Smart charging of Electric vehicles for hosting capacity enhancement of Solar PVs in residential grids

Aleksander Lebiedziński

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MASTER THESIS

STUDENT REPORT
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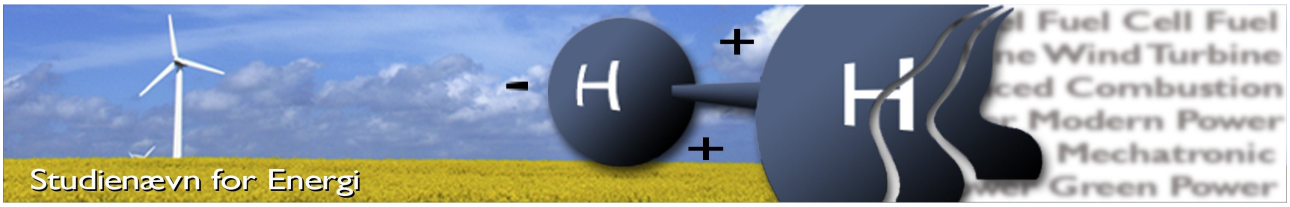

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Aleksander Lebiedziński

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Synopsis

With the targets of decreasing the emission of CO2 established by EU the implementation and investigation electric vehicle into the residential network is crucial. Integration of the PV units as well as EVs, while maintaining stability in the grid is an important issue. The additional task is to optimize the cost of EV charging and increase the hosting capacity in the grid. Therefore, in this work various cases were investigated to present the impact of PV and Ev integration as well as develop a balanced charging scheme which allow to enhance the PV self consumption. These studies help in understanding the effect and complexity of integrating renewable sources and charging stations in a LV network.

Preface

This report is created as a master's thesis during the 4th semester for High Voltage and Power System Engineering at Aalborg University. The project focuses on integration of the PV systems and EV charging stations into a residential network while smart charging the EVs ato minimize the cost and increase the hosting capacity of the considered grid. These components are implemented into a model and investigated through simulation in MATLAB. The project was made under the supervision of Jayakrishnan Radhakrishna Pillai from Aalborg University.

Readers' Guide

References are specified with the Vancouver method as [number, page]. The bibliography is at the end of the report, where books are denoted "author, title, publisher, edition, year of publication and ISBN". Websites are denoted "author, title, URL, edition, year of publication and last visited in dd/mm/yy", when applicable. Technical reports are denoted "author, title, publisher and year". Additionally, the placement of the references determine which part of the text it refers to, as illustrated:

[**?** , p. 1].	*Before period*	Refers to the sentence.
. [**?** , p. 1]	*After period*	Refers to the paragraph.

When referring to figures and tables they are denoted with the number of the chapter and figure/table number. E.g. figure 3 in chapter 2 will be referred to as "Fig. 2.3". The figure and table number is written below the given figure and table.

Nomenclature

Symbols

Symbol	Name	Unit
Tr	Transformer	-
I	Current	[A]
R	Resistance	[Ω]
Q	Reactive Power	[Var]
P	Active Power	[W]
S	Apparent Power	[VA]
X	Reactance	[Ω]

Abbreviations

Abbreviation	Definition
CS	Charging stations
PV	photovoltaic panels
EV	Electrical vehicle
EU	European union
SPV	SOLAR PHOTOVOLTAIC
DSO	Distributed System Operators
DR	Demand response
PEV	Plug-in Electric Vehicle
QDSL	Quasi dynamic simulation
ESS	Energy storage system
HL	High level
LL	Low level
DER	Distributed Energy Resources
TSO	Tansmission system operator
FCEV	Fuell Cell Electric Vehicle
HEV	Hybrid Electric Vehicle

TOD	Time of Day
RTP	Real time pricing

Table of Contents

1 Introduction

Electric vehicles (EVs) could play an important role in reducing petroleum use and while the electrification of transportation appears opportunity to switch to renewable energy sources like PV system could happen. With the increased implementation of EVs and PVs power quality issues in the power system can occur, especially on the low voltage side. However, installing EV chargers and development of forecasting the PV system generation could help rise the number of installed both EV and PV units in the residential grid and increase the flexibility in the power system.

This project investigates different strategies to charge the electric vehicle and by this enhance the hosting capacity of PV system in a residential LV network. The PVs hosting capacity is defined as the maximum capacity that can be installed in the network without disregarding grid constraints. These constraints are based on power quality indicators such as voltage magnitude or maximum loading of the network components. In the first chapter the background on which this project is based is presented. The list of tasks to achieve the main objective and then the limitation of this work as well as the methodology are introduced. Lastly, the outline section, where the content of each chapter of this project is defined.

1.1 Background

Power generation and transportation sectors are directly connected to some of the serious issues of this decade: climate change and dependency of oil. The 60% of global primary energy demand is from electricity generation and transportation. Majority of the world's coal demand is for electricity generation and a majority of the world's oil demand is for transportation[1].

Development of electric vehicles (EVs) may limit transportation related CO2 emissions and reduce the world's dependence on oil. Also the use of renewable energy sources could scale down fossil fuel based electricity generation while reducing greenhouse gas emissions. Hence, the integration by combination of EVs and renewable energy into the distribution grid offers the potential to significantly reduce the world's dependence on fossil fuels and the consequent emission of greenhouse gases[2].

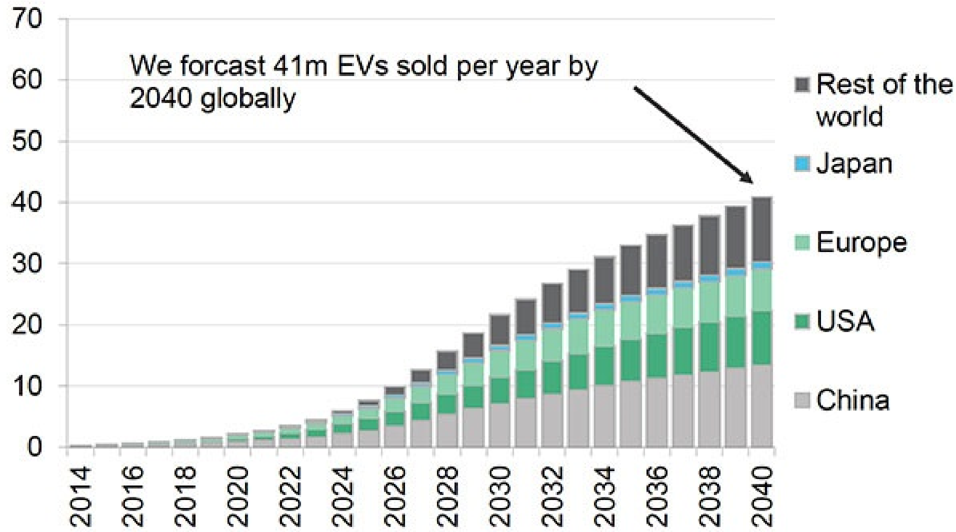

Figure 1.1: Global EV sales forecast[3]

In Fig. 1.1 the prediction of global EV sales graph is presented. As the forecast is showing the number of sold electric vehicles could drastically rise. For example in year 2040 the biggest demand for EVs will be in China and globally the number of sold cars could reach approximately 41 millions. This prediction indicates that in future there will be a higher demand for electricity to cover the needs for EVs. Additionally, as technology improves and more cars are sold, the cost of batteries will decrease. Finally, electric vehicles could become cheaper than conventional vehicles between 2020 and 2030 [3]. Compared to the conventional cars the EVs provide benefits such as reduction of CO2 and noise emission, better reliability due to the reduced number of mechanical components, independence from oil availability and price fluctuations [4]. However, with the electrification of private transportation the generation sector must be reconsidered as well. Charging the EV from fossil fuel power plants electricity could solve some problems but not all of them. Despite decrease air pollution in big cities the global impact is negligible [4]. Therefore the share of electricity produced by Renewable Energy Sources (RES) must increase. One of technology able to significantly impact the global reduction of CO2 and uses the renewable source of energy is Solar Photovoltaics (SPV).

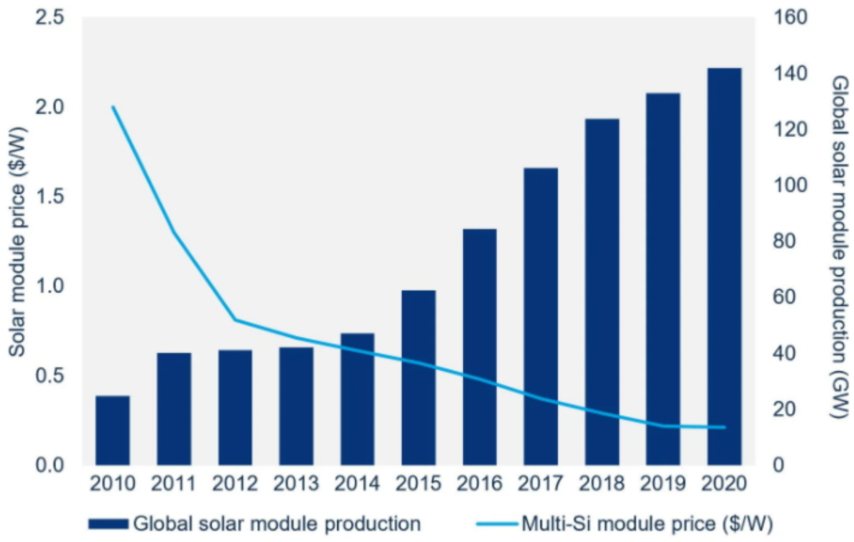

Figure 1.2: Global PV production and price [5]

Fig. 1.2 the global solar module production along with module price is shown. From this graph the trend in solar panels production can be seen and it shows that from 2011 till 2020 there was a significant growth of production with a serious decrease of price for each module. The production in 2012 was slightly above 40 GW to rise till 140 GW in 2020. Meanwhile the installed capacity was increasing the price declined from 1$ per Watt to almost 0,02$ for every generated Watt in 2020[5].

One of the future challenge is to ensure high power quality while utilizing an partially unpredictable renewable energy source. The integration of electric vehicles and solar panels into LV system is restricted by the occurrence of grid bottlenecks [6]. Therefore, better coordination between load consumption and RES production is necessary, in order to reduce the need for investments in reinforcing the power grid infrastructure.

High penetration of distribution generations such as PV units can introduce power quality issues to the LV network. Distribution grids were constructed for a one way power flow operation only. However by implementing a PV unit into the power system and when PV generation exceeds the local total demand a reverse power flow could appear. This could results in overvoltages along the LV feeders and overloading the network apparatus such as cables and transformers. Since large currents changes take places during the connection and disconnection of generation the transients could impact the power quality in the grid [6]. Another issue could happen when the PV system is connected to single phase of the grid and voltage phase unbalance can occur [7]. As it can be seen many challenges must be overcome to utilize a PV unit. Therefore, the assessment of power quality levels is an important topic in the field of studies referring to modern distribution networks [6]. Referring to [8] the EV loads introduce integration issues to the LV grid as well. Since most of the charging activities are appearing in the residential grid the load will rise significantly for which the distribution grid was not designed. Unplanned Increase of demand during a peak time during day can lead to undervoltage and overloading which could results overheating cables and transformers. Although implementing EV chargers into the residential grid can cause many issues there are some advantages too. For instance by a smart charging the voltage can be regulated during the peak demand and overoltages caused by higher number of PV units in the grid [9].

The impact of EV in the grid is significant therefore hosting capacity must be introduced. By definition [10] "hosting capacity is the amount of new production or consumption that can be connected to the grid without endangering the reliability or voltage quality for other customers.". The increase number of Pv units is a challenge for DSO therefore, understanding the hosting capacity of a feeder can play a significant role to help the DSO to make decisions for PV interconnection requests and ensure reliably operation of the distribution grid [11]. This project aims to maximize the PV hosting capacity while implementing the EV into the residential grid. The integration must guarantee high power quality standards while limiting the reinforcement or upgrading of the power grid infrastructure.

1.2 Objectives

The purpose of this project is to develop a suitable EVs charging control for a residential electric distribution network with different penetration of solar panels and electric vehicles. The control scheme is focused on increasing the self-consumption of local solar PV systems and electricity cost-savings in the neighbourhood, and takes into account the mitigation of any grid congestions and voltage issues. The following work objectives have been identified in order to answer main objective, and they are listed below:

1. *State-of-the-art of distribution grid impact of increased penetration of EVs and SPVs.*
2. *Investigate EV driving patterns and study various charging strategies of EVs integrated into residential networks. Select and Apply suitable demand-side participation schemes to optimize charging and economic benefits from controlled EV charging.*
3. *Modeling of low voltage distribution grids and flexible assets like electrical vehicle.*
4. *Develop smart charging control and coordination schemes to utilize maximum electricity generation from solar panels and utilize flexible operation of EVs.*
5. *Apply sensitivity and statistical analysis to understand and provide recommendation on the impacts of smart control and integration of flexible demand units like EVs to increase the hosting capacity of local renewable units.*

1.3 Methodology

1. *Analysis of demand and generation data of a residential system.*
2. *Evaluating the PV hosting capacity in the existing system.*
3. *Smart control algorithm for EVs depending on the tariffs to utilize maximum power from solar panels.*
4. *Integration of EVs chargers and solar panels into the residential network and conducting simulations using MATLAB to determine eventual bottlenecks in the grid.*

1.4 Limitations

Limitations and assumptions are considered in this project. The list of simplifications are shown below:

- The considered grid has radial structure. Other configurations are not taken into account
- The analysis is limited to the LV side of the network
- Only balanced system is considered
- It was assumed that every house has a PV unit as well as own an electric vehicle. For the all of the PV units parameters such as tilt and orientation angle are not investigated, therefore all have the same generation profile
- Three types of EVs with different battery capacity are considered. However the chemistry of the EV batteries and the effects of temperature and discharge rate on their lifetime are not considered
- Power quality issues such as harmonics, unbalances, flicker etc. are not considered in this work

1.5 Outline of the report

- Chapter 1 - Introduction

  This chapter consist an introduction where the background on which the whole project is based is described. Additionally the objectives, limitations and followed methodology are demonstrated.
- Chapter 2 - State of Art

  In this second chapter the theoretical background on which this work is based is presented. An overview of distribution grids is presented, with a focus of structure of distribution network and typical loads. Secondly, the PV technology is discussed and its integration issues into the grid. The hosting capacity as well as the power quality indicators are explained. In the end of this chapter Electric Vehicle technology is presented, where the integration issues in LV networks and the EV driving patterns are described and also the operation costs are included in this investigation.

- Chapter 3 - Residential network

  In this chapter the considered model of a residential LV network is introduced. At first the included components are modelled and analyzed. Next point is to analysis the provided data for household and PV generation. In the end, the model is tested, through a simple power flow analysis conducted in POWERFACTORY.

- Chapter 4 - PV integration in residential grid

  This chapter is introducing PV system into the considered grid. Integration of PV units with the evaluation of the grid hosting capacity is presented. The reason of implementing an deferrable load is investigated.

- Chapter 5 - Integration and smart charging the EVs in the LV network

  In this chapter the EVs are integrated while minimizing the electricity cost and increase the hosting capacity in a residential grid by conducting simulations in MATLAB for different scenarios. The algorithm to determine the lowest price, obtain the EVs load profile as well as calculate the hosting capacity of the grid is utilized. In results the impact of the EVs integration and PV hosting capacity could be investigated and discussed.

- Chapter 6 - Conclusions and Future Work

  In this final chapter the summary with results of the simulations of the whole project is presented. The advantages and drawbacks for integration of EVs and PVs in LV distribution grids are discussed and analyzed. In the end, possible future works are presented.

2 Challenges and solutions for grid integration of electric vehicles and solar panels

This chapter describes the state-of-art of this work. First section presents the structure and operation of a residential network with a focus on the issues caused by increase implementation of PV units. Following a description of connected load and generation elements into the LV distribution grid has been shown. In the end, the EV as a flexible load in the residential power system as well as its limits are presented.

2.1 Distribution Grid

In this section an overview of distribution grids is presented. followed by more specific description of a radial network. Further, the transition of low voltage grid is introduced with the benefits and challenges to use the green electricity.

2.1.1 Structure of a distribution network

The main aim of the electricity supply system is to meet the customer's demand for energy with quality power supply while giving the most overall economic selling cost [12]. To provided electricity to the consumer the power system must consist in three subsystem:generation, transmission and a distribution [13]. The transmission system is utilized to transfer the large amount of electricity from the generation plant to the main load areas. While the distribution system is supplying the furthest customers with energy at the appropriate voltage level [12]. The primary distribution system is usually providing energy to the industrial customers. Whereas the secondary distribution network reduces the voltage and the commercial or residential customers are supplied with electric supply [14].

Fig. 2.1 describe a typical scheme of electrical power system with the voltage ranges for each level. The HV network is supplied by the EHV/HV substation which are supplied by the EHV lines. The EHV transmission lines can reach the voltage above 300 kV, while the HV networks voltage vary between 36-300 kV. The HV/MV substations is decreasing the voltage to the range of 1-36 KV. The MV network can supply directly the large industrial consumers but the vast majority of consumer are connected to the LV network. The low voltage network is connected to the MV/LV substation where the voltage is set below 1kV [12]. Most of the RES components are installed and connected to the distribution network. Large wind turbines and solar power plants are generally associate to the MV level. Whereas units with smaller rated capacity including installed PV system, are connected to the LV level [15].

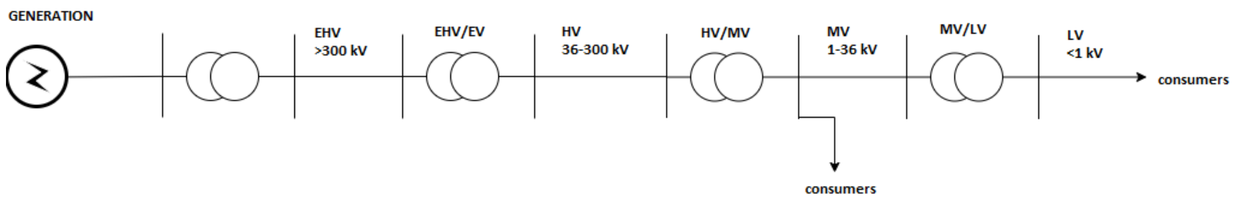

Figure 2.1: Typical electrical power grid scheme [12]

The most common configuration for the residential network is the radial topology. This type of structure is a system or part of a system consisting of single feeders supplied from a single source of supply [16].

In the Fig. 2.2 a typical radial topology for a residential network has been shown. The MV grid is supplying the LV network through the transformer to the primary main feeders and then the energy is provided directly to the customers. This configuration is the most common one because its advantages are simplicity and low cost. However the reliability of continuity of service for the radial type is low because in a case of fault occurrence at any location on the primary main feeder will results an outage a every feeder supplying the customers [13]. Moreover due to the high impedance of the conductors used in LV network significant voltage changes can occur. During a high demand or power generation from RES the voltage can vary [17].

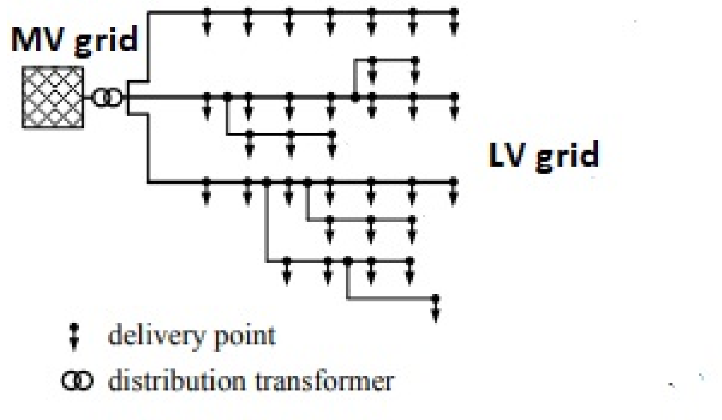

Figure 2.2: Radial topology of a residential network [16]

Fig. 2.3 represents the voltage drop in a single three phase AC line depending on the X/R ratio. According to the equation the P and Q are active and reactive power respectively, R is the line resistance, X is the line reactance and V is the line voltage. Comparing to the HV network in the LV system due to the lower X/R ratio the resistance is no longer negligible. It means that the active power has a greater influence than the reactive power on the voltage magnitude. Therefore, with a high resistance in the LV network will cause a significant voltage drop [17]. Additionally, the high share of renewable generation units such as solar panels in the distribution system can results in a reverse power flow in the feeders and it could lead to a voltage rise where the voltage could go above the allowed +/-5% limits [18].

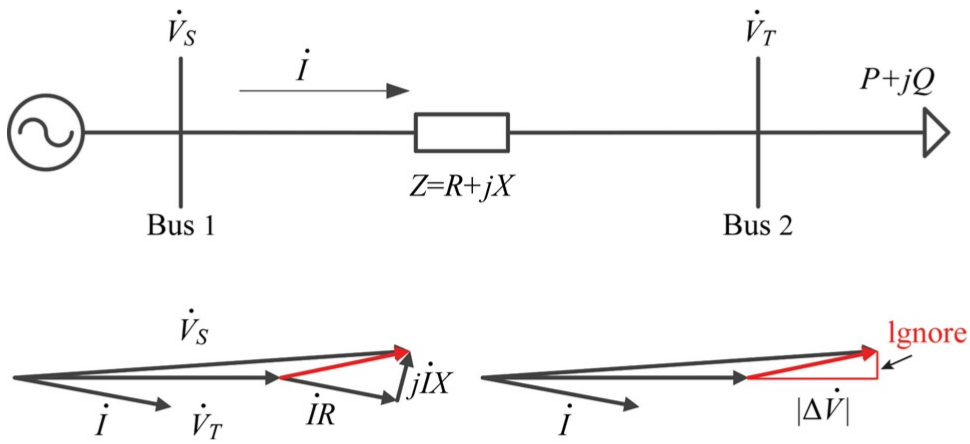

Figure 2.3: Voltage drop for a single line due to X/R ratio [17]

$$\Delta V \cong \frac{RP + XQ}{V} \tag{2.1}$$

2.1.2 Low Voltage grid transition

In this section of this chapter the transition of a low voltage grid is presented. The conventional concept of the power grid must be adjusted to provide a sustainable integration of RES into the distribution grid. To achieve that a new concept called active distribution grid was developed to integrate the components maintaining the reliability, quality and security of supply of the system. Active distribution grid is a network, where more DGs and loads are getting integrated compared to the old conventional distribution grids, where such units were minimal or not present [19].

However with the further penetration of RES and transition the conventional grid many challenges occurs. Challenges such as power quality, protection and voltage regulation can appear. Depending on the circumstances connecting RES components could either deteriorate or improve the power quality [20]. The protection challenges can appear because most of the power systems are build for unidirectional power flow but with a high share of RES components during a fault the protection relays cannot coordinate properly. Additionally, voltage regulation is a challenge because due to the not unidirectional power flow the regulation of the voltage through the feeders require a more advance strategy [21].

Another challenges are appearing when a proper active management must be applied to benefit the integration of the renewable components in the distribution network. The profits in developing such scheme of management can be greater than the installation cost. Therefore, a well designed scheme must be established and implemented by the companies. However, implementation cost of an appropriate active management scheme can put effect on the electricity price for the consumers. Another main challenge is to properly form the regulations, which are utilized to develop a strategy to ensure an uninterrupted operation of the system [21].

The conclusion is that a rapid increase of electrical consumption and penetration of distributed generation have a big impact on the expected power quality in the grid. In order to mitigate these impact and manage the interaction challenges a Smart Grid must be utilized [22].

Fig. 2.4 shows a diagram with basic elements in the smart grid control. The objective for the smart electric grid is to make interactions between elements such as charging station, household appliances or heat pumps. All elements interact between each other to make the prices more economical for the consumers. Integrated price system is sending the data when is economical profitable to use the appliances. However, the consumers may participate in grid control with a demand response [22].

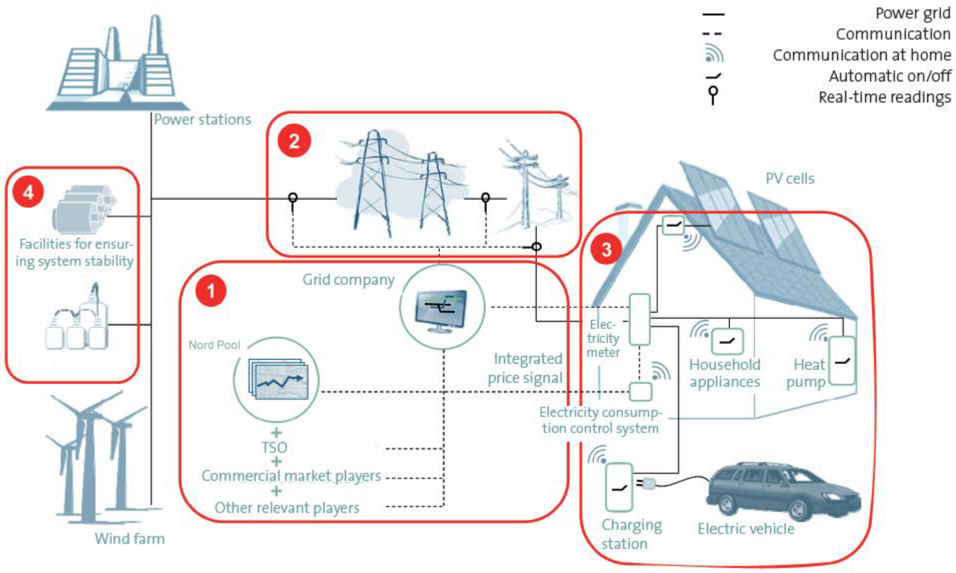

Figure 2.4: Elements of a smart grid [22]

Important element in the smart grid are the consumers and their participation. The smart grid interaction can results in exchanging information between Power Supply companies and customers. The customer have the opportunity to obtain information such as electrical energy, load curve, grid situation, maintenance plan, the new technology and product [23]. Therefore with these parameters an energy management scheme may be possible to implement. The energy management schemes are mainly based on two types, efficiency oriented and user oriented. In the efficient type the generated power and the battery status are transmitted to the energy management system and compared with the energy consumption data to obtain the most efficient way to consume the power. Alternatively a demand response (DR)which is a user oriented type energy management, can be implemented. In this case the input data to the management controller is set based on: measured energy consumption of each load, loads importance (vital, essential, and non-essential), and the status (checking) of smart meter commands from utility (utility events). This strategy is defined based on the percentage of demand response, load priority and consumer's preference, comfort level, electricity bill limitation, and battery status [24].

Residential loads can be divided to three main types:thermal loads, electric vehicles and appliances such as dishwashers, washing machines and clothes dryers. They can be easily controlled to decrease the energy consumption without affecting the comfort level of the customer. Those loads by smartly controlling their behaviour could provide cost savings along with high effectiveness. Therefore a control algorithms are necessary to change the conditions and meet operational requirements. Although these algorithm can be quite complex because they require many input signals and output actions [22]. To obtain all of the crucial data and information a smart meter must be installed. It is informing the about utility status and communicate in real time the operational between end-user and utility. This component has the capability to record consumption data, communicate with home appliances and send these information to the utility company [24].

2.2 Solar Photovoltaics

In this section the PV technology and the impact on the grid will be discussed. The issues related to a high penetration of solar panels in the distribution grid are presented. In the end, the definition of the maximum hosting capacity in a distribution network which is based on a set of power quality indicators is described.

2.2.1 PV integration issues

Three main problems prevent in a large-scale integration of PV units in the LV network: voltage rise, voltage phase unbalance and overloading of network equipments [25][26]. The voltage rise is a direct aftermath of the reverse power flow phenomena. This could occur when a low load condition meet a high PV generation in the same feeder. It is particularly relevant problem in a low voltage network because of the resistive characteristic. Hence, the active power which is generated by the PV units has a greater impact on the voltage [27][26]. The voltage rise can have damaging effects for the customer as well as grid infrastructure. Due to a long term heating caused by remaining the voltage level above the designed limit could results in destroying the electronic components [28]. Additionally with exceeding the voltage upper limit the regulations will prevent the RES component providing green energy [29]. Another problematic issue is represented by the voltage phase unbalance. The increased share of RES in the generation could result in the amplification of the unbalance [30]. The last main issue is the overloading the network equipments. If the loading is over 90% consequences could occur as higher losses and increased probability of damaging components [31][25].

2.2.2 Hosting capacity of PV system in LV grids

It becomes important to measure the maximum amount of RES generation used for the distribution power system with the desire to expand the use of RES components. Therefore, a parameter called hosting capacity was introduced. The hosting capacity of SPV is defined as ***"maximum share of PV share in power grid that can be accepted without endangering the reliability or quality of power"*** [32].

Fig. 2.5 shows a graph where the performance index can determine the hosting capacity which cannot be below the limit where unacceptable deterioration of the power system happens.

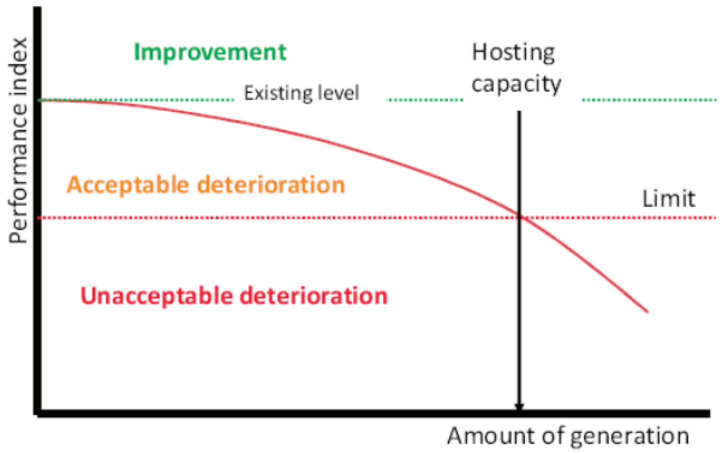

Figure 2.5: Use of performance index to determine the hosting capacity [32]

The impact of RES components on the network can be determined by performance indicators of the network components. If the limits of those parameters are defined the maximum share of PV units without violating any constraints can be calculated [32]. In the following paragraphs the indicators used to define the hosting capacity in this project are presented.

Overloading the network components

Overloading of the network components could deteriorate feeder components much faster or even damage these devices. Thus, the feeder thermal overload capacity needs to be carefully evaluated [33]. For instance the distribution transformer as well as cables cannot exceed the maximum allowed current at any time due to the possibility of insulation deterioration or damaging the equipment. This constraint can be formulated as:

$$I \leq I_{max} \tag{2.2}$$

A common practice for LV and MV installations is to check the allowable current limits in the provided by the cable manufacturer datasheet.

Voltage magnitude

Voltage rise can occur in the LV grid because of high impact of the active power due to the high R/X ratio of the conductors in a low voltage network. hence, the increased penetration of RES components can lead to a voltage variation. According to the EN 50160 regulations under normal conditions the voltage should be in the +/- 10% range. However in this project this parameter will be considered conservatively and the voltage variation limit will be set +/- 5% [34]. The requirement will be used in a way that V in any of the LV nodes of the grid must fulfill the equation:

$$V_{min} \leq V \leq V_{max} \tag{2.3}$$

Where Vmin and Vmax are summarized in the table 2.1.

Table 2.1: Voltage magnitude range determined by regulations[34]

	Single-Phase	Three-Phase
V_{rated}	230	400
V_{min}	218.15	380
V_{max}	241.15	420

2.3 Electric Vehicles

In this section, the EV as well as chargers technology has been described. Following the driving patterns of the EVs along with the integration issues are indicated. In the end, both Polish and Danish tariffs for charging the EVs are demonstrated.

2.3.1 EV and chargers technology

Vehicle which can be only plugged in to charge from an off-board electric power source is called Electric Vehicle (EV). This definition can be used for road vehicles, rail vehicles, electric boats or electric aircraft. However in this project the focus will be on electric city cars [35].

On the market several types of EVs are available to purchase:

- **Plug-in Electric Vehicle (PEV)**
- **Fuell Cell Electric Vehicle (FCEV)**
- **Hybrid Electric Vehicle (HEV)**

The objective of this project is to investigate the impact of EVs and minimized cost in the residential grid while increasing the hosting capacity. Therefore, only the PEV which is using the grid to charge batteries will be utilized [35].

The battery type used for the EVs can be divided into three categories:lead-acid,nickel metal hybrid (NiMH) and lithium-ion (Li-ion). For the small range EVs the best choice would be the lead-acid battery. However with the increased energy density offered by Lithium-ion batteries they are a better alternative for electric vehicles. Therefore, this project will consider only the Li-ion battery type [36]. Three electric vehicles with different Lion-based battery capacity are considered in this work.An example of the technical information about one of the considered EV can be found in table. 2.2.

Table 2.2: Volkswagen ID.3 PRO specification

Parameter	Value	Unit
Battery capacity(C_{rated})	58	kWh
Average driving efficiency(η_d)	0,15	kWh/km
Maximum range(R_{max})	400	km

If the considered electric car Volkswagen ID.3 would be driven 40 km every day average for 320 days in a year [37], the yearly energy demand will be:

$$E_{EV} = D_{av} * 320 * \frac{\eta_d}{\eta_{charging}} = 40 * 320 * \frac{0,15}{0,85} = 2710 kWh/year \tag{2.4}$$

where D_{av} is the average daily driven distance, η_d is the average driving efficiency and $\eta_{charging}$ is the EV charger efficiency.

Battery charger technology is also important in regards of integration the EVs. Electric vehicles are mainly charged at home [35]. Therefore only home-charging is considered in this project. The charger utilized in this project is provided with the considered EV [38]. The specification is presented in the table. 2.3.

Table 2.3: EV charger model used in this project

Parameter	Value	Unit
Power input AC($P_{max,AC}$)	8,7	kW
Power output DC($P_{max,DC}$)	7,4	kW
Input voltage(C_{rated})	400	V
Maximum current(C_{rated})	19	A
Charging/discharging efficiency(C_{rated})	0,85	-
Power factor(PF)	1	-

2.3.2 EV integration issues in residential network

Charging the EVs increase the number of technical issues for the DSO because of the large amount of power required, which can even exceed the household load demand. The main issue is the time when most of the customer want to charge their vehicles. Commonly the demand will occur on the evening when the household demand has its peak as well [27].

From 2.3.1 the yearly driving demand for an EV equals 2710 kWh/year which could be higher than yearly domestic load demand. Therefore, with this added load the increase of line losses, voltage variation below the required limit along the feeder or overloading components can happen. This can be seen particularly in the residential LV network where uncoordinated charging of EVs may overlap the evening household power consumption. It can results in a rise of peak load demand which this grid was not designed [39].

Another issue concerns the voltage phase unbalance. Since the chargers are single-phase appliances an unequal distribution over the three phases could be possible. It may lead to voltage imbalance on the LV feeder. Therefore, the already existing unbalance could rise significantly [40].

2.3.3 EV driving patterns

The driving patterns and additional data can be obtain from the European survey. Referring to [41], an assumption was made that the EV users driving patterns are following the same driving patterns as conventional cars users is an acceptable approximation. Therefore, the analysis of the driving data of conventional cars will be used to create driving patterns for EVs in this project. The survey contains information such as the average daily travel and average driven distance, from which the EV availability for charging can be determined. Additionally, with the knowledge of the driven distance along with the vehicle average efficiency (kWh/km), it is feasible to indicate the SOC at the arrival to the end destination and determine the time and energy needed to restore the SOC to the desired level [37].

For instance for a Poland case of study the 2012 EU mobility survey presents that the approximately driving distance is 80 km and it is showed on the right plot on Fig. 2.6. Moreover, from the left plot on Fig. 2.6 the average daily driving time is presented. Polish car owners are driving every day almost 2 hours averagely. Therefore it is possible to conclude the percentage the electric vehicle stays parked during the day.

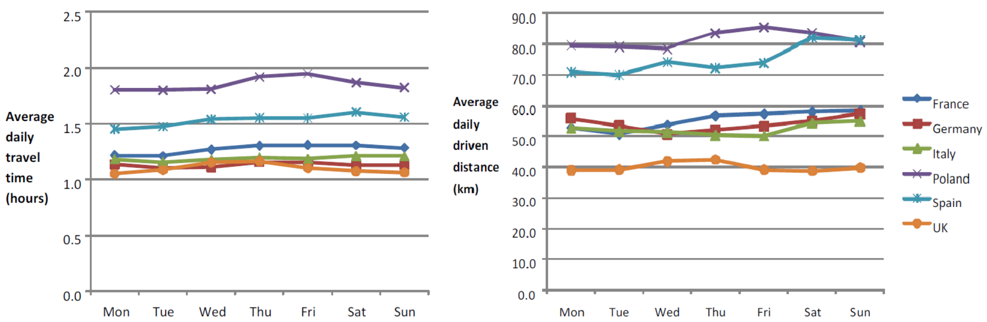

Figure 2.6: Average daily driven distance on the right plot and average daily travel time per day of the week on the left plot from the Europe survey about electric vehicles [41].

In the survey it has been highlighted that the average driving time for Polish drivers is around 2 hours. This means that for approximately 22h every day, which is 92% of the time the electric vehicle is parked somewhere. As it was assumed that EVs can only be charged at home the time when the car is available for charging is shorter than the time the car is not used for driving. For instance the user may park the car at the working place where there is no EV charger available [41]. In the next chapter the charging availability profile will be introduced.

2.3.4 Residential electricity tariffs

In the following paragraphs the tariffs which could be found in the Polish policy are presented. In this project the focus is on the TOD and Net metering tariff. These tariff structures are important in the Ev charging optimization which is base on the price minimization.

Time of Day tariff

The tariffs which is applying a variable price according to the time of the day is called Time of Day(TOD) or Time of Usage(TOU). This tariff could help to avoid an excessive load peaks in the grid by setting a higher price during peak load demand and lower for off-peak period. Therefore, the customers can decide whether to shift part of the energy demand during off-peak hours, or pay accordingly [42][43].

Real Time Pricing

Real time pricing (RTP) represents a tariff where the price of electricity vary with time according to the grid conditions, such as voltage magnitude, the loading level of the network components to better demonstrate the variable costs of energy generation, transmission and distribution. For DSO as well as for customers covering the demand during load peaks are expensive comparing to the off-peak hours due to the congestion in the network and higher line losses. Additionally, during the peak demand time the value of power from PV components are higher, since it can help reducing the loading of the distribution network by providing locally the required energy [44][43].

Net Metering Service

Net metering is a service available for consumer who owns a generating units, such as SPV. When using the net metering service energy generated by the PV system the excess is delivered and sold to the distribution network. In the event that the consumer's production of energy is exceeding the consumption over the billing period, the customers are paid for the energy sold to the network. This tariff is most profitable when the energy is self consumed because the cost of power provided by DSO is higher than the earning from selling the surplus to the grid. Hence, Net Metering is most suitable for households where the EV charging station is utilized because it is a load which may increase the self consumption of PV system [42][45].

High penetration of PV units in the distribution network is limited by the probability of problematic incidents such as overloading the network components or overvoltages. The introduction of electric vehicles to the distribution network could solve some of the issues caused by PV system to the network. For instance, EVs can utilize the power generated from solar panels and therefore reduce the risk of reverse power flow and attached to that problems. On the other hand, charging electric vehicles are causing issues as well. Since in residential network the charging could happen during the peak load demand of a household this may result into undervoltage and possible overloading the components. The combined system with EV and PV technology could mutually benefit only if a EV charging strategy would be designed properly. In this project a smart charging scheme will be presented. The goal is by minimizing the cost of electricity to optimize the EV charging and increase the grids hosting capacity while fulfilling the voltage and loading constraints. In the next chapter the considered network is introduced as well as the PV generation and household demand profiles. These data were used to achieve the goal of this project.

3 | Low Voltage Distribution Grid Analysis

In this chapter the investigated residential power system is introduced. Additionally the data analysis with he household load demand, PV generation profile as well as the EV availability for home charging is presented. In the end a simulation in Power Factory is conducted to show the issues in the grid where the PV system and EV charging station are not integrated.

3.1 Description of the model

The considered model represents a LV residential network supplied from the external grid, which is serving the residential area by a LV busbar of a MV/LV transformer. The transformer is connected the main LV terminal which is indicated as B1 busbar. The "M" cables are the main one which are supplying all of the components installed in the house. Each residential customer is represented as a household load with the possible addition of PV system as well as EV charging station. DIgSILENT PowerFactory has been used to recreate the model of the benchmark LV network. In Fig. 3.1 the considered model of the residential grid is presented. The benchmark for this LV network is provided by [46].

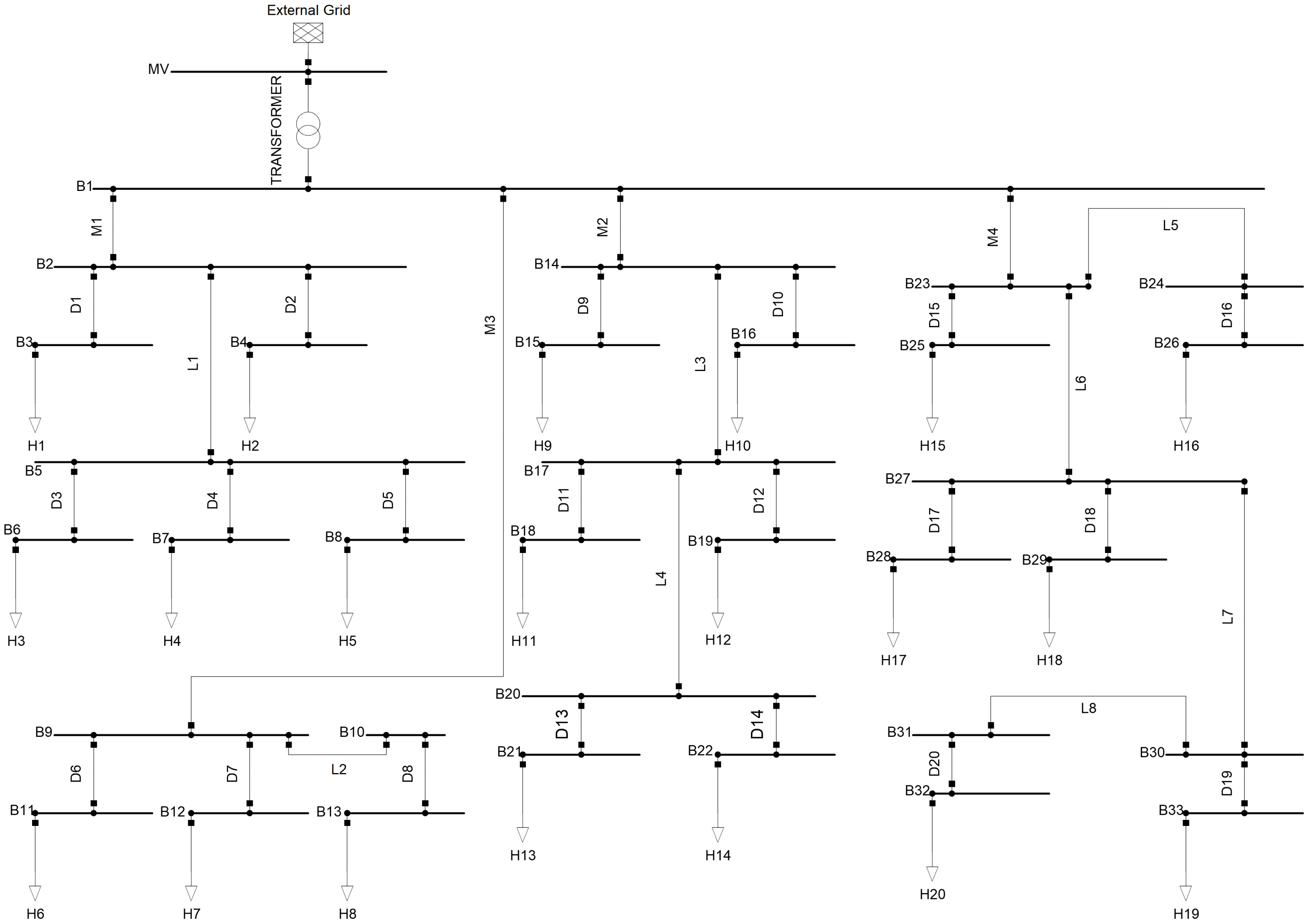

Figure 3.1: Residential grid model created in Power Factory

In the Table 3.1 and Table 3.2 the parameter of the residential grid as well as transformer data are presented. Considered network is a common grid with a radial topology. The residential network have 20 unit, which includes the household load and later integrated PV system and EV charging station. The furthest node in the grid is the busbar 32 and it is 960 meters far from the transformer. The transformer has a capacity of 100 kVA and converts the voltage from 10 to 0,4 kV.

Table 3.1: Parameters of the residential model

Element	Number of units	Name in model	Installed capacity[kVA]	Value
Grid topology	-	-	-	Radial
Household loads	20	H1-20	115	-
PV systems	20	PV1-20	60	-
EV charging stations	20	EV1-20	148	-
Distance FN-Transformer	-	B33	-	960m

Table 3.2: Transformer specification

Parameter	Value	Unit
Primary voltage	10	kV
Secondary voltage	0,4	kV
Capacity	100	kVA
Impedance	5	%

The feeder parameters are listed in Table 3.3. In the considered grid three cable types of cross section was introduced along with a changing length of these cables. The main cables which are connecting the LV terminal with the rest of the grid have 70 mm2 and 600 meters length.However one of them the M3 cable has 1 km because it was assumed that sometimes the houses can be outside of the neighbourhood. The domestic cables (D1-20) which are connecting directly the houses with the nearest busbar have 100 meters and cross section 35 mm2.

Table 3.3: Line data for the residential grid

Line type	Length[m]	Cross section[mm^2]	Resistance[Ω]	Reactance[Ω]	Rated current[kA]
M1,M2,M4	600	70	0,266	0,049	0,176
M3	1000	70	0,44	0,08	0,176
L1,L3,L4,L6,L7	500	50	0,32	0,04	0,144
L2,L5,L8	200	50	0,128	0,016	0,144
D1-20	100	35	0,086	0,0086	0,119

3.2 Data analysis

In this section the data analysis for PV generation, household load and availability of EVs for home charging is presented. The household demand data and PV generation data are demonstrated for one whole week. Whereas the EV home charging data are only for one day. It is assumed that the availability are the same every day.

3.2.1 Household loads

The household demand profile is a sum of all of the loads profile of residential loads such as appliances, heating, cooling and others. Household loads are the main components in the LV grid demand. Due to the low energy consumption by individual loads they are usually connected only to a single-phase of the grid. Therefore a certain unbalance is present in the LV grid because the LV feeders cannot always maintain a equal distribution of single phase loads among the three phases [47][48]. The household demand data presented in [49] was utilized to introduce the demand profile of the residential unit of this work. Data were gathered for one week in summer with a sampling period of 1 hour. The measurements provided by [49] has been obtained from a single house inhabited by 3 people. The main appliances in this house are dishwasher, electric oven, fridge, microwave, tv, electric heater and 2 laptops.

In the Fig. 3.2 the household demand profile is demonstrated. The domestic load profile has a weekly consumption of 87,9 kWh/week and a peak consumption equals 2,85 kW.However some assumption must be made . In this work the power factor for the domestic load demand is equal 0,95. All of the parameters are summarized in the table 3.4.

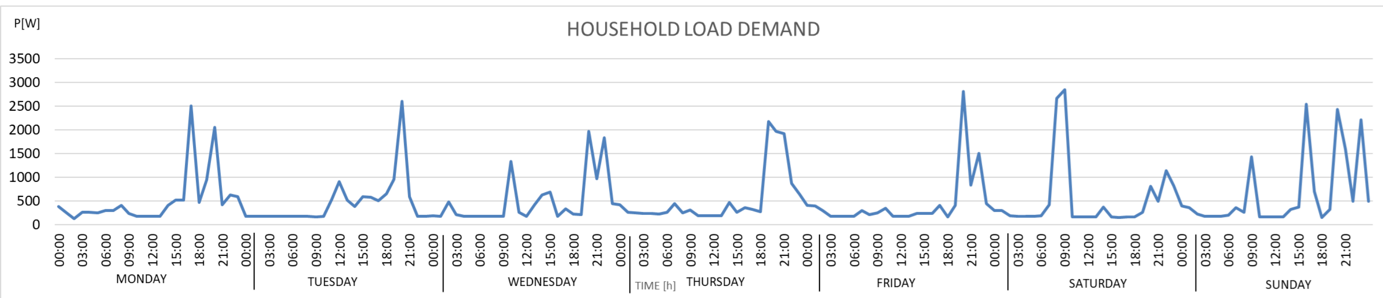

Figure 3.2: Household demand profile for one week in summer.

Table 3.4: Summarized parameters of household demand profile

Parameter	Value	Unit
Peak Consumption	2,85	kW
Weekly Consumption	87,9	kWh
Power factor(PF)	0,95	-

All of the loads mostly do not absorb their rated power simultaneously. Hence, the sum of the single load rated powers are always lower than the maximum system power demand. The coincidence factor f_{co} is a parameter used to express this phenomena. This factor is defined as the ratio between the system maximum power demand P_{maxd} and the sum of the single loads maximum demand $P_{maxd,i}$ [50], as expressed by equation:

$$f_{co} = \frac{P_{maxd}}{\sum_{i=1}^{n} P_{maxd,i}} = 0,52 \tag{3.1}$$

From the Fig. 3.2 the coincidence factor is equal to 0,52 , which is a common value for the residential units [50].

3.2.2 PV generation profile

The generation profile for one solar panel rooftop installed on a residential house was provided by GECAD [49]. The measurement profile has a typical one summer week length and hourly resolution.

To obtain a PV system generation profile for a residential unit an assumption was made that on every roof 15 solar panels with a rated power 200 W each are installed. Every panel has the same dimension which is 1480mm x 680mm x 35mm [51]. Therefore the PV system would occupy roughly 15 square meters of the roof. Since the generation comparing to the household profile in section 3.2.1 is exceeding sometimes the demand a battery is suitable for this residential grid. As it can be seen in Fig. 3.3 the peak generation is equal 2,94 kW and takes place usually at noon. The weekly generation is approximately 186,05 kWh. The main parameters of the PV generation profile are summarized in table 3.5.

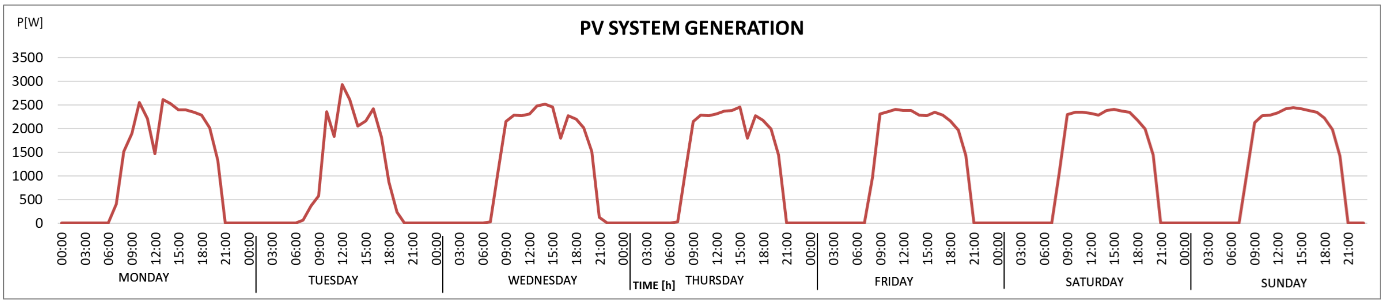

Figure 3.3: PV system generation profile

Table 3.5: Main parameters of PV system generation profile

Parameter	Value	Unit
Peak Production	2,94	kW
Rated power	3	kW
Weekly Production	186,05	kWh
Installation type	Rooftop	-

3.2.3 EV availability for home charging

The availability of EVs is meant by the time when the electric vehicles are plugged into the network. Based on the data provided by [41] assumption about home departure and arrival times and the average number of trips can be made.

In the Fig. 3.4 the graphs indicating the time of parked EVs during a typical day is presented. As it can be seen on the top graph almost all day the EV is parked somewhere, at work or at home. The only exception is the time in the morning and afternoon when the people are driving to work or to home accordingly. Therefore the only time when the EVs can be charge at home is introduced in the bottom graph. All night the electric vehicle is available to charge but from 7:30 to 17:00 the EV is unavailable for home charging [52].

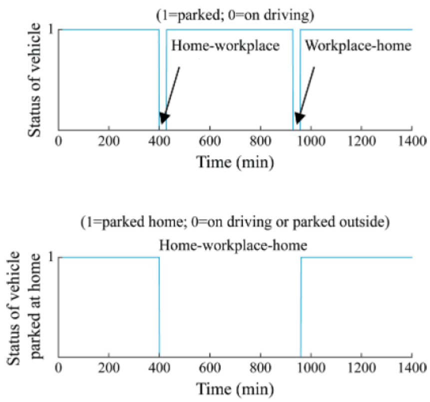

Figure 3.4: Status of electric vehicle for a typical day[52].

However the assumption that from 00:00 to 7:30 and from 17:00 to 24:00 are the only hours when the EVs can be charge at home must be corrected. There are many situation when the EVs are charged at home despite the working hours. In the Fig. 3.5 the graphical representation of EVs availability for charging in weekdays and weekend are shown. The highest drop with the availability to charge at home electric vehicle can be seen during the weekdays. During the day the probability can reach only 48% approximately at noon. From 00:00 to 7:00 and from 21:00 to 24:00 the availability is at highest at stays above 95%. However from 7 o clock start of the decrease is significant due to the start of working hours and people driving to work. With the beginning of late afternoon when people are usually going back home the availability is rising and at 18:00 is above 80%. Moreover the difference to the weekends can be seen as well. According to the graph the probability is much higher to charge at home comparing to the weekdays because most people are staying home during Saturday and Sunday. There is a significant decrease starting at 10 o clock which goes from above 90 % to almost 70 %. Although after 21:00 the probability is going back to the 90% level.

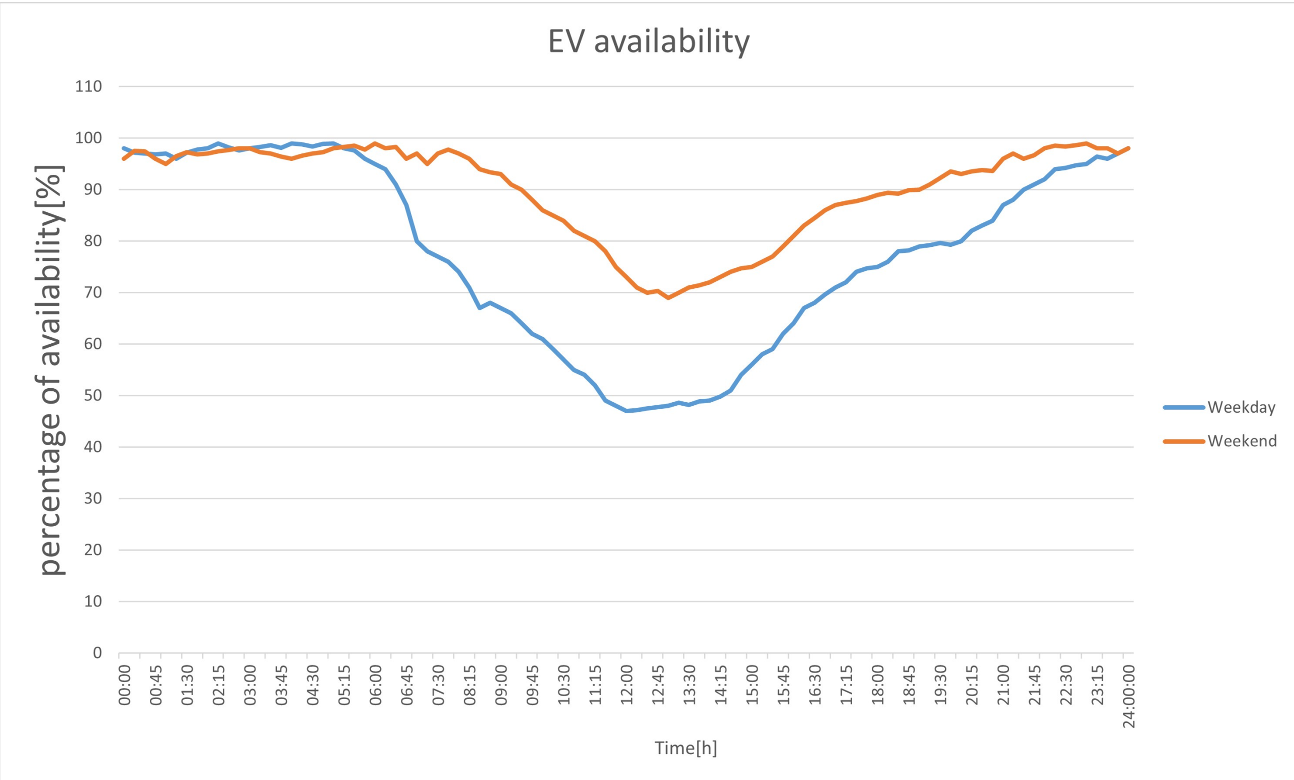

Figure 3.5: EV availability for home charging in the weekend and weekdays

3.3 Load flow analysis

The power flow analysis conducted in Power Factory is presented in this section. To simulate a grid consisting only household load a Quasi Dynamic simulation was conducted. The purpose to exclude the PV system, EV charging stations and battery is to present the state of the residential grid before integrating the RES components and what are the reasons to do so. The simulation is divided into two days. For the weekday the highest demand which will indicate the worst case is Friday. Moreover the worst case for the weekend is during Saturday. Therefore for these days the simulation are conducted. In Fig. 3.6 the results for a Quasi Dynamic simulation is shown. The results are showing the voltage magnitude variations and line loading during Friday. The voltage magnitude is presented for the busbar 32. It can be seen that at the evening when the demand is at the highest point for a weekday the voltage magnitude significantly is decreasing. Additionally the line loading of the cable M4 is increasing while the demand rises.

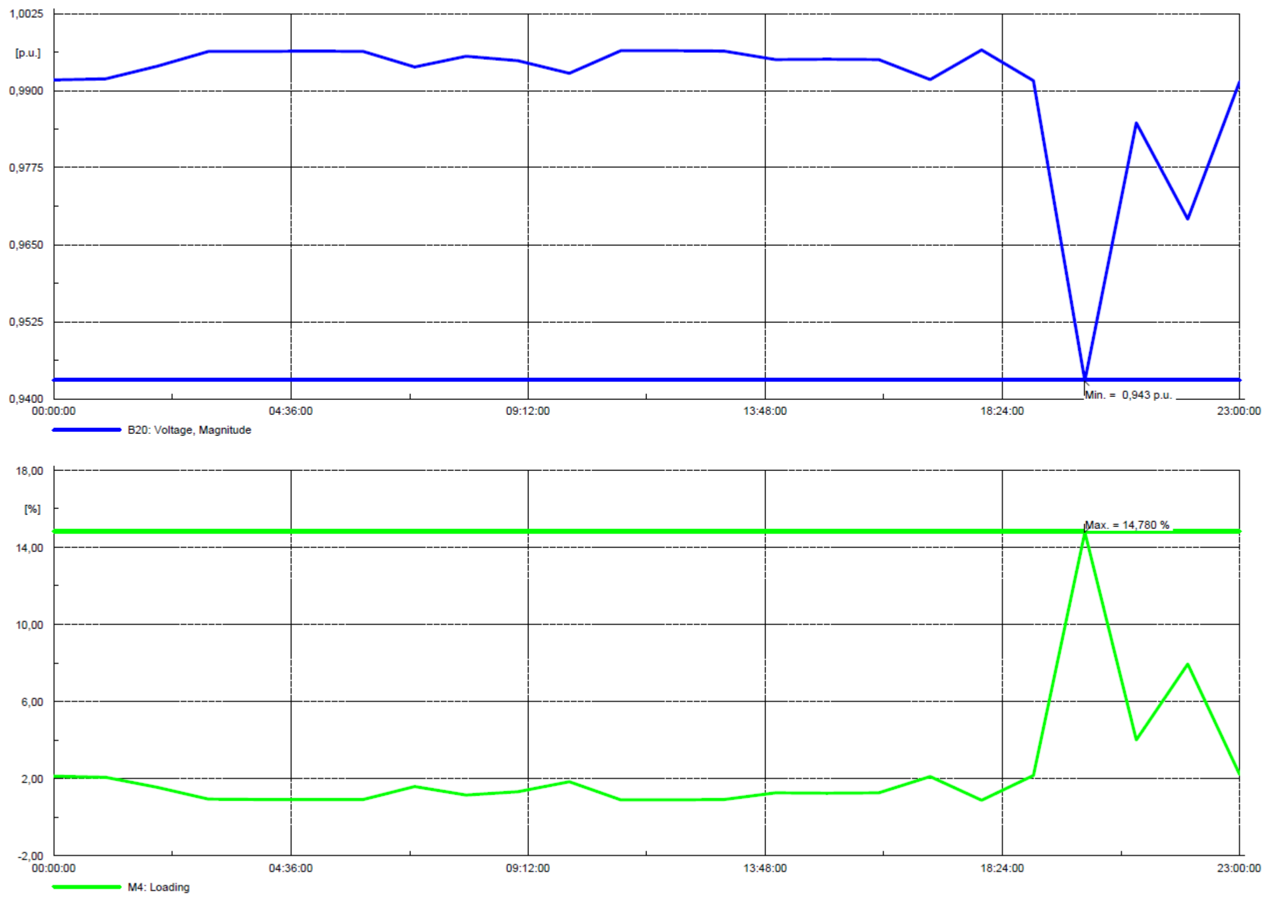

Figure 3.6: Results of the grid with only household loads

A summary of the power quality indicators for the Friday case is presented in the table. 3.6. The B32 in the considered grid is the furthest node as well as the node where the lowest voltage magnitude can be seen. The voltage magnitude is lower then the limit range and is decreasing to 0,943 pu during the highest demand. The maximum cables losses is occurring in the M4 cable and can reach 14,78 %. The loading of the transformer is 60,25% and the maximum is 100 %. Therefore there is a space of additional loads which can be installed in the grid.

Table 3.6: Power quality indicators

Indicators	Unit	Position	Value	Limit
Minimum bus voltage	pu	B32	0,943	0,95-1.05
Maximum line loading	%	M4	14,78	100
Maximum transformer loading	%	Transformer	60,25	100

In Fig. 3.7 the voltage magnitude as well as line loading for Saturday is presented. The decrease of voltage magnitude in the morning is violating the constraint and the line loading increase at the same moment of day but it is not reaching the limit value.

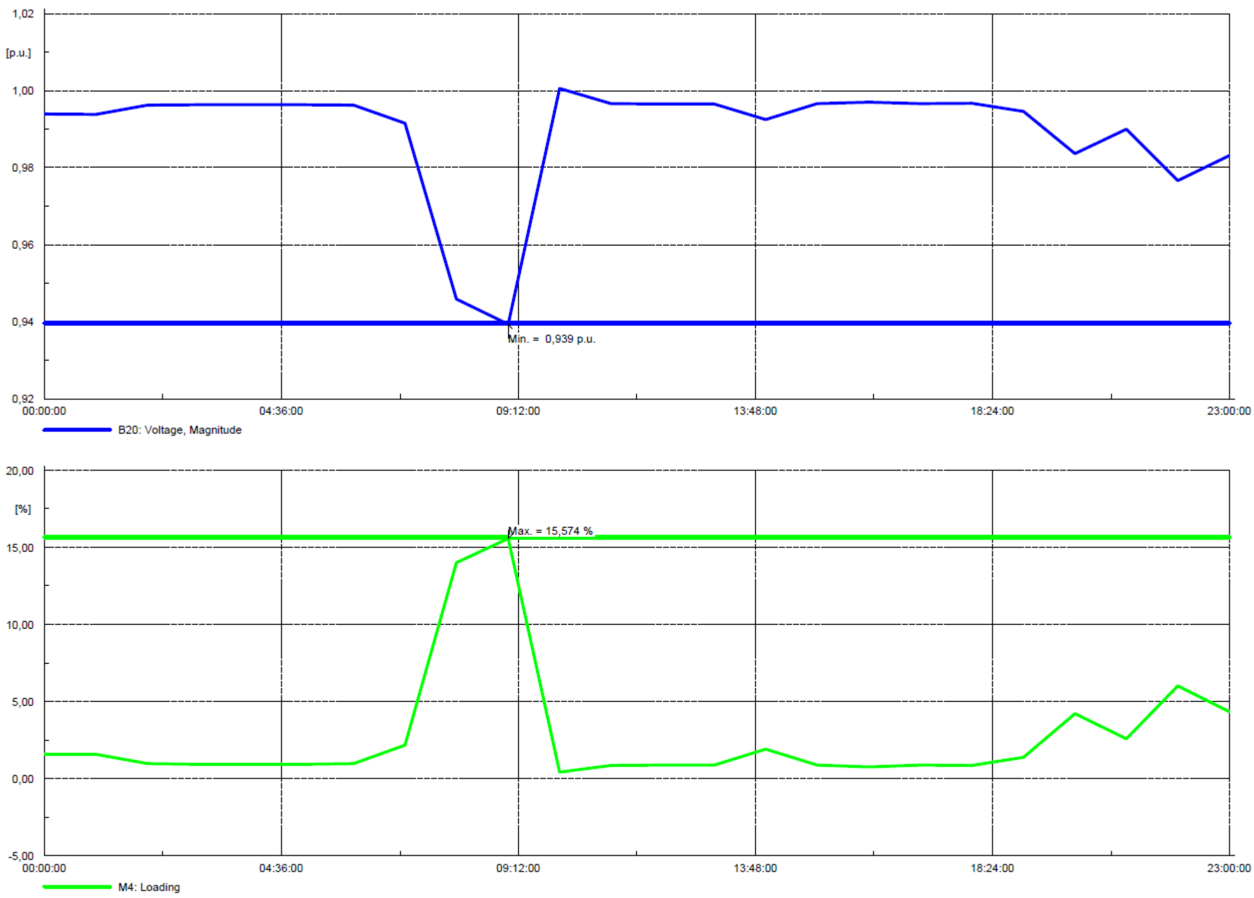

Figure 3.7: Voltage magnitude on the furthest busbar

A summary of the power quality indicators for Saturday case is presented in the table. 3.7. A decrease of voltage magnitude in the morning can be seen and could reach 0,939 pu which is not fulfilling the

+/-5% constraint. The maximum cables losses is occurring in the M4 cable and can reach 15,57 %. The loading of the transformer is 63,28% and the maximum is 100 %. Therefore there is a space of additional loads which can be installed in the grid.

Table 3.7: Power quality indicators

Indicators	Unit	Position	Value	Limit
Minimum bus voltage	pu	B32	0,939	0,95-1.05
Maximum line loading	%	M4	15,57	100
Maximum transformer loading	%	Transformer	63,28	100

This section is showing that the grid without the PV system and EV charging stations on the furthest points is not fulfilling the voltage constraints therefore a additional distribution generation is required to maintain the voltage on a +/-5% range. Moreover from the data analysis it can be seen that the household demand is not overlapping the generation from PV. Hence, an flexible load is necessary to fully benefit the power from solar panels. To overcome the voltage issues in the grid in next chapter the integration of PV units is presented.

4 | Solar photovoltaic integration in LV Distribution Grid

In this chapter the PV units are introduced in the residential network. First the simulation procedure is explained. After this the results of the conducted simulations for PV systems integration are shown. In the end the hosting capacity of the grid is determined.

4.1 Simulation procedure

To simulate the PV integration in considered residential grid the MATLAB/SIMULINK software is used. Moreover the balanced power flow simulation with the newton-raphson method is utilized. The simulation is performed for a one typical week on summer and for different PV penetration percentage in the grid. The PV generation as well as household load profile were used from 3.2.2 and 3.2.1 respectively. For each simulation conducted, a list of power quality indicators is extracted from the simulation model and analyzed, in order to determine the impact of the PV generation units in the network. The parameters considered to evaluate the power quality are: the maximum loading of all the network components and the bus voltage. The power quality indicators for each node are going to be displayed in a table in respect to the percentage of penetration. Moreover in a case of violating one of the constraints the problematic nodes will have graphs for one week with an hour resolution to demonstrated the issues in respect of the whole simulation time.

Different PV shares are considered and summarized in Table 4.1. The PV systems are added starting from the furthest nodes and proceeding towards the distribution transformer. All the parameters are assessed during a summer time in order to consider the highest power generation from PV systems.

Table 4.1: Different shares of PV considered in the simulations; 100% = 1 PV for every residential customer in the feeder.

PV shares[%]	**0**	**25**	**50**	**75**	**100**
Number of PV units in grid	0	5	10	15	20

4.2 PV units integration in the residential grid

This section provides results of newton raphson simulation conducted in MATLAB. The output shows the most important power quality indicators of power flow when household loads are implemented and the PV penetration is changing.

In Table 4.2 the results after conducting power flow simulations after PV integration are shown. The outcomes are divided in respect of the number of PV units implemented in the residential grid.It can be observed that while implementing above 50% of the PV units the voltage is violating the limits. The maximum voltage magnitude is varying from 1,028 to 1,052 and its rising along with the increase of PV shares. When 100% of PV system are installed he violation occurs two times during the week on 3 different busbars. Moreover, the cable loading in every case is not exceeding 35% which is acceptable.

Table 4.2: PV integration results for different share percentage

		PV share[%]			
Power quality indicators	**Limits**	**25**	**50**	**75**	**100**
Maximum voltage	1.05pu	1.028	1.046	1,05	1,052
Location (busbar)	-	32	32	32	33,32,21,31
Number of violation occurrences(weekly)	-	-	-	1	2
Maximum line loading	100%	33.59	33.54	22.5	20
Location	-	M1	M1	M4	M4

In Fig. 4.1 and Fig. 4.2 the voltage magnitude for 100% and 0% of PV share are presented. As it can be seen the voltage rise while the PV units are installed is significant. The lowest point which the voltage reach is below the 0.95 pu limit in a case without any PV systems in the grid. However, with the addition of solar panels into the considered network the voltage increase above 0.95 pu and not violating the constraints.

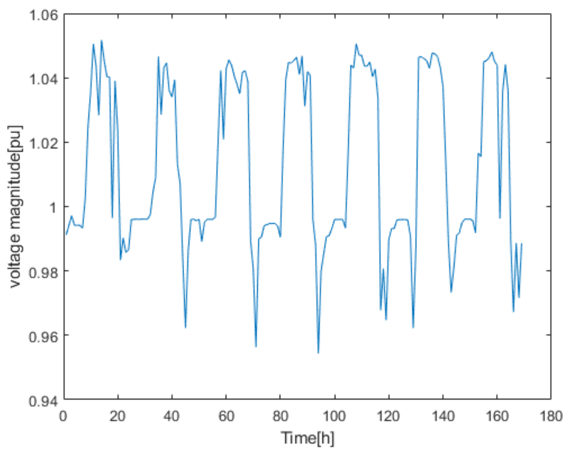

Figure 4.1: Voltage magnitude for B32 for 100% PV share.

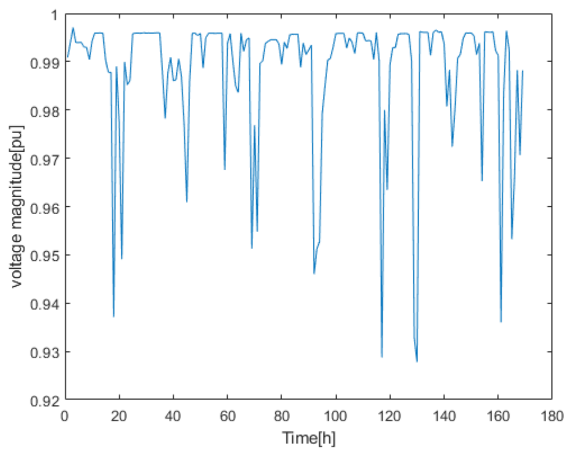

Figure 4.2: Voltage magnitude for B32 without any PV units installed.

In Fig. 4.3 and Fig. 4.4 the voltage magnitude for 100% and 0% of PV share are presented. The highest cable loading while all of the PV units are installed can reach almost 34%. However, in the

Fig. 4.4 can be seen an increase of loading during the evening time when more power is provided by the external grid. Comparing with cable loading for installed PV units, without the distribution generation the loading shifts and increase towards evening hours.

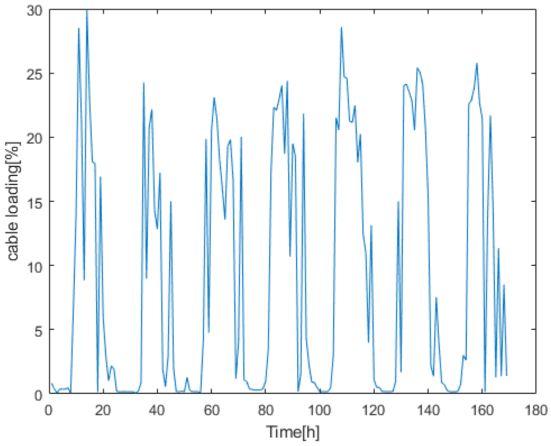

Figure 4.3: M4 cable loading for 100% PV share.

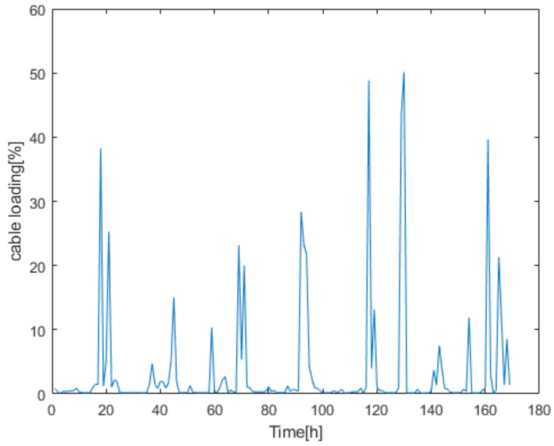

Figure 4.4: M4 cable loading without solar panels.

In the next paragraphs the PV hosting capacity for the investigated residential grid is calculated.

4.2.1 Hosting capacity of the residential grid

To determine the maximum PV hosting capacity an iterative process is introduced. The proposed process is conducted in MATLAB software. The maximum PV hosting capacity can calculated by multiplying the measured rated power of the PV system with the scaling factor:

$$P_{host} = s * P_{measured} \tag{4.1}$$

where the $P_{measured}$ is the rated power and the s is the scaling factor. In the starting point the scaling factor is set to zero. Each iteration increases the scaling factor by a fixed step. To check if the constraints about power quality indicators are fulfilled a power flow is conducted at each iteration. If a violation will appear in any of the busbar the maximum PV hosting capacity has been reached. In the Fig. 4.5 the flowchart of the algorithm implemented in MATLAB has been shown.

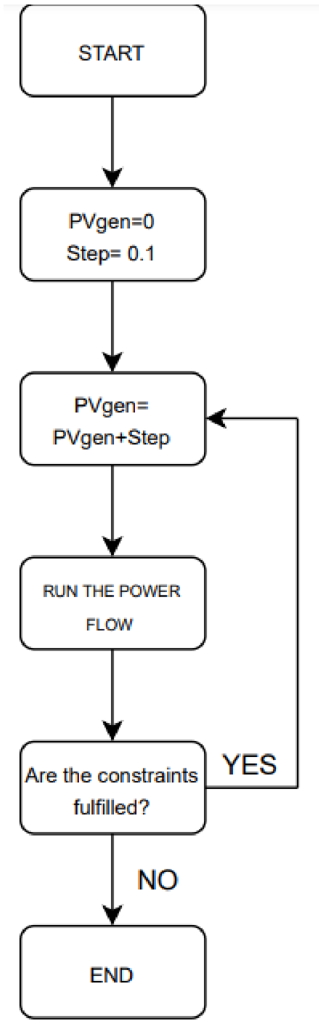

Figure 4.5: Flowchart of the algorithm used to calculate the PV hosting capacity

From the simulation the maximum PV hosting capacity has been found to be 2.8 kW for the 3 kW rated power of PV system. The maximum PV hosting capacity for the residential grid can be calculated as follow:

$$P_{host} = n_i * P_i = 20 * 2.8 = 56kW \tag{4.2}$$

The 56 kW represents the power which can be produced by all of the PV systems and which is not violating any of the constraints. Determined hosting capacity is limited by the voltage magnitude at the busbar 32 which is the furthest node in the grid from the transformer. In the Fig. 4.6 the voltage magnitude during one week for busbar 32 is shown. It can be seen that in the beginning of the week the voltage magnitude almost reaches the top limit which is 1.05 pu.

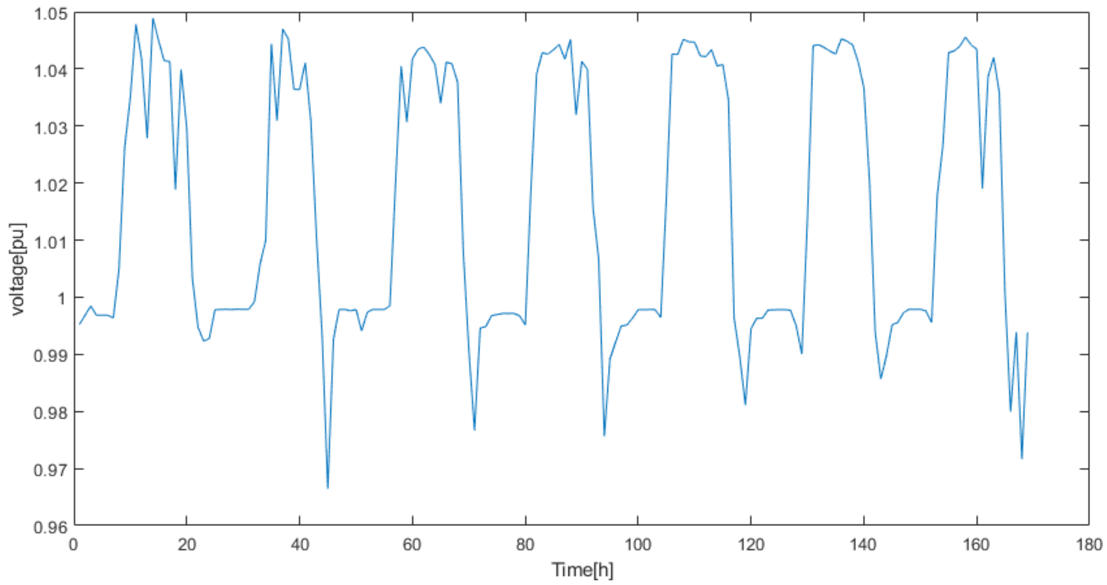

Figure 4.6: Voltage magnitude B32

Any increase of the installed power over the evaluated P_{host} value will result in a violation of the +5% overvoltage constraint. In the Table. 4.3 the summarized power quality indicators for the maximum PV hosting capacity has been shown.

Table 4.3: Power quality indicators for the maximum PV hosting capacity

Indicators	Unit	Position	Value	Limit
Maximum bus voltage	pu	B32	1,049	0,95-1.05
Maximum line loading	%	M4	32	100

In the considered residential LV grid with the integrated PV system the issues occurs when the PV shares is higher then 50%. The results obtained from the simulation which were conducted by a algorithm in MATLAB, describe the voltage rise due to the addition of solar panels to the house. By utilizing the algorithm the PV hosting capacity of considered LV network could be determined. Therefore, the maximum calculated hosting capacity for the whole grid is equal 56 kW and the maximum rated power for each PV system is 52.8 kW. From the results obtained in the evaluation of the PV hosting capacity it can be concluded that the overvoltage issue is the limiting factor for a further increase of the installed power in the considered residential network. Therefore, to improve the PV hosting capacity the use of EVs chargers seems feasible, since it has been defined as an effective solution in solving the voltage rise [53]. In the next chapter it will be proved that the depending on the strategy of cost savings for residential customers the integration of EVs in the grid will increase the hosting capacity while improving the voltage magnitude at the most sensitive busbar.

5 | Smart charging of EVs in a distribution grid

In this chapter the Electric Vehicle is integrated to the residential LV network. In this work two scenarios for EV charging are proposed based on the residential tariffs. The first considered is the Time of Day tariff (TOD), while the second is for customers which own PV units (Net Metering tariff). The scenarios are evaluated depending on the price of electricity and occurrence of voltage issues. An optimization process is proposed for each scenario, with the EV load demand as control variable and the cost of electricity for the EV owner as cost function. The impact of different EV shares and the feeder PV hosting capacity is analyzed.

5.1 Simulation procedure

The simulation procedure is introduced as follow:

- By importing important data which are summarized in Table.5.3 and determination the EV availability as well as EV energy demand the generation of the EV demand profile while minimizing the cost function was possible. The cost function are described in details in the further sections. The EV load profiles are applied to the simulation model of the LV residential network. Next a balanced load flow simulations are performed for different EV penetration percentage levels, which are presented in Table.5.1. The power demand needed to charge the EVs every hour for one week must be in the +/- 5% voltage constraint. While conducting the simulation the control variable is the EV charger load demand, the cost function is the cost of the EV home-charging for the EV owners and the constraints are obtained from the charger technology, the driving patterns, EV availability and the battery SOC. In Fig. 5.1 the flowchart of the process used to generate the EV profile and the voltages in the grid is presented.

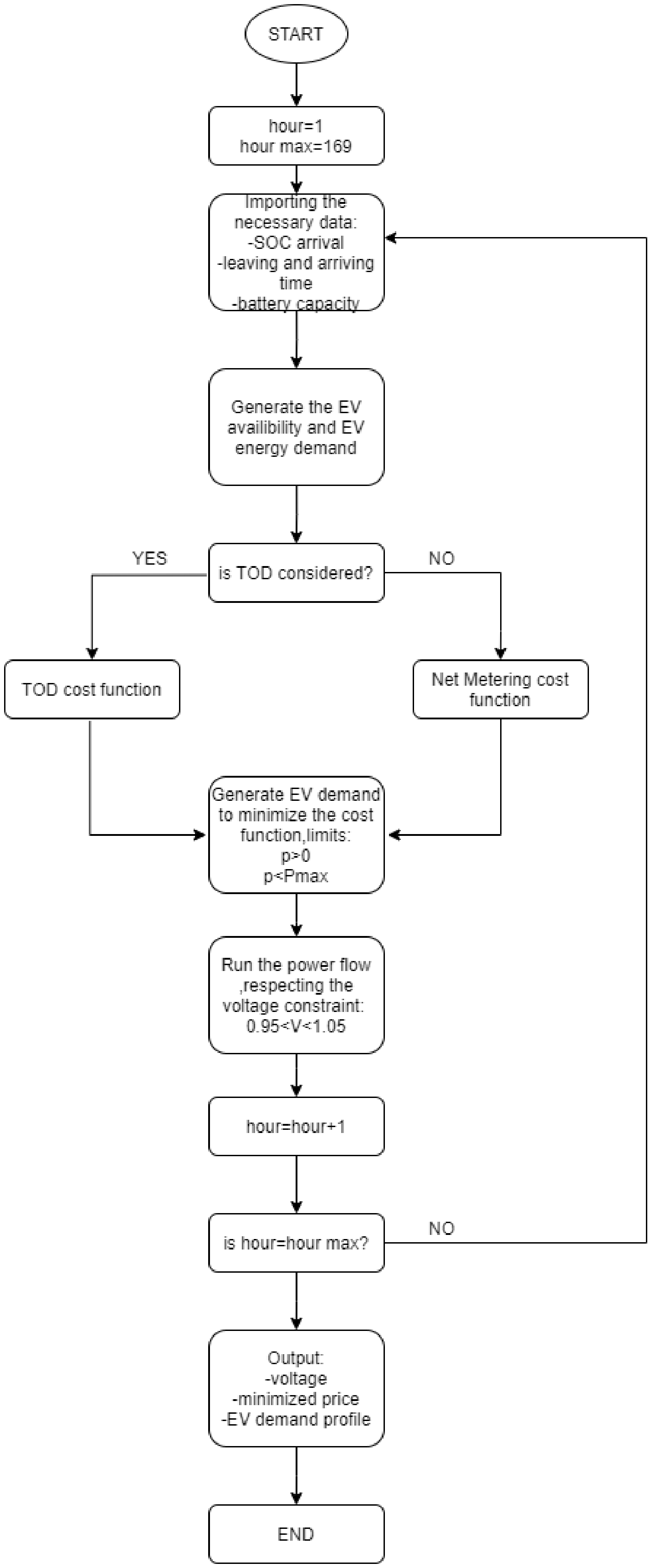

Figure 5.1: Flowchart of the algorithm used for integrating the EVs.

- After the simulation a list of power quality indicators is imported from the simulation model and analyzed, in order to determine the impact of the EV loads in the network and the grid issues.

- By applying the PV hosting capacity algorithm described in 4.2.1 the new PV hosting capacity can be find. For each percentage of EV penetration the TOD and Net metering scenario is conducted. In Fig.5.2 the block diagram for performing the hosting capacity algorithm with different EV penetration percentage has been shown.

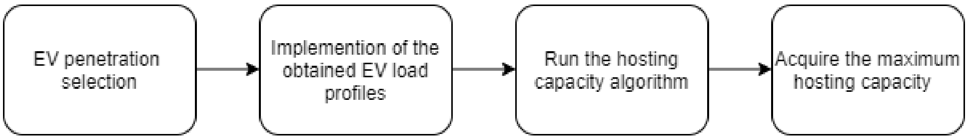

Figure 5.2: Flowchart of the algorithm used for integrating the EVs.

All the parameters are evaluated on a weekly base, in order to consider the behavior on weekdays and weekends of the domestic load demand and the PV power output. The simulation's resolution is one hour. In case of one or more violations of the constraints the occurrences of the violation are presented.

Different EV shares are considered and summarized in Table. 5.1. All of the electric vehicle loads are connected to the same busbar as PV units and household load.

Table 5.1: Different shares of EV considered in the simulations; 100% = 1 EV for every residential customer in the feeder.

EV shares[%]	**0**	**25**	**50**	**75**	**100**
Number of EV units in grid	0	5	10	15	20

It is assumed that the EVs are added to the residential network by starting from the furthest node of the grid (busbar 32) and proceeding towards the distribution transformer. In Fig. 5.3 the summarized data for each EV in the residential grid is presented. In the obtained data the leaving time and arrival time is introduced as well as the battery capacity for each EV. In considered LV network the customers have 3 types of electric vehicle. The customers own EVs with 58, 50 or 30 kWh battery capacity. Additionally the arriving state or charge (SOC) and maximum SOC is presented. Moreover in the table the driving efficiency , number of kilometers done every day can be found.

	Batter capacity[kWh]	State of SOC when arriving home	kWh used every day	Number of busbar	Number of km made	Driving efficiency	SOC max[%]
1	58	80.1	11.25	3	75	0.15	95
2	58	79	12	4	80	0.15	95
3	58	80	11.1	6	74	0.15	95
4	58	78	12.45	7	83	0.15	95
5	50	72	13.6	8	81	0.17	95
6	30	48	15.6	11	78	0.2	95
7	50	75	12.24	12	72	0.17	95
8	30	43	17.2	13	86	0.2	95
9	50	76	11.73	15	69	0.17	95
10	58	81	11.7	16	78	0.15	95
11	50	69	15.13	18	89	0.17	95
12	58	76	13.5	19	90	0.15	95
13	50	71	14.11	21	83	0.17	95
14	30	46	16	22	80	0.2	95
15	50	73	13.43	25	79	0.17	95
16	58	79	11.7	26	78	0.15	95
17	50	71	14.11	28	83	0.17	95
18	58	79	12.15	29	81	0.15	95
19	30	46	16	32	80	0.2	95
20	58	80	11.55	33	77	0.15	95

Figure 5.3: Summarized data for each EV in the network.

In the following sections the Time of Day and Net metering scenarios are described. In the end a summary for customers cost and impact on the hosting capacity while integrating EV smart charging is presented.

5.2 Time of Day scenario

In this section the Time of Day scenario is presented. First the cost of electricity when the TOD tariff is implemented is shown. Afterwards the optimization process is introduced. In the end the simulation results are described.

5.2.1 TOD tariff for residential customers

The TOD tariff foe the residential customers is introduced by the polish power grid company PSE.SA in [54]. In the Fig.5.4 all of the diagram for polish electricity fees is presented. The cost is divided into two main categories, the transmission and support fees. The transmission fee is divided into three main rates.

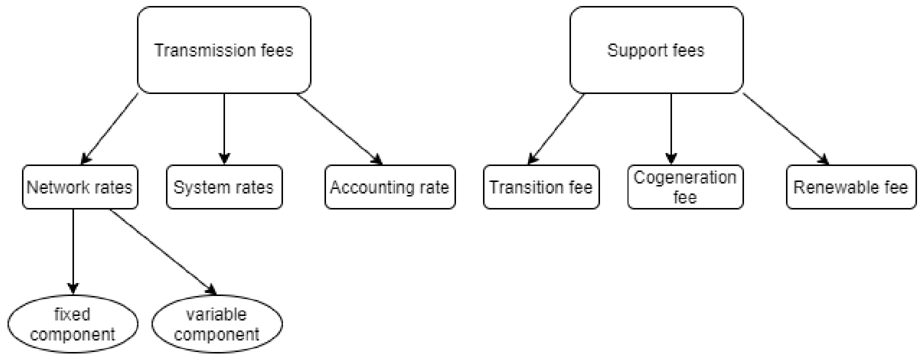

Figure 5.4: Diagram with polish electricity fees.

The fees showed in the diagram are regarding the whole system. Therefore for the TOD tariff the final price which the customers have to pay is the result of the addition of three transmission components, which are listed below:

- **Network rates** ->for providing transmission and distribution of electric energy through the transmission grid.
- **System rate** ->for maintaining quality, reliability ans security of electric energy supply.
- **Accounting rate** -> for accounting services.

The Network rate is divided into two types of fees. The fixed component is paid for the power grid company and the variable components is the cost of used electricity by the customer. To every individual fee the 20% of tax is added. Therefore the prices shown further are the gross rate which is already including the tax.

Table. 5.2 is showing the prices for the fixed components. The network rate has to be paid once for one year. Therefore to add this fee to the price for one kWh it has to be divided with the yearly domestic demand.

Table 5.2: Summarized fixed components fees.

Component	Rate	Unit
Network rates(fixed fee)	88	zl/customer/year
System rates	0.089	zl/kWh
Accounting rate	0.00312	zl/kWh

Additionally the variable component which is dependent on the time of the day. The first case of this work express the real case from the polish grid. It includes three zones of pricing thorough the day. In Table.5.3 the rate of price during specific hours during one day is introduced. The symbol for each time range application has been shown. Also the unit to present price is zl/kWh (polish currency). To the usually rates for the particular hour the fixed values are added from Table.5.2. As it can be seen the lowest fee for one kWh is during night till 6 in the morning. While the highest price which customers must pay for electricity is from 16 to 22 o'clock because during this period the highest demand is occurring.

Table 5.3: The three zones pricing.

Time application	Rate	Rate(fixed fees included)	Unit	Symbol
22:00 to 6:00	0.12	0.231	zl/kWh	G1
6:00 to 16:00	0.177	0.288	zl/kWh	G2
16:00 to 22:00	0.19	0.301	zl/kWh	G3

The second considered case which is investigated in this project is by adding one more zone during the day. Therefore the typical day is divided into four zones, which are divided into 8 hour intervals. This action has been proposed to obtain a more diverse electricity prices. Therefore, the customers can decide when it is more convenient for them to use electricity and in the same time decrease the cost. Additionally the peak demand can be lowered because of the higher demand respond from the customers. In Table.5.4 the pricing for the investigated four zone case is presented. It can be seen that additional zone was created and the hours of particular zones are shifted. The main rules are still applied. During the night and evening the cost is the lowest and highest respectively. The major difference can be seen before the noon, when the cost is lower then during afternoon.

Table 5.4: The four zones pricing.

Time application	Rate	Rate(fixed fees included)	Unit	Symbol
24:00 to 6:00	0.12	0.231	zl/kWh	G1
6:00 to 12:00	0.15	0.261	zl/kWh	G2
12:00 to 18:00	0.177	0.288	zl/kWh	G3
18:00 to 24:00	0.19	0.301	zl/kWh	G4

5.2.2 Optimization process

The main assumption for this work is that the EV owners are using the electric vehicle for driving in a specific pattern described in Table. 5.3. Therefore no adjustments to the EVs availability depending on the electricity price are considered in this project. It is assumed that the EV owners want to charge their electric vehicle at the lowest available price depending on the driving patterns. To generate the EV load profile an optimization process is utilized, with the charger power demand as a variable, and the cost for the EV home-charging as cost function. The EVs owners focus on the economical inputs rather then the integration issues. The optimization process is introduced to minimize the cost for the customer along with the assurance that the voltage and line loading is within the limits. The optimization process is implemented with a MATLAB script and the objective is to determine the daily electricity cost for the EV home-charging. The cost function can be expressed as an integral of the energy demand of the EV charger e(t), multiplied by the price of electricity c(t), over a period of time dt. The daily cost function can then be expressed as:

$$f(p) = \int_{1}^{24} e(t) * c(t) dt \tag{5.1}$$

Since the Time of Day tariff prices are constant for every hour, the cost function equation can be simplified. It can be represented as the sum of the products between the hourly power demand of the EV charger (p_i), and the hourly cost of electricity (c_i). The optimization process can be expressed as a linear optimization problem. Hence, it may be written as followed:

$$f(p) = c_1 * p_1 + ... + c_{24} * p_{24} = \sum_{i=1}^{24} c_i * p_i \tag{5.2}$$

The charger power demand cannot be negative because no V2G function is considered ($p_i \geq 0$). Also the maximum charging power should not exceed the rated power of the charger ($p_i \leq P_{max}$). With this assumption the constraints can be defined:

$$p_i \geq 0$$

$$p_i \leq P_{max}$$

$$i = 1, 2, ..., 24$$

By defining the limits regarding the maximum charging power as mentioned above the EV availability is taken into account by assuming the following values:

$$P_{max} = \begin{cases} 0 & \text{if the EV is not available} \\ P_{max} & \text{if the EV is available} \end{cases}$$

When the electric vehicle is not available then the power demand is equal zero. However if the EV is available to the home-charging then the maximum power demand is varying in the range between 0 and P_{max}. It is assumed that the SOC battery is restored every 24 hours to the specific value provided in Table. 5.3.

By knowing the parameters such as $SOC_{arrival}$, SOC_{max} and driving patterns the power needed to charge the battery can be determined. Therefore, the additional constraint can be formulated:

$$\sum_{i=1}^{24} p_i = SOC_{max} - SOC_{arrival} \tag{5.3}$$

The summarized optimization problem can be expressed as following equations.

cost function:

$$f(p) = \sum_{i=1}^{24} c_i * p_i \tag{5.4}$$

subject to:

$$i = 1, 2, ..., 24 \begin{cases} p_i \geq 0 \\ p_i \leq P_{max} \\ \sum p_i = SOC_{max} - SOC_{arrival} \end{cases}$$

After the cost function is applied in the algorithm and the EV load profile is utilized the voltage range is checked at every hour. The final demand profile is generated when the voltage at every hour is between $0.95<V<1.05$.

5.2.3 Simulation results

This section demonstrate the simulation results of the integration in the considered residential network, in terms of grid bottlenecks and increase of the grid PV hosting capacity. First the quality indicators as well as electricity price and hosting capacity for the TOD three zone case are presented. After that the new concept four zone scenario and all of the results are introduced.

3 zone case

Optimization process for this case results in an average price 0.259 zl per one kWh for every EV owner. The cost is an average for the 20 EVs simulated for 100% penetration to measure without any influence from the driving habits the particular owner. This value was evaluated by the obtained cost function value ($f(p)$) and divided with the weekly EV demand. The obtain price is closer to the cost of G1 rate then to the highest price. Therefore, its proving the efficiency of the minimization of the EV charging cost by the implemented algorithm. The busbar 32 is chosen to show the voltage variation, since it is the furthest busbar of the grid and has the highest voltage sensitivity, where the voltage magnitude perturbations will present their peak values. In Table. 5.5 the integration power quality indicators for different EV shares and 3 zones TOD scenario are presented. Due to the voltage limits included in the algorithm all of the constraints are fulfilled for every EV share percentage. As it can be seen the voltage at the busbar 32 is decreasing while adding more electric vehicle into the grid. The lowest voltage value is set to 0.952 pu. Additionally the line losses as well as cable loading are increasing with the rise of EVs shares because higher power is demanded from the external grid.

Table 5.5: Summarized power quality indicators for different EV shares for three zone case.

		EV share[%]			
Power quality indicators	**Limits**	**25**	**50**	**75**	**100**
Bus32 minimum voltage	0.95pu	0.964	0.96	0.958	0.952
Bus32 maximum voltage	1.05pu	1.04	1.036	1.03	1.027
Line loading	100%	38.1	41.32	45	53.7
Line losses	-	0.1	0.132	0.173	0.21

In Fig. 5.5 the 20 EVs combined demand profile for a typical day is presented. As it can be seen from the cumulative plot most of the EVs start to charge as soon as the price of electricity moves to the lowest price value. The most EVs are charge during late evening which could in some point overlap the evening load peak and cause undervoltages in the end of the feeder. To fulfill the constraints higher charging demand is during the night and early morning. Since the number of EVs plugged into the network increased it is resulting in an additional load, which is causing additional line losses.

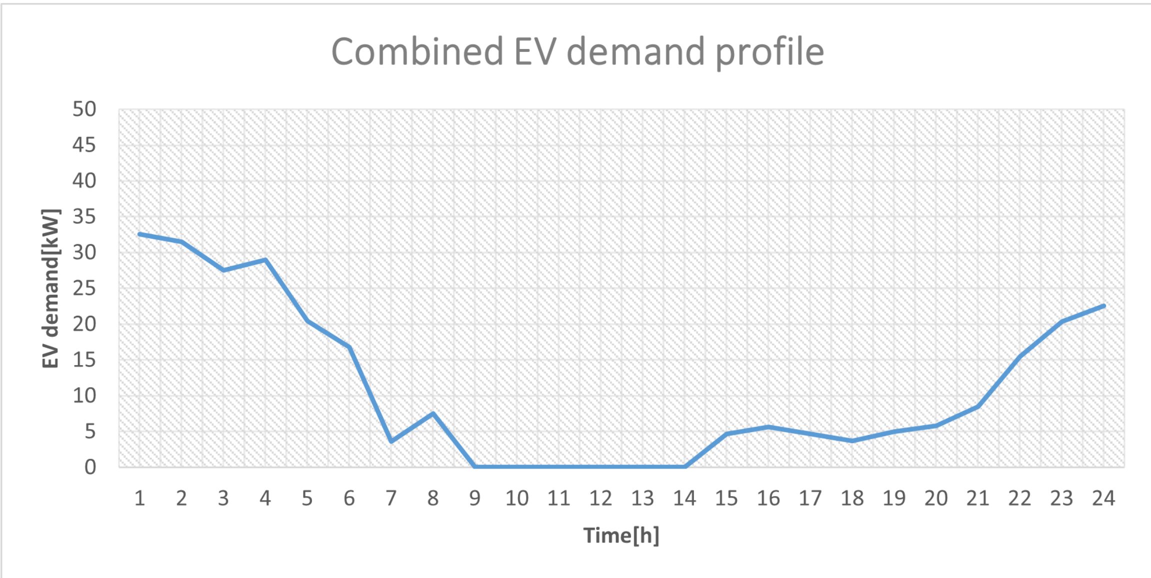

Figure 5.5: Combined 20 EVs demand profile for three zone case.

In Fig. 5.6 the voltage magnitude B32 for a typical day is presented. It can be seen that during night and early morning (24:00 to 6:00) as well as late evening (20:00 to 24:00)the voltage droops occurs as expected. However without the additional load during the working hours due to the PV generation a voltage rise is introduced.

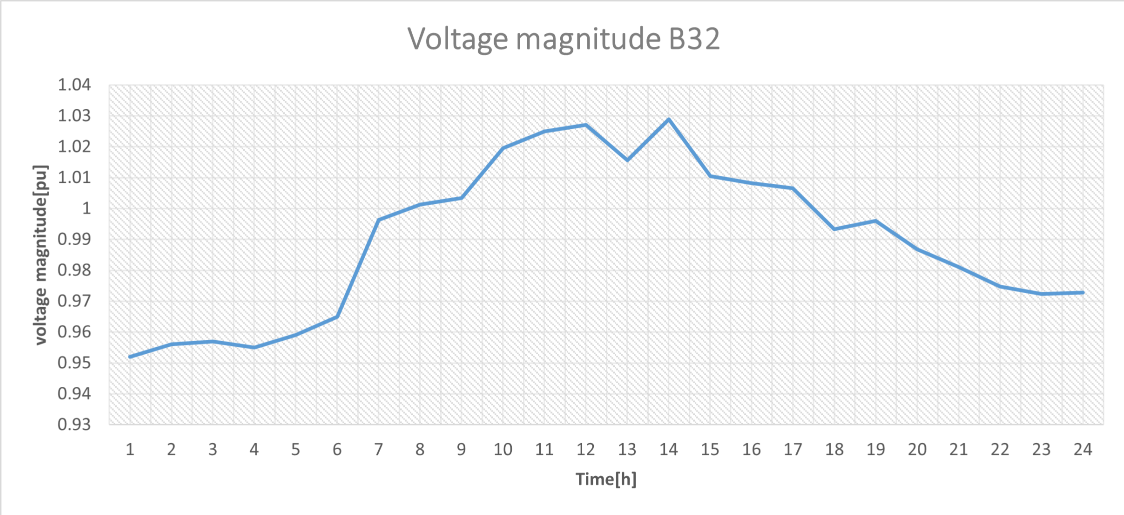

Figure 5.6: Voltage magnitude B32 with 100% penetration for three zone case.

In Fig. 5.7 the summarized voltage magnitude B32 for different EVs shares is presented. It can be seen as expected that the lowest voltage magnitude is when the Ev share is 100% and can reach 0.952 pu. Additionally while 25% of electric vehicle is installed the highest voltage magnitude occurs and reaches 1.04 due to the lower self consumption of PV systems.

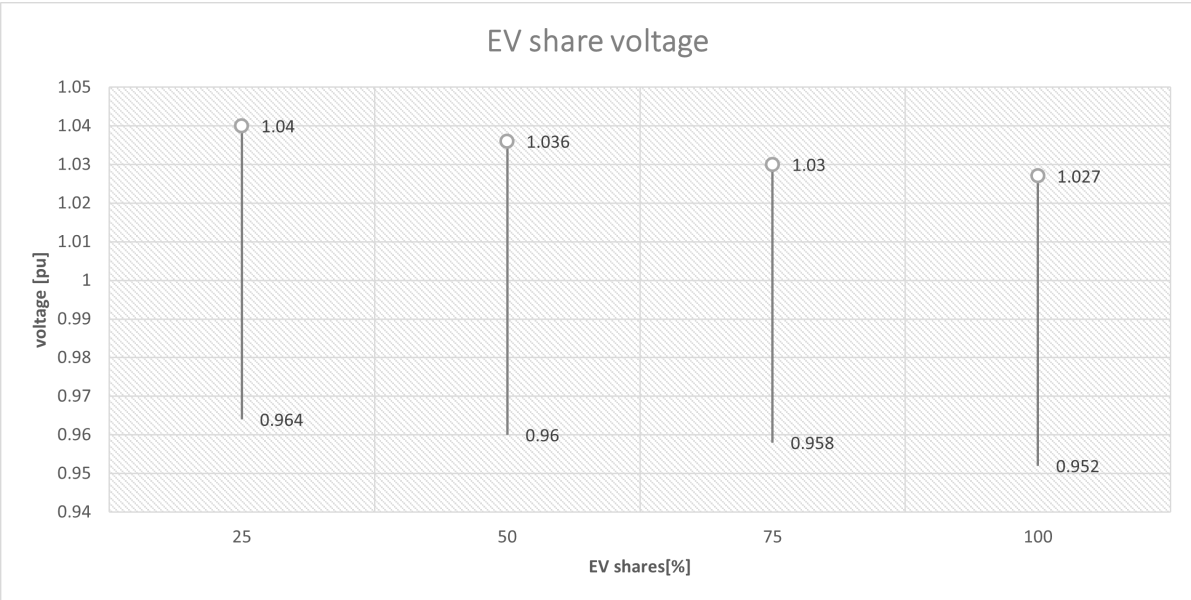

Figure 5.7: Summarized voltage magnitude B32 for every penetration percentage,three zone case.

In Table. 5.6 the hosting capacity for different EV shares and 3 zones TOD scenario are presented. The impact of the integration of electric vehicle to increase the PV hosting capacity is limited to 8.6% at highest. The reasons for this small increase in the hosting capacity of PV systems are to be found in the structure of the TOD tariff. This is caused by encouraging the EV owners to charge during the time when most of the power from solar panels are not available.

Table 5.6: Hosting capacity for different EV shares TOD scenario,3 zones.

		EV share[%]				
	units	**0**	**25**	**50**	**75**	**100**
Individual hosting capacity	kW	2.8	2.9	2.98	3.02	3.043
Grid hosting capacity	kW	56	58	59.6	60.4	60.86
Variation of hosting capacity	%	-	3.5	6.4	7.8	8.6

In the following paragraphs the same analysis will be performed for the four zone case.

4 zone case

Optimization process for this case results in an average price 0.242 zl per one kWh for every EV owner. As in the previous case the cost is an average for the 20 EVs cost functions in order to not have any kind of influence by driving habits. This value is a little bit lower then in the three zone case and much closer to the G1 price from Table.5.4. A comparison between the cost of electricity is available in Table.5.14. In Table. 5.7 the integration power quality indicators for different EV shares and 4 zones TOD scenario are presented. From the data it can be seen how the implementation of the additional zone is impacting the power quality indicators. As it can be seen all of the voltage at the busbar 32 for different Ev shares are in the limit range. The highest voltage point is set to 1.042 pu while the lowest can reach 0.951 which does not violate the constraints. With the slight increase of the PV self consumption the cable loading as well as line losses are decreasing proportionally.

Table 5.7: Summarized power quality indicators for different EV shares for four zone case.

		EV share[%]			
Power quality indicators	**Limits**	**25**	**50**	**75**	**100**
Bus32 minimum voltage	0.95pu	0.969	0.966	0.962	0.951
Bus32 maximum voltage	1.05pu	1.042	1.039	1.034	1.028
Line loading	100%	37.4	40.45	43.9	52.3
Line losses	-	0.097	0.119	0.171	0.19

In Fig. 5.8 the 20 EVs combined demand profile for a typical day is presented. It can be seen on the cumulative plot almost all of the EVs are charged during night and in the morning because the prices shifted from being expensive to the midnight to have a lesser cost before noon. Therefore the charging demand is expanded to 10 o'clock. A small load value still can be seen on the evening despite the higher price due to the driving habits and constraints of the customers.

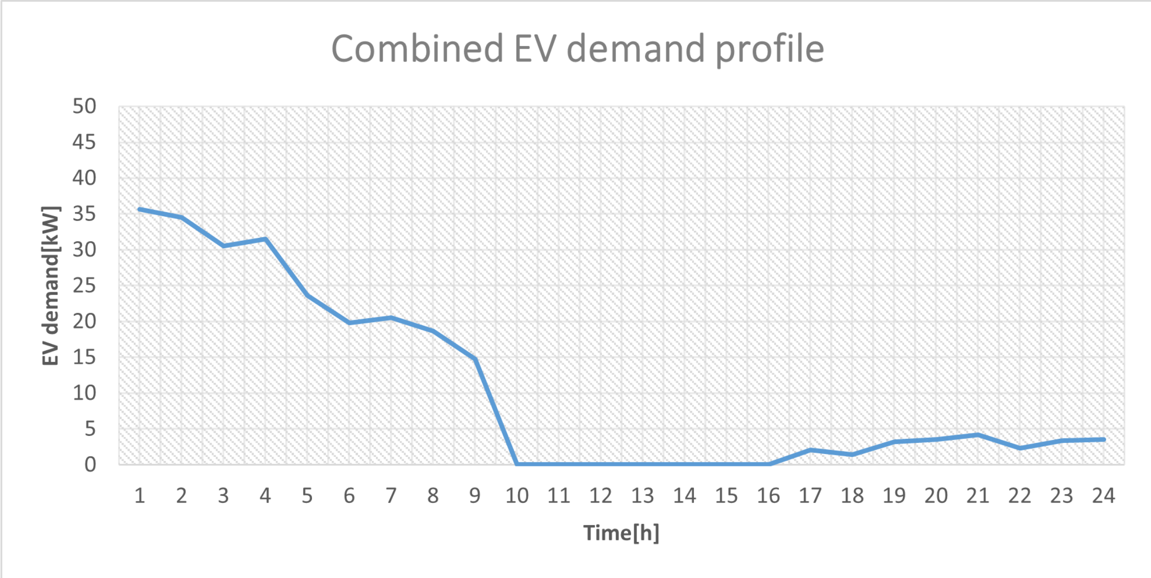

Figure 5.8: Combined 20 EVs demand profile for four zone case.

In Fig. 5.9 the voltage magnitude B32 for a typical day is presented. Comparing to the voltage state at the furthest busbar in the previous case, in the four zone case the voltage is lower from 7:00 to 9:00 due to the demand increase and higher during late evening because of the shifted load to the morning.

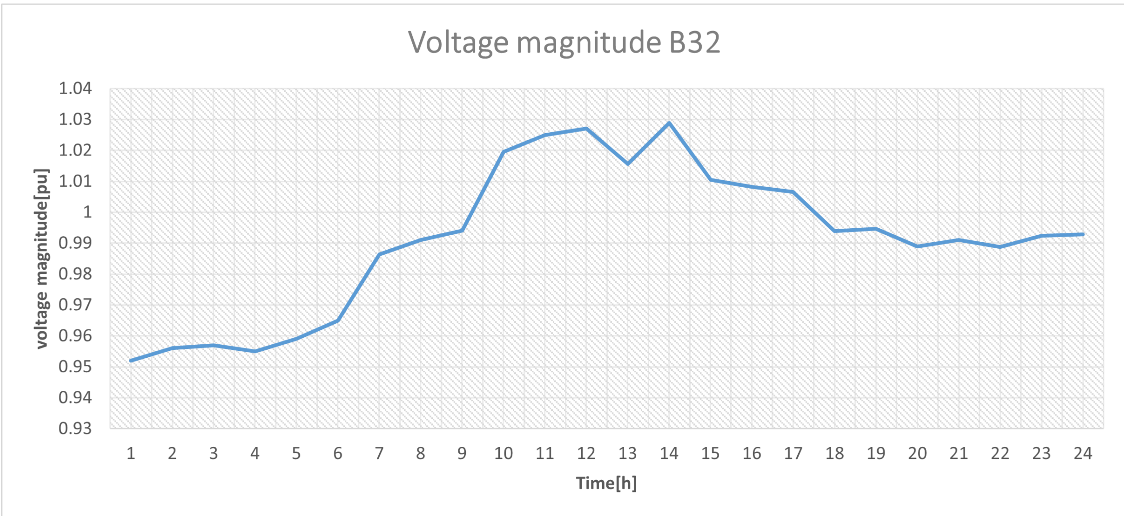

Figure 5.9: Voltage magnitude B32 with 100% penetration for four zone case.

In Fig. 5.10 the summarized voltage magnitude B32 for different EVs shares is presented. As it could be seen in the three zone case the lowest voltage magnitude is when the EV share is 100% and can reach 0.951 pu, while for the 25% share the highest voltage magnitude occurs and reaches 1.042.

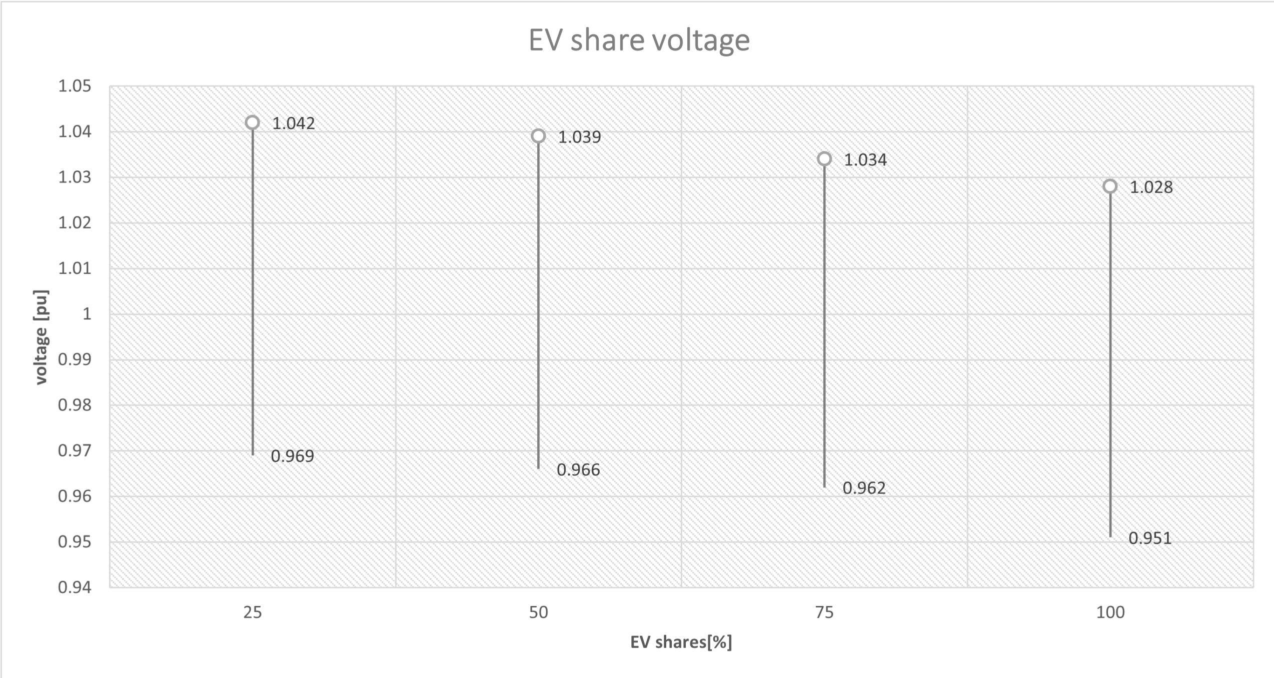

Figure 5.10: Summarized voltage magnitude B32 for every penetration percentage,four zone case.

In Table. 5.8 the hosting capacity for different EV shares and 4 zones TOD scenario are presented. As in the previous case the rise of hosting capacity is restricted due to the low PV self consumption. However there is a slight increase in regards to the previous 3 zone case, by shifting the charging demand from late evening to the lower cost time interval which is after 6 0'clock. Hence, the PV self consumption rises marginally and the highest hosting capacity reaches 9.7%.

Table 5.8: Hosting capacity for different EV shares TOD scenario,4 zones.

		EV share[%]				
	units	**0**	**25**	**50**	**75**	**100**
Individual hosting capacity	kW	2.8	2.94	3	3.04	3.07
Grid hosting capacity	kW	56	58.7	60.03	60.78	61.44
Variation of hosting capacity	%	-	4.8	7.2	8.5	9.7

In the next section the Net Metering scenario is propose. A new approach to the EV optimization procedure is introduced. Hence, to minimize the cost for home charging the electric vehicle the domestic load demand and PV generation profile is included in the function as well. The proposed optimization will take into account the possibility to charge the EVs with the PV generation excess power.

5.3 Net Metering scenario

In this section the Net Metering scenario is presented. First the cost of electricity when the Net Metering tariff is implemented is shown. Afterwards the optimization process is introduced. In the end the simulation results are described.

5.3.1 Net Metering tariff for residential customers

Net metering tariff is used when the customer with self generated power from PV units have an excess of energy. The delivered power to the grid from the solar panels is sold to the utility but with a lower rate then the common electricity prices [55]. The obtained savings of the PV owner under net metering conditions is the sum of two components. The first component is the value of the PV energy self-consumed that has not to be bought from the grid. It can be computed as the PV power generated and self-consumed multiplied by the hourly TOD electricity tariff price. The second value is the price of the power excess from PV units, which has to be injected into the network. The purpose of net metering is to reduce the reverse power flow in the feeder. For this reason the maximum economic benefit for the PV owner is realized when the PV generated energy is instantaneously self-consumed, rather than injected and consumed in a different time. In the net metering strategy, there is one bi-directional meter, which can run forward and back-ward, measuring imported minus exported energy in kWh [56]. In Fig. 5.11 the scheme for net metering strategy is presented. Where DE is demand of energy(electricity demanded by the load),GE is generation of energy(electricity produced by the PV generator),EE is exported energy(electricity injected to the grid), and IE is imported energy (electricity consumed from the utility).

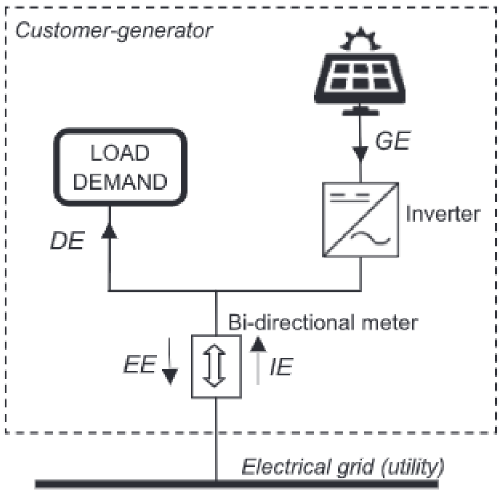

Figure 5.11: The net metering scheme[56].

In Table.5.9 the summarized prices utilized in the net metering case have been presented. As it can be seen in the table an added price which describe the fee for excess of PV generation and is equal to 0.06 zl/kWh.

Table 5.9: The electricity prices in the net metering scenario.

Application	Price(fixed fees included)	Unit
TOD (G1)	0.231	zl/kWh
TOD (G2)	0.261	zl/kWh
TOD (G3)	0.288	zl/kWh
TOD (G4)	0.301	zl/kWh
Net Metering(PV)	0.06	zl/kWh

The economical solution to increase the benefits for the residential customer is to increase the self consumption of PV generated energy. This can be done by shifting the deferrable loads such as electric vehicle when the power generation from PV units is the highest. In the next section the optimization process has been presented. Furthermore it will be proved that the net metering strategy is economically more suitable for the EV owners than the TOD tariff (charging during off peak hours). Additionally it is limiting the reverse power flow in the grid and increases the PV self consumption.

5.3.2 Optimization process

Smart charging of the EVs in a residential network is interpreted into an optimization problem. The purpose is to minimize the cost of energy for the electric vehicle owners. Similar optimization process is introduced in section. 5.2.2. However, in this case the domestic consumption as well as PV generation are added to the cost function.

The price is calculated by indicating if the TOD tariff price is used or the net metering price. If the hourly energy consumption is exceeding the PV production then the TOD price is utilized. While if the PV generation surpass the household demand and EV load then c_{PV} value is used. The optimization problem for this scenario can be expressed as:

cost function:

$$f(p) = \sum_{i=1}^{24} c_i * (p_i + P_{household} - P_{PV}) \tag{5.5}$$

where:

$$c_i = \begin{cases} c_{PV} & \text{when} \quad p_i + P_{household} - P_{PV} \geq 0 \\ c_{TOD} & \text{when} \quad p_i + P_{household} - P_{PV} < 0 \end{cases}$$

subject to:

$$i = 1, 2, ..., 24 \begin{cases} p_i \geq 0 \\ p_i \leq P_{max} \\ \sum p_i = SOC_{max} - SOC_{arrival} \end{cases}$$

5.3.3 Simulation results

3 zone case

The minimization of the weekly cost of electricity for the residential user results in an average price equals to 0.15 zl/kWh. this value was determined with the use of complete domestic demand for the considered week ,which consist the household and EV demand as well. The savings originated from the increased self-consumption of the PV generated energy and the costs coming from the PV energy excess injected into the network. The obtained price is significantly lower comparing to the TOD tariff. However this price cannot be directly compared to the TOD scenario, since the cost functions are different. In Table.5.10 the integration power quality indicators for different EV shares and 4 zones TOD scenario are presented. It can be seen that the highest voltage magnitude occurs when the 25% EV share is applied and can reach 1.028 pu. Comparing to the TOD scenario there is a significant decrease while the EV charging hour were shifted. The lowest voltage magnitude equals 0.955 which is within the limits. The line losses as well as cable loading are slightly lower comparing with the TOD case, because the greater part of EV demand is consuming energy from the power generated by PV units. Therefore the cable are lesser loaded then in the TOD case.

Table 5.10: EV integration results for three zone case

		EV share[%]			
Power quality indicators	**Limits**	**25**	**50**	**75**	**100**
Bus32 minimum voltage	0.95pu	0.972	0.967	0.96	0.955
Bus32 maximum voltage	1.05pu	1.028	1.021	1.016	1.012
Line loading	100%	36.8	39.16	42.21	50.56
Line losses	-	0.088	0.107	0.134	0.179

In Fig. 5.12 the 20 EVs combined demand profile is presented. It can be seen That most of the charging occurs during the daylight hours where the power from Pv units can be utilized. Still there are charging during nigh time and late evening. This is cause by the drivers habits and lower price comparing to the other hours during the day.

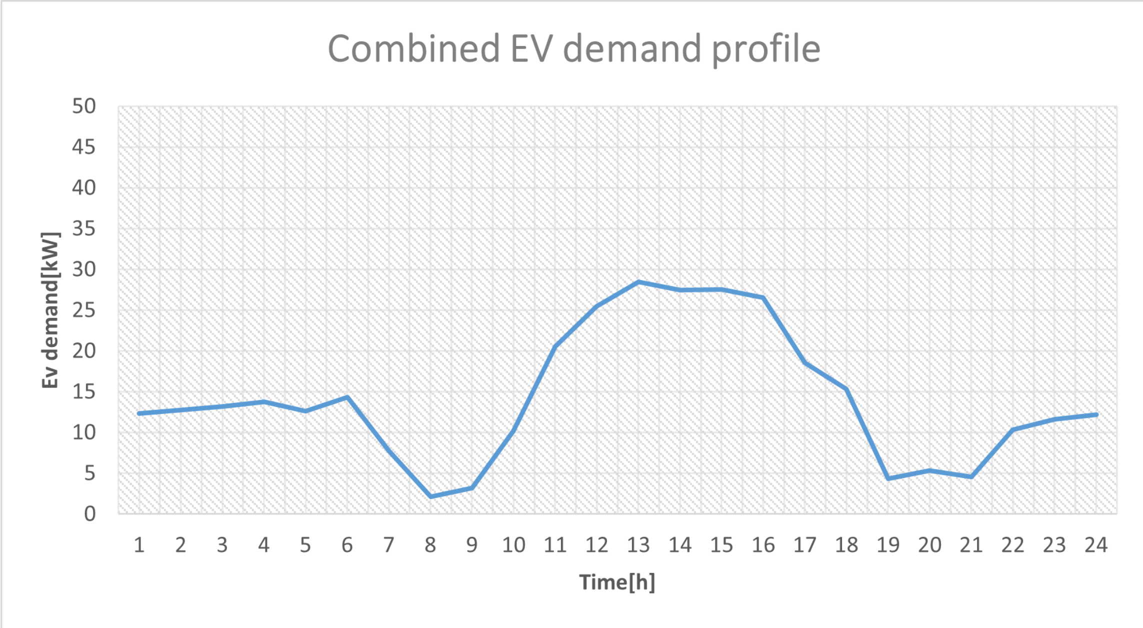

Figure 5.12: Combined 20 EVs demand profile for three zone case.

In Fig. 5.13 the voltage magnitude B32 is presented. The voltage magnitude comparing to the TOD scenario has a decrease at the highest point due to the added load during these hours. The same pattern can be seen during the night when the voltage is reaching almost the limits.

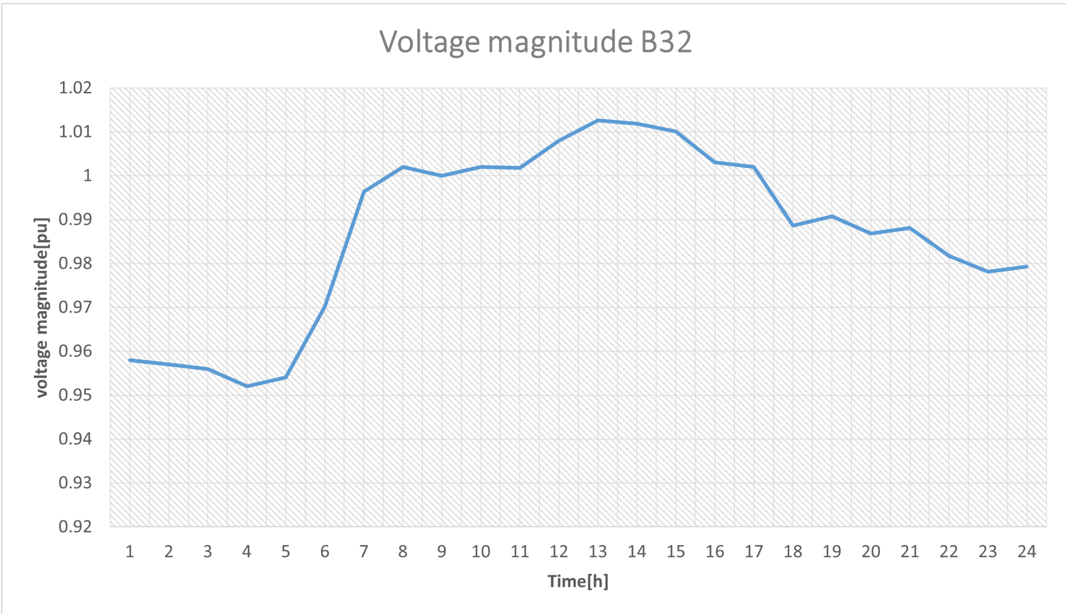

Figure 5.13: Voltage magnitude B32 for three zone case.

In Fig. 5.14 the summarized voltage magnitude B32 for different EVs shares is presented. As it could be seen in the three zone case the lowest voltage magnitude is when the EV share is 100% and can reach 0.955 pu, while for the 25% share the highest voltage magnitude occurs and reaches 1.028. Comparing to the TOD scenario the decrease of the highest voltage magnitude can be seen clearly.

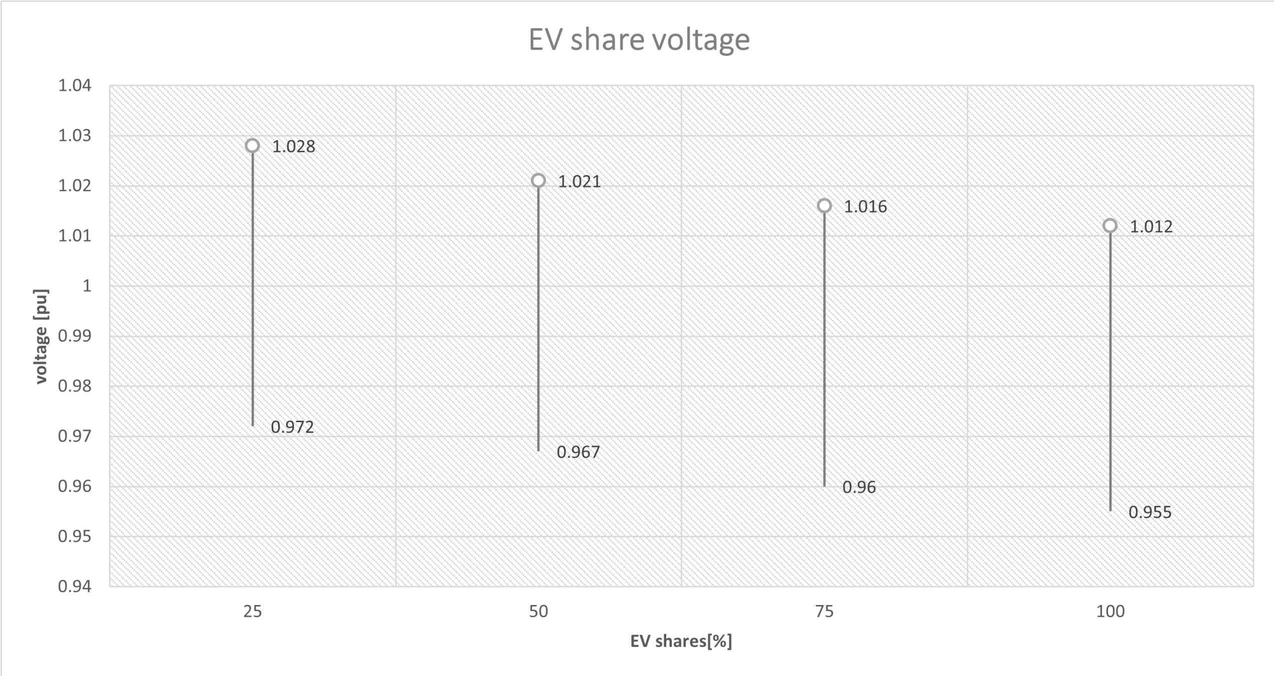

Figure 5.14: Voltage magnitude B32 for three zone case.

In Table. 5.11 the hosting capacity for different EV shares and 3 zones TOD scenario are presented. In this scenario the increase of the PV hosting capacity is rising proportional to the EV share in the grid. The maximum hosting capacity for the whole network is over 78 kW for a 100% EV share in the grid, which is more than 40% over the hosting capacity at the state without any EVs installed in the grid. Unlike the TOD tariff, the net metering functionality allows to obtain a more profitable strategy when the EV owners are charging during daylight hours to increase the self consumption of PV units.

Table 5.11: Hosting capacity for different EV shares TOD scenario,3 zones

		EV share[%]				
	units	**0**	**25**	**50**	**75**	**100**
Individual hosting capacity	kW	2.8	3.276	3.69	3.83	3.92
Grid hosting capacity	kW	56	65.52	73.93	76.6	78.5
Variation of hosting capacity	%	-	17.2	32	36.8	40.2

4 zone case

Optimization process for this case results in an average price 0.12 zl per one kWh for every EV owner. This value is the lowest from all of the cases presented in this work. Therefore an conclusion can be made that the most profitable strategy is the four zone net metering tariff. A comparison between the cost of electricity for all of the cases is available in Table.5.14. In Table. 5.12 the integration power quality indicators for different EV shares and 4 zones TOD scenario are presented. It can be seen that the highest voltage magnitude occurs when the 25% EV share is applied as expected and can reach 1.025 pu. Comparing to the net metering three zone case there is a slight decrease. The lowest voltage magnitude reaches 0.951 which is caused by the higher demand in the morning. However this value is close to the constraints it is still acceptable and in the limits. The line losses as well as cable loading are slightly lower comparing with the three zone case.

Table 5.12: EV integration results for three zone case

		EV share[%]			
Power quality indicators	**Limits**	**25**	**50**	**75**	**100**
Bus32 minimum voltage	0.95pu	0.97	0.962	0.957	0.951
Bus32 maximum voltage	1.05pu	1.025	1.02	1.017	1.01
Line loading	100%	35.5	38.6	41.8	48.45
Line losses	-	0.076	0.102	0.127	0.153

In Fig. 5.15 the 20 EVs combined demand profile is presented. The changes comparing to the three zone case can be seen at th evening and after 6 o'clock. In this four zone case the profitable hours to charge the EVs are shifted from evening to the morning. A significant decrease of demand are from 20:00 to midnight. However this load is shifted to hours before work to minimize the cost.

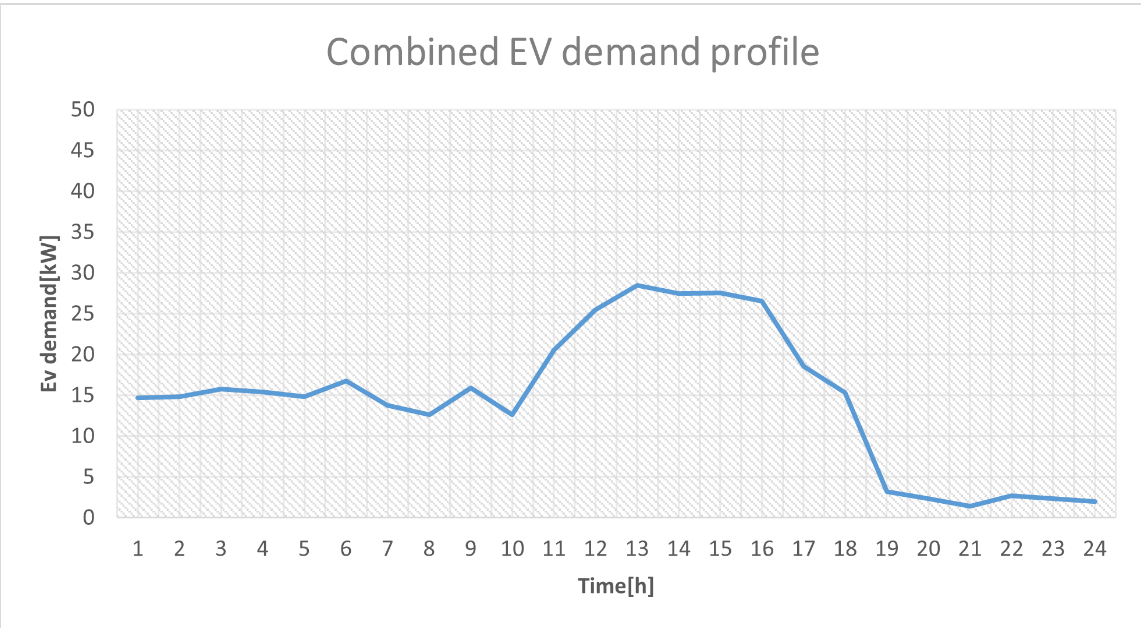

Figure 5.15: Combined 20 EVs demand profile for three zone case.

In Fig. 5.16 the voltage magnitude B32 is presented. From the EV demand profile it can be concluded that the voltage magnitude will change in the same hours as the demand. It is clear that the voltage rises in the late evening due to the lack of demand which can decrease the voltage. A change can be seen during hours where the load was shifted as well.

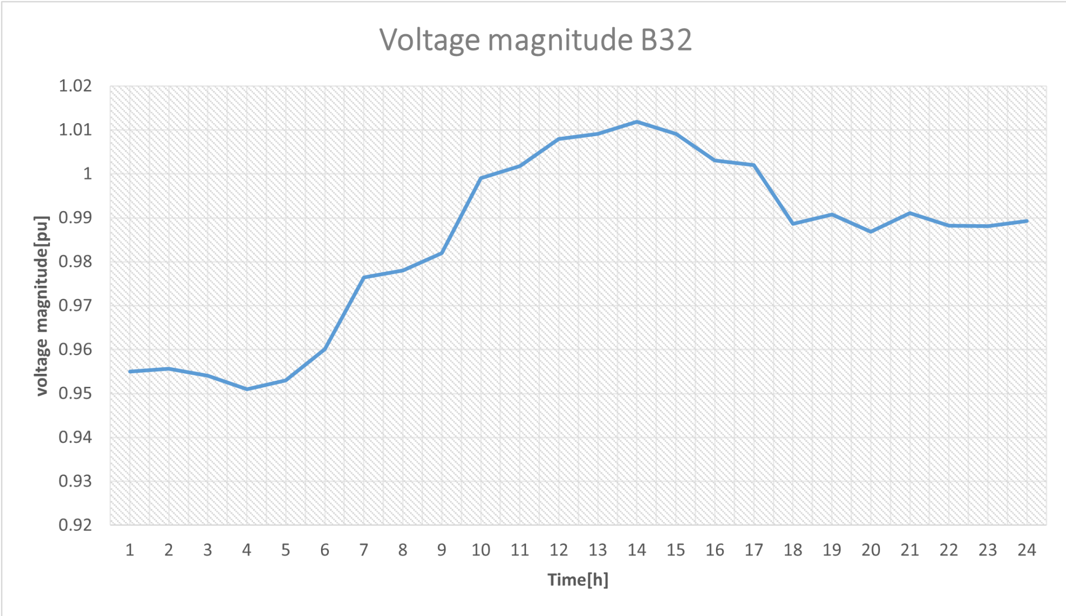

Figure 5.16: Voltage magnitude B32 for three zone case.

In Fig. 5.17 the summarized voltage magnitude B32 for different EVs shares is presented. As it could be seen in the four zone case the lowest voltage magnitude is when the EV share is 100% and can reach 0.951 pu, while for the 25% share the highest voltage magnitude occurs and reaches 1.025. Comparing to the the three zone case it is a decrease equal 0.003 pu.

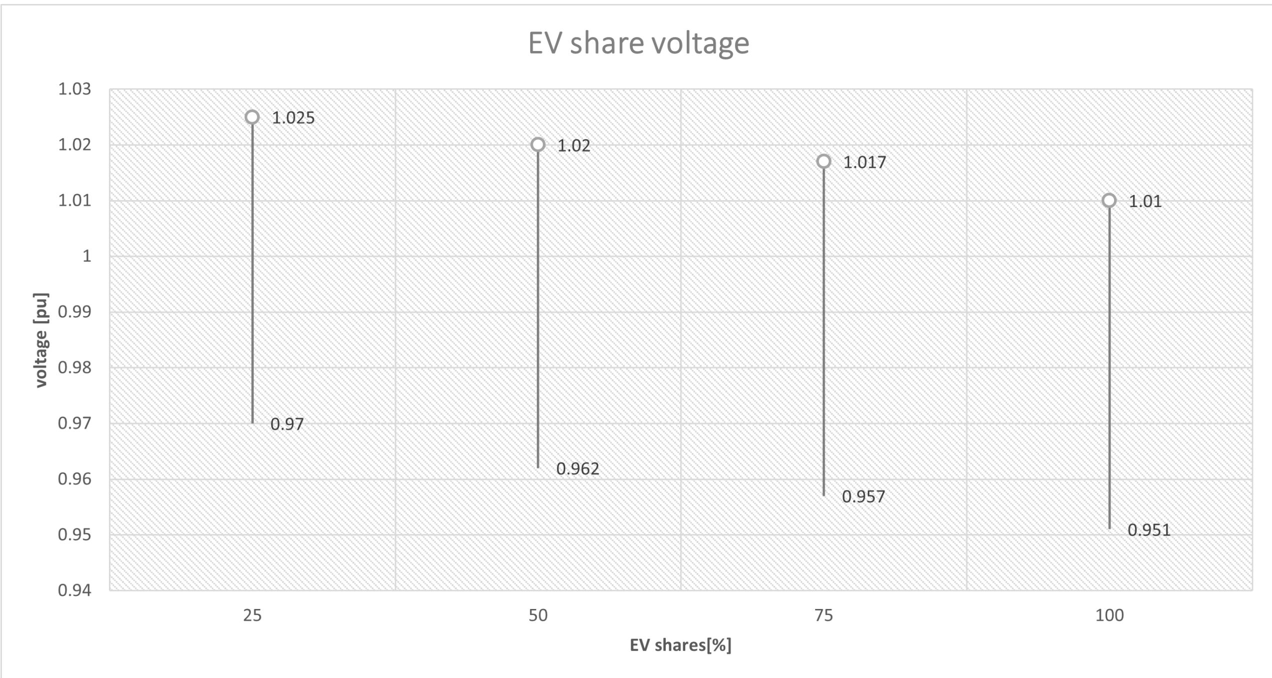

Figure 5.17: Voltage magnitude B32 for three zone case.

In Table. 5.13 the hosting capacity for different EV shares and 4 zones TOD scenario are presented.

In this case the hosting capacity has been increased comparing to the previous 3 zone case. It can be seen that the highest hosting capacity which can be obtained is 44.2% for the maximum EV share in the residential grid.

Table 5.13: Hosting capacity for different EV shares TOD scenario,4 zones

		EV share[%]				
	units	**0**	**25**	**50**	**75**	**100**
Individual hosting capacity	kW	2.8	3.33	3.78	3.94	4.04
Grid hosting capacity	kW	56	66.64	75.6	78.74	80.75
Variation of hosting capacity	%	-	19.8	35.3	40.6	44.2

5.4 Discussion

In this section a comparison between the results of the TOD and Net metering scenarios are presented. These two scenarios are divided into two cases with different time zones for electricity pricing. First the minimized cost of the purchased electricity for each kWh and for different zones is calculated. With the minimized cost and obtained EVs load profiles the integration in the residential network was analyzed. In the end, the impact of the different EV charging strategies on the grid PV hosting capacity is evaluated. Based on the results from the conducted simulations, it can be seen how the EVs implementation can overcome the voltage issues while installing only PV system into the LV residential network. The EV load profile as well as minimized cost are determined with the voltage +/-5% constraint. The implementation of EV charger is effective in reducing the impact of the PV generation on the voltage magnitude, and allows a higher self consumption of power from solar panels. It has been shown that while minimizing the cost of EV charging the hosting capacity can be increased while fulfilling the constraints. In Fig. 5.18 and Fig. 5.19 the comparison of voltage magnitude for all of scenarios are presented. It can be seen that the highest voltage is while the TOD 4 zone case is simulated and can reach 1.042 pu, while 25% of EVs are installed. Moreover the lowest point of voltage is very close to the voltage constraint and the only cases where it can be seen is the TOD 4 zone and net metering 4 zone scenarios.

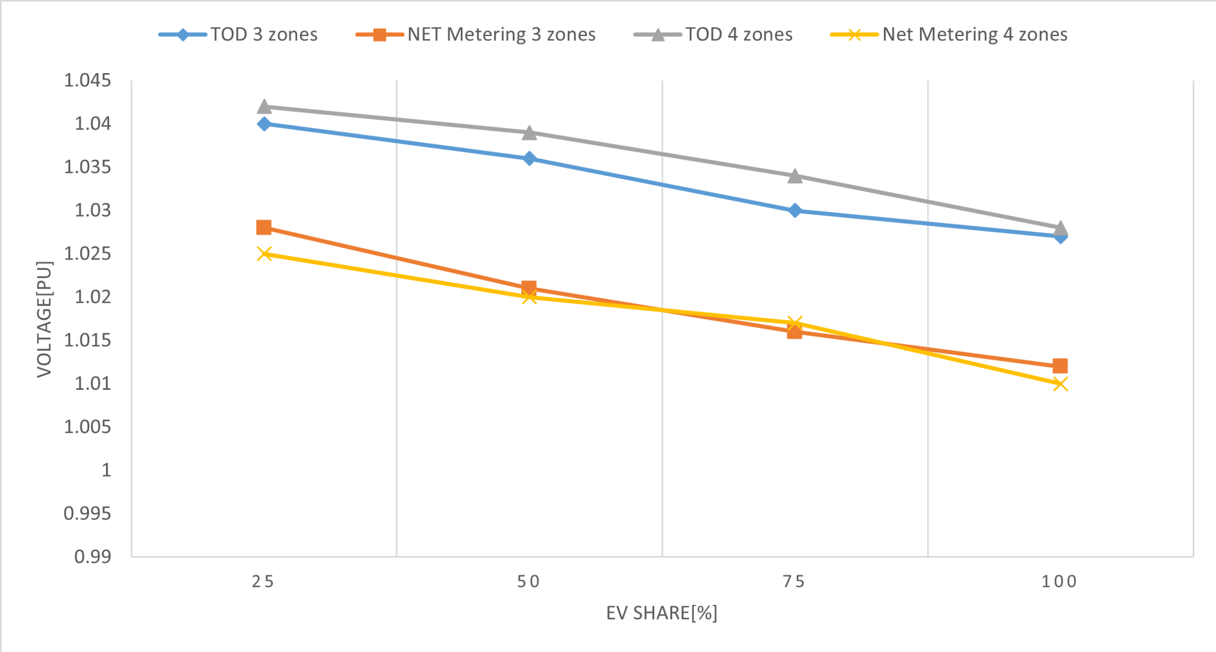

Figure 5.18: Higher range of voltage magnitude for different EV shares and pricing strategies.

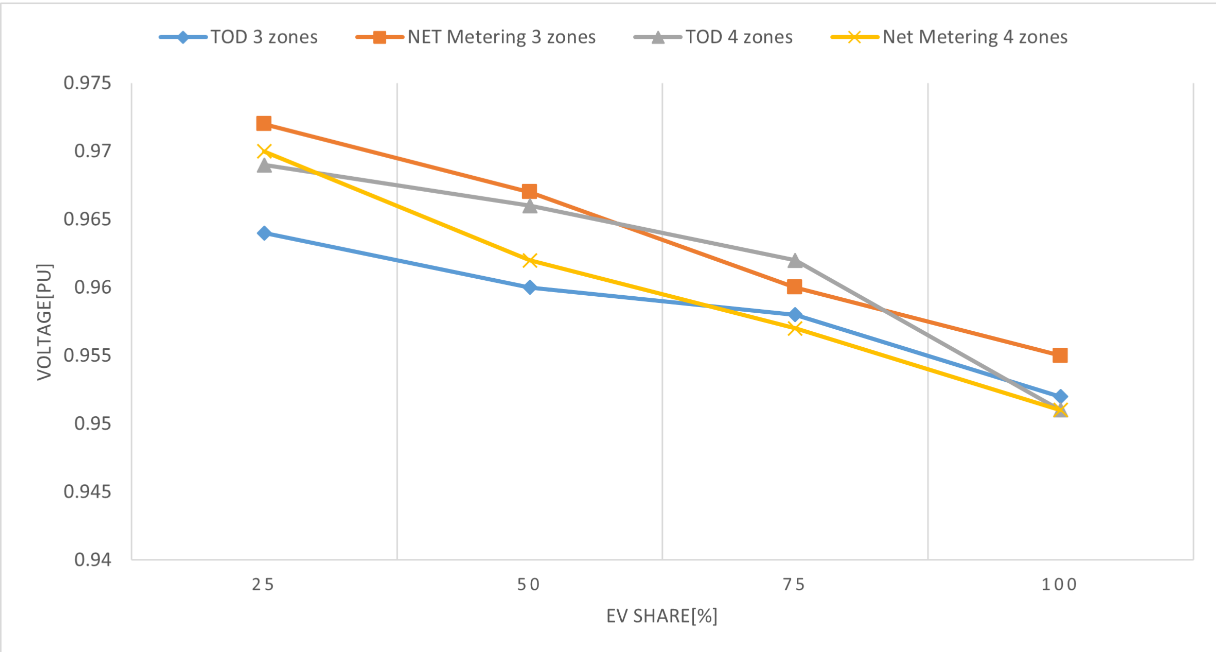

Figure 5.19: Lower range of voltage magnitude for different EV shares and pricing strategies.

5.4.1 Cost of the EV owners

A comparison of the residential network average cost of electricity for TOD as well as Net metering case is presented. It can be noticed that the average costs of electricity between TOD and Net Metering cases cannot be directly comparable, because no household load as well as PV generation are included in the time of day scenario cost function. In the Table. 5.14 the comparison of electricity cost between TOD and Net Metering scenarios is presented. It can be seen that implementation of the 4 zone case can decrease the electricity price for one kWh in both cases. The reduction is due to the addition of lower cost time interval and by shifting the charging from evening to the hours before noon along with not violating the constraints. The lowest price can be seen for the 4 zone net metering case because most of the charging is during solar panels generation.

Table 5.14: Comparison of electricity cost between TOD and Net Metering scenarios.

Scenario	Case	Average cost of electricity(with fixed fees) [zl/kWh]
TOD	three zone	0.259
	four zone	0.242
Net Metering	three zone	0.15
	four zone	0.12

5.4.2 Impact on the hosting capacity

The Net metering scenario allows a significant increase of the hosting capacity, because for this case the EV owners most convenient charging time is during working hours when PV generation is the highest. The time of day tariff is not efficient for the EV and PV integration if the net metering tariff is unavailable. Since when the TOD tariff is used the EV owners are overlapping the EV demand profile with the evening peak load demand rather than charge the electric vehicle during the PV peak production. In the Table. 5.15 the maximum PV hosting capacity compared between TOD and Net Metering scenarios for different EV penetration is presented. It can be seen that the highest increase of hosting capacity is for the net metering 4 zone case and can go up to 44.22%. This result is as expected because most of the EV load is covered by the power generation from PV system. Therefore the self consumption of solar panels is higher then during TOD scenario.

Table 5.15: PV hosting capacity compared between TOD and Net Metering scenarios.

		EV share[%]			
Scenario	Case	25%	50%	75%	100%
TOD	three zone	+3.5	+6.4	+ 7.8	+ 8.6
	four zone	+4.8	+7.2	+8.5	+9.7
Net Metering	three zone	+17.2	+ 32	+ 36.8	+40.2
	four zone	+19.8	+35.3	+40.6	+44.2

6 Conclusions and Future work

This chapter will conclude on the important findings presented in the report.

6.1 Conclusions

The goal of this project was to investigate the effect of PV systems and EV charging station in a residential network while minimizing the electricity cost and increase the hosting capacity. This has been done by analyzing the background regarding the integration of electric vehicles and solar panels. In the second chapter the description of the challenges and solutions for implementing PVs and EVs into the residential grid has been shown. After acquainting the theory a simulation in MATLAB for the considered grid was conducted.

In Chapter 3 the considered LV residential network model was introduced along with all of the necessary grid parameters. Furthermore the data analysis which consist the household load profile as well as PV generation profile is presented. This analysis also includes the standard data for the household loads such as peak consumption, weekly consumption or main appliances located in the house. Likewise the information about the PV system on each house has been provided as well. Additionally the Ev availability for home charging was introduced and described. In the end of this chapter a load flow analysis with the basic case (without PVs and EVs) in POWERFACTORY was conducted. The purpose of this simulation was to shown the voltage issues occurring in the considered LV grid, when the solar panels are not installed.

In Chapter 4 the PV integration in the residential grid is analyzed, from a load flow point of view conducted in MATLAB. To evaluate the considered grid specific power quality indicators were checked for different EV percentage penetration. Additionally the simulation results are compared with the outputs from simulation where only household load was included. The results are clearly demonstrate that the PV integration cannot be without any grid issues. The problematic indicator in this case is the voltage magnitude. Hence, it can be seen that during the implementation of solar panels the voltage exceeds the allowable 1.05 pu point while 75% and 100% of PV systems are installed. When all of the PV systems are implemented the voltage rise above the limits two times while for 75% PV share only once during the whole week. Also it has been shown that at any point of time the cable loading is not causing any issues. However it can be seen clearly that without the the solar panels the cable loading rise significantly. In the end of this chapter the hosting capacity was determined. A special algorithm was implemented to measure the available PV capacity which can be used without causing any issues. After the simulation the hosting capacity for the whole grid was calculated and equals 56 kW, which corresponds to 2.8 kW for each PV system. From the results obtained it can be concluded that the overvoltage issue is the limiting factor to increase the utilization of power from solar panels. Therefore, an additional deferrable load could help in overcoming this voltage issue.

In Chapter 5 the smart charging of EVs in a distribution grid is presented. As an introduction to the problem a simulation procedure where the flowchart of the used algorithm and data of the electric vehicle for each owner has been described. The electric vehicle integration is divided into different percentage penetration as in the previous chapter with the PV systems. Two different EV charging scenarios are considered in this work. The Time of Day (TOD) and Net Metering are the chosen tariffs for the customers which are analyzed in the simulation. Due to the results a conclusion can be made that the limitation of the TOD scenario is that the electricity prices during working hours are higher than during late evening and night time. By adding an additional zone (4 zone case) the price can be decreased. However, under this circumstances a coordination between EV load demand and PV generation is not suitable for the EV owner. Therefore, as a consequence of this is a low PV self consumption in the EVs integration, which results into insignificant increase of the grid hosting capacity. Net metering tariff was proven to have a significant impact in increasing the PV hosting capacity in the residential grid, by encouraging the PV self-consumption. The aim was to as much as it is possible charge the EVs with the power provided by PV systems. To do so an optimization problem was implemented, where the excessive power,which is used locally is cheaper then using the prices from TOD tariff. With the decrease of the price the PV self consumption increases. Therefore, from the results it can be seen that the cheapest cost for one kWh is when the four zone case is utilized. Additionally with setting the voltage constraint a EV demand profile was possible to obtain. After providing these profiles to the hosting capacity algorithm it was presented that the Net Metering tariff with four zones could increase the hosting capacity by 44.2%. Summarizing, these simulations were conducted to investigate the power system reaction on the PV and EV charging stations integration while minimizing the electricity cost and increase the hosting capacity in a residential grid. The results are indicating that while the net metering tariff is available the customers could decrease significantly the electricity cost by increasing the PV self consumption.

6.2 Future work

It was proven that the integration of EVs can increase the PV hosting capacity in the residential network. However a future work can be done to enhance the complexity of the network and to make the simulation more similar to the real word case. Therefore, the following points could be taken into investigation for future work:

- Consideration of the real time pricing
- Other flexible loads can be model such as heat pumps or e;ectric boilers etc. which could adjust the demand to the price signal and increase the local self consumption of the PV generated power
- Adding additional renewable components such as wind turbines to enhance the use of renewable energy even during evening peak demands

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