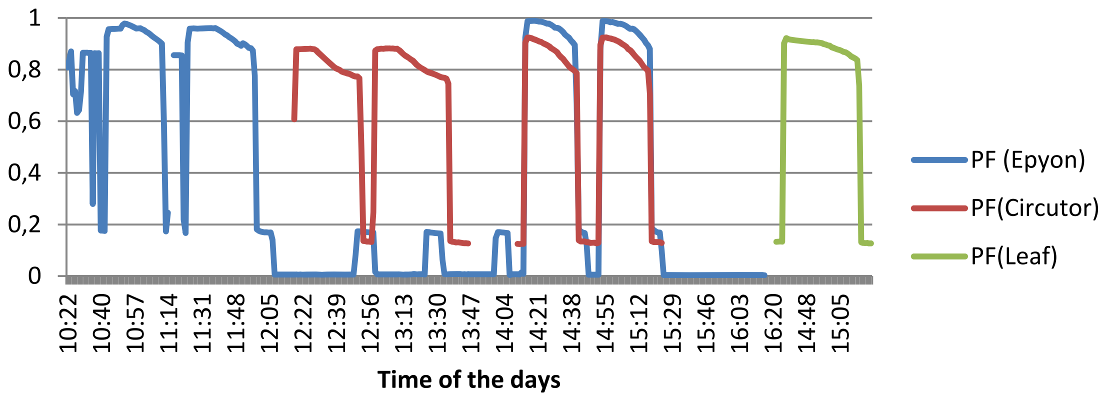

Figure 5.15. *Power factor profiles during the charging events.*

As can be seen from Figure 5.15, the power factor of Epyon is near to one at the beginning of the charging events, whereas the power factor of Circutor is 0.92 at maximum. The maximum point of the power factor profiles was when the current peaked. When the current was reduced, the power factor was reduced as well.

The total power profiles showed in Figures 5.12, 5.13, and 5.14 can be used when analyzing the losses or thermal characteristics of cables. However, when the operation of the chargers is wanted to analyze, the powers at fundamental frequency have to be analyzed. In Figure 5.16, the powers at fundamental frequency are presented.

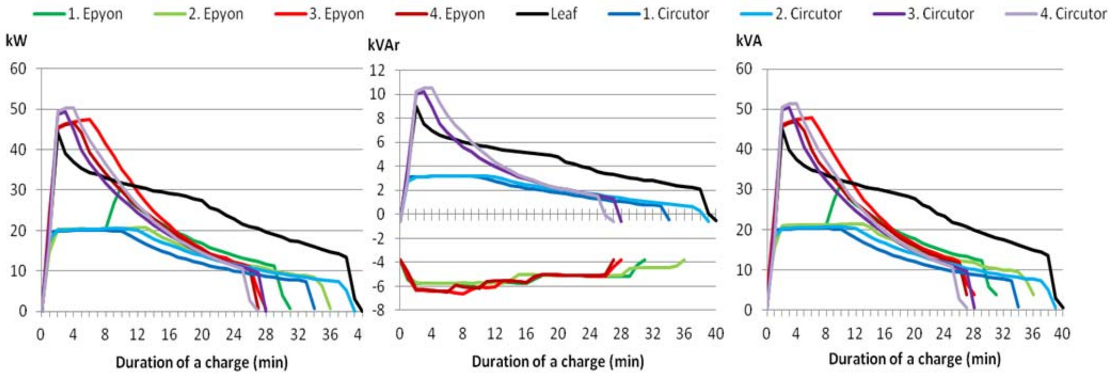

Figure 5.16. *Active power, reactive power and apparent power profiles at fundamental frequency during the charging events.*

As can be seen from Figure 5.16, the power profiles at fundamental frequency were almost the same than the total power profiles, but the values were lower. The difference between active power and apparent power can also be analyzed with help of the power factor at fundamental frequency. During the charging events, the power factor of the charger of Circutor was fluctuating around 0.99, whereas the power factor of the charger of Epyon fluctuated between 0.90 and 0.99. The average power factors during the charging events are combined in Table 5.1. The negative sign in front of the values means that the power factor is leading.

Table 5.1. *Average fundamental frequency power factors of the chargers during the charging events.*

1. Epyon	2. Epyon	3. Epyon	4. Epyon	Leaf	1. Circutor	2. Circutor	3. Circutor	4. Circutor
-0,95	-0,93	-0,97	-0,96	0,98	0,99	0,99	0,98	0,98

Losses of the chargers can be analyzed when the efficiencies of the chargers are known. When analyzing the efficiency, the DC power that a charger feed into an EV has to be compared with the active power that the grid feeds into the charger. In Figure 5.17, the average efficiencies of each charging event are presented. The results are based on DC active power one minute mean values and total AC active power one minute mean values.

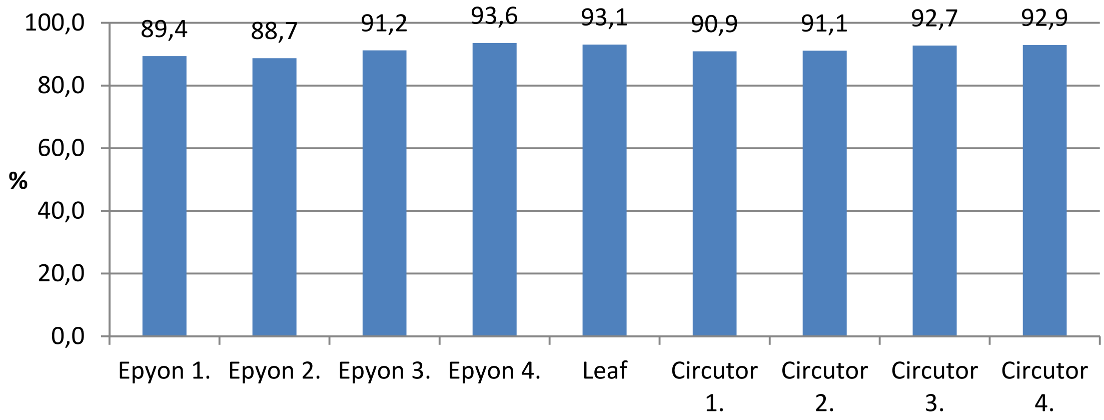

Figure 5.17. *The average efficiencies of the charging events.*

As can be seen from Figure 5.17 the average efficiencies of both chargers are close to 90 %. Therefore, about 10 % of the active power that the grid fed into the charger will be lost because of the losses of the charger. The average efficiencies of the first two charges (Epyon 1 and Epyon 2) were the lowest (under 90 %) and the average efficiency of the other charging events were higher than 90 %. However, it should bear in mind that in case of Circutor the cable losses causes extra loss to these results.

Energy

In this subchapter, energy means kilowatt-hours. This is because it can be compared with the battery capacity and the SOC of the battery. When comparing the battery capacities, the DOD of 80 % is used. Therefore, the effective battery capacity of i-MiEV type EV is 12.8 kWh and the capacity of Nissan Leaf is 19.2 kWh. When analyzing the results with these values, it has to bear in mind that the DOD of 80 % is theoretical value. Practically the DOD of a battery depends on age and usage of the battery and it is not the same for every EV used in this study.

In Figure 5.18, the energy charged into the EVs during the charging events is illustrated. Figure 5.19 represents the total energy that is charged into the EVs at the end of each charging event. Different charging events are named by the charger's charging event. Nissan Leaf is named differently to make a difference between i-MiEV type EVs. The increase of the battery SOC of different EVs during the charging events is calculated and showed in Figure 5.20 and the charging events are named by the charged EV. In Figures 5.18 and 5.20, the second charging event of Epyon (Mitsubishi i-MiEV) and the second charging event of Circutor (Citroen C-Zero) were so equal that the curves were one on the other. The x-axis of Figures 5.17 and 5.19 represent the duration of a charge in minutes.

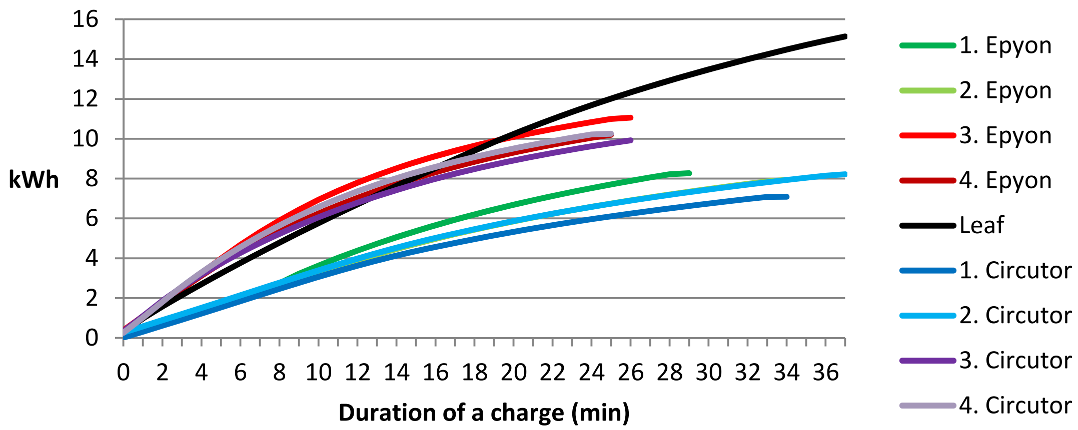

Figure 5.18. *Energy charged into the EVs in kilowatt-hours.*

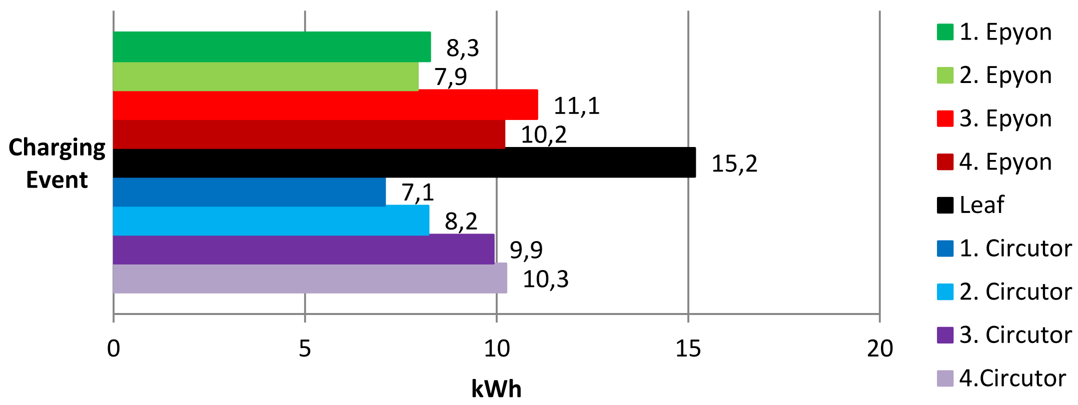

Figure 5.19. *The total energy charged into the EVs in kilowatt-hours.*

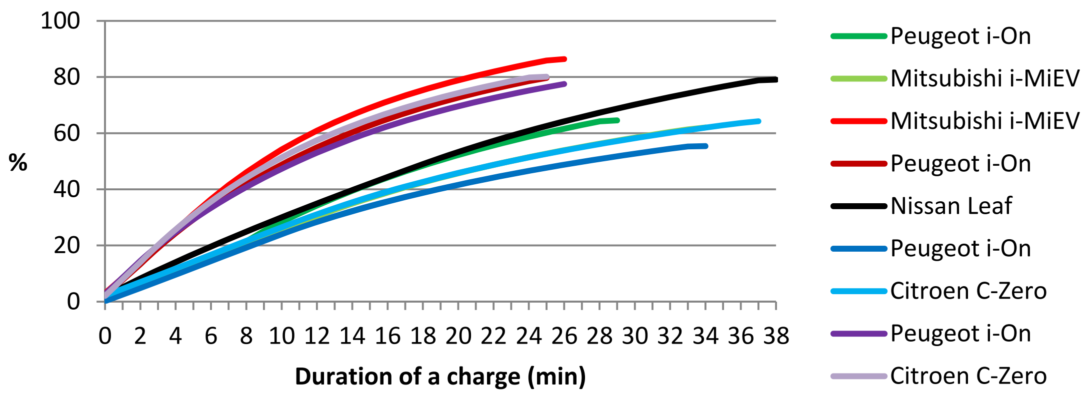

Figure 5.20. *The percentage value of the battery SOC during the charging events.*

As can be seen from the figures above, the EVs that were charged with higher power gained more energy and the SOC of the battery increased faster than energy and SOC of the EVs that were charged with lower power. The i-MiEV type EVs that were charged with the unlimited current gained energy about 9.9 kWh at minimum and about 11.1 kWh at maximum. This means that the SOC of the batteries increased about 77.5 % at minimum and about 86.4 % at maximum. The durations of the charging events were about 25 or 26 minutes and the average energy of the charging events was about 10.4 kWh. Whereas the i-MiEV type EVs that were charged with the limited current gained energy about 7.1 kWh at minimum and about 8.3 kWh at maximum. This means that the SOC of the batteries increased about 55.4 % at minimum and about 64.6 % at maximum. The durations of the charging events were between 29 and 37 minutes and the average energy of the charging events were about 7.9 kWh.

The energy charged into the Nissan Leaf was about 15.2 kWh. This is more than two times the energy that was charged into the i-MiEV type EVs at minimum. When comparing the energy charged into Nissan Leaf with the i-MiEV type EVs that were charged with higher power (see Figure 5.18), the energy charging profile was quite similar. However, the Leaf was charged with lower peak power and the energy of the i-MiEV type EVs increased more at the beginning. After the charging power profiles intersected (see Figure 5.12), the Leaf was charged faster. After 18 minutes from the beginning of each charge, the Leaf was gained more energy than other EVs and the energy continued to increase almost the same speed. Although, the Leaf gained more energy in kilowatt-hours than the i-MiEV type EVs, the percentage value of battery SOC was not increasing as fast as the i-MiEV type EVs that were charged with higher power due to higher battery capacity. The SOC increased about 79.0 %, and it took 38 minutes. However, the SOC increased faster than the i-MiEV type EVs that were charged with lower power.

In case of energy, the chargers are similar. In addition, it seems that charging speed and increase of SOC are not dependent on the charger used, but they are dependent on the state of the battery.

Voltage harmonic distortion

The waveforms of the phase voltages were always nearly sinusoidal. A detailed voltage waveforms are showed in Figure 5.21, where the phase voltages (CHA, CHB and CHC) as well as DC voltage (CHD) is presented during the charging event of Nissan Leaf at 14:45:59.

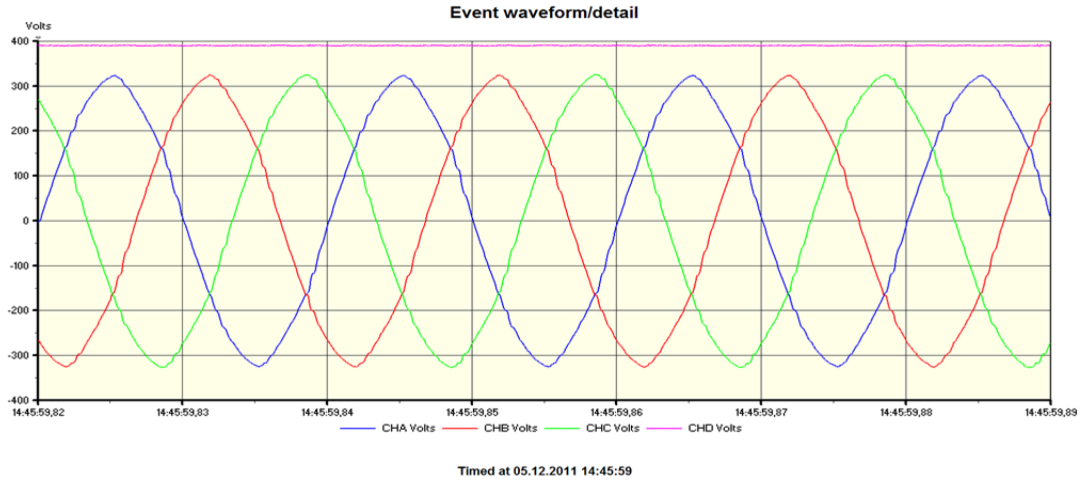

Figure 5.21. *Voltage waveform.*

As can be seen from Figure 5.21, the waveforms of phase voltages were not absolutely sinusoidal. Therefore, the harmonic distortion has to be analyzed. In Figure 5.22, the odd order harmonic voltage RMS values measured from Circutor are presented. In Figure 5.23, the odd order harmonic voltage RMS values measured from Epyon are presented. The absolute values of even order harmonic voltages were insignificantly low and are therefore neglected. Harmonic voltages are named by the order of the harmonic. In the horizontal axis, time of the charging day are showed. In Figure 5.22, Nissan Leaf is added at the end of the fast charging day with its own time of the day.

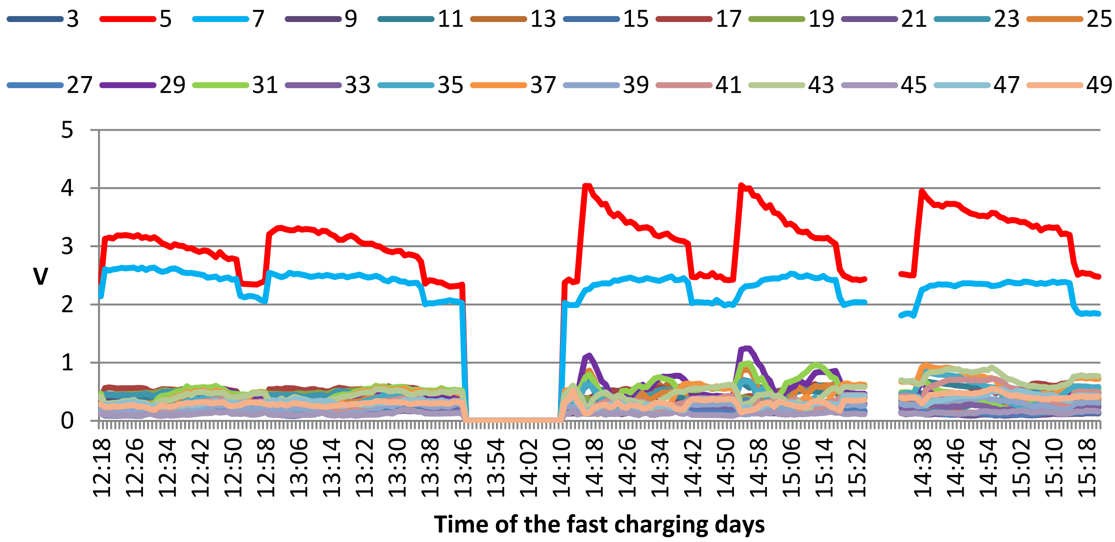

Figure 5.22. *RMS values of odd order voltage harmonics, measured from Circutor, during the fast charging days.*

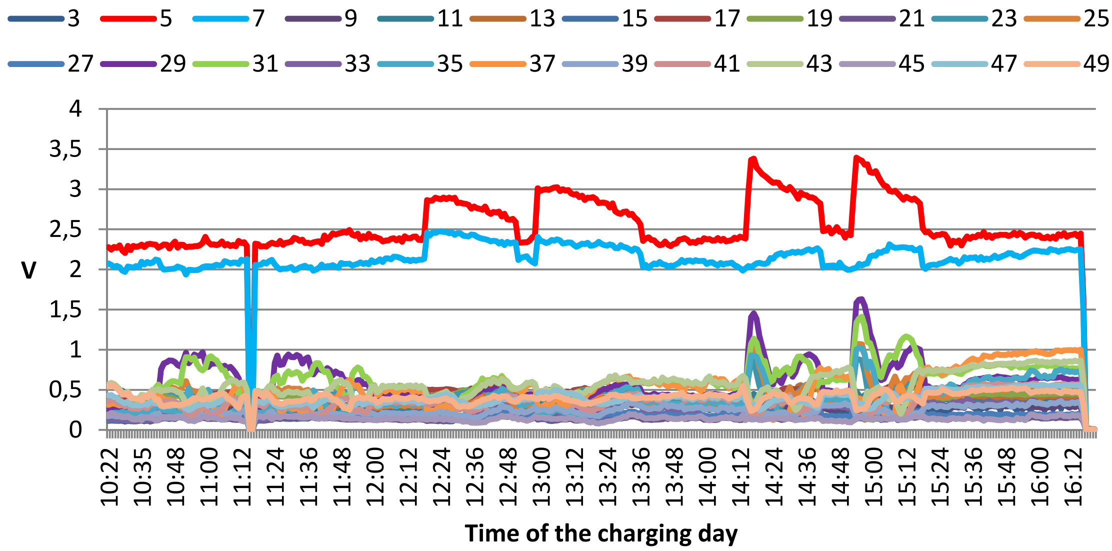

Figure 5.23. *RMS values of odd order voltage harmonics, measured from Epyon, during the fast charging day.*

As can be seen from the figures above, the most dominant harmonic voltages are fifth (red) and seventh (light blue). The other voltage harmonic RMS values are for the most part under 1 V. However, there is a peak of 29th (purple) and 31st (light green) harmonics during the charging events of Epyon. The fifth and seventh harmonic RMS values are most of the time above 2 V. In addition, the charging events can be easily noticed from the harmonic profiles as an increase of the dominant harmonics. In Figure 5.24, average odd order voltage harmonics from 3rd to 49th during each charging event of Circutor are represented by a bar chart. In Figure 5.25, the average odd order voltage harmonics are represented relatively to the fundamental voltage. The harmonic values as well as fundamental voltages are average values of the charging events.

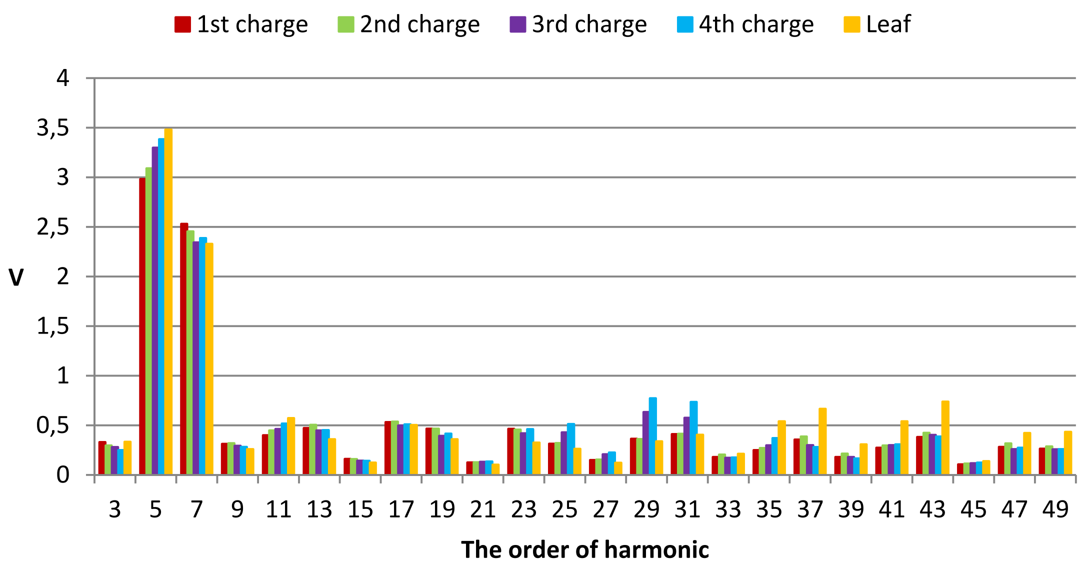

Figure 5.24. *The average odd order voltage harmonics during each charging event of Circutor.*

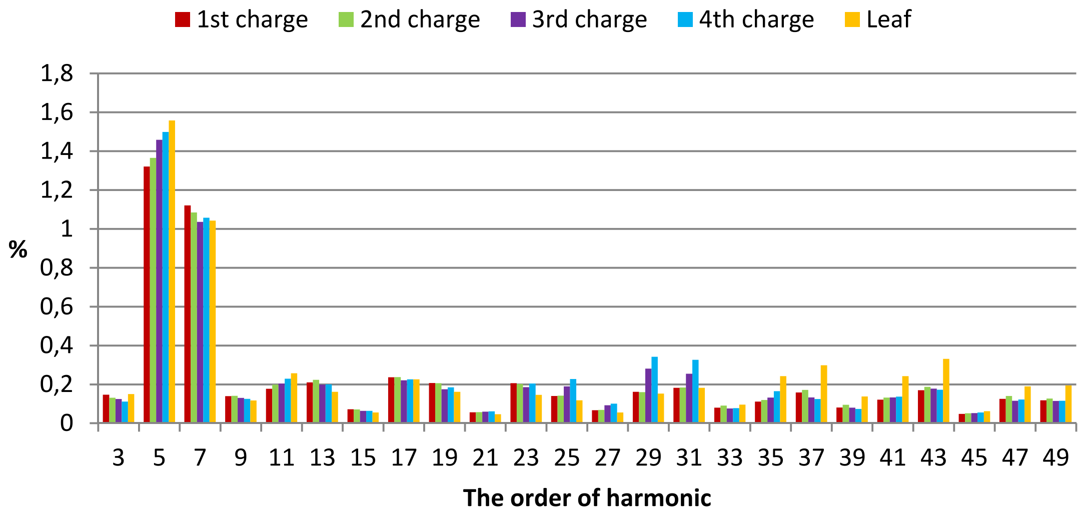

Figure 5.25. *The percentage values (in relation to average fundamental voltage) of odd order voltage harmonic during the charging events of Circutor.*

As can be seen from the figures above, the 5th and 7th are the most dominant harmonic voltages, but still the percentage values are less than 1.6 % from fundamental voltage. The standard EN 50160 allows the relative amplitude of 5th harmonic voltage to be 6.0 % and the relative amplitude of 7th harmonic voltage to be 5.0 %. The other harmonics seem to be under 0.5 %, which is the minimum limit of the standard. Therefore, it can be said that in the case of Circutor, the voltage harmonics were not a problem. The harmonic distribution of Circutor is a typical harmonic distribution of a 6-pulse uncontrolled power rectifier. Therefore, it can be assumed that the charger uses the diode rectifier to convert AC into DC. As a comparison, Figure 5.26 and Figure 5.27 present the same two block diagrams, but in case of Epyon. In case of the third and the fourth charge, the EVs were charged with the charger of Circutor and the measuring device inside Epyon was on. Therefore, six charging events are presented in the figures.

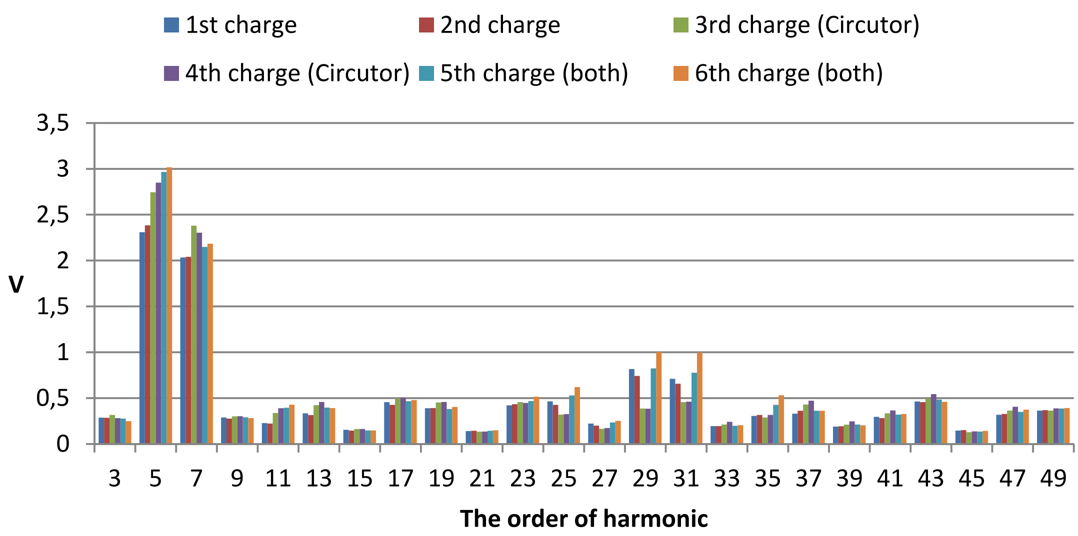

Figure 5.26. *The average voltage harmonics during each charging event of Epyon.*

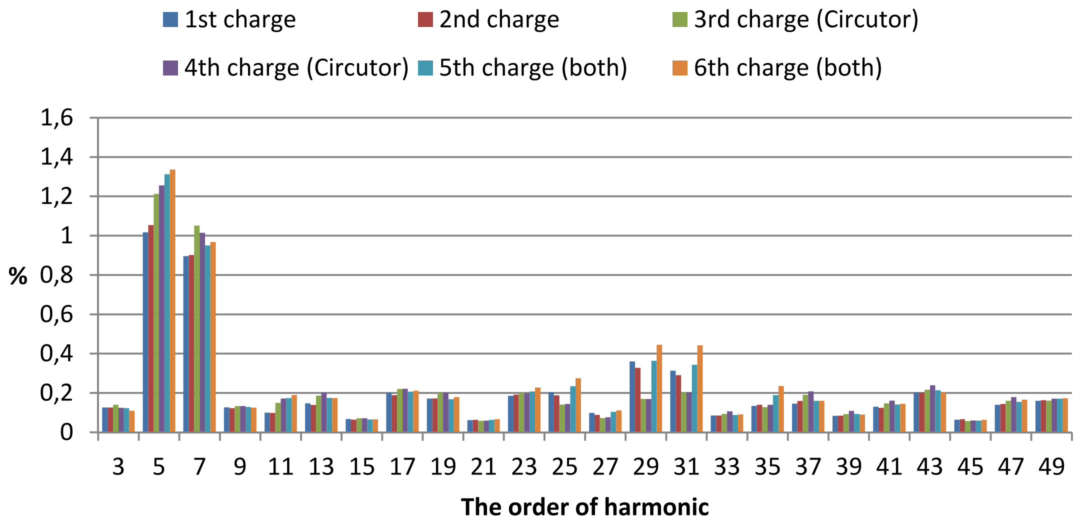

Figure 5.27. *The percentage values (in relation to average fundamental voltage) of each voltage harmonic during the charging events of Epyon.*

As can be seen from the figures above, the distribution of the voltage harmonics of Epyon is quite similar to the distribution of the voltage harmonics of Circutor. All the harmonics are also under the limits of the standard. However, two differences can be noticed. The average amplitude of the 5th and 7th harmonic of Epyon are lower than the amplitude in case of Circutor. However, the average amplitude of the 29th and 31st harmonic of Epyon are higher than in the case of Circutor. Therefore, the charger of Epyon cannot use the same rectifier as the charger of Circutor uses. Based on the results it can be supposed that the charger of Epyon contain some controllable components in structure of the rectifier. In addition, the high relative amplitude of the order 29th and 31st harmonics are caused by resonance effect. The standard does not contain higher order harmonics than 25. Therefore, the harmonics cannot be compared with the standard, but they are close to the minimum 0.5 % limit.

The standard allows the THD of the supply voltage to be less than or equal to 8 %, when all harmonics up to the order 40 are included. In Figure 5.28, the relative voltage THD values of Circutor and in Figure 5.29, the relative voltage THD values of Epyon are showed during the charging days. In the figures, CHA, CHB and CHC represent the total harmonic distortion of each phase. In Figure 5.28, the THD of Nissan Leaf is added at the end of the fast charging day with its own time of the day. The peaks in Figure 5.29 are caused by the starting and stopping the measuring devices. The voltage THD values include all harmonics up to the order 49.

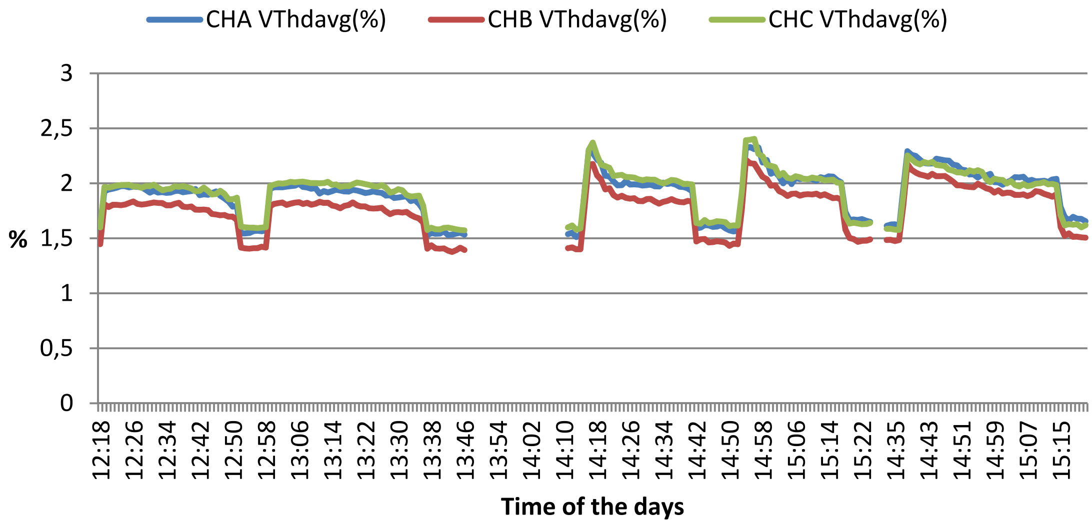

Figure 5.28. *Relative voltage total harmonic distortion of Circutor during the charging days.*

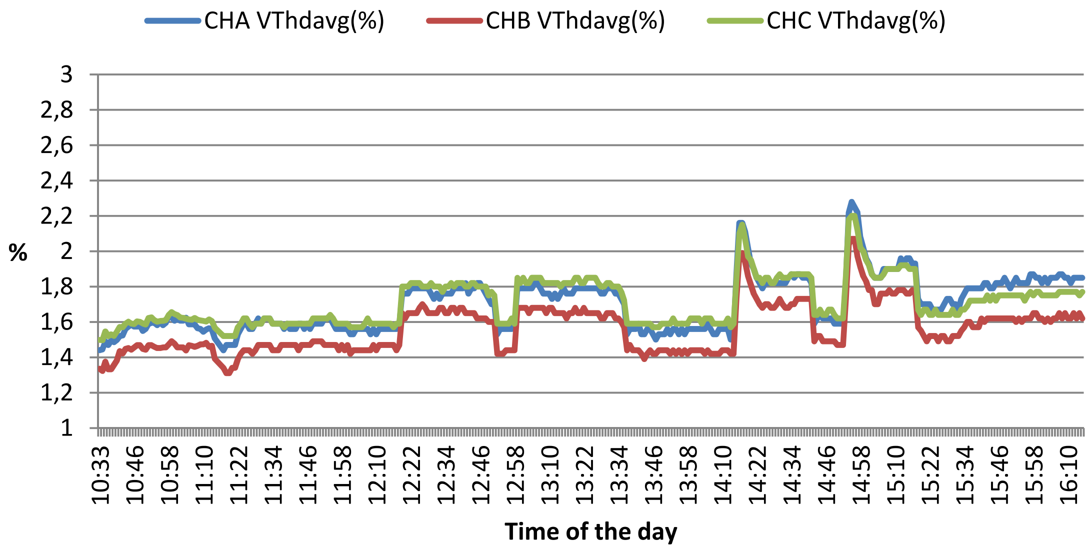

Figure 5.29. *Relative voltage total harmonic distortion of Epyon during the charging day.*

The relative voltage THD value was less than 2.5 % all the time during the charging days. This is less than the standard allows. However, the increase of THD can be noticed during the charging events.

Current harmonic distortion

On the contrary to the waveforms of phase voltages, the waveform of phase currents were significantly distorted. The waveforms were totally different when comparing the chargers. In addition, the waveform was different in different time of the charging events. In this subchapter, the phase currents are named CHA, CHB and CHC and direct current is named CHD. The waveforms are measured from a certain period of the charging events.

When analyzing the waveforms of the chargers, the first charging event when both chargers were in use, is examined. Figure 5.30, represents the current waveforms of Circutor and Figure 5.31 represents the current waveforms of Epyon during the maximum direct current of the charging event.

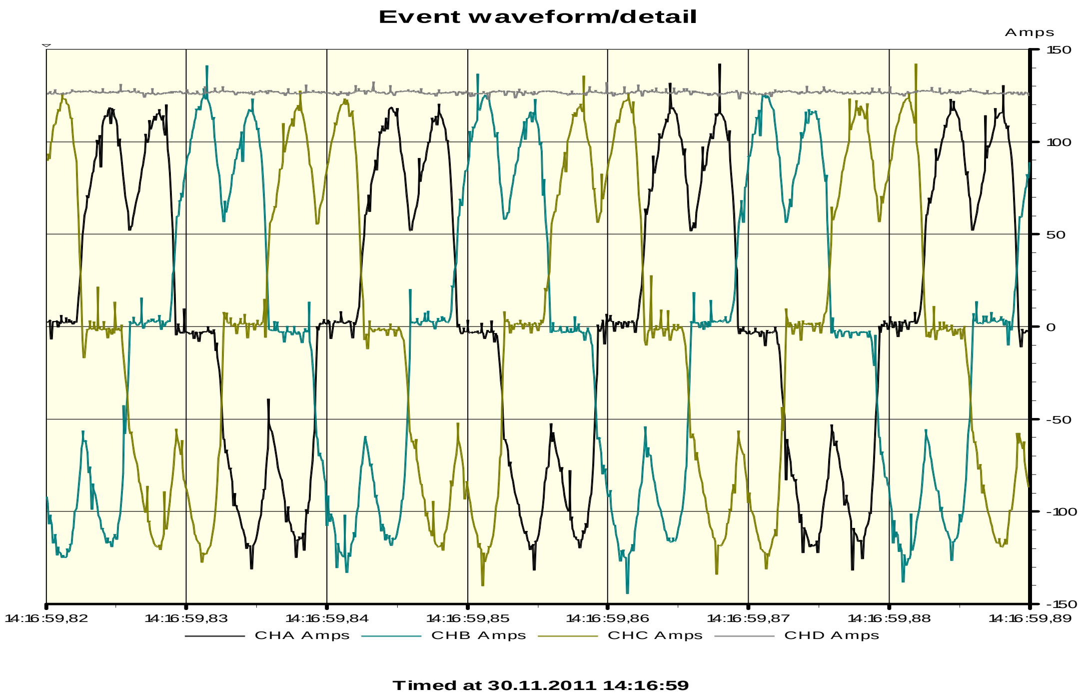

Figure 5.30. *The current waveforms of Circutor during maximum current.*

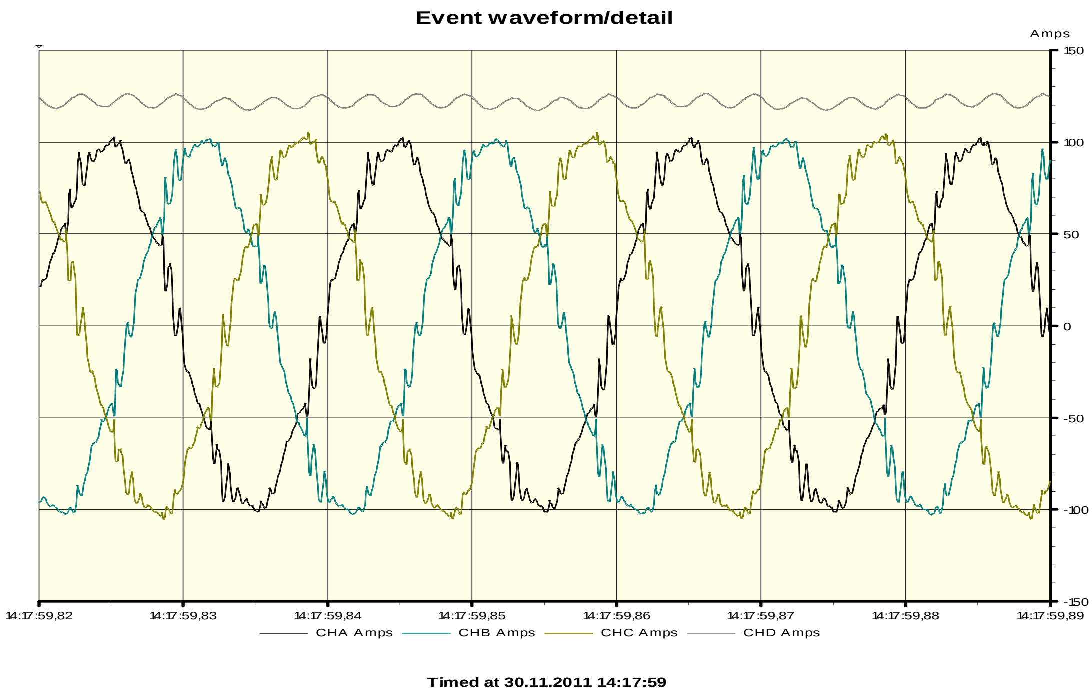

Figure 5.31. *The current waveform of Epyon during maximum current.*

As can be seen from the figures above, the waveforms are different. The phase currents of Circutor make two peaks during one half cycle and are near zero about one third of a half cycle, whereas the phase currents of Epyon are fairly sinusoidal. However, both waveforms contain some distortion. Distortions in the phase currents of Circutor are very infrequent and there are transient peaks and dips infrequently. The THD of the charging period was about 34.9 % of fundamental current (77.0 A) and order 5 harmonic was the most dominant of all harmonics, as can be seen from Appendix 3A. On the contrary, distortions in the phase currents of Epyon are more frequent. For example, there is always distortion after the intersection of the phase currents. In addition, the charger of Epyon does not cause as high transient peaks or as low dips as the charger of Circutor. The THD of the charging period was 8.3 % of fundamental current (69.3 A) and order 7, 29 and 31 harmonics were the most dominant of all harmonics, as can be seen from Appendix 3B. The formed direct current of Circutor is very close to the 128 Amperes all the time during the period, whereas the direct current of Epyon fluctuates around 121 Amperes. When charging events were close to the end, the direct currents were decreased into about 20 or 30 amperes (see Figure 5.11). Figure 5.32 illustrates the current waveforms of Circutor and Figure 5.33 illustrates the current waveforms of Epyon during the low direct current periods of the first charging event when both chargers were in use.

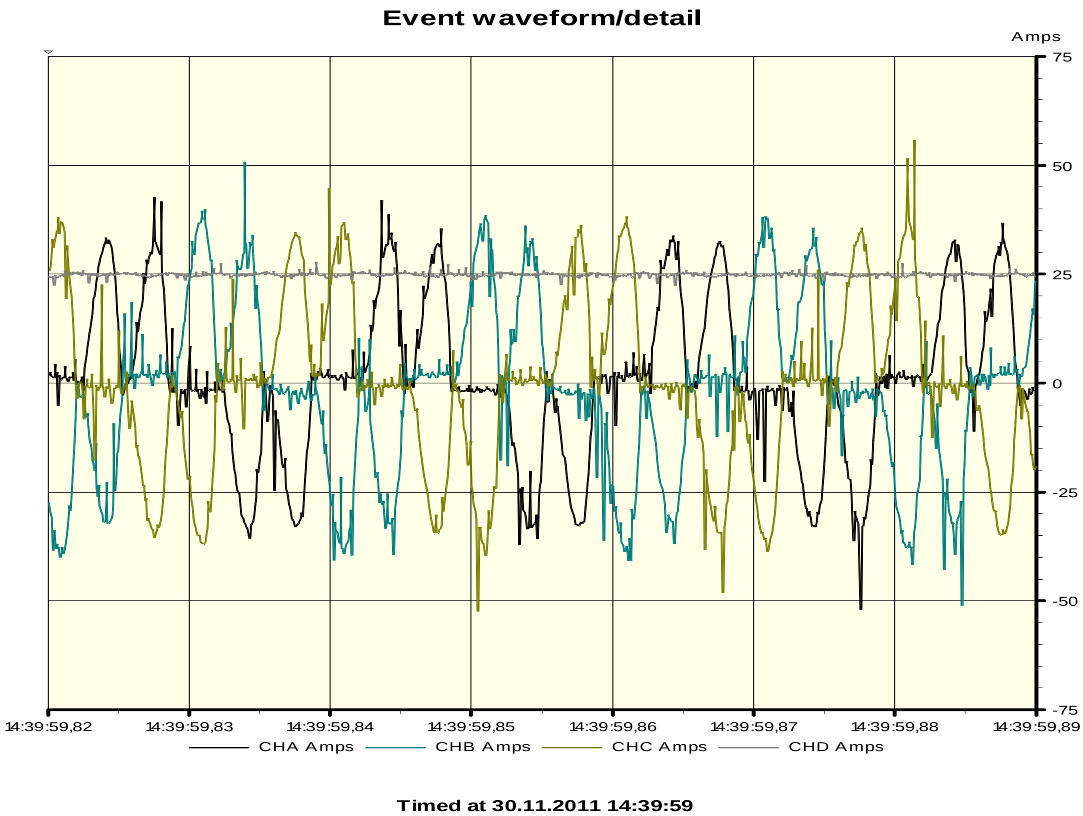

Figure 5.32. *The current waveform of Circutor during low current period.*

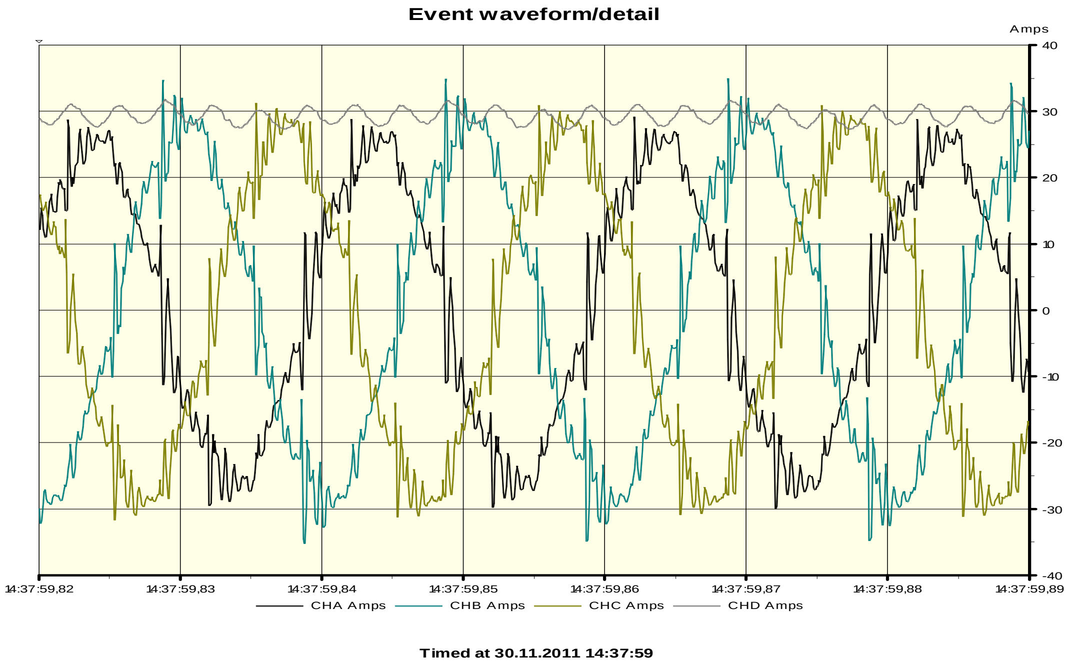

Figure 5.33. *The current waveform of Epyon during low current period.*

As can be seen from the figures above, the waveforms were fairly similar to in case of maximum current. However, the waveform seems to be more distorted and amplitudes were lower. In case of Circutor, the direct current was 25 amperes and the waveform of the phase currents were highly distorted. The total harmonic distortion was 75.2 % of fundamental current (17.4 A) and the order 5 and 7 harmonics are the most dominant, as can be seen from Appendix 3C. However, the amplitudes of transients were not as high as in the case of maximum current. In case of Epyon, the direct current fluctuated around about 29 amperes and the waveforms of the phase currents were more distorted than in case of maximum current. The total harmonic distortion was 15.3 % of fundamental current (18.3 A) and the order 29 and 30 harmonics are the most dominant of all harmonics, as can be seen from Appendix 3D.

The current waveforms were the same at other charging events as well. Only the amount of distortion changed depending on the fundamental current and the charger used. The different charging periods are combined in Table 5.2. The table shows the relative value of total harmonic distortion as well as the values of the direct current and the fundamental current during each charging period. In addition, it shows the dominant harmonics during the charging periods. The current profile of the first charging event of Epyon was different from the other charging profiles with limited charging current, because the charging current peaked during the time when the current was limited (see Figure 5.11). The peak current in Table 5.2, represents the charging period when the current peaked.

Table 5.2. *Compilation of current parameters of the charging events.*

Charging event	Period of a charge	THD (%)	Direct current (A)	Total RMS (A)	Fundamental current (A)	Dominant harmonic(s)
Epyon 1.	Maximum current	10.3	52.5	29.6	29.4	29th, 31st and 5th
	Peak current	7.3	72.5	41.3	41.2	31st, 29th and 35th
	Low current	29.4	0	5.8	5.4	37st, 31th and 41st
Epyon 2.	Maximum current	9.2	51	29.8	29.7	29th, 31st and 5th
	Low current	28.1	0	5.7	5.7	37th
Epyon 3.	Maximum current	8.3	120	69.3	69.1	29th, 7th and 31st
	Low current	15.3	29	18.3	18.1	29th and 31st
Epyon 4.	Maximum current	9.2	120	69.4	69.1	29th, 31st and 7th
	Low current	17.8	27	17.5	17.1	29th and 31st
Leaf	Maximum current	37.1	100	64.6	60.5	5th
	Low current	65.3	30	22.5	18.7	5th
Circutor 1.	Maximum current	52.5	52	32.0	28.2	5th
	Low current	83.0	18	13.4	10.2	5th and 7th
Circutor 2.	Maximum current	52.1	53	31.9	28.2	5th
	Low current	84.2	18	12.7	9.6	5th and 7th
Circutor 3.	Maximum current	34.9	128	77.0	72.6	5th
	Low current	75.2	25	17.4	13.8	5th and 7th
Circutor 4.	Maximum current	35.0	130	78.1	73.7	5th
	Low current	75.4	26	18.2	14.4	5th and 7th

It can be seen from the table above that the charger of Circutor produced higher THD values than the charger of Epyon. In addition, the lower the charging current was, the higher the THD value seemed to be. Therefore, the value increased during the charging events. The increase of THD can be seen from Figure 5.34, where the average phase current THD of both chargers during the charging days are presented. The THD of Nissan Leaf is added at the end of the fast charging day with its own time of the day. The average THD values are presented relatively to the fundamental voltage.

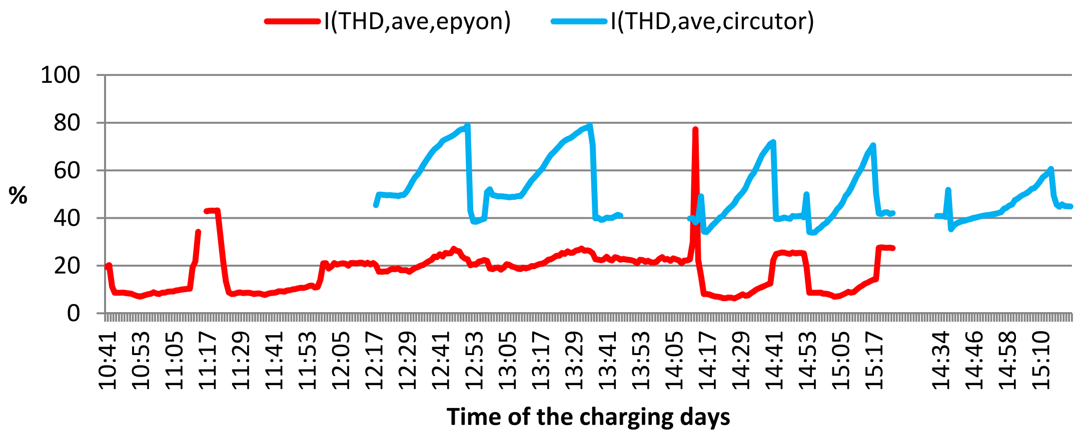

Figure 5.34. *The average phase current THD values of the chargers during the charging days.*

As can be seen from Figure 5.33, the charger of Epyon reduces the THD value during charging events from the times when there were no charging events. However, the THD value increased during the charging events. On the contrary, the charger of Circutor increased significantly the THD value during the charging events. The value was about 80 % in maximum at the end of the second charging event. To understand the increase of the THD value, the amplitudes of current harmonics have to be known. Therefore, in Figure 5.35, the dominant average harmonic current RMS values of Circutor and in Figure 5.36, the dominant average harmonic current RMS values of Epyon are presented. In case of Circutor, Nissan Leaf is added at the end of the fast charging day with its own time of the day.

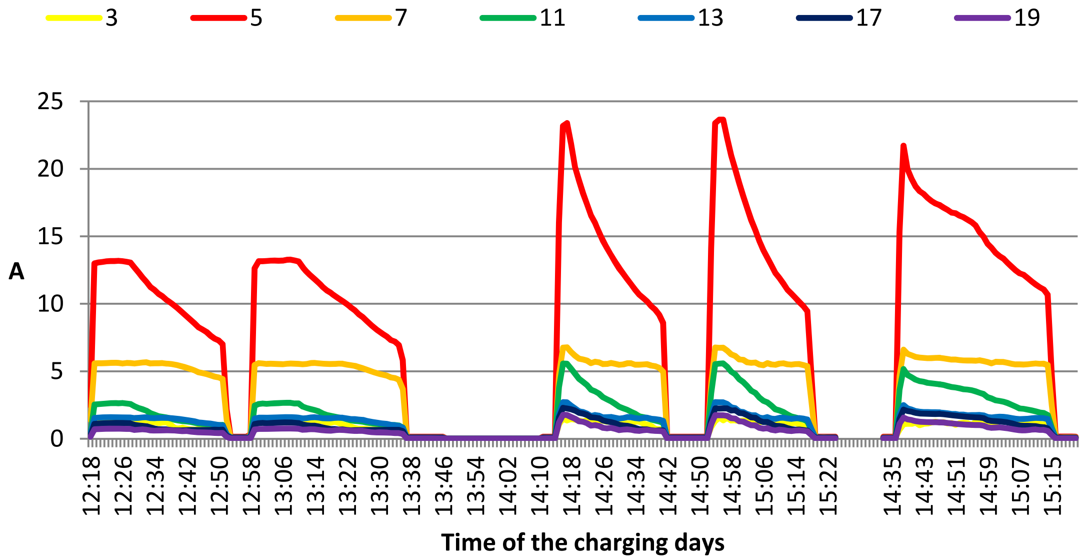

Figure 5.35. *The dominant average current harmonics of Circutor during the charging days.*

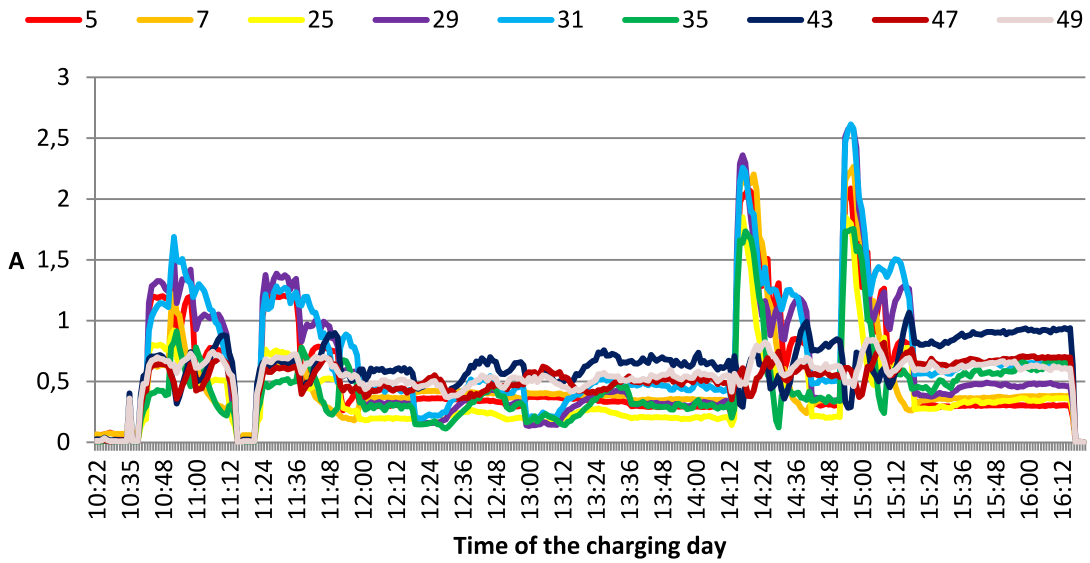

Figure 5.36. *The dominant average current harmonics of Epyon during the charging day.*

As can be seen from the figures above, the charger of Circutor produces higher harmonic current values than the charger of Epyon. The major difference is caused by order 5 and 7 harmonics. Especially, the fifth harmonic makes a significant effect to the current waveform during the charging events. In addition, the 11th harmonic was more than five amperes at maximum during the charging events of Circutor. The other RMS values of harmonics were lower than 2.5 Amperes all the time during the charging days. On the contrary, the maximum harmonic current value of Epyon was about 2.6 Amperes (31st harmonic at 14:56). Therefore, the harmonic RMS values of Epyon were significantly low in comparison with the harmonics of Circutor.

In Figure 5.37, average odd order current harmonics from 3rd to 49th during each charging event of Circutor are represented by a bar chart. In Figure 5.38, the average current harmonics are represented relatively to the fundamental voltage. The harmonic values as well as fundamental voltages are average values of the charging events.

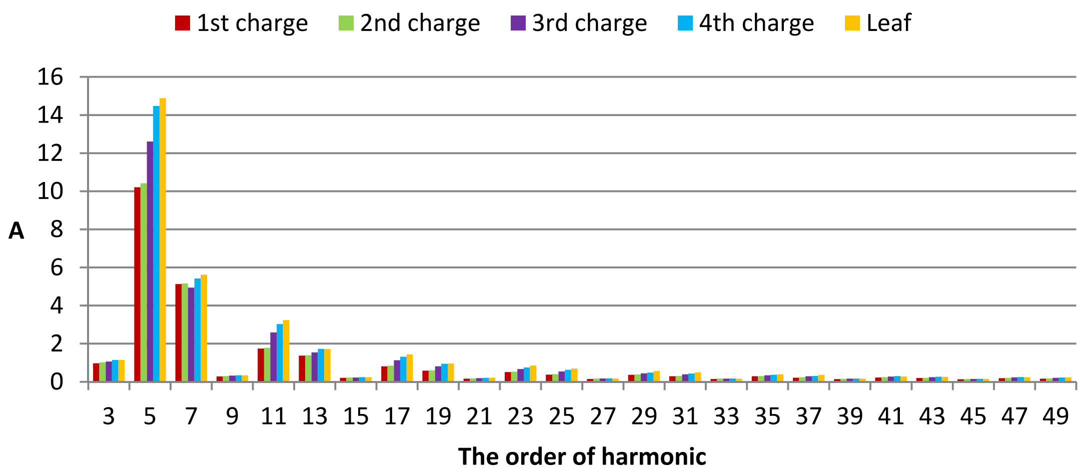

Figure 5.37. *The average odd order current harmonics during each charging event of Circutor.*

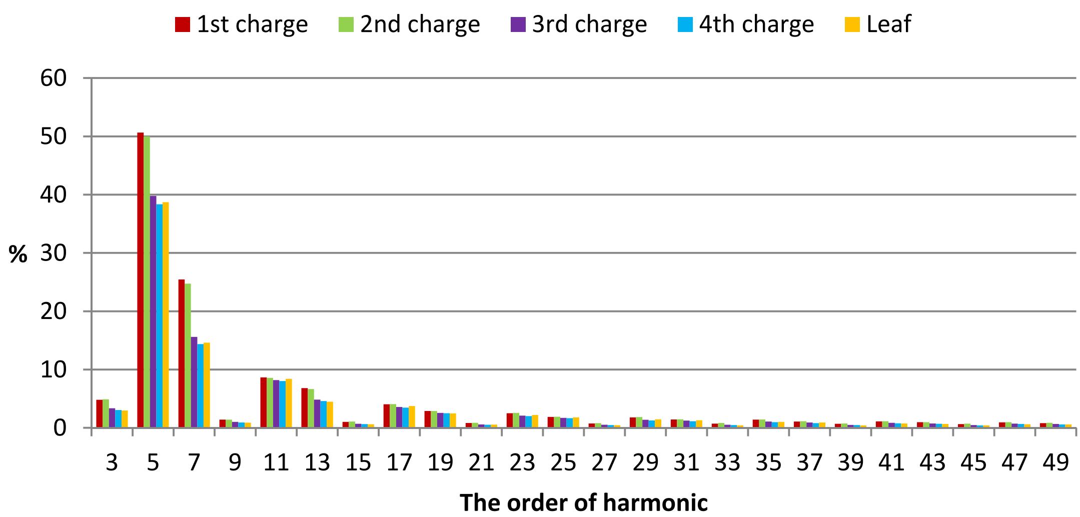

Figure 5.38. *The percentage values (in relation to average fundamental current) of odd order current harmonic during the charging events of Circutor.*

The figures above show the distribution of the current harmonics in case of Circutor. It can be seen that the values of the 5th and 7th harmonics are dominant and the rest are more or less negligible. In addition, the average relative amplitudes of 5th and 7th harmonic were higher in the charging events of limited current (first and second charge) than the other charging events, because the amplitudes were lower. As a comparison, Figure 5.39 and Figure 5.40 represent the same two block diagrams, but in case of Epyon. In case of the third and the fourth charge, the EVs were charged with the charger of Circutor and the measuring device inside the charger of Epyon was on. Therefore, six charging events are presented in the figures.

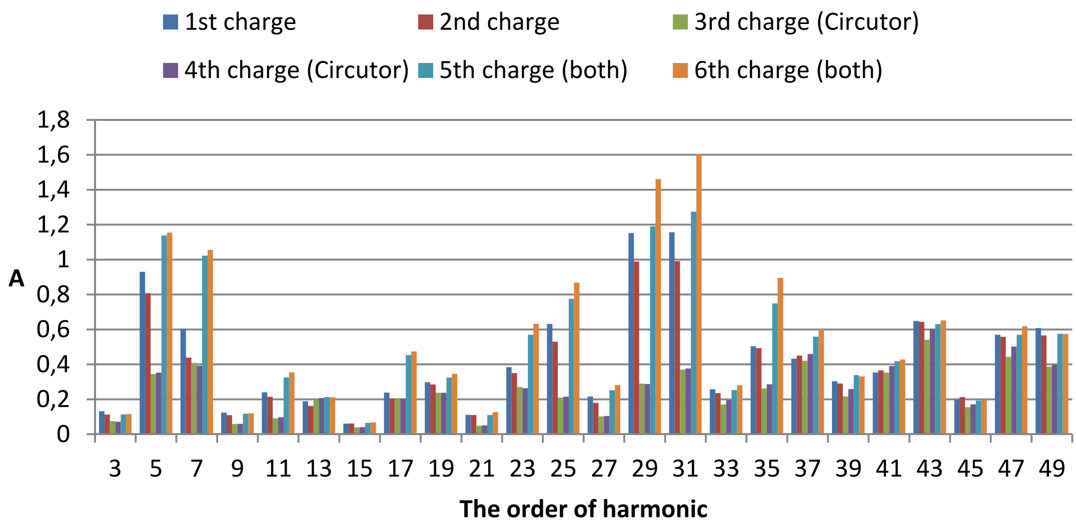

Figure 5.39. *The average odd order current harmonics during each charging event of Epyon.*

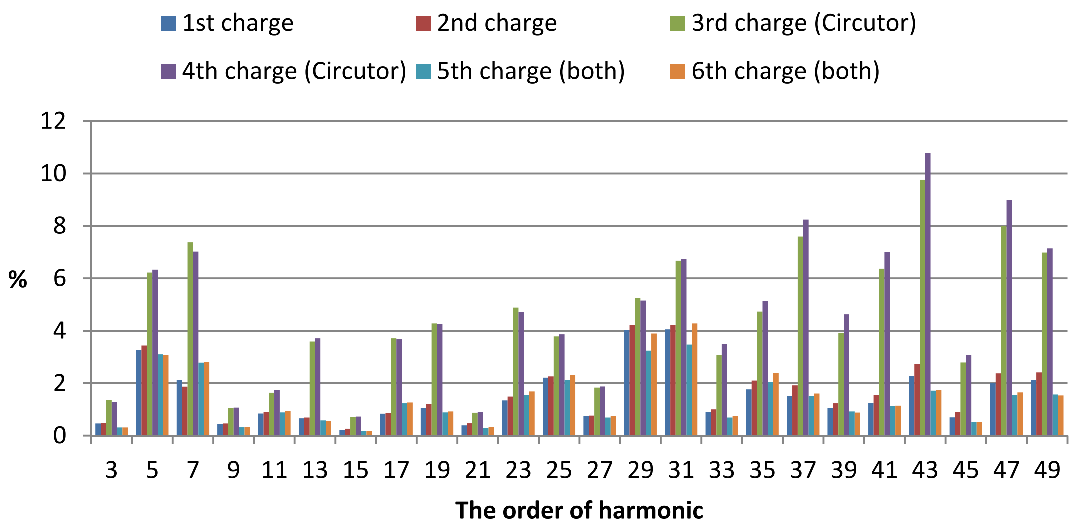

Figure 5.40. *The percentage values (in relation to average fundamental voltage) of each current harmonic during the charging events of Epyon.*

The figures above show the distribution of the current harmonics in case of Epyon. It is more evenly distributed than in a case of Circutor. It can be seen that the values of the 5th and 7th harmonics are not as dominant as they were in case of Circutor. In fact, the percentage values of 29th and 31st are higher than the values of 5th and 7th harmonic. As can be seen from Figure 5.40, the relative amplitude of every current harmonic caused by Epyon was less than 5 %.

5.2 Costs in DSO perspective

The energy cost at DSO point of view is dependent from the power profile and the effective battery capacity of an EV that is charged. In this case, the DSO must supply all the energy that is used when charging an EV because it owns the charging station. Therefore, the energy that DSO uses is not the same than the energy that is charged. The difference can be seen from Figure 5.17, where the average efficiencies of different charging events are presented. For example, the total energy that was charged into Nissan Leaf was about 15.18 kWh, whereas the total energy that was charged into Mitsubishi i-MiEV type EVs in minimum (1st charging event of Circutor) was about 7.08 kWh. If the average efficiencies of the charging events are included (93.1 % in case of Leaf and 90.9 % in case of the i-MiEV), the energy that the DSO had to feed into the charger was about 16.31 kWh in case of the Leaf and 7.79 kWh in case of the i-MiEV. The measured values were 16.30 kWh in case of the Leaf and 7.79 kWh in case of the i-MiEV. Therefore, in case of the Leaf the DSO had to feed 1.13 kWh more energy than what was charged into the EV and in case of the i-MiEV the value was 0.71 kWh. According to Nord Pool spot price in Finland at 6th January 2012 (32.44 €/MWh), the energy loss would cost about 0.037 € in case of Leaf and about 0.023 € in case of the i-MiEV. Similar calculations are made for all charging events and a compilation of the results is presented in Table 5.3. The energy loss is affected because of resistive losses inside the charger.

Table 5.3. *Compilation of the losses of the charging events.*

	Total energy (kWh) (charged into EVs)	Total energy (kWh) (from grid)	Losses (kWh)	Cost (€)
Epyon 1.	8.26	9.24	0.98	0.032
Epyon 2.	7.94	8.95	1.01	0.033
Epyon 3.	11.06	12.13	1.07	0.035
Epyon 4.	10.20	10.90	0.70	0.023
Leaf	15.18	16.31	1.13	0.037
Circutor 1.	7.08	7.79	0.71	0.023
Circutor 2.	8.22	9.02	0.80	0.026
Circutor 3.	9.92	10.70	0.78	0.025
Circutor 4.	10.25	11.03	0.78	0.025

The apparent power that the grid feeds into the charger does not only contain active power, but reactive power as well. However, the charger does not feed the reactive power into the EV. Nonetheless, one should bear in mind that the charger of Epyon fed reactive power into the grid and the charger of Circutor consumed reactive power from the grid. Therefore, the value of the losses has to be considered in a case-specific way. In some cases, DSO may have to buy reactive power compensators to keep standard accordant voltage level. This will cause costs for the DSO.

5.3 Conclusion

The grid where the fast charging stations are located has a very high short-circuit power. Therefore, fast charging did not have an impact on frequency and it did not affect problematic voltage variations. In addition, the power quality was high when compared with the standard EN 50160. In Table 5.4, the power quality parameters of the chargers as well as the parameters of the standard are combined. In the table, "Circutor" means the third and the fourth charging events of Circutor where the direct current was not limited. During the first and the second charging event of Circutor, the direct current was limited. Therefore, the charging events are named accordingly. In case of Epyon, the charging events are named in the same way.

The relative amplitudes of voltage harmonics according to the standard as well as during the charging days are combined into Table 5.5. The voltage harmonics of Circutor and Epyon are maximum values of the charging events of each charger.

Table 5.4. *Compilation of the power quality requirements of the LV network and the power quality results of the fast chargers.*

The property of voltage	High quality	Normal quality	EN 50160 accordant quality	Circutor	Circutor with limited current	Epyon	Epyon with limited current
Frequency	49.75 - 50.25 Hz	49.5 - 50.5 Hz	99,5 % per year: 49.5 - 50.5 Hz, 100% per year: 47 - 52 Hz	50.1 - 49.9 Hz (High quality)	50.1 - 49.9 Hz (High quality)	50.1 - 49.9 Hz (High quality)	50.1 - 49.9 Hz (High quality)
Voltage variation	220 - 240 V and average 225 - 235	207 - 244 V	95 % per year: $U_n \pm 10$ %, 100 % per year U_n +10 %/-15 %	226 - 228 V (High quality)	226 - 228 V (High quality)	225 - 228 V (High quality)	225 - 228 V (High quality)
Rapid voltage changes	Pst ≤ 1 and Plt ≤ 0.8	Plt ≤ 1	95 % of Plt values are ≤ 1 and $\Delta U_n \leq 5$ % U_n	Pst ≤ 0.13 and $\Delta U_{n,max} \approx 1$ V (High quality)	Pst ≤ 0.13 and $\Delta U_{n,max} \approx 0.5$ V (High quality)	Pst ≤ 0.13 and $\Delta U_{n,max} \approx 2$ V (High quality)	Pst ≤ 0.13 and $\Delta U_{n,max} \approx 1$ V (High quality)
Voltage harmonics	THD ≤ 3 %	u_h ≤ the values in the table 3.1 and THD ≤ 6%	u_h ≤ the values in the table 3.1 and THD ≤ 8%	u_h values are presented in the table 5.3 and THD ≤ 2.4 % (High quality)	u_h values are presented in the table 5.3 and THD ≤ 2 % (High quality)	u_h values are presented in the table 5.3 and THD ≤ 2.3 % (High quality)	u_h values are presented in the table 5.3 and THD ≤ 1.7 % (High quality)

Table 5.5. *Compilation of the voltage harmonics.*

Odd harmonics								Even harmonics			
Not multiples of 3				Multiples of 3							
Order h	Standard u_h (%)	Circutor (max)	Epyon (max)	Order h	Standard u_h (%)	Circutor (max)	Epyon (max)	Order h	Standard u_h (%)	Circutor (max)	Epyon (max)
5	6.0	1.56	1.34	3	5.0	0.15	0.11	2	2.0	0.02	0.01
7	5.0	1.12	1.02	9	1.5	0.14	0.13	4	1.0	0.01	0.00
11	3.5	0.26	0.19	15	0.5	0.07	0.07	6...24	0.5	0.02 (22nd)	0.02 (22nd)
13	3.0	0.22	0.17	21	0.5	0.06	0.06				
17	2.0	0.24	0.21								
19	1.5	0.21	0.18								
23	1.5	0.21	0.23								
25	1.5	0.23	0.27								

As can be seen from the tables above, the power quality of the chargers was very high. All the parameters shown in Table 5.4 are between the limits of the standard. In addition, the voltage harmonics are much lower than the standard allows. However, one should bear in mind that the situation can be different when the chargers are connected to a LV network with low short-circuit power.

On the contrary to the voltage waveforms, current waveforms were significantly distorted. Total harmonic distortion increased during the charging events due to the decrease of the fundamental current. The faster the current decreased, the faster the THD increased. The THD was about 80 % at maximum. However, the content of odd harmonics divisible by 3 was very low.

In case of voltage, there were no significant differences between the chargers. The power quality was high during the charging events of both chargers and the relative amplitude of every voltage harmonic was much lower than the standard allows. However, the chargers produced totally different charging currents. The reason for that is the structure of the power converters. In case of Circutor, the AC/DC converter is three-phase diode-rectifier. Therefore, the order 5, 7, 11 and 13 harmonics are the most dominant and the effects of the other harmonics are negligible. This is also the reason why the current waveform was that far from sinusoidal. In addition, both chargers have a DC/DC converter, which controls the charging current. It adds high frequent components (switching frequent of the converter) to the harmonic content of the chargers and it shows more or less in the mains currents. In case of Epyon, the AC/DC converter is so called a grid tie inverter, where the current harmonics are close to the switching frequency and its multiplies. In this case, the switching frequency seems to be 1500 Hz (30^{th} harmonic) because the most dominant harmonics were order 29 and 31 harmonics. In addition, a mains filter has an effect on the harmonic content of Epyon. The charger of Epyon also includes five parallel chargers to produce the maximum power. In practice, all the five chargers do not cause the same mains current (amplitude and phase). Therefore, the mains current is some kind of mixture of the currents of the chargers.

Despite the different alternating currents, both chargers produced similar direct current profiles. In addition, the DC voltage profiles were similar as well. When a battery of an EV was not able to receive maximum charging current, the current was limited to about 52 amperes. This happened because of the battery conditions were not able to receive maximum current and the battery was not warm enough. When the temperature as well as other battery conditions were between certain values, it was possible to increase the charging current as well. In case of Circutor, the maximum charging current was about 130 amperes, whereas the maximum current of Epyon was about 125 amperes. The difference caused no difference between the duration of a charge.

Because the charging current and voltage profiles were the same with both chargers, active power and apparent power were the same as well. In addition, the efficiency of the chargers was the same and naturally, the energy charged into EVs was not dependent from the charger used. However, reactive power profiles differed significantly between the chargers. The charger of Circutor consumes reactive power from the grid (10.5 kVAr at fundamental frequency at maximum), whereas the charger of Epyon feeds reactive power to the grid. The reactive power fed by Epyon was almost the same during each charging event (between 6.5 to 4 kVAr at fundamental frequency) although the current was higher during the last two charging events. In addition, the power factor (at 50 Hz) of Epyon was lower (0.97 at maximum) than the power factor of Circutor (0.99 at maximum) during the charging events. In order to maintain the standard accordant voltage level in LV or MV network, this has to be taken into consideration. In this case, it cannot be said which solution is better, because the voltage level of LV and MV network is dependent from the relation as well as absolute values of active and reactive power of loads. Therefore, it has to be considered in a case-specific way.

The content of the voltage harmonics was very similar with both chargers. However, the charger of Circutor produced higher voltage THD values than the charger of Epyon. Nonetheless, the difference was so small that it was insignificant.

The content of the current harmonics of the chargers was significantly different. The charger of Circutor produced significantly higher current THD values than the charger of Epyon. In fact, the charger of Epyon decreased the value of THD during the charging events. The maximum THD values were affected during the low charging current periods.

In the measuring days, two types of EVs were used: Mitsubishi i-MiEV type EVs and Nissan Leaf. The Leaf stood out from the rest because of the higher DC voltage profile, different direct current profile and significantly higher energy capacity. The maximum DC voltage of the Leaf was about 396 volts and the maximum charging current was about 108 Amperes. Whereas the DC voltage of i-MiEV type EVs was betweem 360-363 volts and the maximum charging current of i-MiEV type EVs was about 52 amperes during the charging events with the limited current and between 120 and 130 amperes during the charging event with the unlimited current. In addition, the charging current of the Leaf did not decrease as fast as the current in case of i-MiEV type EVs. Therefore, the battery of the Leaf received more energy and it was charged faster than the batteries of other EVs. However, the charging of the Leaf took longer than the other charging events because of higher battery capacity.

6 CASE STUDY: IMPACTS OF FAST CHARGING OF ELECTRIC VEHICLES ON THE DISTRIBUTION NETWORK

In this chapter, three fast charging stations that are connected into the distribution network are simulated. The fast charging stations are analyzed in separate cases. The location of the fast charging stations is selected so that it would correspond the conceivable locations of new fast charging stations. In the first case, a fast charging station locates in a parking area of a big shopping mall and the maximum consumption of the fast charging station with the EV charging capacity of 2, 20 and 40 EVs is added into the consumption of MV/LV transformer. In the second case, a fast charging station locates at a big sized service station and the maximum consumption of the fast charging station with the charging capacity of 2, 4 and 6 EVs is added into the consumption of a LV consumption point. In the third case, a fast charging station locates at a small sized gas station and the maximum consumption of the fast charging station with the charging capacity of 1 and 2 EVs is added into the consumption of a LV consumption point. In the second and third case, MV/LV transformers and LV distribution lines are analyzed. In practice, fast charging stations would be connected into the grid with a connection cable of they own. Therefore, it should bear in mind that the analysis is very theoretical.

The objective of this Chapter is to model worst-case scenarios when new fast charging stations are connected into the distribution network. At first, the modeling of fast charging stations as well as the connection point is clarified. In addition, case-specific grid parameters and components are introduced. After the grid has been described and the maximum consumption of the fast charging stations are added into the consumption points, the calculation of the grid impacts are presented. At the end of this chapter, the grid impacts are analyzed and conclusions are made. In this chapter, the powers are one-year maximum values and dissipation costs are one-year total values.

6.1 Modeling and simulations

In this subchapter the distribution network of different cases is introduced. First, the grid structure and the parameters of components are presented. After that, different cases are modeled. In the cases, when there are EVs connected into the grid, each EV will take the full 50 kW power at all times. This is not the case in practice, but here the worst-case scenario is presented. The load factor of a MV/LV transformer defines the relation of apparent power of the MV/LV transformer and capacity of the MV/LV transformer. The load factor of cables defines the relation of current that flows in the cable and the maximum current capacity of the cable. The results of the simulations are calculated with PowerGrid Finland network operation software.

6.1.1 Case 1: Shopping mall

In case 1, fast charging stations will be connected into MV network inside a car park of Sello. Sello locates in Leppävaara (Espoo, Finland). In Figure 6.1, the grid view and basic principle of distribution arrangement are presented. A pink square inside a red circle presents the MV/LV transformer (20/0.4 kV), where the fast charging station will be connected. The full MV/LV transformer capacity is 5 MVA, which consist on five parallel connected 1 MVA transformers. The blue dashed line presents MV cable and green dashed line presents LV cable. The MV cable type, which connects the MV/LV transformer to the primary substation (110/20 kV), is AHXAMK-W 3X2440+50.

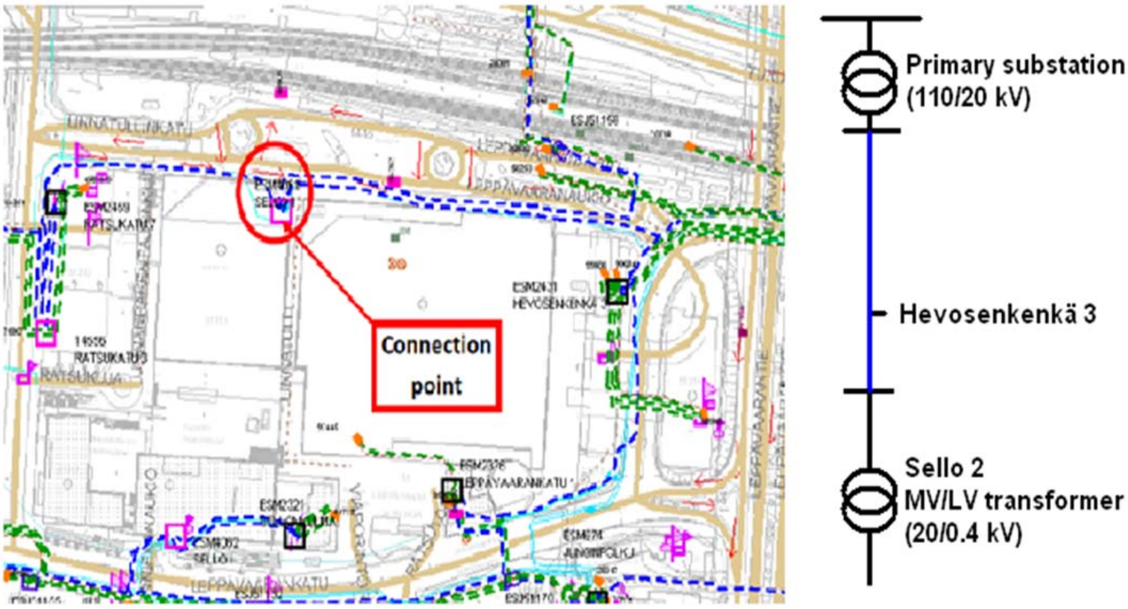

Figure 6.1. *The grid view and basic principle of distribution arrangement of the case 1.*

In a case, when there were no EVs connected, the maximum active power that the primary substation fed into the connection point was about 3.5 MW. The annual energy loss of the MV cables measured from primary substation was about 12.6 MWh and the total cost of the losses was about 478 €. The load factor of the MV/LV transformer was about 74.2 during the peak hours. The calculated utilization period of maximum load was 4560 hours. The load factor of the MV cables that connects the MV/LV transformer to the primary substation was about 27.9 %, as can be seen from Appendix 4A.

When different numbers of EVs were connected into the network, the parameters changed. Table 6.1 shows the compilation of the parameters, when there were 2, 20 or 40 EVs connected simultaneously. The load factor of the MV cables that connects the MV/LV transformer to the primary substation was about 44.5 % when 40 EVs were charged simultaneously, as can be seen from Appendix 4B.

Table 6.1. *Compilation of important parameters in case 1.*

Number of EVs	Added power (kW)	Total power of the MV/LV transformer (kW)	Dissipation cost (€)	Load factor of the MV/LV transformer (%)
0	0	3542.0	478.1	74.2
2	100	3642.0	509.8	76.3
20	1000	4542.0	811.3	95.2
40	2000	5542.0	1188.7	116.3

6.1.2 Case 2: Big service station

In case 2, fast charging stations will be connected into a parking area of big service station. The service station locates in Riihimäki (Finland). In Figure 6.2, the grid view and basic principle of distribution arrangement is presented. An orange square inside a red circle presents the MV/LV transformer (20/0.4 kV), and an orange parallelogram inside the red circle and the orange square is the connection point of the fast charging station. The MV/LV transformer capacity is 1 MVA. The blue dashed line presents MV cable and green dashed line presents LV cable. The MV cable type, which connects the MV/LV transformer to the primary substation (110/20 kV), is AHXAMK-W 3X1350+35. The type of the LV cable that connects the MV/LV transformer and the fast charging station is AXMK 4X2440. The other LV cable types that the MV/LV transformer feeds are also AXMK, but circumstances of the cables are smaller. The types of the cables are: AXMK 4x50 (feeds the road lightning), AXMK 4X245 (feed only one household), AXMK 4x95 (2 cables, the other feeds water supply and sewerage as well as the other feeds two households).

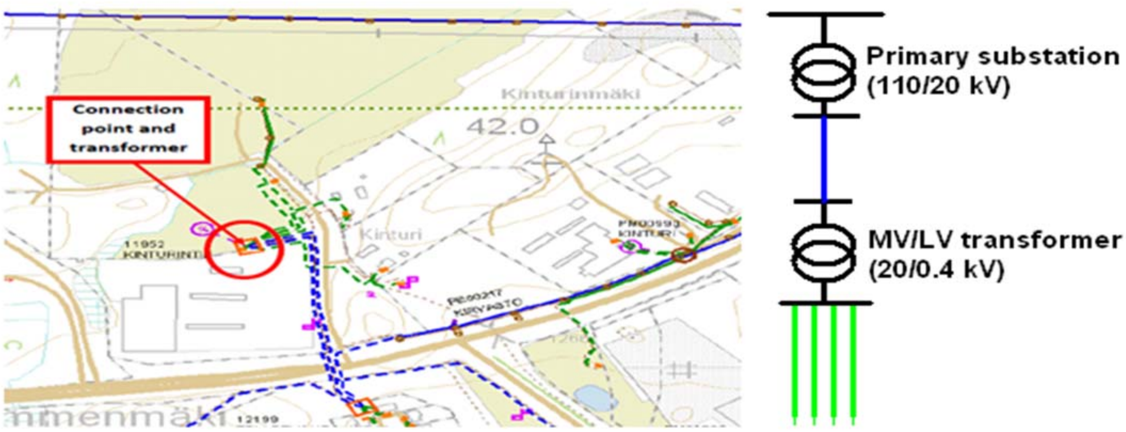

Figure 6.2. *The grid view and basic principle of distribution arrangement of the case 2.*

In a case, when there were no EVs connected, the maximum active power that the MV/LV transformer fed into the connection point was about 615.0 kW, where about 0.7 % was lost because of MV/LV transformer losses. The annual energy loss of the MV/LV transformer was 10.2 MWh. The annual energy loss of the MV cables measured from primary substation was about 6.9 MWh, which costs annually about 260 €.

The load factor of the MV/LV transformer was about 64.7 % during the peak hours. The load factor of the LV cables that feed the charging station was 61 %, as can be seen from Appendix 4C.

When different numbers of EVs were connected into the network, the parameters changed. Table 6.2 shows the compilation of the parameters, when there were 2, 4 or 6 EVs connected simultaneously. The load factor of the LV cables that feed the charging station was 92 % when six EVs were charged simultaneously can be seen from Appendix 4D.

Table 6.2. *Compilation of important parameters in case 2.*

EVs connected	Added power (kW)	Total power of the MV/LV transformer (kW)	Power loss of the MV/LV transformer (kW)	Dissipation cost (€)	Load factor of the MV/LV transformer (%)
0	0	615.0	4.1	259.7	64.7
2	100	715.0	5.5	328.4	75.3
4	200	815.0	7.2	406.0	85.8
6	300	915.0	9.1	491.4	96.3

6.1.3 Case 3: Small service station

In case 3, fast charging stations will be connected into a parking area of small service station. The service station locates in Otaniemi (Espoo, Finland). In Figure 6.3, the grid view and basic principle of distribution arrangement is shown. A black square inside a red circle presents the MV/LV transformer (20/0.4 kV), and an orange parallelogram inside another red circle is the connection point of the fast charging station. The MV/LV transformer capacity is 0.5 MVA. The blue dashed line presents MV cable and green dashed line presents LV cable. The MV cable type, which connects the MV/LV transformer to the primary substation (110/20 kV), is APYAKMM 3X1385. The type of the LV cable that connects the MV/LV transformer and a distributing cabinet is PLKVJ 3X1320+70 and the type of the LV cable that connects the distribution cabinet and the fast charging station is MCMK 2X130.

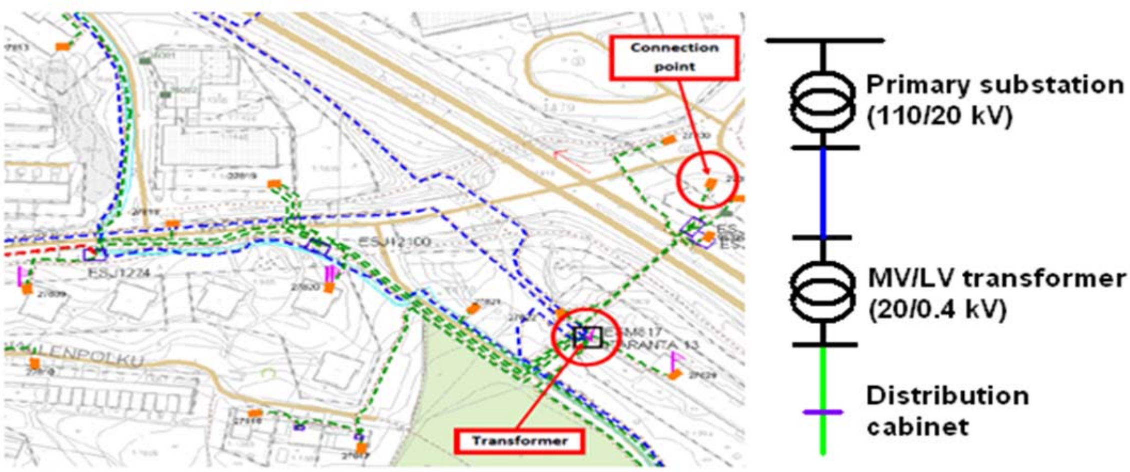

Figure 6.3. *Grid view and basic principle of distribution arrangement of the case 3.*

In a case, when there were no EVs connected, the maximum active power that the MV/LV transformer fed into the connection point was about 260.5 kW, where about 0.6 % was lost because of MV/LV transformer losses. The annual energy loss of the MV/LV transformer was about 3.6 MWh. The annual energy loss of the MV cables measured from the primary substation was about 63.4 MWh, which costs annually about 2400 €. The load factor of the MV/LV transformer was about 54.9 % during the peak hours and the load factor of the LV cables can be seen from Appendix 4E.

When one or two EVs were connected into the network, the parameters changed. Table 6.3 shows the compilation of the parameters, when there was none, one or two EVs connected simultaneously. The load factor of the LV cable that feed the charging station was over 100 % when two EVs were charged simultaneously, as can be seen from Appendix 4F.

Table 6.3. *Compilation of important parameters in case 3.*

EVs connected	Added power (kW)	Total power of the MV/LV transformer (kW)	Power loss of the MV/LV transformer (kW)	Dissipation cost (€)	Load factor of the MV/LV transformer (%)
0	0	260.5	1.4	2398.7	54.9
1	50	310.5	2.0	2490.7	65.4
2	100	360.5	2.8	2562.2	75.9

6.2 Analysis

The cases differed significantly due to different connection points of the fast charging stations. In case 1, the fast charging station was connected into MV network. As can be seen from Table 6.1 and Appendix 4B, the capacity of the MV/LV transformer was a limiting parameter. When 40 EVs were charging simultaneously, the load factor of the MV/LV transformer increased over its full capacity. The maximum load factor of the MV cables instead was 44.5 %. Therefore, there was remaining capacity to increase the load. However, the dissipation cost of the primary substation, when there was 40 EVs connected, increased about one and a half times from the value that was before the installation of fast charging stations. In Figure 6.4, the active power (P), reactive power (Q) and apparent power (S) profiles as well as the MV/LV transformer capacity are illustrated in relation to connected EVs in case 1. In addition, annual dissipation costs of the energy losses of MV cables measured from primary substation (red curve) are illustrated in secondary vertical axis.

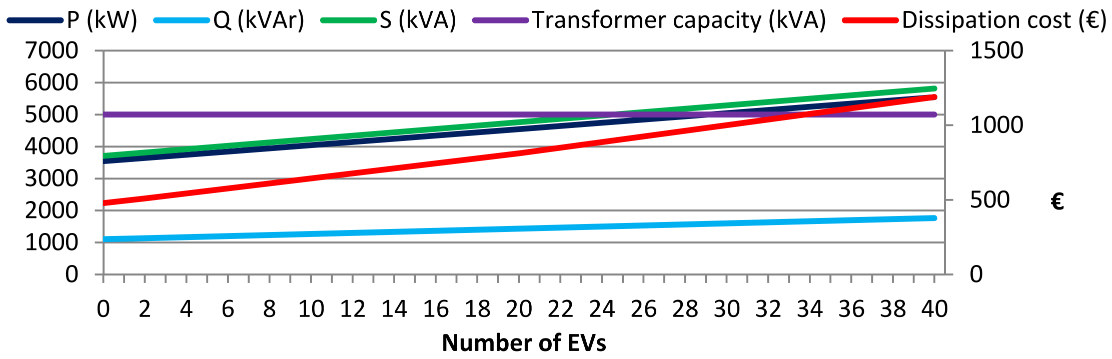

Figure 6.4. *The power profiles and dissipation cost in relation to the connected EVs in case 1.*

Figure 6.4 shows that the MV/LV transformer capacity and apparent power profile intersected when about 24 EVs were charged simultaneously. Therefore, this is the maximum amount of EVs that can be charged simultaneously without affecting overload to the MV/LV transformer. At that point, the dissipation cost was about 900 €, which is about 420 € more than the value that was before the installation of fast charging stations. In this case, there were no other reinforcement investments if the charging capacity of 24 EVs meets the requirements of Sello. If not, a new MV/LV transformer has to be bought. However, when the prospective load increase is also taken into consideration, the maximum charging capacity would be less than 24 EVs.

In case 2, the fast charging station was connected into LV network. As can be seen from Table 6.2, the capacity of the MV/LV transformer was not a limiting parameter in this case. When 6 EVs were charged simultaneously, the load factor of the MV/LV transformer increased from 64.7 % into 96.3 %. The limiting parameter was not either the load factor of LV cables. As can be seen from Appendix 4C and 4D, the load factor of the LV cables increased from 61.0 % into 92.0 %, when six EVs were charged simultaneously. In Figure 6.4, the active power (P), reactive power (Q) and apparent power (S) profiles as well as the MV/LV transformer capacity are illustrated in relation to connected EVs in case 2. In addition, energy losses of the MV/LV transformer are illustrated in secondary vertical axis.

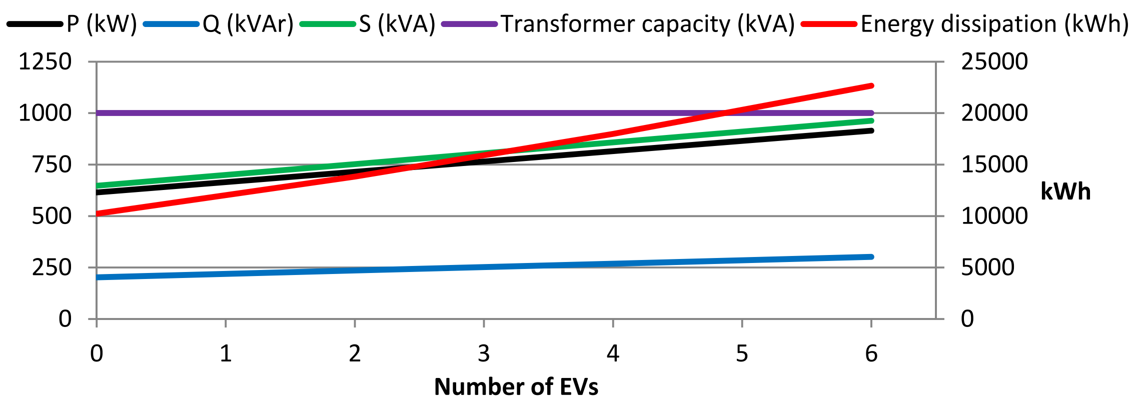

Figure 6.5. *The power profiles and energy dissipation of the MV/LV transformer in relation to the connected EVs in case 2.*

Figure 6.5 shows that the MV/LV transformer capacity and apparent power profile do not intersect. If the increase in apparent power continues to increase linearly, the apparent power profile will intersect the MV/LV transformer capacity when about 6.7 EVs are charged simultaneously. Therefore, the present grid was suitable for installing 6 fast charging stations at maximum. However, the load of the MV/LV transformer and the LV cables are close to their maximum capacities. In addition, when the prospective load increase is taken into consideration, the maximum charging capacity would be less than 6 EVs. When 6 EVs where charged simultaneously, the energy dissipation of the MV/LV transformer was about 22.7 MWh, which is about 12.5 MWh more than the value that was before the installation of fast charging stations. The losses were about doubled when 5 EVs were connected.

In case 3, the fast charging station was connected into LV network. As can be seen from Table 6.3, the capacity of the MV/LV transformer was not a limiting parameter in this case. When 2 EVs were charged simultaneously, the load factor of the MV/LV transformer increased from 54.9 % into 74.8 %. The limiting parameter was the LV cable that feeds the fast charging station. As can be seen from Appendix 4E and 4F, the load factor of the LV cables increased from 0.0% into 329.0 %, when two EVs were charged simultaneously. The energy losses of the MV/LV transformer increased about 1.6 MWh per connected EV. In Figure 6.6, the active power (P), reactive power (Q) and apparent power (S) profiles as well as the MV/LV transformer capacity are illustrated in relation to connected EVs in case 3. In addition, energy losses of the MV/LV transformer are illustrated in the secondary vertical axis.

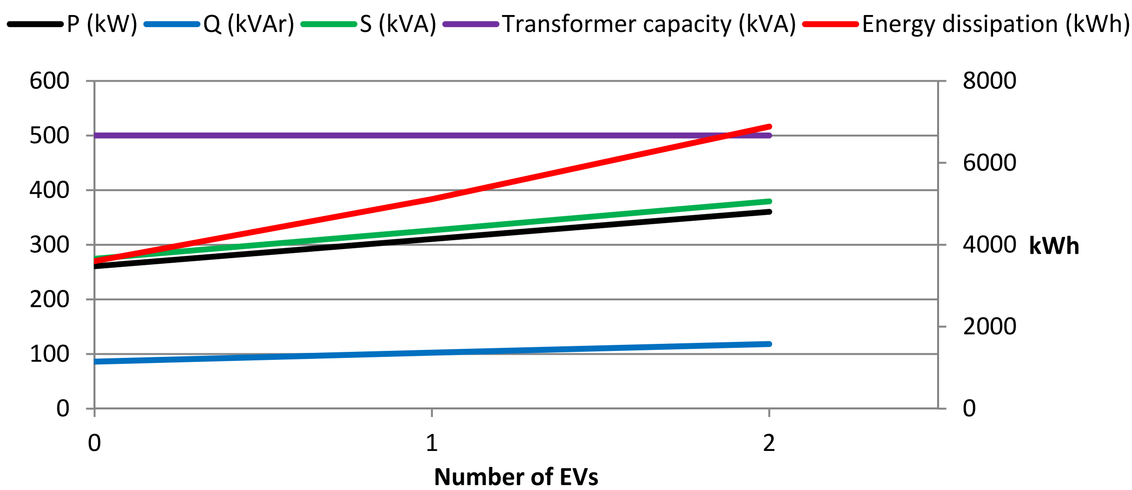

Figure 6.6. *The power profiles and energy dissipation of the MV/LV transformer in relation to the connected EVs in case 3.*

Figure 6.6 shows that the MV/LV transformer capacity and apparent power profile do not intersect. If the increase in apparent power continues to increase linearly, the apparent power profile will intersect the MV/LV transformer capacity when about 4.3 EVs are charged simultaneously. However, the capacity of the LV cable that feeds the fast charging station does not sustain the power that an EV uses during the charging period. Therefore, the connection has to be reinforced.

When the reinforcement is wanted to do properly, the LV cables that connect the MV/LV transformer and the distribution cabinet as well as the fast charging station has to be changed. In Figure 6.7, the reinforced grid view is showed. There the old PLKVJ cable is changed into two AXMK 4X1385 cables and the old MCMK 2X130 cable is changed into two AXMK 4X1385 cables as well. In addition, the distribution cabinet is changed because there was not enough space to do additional connections inside the old distribution cabinet and the current capacity of the bus inside the distribution cabinet was not enough high to withstand the required current.

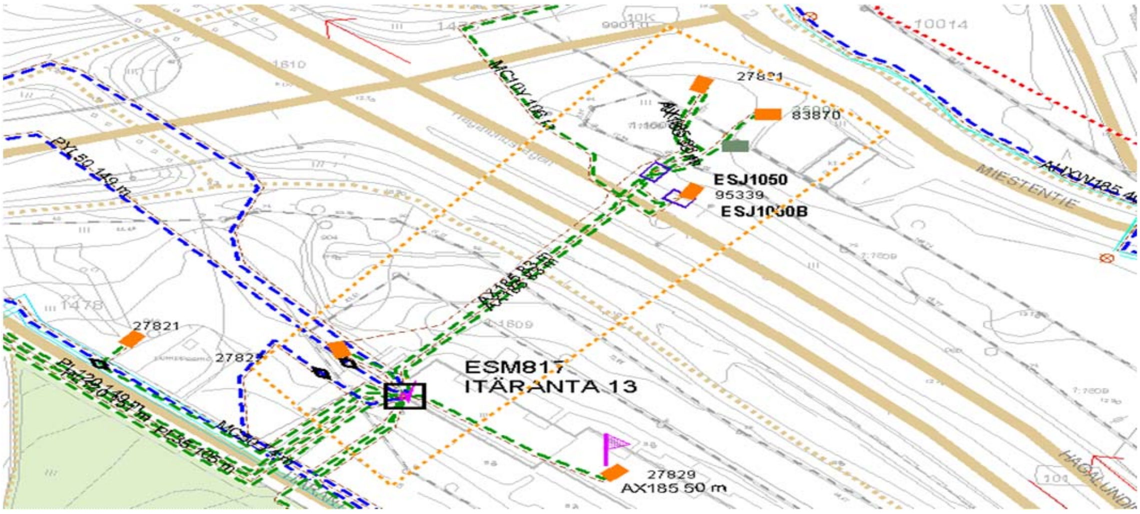

Figure 6.7. *Reinforced grid view in case 3.*

When the reinforcements were done, the load factor of the cables that connects the fast charging station was reduced into 36.0 % as can be seen from Appendix 4G. According to the prices of Finnish energy market authority, implementing the reinforcement plan would cost about 10856 € (including taxation 23 %). This value is estimated so that buying 240 meters of AXMK 4X1380 cables would cost 4696 €, a new distribution cabinet would cost 1540 € and digging the cables underground in urban area would cost 2590 €.

6.3 Conclusion

The cases differed significantly from each other due to different connection points, different EV capacities of fast charging stations as well as the different grid structures. The cases did not take into account the reactive powers of the fast charging stations and EVs were charged at maximum power at all times. Therefore, the losses will not give the right values, but the relation of the values can be compared.

In the case 1, the fast charging stations were installed into MV network. In the case, the MV/LV transformer and the MV cable capacity was so high that the load increase did not affect problems for the grid. However, connecting EVs into the station increased the power losses of the MV/LV transformer about 0.2 kW per EV and the dissipation cost of the MV cables measured from primary substation about 17.8 € per EV. 24 EVs was the maximum capacity that can be charged simultaneously without affecting overload into the MV/LV transformer. However, this value does not take into account the prospective load increase. Therefore, installing the fast charging station with 20 EV capacity would be better solution. This enables possibility to increase the load of the shopping mall in future and charge 20 EVs simultaneously at maximum power without affecting overload into the MV/LV transformer. In addition, there would be no reinforcement requirements. However, the increased losses affected some additional costs for DSOs. This would also be a sufficient amount of charging spots at the beginning. If more spots are wanted, some kind of power limiting automation has to be installed or new transformer has to be built. The power limiter would limit the charging power if it increases over a certain limit, which would cause hazardous conditions into the grid. In practice, the power limiter would be worthwhile to install anyway, to prevent overload into the MV/LV transformer.

In the case 2, the fast charging station was installed into LV network, near to MV/LV transformer. In the case, the MV/LV transformer capacity was so high that the load increase did not affect overload until 7 EVs were charged simultaneously. However, connecting EVs into the station increased the power losses of the MV/LV transformer about 0.8 kW per EV and the annual dissipation cost of MV cables measured from primary substation about 28.6 € per EV. The load factor of LV cables that feed the fast charging station was high at normal operation conditions (61 %). When 6 EVs was charged simultaneously, the load factor of the cables increased into 92 %, which is very close to its maximum capacity. In addition, this value does not take into account the prospective load increase. In practice, installing the fast charging station with 4 EV capacity would be better solution to prevent the overload of the cables. In that case, the load factor was 82 %. This enables possibility to increase the load of the service station in future and possibility to charge 4 EVs simultaneously at maximum power without affecting overload into the cable. If more charging spots are wanted, the fast charging station has to contain an automatic power limiter or the grid has to be reinforced.

In case 3, the fast charging station was installed into LV network. In the case, the MV/LV transformer capacity was sufficient to charge 4 EVs simultaneously. However, connecting EVs into the station increased the power losses of the MV/LV transformer about 0.7 kW per EV and the dissipation cost of the MV cables measured from primary substation about 81.8 € per EV. In the present grid, the LV cable that feeds power into the consumption point, where the fast charging station is wanted to install, has too low current capacity. Therefore, the grid has to be reinforced if the fast charging station is wanted to install into the consumption point. A reinforcement plan was introduced in Chapter 6.2. Implementing the plan would cost about 10856 € for DSO. When the plan is implemented, the load factor of the cable that feeds a fast charging station with 2 EV capacity will be reduced from 329 % into 36 %. In addition, there seems to be no prospective load increase in future. Therefore, this EV capacity of the fast charging station would be suitable for this purpose. However, the installation of the fast charging station causes significant reinforcement cost and the losses increased. Therefore, the location of installation would not be the best place at DSO point of view.

The cases showed that installation of fast charging station causes different kinds of problems. In case 1, the problem was the load factor of the MV/LV transformer. In case 3, the load factor of LV cables was the problem. Whereas both the load factor of MV/LV transformer and the load factor of LV cables were the problem in case 2. However, the cases do not take into account different EV charging levels. For example, one CHAdeMO plug (Level 3), two Schuko sockets (Level 1) and one Mennekes socket (Level 2) would be a good combination for one charging station. The levels are based on the information of Table 2.7. The combination requires the active power of about 66 kW at maximum from the grid. It means that three combination chargers of this kind require the same active power than six fast chargers. Therefore, Figures 6.4, 6.5, and 6.6 can be used to analyze the effects of the combination charger. In case 2, for example, fast charger of 4 EV capacity was selected. This means that 200 kW was added into the consumption point. This is about the same amount that three combination chargers require at maximum. Therefore, the effects can be analyzed similarly.

The analysis and simulations presented in this chapter are highly theoretical and case-specific. Results presented the worst-case scenarios with the help of the powers that the chargers can feed into EVs at maximum, but in practice, there can be other problems as well. Possible practical challenges can be overheat of charging cables and current distortion.

7 CONCLUSIONS

The number of EVs is increasing all over the world. Therefore, DSOs have to be prepared for a fully new load type. An EV can be considered as a mobile load, but it also provides possibilities for a demand response.

From the DSO point of view, the most important part of EV is the battery and the BMS of the battery, because they decide the power that can be charged into the EV. In this study, three different power profiles of fast charging were distinguished due to different types of EVs as well as different battery conditions. Nissan Leaf required the higher current and voltage rates during the charge. Whereas the current profile of Mitsubishi i-MiEV type EVs was highly dependent on the battery conditions. When the battery was not warm enough as well as other battery conditions were not able to receive maximum charging current, the current was limited into about 52 Amperes. On the contrary, the charging current reached the maximum value of the different fast chargers when the battery conditions were between certain values. The average power profiles of different power profiles are shown in Figure 7.1. In the figure, the profile 1 is the average value of second charging period of Epyon and the first and second charging period of Circutor. Similarly, the profile 3 is the average value of the third and fourth charging period of Epyon and the third and fourth charging period of Circutor. The first charging period of Epyon was not presented in the figure, because it was significantly different from the profiles presented in the figure. It started like profile 1 and after about 8 minutes the charging power changed to follow the charging profile 2.

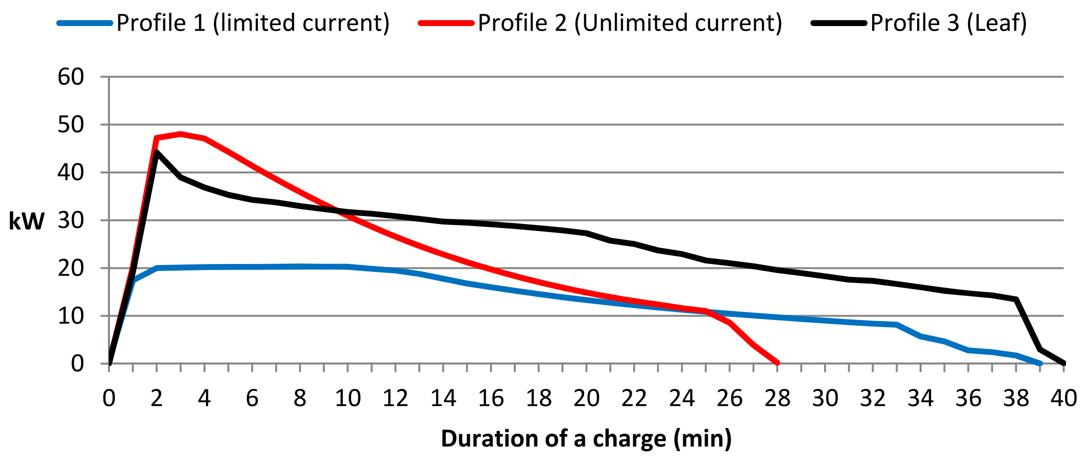

Figure 7.1. *Three different active power profiles occurred in the fast charging days.*

The fast chargers that were used in this study have very similar input and output parameters. Therefore, the EV fast charging grid impacts were similar as well. During the fast charging days, neither charger did affect conditions that would not be standard EN 50160 accordant. In fact, the power quality was high during the days. This is because the grid where the fast charging stations are located has a very high short-circuit power. Therefore, fast charging did not have a huge impact on frequency and it did not affect problematic voltage variations. However, both chargers had different current waveforms and the current was highly distorted. The separation occurred due to different power converter structures. Another difference between the chargers occurred when the reactive power of the fast chargers was analyzed. The charger of Circutor consumed reactive power, whereas the charger of Epyon produced reactive power. DSOs have to consider this when planning the installation of fast charging stations.

The grid impacts of EV fast charging is highly dependent on the connection point, grid structure and required power. In the study, three different conceivable locations of fast charging stations are introduced. It seems that installing fast charging stations into MV network, do not affect problems although the losses will increase. However, when a fast charging station is installed into LV network, different kinds of problems occurred. It seemed that the LV networks have to be reinforced if new fast charging stations are wanted to install. This causes costs for DSOs.

The energy cost during fast charging is dependent from the power profile and the effective battery capacity of an EV that is charged at DSO point of view. According to this study, the energy loss was about 1 kWh during the charging periods, which affects about 0.034 € cost for the DSO. In addition, when the load factor of the grid components increased during the charging periods, the grid losses increased as well. In the examined cases, the MV/LV transformer losses increased 0.7 kW or 0.8 kW per EV when the fast charging station was installed into LV network, but when the station was installed into MV network, the MV/LV transformer losses increased only 0.2 kW per EV. In addition, the dissipation cost of primary substation seemed to be higher when the station was installed into MV network. Therefore, installing the fast charging station into MV network seemed to be the cheaper and easier choice in DSO perspective.

7.1 Further research

Many topics and issues for future works arose during this study. The simulations and loss calculations contain a lot of uncertainty. Therefore, a load curve that contains the information about relative powers and time of use would help to analyze the grid impacts in a more accurate way. The accurate load curve would give better simulation as well as loss calculation results, which would be useful information for DSOs.

The grid where the fast charging stations were measured has very high short-circuit power. Therefore, the grid impacts were minimal. However, the situation can be different if a grid with lower short-circuit power will be researched. In addition, the grid impacts during a network fault were not examined and the relation of battery temperature and charging current would give useful information for DSOs and for EV owners. This thesis will give good base information for these future works.

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APPENDIX

APPENDIX 1 - SUMMARY OF PUBLISHED PRESENT, PROJECTED AND TARGETED COST TARGETS FOR HIGH ENERGY EV BATTERIES

Source	Price (€/kWh)	When	Comment
Recent price data			
EUROBAT (2005)	700 - 1500	2005	
Challenge Bibendum battery round Table (2207)	702 - 1545 (1)	2007	
Future price projection			
EUROBAT (2005)	200 (1)	2020	at end of 15 year research program; 100k production volume/a; 30 kWh battery
ANL (200)	176 (1)	Future	
IEA (2005)	190 (1)	Future	Data taken from EPRI 2003
EPRI (2005)	197 (1)	Future	100k production volume/a; 30 kWh battery
CARB (2007)	169 - 197 (1)	Future	100k production volume/a; 25 kWh battery
ABB (SAB Input)	211 - 351 (1)	Unknown	
Renault (SAB Input)	400 (1)	Unknown	10k € for 25 kWh, maximum values for Li-Ion batteries
Long-term target			
USABC	70 (1)	Long-tem target	25k production volume/a; 40 kWh battery

Data taken from: EUROBAT (2005)-Battery Systems for Electric Energy Storage Issues, July 2005; Shanghai Challenge Bibendum, Round Table 2, Batteries and Supercapacitors, November 2007; ANL (200)-Costs of Lithium-Ion Batteries for Vehicles, L.Gaines et. al, ANL, May 2000; IEA (2005)-Prospects for Hydrogen and Fuel Cells, D. Gielen et. al, IEA, 2005; EPRI (2005)-Batteries for Electric drive vehicles-Status 2005, M. Duvall et. al., CARB, April 2007; USABC-Goal for Advanced Batteries for EVs.
(1) Prices have converted from dollar to euro at the rate 0.702411 of exchange.

[12]

APPENDIX 2 - FAST CHARGING DAY

2A - Timetable of the fast charging day (30.11.2011)

<table>
<tr><th>Time</th><th>Peugeot</th><th>Mitsubishi</th><th>Peugeot</th><th>Citroen</th></tr>
<tr><td>8:00-8:30</td><td></td><td></td><td></td><td></td></tr>
<tr><td>8:30-9:00</td><td></td><td></td><td></td><td></td></tr>
<tr><td>9:00-9:30</td><td></td><td></td><td></td><td></td></tr>
<tr><td>9:30-10:00</td><td></td><td></td><td></td><td></td></tr>
<tr><td>10:00-10:30</td><td>Epyon</td><td></td><td></td><td></td></tr>
<tr><td>10:30-11:00</td><td rowspan="5">DRIVE</td><td>Epyon</td><td></td><td></td></tr>
<tr><td>11:00-11:30</td><td rowspan="5">DRIVE</td><td>Circutor</td><td></td></tr>
<tr><td>11:30-12:00</td><td rowspan="5">DRIVE</td><td>Circutor</td></tr>
<tr><td>12:00-12:30</td><td rowspan="5">DRIVE</td></tr>
<tr><td>12:30-13:00</td></tr>
<tr><td>13:00-13:30</td><td></td></tr>
<tr><td>13:30-14:00</td><td></td><td></td></tr>
<tr><td>14:00-14:30</td><td colspan="2">Both chargers</td><td></td></tr>
<tr><td>14:30-15:00</td><td></td><td></td><td colspan="2">Both chargers</td></tr>
<tr><td>15:00-15:30</td><td></td><td></td><td></td><td></td></tr>
<tr><td>15:30-16:00</td><td></td><td></td><td></td><td></td></tr>
</table>

2B - Record of the fast charging day

Minutes of measuring days

Wednesday 30.11.2011:

Epion

Time when started: 10:43, **EV**: Peugeot i-ON, **SOC**: 14 km (%)
Time when ended: 11:12, **SOC:** 79 km (%)

Time when started: 11:23, **EV**: Mitsubishi i-MiEV, **SOC**: 13 km (%)
Time when ended: 11:58, **SOC:** 76 km (%)

Circutor

Time when started: 12:17, **EV**: Peugeot i-ON, **SOC**: 17 km (32.7 %)
Time when ended: 12:52, **SOC:** 73 km (79.5 %)

Time when started: 12:58, **EV**: Citroen C-Zero , **SOC**: 17 km (26.9 %)
Time when ended: 13:36, **SOC:** 50 km (76.9 %)

Both chargers (Epion & Circutor)

Time when started: 14:15, **EVs**: Mitsubishi i-MiEV (Epion), **SOC**: 1 km (10 %)
Peugeot i-ON (Circutor), **SOC**: 7 km (17.9 %)
Time when ended: 14:45, Mitsubishi i-MiEV (Epion), **SOC**: 79 km (82 %)
Peugeot i-ON (Circutor), **SOC**: 66 km (%)

Time when started: 14:52, **EVs**: Peugeot i-ON (Epion), **SOC**: 4 km (14 %)
Citroen C-Zero (Circutor), **SOC**: 8 km (18.6 %)
Time when ended: 15:18, Peugeot i-ON (Epion), **SOC**: 70 km (82 %)
Citroen C-Zero (Circutor), **SOC**: 67 km (%)

Monday 5.12.2011:

Circutor

Time when started: 14:36, **EV**: Nissan Leaf, **SOC**: 20 km (19.1 %)
Time when ended: 15:14, **SOC:** 90 km (89.5 %)

2C - The measured quantities and the used current probes during the fast charging days

Table 1. *The measured quantities and the used current probes with the charger of Circutor.*

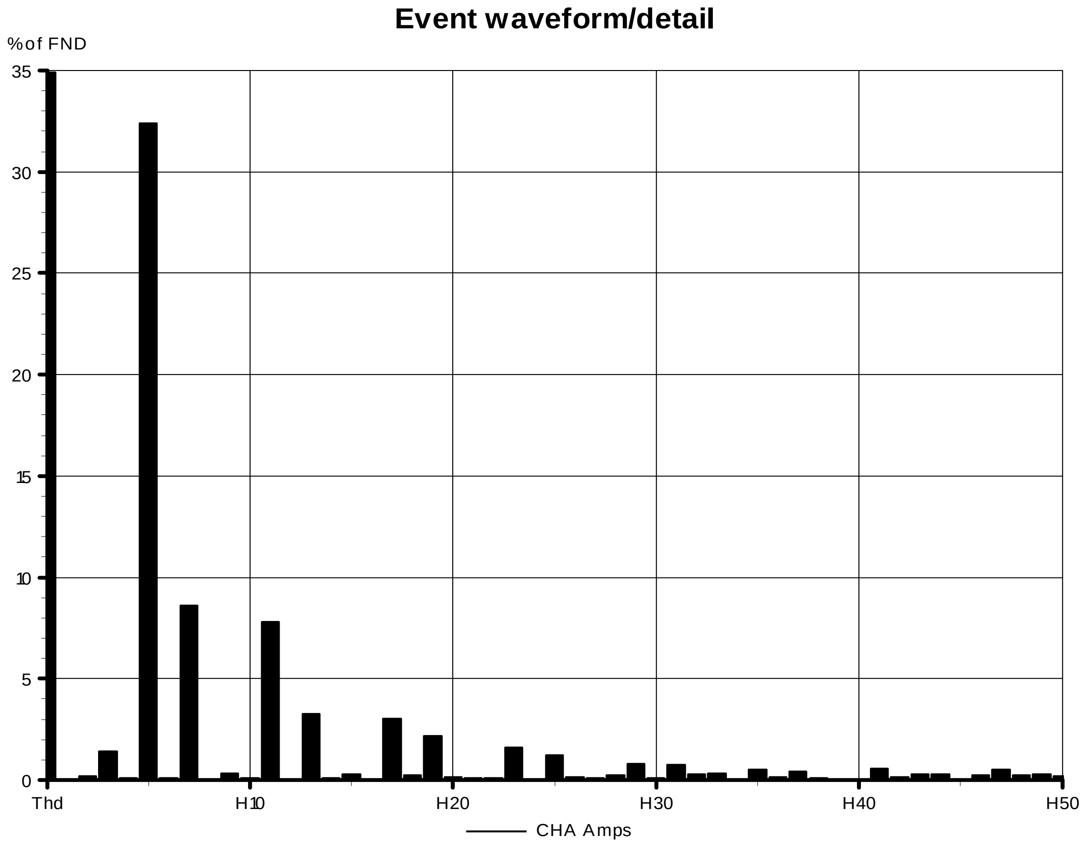
Channel	Measured quantity	Probe
AV	Phase-to-earth voltage U_{L1}	Connected straight to the voltage channel input A
BV	Phase-to-earth voltage U_{L2}	Connected straight to the voltage channel input B
CV	Phase-to-earth voltage U_{L3}	Connected straight to the voltage channel input C
DV	DC-side voltage U_{DC}	Connected straight to the voltage channel input D
AI	AC-side phase current I_{L1}	Fluke i1000s clamp on AC current probe, range 100 A
BI	AC-side phase current I_{L2}	Fluke i1000s clamp on AC current probe, range 100 A
CI	AC-side phase current I_{L3}	Fluke i1000s clamp on AC current probe, range 100 A
DI	DC-side current I_{DC}	Tektronix AC/DC current probe TCP303 and current probe amplifier TCPA300 (50 A/V)

Table 2. *The measured quantities and the used current probes with the charger of Epyon.*

Channel	Measured quantity	Probe
AV	Phase-to-earth voltage U_{L1}	Connected straight to the voltage channel input A
BV	Phase-to-earth voltage U_{L2}	Connected straight to the voltage channel input B
CV	Phase-to-earth voltage U_{L3}	Connected straight to the voltage channel input C
DV	DC-side voltage U_{DC}	Connected straight to the voltage channel input D
AI	AC-side phase current I_{L1}	Fluke i200s clamp on AC current probe, range 200 A
BI	AC-side phase current I_{L2}	Fluke i200s clamp on AC current probe, range 200 A
CI	AC-side phase current I_{L3}	Fluke i200s clamp on AC current probe, range 200 A
DI	DC-side current I_{DC}	Tektronix AC/DC current probe TCP303 and current probe amplifier TCPA300 (50 A/V)

APPENDIX 3 - CURRENT HARMONICS

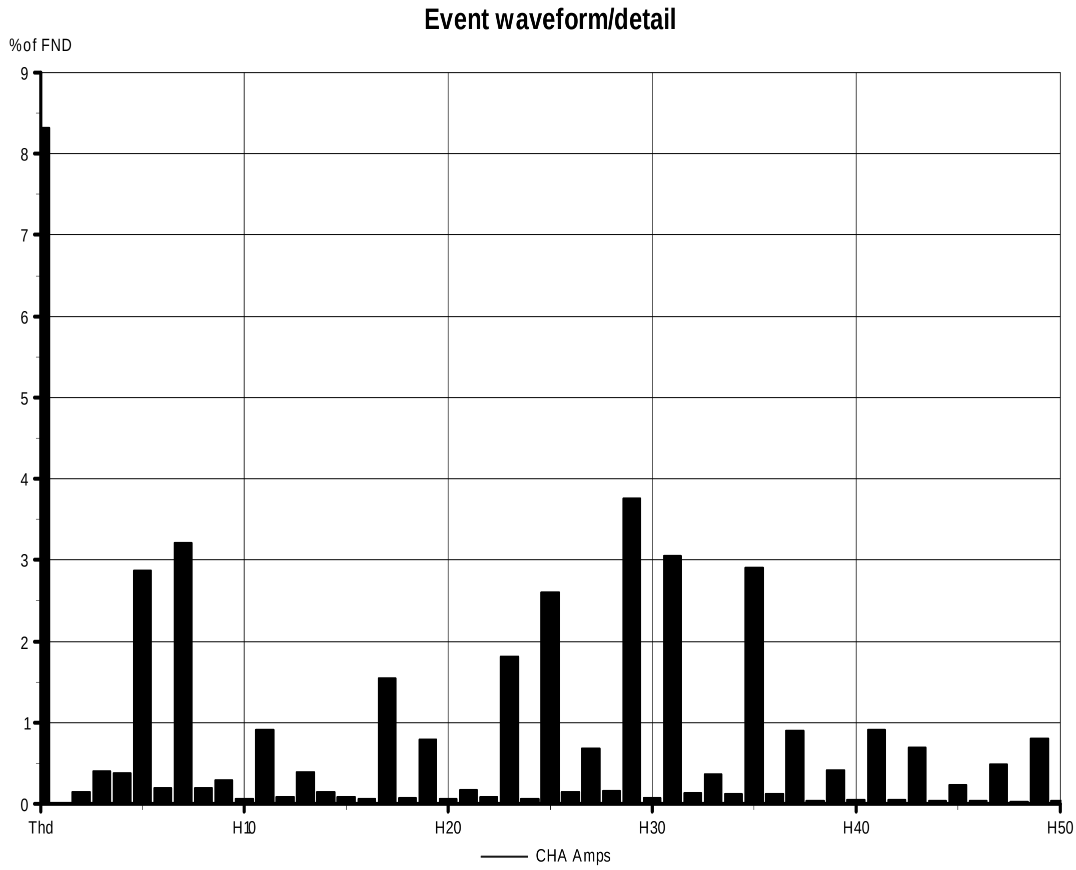
3A - Distribution of current harmonics in case Circutor during maximum charging current



Total RMS: 76.99 Amps
DC Level : -0.12 Amps
Fundamental(H1) RMS: 72.61 Amps
Total Harmonic Distortion (H02-H50): 34.91 % of FND
Even contribution (H02-H50): 0.75 % of FND
Odd contribution (H03-H49): 34.90 % of FND

Timed at 30.11.2011 14:16:59

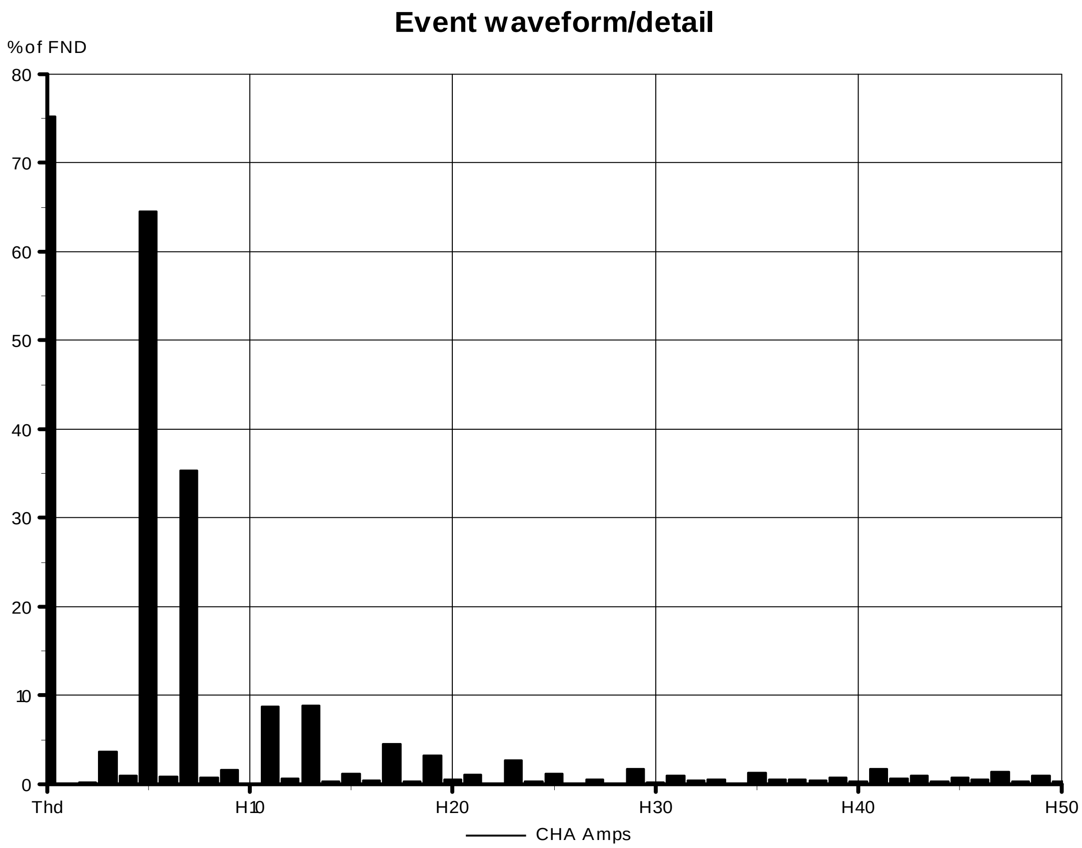
3B - Distribution of current harmonics in case Epyon during maximum charging current



Total RMS: 69.30 Amps
DC Level : -0.00 Amps
Fundamental(H1) RMS: 69.04 Amps
Total Harmonic Distortion (H02-H50): 8.33 % of FND
Even contribution (H02-H50): 0.65 % of FND
Odd contribution (H03-H49): 8.30 % of FND

Timed at 30.11.2011 14:17:59

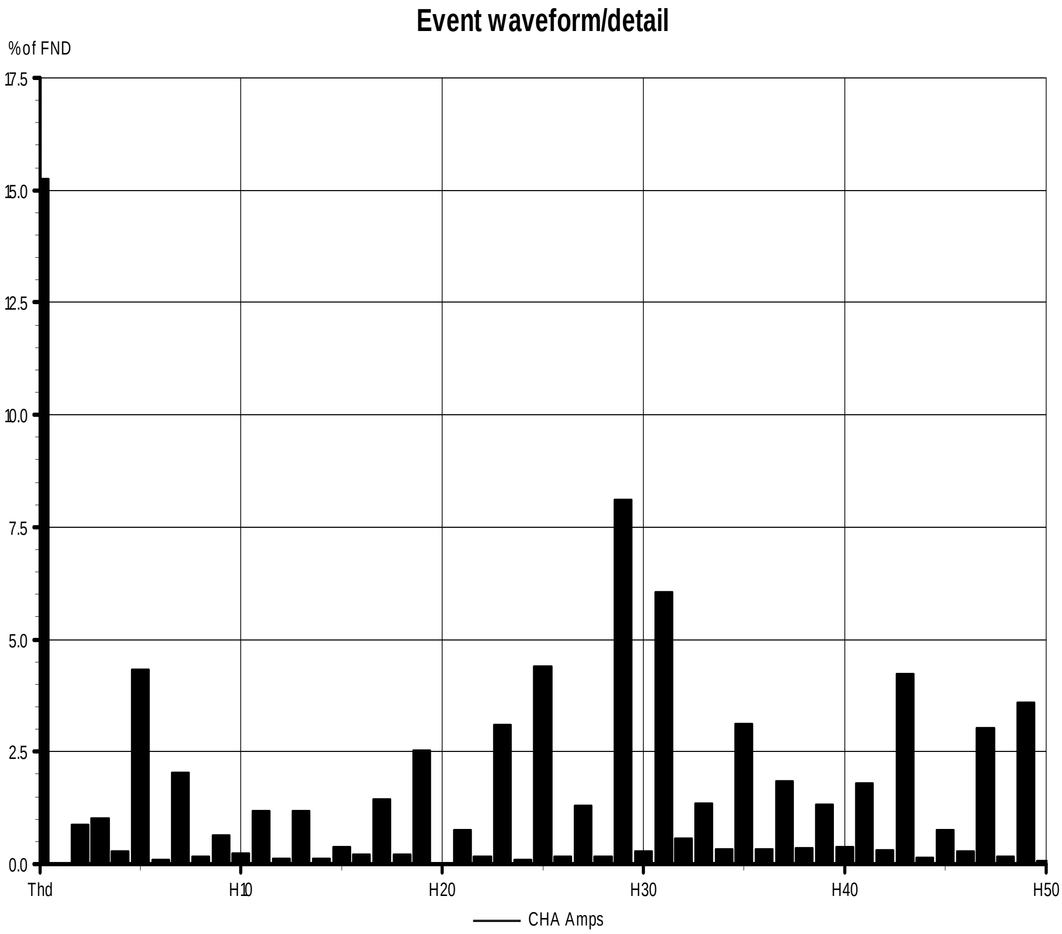
3C - Distribution of current harmonics in case Circutor during minimum charging current



Total RMS: 17.39 Amps
DC Level : 0.06 Amps
Fundamental(H1) RMS: 13.77 Amps
Total Harmonic Distortion (H02-H50): 75.21 % of FND
Even contribution (H02-H50): 2.30 % of FND
Odd contribution (H03-H49): 75.17 % of FND

Timed at 30.11.2011 14:39:59

3D - Distribution of current harmonics in case Epyon during minimum charging current

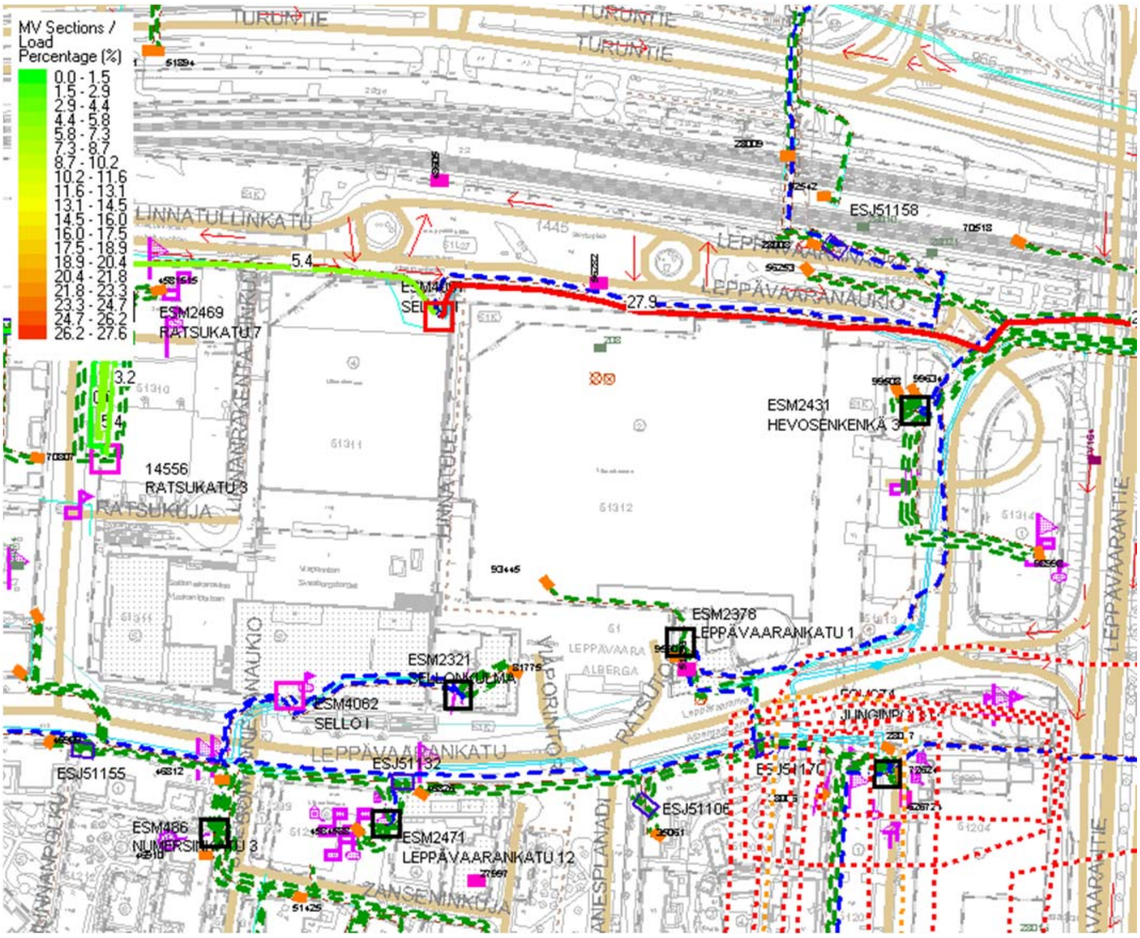


Total RMS: 18.34 Amps
DC Level : -0.01 Amps
Fundamental(H1) RMS: 18.09 Amps
Total Harmonic Distortion (H02-H50): 15.26 % of FND
Even contribution (H02-H50): 1.51 % of FND
Odd contribution (H03-H49): 15.18 % of FND

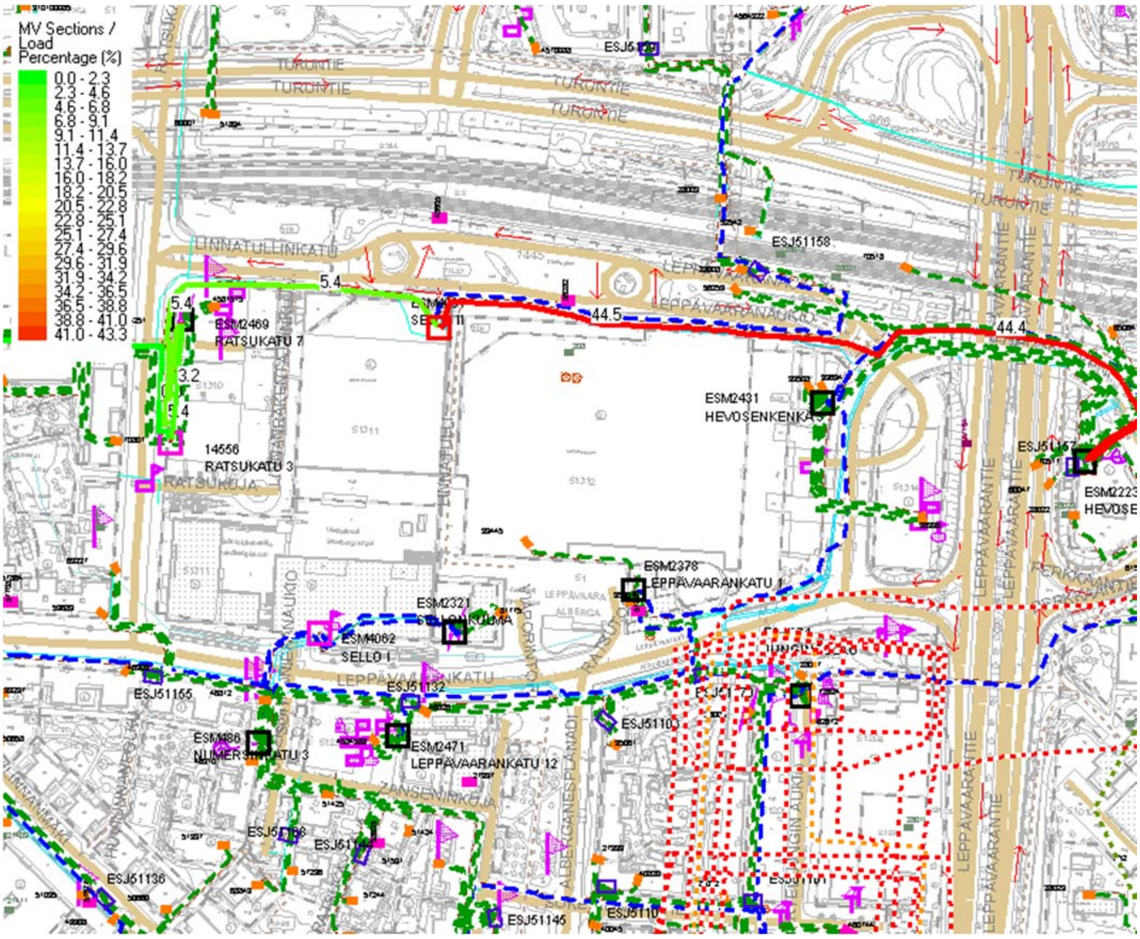
Timed at 30.11.2011 14:37:59

APPENDIX 4 - LOAD FACTORS OF THE CASES

4A - Load factor of MV cables of case 1 without EVs connected



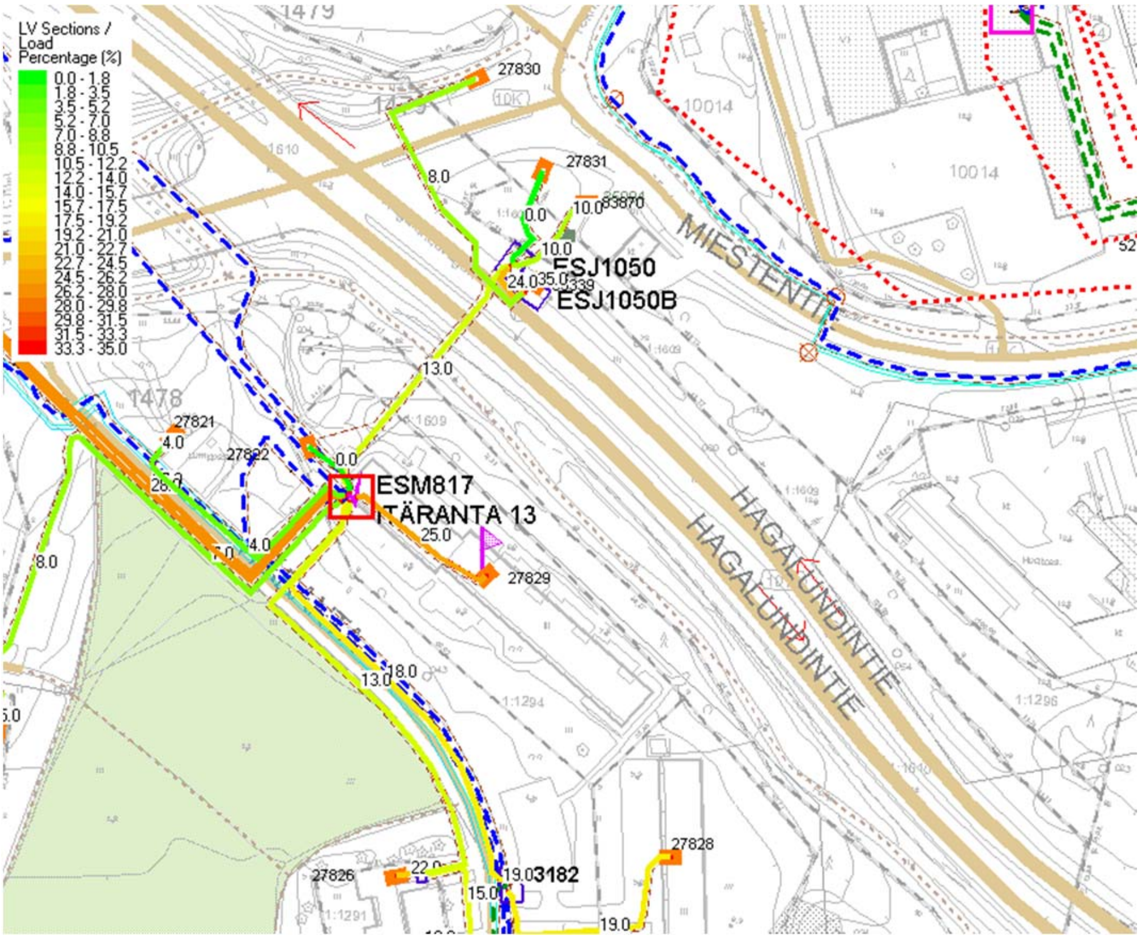
4B - Load factor of MV cables of case 1 with 40 EVs connected



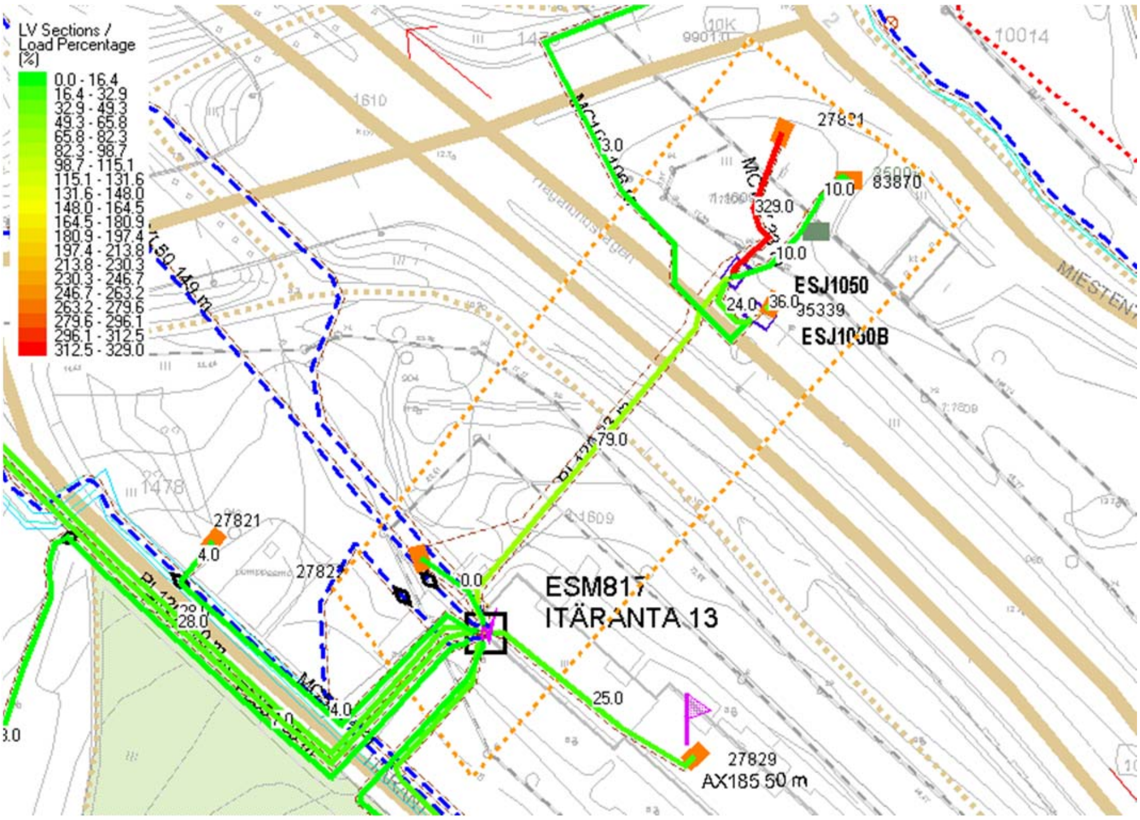
4C - Load factor of LV lines of case 2 without EVs connected

4D - Load factor of LV lines of case 2 with 4 EVs connected

4E - Load factor of LV lines of case 3 without EVs connected



4F - Load factor of LV lines of case 3 with 2 EVs connected



4G - Load factor of LV cables of case 3 with 2 EVs connected in reinforced grid