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Applying a smart management system for EVs in electrical power grids using smart grid capabilities

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Abstract

Power system stability and security are becoming recently a challenging issue due to the high penetration of renewable energies in power grids such as wind and solar regarding their unpredictable nature. Furthermore, the presence of electric vehicles (EVs) in the near future, mainly in the power distribution network is inevitable as the EV’s worldwide popularity is growing. In this Doctoral thesis, a smart, fast and uncomplicated control method is proposed for the plugged-in EVs charging and discharging procedure applying smart grid capabilities. Essential grid operation constraints, including overload occurrence, system loss reduction and market energy prices tracking are considered. The proposed smart charging and regulation (SCRM) management method is evaluated in a standard distribution network in the MATLAB environment. Real data of users driving behaviours, utilized from performed studies is applied in the model to obtain realistic results. Different EV-penetration scenarios are derived in a day time horizon to show the effectiveness of this smart charging and discharging method. Furthermore, in this thesis also the Germany 2030 condition has been taken into account to perform a future plan for the EVs in Germany. The results demonstrate the positive impact of this methodology in saving operational costs and increasing system stability and operation efficiency.

Kurzfassung

Die Stabilität und Sicherheit des Stromnetzes ist auf kurzem ein herausforderndes Thema, aufgrund des steigenden Anteils von erneuerbaren Energien in der Stromerzeugung (wie z.B. Wind und Solar) in Bezug auf ihrer unvorhersehbaren Natur. Darüber hinaus ist die Anwesenheit von Elektrofahrzeugen in der nahen Zukunft an Häusern unvermeidlich, so wie die weltweite Popularität der Elektroautos zunimmt. In dieser Dissertation wird eine intelligente, schnelle und unkomplizierte Steuerungsmethode für die Lade und Entladeverfahren des an das Netz angeschlossenes Elektroautos, vorgeschlagen. Hierzu werden intelligente Netzfähigkeiten angewendet. Wesentliche Netzbetriebsbeschränkungen einschließlich Überlastungen der Netzkomponenten, Systemverlustreduzierung und Energie-Markt-Preisverfolgung, werden berücksichtigt. Die vorgeschlagene intelligente Lade Management- und Kontrollmethode (SCRM) wird in einem Standard-Niederspannungsnetz in der MATLAB-Umgebung ausgewertet. Echte Daten von Nutzern (gemäß Ihres Fahrverhaltens) aus durchgeführten Studien werden im das Modell integriert, um realistische Ergebnisse zu erhalten. Verschiedene Szenarien gemäß dem Anteil von Elektrofahrzeugen in den Haushalten, werden in einem Tageszeithorizont abgeleitet, um die Wirksamkeit dieser intelligenten Lade- und Entlademethode zu zeigen. Darüber hinaus wurde in dieser Arbeit auch die Situation der vorhandenen Smart-Infrastrukturen und Anzahl der Elektroautos in Deutschland für das Jahr 2030 berücksichtigt, um einen Zukunftsplan für die Elektromobilität in Deutschland durchzuführen. Die Ergebnisse zeigen die positiven Auswirkungen dieser Methodik auf die Einsparung von Betriebskosten und die Erhöhung der Systemstabilität und der Betriebseffizienz.

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Abbreviations

DG	Distributed Generation
DoD	Depth of Discharge
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EPRI	Electric Power Research Institute
EV	Electric Vehicle
FACTS	Flexible AC Transmission Systems
G2V	Grid-to-Vehicle
HEV	Hybrid Electric Vehicle
LoLE	Loss of Load Expectation
LoLP	Loss of Load Probability
LSP	Load Shifting Potentials
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydraulic Storage
PSA	Power System Analyser
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SCRM	Smart Charging and Regulation Management
SoC	State of Charge
TSO	Transmission System Operator
V2G	Vehicle-to-Grid

List of Symbols

Indices and sets

i	Index of network nodes
N	Set of network nodes
t	Index of time periods
T	Set of time periods

Parameters

$B_{i,k}$	Susceptance of $i^{th}k^{th}$ element of the bus admittance matrix
C^{bat}	Investment cost of the battery
$D^{\max}$	The maximum total demand without EVs
DoD	Depth of discharge
DoD^{end}	Depth of discharge of the battery at the end of discharging
DoD^{start}	Depth of discharge of the battery at the start of discharging
E^{bat}	Usable energy of the battery
$G_{i,k}$	Conductance of $i^{th}k^{th}$ element of the bus admittance matrix
J	Jacobian matrix of the system
N^{cycle}	Number of life cycle, during the lifetime of the battery
$R_{i,k}$	Line resistance between node i and k
$V^{\max}$	Maximum allowable voltage magnitude

$V^{\min}$	Maximum allowable voltage magnitude
$\tilde{Y}_{i,k}$	The $i^{th}k^{th}$ element of the bus admittance matrix

Variables and functions

$\delta_{i,t}$	Vector of voltage angles $\delta_{i,t}$ at node i at time t
A_t	Amount of available energy at time t
$c^{\mathrm{dis}}(0, DoD)$	Cost function of the battery discharge for $DoD^{\mathrm{start}} = 0$
$c^{\mathrm{dis,energy}}(0, DoD)$	Cost function of the battery discharge degradation for $DoD^{\mathrm{start}} = 0$
Dem_t	Total power demanded by the system, at time t
Dr^{en}	Average energy usage of the EVs
Dr^{sp}	Average driving speed of the EVs
E_t	Amount of average used energy in a day at time t
E_t^{avail}	Amount of available energy at time t
E_t^{req}	The requested energy at time t
$f(t)$	Probability of car usage during period t
$Loss^{\mathrm{tot}}$	The accumulated system loss for the time horizon
$P_{i,t}^{\mathrm{load}}$	Power demand of node i and time t
$P_{i,k,t}^{\mathrm{loss}}$	Power loss between node i and k at time t
$P^{\mathrm{loss,tot}}$	The total power loss of the distribution network
$P_t^{\mathrm{loss,tot}}$	The total power loss of the distribution network at time t
$P_{i.t}$	Active power injection at node i and during period t
$Q_{i.t}$	Reactive power injection at node i and during period t

S_t	The energy availability at time t
U_t^{time}	Average usage of the cars during time t
$V_{i,t}$	Vector of voltage magnitudes $V_{i,t}$ at node i at time t
$\tilde{V}_{i,t}$	The voltage phasor of the bus number i

Chapter 1

Introduction

1.1 Preface

Today, the power industry is faced not only with providing resources to supply the energy demand for industries, but also with minimizing and mitigating the effects of humans on the environment associated with the provision of these energies. Smart grid is a solution for this challenge, which offers huge profit. From the consumers' side of view, a smart grid means that they could intelligently manage their own consumption, paying lower prices in peak hours when the energy price is high, for ecologists, this network means using technology to help avoiding climate change and excessive carbon emissions, and for power industry colleagues, peak shaving, smart decision making, and providing precise information about the network status are enabling improved network operation capabilities and security [1]. Distributed generation units and electric vehicles (EVs) will form two major parts of future smart grids that we are dealing increasingly with their expansion. In big cities, smog caused by internal combustion vehicles and noise pollution has led people and officials to use EVs that are free of contamination [30].

1.2 Introduction

CO_2 emissions in the transport section, has encouraged the rapid growth of the electric vehicles. With the worldwide growing popularity of EVs, the investigation of their available potentials and effects on the power grid operation is inevitable. The availability of charging stations for EVs is one of the important factors to realize the distribution of EVs throughout the country. Despite the many benefits of EVs from the environmental and economic perspective, EVs charging has negative effects on the network performance. The main impact could be the extra load that would be imposed to the grid while people plug their cars into the grid and start to charge. Due to the zero amount of emission in the EVs as their major advantage, they have recently attracted international attention and acceptance in the transportation level. Compared to other electrical consumers in the residential section (e.g., washmashines), beside to their higher load, a high amount of EVs could start charging right after they arrive home, which could be very challenging for the grid, because of probable overloads and consequently additional operation costs due to expanding the grid and reinforcement in new components (e.g., power transmission lines with higher capacity) [1]. Therefore, controlling the charging procedure of the EVs considering essential grid operating constraints could help obviating this problem and allow the grid operators to manage the grid with negligible additional costs. Furthermore, the EV's batteries could also be applied for grid regulation purposes of maintaining the grid stability due to their energy characteristics and fast response time [2, 3], by mean of offering ancillary services such as voltage and frequency regulations [1, 3].

Especially in the near future in developed countries (for example Germany), where a significant share of the power production is delivered by renewable energies like wind and solar plants, the EV's batteries could play an important role for smoothing the natural variabilities of renewable energies and ensuring grid-wide stability [2], [4, 5]. Applying smart grid capabilities could provide real time information about the State of Charge (SoC) and the amount of available energy capacity from all plugged-in vehicles [3], [6, 7] to help the grid operators to control the EVs' charging procedures and available grid control capacity [7].

An aggregator is necessary to deal with the plug-in time of the distributed EVs and their batteries' SoCs, to provide an optimal charging plan to obtain minimal operation cost and regulation service on the appropriate large-scale power level [8, 9]. The desired battery level guarantee by the next driving time, is an essential precondition for the vehicle owners' participation in providing this kind of services. In addition, some incentives such as direct payment for used battery capacity or lifetime warranty of the battery should be given for voluntary participation of the vehicle owners [8, 9].

1.3 Thesis context

There are different charging mechanisms for charging EVs. Slow charging is a common and inexpensive method for charging EVs without draining much power from the distribution network. However, slow charging requires a long time for recharging empty batteries of common EVs, so that this procedure would take normally and according to standards, between 6 to 8 hours for a full charge. On the other hand, in common fast charging technology, it takes just 30 minutes to recharge the battery to 80 percent [20]. However, EV fast charging, is draining the network considerably so that it imposes supply problems to the distribution grid [19].

From the power utilities' point of view, increased EV numbers is not desirable, because EVs receive their charging power from the network, and while many studies have shown that, high penetration of EVs on the power grid can affect the system performance by undesirable consequences as mentioned as follows. The impact of EVs charging on system losses and the voltage profile has been studied comprehensively in the references [21- 23] respectively. The results show that uncoordinated charging of all EVs at the same time, by simultaneous network connection, brings the network out of safe mode at peak times. Strengthening the power grid and upgrading the power components is the easiest way to deal with the negative effects of charging EVs. However, this solution requires high capital investment for its implementation. In [24] the authors have shown that this approach requires investment increase.

Hence, there is a need of a more affordable and efficient solution for utilizing EVs in the grid. EVs create challenges for network operators, but it is possible to apply their high potential, and to avoid their possible negative charging impacts. EVs have storage batteries and bidirectional electric chargers that can be used for power distribution. Due to the development of telecommunication infrastructures in smart grids, rapid data exchange of network components with each other or with a control center in distribution networks is becoming possible. Also, minimizing power losses and frequency control are the other aims in distribution network operation. Thus, the idea of real-time control of distribution network equipment is extended for optimal utilization of them.

In [1, 18] a new load management solution is discussed for coordinated charging of a few plugged-in cars in a smart grid. Power utilities are concerned about the performance reduction or possible overload in their distribution networks, due to the charging procedure of several vehicles at the same time as a group. Uncoordinated and uncontrolled charging of EVs can increase power losses, overload and voltage fluctuations. These items can damage the security and reliability of new smart grids, which are under development.

Regarding EVs, if there is sufficient stored energy for travel requirements, rescheduling the charging/discharging pattern mostly does not influence the customers' experience. This is due to the relative high capacity of the batteries in respect to the travel requirements. Although, the use of charging and discharging of batteries could affect their life cycle, however this impact is negligible if this option is only taking advantage of during required grid services and not normal grid operation conditions. In this research, due to the above-mentioned considerations, it is assumed that consumers do not bear any cost because of exploiting EVs' flexibility [5, 47].

So, a real-time, smart and uncomplicated charging and regulation management control mechanism (SCRM) is proposed for coordinating charging and discharging of the EVs. This method is designed to reduce the energy consumption costs and total energy losses in the affiliate network. The approach of reducing energy costs could be selected by combining time variable energy market prices and definition of preferred charging time periods by the EV owners. In the proposed algorithm, EVs can start charging as soon as possible according to the SCRM first step charging plan so that network standards, including losses and generation and voltage profile constraints remain in their given limits. Furthermore, offering ancillary services will help in maintaining the grid frequency at its nominal value.

1.4 Thesis motivation

Although the effect of a single electric vehicle’s charging on the distribution grid is very slight and minor, but the presence of planned 6 million EVs in Germany in the year 2030 will be noticeable [13]. It is also schemed to achieve 6.3 million smart homes in 2030 [14], which means a 95% penetration level of EVs in smart homes in Germany for the year 2030. Not controlling the charging procedure of these amount of EVs will certainly harm the German grid stability and impose high investment costs and voltage and frequency fluctuations [11]. Therefore, an appropriate smart charging management solution will be inevitable for the future of the German grid. Otherwise, a huge grid expansion will be unavoidable for Germany in 2030.

By moving of smart grids toward implementation and operation, the study and analysis of distribution systems becomes more urgent. To achieve a desirable result, the management and smart control of a group of vehicles charging procedure, is very important. These vehicles are able to have a bidirectional power exchange with the grid. So, in addition to the charging capability, they have also the potential to be discharged and inject their power into the grid. Therefore, assuming a large number of vehicles, they can be utilized as controllable loads and also as a source of distributed generation. Undoubtedly, this scenario is one of the best cases for power and distribution systems. Because of such characteristics, their high setup speed and low depreciation, can be applied as distributed generation for peak shaving at peak hours or like pumped storage power plants, they can be used for peak shaving and valley filling of the load curve [70]. Furthermore, their quick setup can be applied for the utilization of ancillary services. According to these applications, that require a large group of vehicles, an aggregator can mainly manage them.

In fact, with the utilization of these vehicles in the distribution grid, the aggregators can manage the batteries charging and discharging time. It means that charging should be mostly at low load hours and discharging should be at peak hours, and this action, apart from increasing the reliability of the system and offering ancillary services, leads to peak demand reduction, raising the valley and flatting of the system load curve, delaying the upgrade of system equipment and components, lower energy cost for EV owners and at last, loss and investment reduction in distribution grids [99].

1.5 Scope and contributions

This research tries to examine the presence of electric vehicles in smart distribution grids and apply the results for the situation in Germany for the year 2030, concerning the EVs penetration level in the distribution network. In this regard, a smart charging and regulation management (SCRM) method has been proposed to control and manage the probable high penetration level of EVs in the distribution grid. The impact of this methodology on energy cost reduction and optimal and secure operation of the grid has been investigated. In other words, both economic and technical aspects will be considered. The objective of this work is to develop a framework for optimal distribution network operation and planning, considering technical and economic standpoints.

The thesis contributions are as follows:

- Real-time management of the charging procedure of the EVs, considering real driving patterns and flexibility of EV owners, while assuming grid operation limitation.

- Applying a smart data exchange system to make the central control aware of the SoC of the batteries, charging priorities, plug-in state of the EVs, long distance travel plans, next travelling time, online energy market prices, regulation-market status for offering ancillary services and daily system peak hours.

- Offering a fast and uncomplicated method that avoids large mathematical calculations employing a fuzzy logic controller, which transforms the above-mentioned input data of the EVs and the power system to, simple digital signals and decides the charging procedure and regulation participation of the EVs, applying practical fuzzy rules.

- An optimization problem based on the fuzzy logic results for charging requests and offered regulation services is taken into account, which applies AC optimal power flow to meet the grid operation limitations to prevent overloaded grid components and minimize the system power loss and energy costs.

- Modelling real driving patterns of EV groups from studies that have been performed, have also been utilized in the simulation to achieve realistic results that could be also applied in practice.

Similar schemes are widely used in literature, [5, 9] and have also been suggested for the distribution level [1, 9]. Similar to the proposed SCRM system in this thesis, fuzzy logic has been also applied in [9], but as an online coordination algorithm which fuzzifies the system constraints such as voltage deviation, power loss and maximum demand level. The power regulation market and offered regulation services by the EVs is not taken into account, as another difference between [9] and the proposed SCRM system, next to a lower penetration level of EVs. Simillary, reference [19], applies fuzzy logic controllers to control the medium DC voltage and the SoC of fast charging EVs in a small and simple system. Whereas reference [10], uses fuzzy logic to determine the priority level (i.e., charging or discharging status) of each EV in parking stations due to different parameters of: (a) the associated remaining charging time, (b) SoC level of battery, and (c) the dynamic electricity tariff.

In this work, however, both technical and economic grid operation aspects have been considered, while offering a smart real-time and uncomplicated methodology for managing the high penetration level of the EVs in the residential sector for the conditions in Germany in the year 2030 with a different application of fuzzy controllers.

1.6 Thesis outline

The remainder of this thesis is organized as follows:

Chapter 2 defines “Smart Grids” and its components and introduces the achieved opportunities while equipping power grids with smart capabilities. Furthermore, extended grid capacities and raised system efficiency and reliability is presented in detail. At the end, the integration of EVs and storage systems is discussed as an inevitable part of future smart grids. In summary, this section introduces smart grids as a suitable solution for future power grid operation.

Chapter 3 analyses various aspects of the integration of EVs in power systems. Different features of EVs for a better grid operation are discussed. The V2G concept is being presented as an opportunity for avoiding high grid expansion costs. In addition, different market participation potentials for the EVs have been introduced to highlight the role of EVs in future power grid operation.

Chapter 4 introduces “Fuzzy Logic Controllers” as an uncomplicated control method compared to other classic controllers, which applies sentences instead of complicated mathematical equations. Furthermore, the history of fuzzy logic and practical control application of this method are presented. Different parts of a fuzzy controller are demonstrated and described. Finally, other decision making methods will be introduced, discussed and compared with fuzzy logic, to show the suitableness of this method in the proposed system in this thesis.

Chapter 5 presents a methodological framework and modelling tools that have been applied throughout the thesis. The proposed smart real-time charging and regulation management (SCRM) system, has been introduced. This includes the fuzzy control method applied to define the first step charging request, offering regulation services and the related flow charts that describe the control mechanism of the proposed SCRM system. The optimization problem is laid out in this chapter, which operates the network within the system limitation. The objective of this problem is to optimize the system operation, applying load shifting, valley filling and peak shaving of the system load curve and minimizing the system power loss. This problem incorporates both, network and customer constraints.

Chapter 6 clarifies the discussed framework of chapter 5 in practice. The simulation results of the proposed SCRM system have been demonstrated to show the effectiveness of this method in a standard distribution grid for two case studies, considering the Germany 2030 situation and according the penetration level of EVs in the residential sector. These results demonstrate the amount of peak reduction, load shifting and valley filling for a typical work day in a winter and summer month, respectively. Finally, the possible annual energy cost savings for each season in 2030 have been presented and compared for each simulated case study.

Chapter 7 concludes findings of this thesis by reviewing the main contributions of this research and revealing potential directions for future work.

Chapter 2

Smart Grid: A Solution for Future Power Grid Operation

2.1 Introduction

Before identifying and up taking smart grids, we must first have a comprehensive understanding of the electric grid. Each power supply grid, has a number of power generating units, transmission and distribution lines, multiple monitoring levels, controllers and different rule adjustments. Transmission lines are used to dispatch power from power plants to local distribution grids and decrease the voltage by mean of transformers to the needed value. Finally, the power will be delivered to homes and consumption centers. Although nowadays, some distribution grids also contain generating units, such as small-scale PV’s which inject the power directly to these grids. This is the current mechanism in the electricity industry. Along this route, sensors, power switches, capacitors, automatic and non- automatic reclosers control the system well and protect it against damages and power outage risks. On the other hand, the grid operator provides some plans. These layouts seek some ways so that the power outage risk in one part of the grid couldn’t have any influence on other parts [25]. The main part of this grid has been gathered in a relatively disordered manner which reflects a century of changes and slow progress in power supply. Even the use of the term grid requires an organized process which is still not available in the ideal form. The power transmission system is a very large and complex system, which consists of transmission lines, transformers and switches. In fact, a power transmission system is a mechanical/electrical system that is working with little use of sensors, electrical connections and controllers [25]. Even in many developed countries the electricity grid, as it is being used at the present, was designed many years ago and has to be updated. By modernizing the power grid, it will be possible to increase the efficiency of power generation and utilization of grid assets, that results in the reduction of carbon production. This will generally, increase the safety and reliability of the grid. Smart distribution power networks are one of the newest existing technologies for modernizing distribution networks and increasing their efficiency [27].

The main purpose of “Smart Grids” is a reliable power supply while meeting the growing needs of customers with minimum harm to the environment. Using smart methods in these networks, such as two-way communication between consumers and suppliers, distinguishes it from traditional power systems [28]. However, the smart grid has no clear and single definition. European modern technology defines it as follows: smart grid is an electric grid that can smartly integrate and control the functions of elements connected to it, such as generation and consumption, and thereby provides a more stable and safe power delivery [34]. The traditional power grid includes centralized generation and through transmission and distribution lines, energy is delivered to end users. Currently, this type has been improved by added renewable energies and the use of storage systems. Also, there will be new communication layers in the existing power grids to control them and exchange information. From the global perspective, the main objectives of smart grids are capacity, performance, stability and interaction with the customers [28].

The world's first smart grid was introduced in March 2008. Balder town in Colorado was the first city with a smart distribution power network. The designer's goal of using smart technologies is centered on three main axis: subscribers, equipment and communication. Smart technologies can make fundamental changes in the generation, transmission, distribution and consumption of electrical power, along with economic and environmental benefits. These benefits will eventually lead to meeting the needs of subscribers and the availability of reliable and stable power. On the other hand, smart grids can make fast decisions in critical situations by mean of the gathered information and avoid unnecessary blackouts [27].

Reliability is another important issue. Most of the system failures that are the result of problems of the distribution system, lead to load shedding. Advanced sensors get the information through control, monitoring and system data acquisition. This information may prevent further events and faults [34]. Smart grids can be imagined as electric grids, which controls electricity and is able to control and improve the electricity generation by mean of information about consumers' generation and consumption at a specific point. In fact, it determines the way of selecting system parameters and their behavior. Researches show that the greatest advantage of the smart grid is related to its ability to improve performance, reliability and customer responsiveness and has a great impact on customers' better performance and provides more profits for the system. This improvement is related to the system and its sensors, automatic measurement, smart devices and its specific functions. The smart and modern measure of information and communication technologies are a perfect solution for energy management in this structure and in fact, it can be considered as a suitable opportunity to improve the energy saving resulted from the operation of renewable energy resources and support customers in relation to the energy market [26, 28].

In short, a smart grid involves the utilization of sensors, communications, computing capabilities and control in various forms and tries to improve the performance of the entire power system in providing a more reliable power supply. Also, an imperfect system can become smart by the proper use of sensors, communications, and the application of smart circuits, control procedures, feedback circuits and some additional settings. By using mass generation and saving the generated energy, power systems can be optimized. Meanwhile, a smart grid can lead the power system toward high reliability, optimization, reduced energy consumption, reduced environmentally destructive impacts and asset management, which are very valuable factors [25, 28].

2.2 Concept of smart grids

Smart grid was created by a group of experts who worked with the U.S Energy Association (USEA) [25]. This organization points out that the real purpose is to make a smarter grid out of the current grid, assuming a series of reforms which will try to face no deficiencies and failures. Then the question arises: "what makes a grid smarter?" The answer can be summarized in several functions. The smart grid is not just a technology but it is a goal that researchers and industry experts hope to achieve it. Mostly, the nature of the bidirectional characteristics of the future power grids has not been explained clearly [25].

The U.S Energy Security and Independence act in 2007, for example, stated ten features of a smart grid: Increased utilization of digital data and technology in order to improve and modify its capability.

- Increased efficiency of resources and performance of the grid by full cyber protection and security.
- Development and integration of generation and distributed generation units, including renewable resources.
- Demand response development.
- Development of smart technologies for grid assessment and automation of the distribution process.
- Integration of smart electronic home appliances and its application practices.
- Development and integration of power storage systems and technologies for saving like electric or hybrid vehicles.
- Providing timely information for consumers while controlling and considering solutions.
- Development of standards to improve the control of electrical home appliances and other equipment that are connected to the network.
- Identification and reduction of barriers to the adoption of smart grid technologies.

Most of these features have a prominent role, because they represent key features of a smart grid and on the other hand, they are probable targets of cyber damages and attacks [25, 37]. The modern power grid structure is a mix of reforms and created infrastructures within a few decades. The subject is not very simple, establishing power plants for energy generation based on coal, diesel, natural gas, nuclear, wind and solar energy, construction of large power transmission lines for delivering energy to other areas and electric power distribution, require some infrastructures, monitoring, control and evaluation in key situations and circumstances with the measurement of demand for determining the amount of required generation in each area. Power grids rely on the balanced growth and the prediction process of power consumption rise and its components. If the power generation is provided from various locations and different companies at a certain time, it will result in more inconsistencies [25, 28]. Similarly, if residential, commercial and industrial consumers want to generate their own power and inject a part of it to the power grid, some problems may rise by factors such as lack of proper and advanced assessments, and lack of communication facilities. Finally, if demand was high in some parts, and there were no adequate supply resources and no convenient way to transfer that information to consumers to balance the consumption, in this case the power system is facing with the danger routine of frequent power outages or so called blackouts [25].

Smart power grids have targeted future challenges. Due to the limitations of control facilities, low dominance and reactivity of consumers and the expansion of renewable energy sources, power grids have continued their function extraordinary, in comparison to the past century. In the past, energy prices were cheaper in many parts of the world and power outages and blackouts were controlled and restrained. If there weren’t wide differences in population changes, technical, social and economic recognition, which have great influence on the development and fast movement of the world, it could be assumed that the current power grid works well and does not need any changes in it. Like many other technical improvements, smart grids have a potential power of efficiency and high reliability; it also has greater potential for vulnerabilities and security challenges as well. As a result, power service companies, traders, and regulators of this industry need to make decisions, profoundly and impartially. Their decisions should consist of a variety of safety monitoring that includes vulnerable points of the grid and recognize threats that could lead to the collapse and damage of the smart grid [25, 28].

2.3 Describing power smart grids

Smart distribution grids are interconnected two-way networks in which information exchange plays a fundamental role in the process of energy distribution. The two-way approach means that information is established bilaterally between consumer and producer. Smart power distribution is done by systems based on the combination of information and communication technologies with computer processing capabilities and electrical systems. Upgrading current non-smart hardware systems, to two-way smart, efficient and economic networks, where the productivity of investment in the power industry rises intensely, is one of the main goals of this change. Increased system reliability and stability is another goal of applying smart technologies [30, 31].

In summary, the following requirements result in fundamental changes [30, 31]:

- Self-healing grids
- The expansion of renewable energy sources
- Having a network with inherent high reliability and security at all levels
- Expansion of renewable energy sources
- Decentralized and pervasive control with widespread use of sensors and measuring equipment
- Economical distribution grids
- Optimal use of valuable assets by applying the concept of “Demand Response”
- Non-hierarchical distribution of power generation and utilizing distributed generation by consumers
- Extensive automation and reduction of the involvement of human factor
- Environment-friendly power distribution network
- Integration and diversifying of energy sources and storage units
- Management of pollutants and carbon dioxide

Some of these features will be described in the next parts. In intelligent power distribution systems known as smart grids, not only data are transmitted bidirectional from the network to the subscriber and vice versa, but also the power flow could be bidirectional so that the network can be potentially consisted of thousands of small energy producers and sellers. These traders enter in the electricity retail market through renewable energy sources such as solar cells, wind, geothermal or through energy storage in low load hours (cheap energy prices) or days and sell it at peak hours (expensive energy prices). Therefore, in smart grids, two new networks are introduced [30, 31]:

- Power distribution micro-grid
- Virtual power distribution company (or virtual electricity market)

2.4 Importance of applying smart grids

In the smart power system, many new methods and theories are considered even those that have not been designed yet. So, it can be concluded that a series of developments made in this system eventually will reduce the risk of blackouts in the future. The original plan provided for making smart in order to reduce blackouts, was presented for the first time in the power transmission system of some parts of the U.S, in which there was a high-risk possibility of blackouts [28]. Much work has been done for power transmission. Especially in this sector, new technologies have been applied and the reliability has been increased. The main goals are just economics and technology that can use many of these facilities. These technologies were used widely and represented the formation of new and necessary factors in this area. Moreover, these factors are the cause of the utilization of the new group of renewable energies application. Nevertheless, solar and wind resources can also be used in many populated centers. In general, development of new technologies, requires the available relationship between governmental and industrial sections [28].

2.5 The reasons of tendency for making a grid smart

Almost 90 percent of blackouts are because of disruptions in the distribution network and thus, movement toward a smart grid for solving the problems should be started from the bottom of the chain that is the distribution system. In addition to the rapid increase in fossil fuel prices as well as the inability of companies in expanding their generation capacity, according to the increased demand, the need for an advanced distribution grid and the use of technologies that help the system by improving demand-side management and protecting the facilities, have been increased [26, 29]. The idea of smart grid began with the idea of advanced measuring equipment for developing demand-side management, increased energy efficiency and self-healing electrical grids, in order to improve the reliability of resources and respond to natural disasters or deliberately sabotages. But the subsequent developments, improved the basic assigned aspects of a smart grid and contributed to the formation and development of a new power industry [29, 30]. Some of these developments could be mentioned as follows:

- Emphasis on environmental protection, including the use of distributed generations (wind, solar and electric vehicles, etc.), and demand response.
- Motivation for better utilization of equipment, including safe operation of the system.
- The need to increase customer choices.

One of the important factors of creating a smart grid, is the creation of two-way communication between the wholesale markets or transmission operation and retail markets or distribution operation. The tendency to increase demand response rates, renewable resources, and distributed generation and storage systems at distribution level or retail will have a direct impact on the operation of transmission systems and wholesale energy markets. Developments in technology such as advances in information and communication technology, enables the conversion of this new functionality to useful controllable products for the wholesale market and transmission system operators [29]. Figure 2.1 shows the power transmission and information flow in the traditional operation environment. The power flow from centralized generation resources (power plants) to demand is almost a one-way path and the information flow is from operation centers with lower voltage to higher voltage centers [29].

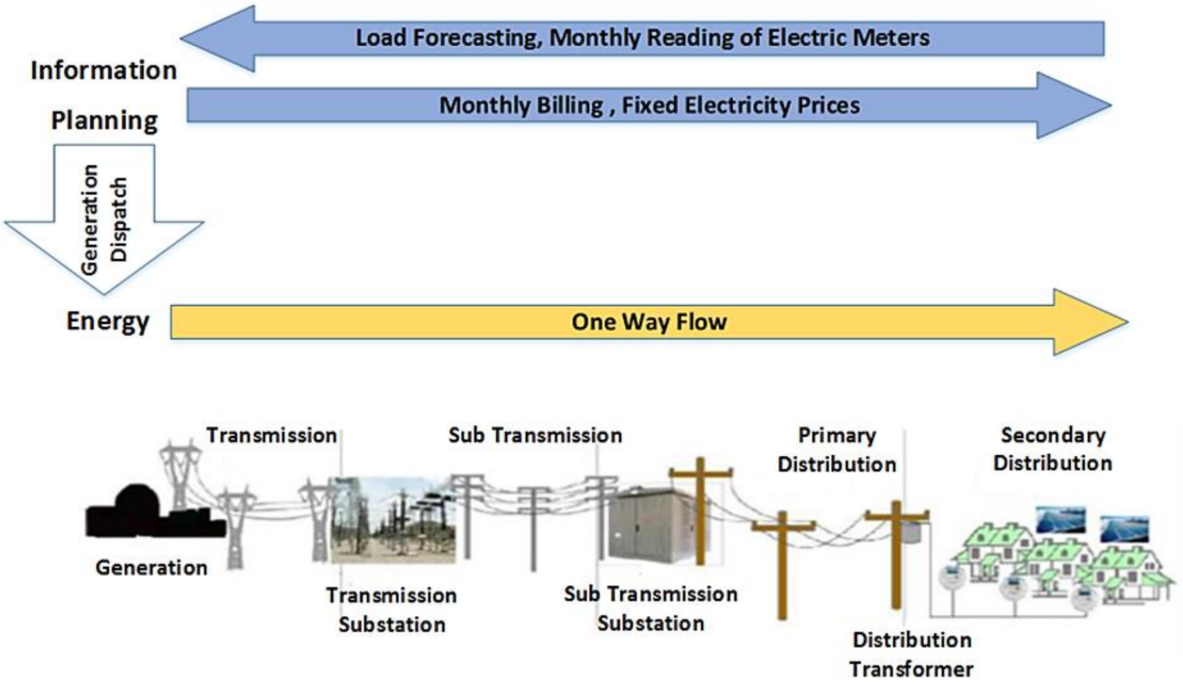


Figure 2.1: Power and information flow in traditional operation environment [29]

In contrast, in the smart grids, both power and information flow are two-way and bilaterally as shown in Figure 2.2. It is expected that the utilization of new thermal storage systems for peak load shifting, decreased solar photovoltaic generation cost on residential and urban levels and thus the increase of PV application, replacement of conventional fuel based transportation with rechargeable EVs, the emergence of smart sensors sensitive to electricity prices and establishing of a safe two-way communication network throughout the territory of power utilities, significantly will change the nature of power generation resources and power system operation as well as the subscriber’s behaviour, in the future [29, 30].

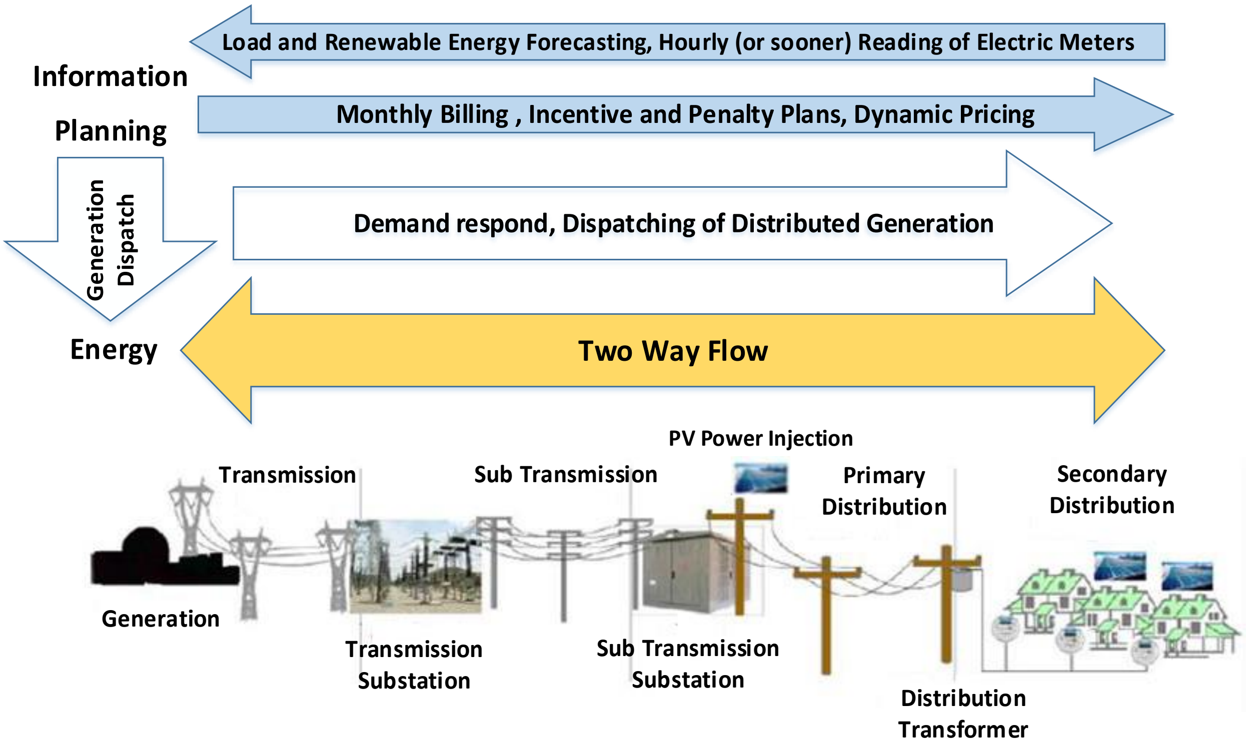


Figure 2.2: Power and information flow in smart grids [29]

2.5.1 Resulted benefits

In summary, the benefits of smart grids are as follow:

- Peak shaving, this is the main result of the utilization of smart grids and advanced technologies in the distribution substations and residential subscribers
- Reduction of fossil fuel consumption, that results from decreasing the peak load

- Decreasing the amount and duration of subscribers’ load-outages
- Reducing the required investment in transmission and distribution projects, because of improved load balancing and reduced peak load, due to advanced demand side management
- Network security and reliability improvement with real-time data
- Reducing costs that are resulting from remote switching of the subscribers

Due to the growing application of renewable energies in distribution networks, the control systems must increasingly be managed with methods such as monitoring capabilities, data integration, advanced analytics and effective communications. Smart grids, supply the demanded power with simultaneous increased efficiency and reduced costs [28].

Different technologies must be applied to create a smart grid as an efficient and effective management system. Communication systems exchange data with sensors and available actuators on the electric grid is a feature of smart grids [29, 30].

2.5.2 Monitoring the system instantly

This qualitative feature makes a big expansion of many advanced sensors throughout the system. These sensors should connect to an online communication system and have a special structure in this regard. Data should be managed based on a quick simulation and modelling and be presented in a visual form such as monitors in order to be responsive to system operators [28].

2.5.3 Increasing the system capacity

This function includes administrative processes that cause or increase the system capacity at the transmission voltage level. Also, this section contains many lines and transmission sections and the acts of energy regulatory commission scale of that country, which improves the control centers through expansion and development of data infrastructures and updating supportive projects in it [28].

2.5.4 Reducing barriers and bottlenecks

This function allows government to resolve the barriers that restrict an act in the wholesale market, and bring adequate trust in system stability. In addition to increasing system capacity, it can be stated that this general concept increases load flow, supports high voltage and the performance of all other functions included in this section. These kinds of factors should use a special technology in order to manage any improper load flow [28].

2.5.5 Developing a self- healing system

Concurrent with the above-mentioned factors, it is now possible to control a system online. To activate these executive factors, it is necessary to use electronic components in a wide range such as: electronic switching keys and flexible AC transmission system technologies (FACTS). These technologies are associated with the structure of the controlling model and they can make a system that automatically repairs and heals itself [28, 38].

2.5.6 Improvement in customer relationship

Above mention factors represent a combination of these communication tools in the power system. These wide and executive factors raise new topics in this field. One of these factors is directly related to electrical services (like billing information or momentary pricing). Another factor includes electric services (such as home security or control instrument); the third factor is related to all general factors based on generation services in this field. Above mentioned functions, facilitate the performance and success in achieving the goals of the grid. A smart grid has the needed potential to reduce harm and damage to the environment, customers, and other practical factors. This potential includes mechanisms for increasing the amount of reliability, stored power quality and reduction of carbon emissions [28].

2.6 Benefits of smart distribution grids for subscribers

Due to the alternate nature of renewable source output power, subscribers need to have information about the availability and amount of generation of these resources to make the right decision according to their incomes and environmental priorities. According to this, there is a need to train and empower the subscribers and cultural preparation, therefore a good investment must also be considered in the educational context [29, 30].

Another advantage of smart grids is demand side management. In this framework, real-time pricing software help demand management, so that, once the electricity is expensive, they raise the retail prices and when the electricity price is low, they reduce it. However, people are not familiar with this software, but now a system is designed that controls the consumer's energy usage due to time and price, based on his own settings (which is conducted by the consumer) [26]. These systems make consumers who worry about the environment, able to control the energy generation sources so that they can use the kind of energy with less environmental damage. Another benefit of smart grids is investments optimization. The intelligent distribution network enables us to be aware of the health and security of the network. Collecting and transmitting data, creates a system that can make smart decisions. The result of this operation is optimal utilization of capital, because of:

- Avoided failure in networks with timely replacement of cables, electrical equipment, substations and distribution transformers.
- Dynamic regulation of transformers to help defer the investment in this field and extending the lifetime of the equipment that prevents the further reinvestment for the required energy generation [29, 30].

2.7 Smart grid effects on power systems

Advanced control systems are responsible for monitoring the power grid and managing energy flows in real time. This section examines new technologies in smart grids. The reference in this section has a specific focus on telecommunication systems which perform the monitoring work through the latest smart metering software. Effects and benefits of real-time control of the network are improving the operation, security and quality of power systems [31]. Electric load forecasting is a necessary action for network planning and operation. In traditional networks, the electricity generation is "load based" and flexible to provide at any time and for any amount of load, proper demand capacity. In recent years, many changes have occurred in the power chain and among them two had the greatest impacts:

1- Development of renewable energy sources, especially solar and wind farms in small and medium sizes.
2- Connecting EVs to the grid, also including issues related to the connection of hybrid EVs.

Both changes are designed to improve the environmental sustainability of the energy generation process, transmission and end-use, as well as modernizing the electricity grid infrastructure. The actual promotion of renewable energies and distributed generation (DG) requires analyzing the change in traditional loads from top to bottom, in power systems. Renewable energy sources like solar and wind, have a low energy density value and an unpredictable nature which makes planning very difficult. Many research groups and energy companies have developed predictive algorithms through complex analysis, which are used to calculate solar and wind energy generation in the future and they have reached acceptable results for the next day, but not accurate enough for a whole week or a month later. On the other hand, the expansion of EVs connected to the grid as large residential network loads, results in a challenging network load increase in short term as well as long term period. Even if the EVs' plug in pattern could be predicted in an accurate way, a costly network expansion would be inevitable. However, this type of cars has a limited charge in terms of space and time compared to vehicles with internal combustion engines. That's why EVs require batteries with higher energy storage capacity and more efficient charge rates. Two charge modes are designed for EVs, low-power and high-power charge modes. The low - power charge is designed for charging vehicle batteries during the night time for 7 to 8 hours, as well as ensuring the low load situation of the network. EV-charging during the day or during long travel distances, requires many charge stations along the way which should satisfy a significant power demand levels. In order to charge car batteries at the time like fuelling, in internal combustion engine vehicle, fast charging (high-power charging) is required. In this case, the battery can be recharged from 20kW (for small EVs) to 250kW (for heavy vehicles) in a few minutes [31]. Thus, the growing DGs and EVs could cause network instability or a dysfunctional operation state. Of course, the benefits of clean and environmentally energy generation must be considered. As well, utilization of EVs may result in additional energy demand about ten percent of the total network energy. High generation brings restrictions in pure transmission and negotiation on power quality. These effects require a coordinated and smart control. The European Union has defined a smart grid as a power grid that can effectively manage costs through behavior and actions of all users connected to the network, including generation units and consumers, while ensuring efficient economy, reliable and sustainable energy systems with low loss and high-quality level and supply security. Figure 2.3 demonstrates the smart grid concept and the relationship between its components due to reference [31].

The U.S Energy Department has analyzed power grid systems and they found that smart grid shareholders will benefit from the following items:

- Reliability that reduces the number and duration of power outages and provides adequate power quality and improved customer services.
- Security that reduces vulnerability to natural attacks and disasters.
- Economically, provides opportunities and options for consumers to save their energy consumption costs.
- Operation, resulting in energy protection, reduction of system losses, maintenance and investment costs.
- Environmental friendliness, replaced renewable energies.
- Safety, for the protection of line workers and the public.

All these features will be achieved, when the grid implements the full potential of the smart-making procedure [28, 31].

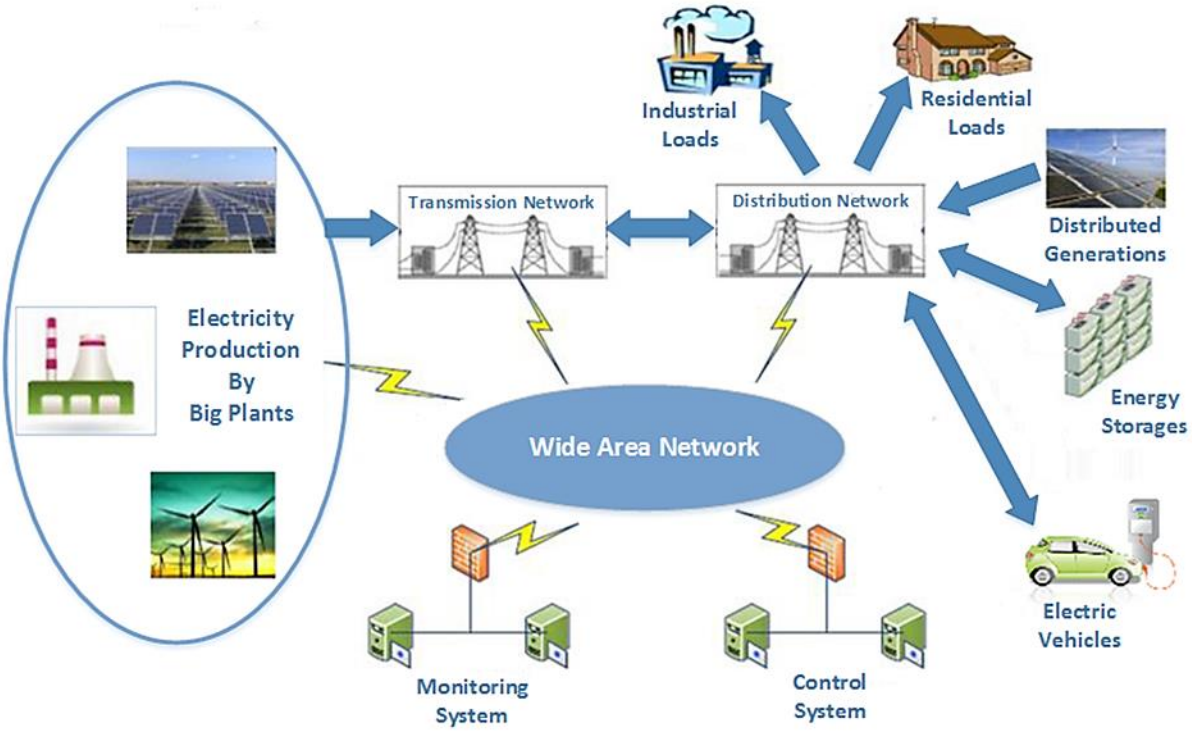


Figure 2.3: Smart grid concept and relationships between components (based on [31])

2.8 Virtual electricity market

Virtual electricity market is a market in which subscribers are not only the recipients of energy but also can buy and store energy in low load times where the energy is cheap and sell it to the network on peak hours where the energy price is high. It is obvious that the realization of the virtual electricity market is impossible without utilization of smart grids and advanced information and communication technologies. Installing and running smart sensors on all key elements of the distribution network and establishing bidirectional communication networks, integrating and synchronizing of measuring systems with other applications of the central and communication system, voice services to subscribers, installing software systems for real-time fault detection, load balancing, mass and selective power switching, are of the main activities for establishing a complete smart electric power distribution grid. Alignment and integration with real-time distribution and sub-distribution control systems like SCADA and information exchange for complete interactivity in the network, are further essential actions of setting up a smart grid. The use and purchase of energy from small producers, typically based on renewable energies and inclusive storage resources (Such as stored energy in EVs during peak hours) and combined heat and power plants, two-way data and energy communication with these producers, are more examples of smart grid benefits. [30, 32]

2.9 Demand side management (DSM)

Demand side management includes everything that focuses on the demand side and it is an inseparable part of a smart grid and one of the most important techniques in energy saving. Infrastructures of information and communication technology support efficient performance of the grid and allow communication to be updated frequently and with respect to real time balance of supply and demand, there will be a better pricing mechanism [26]. This managing program is related to planning, performance and control of all executive operations and has desirable impacts on power consumption and finally it creates suitable and desirable changes in the shape of the load curve and its function.

DSM can have a great impact on power consumption and changes in customers' load patterns. Demand side management should achieve its goals. To achieve changes in the load form, this program should consider the customers' aims. It means that, this section increases customers' satisfaction and achieves desirable goals. DSM can assess managerial options where there are no demand factors in it. This concept needs that the managing programs could consider all these goals in a remarkable range. Executive functions in this section are: establishing new power generation units, the use of power and its storage tools. In other words, this section requires a comparison of executive options and other power supply options. All assessments are related to a part of the process of integrated resource planning [33].

This management method can identify the manner of customers' reactions. In some cases, the offered positive impact of these functions is needed. Therefore, executive concepts can identify the manner of customers' reactions without any impacts on them, in this field. DSM can be influenced by the load shape. The evaluation process examines the value of programs and to do this, it uses the way of its impact on the costs and benefits obtained during the day, week, month or year. Therefore, DSM is a wide factor that can include all the functions that cover key aspects in energy planning [33]. The DSM planning is the performance and monitoring of system activities, designed to have influence on customers' power consumption which will cause changes in consumption patterns and the amount of load. The main purpose of load consumption management is to encourage consumers to consume less power during peak hours or energy usage at off-peak hours in order to flatten the load curve.

Reliable operation in power grids, depends primarily on the perfect balance between supply and demand at any time. It will be even harder when the distributed energy generation is higher. Renewable generation fits with the weather conditions and generally for following a certain load shape, the detection of the exact amount of its output is not clear [34]. Necessarily, the renewable generation peak is not the same as the consumption peak, so it needs stored energy for later. This system can rely on fossil fuel during its peak. But diversity in generation can maintain more reserve margin, which will also increase the cost dramatically.

New methods and technologies are used to keep the supply and demand balance which is mainly based on the interaction with the customers. In short, the classic method is the supply of all required demands at any time, but new strategy believes that demand should be controlled through the consumers' involvement in responding to the current situation of the system [34]. Responding to demand, plays a key role in the future power balance. Consumers, currently have no purpose of the received information about the system state, so that they react to them and lead to system balance and efficiency increase. Due to renewables nature, there will be no possibility of power control or power request any time it is needed.

The main objectives of demand response techniques are: Peak load shaving, the ability to control consumption according to generation. In other words, there should be a way for energy availability at the time of energy shortage [34]. Current fixed tariffs for electricity, offer no incentive for customers to make them help in building a more efficient system. The increased number of renewable resources, is changing the supply. When there is a green energy shortage, the price for the same amount of energy will increase and it leads to changes in the curve. All of these factors get customers to participate in saving money and adaptability to the environment. Demand side management plays a key role in increasing the return on investments made by applying equipment and it is more attractive for investors [34].

Basically, there are two ways for energy management function: Supply side management which contains a new structure of generating units and control methods through energy conservation policies. The DSM contains loss reduction and efficient utilization of equipment. Most of the researchers consider the demand side management as a program or a set of activities organized by software that affects the usage time of the consumers. DSM is a tool for mediating in applying various energy consumption ways [35]. One of the goals of the demand side management is peak shaving. DSM is a set of main policies that seeks an economic return on the installed investments and or postponing new facilities. It also includes the control of consumers' lateral loads to improve the system’s function and to obtain an optimized load factor. Implementation of DSM program or its activities may encourage the customers to change their load and consumption method to avoid maximum load in the system. This is practical only with the installation of smart measures for every consumer. They measure the differences and exact rate and amount during the time and inform consumers about their consumption and quality of their indicators [35].

It is technically impossible or almost impossible for all EV consumers to access the daily load curve without the help of new technologies. Because classical energy measurement devices cannot record this information. So, every four or five years, small populations are taken as samples. Then obtained data are estimated in that society.

The main issue is that whether we can generalize sampled behavior without any changes to the entire population or not. We should be sure about the accuracy of information. This method could reflect a fixed condition for every four years [35]. The use of smart grid changes this condition and it allows us to access the daily load curve data for every consumer and to extract the information of each consumer behavior using the right tools. Most of the methods used in demand side management are shown in Figure 2.4, which are used for peak shaving, valley filling, protection strategies and flexible modelling. These different applications are described in the following section:

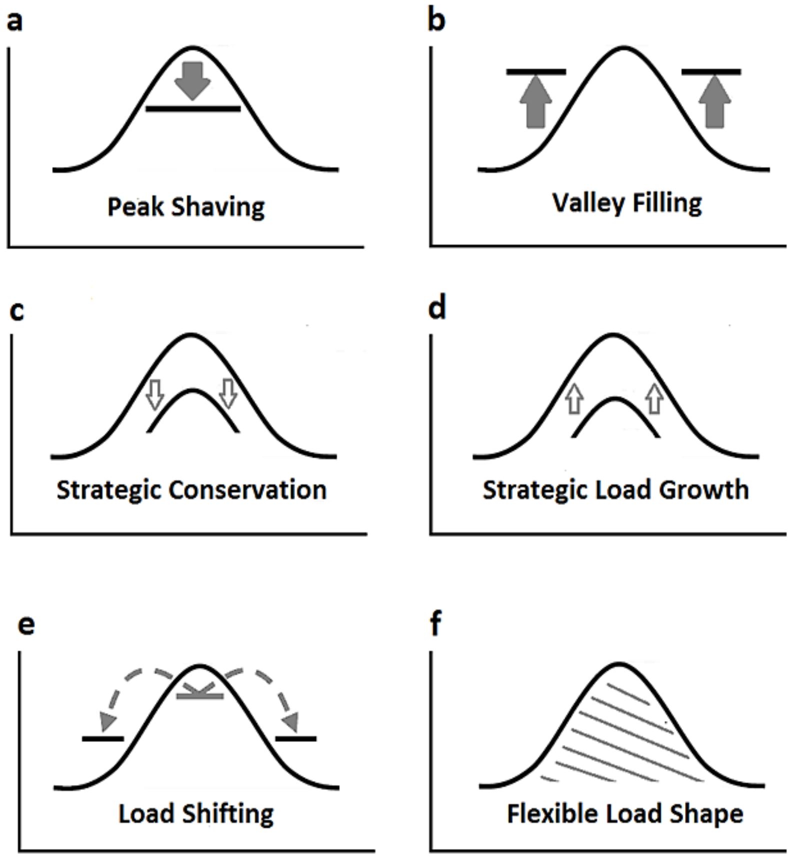


Figure 2.4: Different applications of DSM (derived from [70])

a) Peak shaving:

Load shedding, demand reduction at peak time. Peak times can be reduced through direct control of the load, turning off the consumer's equipment or generation distribution.

b) Valley filling:

To encourage consumers to consume at the off-peak hours at which generation prices are low and average price reduction and improvements in system operation are highly desirable. Various incentives such as discounts and other motivation make customers to change their habits.

c) Strategic conservation:

The reduction of seasonal energy consumption mainly increases efficiency and leads to energy loss reduction.

d) Strategic load growth:

Controlling the increases in seasonal energy consumption and the utilization of more efficient and more competitive smart systems, processes and equipment of energy resources to achieve the goals.

e) Load shifting:

The transfer of the high work load period of the largest consumer (peak period to low consumption period) and transferring the loads without any changes in the total consumption. This is possible through the application of distributed generation.

f) Flexible load shape:

Contains a set of consistent procedures and planning between consumers and suppliers. This model can continue its function through the installation of power limiter devices without any impacts of the security situation and limited amount of consumed power and energy at the time, by consumers [35].

2.9.1 Demand response (DR)

Demand response is related to all demand management mechanism of the customers that can provide suitable conditions to change load patterns. It decreases the amount of consumption and has effects on market costs. The recent researches conducted about the interest rate and the activities related to demand response were wide and they are related to the conditions of power supply in areas where it can be applied quickly [25].

DR is a plan to motivate end users to respond to cost changes or electricity availability, in order to change their daily consumption pattern. It can also be described as decreasing the power consumption when the reliability of the grid is at a risk level [34]. The customer is able to have some kinds of actions in response. In the first action, customers can only experience load shaving during critical peak times and maintain their normal load pattern at off-peak hours. The second action is a response to the high price of energy or its low availability to compensate power consumption at peak hours. This method flattens the load curve by peak load shaving and fills the valleys at low load hours.

This method does not reduce the average amount of energy consumption, but it keeps the efficiency of transmission and distribution system in a more stable mode [34]. Most of demand side management methods require an extensive and reliable communication between end users and suppliers to transfer pricing signals. So, consumers need to install home energy management device and smart appliances to be able to respond in time without human collaboration. DSM and DR will be useful both for consumers and power suppliers. Generally, there will be a more secure system and thereby it leads to a maximized social welfare [34].

2.9.2 Storage technology and electric vehicles

Electric energy is volatile and could be unstable. It needs to be generated at accurate time and an exact amount unless it is being changed or saved in the same form. It is clear that a fully coordination between demand and generation is not possible, so, energy-saving is necessary to maintain this balance which is the biggest challenge in power grids. There are many ways to save energy in the market. According to Electric Power Research Institute (EPRI) pumped hydraulic power plants, form about 99% of the world’s storage capacity. Its output power can normally reach up to 3GW for a short period of time that is 15 seconds. Having high capacity and fast response increases the system stability [34].

Most of the storage systems, can generate power only for a short time and have low capacity and high prices. So, a storage system that saves a great amount of energy did not exist. Developments in battery storage, promise an increase in the number of electric vehicles in the future, which will increase the power consumption dramatically. If this growth is not being managed, the amount of system peak will increase. On the other hand, thousands or even millions of electric vehicles may save a huge amount of the distributed power [34]. This will be discussed in the next section.

2.9.3 Types of electric vehicles

In this work, an electric vehicle is assumed as a car that one of its propulsion forces comes from the stored system energy in the battery. By using suitable equipment, it changes this energy into the required mechanical energy for moving [36].

Commonly electric vehicles are divided into three groups:

- Electric Vehicle (EV).
- Hybrid Electric Vehicle (HEV).
- Plug-in Hybrid Electric Vehicles (PHEV).

Electric Vehicles (EV)

Electric vehicles have an electric engine and batteries to provide electric power. Battery energy can be used as propulsion of the vehicle’s electric engine and to provide energy for other equipment. Batteries can be charged through the connection to the power grid, as well as the energy from automotive brakes or even non-grid electric resources like solar panels.

The main advantages of these vehicles are:

- They are free of greenhouse gas emission.
- They produce very slight noise.
- They have much higher efficiency than internal combustion engines.
- The price of their electric engine is low.

The main disadvantage of these vehicles is its full dependence on batteries (its technology has not yet reached to comparable capacity and energy density with fossil fuels).

Hybrid Electric Vehicles (HEV)

These vehicles have both a fuel engine and an electric engine with a sufficient battery (1-3 kWh) and they are able to save the generated energy from fuel engines or automotive brakes. Batteries help vehicles anytime their help is needed to produce supporting power or provide vehicle propulsion in low speeds when the fuel engine switches off. In the past decade, about 1.5 million hybrid vehicles have been sold. In developed countries like the United States of America almost 3% of the vehicles are hybrid electric ones [51].

The disadvantages of these vehicles are:

- Their batteries cannot be charged through power grids.
- Their dependence on fossil fuel engine

Plug-in Hybrid Electric Vehicles (PHEV)

These vehicles, designed to eliminate the disadvantage of hybrid electric vehicles, are chargeable and need bigger batteries than the hybrid vehicles. A full fossil fuel engine system is also available in these vehicles. As mentioned, plug-in hybrid electric vehicles have bigger batteries than hybrid electric vehicle. The major battery difference in these two electric vehicles is that the battery in plug-in hybrid electric vehicles should have the capability of fast charge and discharge, whereas hybrid electric vehicle battery operates when it is almost fully charged and the battery rarely discharges [36, 51]. For these vehicles, we can mention according to [36]:

- By battery mass production, the price of it will be 750 US$/kWh that for a vehicle with medium range (40 km with an 8 kWh battery), the total price of battery will be 6000 US$.
- If the vehicle life lasts for 200 thousand kilometers, the price of saving fuel will be about 4000 US$ that is less than the battery price.

Reduction in battery price (500 US$ per kWh) results in competition between plug-in hybrid electric vehicles and the common gasoline vehicles.

2.10 Reliability evaluation and power system security

Most of the activities in the electrical field, is along with the minimization of the operation costs. But another important factor in the power system operation is the tendency to maintain the system security.

The engineers' and planners' purposes in designing and making simple and complex systems are: increasing system performance, the growth of economic indicators and the most important one is, increasing consumer satisfaction. Inefficacy and disruption in the system, cause sometimes irreparable damages in the system [61].

Therefore, a discussion about reliability and system security have been considered as an important issue of system operation. System security includes practices and ways of maintaining the system when components face failures. Also, reliability is defined as the probability of proper function of an element in a specific period, without any errors. For example, a generation unit may be confronted by a complete outage due to failure of the main and assisting equipment. Keeping an adequate amount of spinning reserve in power system as well as being prepared to load shedding in case of loss of a part of the generation, could help in maintaining the system security and operating a system with high reliability. Similarly, a transmission line could be damaged by a storm and being switched off automatically by a relay. In such a case, the amount of transmitted power must be decreased or parallel lines should be designed so that they could transmit the whole crossing power, to maintain the system security. All equipment in the power system is designed to prevent undesirable power outages [37, 38]. It is obvious that all engineers must be aware of the basic concepts of reliability assessment, because by the law of most countries, designers and constructors are responsible for damages on customers, as a result of poor performance of their products.

2.10.1 Importance of the distributed grid reliability

It is difficult to imagine life without electric energy. Many occupations and social activities have become dependent on it. The reliance on electric energy is so high that a power outage imposes very high damages to the people and takes them out of normal life. This reliance on electric energy, increases people's expectations of receiving electric power, so that if the received power does not fit good quality standards, they will protest. These factors get the power distribution grids to increase the reliability of distribution grids [60].

2.10.2 Reliability aspects of distribution grids

The most basic goal of power systems is to provide continuance, cheap and high quality electric energy. However, for reasons such as possible breakdowns or failures in applied equipment, foreseen and unforeseen errors, it cannot be expected to have this energy available, all the time. Thus, reliability assessment of power systems has been a very important issue [61].

The distribution power system is the widest part of the power system in terms of area and space. On the other hand, this system is an intermediary between consumers and the power system that receives energy from transmission and sub-transmission grid and delivers it to the customers. Although the distribution grids have simple structures, but the major investments in power systems are made in this part. So, reliability assessment of distribution systems seems to be very essential. About distribution systems, reliability is related to subscribers' power outages and disruptions in the performance of equipment. In this regard, some indicators are defined to assess the reliability of distribution systems, which will be introduced in the following sections [61].

2.11 Conclusions

In this chapter, due to the limitations and disadvantages of the traditional grid, the smart grid concept has been evaluated. A smart grid includes the use of sensors, communications and a smart control in different forms to improve overall system performance. Smart grids can resolve many problems of current grids through demand side management and demand response and it provides suitable conditions for the application of many distributed generation resources like plug-in electric vehicles. In the next chapter, the literature on electric vehicle and its impact on power grid will be investigated.

Chapter 3

EVs Integration in Power Grids

3.1 Introduction

The first electric vehicles appeared in the nineteenth century. The production of these vehicles was suffered a sharp drop because of mass production of ignition vehicles. In the decades of 1970 and 1980, electric vehicles became interesting again, that was because of the energy crisis, but this attention could not cause mass production and competitive markets. Thus, they were replaced soon by internal combustion engine vehicles. The invention of silencer and electric starter that reduces the loud noise of the internal combustion engine and removes the manual starter for running the engine, were the main reasons. However, today the excessive pollution caused by internal combustion engine vehicles brings governments around the world to try to find a solution.

Since 2008, according to developments of battery technology and power grid management, concerns about oil price and needs for decreasing greenhouse gasses, a major change happened in electric vehicle production. The advantages of electric vehicles compared to gasoline vehicles are the significant reduction in local air pollution, greenhouse gas emissions and dependence on oil. So, returning of the EVs is considered as a promising solution in reducing carbon emissions and preventing the dependence on fossil fuels. Some of the countries and governments are using governmental incentives for electric vehicles in order to promote and expand the market for EVs.

Reference [39], a study of the behavior of EV owners during 16 weeks, shows that the vehicles are 90 % of a day in the parking lot. Therefore, they are available to be used as energy storage. The use of EVs as storage has been formed based on the concept known as V2G. V2G means to deliver power to the electrical grid by electric vehicles parked in parking lots. On the other hand, based on the definition of the smart grid in important references, V2G concept is considered as a fundamental component of these definitions. This issue increases the speed of the influence of EVs on the grid. Vehicle to grid (V2G) are capable of bidirectional power exchanges [43]. In fact, 62.3% of the world's consumption of fossil fuels in 2011 were related to the transportation sector [71]. According to the studies, if energy consumption continues in current fashion, until 2050, the carbon dioxide level in the environment will be enormous and it will not be acceptable from environmental and available road map views.

3.2 Features of electric vehicles

Electric vehicles have two noticeable features; (a) electric vehicles can use clean and emission-free energy (from renewable energy sources such as the times of wind and solar power surplus), and (b) containing battery which can produce or store electricity [43]. A study conducted in 2005 in the United States of America has shown that the average of short distances that are coursed daily by vehicles is 50 kilometers and the mean time necessary for travelling this distance is 52 minutes. The research on the behavior of American drivers have shown that 61% of drivers travel a distance less than 80 km with their electric vehicle during the day [36]. Also, in a study for city use of EVs [40], it is shown that the average time, which personal vehicles are used has been 4% of the day. So, if electric vehicles are used in distances within the city, they will be parked for about 23 hours in a day. Since the stored energy in batteries will not be used over short distances fully, we can consider electric vehicles as a potential source of energy supply and storage [36] (Similar information about EV usage in Germany will be discussed in more detail in chapter 5, including tables and different figures).

In addition to storage capacity, another important feature of the battery is the state of charge (SoC) that is mostly defined as the ratio of stored energy in a battery to the useable capacity of the battery storage. State of charge is between 0 and 1 and is expressed in percentage. As the battery gives energy, state of charge reduces and when it gets energy, state of charge increases [36, 47]. Continuous switching of the charge current of a battery reduces the energy storage capacity. If a battery's state of charge is used as a measure to optimize the performance and avoid reducing the energy storage capacity, the battery charger could stop receiving power from the grid when the charge is equal to 85% or 90%. If this rule will be used properly, the battery life will increase greatly. Now, some manufacturers of batteries produce batteries with a lifetime of 10 years [36, 47].

3.3 Role of EVs in power systems

EVs can store electrical energy in their batteries in addition to the ability to satisfy their transportation function. This role has been led to the flexibility of EVs in being connected to the power grid. As mentioned before, EVs are generally divided into three types. Hybrid EVs, plug-in hybrid EVs and EVs with battery only. To study the effect of EVs on the grid, just plug-in hybrid EVs (PHEV) and EVs with battery were considered, because only these two types can receive power from the grid; so, from this point onwards, these two types were considered as EVs in this work.

The emergence of EVs adds a new type of electric load to the power grid. On the other hand, the expansion of vehicle to grid (V2G) technology presents the vehicles as distributed generators. In recent years, the manner of energy exchange between the power grid and electric vehicles have become an important issue for the electric and automotive industry and have been studied and examined a lot. For example, in reference [41], it has been shown that the required power for electric vehicles is 24 times of the productive power capacity of the power grid of United States of America. In another study, it was shown that replacement of a quarter of vehicles in America with electric vehicles will produce more productive capacity than the capacity of the available power plants in the United States of America [42].

3.3.1 V2G concept

In the V2G concept, the power grid is able to receive power from the electric vehicles, so electric power charger has the capability of a two-way power transfer. V2G technology was evaluated for applying EVs as power storages and peak power providers [44, 45]. In another definition of this concept, V2G does not necessarily mean bidirectional power flow from vehicle to the grid and vice versa; because vehicles with a one-way power control, can also provide V2G services. In this type of one-way charging, the electric vehicles will respond to frequency variations due to a received control signal and set their amount of energy usage (increase or decrease) as a controllable load.

Another statement raised about the concept of V2G: when the vehicle delivers power to the grid it is called vehicle-to-grid (V2G) [46], but when the network delivers power to the vehicle it is named grid-to-vehicle (G2V), as separate definitions. Despite different definitions that have been proposed for the V2G concept, what is considered in most studies of V2G technology is as follows: Vehicle-to-grid (V2G) is a concept for applying EVs to deliver power to the electrical grid [45, 48]. This concept is shown schematically in Figure 3.1, which is adapted from reference [48].

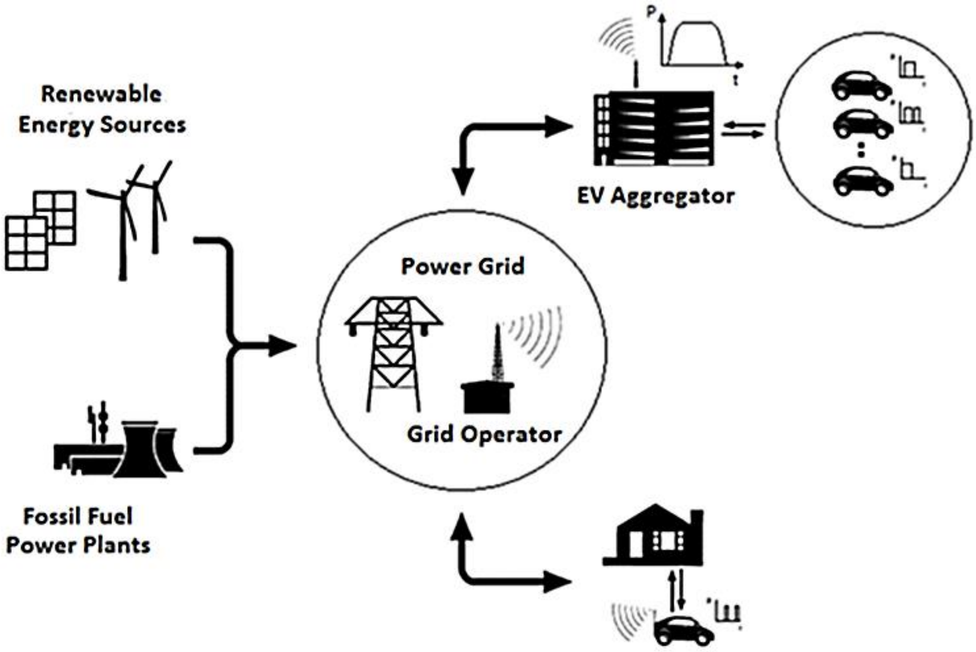


Figure 3.1: The concept of V2G Technology (derived from [48])

The power is transmitted from conventional power plants and renewable energies to the consumer through the transmission system. Electric cars can also inject power to the grid by receiving a signal from their operator. EVs can do this in two ways [48]:

- Available vehicles at homes that are connected to the distribution network.
- Aggregation of these vehicles and their final connection to the transmission system.

3.3.2 Status of EVs and charging stations in the world

TOYOTA and HONDA were the first companies in the world which build electric and hybrid vehicles. In 1990, the first series of hybrid vehicles were built by these companies. In 2004, these cars were well positioned in the global market. Then other auto companies came to build hybrid cars. Currently, most of the car companies have invested in EV projects [110, 111].

One example of new EVs is Volkswagen's electric micro bus. This company introduced the concept of an EV for public transportation at CES 2016 called “Micro-Bus”. Obviously, this EV is equipped with the latest smart communication technologies and is in many aspects, an example of using the idea of the Internet of Things. This car is fully electric in addition to its completely different and futuristic design, and welfares from very advanced digital technology. It is equipped with a 101-kWh battery which has enough energy to travel about 600 km. It is noticeable, applying fast charging equipment, its battery could be recharged within 15 minutes about 80 percent. The car has two electric motors that can reach a speed up to 150 km/h. In addition, the car could be connected to the Internet and brings a high functionality. When you're in the car, you can control your home through voice or touch command. For example, seeing what home security cameras show or setting the heating system’s temperature [66].

In the world, there are many homes or public charging stations so that the number of EV charging stations in Japan is more than fossil fuel stations. Recently, Norway opened the largest fast charging station for EVs [92]. This station is part of the Charge & Drive Network of a company named "Fortum" and it is done in a partnership with Tesla. Fortum says they are partnering with Tesla specifically to make it possible that there are all required EV charger types, available. Of the 28 chargers, four are 50 kW fast chargers. The other devices are chargers with 22 kW and average speed, along with Tesla super chargers. Fortum is currently building charging stations between major cities of Norway. Apparently, this company has built about 160 new fast charging stations in Norway in 2016 and they are hopeful to set up charging stations, every 50 km between Oslo and other major cities of the country, by the end of 2017 [92].

3.3.3 Electric vehicle aggregator: a factor for efficiency of V2G technology

The storage capacity of a single battery cannot have an enormous impact on the power grid; it acts like a small noise on the network. To create influential powers in the MW scale, players in the role of EV aggregator have been introduced in 2001. Aggregators are new actors whose tasks are to collect the energy of the vehicles to a specific amount of power so that they can reach effective amounts for the grid. This aggregation can be utilized as a source of energy generation and storage, on the network. From the load perspective, aggregated EVs could be assumed as large industrial or commercial loads, where the final charging cost of each EV is significantly reduced [49].

From the economic perspective, EV aggregation has this advantage, that a decision-making unit, contracts the energy supply of the aggregated EVs with a lower price than the owners of each EV separately. So, in terms of electrical cost, batteries and other services perspective, this will be profitable for EV owners [49]. So far, several models have been proposed for aggregators. In the first model, the aggregator is intended in manners that manages a group of cars that are parked in a specific parking lot [49]. In the second type, the aggregator is a battery manufacturer that gains a part of the obtained profits from the sold power to the grid by owners, for free battery replacing [49]. In the third model, a group of vehicles that are distributed in different places were considered and the aggregator acts as a retail seller that buys the electricity from hundreds and thousands of EVs and offers services in the electric power market [42, 50].

In another proposed type, the aggregator gives incentives and discounts for the purchase and recharging of the batteries to EV owners. In contrast, the owners, connect their vehicles to the grid at times that are predetermined in the contract. If they break the terms of the contract, some penalties will be incurred. This aggregator model is more attractive to EV owners, due to lower charging costs and lack of concern about their battery degradation [52].

Regardless the proposed models for aggregators, the existence of these actors are essential for the effectiveness of V2G technology. With the aggregation of electric vehicles, the expected power and energy at any time, can be predicted with less uncertainty than a single vehicle and they could act as an effective load or power source. As previously mentioned, due to limited capacity of batteries, it is essential to apply an aggregation entity that collects small energy units and offers them in the form of a major energy unit, which duty is to collect plug-in electric vehicles, management and smart control of their battery charging procedure. This institution is in fact an intermediate between the Independent System Operator (ISO) and vehicle owners. The contract between the aggregator and EV owners can be made through an internet platform where the car holder can record the times and places where the vehicle could be plugged-in to the grid and the state of charge of the battery before the next trip.

In addition, there are some exceptional situations like when the EV is not available during the next two weeks because of a travel or the car is fully connected to the network in the next week due to traveling by plane. These exceptions could be defined by owners on the website. Note that, these special cases are important when the number of cars is not low, because as the number of cars increases the changes in their registered information of the EVs could help in a better prediction of their availability status. As a result, aggregators could combine the vehicles’ information and have an accurate estimation of the status of their availability in different times and places. This means, being aware of the amount of available capacity at any place and time.

3.4 Possible markets for V2G

Regulators and operators of electricity grids are responsible for providing electricity with high reliability, while keeping the supply-demand balance at all times. A planning strategy is required in order to keep the stability of the power system. This would be achieved through (a) ensuring that generating capacity resources are available over the long term to provide electricity when it is needed, and (b) the system is able to deal quickly with the fluctuations in demand as well as failures.

All countries face the technical challenge of balancing the supply-demand in real time. For example, in the EU and China, this means to maintain the system frequency within a range around 50 cycles per second (Hz); In the United States of America, the system frequency is 60 Hz. If the demand is more than supply, the frequency will drop, and vice versa. Grid operators could avoid system imbalances by ensuring the ability to increase or decrease supply or demand, communicating with generator operators and other market participants who provide a variety of “grid services". The grid services mainly include capacity, energy, and ancillary services.

V2G could participate in three types of markets including base load, peak load and ancillary services. In this section, the aforementioned markets are presented.

3.4.1 Base load

In reference [49], the price of providing electricity by three types of electric vehicles (all electric, fuel cell and hybrid) has been calculated in California. The results of this study indicate that the price of generating power from electric vehicles is more than the power cost of base load. For example, the cost of generating power from the electric vehicle of Honda is 0.42 €/kWh, while the price of base load is 0.09 €/kWh. Reference [53] confirms these results.

Thus, it can be said that the V2G technology is not a proper and economical solution to provide the power requirements of base load. Despite of this point, electric vehicles can increase the base load and as a result reduce the total prices. This means that vehicles can connect to the grid at night when the electricity prices are lower and the amount of required load is less and buy cheap energy from the grid for charging their batteries. This charging time is desirable for the power system and producers because it flattens and grades the shape of the load curve and increases the total efficiency of the system by increasing the base load.

On the other hand, instead of consuming a large amount of fossil fuel in internal combustion vehicles, with low efficiency, the fossil fuel can be used up in power plants to generate power and finally being used in electric vehicles with high efficiency [53]. As shown in Figure 3.2, by adding electric vehicle to power system, the valleys in the load curve can be filled and it prevents forced blackouts of power plants which provide load.

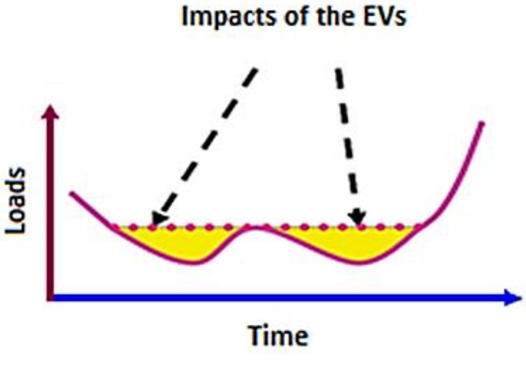


Figure 3.2: Flatted load curve in non-peak hours by means of electric vehicle charging [52]

3.4.2 Peak power

The generated power for covering the peak load is more expensive than the one for base load. Construction of power plants which provide peak power only for a few hours is not economically affordable. For these kinds of power plants, gas turbines or diesel engines are commonly used. Electric vehicles can be applied as a source of electrical power supply for peak hours. In 1997, the economic value of peak power supply was calculated by three kinds of electric vehicles for the first time [43].

By comparing peak power supply of electric vehicles and the electric grid in reference [43], it was clear that peak power prices in the electricity market are more than two times of the required monthly investment cost for operating the storage capacity of electric vehicles. The results of the calculations in this study suggest that peak power supply through electric vehicles has economic benefits for both the vehicle owners and the power grid. The economic operation of electric vehicles for providing peak power depends on different factors such as the type and capacity of the battery, degradation cost because of V2G power and the electricity prices [54].

The reduction in the battery prices, changes in the electricity prices and various incentives for vehicles, make EVs suitable and economic resources for providing peak power [53]. When the electric vehicles participate in peak load market, the need to build traditional power plants will decrease [56]. For participation of EVs in order to supply power at peak hours, there should be enough motivation in electric vehicle owners to put their electric vehicles into the grid. In reference [55], it is clear that without incentive programs for vehicle owners, the obtained profits do not make enough motivation for electric vehicle owners to put their vehicles in the hand of the grid.

3.4.3 Ancillary services

The purpose of the ancillary service market is to support the reliability of the power system and provide acceptable power quality to the grid. These services could be provided either by mean of loads or productions.

The ancillary services are required to be available in the system within minutes or seconds, in order to manage the short-term frequency and voltage fluctuations due to changes in supply and demand.

This kind of services will be discussed in more detail, further in this section.

3.4.4 Spinning Reserve

Reserve capacity is used to keep the system frequency at the standard level. In power systems, unforeseen events such as the increase of unexpected load, unexpected outage of generators or lines and transmission equipment are resulting in an imbalance between production and consumption. In the absence of sufficient reserve capacity in the system, these events will lead to load shedding.

The spinning reserve supply unit, should respond immediately and reach its maximum capacity within less than 10 minutes. The reserve capacity usually is considered as the same capacity of the biggest generator plus a portion of peak load capacity. Spinning reserve is the most valuable part of electric power production chain. The spinning reserve cost is paid based on the time on which the units are ready at work and the energy that they inject to the grid [49].

It should be noted, that the participation in this market is highly desirable for electric vehicle owners because these vehicles are at the park estate, most time of the day (23 hours), therefore they can get the price of spinning reserve for many hours of the day. Technically, it is no problem for connecting electric vehicles to the power grid because the running time of electric vehicles is very low and they can easily get into the circuit less than 10 minutes [49].

3.5 Impact of electric vehicle on power grids

3.5.1 Impact on the grid load

As mentioned before, electric vehicles have attracted much attention in recent years because of high energy efficiency, easy and cheap charging and the reduction of dependence on oil. As the number of electric vehicles in the grid increases, the load curve of the part under investigation can change due to this EVs charging. The question that shows up, is that whether the existing or planned production capacity has the ability to meet the load growth resulted from the charge of the electric vehicles or not.

This section explores some studies in order to answer this question. In reference [98], various scenarios are defined for charging the electric vehicles and the impact of charging them on the grid load is examined in different scenarios. In this study, V2G technology is not considered and only the required power supply for electric vehicle is focused. Also, driving patterns have been extracted using transportation information in California. It has been shown that the use of connectable electric vehicles to the grid will reduce the fuel consumption, for example in two vehicles, there is 45% and 70% of reduction in fuel consumption respectively. Also, non-smart charging of electric vehicle increases the grid load in peak hours, which can raise the amount of load peak of private homes from 1.44 kW to 7.2 kW. While smart charging of electric vehicle increases the grid load in low load hours.

Reference [57], examines the potential impact of electric vehicles on Australia's power network. Therefore, the impact of different EV charging strategies on the amount of the Australian power gird load has been investigated. The results of this study suggest that the proper management of electric vehicle charging, leads to more application of the available grid. Also, by charging electric vehicles at low load hours, there is no need to establish new power plants to supply the additional load of electric vehicles. Also in study [58], it is recorded similar results for Ireland. In reference [100], different strategies of charging vehicles based on their impact on local distribution has been evaluated and electric vehicle charge and discharge planning have been examined in order to minimize costs and the load changes. The performed study for 63 houses at the charge levels of 15%, 45%, and 75 % has been considered and the results show that the applied algorithm reduces 29%, 53%, and 64% of the load peak, respectively.

In reference [59], the focus is on presenting a way of online coordination of electric vehicle charging and discharging in order to reduce the system costs. In this study, the information about the electric vehicle load is predicted for more coordination of the vehicle charge. It acts well at the time of loading intensification and it has an acceptable computation time. Despite all its advantages, there are some disadvantages as follow: it challenges the battery lifetime in discharges and the lack of adequate incentives for electric vehicle owners to charge and discharge at off peak hours. In references [60, 61], due to load changes caused by the presence of EVs, the reliability of distribution grid has been investigated. It has been shown that the presence of electric vehicles does not necessarily enhance the system reliability and may reduce it. The reliability of the grid can be improved using a suitable application of the EVs as a storage unit. The results show an improvement in reliability, but as the reliability increases, the costs increase too which may dissatisfy the consumers.

The ability of the grid to supply the load growth resulted from an electric vehicle charge depends not only on the vehicles charging patterns but also on the characteristics of the studied grid. So, depending on the zone under investigation and the vehicles charging pattern, the presence of electric vehicles may increase the electrical load on the grid.

3.5.2 Impact on renewable energy utilization

Due to environmental issues, renewable energy resources have attracted much attention. Despite of this, renewable energy resources like wind and solar cannot produce energy at the time of demand due to their stochastic nature. Demand side management and energy storage systems can result in a greater role of renewable energy resources in providing the grid power. This can increase the system efficiency, reliability and flexibility.

However, storage systems, due to their high investment costs are not an economic solution for adding renewable energy resources in the power production system. Since the primary purpose of EVs is to meet the needs of transportation, these vehicles can be used as economic storage systems for applying renewable energies in the grid. Electric vehicles can be combined appropriately with these distributed generation units and save energy at certain times and deliver it to the grid in other times. In the study of [62], it has been shown that the use of the electric vehicle batteries in storing wind energy and deliver it to the grid, is very effective in the efficient use of this renewable energy source. Reference [63], investigates the integration of electric transportation vehicles in order to coordinate the EVs charging for reducing peak and costs and challenges the grid while renewable energies are a substantial part of it. The effects of the uncertainty of renewable energies have been carefully examined.

The proposed method predicts the amount of load and charging requests by the vehicles on the next day and according to it, relevant plans are made. The results show that there were 56 % cost savings. One of the remarkable effects of renewable energy sources in the power system frequency is the reason that electric vehicles compared to other distributed energy storages can provide more reliable services.

References [64], investigates the effects of electric vehicles on the frequency control, considering random load fluctuations of wind.

3.5.3 Economic impact on the power grid

In reference [65], the planning and optimal operation of the power grid in the presence of electric vehicles is investigated. In this study, it is shown that the presence of V2G technology reduces 3% of the planning and operation costs of power grids in the north of Europe. In this case, electric vehicles can be considered as a perfect replacement for boilers and storage systems and cause the reduction of gas turbine application in power plants.

Reference [24], presents a method in order to evaluate the impact of electric vehicles on the amount of investment and the losses of distribution grids. This study was conducted in two different areas: urban and rural. The results of this study showed that EV charging at peak hours, will increase 19% of the investment costs for developing the distribution grid, while electric vehicle charging at off-peak hours will decrease 60 to 70% of these costs. It also has been shown that in the worst case, electric vehicle charging will increase 41% losses in the distribution system. In this study, the driving pattern and V2G technology are not considered. Electricity generation in electric vehicles will have a significant impact on the increase of the grid load and it may reduce the reliability of the system in future smart grids.

In reference [67], due to the presence of electric vehicles, the economic evaluation and reliability of a micro-grid consisted of renewable energies is examined. The results indicate that through the coordinated charging of EVs, the reliability increases and accordingly the cost decreases, but the problem with this study is based on the preferences of vehicle owners for charging, there is no charging time period and all EVs will be charged in one period of time. In reference [68], the economic evaluation of the application of vehicles as responsive loads, to reduce the imposed stress on a smart distribution grid, was investigated. The results show that with this method, 7.9% of renewable energy is stored and the costs has been decreased.

3.5.4 Impact on the environment

Electric vehicles have the necessary potential to reduce greenhouse gas emissions in populated areas, where most of the emissions are from the exhaust pipes of vehicles.

Although it has to be considered that the electricity for the vehicles is generated with no or low greenhouse gas emissions. With the advent of electric vehicles and increasing demand for electricity and vehicle charging, significant challenges in the network in terms of electric load, will be applied in the grid due to unmanaged factors, at the time of charging. To reduce these problems, vehicle charging needs to be managed.

Reference [69], presents a dynamic structure to control vehicle charging and considers the proper function in local distribution grids and minimization of environmental impacts. The results show that when vehicle charging is not managed, the peak load increases and thus the generation of electricity from power plants increases too which will have a negative impact on the environment.

3.5.5 The German electrical infrastructures and EV integration

As presented in Figure 3.3, the electricity grid in Germany is divided into four different levels, as follows:

- Transmission grid (380 kV): This level is the main grid for electricity transmission. This grid level will also be responsible for providing electricity to the other grid levels.
- Distribution grids: The second and third levels are the distribution grid (110 kV and 10/20 kV). These grids will operate as the distributor of electricity within a given region and industrial demands. Finally, the low voltage grid (under 1 kV), will deliver the electricity to the houses, which would be affected significantly due to the integration of the EVs (since the costumers will charge usually their EVs in their home) [70].

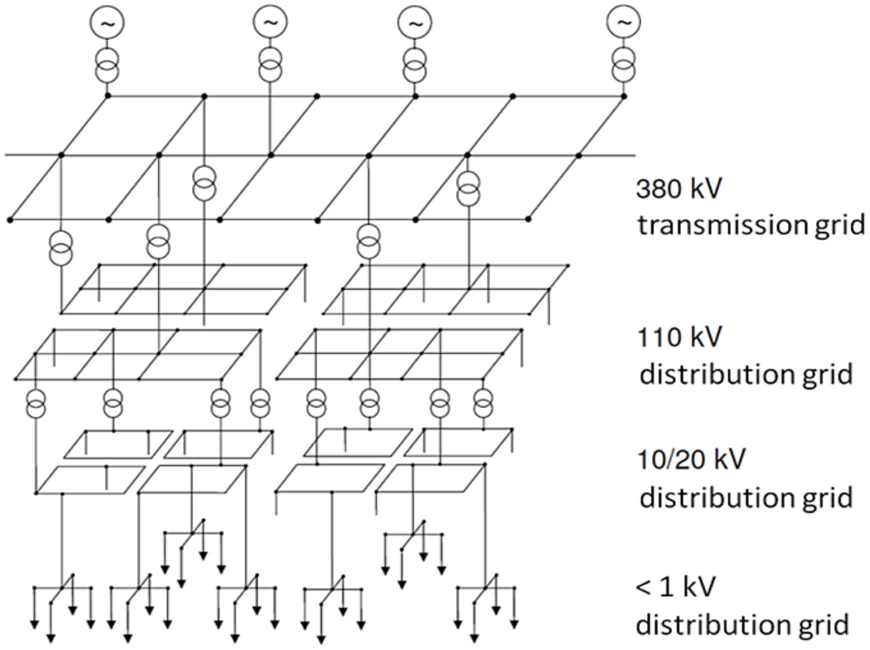


Figure 3.3: Grid's levelling in Germany [70]

An important issue that is needed to be considered is that integration of EVs in the households, would increase the peak demand in the distribution level (mainly, less than 1 kV). Consequently, the low voltage grid may be overloaded and tripped during uncoordinated charging of the EVs. Therefore, it is required to find a solution to obviate this problem, in order to make the application of EVs in Germany, feasible.

In this regard, two possible solutions are presented. First, increasing the capacity of the German’s current electrical infrastructure. In this approach, reinforcement in the current electricity system (e.g. transmission grid capacity, transformer upgrade), so that the EVs could integrated in the future power system. Due to the high costs of this kind of investments in the system, this option may not be economically justified. Second, optimizing and managing the current system through optimal generation scheduling and some other “minor" adjustments. This solution will increase the system efficiency and it is more cost-effective [70].

3.6 Review of smart charging methods of EVs

Smart charging of electric vehicles allows customers and grid operators, by considering demand side management, plan the way of charging to get technical and economic advantages. Smart power charging seeks to control the loads and can be planned by heuristic algorithms and optimization to achieve certain goals such as: avoidance of saturation of the transformers and lines, reducing greenhouse gasses and minimizing generation costs, peak load shaving and loss reduction. In addition, an institution called aggregator, is necessary in order to establish a technical and economic management to coordinate electric vehicle charging. Finally, smart charging of EVs can be applied in two different structures called: centralized control and decentralized control [71].

3.6.1 The structure of centralized control

As shown in Figure 3.4, in the structure of centralized control, the aggregator is responsible for direct charging of all available electric vehicles in their areas. Also, the bidirectional connection of the aggregator with the transmission system operator (TSO) and distribution system operator (DSO) is demonstrated.

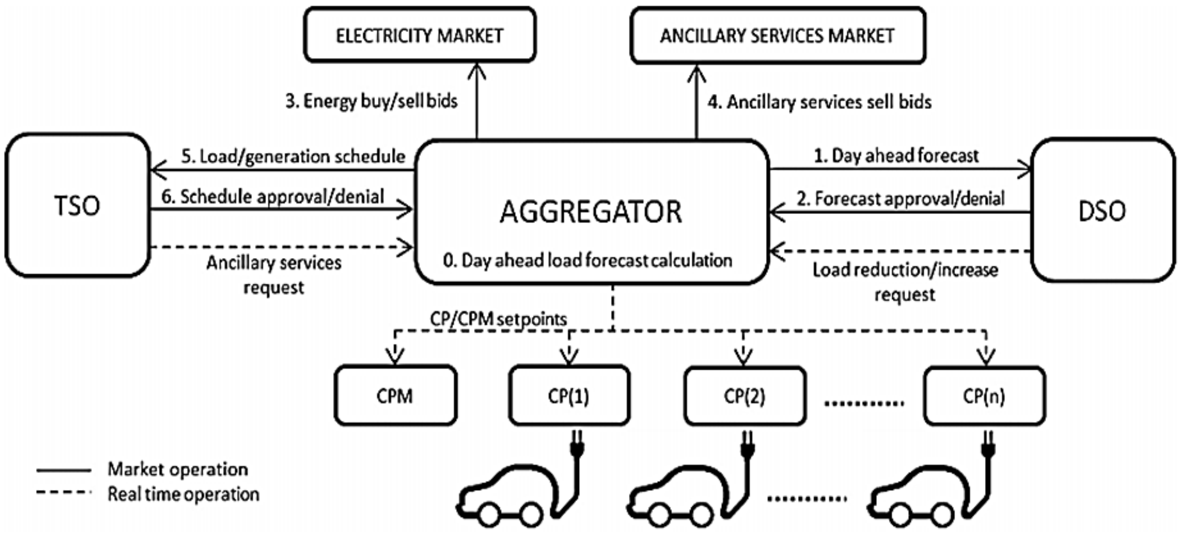


Figure 3.4: The schematic structure of centralized control [71]

In addition to technical management, aggregators are responsible for the participation of electric vehicles in the electricity market. So, they do this based on past data, consumer preferences and the prediction of daily demand. When specifications of the vehicles demand were predicted by aggregators, the specifications and characteristics should be sent to the distribution system operator to be checked and approved. The operators verify the specifications in order not to endanger the operation of the distribution grid. After receiving the approval of the distribution system operator, the aggregator will offer the tender of power purchase from the grid, directly. After negotiation in the market, the transmission system operator considers all changes that could happen in the case of problems. If this evaluation is positive technically, the aggregator will meet the charge or discharge requests of the vehicles [71].

During the operation, the aggregator should collect a series of information such as: identification of vehicles, battery state of charge, consumer preferences. Using this information, considering the needs of electric vehicle owners, the aggregator provides an algorithm to achieve the proposed objectives and actions needed to charge the vehicles. In different studies, different algorithms can be found to achieve specific goals. For example: the authors of reference [72], compared three different optimization algorithms and sub-optimal modes. The purpose was to maximize the benefits of the aggregator, to reduce the costs for consumers and to limit the destructive effects on the grid. The applied algorithms depend on electricity price, vehicle loads and the price of ancillary services. The used algorithms are simulated in the MATLAB software and the optimization problems are being solved. Minimizing the production cost of electricity is the purpose of some other authors. Reference [73], presents a smart charging algorithm for the electric vehicles’ load, in order to minimize the production cost of the generator. The optimization problem, solved by the meta-heuristic method, shows that the cost would be reduced to about 16%. It is desirable to examine the decentralized control structure in the next part.

3.6.2 Decentralized control structure

Figure 3.5, shows the structure of decentralized control. Although in the structure of decentralized control the owners of electric vehicles make decisions about "when" and "how" their vehicles should be charged, there are some ways to have an influence on these decisions. Thus, electric vehicle’s charge and discharge follow pre-set criteria. This influence may come through cost control signals and can be sent through aggregators or directly from the grid. Therefore, the optimization of charging cost can be sought directly, considering consumers' preferences [71].

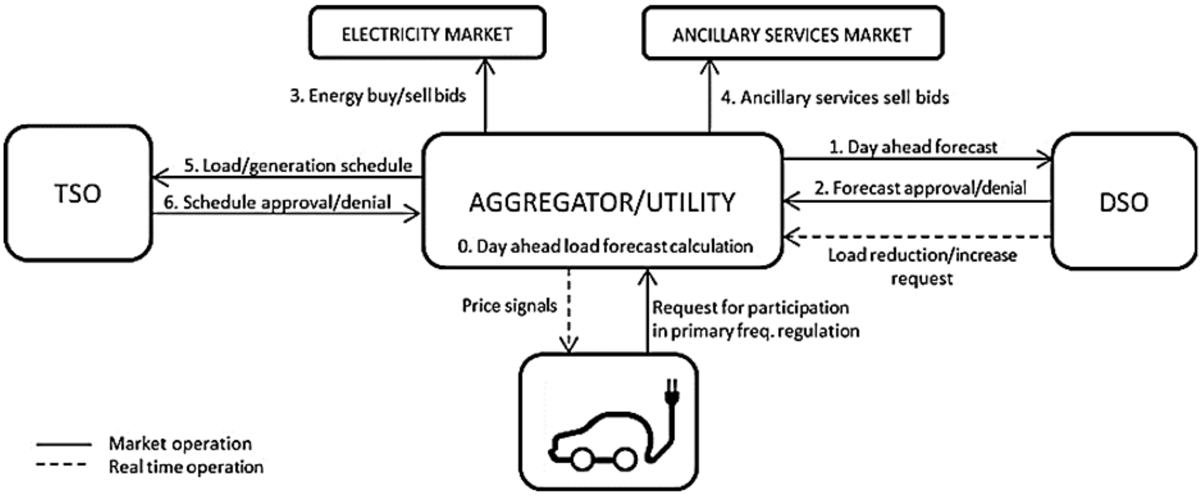


Figure 3.5: The schematic structure of decentralized control [71]

In this structure, EVs can be connected individually to the grid. It is better to apply the active power control, in order to reduce the power demand and inject power into the grid which will be accessible only in V2G mode. To do this, in the market environment, the consumers should participate in the power storage in the grid and provide ancillary services, to supply power at the specific time. In this method each electric vehicle, according to conditions, will follow its explicit goals. For example, the goal of one car might be charged at minimal price while the other one is responsible for preventing overload of transformers [71].

In a decentralized system, the vehicles must be connected to the network smartly, which means that they need hardware for data processing. Thus, some costs are imposed to the grid and this additional cost can be compensated through the concept of V2G and the use of it as distributed generation and distributed storage. Electric vehicles are in motion, so the distribution grid, which vehicles are connected to, calculates the demand as a variable. It means that because they can move, they should benefit from the same level of service quality at different locations, this fact is known as roaming. This concept requires a two-way communication between EVs and the grid. As a result, a system is needed to apply different strategies of charging, discharging and participating in the market. So locally, there is a management agent for residential energy that collects all the information and smart control of battery's charge and discharge [71].

3.6.3 Comparison between centralized and decentralized control

A comparison among various aspects of the two control systems and the advantages and disadvantages of both methods are presented. In the centralized control, the use of optimization algorithm for charging electric vehicles is easier. Because the system information is available at each point. This makes the distribution grid management easier and the capacity of using the grid will be maximized which results in providing supplementary services. However, it requires a large amount of data, such as the amount of charge request, availability during charging, and battery capacity.

In practice, it will be difficult to get all of this data. In the decentralized option, the optimization is used to influence the prices and control the electric vehicles. However, the final decision will be made by each vehicle. It means that there may be some uncertainties in final results so that a large number of vehicles change their amount and time of charging [71]. Finally, the integration of electric vehicles can be very complex. In fact, many of the papers analyze the technical solutions, economic problems or other issues, such as frequency regulation, voltage, and overload. This study tries to provide a suitable framework for electric vehicles charging management in a smart distribution grid.

3.7 Load shifting

In order to smooth the integration of EVs to the German electricity system, shifting the charging time of the EVs is the first solution to be considered. This will improve the system efficiency and prevent overload in the system. As a result, the system stability would be increased and it will keep the supply-demand balance properly.

In the past, as a disadvantage of this approach was that the customers were not always ready to shift their electricity usage to another time, given that the electrical equipment in the households were not smart enough. But, thanks to the current technologies, applied in EVs, the load shifting is increased significantly, since the energy consumption in an average household will increase (in fact, it will be almost double and likewise its storage capacity [70]). To this end, parking time of an EV will be long enough to enable the load shifting without constraining the consumers' activities. It is worth mentioning that, the load shifting strategy will not fully replace the grid expansion, since in some regions load shifting potentials are low. However, this approach would help to improve the efficiency the German’s current electrical infrastructure.

3.7.1 Load Shifting Potentials

The energy demand that could be shifted during specified times is defined as the load shifting potential. The potential of a single EV for two extreme charging scenarios (instant complete charging scenario and maximum-delay charging scenario) is illustrated in Figure 3.6 [70].

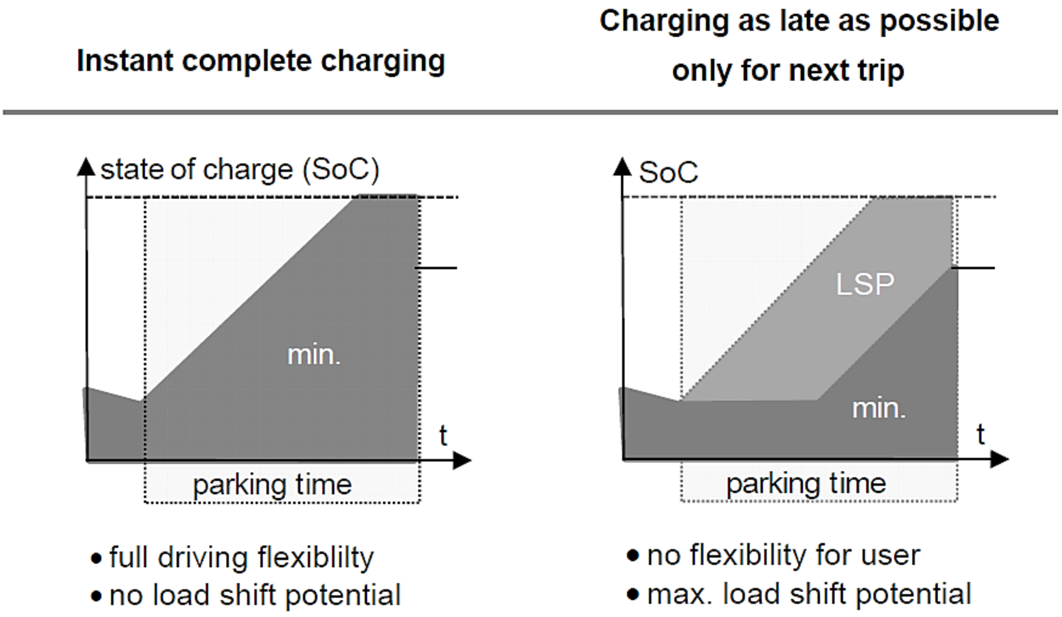


Figure 3.6: Extreme charging strategies to estimate the load shifting potentials of EVs [70]

The first charging scenario (instant complete charging) full driving flexibility is given to the driver, but there is no load shifting potential of EVs. In the other scenario, charging of the car would be scheduled so that the system could get the benefit of maximum load shifting potential. It is demonstrated that, based on the extreme charging scenarios, the system will provide two extreme values of load shifting potential and driving flexibility.

In [70] through using the data obtained from the 2008's mobility study in Germany, the theoretical load shifting potential of electric cars has been calculated that within the range of 40 to 90 percent of the available battery capacity could be possible (depending on the time and day of week). It is also stated that the load shifting potential is at its maximum during the night and its minimum during the midday.

3.8 Secure EV integration in power grids

In this section, possible solutions that could be applied to achieve secure and unproblematic integration of the EVs will be presented.

It was stated before that charging of EVs, while considering the peak load could facilitate the growth of EVs. The term “coordinated charging” of the EVs is defined as follows:

A condition, where the charging procedure in terms of order, length, time and other properties of the EVs are being manipulated so that the electricity would be delivered to the demand centers without any congestions in the transmission system. Although, coordinating the charging procedure of a large number of EVs is a complex task. However, applying smart grid capabilities (mentioned in section 2) could make it possible. Furthermore, the role of EVs as negative control reserve agents, may could lead to voluntary participation of EV owners in the load shifting program in the German power system.

Utilization of the distributed energy resources in the residential area is another solution that could facilitate the integration problem of EVs in the power systems. As presented in [74], the usage of distributed energy resources (i.e. PV) in the residential area will smooth the gap between the peak and the valley time of electricity consumption (as can be seen in Figure 3.6). This could lead to EVs integration into the distribution grid.

Defining a new electricity tariff plan is another method that can realize the energy demand shifting, which forces the consumers to shift their demand. In this strategy, according to the time of usage and the system peak, the electricity provider will apply different electricity prices. In research [75], a new electricity tariff which combines the real-time tariffs and the capacity tariffs is tested on a house with photovoltaic generator. The results indicate a decrease of 30% in the household energy payments.

Although the integration of EVs will postpone the needs to expand the power system, but there are some situations, in which the system operator is faced with the needs of system expansion. Under current circumstances, expansion of the grid is to expand the grid before installing of new storage facilities. As stated in [76], the expansion of storage facilities might be more expensive than the system's grid expansion.

Finally, prioritizing the EV charging, will make the charging more controllable. In this approach, the car with a higher priority will charge first. In order to have higher priority, the users must pay more money than the users that have less priority. Therefore, this will lead to more controllable demand, while the money could be used for extension of the grid capacity. This approach will be applied in section 6, in form of EVs charging priority lists.

3.9 Basics of power system balance

Basically, an electrical system is designed so that to run at a specific frequency (e.g. 50 Hz in Germany and 60 Hz in America). Deviation from the desired frequency will have a negative impact on the lifetime and operation quality of all the equipment that are connected to the system. Therefore, maintaining the system to be run in its designated frequency is of a great importance. The system frequency depends on the supply-demand balance. If supply is more than demand, the frequency increase, and if the demand is more than supply, the frequency will decrease (Figure 3.7)

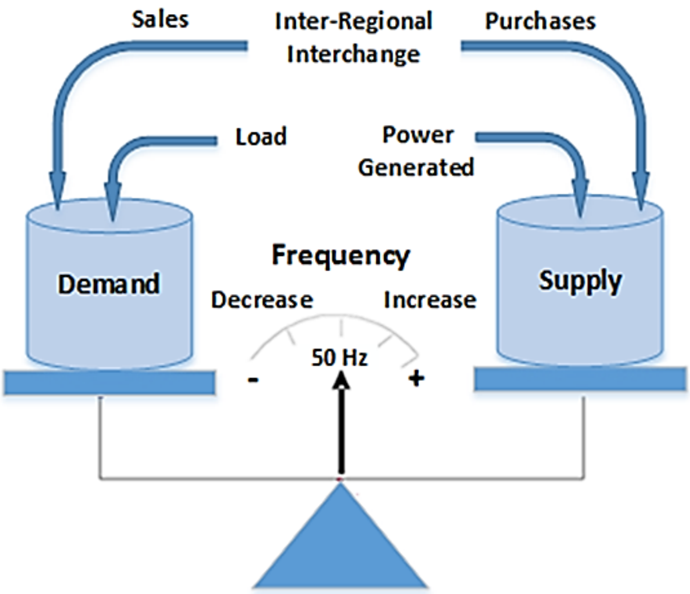


Figure 3.7: Illustration of power balancing and frequency control (derived from [77])

The supply-demand balance could be maintained as follows:

1. Storing the excess of supply when the supply is too high and/or decrease the power generation if it is possible.

2. Using the reserves when the demand is too high and/or increase the power generation if it is possible.

According to the European network of transmission system operators for electricity (ENTSO-E) this kind of control would be categorized as follows: primary control reserve, secondary control reserve and tertiary control reserve (Figure 3.8)

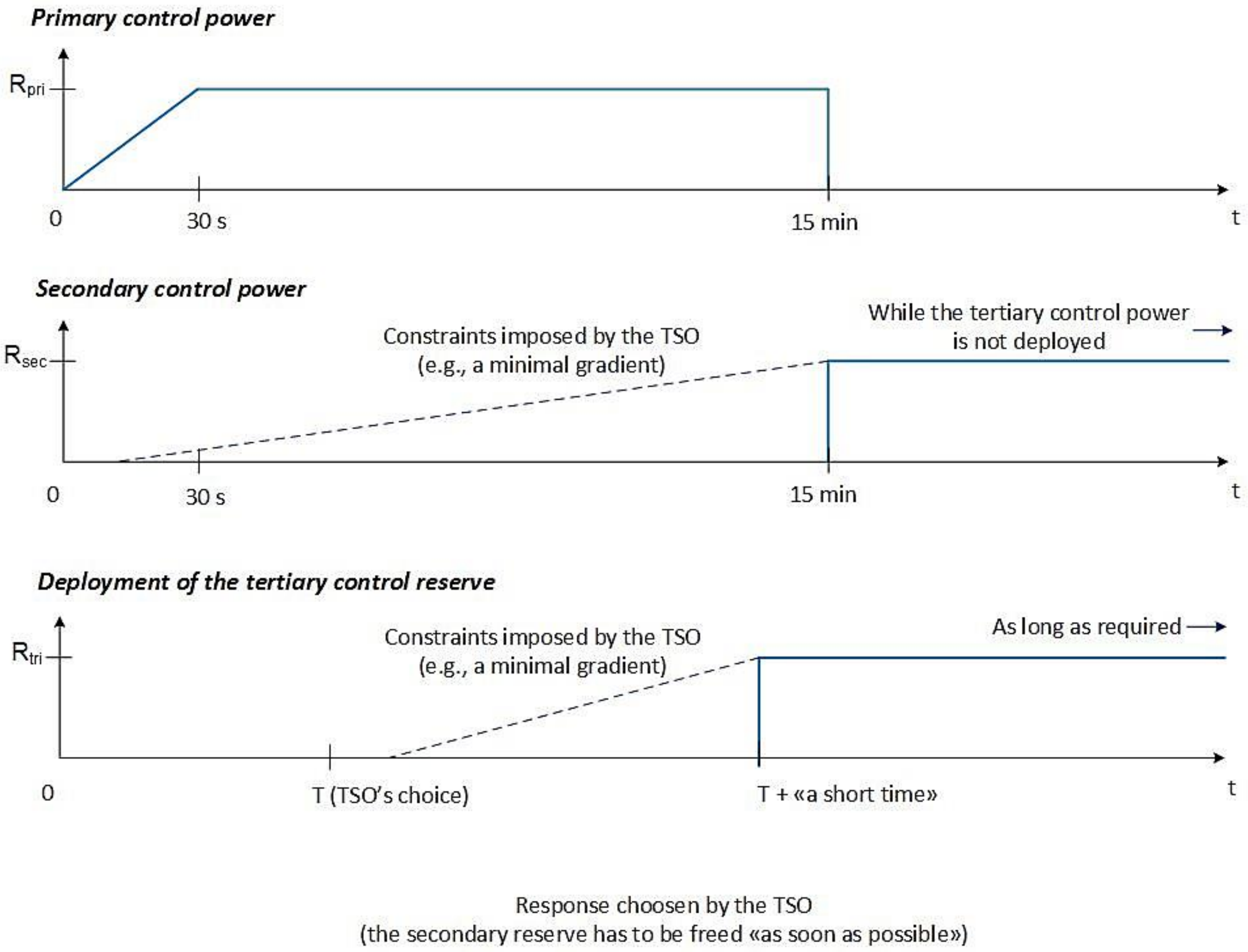


Figure 3.8: Principle frequency deviation and subsequent activation of control reserves due to ENTSO-E (based on [78])

- The primary control reserve, which is provided directly within the power plant would be online in the matter of seconds after the frequency imbalance occurred. In German power systems, the initialization time of this reserve is within 30 seconds after the incident with the activation time of 0 - 15 minutes per single incident.
- The secondary control reserve would be activated automatically after the incident happens longer. In the Germany, this reserve will be initialized within 5 minutes and its activation time is usually between 30 seconds - 15 minutes per single incident.
- The tertiary control reserve is a reserve, would be activated after the secondary control reserve. In the German power system, this control reserve becomes online manually through telephonic or schedule-based request, and will be initialized according to the 15 minutes’ time frame (or within 15 minutes). Its activation time is under 15 minutes up to several hours per single incident (in the event of several disturbances).

3.10 Power reserve storages – Current situation

Different kinds of power reserve storage technologies that are currently available are presented in Table 3.1. The most accommodated technology in the last decades is the pumped hydroelectric storage system (PHS), with more than 90 percent of total world's storage capacity (Over 127 GW installed power capacity worldwide) [79]. In Germany, the installed power capacity of PHS is 7.6 GW, which an additional 4.7 GW capacity is planned to be installed [80]. Due to the high efficiency (more than 80% efficiency [80]), high cycle capability (thus resulting in very low specific energy costs), and low discharge for stationary applications, this technology would remain the desired storage facility under current conditions. Unfortunately, installation of PHS plants is constrained given the geographical and environmental limitations. Furthermore, due to a large integration of renewable energy sources in the future, which are uncertain and variable, the volatility of the system would be increased, and therefore there is a need for other storage systems along with PHS power plant to maintain the power system balance.

Table 3.1: Characteristics of different power and energy storage systems [70]

Type	***Cycles***	***E-Density in Wh/kg***	***P-Density in W/kg***	***Invest Cost per cycled Energy €/kWh***	***Self-discharge***
Pump storage	Very high	1	-	600 -3k	Low
CAES	Very high	2 kWh/m^3	-	400 -800	Low
Lead-Acid	> 1k	20 - 30	80 -300	100 -250	Low
NiMH	eq. Li-ion	50 -80	200 -1.5k	750 -1.5k	High
Li-ion (HE)	2.5k -7.5k	120 -180	80 -300	450 -1.2k	Low
Li-ion (HP)	2M -5M	60 -140	200-2k	1k -2k	Low
Ultra-capacitors	500k -2M	2.2	1.4k	1k -2k	High
Flywheels	> 5M	3.7 -11.1	180 -1.8k	4.5k-5k	High
NaS	1.5k-4.5k	90 -110	100 -120	250 -3k	Low
Redox-flow	5 -15k	20 -65	-	300 -1k	Low

3.11 EVs as frequency controller

In Germany, the topic V2G is becoming very attractive, since the EVs could play a significant role in the future. This comes from the following facts and assumptions:

- The German government’s decision on producing most of its demand from renewable energies (RE), which have a fluctuating nature.
- The cars are parked 95 percent of the time [81].
- Due to the German government, in year 2030, the EVs would have 50% of the market share [83].
- According to [74], the distribution of EVs' charging power in the year 2030 will be 71.3% for 3.7 kW, 19% for 11 kW, 6% for 22.1 kW, and 3.7% for 43.5 kW.

Considering the aforementioned assumption along with the use of full EVs' capacity as power reserve storage, as well as assuming that the total number of the vehicles in

Germany is still not growing, a big potential would be available. Note that unlike the PHS power plant, the EVs are not constrained by geographical conditions and would be environmentally friendly.

EVs are well positioned to provide certain ancillary services because of these three reasons [112]:

1. EVs as a fast-ramping resources have higher value in ancillary services markets.

2. The power plants participating in the ancillary services market, will lose some revenue, since the plant’s operator should reserve some generating capacity. Contrary to these plants, EVs offer ancillary services to the market at no extra costs.

3. In the structure of EVs, if battery cycles are a small percentage of their total capacity, they can provide ancillary services without incurring maintenance costs, caused by frequent cycling.

3.11.1 Load Shifting Potentials EV's charging and reserve types

EVs could play an important role in power frequency balancing. Here, the possibility of employment of EVs as the frequency control agent would be investigated. In light of this, the economical/beneficial aspect for the EVs owner to participate in the power reserve market should be studied [112].

First, essential definitions for this issue should be expressed:

- *Unidirectional charging system: One-way supply or receive of electrical power.*

- *Bidirectional charging is defined as:* Two-way *supply or receive of electrical power (*in this case the grid and the EVs*).*

- *Positive power reserve: Additional supplied power reserve* in case of power frequency imbalance.

- *Negative power reserve: Additional load to the system* in case of power frequency imbalance.

3.11.2 Markets for V2G

The V2G program could participate either in short-term electricity trading market (the day-ahead and Intraday market), or control reserve market (frequency control market).

Participation of V2G in the first market is almost impossible, due to the huge amount of traded energy and long-time frame of this kind of markets. For V2G participation in this market, a large number of reliable and trip-scheduled EVs are required, since the predicted data of the V2G power generation must be met in this kind of market, which is difficult task for the system operator. Regarding the second market, V2G program would fit in this market, since less energy is required to be supplied or demanded. In addition, this market has a free procurement fee (e.g., secondary control reserve market). The primary control is provided by the power plants and because of low demand in the tertiary control reserve [70], these markets are not suitable for V2G program. Hence, the appropriate market for V2G participation seems to be the secondary control reserve market.

3.11.3 PHS vs. V2G – Economic value

As mentioned previously, the main storage technology installed worldwide are the PHS power plants. Thus, the economic value of V2G and the PHS power plant would be compared. The specific generation cost of the PHS is between 0.03 - 0.04 €/kWh [70]. Taking into account this assumption, the V2G program associated costs for entering the secondary power reserve market, should be less or equal to this cost.

3.11.4 Battery degradation cost

The Depth of Discharge (DoD) of the battery plays an important role in the economic cost of the power produced by the EVs, since the battery’s characteristic is non-linear. Furthermore, the battery’s life cycle depends on the DoD. As shown in Figure 3.9, the Li-ion battery’s cycles is very high at low DoD and vice versa.

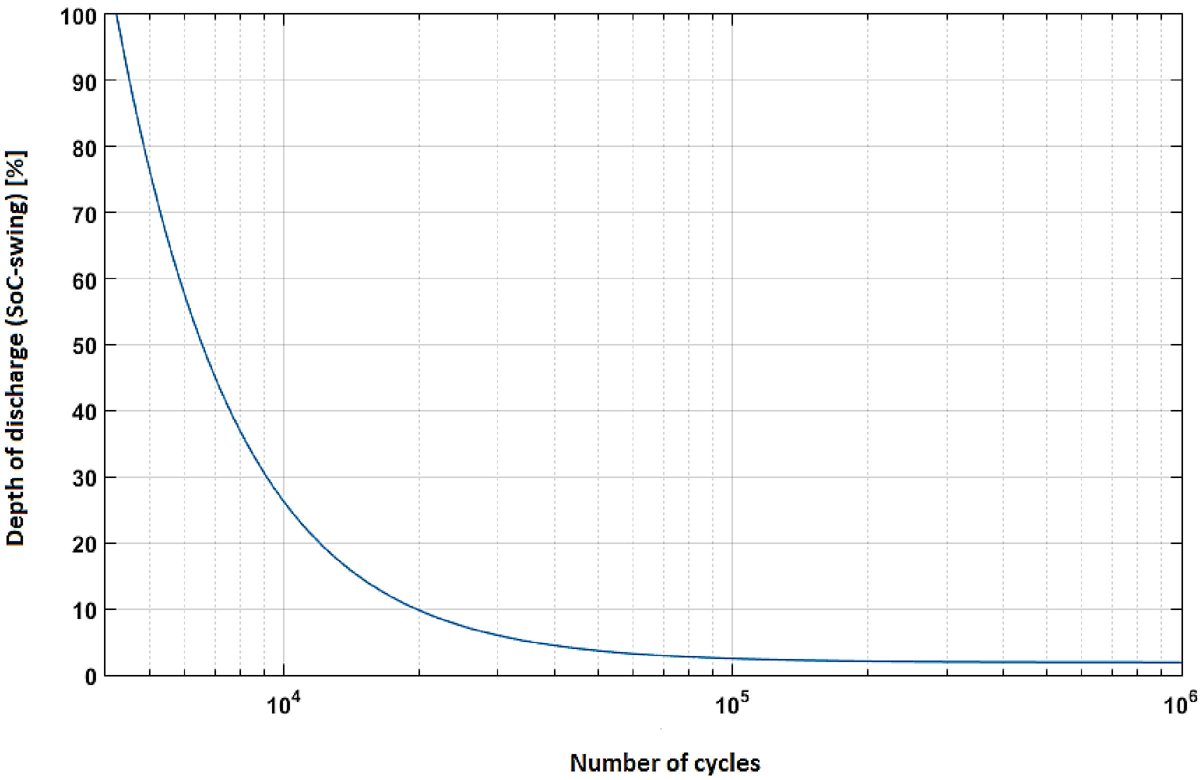


Figure 3.9: Battery cycle life dependence on the DoD for scenario 2030 (derived from [47])

As mentioned before, the number of cycles N^{cycle} is dependent on the battery's DoD and could be formulated as follows based on [47] (3.1):

$$N^{\mathrm{cycle}} = \mathrm{a} \times DoD^{\mathrm{b}} \tag{3.1}$$

Where:

$\mathrm{a} = 4000$ and $\mathrm{b} = -1.632$ were assumed for the Li-ion battery of scenario 2030 according to [47].

In discharging mode of the battery, the degradation costs are related to the DoD at the beginning (DoD^{start}), and at the end (DoD^{end}), of the discharging procedure. The total battery cost is calculated from one discharge procedure (cycle) divided by the number of cycles [47].

The discharge cost of the battery at a specific DoD, is calculated in (3.2) [47]:

$$c^{\mathrm{dis}}(0, DoD) = \frac{C^{\mathrm{bat}}}{N^{\mathrm{cycle}}(DoD)}, \tag{3.2}$$

where C^{bat} is the cost of the battery.

The presented degradation costs per kWh in Figure 3.10, are given by (3.3):

$$c^{\mathrm{dis,energy}}(0, DoD) = \frac{C^{\mathrm{bat}} \times DoD \ \times E^{\mathrm{bat}}}{N^{\mathrm{cycle}}(DoD)}\ , \tag{3.3}$$

where E^{bat} is the usable energy of the battery.

Finally, the general degradation costs are expressed by (3.4):

$$c^{\mathrm{dis,energy}}\left(DoD^{\mathrm{start}}, DoD^{\mathrm{end}}\right) =$$

$$c^{\mathrm{dis}}\left(0, DoD^{\mathrm{end}}\right) - c^{\mathrm{dis}}(0, DoD^{\mathrm{start}}), \qquad \forall DoD^{\mathrm{end}} > DoD^{\mathrm{start}} \tag{3.4}$$

As presented in Figure 3.10, the Li-ion battery technologies has the gentlest slope compared to the other battery technologies (NiMH and Lead Acid). Therefore, Li-ion battery technologies are potential candidates for the EVs in order to be economically feasible compared to PHS power plant. In 2030, the EVs (Li-Ion Ref., with the investment cost of 250 €/kWh [70]), are regulated to serve the secondary control reserve market under the DoD's range of 0-20%. In case of the negative control market, EV's DOD would not be considered, as there is no need to supply power to the grid. The implementation costs of the specialized charging infrastructure and the degradation cost of the battery should be considered in the negative control reserve.

With the invention of the Li-ion battery, the second issue would not be a significant problem anymore.

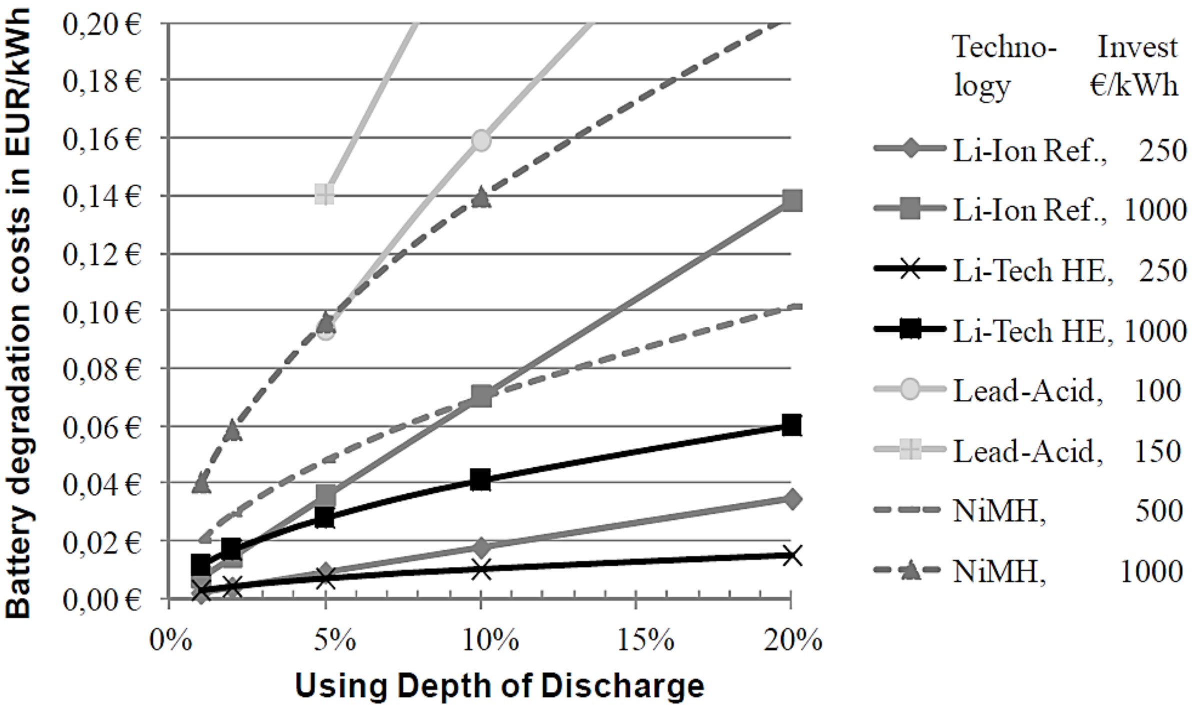


Figure 3.10: Minimum battery degradation costs with respect to its DoD [70]

This is due to the fact that the Li-ion battery technology does not have the “memory effect" like the Ni-MH battery (see Table 3.1). Furthermore, the battery maximum charge in Li-ion batteries will remain the same, and the degradation cost of these batteries will be low. The EV participation in the negative secondary control reserve market will increase the benefits of the system. In [70] and [84], it is demonstrated that the annual net benefits of participation of EVs in the negative power reserve would be €200 and US$146, respectively.

3.12 Conclusions

In this chapter, after describing the concept of V2G, in order to the participation of EVs in the system optimal operation as a load or source of electrical energy generation, an aggregating institution is necessary. It was revealed that the role of EVs would be depended on the characteristics of the studied grid, the electric vehicles charging scheme and the penetration level of the EVs to the grid. The uncoordinated charging of EVs could significantly result in (a) decreasing the reliability in the distribution system, (b) undesirable load flow, (c) low system efficiency and (d) cause economic damage. Therefore, a new approach for smart load management is presented in order to control and coordinate EVs charging program as well as to provide ancillary services. In chapter 6, the proposed framework for vehicle management will be examined. According to studies and analysis of the results, this framework has significant impact on the reliability of smart distribution grids and thereby it leads to demand peak shaving and minimization of grid losses.

Furthermore, the V2G is a potential candidate to be employed as the negative secondary control reserve and positive secondary control reserve with the DoD of 0-20%. Thus, the assumption of high potential of EVs for ancillary services seems to be smaller (due to the DoD). To get the real V2G potential value, we should multiply it by the DoD (in this case 20% in 2030).

It is worth mentioning that, this situation could be different due to the decrease of the battery cost, the invention of the next generation technology of batteries, and the growth of the tertiary control reserve market.

Chapter 4

A Short Approach on Fuzzy Logic

4.1 Fuzzy control system

As explained in section 3, a fuzzy logic controller has been applied for defining the charging procedure and offered regulation services of the EVs in the proposed management system in this work. In this section, first the fuzzy system is defined and then the fuzzy controller is introduced. Then, the structure of a fuzzy controller will be explained in detail. Finally, other decision making methods will be introduced, discussed and compared with fuzzy logic, to show the suitableness of this method in the proposed system in this thesis.

4.2 Fuzzy introduction

“Fuzzy Logic” was presented in 1965 by Lotfi Ali Askar-Zadeh, Professor of Computer Science at the Berkeley University, California, [85]. In 1975, Mamdani and Asilian controlled a cement kiln by fuzzy logic for the first time [86]. In 1978 Holmblad and Osttergaard used the first fuzzy controller to control a complete industrial process, a cement kiln again.

Overall, fuzzy theory was established in 1970s. With the introduction of new concepts, the picture of fuzzy theory was a new field of control. Initial applications such as cement kiln proposed fuzzy theory as a new field.

In the early 1980s, the field of fuzzy logic control had a slow progress from the theoretical perspective. After this period, new solutions and concepts were introduced, because many people were working on it. In fact, it was the applications of fuzzy control that had kept the fuzzy theory standing [87]. Japanese engineers found quickly that fuzzy controllers can be designed easily and being applied. Since fuzzy control does not need a mathematical model, it can be used in many systems that cannot be implemented by conventional control theory, therefore it may be applied well to the proposed management system in this work. In 1980, Sugeno began the construction of the first Japanese fuzzy application, control of Fuji water treatment systems; in 1983, he worked on a fuzzy robot. A remote-controlled car parked by itself, controlled only via fuzzy logic. In this years, Yasunobu and Miyamoto from Hitachi Company began working on the Sendai underground train system. Finally, in 1987 the project came to fruition and made one of the most advanced underground train systems in the world. On July 1987, the second conference on fuzzy systems was held in Tokyo. This conference began just three days after the opening of the Sendai underground train. Hirota showed in this conference a fuzzy robot that was playing table tennis. Before these events, fuzzy theory was not well-known in Japan. But then it attracted the attention of engineers, government officials and businessmen in a way that in the early 90s, there were a large number of appliances and devices worked based on fuzzy theory, available in the shops [88]. Different fuzzy logic systems have recently been applied in various works with different objectives and executions [104].

4.3 Fuzzy systems

The term "fuzzy" is defined as "vague, ambiguous, indefinite and unclear" in the Oxford Dictionary. Although basically fuzzy systems describe indecisive and indefinite phenomena, fuzzy theory itself, is an accurate theory. Important information comes from two sources in practical systems. One of the sources is experts who define their knowledge and information about the system by natural language. Another source of information are measurements and mathematical models that have been derived from mathematical rules. So, an important issue is the combination of these two types of information in designing successful systems. The key question is how to turn human knowledge into a mathematical formula. Basically, what a fuzzy system performs is the same approach [89]. To understand how this is done, we must first know how fuzzy systems are working.

Fuzzy systems are knowledge-based or rule-based. The heart of a fuzzy system is a knowledge base that consists of fuzzy "if-then" rules and some of its contents have been indicated by continuous so called “membership functions”. The expressions "low, medium, more, balanced, high and less" are indicated by similar structured membership functions. It should be noted that more rules will be needed in real conditions; however, we can create a fuzzy system, based on these rules for a semi-real condition. Applying fuzzy logic multiple goals can be optimized and a more similar output to the real world can be achieved [104]. Since the fuzzy system is used as a controller, it is called the fuzzy controller. In short, the starting point in creating a fuzzy system is to get a set of fuzzy "if-then" rules from the experts' knowledge or knowledge of the subject areas. The next step is to combine these rules into a single system. Different fuzzy systems use different methods and principles to combine these rules [89]. Fuzzy control is a control method based on fuzzy logic.

In fact, if we call fuzzy logic simply as "calculation with words instead of numbers", we can call fuzzy control as "control with sentences instead of equations ". For better understanding we can mention the setting of the room temperature by speed control of a heater impeller, first by means of an "on-off" key and then by fuzzy control. As shown in Figure 4.1, the controller receives the room temperature measured by the sensor as an input and suitable output is given to set the speed of the impeller.

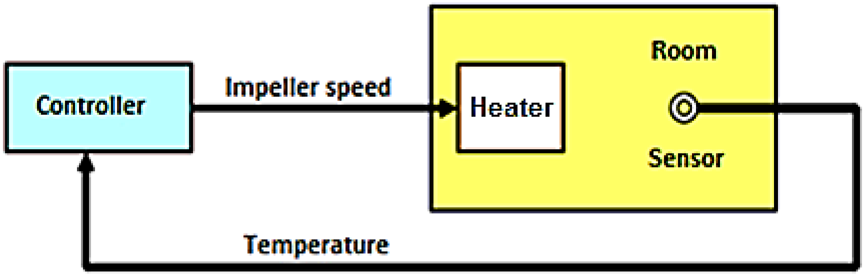


Figure 4.1: A simple temperature controller (derived from [89])

First, suppose the key is used for speed control. This key acts like a thermostat and is opened at a temperature higher than 25°C and is closed at a temperature less than 20°C. In this case, if the room temperature gets lower than 20°C, the closed key operators and the heater impeller start working and when the temperature reaches 25°C, it switches the heater off. So, setting the room temperature is not done well with this two-point-control method. But the fuzzy controller of heater is based on logic that we consider it when we manually set the impeller, for example: "If the room temperature is too cold, impeller speed should be very high ", "If the room temperature is cold, speed should be average "," if the room temperature is warm, speed should be low ", and" if the room temperature is too hot, the impeller speed should be zero."

In a bivalent logic, the precise measured amount is needed to give the command of off-on key on time. But in fuzzy logic, the phrases such as very hot or cold temperature are used as input and phrases such as high speed, very high, medium, etc. are used as output, like what happens in human brains. In fact, fuzzy logic variables can have a range between 0 and 1 which is not limited to these two values like in classic logic with just truth and false statements. In general, in fuzzy logic three things are needed like in conventional logic methods, first the definition or a model for variables, the relationship between the variables (if multiple inputs are available) and the third is the way of conclusions.

Fuzzy control uses fuzzy logic rules to gain control applications. The fuzzy rules are based on control rules. Fuzzy logic system design is not based on a mathematical model. Fuzzy controllers use fuzzy logic to implement human logic that is planned by the membership functions, fuzzy rules, and membership rules. Fuzzy controllers have appeared in different forms that the direct control is one of the most used methods [87]. It is shown in Figure 4.2.

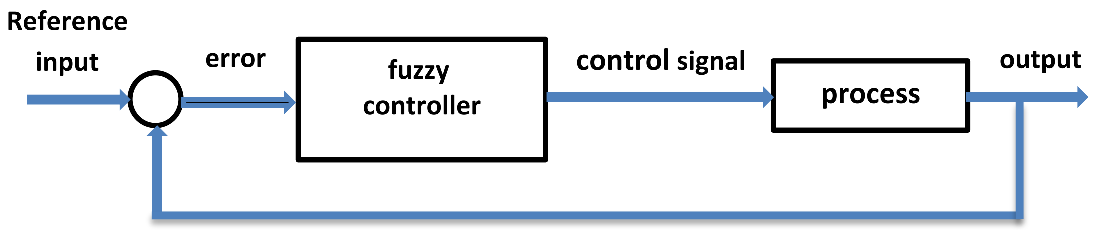


Figure 4.2: Block diagram of applying a fuzzy controller in the direct control form (based on [87])

In this way, the fuzzy controller is placed on the forward path of a feedback control system. The process output is compared with the reference input and if there is an error, the controller produces a control signal in accordance with its control strategy. It should be noted that the controller input can be other features of the system, such as error dot, error integral or a combination of them [87].

4.4 Structure of a fuzzy controller

A fuzzy controller consists of four main parts: fuzzifier, rule base, the decision-making section and defuzzifier. Figure 4.3 shows a fuzzy controller. The pre-processing and post processing is used usually before and after the fuzzy controller respectively as shown in Figure 4.3 [90].

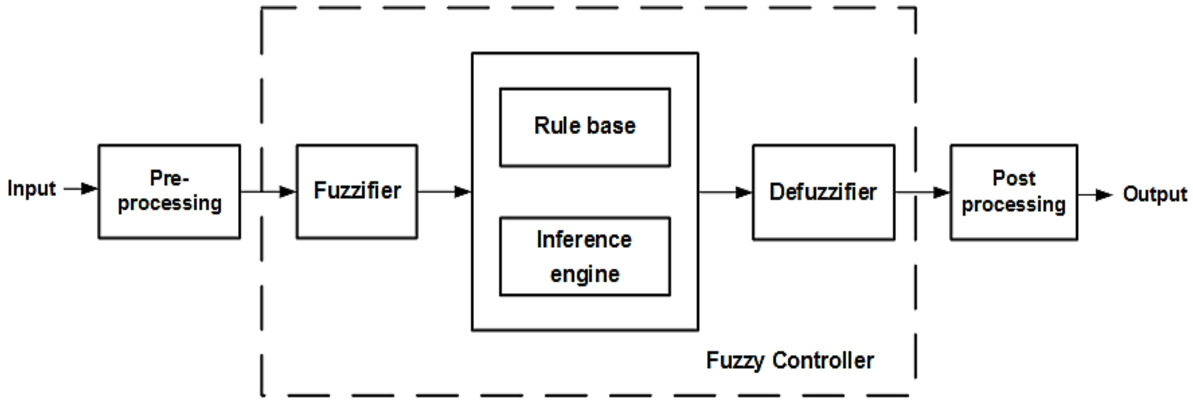


Figure 4.3: Block diagram of a fuzzy controller structure [90]

4.4.1 Pre-processing

Fuzzy controller inputs are absolute values obtained by measurement tools and/ or sensor. These values need some transformation before entering the fuzzy controller. These changes are provided by the pre-processing section.

4.4.2 Fuzzifier

The first block in the controller is called the fuzzifier, where the membership degree of input values to different membership functions is calculated. There are several methods to do this. The first method is that we turn the variable into a fuzzy form in a single value way. In this way, the variable's "α" membership function "$\mu_{(\alpha)}$" is 1 at one point and 0 at the rest points. Figure 4.4.a shows examples of this type.

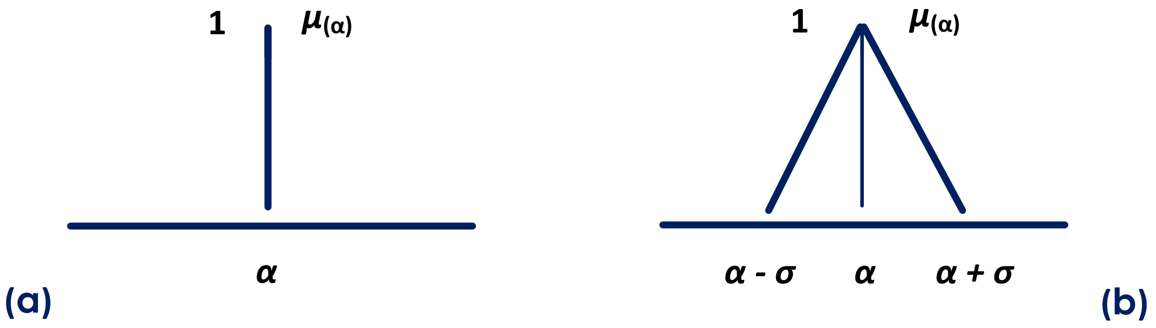


Figure 4.4: a) single-valued membership function, b) triangular membership function with the range of 2σ [90]

In another method, it can be displayed as a curve. For example, suppose the standard deviation in the defuzzification is σ due to noise or measurement error. In that case, the fuzzy function of the variable is defined as an isosceles triangle where the median of its base was in the measured value, the length of its base is 2σ and its height is 1 (Figure 4.4.b).

4.4.3 Rule base

A fuzzy control includes a set of rules.

For example, these sentences can be applied as a sample set of rules for a typical fuzzy controller with measurement deviation of a specific value (error) and its derivation (error dot) as input signals:

If the error is negative and error dot is negative, then output is negative big.

1. If the error is negative and error dot is zero, then the output is negative small.

With a set of rules such as these rules, the computer can run and apply the appropriate behavior by considering the error and error dot as input signals and calculate the control signal (controller output). This type of control can be considered as an operator control action. An operator considers the system behavior (input of the operator) and gives a control command (output) according to their own experience and knowledge (rule base) or sets the parameters of the controller.

There are four methods to set rules:

1. Control engineering knowledge and expert knowledge.

2. The operator’s behavior at the time of control.
3. Based on the fuzzy model of the process (fuzzy identification of the system).
4. Based on self-organizing education.

Each fuzzy controller uses some "if - then" rules as rule base. These rules are given in different ways. The names Pos, Zero, Neg, are related to the fuzzy sets for both inputs and NB; NS, PB, PS (respectively negative big, negative small, positive big, positive small) are related to output fuzzy sets. In this way, the default is that "and" is used among connector inputs and "or" is used among the rules.

Suppose that a fuzzy controller with two error inputs produces one signal as output. In this case, the end user display format for the first rule presented at the beginning of this part is presented as follows:

1 - If an error is Neg error dot is Neg then Output is NB

4.4.4 Inference engine

Since each fuzzy rule base includes more than one rule in practice, the basic question is how to draw conclusions based on a set of rules. There are two ways to draw conclusions. Rule combination based inference and separate rule based inference.

4.4.5 Defuzzifier

The fuzzy set of inference results should turn into a non-fuzzy number to apply a corresponding output as a control signal to the process. This action is called defuzzification.

4.4.6 Post-processing

We use post-processing on the output signal of the fuzzy controller when we need the output in a standard range or we want to change the scale.

In summary, fuzzy logic is a suitable tool for problems that cannot be modelled easily in a mathematical way. As an advantage, Fuzzy logic can be applied to problems with incomplete and imprecise input data. Fuzzy logic can be applied properly for many control applications, due to its representation of human control logic. Furthermore, a shorter time interval, less input data, decisions and rules are required in order to obtain a suitable solution for a stable situation [104].

4.5 Common decision making methods

As explained before, a fuzzy logic controller has been applied for defining the charging procedure and offered regulation services of the EVs in the proposed management system in this work. There are also other artificial intelligence methods such as “Neural Network”, and evolutionary approaches such as “Genetic Algorithm”, particle swarm optimization, ant colony optimization, as well as Bio-inspired computing techniques such as “Artificial Immune Systems” [104]. Fuzzy logic, neural network and genetic algorithm, have been applied in most of the studies for scheduling and decision-making problems [104]. Therefore, in this section these methods have been selected and the advantages and disadvantages of these methods will be reviewed and compared. Clearly, these methods have more suitable adeptness to find a better solution due to profiting from the biological evolution process and human brain. In follows, these selected methods have been introduced regarding their performance and exactness in making decisions.

4.5.1 Genetic algorithm

In recent years, the popularity of genetic algorithms has been increased to solve complicated optimization problems [104]. One of their biggest disadvantages is that different constraints could not be pre-defined through a path in the genetic algorithm. Hence, their application in most real world optimization problems is not possible. However, in specific problems they can find a suitable solution [104]. Genetic algorithm has been mainly applied to very complicated and artificial scheduling problems, as they have the ability to solve nonlinear and large problems. A set of stochastic operators is applied in a repetitious manner on a population of candidate solution called “individuals” to produce and define the most successful solution [105]. This process continues so long until a defined maximum number of generations has been generated or specific suitability is reached for the population. At this time, the best solution may have been found or not which is the main weakness of this method [104].

Increased process times or reduced efficiency of the gained solution happens frequently while applying this method on large and complex problems. Therefore, the population size plays a very important role in the solution time and achieving a suitable solution. Additionally, if the population size is too small, the solution area cannot be sampled properly, and therefore the suitable solution cannot be defined [106].

4.5.2 Neural network

The neural network is a simple method which has the ability for learning and capability to do distributed processing. This is why their application in real life problems is very popular. Neural networks can learn from the experiences (be trained) which helps their skillfulness along with their well adapting to the instabilities of the environment. This training process starts in a random manner and chooses the fundamental weights. The learning process starts with applying two methods, namely supervised learning and unsupervised learning [104]. Neural networks consist of simple processing units which build large parallel divided processors. This distributed structure makes this artificial intelligence method capable of solving complicated problems [107].

Neural networks can learn to make decisions similar to the human brain and also following variable input data due to the environment fluctuations. Although, the processing time depends on the size of the problem or created neural network. In case of massive networks, a high processing time will be expected next to a longer training process [104].

4.5.3 Summary and comparison

In this part, the advantages and disadvantages of the presented decision-making methods (genetic algorithm, neural network and fuzzy logic) will be compared in Table 4.1. This comparison is done to investigate their suitability to be applied in the proposed smart charging and regulation management system in this work.

Table 4.1: Comparison of the selected decision making methods [104]

Type of method	***Genetic algorithm***	***Neural network***	***Fuzzy logic***
Advantage	- Problems will be solved by Multiple solutions. - Able to solve large and nonlinear optimization problems. - It applies a repetitive parallelism in its search method. - It is easy to understand this method and it can be easily transferred to existing models.	- It can be applied in real time operation and has the ability to solve complicated and large problems. - It has an adaptive learning skill. - Able to learn and generalize to overcome new situations. - It is very reliable, when one of its neurons fails, it still keeps on working with no problem. - Self-organization. - Fault tolerance.	- Ability to achieve acceptable outputs in terms of imprecise and incomplete data. - Capable to achieve a fast suitable solution while representing human control logic - Uses linguistic variables - Cheaper to develop as they are easier to design. - Provides a powerful tool to illustrate the problem solution space that arises from its unclear input information. - Less input data, rules, and decisions are required.
Disadvantage	- There is no guarantee to find the best solution. - It is a very time-consuming procedure. - Difficulties to find the exact optimized solution.	- High processing time is required once the neural networks are massive. - Hard estimation of the quality of the trained neural network. - Very difficult to be analyzed by human being once it is trained. - There is no ability of being retrained.	- Membership function estimation is hard in complicated problems. - There is a more need of fine-tuning and simulation before practical application.

4.5.4 Conclusion

Based on the aforementioned advantages and disadvantages of the decision-making methods, fuzzy logic is convinced to be a suitable method to be applied in the proposed smart charging and regulation management system in this work. Some of the advantages of applying fuzzy logic are as follows: (a) their ability to achieve acceptable outputs in terms of imprecise and incomplete data, (b) capability to achieve a fast suitable solution while representing human control logic, (c) applying linguistic variables, (d) being cheap to develop, and (e) easy to design. As it will be discussed in more detail in section 5, the main task of the applied decision-making method is to achieve a fast and appropriate output signal with less input value and minimum rules and decisions while considering the human control logic. As the output signals from the fuzzy controller are not the final decisions and will be further optimized (due to grid operational constraints), an acceptable and less accurate decision will be adequate for this step. Furthermore, fuzzy logic controllers are easier to design and will be cheaper to be developed for EV applications. Over and all fuzzy logic is well suited for the proposed application in this work.

Chapter 5

The Proposed SCRM System

5.1 Introduction

The main objective of this research is to show how applying this method could help in saving charging costs (if dynamic tariffs are present) and increasing the system security, stability and avoiding further power network expanding costs without limiting the EV owners driving behaviors and wishes. In this work, a “Smart Charging and Regulation Management” (SCRM) method due to essential constraints including, overload occurrence, SoC and plug in state of the EVs, next travelling time, market energy prices, regulation-market status is presented. In this research, the proposed method is assumed as a central management solution.

The positive effect of applying this management system in reducing energy cost and maintaining the grid stability with the current infrastructures is shown in the following sections. Furthermore, the condition of Germany 2030 [11- 14] regarding the amount of available EVs due to Germany’s governmental aim scenario and a more realistic trend scenario were taken into account based on the performed studies. The proposed SCRM system and the outcome results for 2030 were presented and analyzed in the following sections.

5.2 Test system

The studied system is a standard 31-bus IEEE distribution network, which contains almost 1400 households (26 buses with each containing 53 residential sectors). As mentioned in the third section of this thesis, the EVs are connected to the grid through the distribution network. The applied load curve of each household is compatible with the consumption pattern of typical German homes for the related season of the year. The simulation is applied in the MATLAB/Simulink environment and over the whole year on an hourly-basis, considering the penetration level of EVs in Germany 2030, in the smart homes, including a governmental aim scenario (Scenario A1) and a more realistic trend scenario (Scenario A2). Finally, the simulation results for both case studies have been shown and compared, for Germany 2030, in the next section.

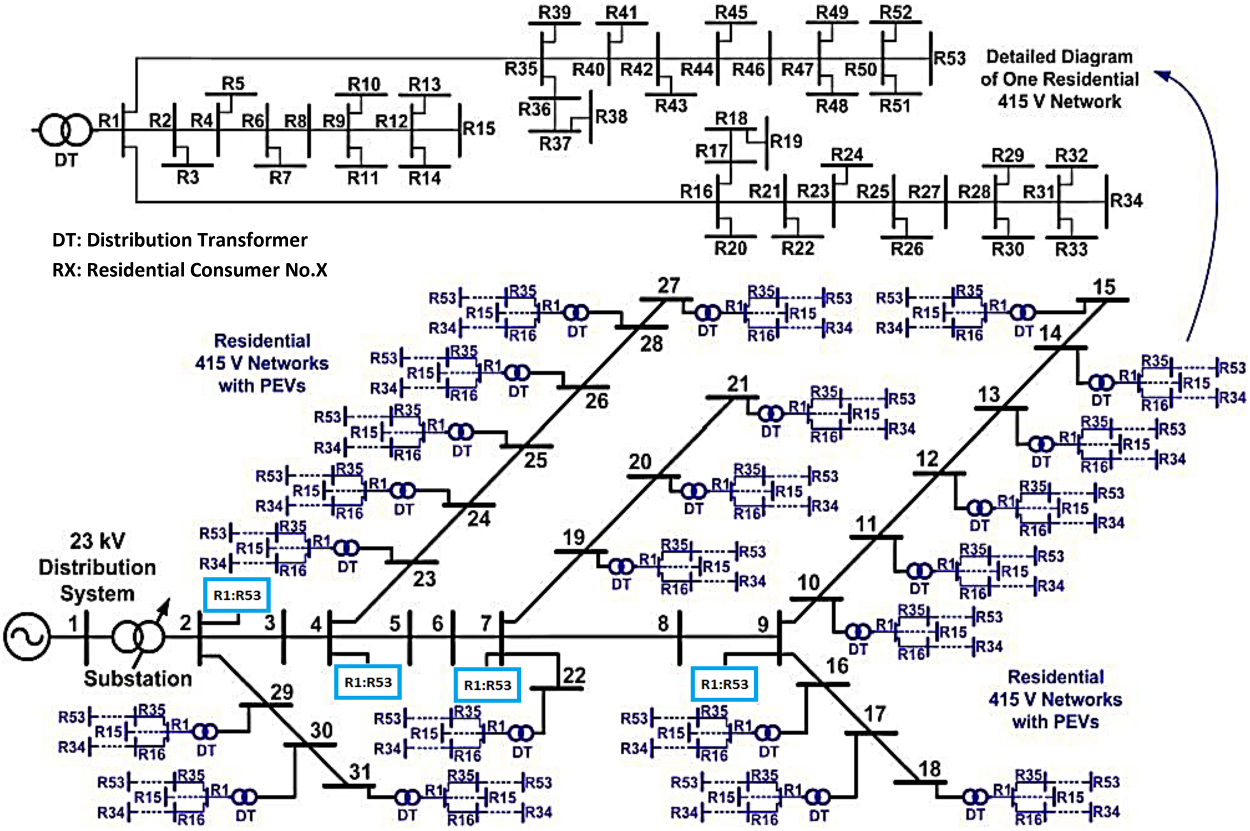


Figure 5.1: 31-Bus IEEE Standard Distribution System (based on [1])

As it can be seen in Figure 5.1, this standard distribution network consists of 31 buses, where 26 of these buses contain residential consumers. There are 53 residential sectors at each of the buses, which makes almost 1400 homes with the capability of charging electric vehicles. For running the SCRM system as a central control method, it is necessary for homes to be equipped with smart home capabilities, so that they could be controlled and managed online and remotely. Due to future strategies in the power network and power economy, this part will be the role of the aggregators who will control the charging and discharging procedure of the EVs from a control center.

Further information about the line parameters of the 31-Bus IEEE standard distribution system could be found in Appendix A. This standard system was first introduced in 1985 in [113], which the parameters are adapted from this reference as well.

5.3 First step of the SCRM system

Figure 5.2 demonstrates the first step of the SCRM system. This system applies different transmitted signals, including the SoC of the EVs batteries, vehicles' plug-in state, the next traveling time, overload occurrence, regulation-market status and energy market price tracking signal. Other input signals will be measured using smart grid capabilities and will be sent to the SCRM system which finally creates a first charging signal by mean of fuzzy logic controller. In other words, due to developed fuzzy rules according to the input signals, the system defines very fast when the cars are being charged or could offer a regulation service.

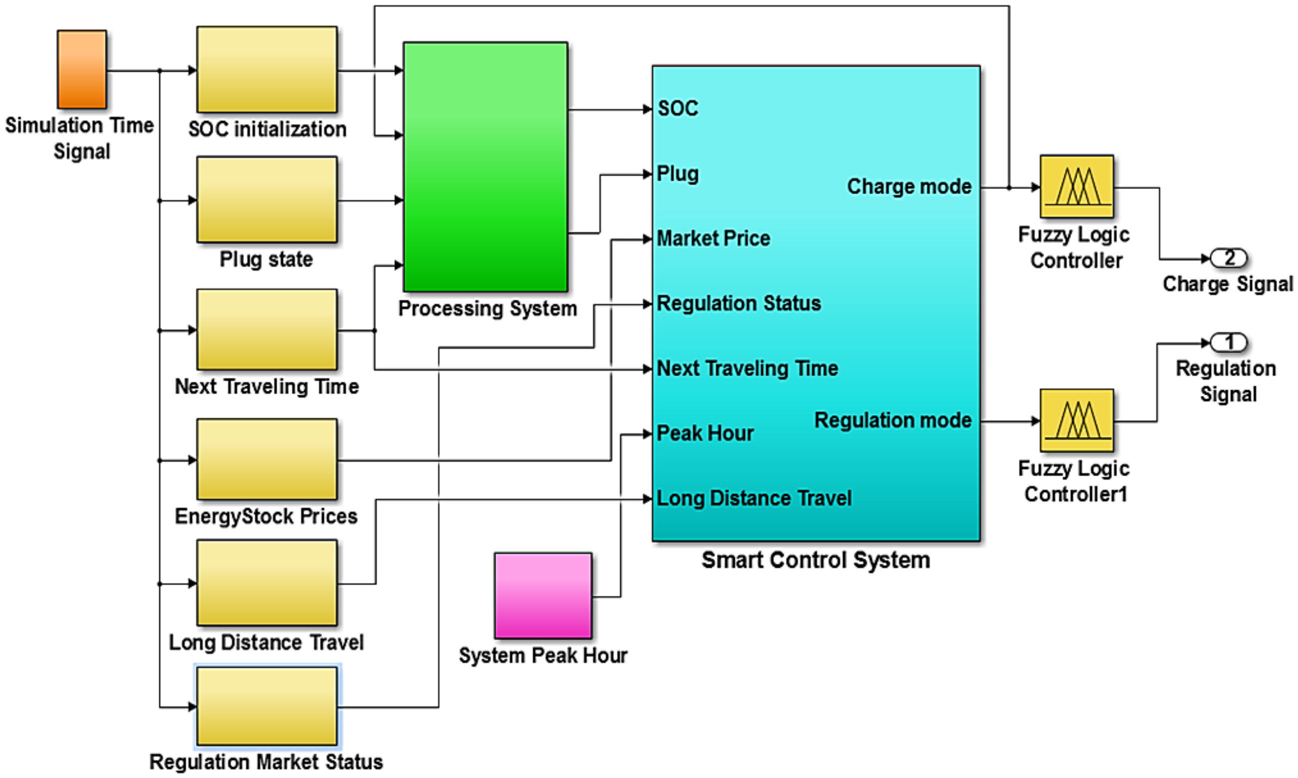


Figure 5.2: The first step of the proposed SCRM system

5.3.1 SCRM input signals

The input signals will be introduced as follows:

- The “SoC” signal informs about the state of charge of the EVs batteries during simulation time.
- The Plug signal is about the plug-in state of the EVs during the simulation.
- The “Market Price” signal is the hourly energy price that will be called from the EEX energy stock market in Leipzig Germany [15]. In this study, the signals of the year 2015/16 were taken into account.
- The “Next Travelling Time” signal will be supplied by the EV owners (via smart phone or PC) and the existing database of their driving patterns.
- The “Regulation Status” signal shows whether the EV’s aggregator has won for regulation services in the regulation-market or not. In this case the internet platform of German regulating service is considered [16].
- The “System Peak Hour” signal considers the peak hours of the system due to the related load curve of the households, to prevent overload occurrences and probable black outs.
- The “Long Distance Travel” signal defines if a specific EV or EV group has any travelling plans. These signals help to control the EVs, considering a high driving flexibility for the car owners.

It is noticeable that all the input signals will be provided online to the SCRM system. Although communication delays in data transfer of the signals could happen [115], but this is out of the scope of this work. It could also be imagined that the EV owners can use a specific application on their smartphones, to transmit their driving plans and unplanned changes.

5.4 Fuzzy controlling system

As it has been mentioned previously, a fuzzy logic controller is used to decide when the cars start being charged or offering regulation services. Regarding the introduced input signals, membership functions for any input signal and a series of related fuzzy rules are developed and applied in this work. This fuzzy controller could decide very fast the charging or regulation mode of the EVs due to the input signals.

MATLAB/Simulink toolbox has been applied to design the fuzzy logic controllers for both charging and regulation control systems.

5.4.1 Charging control system

Figure 5.3 demonstrates this fuzzy logic charging controller's main scheme including the following input signals: market price, SoC status of the battery, plug in state, next travelling time, long distance travel, and system peak hour. The SoC status and plug in state signal of the EVs are derived from the data of the simulated car profiles. These car profiles will be introduced later in this section. The system peak hour signal is retrieved from the system and the market price is obtained from the electricity market (in this research the EEX market [15]). The EV owners could inform about their next travelling time or their long distance travels, for more driving flexibility. The fuzzy logic charging controller applies different rules for the decision process using its rule base, which is presented in Figure 5.4. There are 37 rules applied considering the input signals to decide whether an EV will be charged or remain on standby based on the presented flow chart later (Figure 5.5) in this section. For example, if there is currently a high, medium or low energy price in the market or a system peak hour etc., the best solution will be gained from the fuzzy rules immediately. This rule base is defined in each season of the year, individually to achieve precise results.

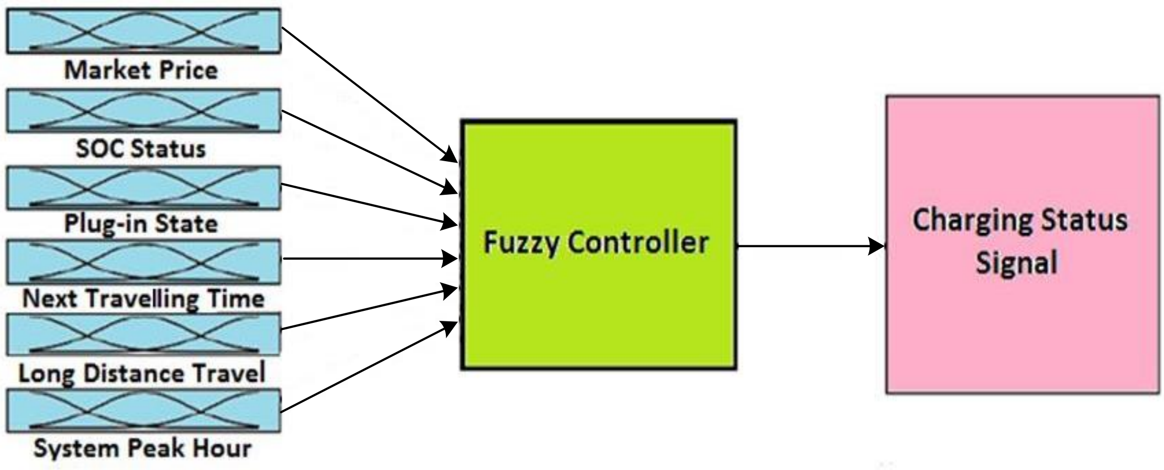
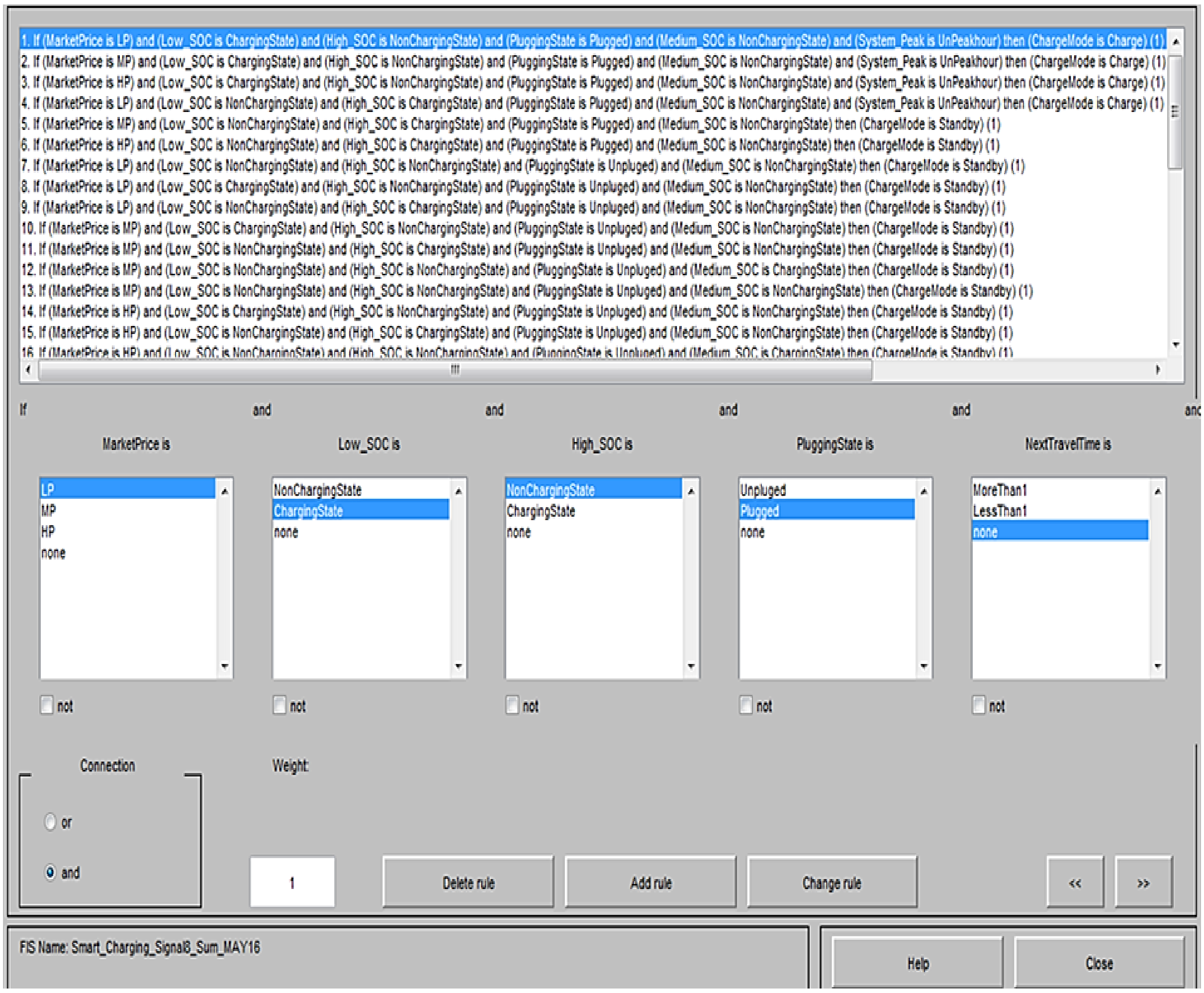


Figure 5.3: Fuzzy logic charging control system

The described SCRM input signals in sub-section 5.3.1, will be transformed into simple digital signals through the fuzzifier. Therefore, the decision-making mechanism of the fuzzy controller and its related fuzzy rules are more simple and fast. Also, the presented input signals of the regulation controller, which will be described in sub-section 5.4.3, were similarly transformed into simple digital signals.



```
1. If (MarketPrice is LP) and (Low_SOC is ChargingState) and (High_SOC is NonChargingState) and (PluggingState is Plugged) and (Medium_SOC is NonChargingState) and (System_Peak is UnPeakhour) then (ChargeMode is Charge) (1)
2. If (MarketPrice is MP) and (Low_SOC is ChargingState) and (High_SOC is NonChargingState) and (PluggingState is Plugged) and (Medium_SOC is NonChargingState) and (System_Peak is UnPeakhour) then (ChargeMode is Charge) (1)
3. If (MarketPrice is HP) and (Low_SOC is ChargingState) and (High_SOC is NonChargingState) and (PluggingState is Plugged) and (Medium_SOC is NonChargingState) and (System_Peak is UnPeakhour) then (ChargeMode is Charge) (1)
4. If (MarketPrice is LP) and (Low_SOC is NonChargingState) and (High_SOC is ChargingState) and (PluggingState is Plugged) and (Medium_SOC is NonChargingState) and (System_Peak is UnPeakhour) then (ChargeMode is Charge) (1)
5. If (MarketPrice is MP) and (Low_SOC is NonChargingState) and (High_SOC is ChargingState) and (PluggingState is Plugged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
6. If (MarketPrice is HP) and (Low_SOC is NonChargingState) and (High_SOC is ChargingState) and (PluggingState is Plugged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
7. If (MarketPrice is LP) and (Low_SOC is NonChargingState) and (High_SOC is NonChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
8. If (MarketPrice is LP) and (Low_SOC is ChargingState) and (High_SOC is NonChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
9. If (MarketPrice is LP) and (Low_SOC is NonChargingState) and (High_SOC is ChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
10. If (MarketPrice is MP) and (Low_SOC is ChargingState) and (High_SOC is NonChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
11. If (MarketPrice is MP) and (Low_SOC is NonChargingState) and (High_SOC is ChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
12. If (MarketPrice is MP) and (Low_SOC is NonChargingState) and (High_SOC is NonChargingState) and (PluggingState is Unpluged) and (Medium_SOC is ChargingState) then (ChargeMode is Standby) (1)
13. If (MarketPrice is MP) and (Low_SOC is NonChargingState) and (High_SOC is NonChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
14. If (MarketPrice is HP) and (Low_SOC is ChargingState) and (High_SOC is NonChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
15. If (MarketPrice is HP) and (Low_SOC is NonChargingState) and (High_SOC is ChargingState) and (PluggingState is Unpluged) and (Medium_SOC is NonChargingState) then (ChargeMode is Standby) (1)
16. If (MarketPrice is HP) and (Low_SOC is NonChargingState) and (High_SOC is NonChargingState) and (PluggingState is Unpluged) and (Medium_SOC is ChargingState) then (ChargeMode is Standby) (1)
```

Weight: 1

FIS Name: Smart_Charging_Signal8_Sum_MAY16

Figure 5.4: Fuzzy logic charging control system rule base for May/June 2016 in MATLAB/Simulink environment

Due to Figure 5.4, for example, considering rule number 1, if the energy price on the market and the state of charge of the EV's battery is low, and it is not a system peak hour due to the specific load curve of the considered month, then the EV will start charging. The displayed flowchart in Figure 5.5 describes completely the decision mechanism of this fuzzy controller due to the input signals applying the rules of the rule base. All the implied rules in this research can be obtained according to this flowchart.

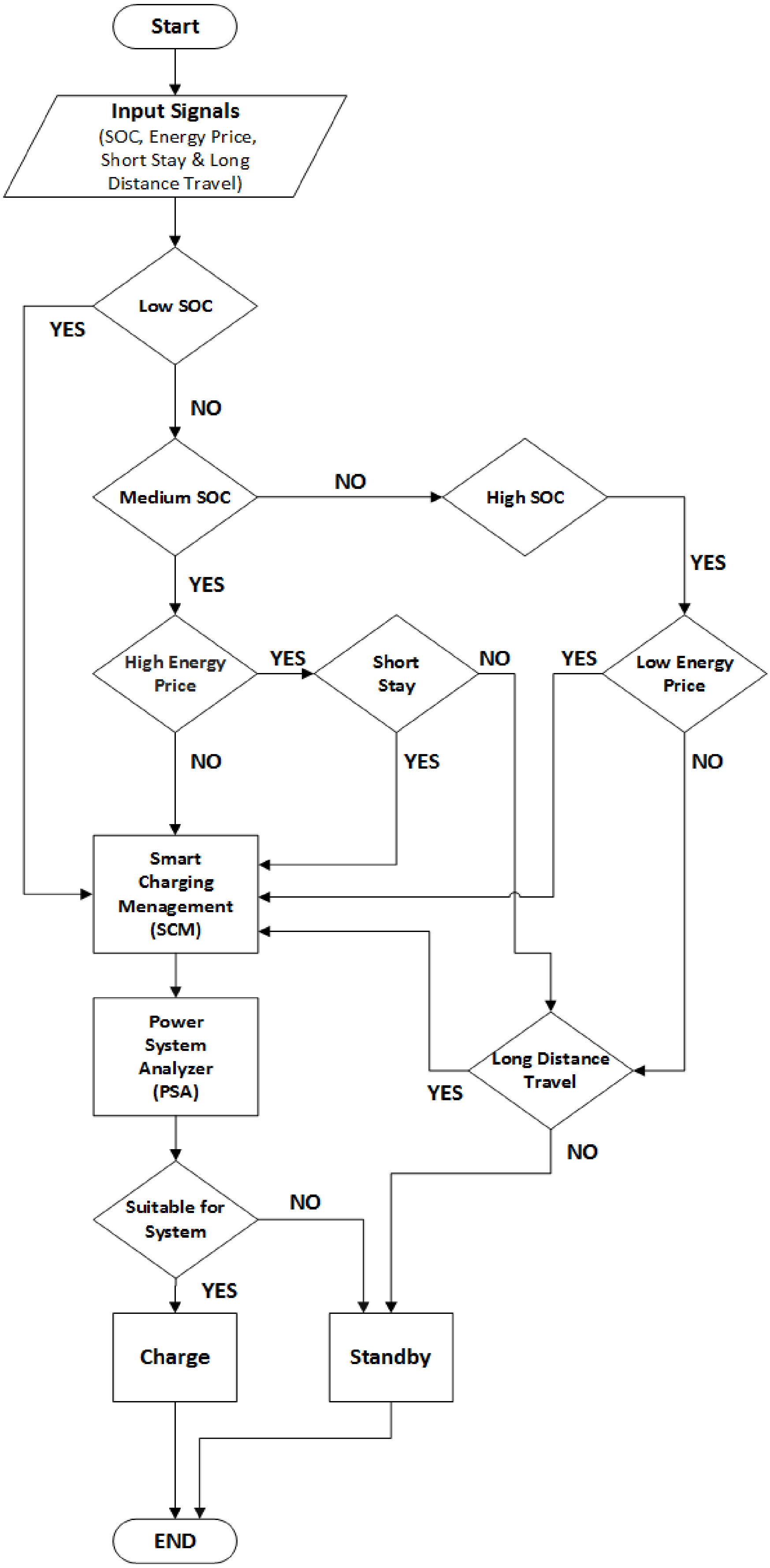
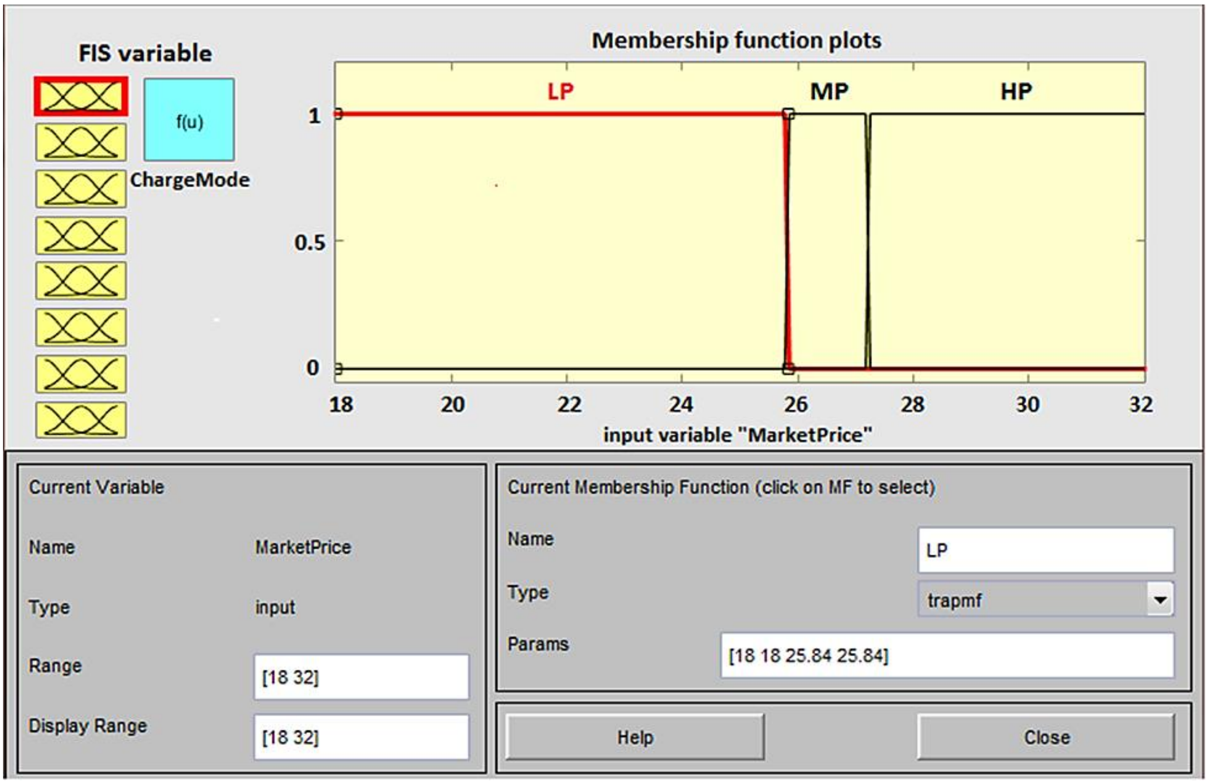


Figure 5.5: Fuzzy logic charging control system mechanism flowchart

5.4.2 *Charging control membership functions*

The input signals were defined by membership functions. For example, the market signal is divided into three membership functions: high, medium and low energy prices of each month. The energy prices are derived from the European Energy Exchange (EEX) internet platform [15] for each month separately. The high, medium, and low energy prices are defined considering the related base and peak load energy prices. These membership functions are displayed in Figure 5.6 for May/June 2016.



Current Variable
Name MarketPrice
Type input
Range [18 32]
Display Range [18 32]

Current Membership Function (click on MF to select)
Name LP
Type trapmf
Params [18 18 25.84 25.84]

Figure 5.6: Market price signal membership function for May/June 2016 in MATLAB/Simulink environment

The SoC status membership functions are divided into low SoC, medium SoC and high SoC of each EV group. These are defined considering the minimum required battery charge of each EV group for their next travel, and the maximum charge, which is the allowable charge that extends the lifetime of the EVs batteries. The other input signals, including plugged-in status, next travelling time and system peak hour are digital inputs (0 or 1) and are being fuzzified and similarly defined by mean of membership functions. For example, for the plugged-in status signal, the digit 1 means plugged and likewise the digit 0 means unplugged. There is also a fuzzy logic controller applied for regulation purposes, which will be presented in the following sections.

5.4.3 Regulation control system

Figure 5.7 demonstrates the main scheme of the fuzzy logic regulation controller. The regulation market status signal is retrieved from the regulation market. The fuzzy logic regulation controller, applies different rules for the decision process, which rule base is presented in Figure 5.8. The complete decision mechanism flowchart of this fuzzy controller is displayed in Figure 5.9. Similar to the charging control system, all the applied fuzzy logic rules can be obtained based on this flowchart for defining the regulation status of the EVs.

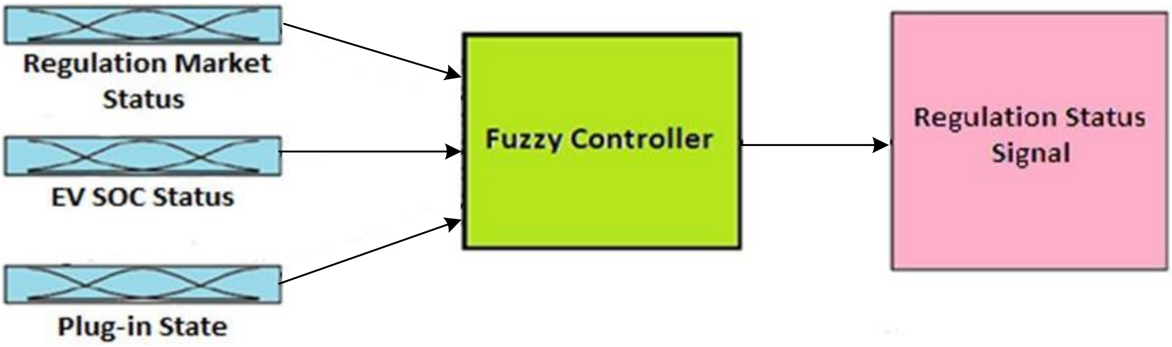
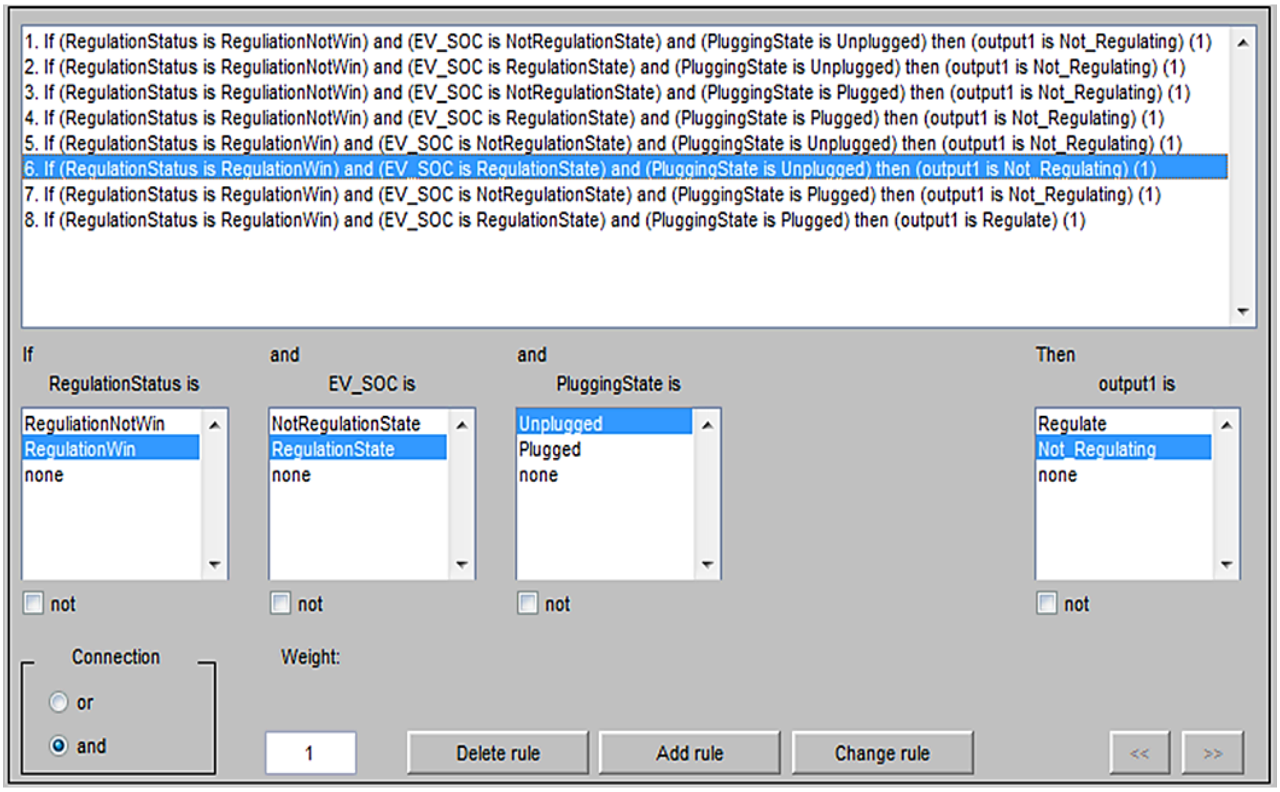


Figure 5.7: Fuzzy logic regulation control system


1. If (RegulationStatus is ReguliationNotWin) and (EV_SOC is NotRegulationState) and (PluggingState is Unplugged) then (output1 is Not_Regulating) (1)
2. If (RegulationStatus is ReguliationNotWin) and (EV_SOC is RegulationState) and (PluggingState is Unplugged) then (output1 is Not_Regulating) (1)
3. If (RegulationStatus is ReguliationNotWin) and (EV_SOC is NotRegulationState) and (PluggingState is Plugged) then (output1 is Not_Regulating) (1)
4. If (RegulationStatus is ReguliationNotWin) and (EV_SOC is RegulationState) and (PluggingState is Plugged) then (output1 is Not_Regulating) (1)
5. If (RegulationStatus is RegulationWin) and (EV_SOC is NotRegulationState) and (PluggingState is Unplugged) then (output1 is Not_Regulating) (1)
6. If (RegulationStatus is RegulationWin) and (EV_SOC is RegulationState) and (PluggingState is Unplugged) then (output1 is Not_Regulating) (1)
7. If (RegulationStatus is RegulationWin) and (EV_SOC is NotRegulationState) and (PluggingState is Plugged) then (output1 is Not_Regulating) (1)
8. If (RegulationStatus is RegulationWin) and (EV_SOC is RegulationState) and (PluggingState is Plugged) then (output1 is Regulate) (1)

If RegulationStatus is: RegulationWin
and EV_SOC is: RegulationState
and PluggingState is: Unplugged
Then output1 is: Not_Regulating
Connection: ● and
Weight: 1

Figure 5.8: Fuzzy logic regulation control rule base in MATLAB/Simulink environment

For example, in rule number 6, if the aggregator has won in the reserve market and the state of charge (SoC) of the EV is suitable for a regulation service, but the car isn't plugged into the grid, the EV couldn't participate in the regulation and has the status "Not Regulating". As mentioned previously, all the input signals will be transmitted online to the SCRM system.

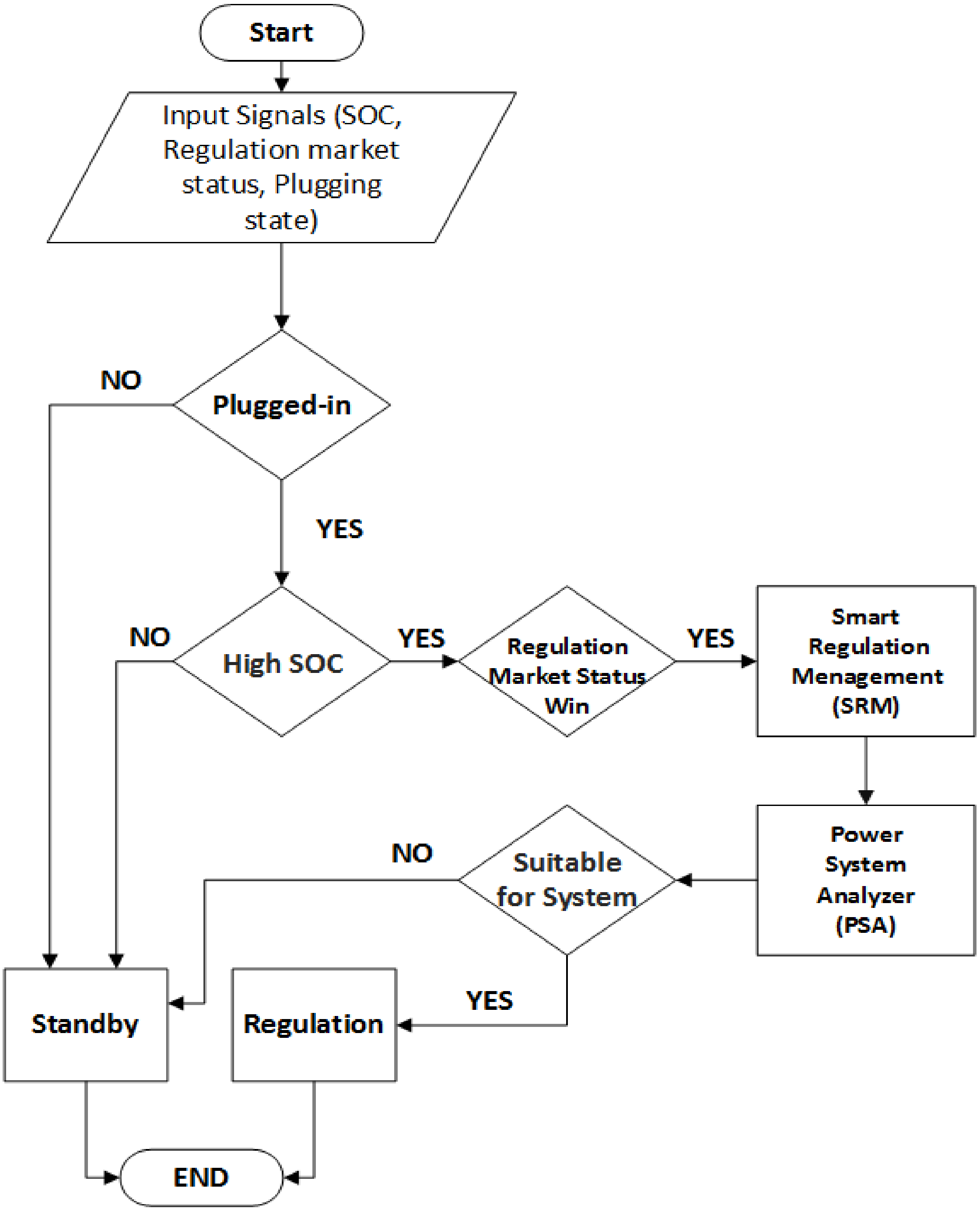
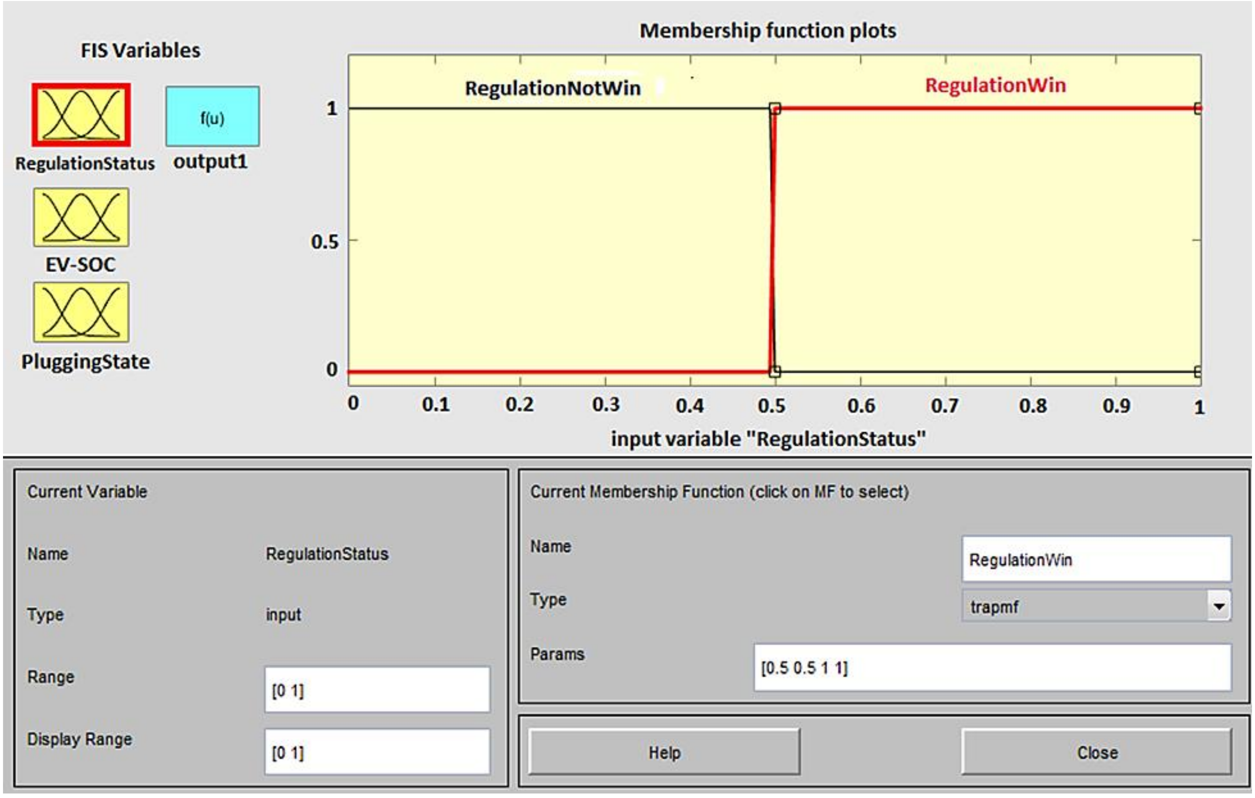


Figure 5.9: Fuzzy logic regulation control system mechanism flowchart

5.4.4 Regulation membership functions

Like the stated charging procedure in subsection 5.4.2, the input signals were defined by membership functions. For example, the regulation status signal is divided into two membership functions as it is displayed in Figure 5.10. The other input signals, including different SoC levels, plugged-in status of the EVs were also similarly defined by mean of membership functions.



Current Variable

Name RegulationStatus

Type input

Range [0 1]

Display Range [0 1]

Current Membership Function (click on MF to select)

Name RegulationWin

Type trapmf

Params [0.5 0.5 1 1]

Figure 5.10: Regulation status signal membership function in MATLAB environment

5.5 Simulated EV groups

The charging profile of the EV's battery, depends on different factors, including its energy capacity, power rating and its efficiency in charging, discharging and self-discharging. The energy capacity of batteries could vary from about 12 to 90 kWh, depending on the EV model [93]. EVs are divided into three main categories in [97]; light models with the energy capacity of 12-30 kWh, medium-large ones with 20-42 kWh and high-performer models with 60-90 kWh. Light to medium and high-performers EV types, are considered in this work to determine the travel energy requirements.

Furthermore, to increase the life cycle of the batteries, the entire available energy capacity might not be utilized [93]. This is indicated as a percentage of the whole battery capacity by a parameter called maximum state of the charge. This parameter for five different EV models are stated in [93], where it varies from 78% to 95%. A similar restriction also applies to the extent that a battery could be discharged, stated by Depth of Discharge (DoD) parameter. DoD depends on the type of the battery and it is usually ranged from 80% to 90% of the capacity [92] and [93]. To reflect these two limitations on the usable energy of the batteries in this chapter, it is assumed that the batteries can be charged to 95% maximum state of charge, but only 80% of their capacity can be discharged (DoD=80%).

There are three main types of charging infrastructure systems available for EVs, namely, standard, fast and rapid charging. The first two are based on single phase supply, which can be available at household level trough a typical home socket, whereas the third one is only available at public stations or wallboxes by three phase or DC voltage interface. The standard charging can be accessed through the normal electrical outlet at home with the output power range of 1 to 4kW. The fast charging can also be installed at home with an extra charge, in which the output power is between 6 and 8 kW, depending on the country and EV model. In Germany, a power output of about 4kW is being considered for the EVs in the residential sector. A more detailed description of these charging levels for different EV models are presented in [91] and [94]. Additional parameters describing the battery performance are the efficiency related to the power electronic converter and self-discharging of the battery. The latter is assumed 100% for the sake of simplicity, while the former is ranged from 85 to 95% [91, 92].

In this work, home charging, in contrast with the public one, is considered as the likely scenario [95] and [96]. Further, it is assumed that vehicles are connected to the grid and are available for charging after termination of the second journey and before the start of their first journey on the upcoming day. Four different groups of EVs are simulated in this work as follow:

Car profile 1:

People driving to work with no possibility to charge their cars at work. The technical specification of Tesla S [101] is modelled on the system. This EV has a battery with the energy usage of 185 Wh/km. Assuming the average car speed of 42.2 km/h in Germany due to ADAC report [102] and 2 hours driving, this EV requires 15.6 kWh energy for full charging status.

Car profile 2:

People driving to work with possibility to charge their cars at work (Tesla S). The mobility behaviour and plug in time of the EVs as well as the SoC of their batteries at the start of charging are this research assumptions for car profile 1 and 2.

Car profile 3:

DHL-Cars from „Smart E-User" project performed by DAI Laboratory TU Berlin. The "Street Scooter" has a battery with the energy usage of 155 Wh/km and drives an average of 51km in 24 hours, which leads to an energy request of 8 kWh (60%-90% SoC) [17]. The typical load curve of a Street Scooter (DHL-Car), for a specific day has been demonstrated in Figure 5.11.

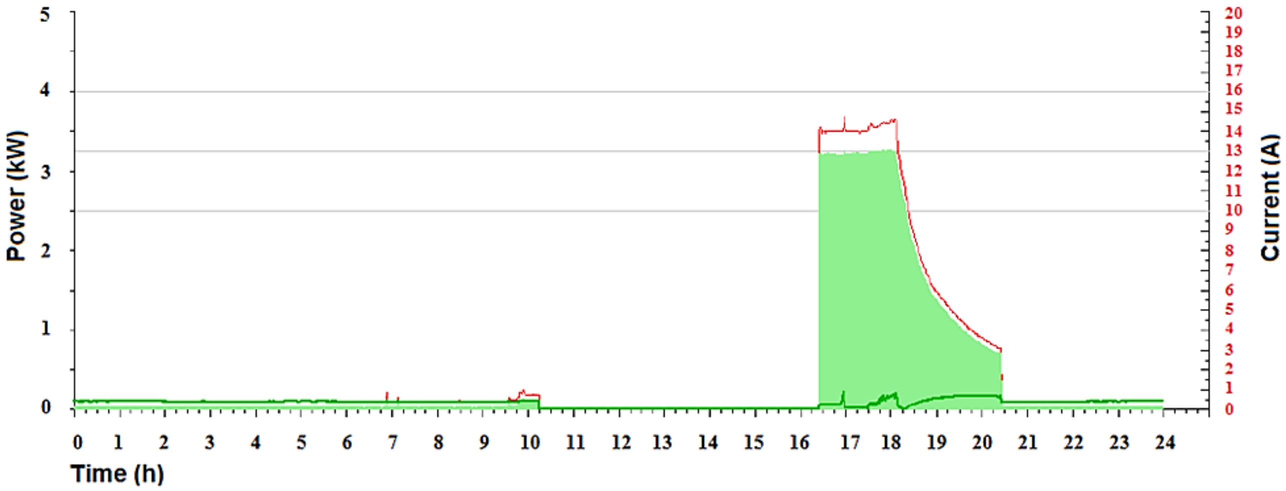


Figure 5.11: Street scooter's typical load curve during a specific day [17]

The plug in time and mobility behaviour of these car profile, are derived from reference [17].

Car Profile 4:

This profile contains different types of EVs that are applied due to the Fraunhofer, KIT research for the BMBF [5]. The frequency of car movement during a typical work day is assumed as it is demonstrated in Figure 5.12.

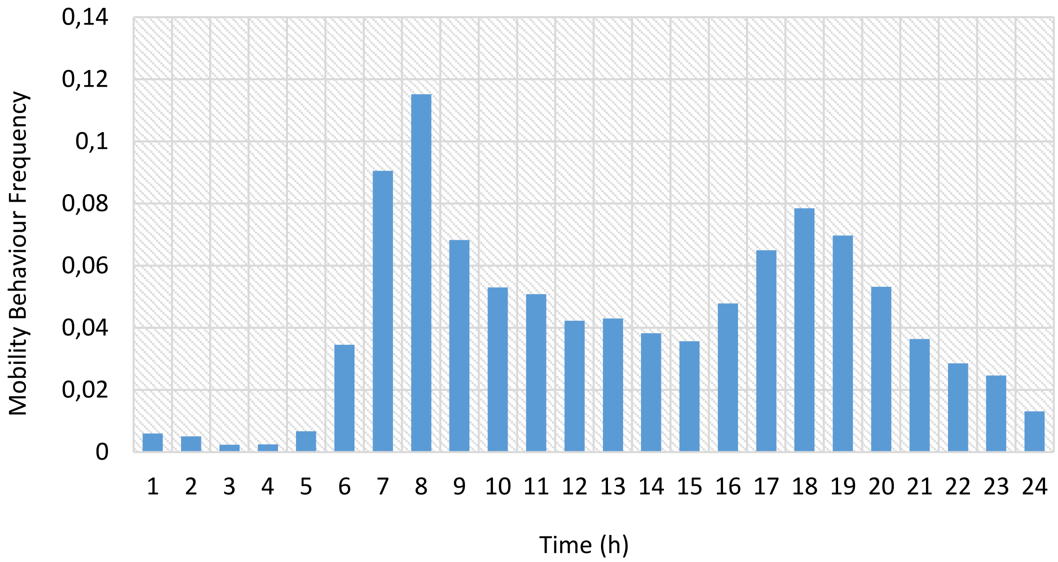


Figure 5.12: Car mobility during a typical work day in Germany (derived from [5])

Table 5.1 can be resulted from Figure 5.12 and demonstrates the resulted plug-in frequency of the EVs to the grid.

Table 5.1: Resulted plug-in frequency of an EV during a typical work day (derived from [5])

Day	***Typical work day***
Hour	Plug-in frequency
0-1	0.994
1-2	0.9949
2-3	0.9976
3-4	0.9975
4-5	0.9933
5-6	0.9655
6-7	0.9095
7-8	0.8848
8-9	0.9317
9-10	0.947
10-11	0.9492
11-12	0.9577
12-13	0.957
13-14	0.9617
14-15	0.9634
15-16	0.9521
16-17	0.935
17-18	0.9215
18-19	0.9303
19-20	0.9468
20-21	0.9636
21-22	0.9714
22-23	0.9754
23-24	0.9869

Having these data, the required energy of these EVs in a day is calculated using the following equations.

EV usage at time t:

$$U_t^{\text{time}} = \int_1^t f(t)dt \tag{5.1}$$

Where:

$f(t)$ is the probability of car usage at time t, and U_t^{time} the average usage of the cars accumulated from 0 to to the time point *t*.

The calculated amount of average usage time of the EVs due to Table 1, is presented in Figure 5.13. It is shown that the car owners use their cars an average by 60 minutes during a normal work day in Germany.

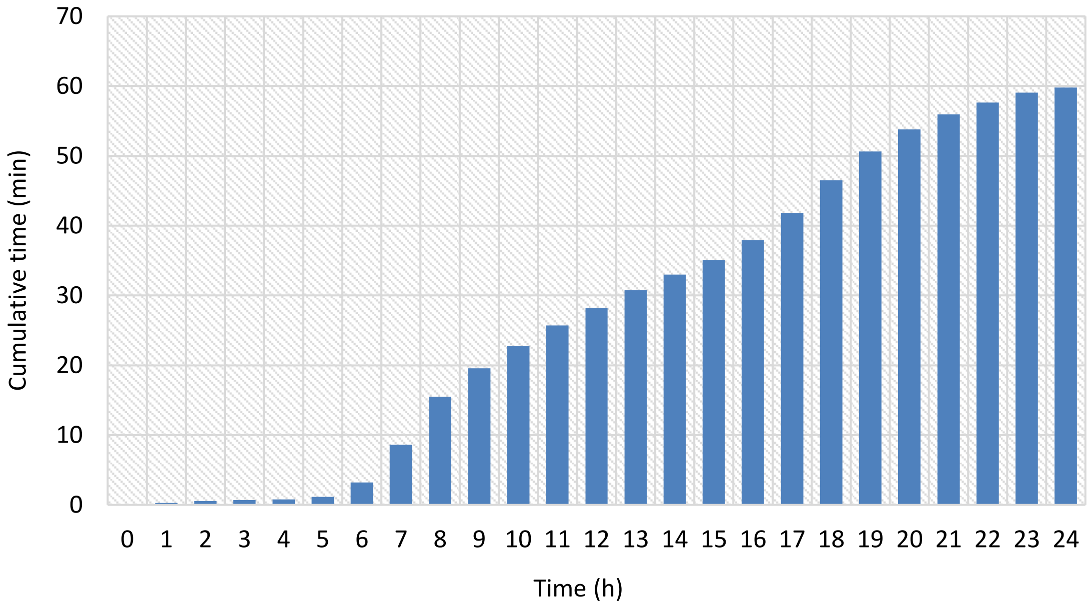


Figure 5.13: Cumulative time of EV usage during a typical day (derived from [5])

Daily consumed energy:

The amount of average used energy in a day at time t, is calculated with the following equation (5 - 2):

$$E_t = U^{\mathrm{time}} \times Dr^{\mathrm{en}} \times Dr^{\mathrm{sp}} \tag{5.2}$$

Where:

Dr^{en} is the average energy usage of the EVs in $\frac{Wh}{km}$, and Dr^{sp} their average driving speed in $\frac{km}{h}$.

In Germany, we assume 42.2 $\frac{km}{h}$ due to the ADAC study [102]. Regarding the previous figures and calculations, an EV requires an average energy of about 8 kWh per day, which approves also the assumptions of reference [119].

5.6 Power System Analyzer (PSA)

This sub-part of the demonstrated flow chart in the Figures 5.5 and 5.9, defines the exact charging time of the EVs considering operational system constraints, including overload prevention of the lines and other components, loss minimization and cost optimization of the charging procedure. The charging requests of the EVs, resulting from the fuzzy controllers in the first step of the SCRM system is considered as one of the main inputs of the PSA. The EVs are divided into three different groups due to their charging priority. The group with the highest priority is classified as the “urgent charging” group, the ones with lower charging priority as the “normal charging” and the EVs with no charging priority as the “flexible charging” group. First of all, the EV with the highest charging request of the urgent charging group will be added to the system and the charging start time will be defined by the PSA, considering the above mentioned system constraints. This procedure will continue from the highest charging request up to the lowest in each priority group, respectively, while the system operation constraints are met. At the end after defining all charging start hours of the EVs, a load flow will be run for a whole day to update the related load curve of the system. The mechanism of this final step of the proposed SCRM system is shown in Figure 5.14.

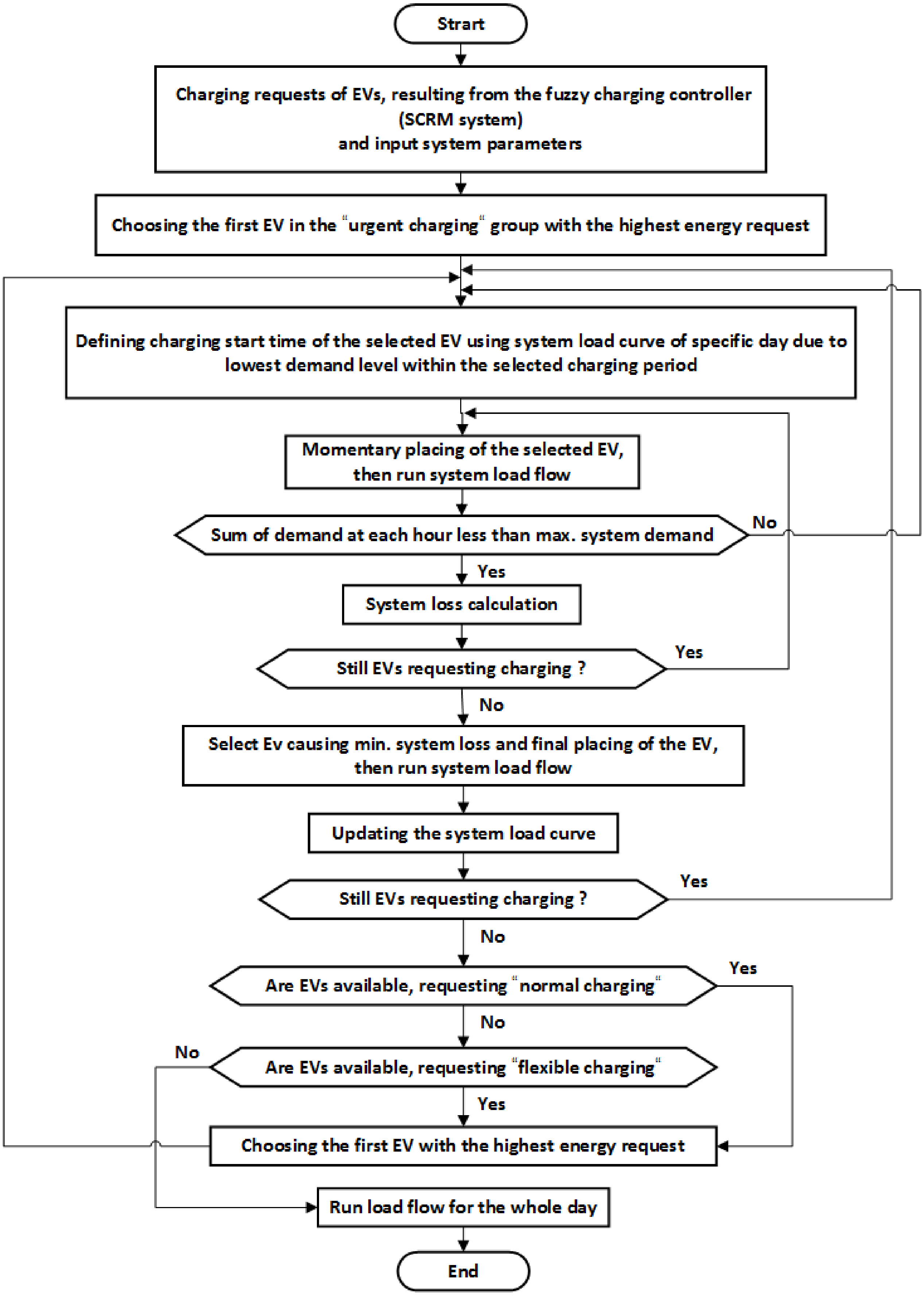


Figure 5.14: PSA mechanism flowchart

The input signals of the PSA are as follows:

- Urgent, normal and flexible charging request of the EVs resulting from the fuzzy charging controller (SCRM system outputs)
- Daily load curve for a specific day of the year
- Number of available EVs in each charging zone
- Each EVs location in the power system
- Maximum demand level of the system
- Node and line impedance and resistance data
- Power system parameters (This will be defined in the following parts)

5.7 Mathematical formulation

A Newton-based optimal AC power flow [103] is applied in this work using MATLAB in order to define various system variables and achieve optimal results. The decision variables are voltage magnitude and angles at each node of the network, each household supplied demand level and power loss related to each branch of the network. The solution should satisfy the constraints associated with the household's demand limit, voltage magnitude restrictions and minimizing the power loss of the system of each branch. The simulations are conducted based on an hourly time step for a day (24 hours). Considering this, the procedure is formulated by the following equations:

5.7.1 System constraints

System voltage:

Voltage constraints of the distribution systems are defined by lower and upper ranges. These ranges are in accordance with voltage limits and the defined settings by the power utilities. In this reference, the voltage range is adjusted to ±10% for variations.

That means $V^{\min} = 0.9$ pu and $V^{\max}$ = 1.1 pu, that are standard values in distribution systems [1].

$$V^{\min} \leq V_i \leq V^{\max}, \forall i \in N \tag{5.3}$$

Where:

i: Number of the node,

N: Set of the network nodes.

Total system demand:

The second constraint is for adjusting the maximum total demand (upper range) of the distribution system in order to prevent overloads due to EV charging [1].

$$Dem_t = \sum_{i \in N} P_{i,t}^{\text{load}} \leq D_t^{\max}, \forall t \in T \tag{5.4}$$

Where:

T: Time horizon of the day (24 h),

Dem_t: The total power demanded by the system, at time t of total 24 hours,

$P_{i,t}^{\text{load}}$: The power demand of node i at time t,

$D_t^{\max}$: The maximum power demand level of the system at time t without EVs.

Definitions:

$$\tilde{V}_{i,t} = V_{i,t} < \delta_{i,t}, \forall i \in N, \forall t \in T$$

Where:

$\tilde{V}_{i,t}$: The voltage phasor of the bus number i at time t,

$V_{i,t}$: Vector of voltage magnitudes node i at time *t*,

$\delta_{i,t}$: Vector of voltage angles at node i at time *t*.

$$\tilde{Y} = \begin{pmatrix} \tilde{Y}_{1,1} & \cdots & \tilde{Y}_{1,N} \\ \vdots & \ddots & \vdots \\ \tilde{Y}_{N,1} & \cdots & \tilde{Y}_{N,N} \end{pmatrix} \tag{5.5}$$

Where:

$\tilde{Y}$ defines the admittance matrix of the system (5.6). To calculate the net active and reactive power injected to each node, equations (5.7) and (5.8) are presented.

$$\tilde{Y}_{\ i,k} = G_{i,k} + \ jB_{i,k} \tag{5.6}$$

$$P_{i,t}\ (V_t, \delta_t) = V_{i,t} \sum_{k \in N} V_{k,t} \big(G_{i,k}\, cos\big(\delta_{i,t} - \delta_{k,t}\big) + B_{i,k}\, sin\big(\delta_{i,t} - \delta_{k,t}\big)\big), \forall i \in N,$$

$$\forall t \in T \tag{5.7}$$

$$Q_{i,t}\ (V_t, \delta_t) = V_{i,t} \sum_{k \in N} V_{k,t} \big(G_{i,k}\, sin\big(\delta_{i,t} - \delta_{k,t}\big) - B_{i,k}\, cos\big(\delta_{i,t} - \delta_{k,t}\big)\big), \forall i \in N,$$

$$\forall t \in T \tag{5.8}$$

The parameters are defined as:

$\tilde{Y}_{i,k}$: The $i^{th}k^{th}$ element of the bus admittance matrix,

$G_{i,k}$: Conductance of $i^{th}k^{th}$ element of the bus admittance matrix,

$B_{i,k}$: Susceptance of $i^{th}k^{th}$ element of the bus admittance matrix,

$P_{i,t}$: Active power injection at node i and time *t*,

$Q_{i,t}$: Reactive power injection at node i and time *t*.

The Newton’s method [114] is applied to solve the system (5.9):

$$\begin{pmatrix}\Delta P\\ \Delta Q\end{pmatrix} \approx \begin{pmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}\end{pmatrix}\begin{pmatrix}\Delta \delta\\ \Delta V\end{pmatrix} \approx J\begin{pmatrix}\Delta \delta\\ \Delta V\end{pmatrix} \tag{5.9}$$

Where:

J is the Jacobian matrix of the system.

System Loss calculation:

$$P_{i,k,t}^{\text{loss}} = R_{i,k}(|V_{i,k,t}||y_{i,k}|)^2 \ ,\forall i,k \in N, i \neq k,\ \ \forall t \in \mathrm{T} \tag{5.10}$$

$$P_t^{\text{loss,tot}} = \sum_{i,k \in N} P_{i,k,t}^{\text{loss}} \quad ,\forall i,k \in N, i \neq k,\ \ \forall t \in \mathrm{T} \tag{5.11}$$

Where:

$V_{i,k,t}$: The voltage magnitude between nodes i and k at time *t*,

$P_{i,k,t}^{\text{loss}}$: Power losses between nodes i and k at time *t*,

$R_{i,k}$: Line resistance between nodes i and k,

$y_{i,k}$: Admittance between nodes i and k,

$P_t^{\text{loss,tot}}$: The total power loss of the distribution network at time *t*.

Objective functions:

In this research, the aim is to minimize the peak load and loss of the distribution system [1]. As presented in (5.12), in order to minimize the system peak, the system demand is minimized through the following equation (5.12):

$$\min \sum_{t=t^{\text{start}}}^{t^{\text{end}}} Dem_t = \min \sum_{t=t^{\text{start}}}^{t^{\text{end}}} \sum_{i\in N} P_{i,t}^{\text{load}}, \quad \forall i \in N, \forall t \in T \tag{5.12}$$

For minimizing the total power loss of the distribution system during the day, based on (5.11), following equation is expressed (5.13):

$$\min \; Loss^{\text{tot}} = \sum_{t\in \text{T}} P_t^{\text{loss,tot}} \tag{5.13}$$

Where:

$P_t^{\text{loss,tot}}$: The total power loss of the distribution network at time t,

$Loss^{\text{tot}}$: The accumulated system loss for the time horizon.

In this method, the aim of minimizing system losses at any time, while taking changes of energy prices in time periods of 24 hours into account and considering the charging interest of the EV owners based on priority lists, is considered.

5.8 System security index

An uncontrolled charging of a large group of EVs could harm the system operation security of the distribution network. To show the effectiveness of the proposed method, some definition and security indexes are presented as follows:

5.8.1 Loss of load expectation (LoLE)

The amount of the total hours where the requested energy (i.e., system demand) is larger than the energy availability (i.e., produced energy by the generation units of the system) is defined in equation (5.14) [108].

$$S_t = \begin{cases} 1 & E_t^{\text{req}} > E_t^{\text{avail}} \\ 0 & \text{otherwise} \end{cases} \tag{5.14}$$

$$LoLE = \sum_{t=1}^{\text{T}} S_t \tag{5.15}$$

Where:

S_t: The energy Availability at time t,

E_t^{req}: The requested energy at time t,

E_t^{avail}: Amount of available energy at time t.

5.8.2 Loss of load probability (LoLP)

LoLP defines the probability of having less available power than requested. This is a useful security index that is commonly applied to show whether a system is secure or not. The LoLP is equal to 0 in a secure system [108].

$$LoLP = \frac{LoLE}{T} \tag{5.16}$$

5.9 Communication structure of the EVs

The proposed SCRM system will be applied in a centralized control structure. This structure was completely described in the subsection 3.6.1. The SCRM system controls the charging of the available EVs in their areas based on the predicted daily demand, load curve, and the consumer preferences. This is done according to the online first step input signals and applying the PSA optimized algorithm. Although the detailed communication structure of the EVs with the SCRM system is out of scope of this research, the EVs could communicate with the related local load stations (local aggregators) due to the ISO/IEC15118-2 standard [116]. A general layout has been drafted that describes the data and message format of the vehicle to grid communication interface. The corresponding data which has to be exchanged is defined in the V2G communication interface working draft of ISO/IEC 15118-2 [116] by several message patterns. The ISO/IEC15118-2 defines these message patterns involved in a regular charging process like plugging in, service discovery (available services after set up), authorization (exchange of security details), power discovery (charging parameters and pricing table), power request, payment, charging cycles and unplugging [117]. Hence, the input signal data of the SCRM system which are provided by the EVs could be exchanged due to this ISO/IEC standard.

Chapter 6

Simulation and Results

6.1 Introduction

In practice, EVs chargers are appropriate in relation to the battery capacity and reasonable lifetime periods. However, household wiring limitations must also be considered. A single-phase 230 V standard outlet in Germany is characterized by a maximum power of about 4 kW. As well as 10 A and 16 A outlets and fuses for single phase, which can pass powers about 2,5 kW and 4 kW respectively. A 400 V three-phase outlet includes 16 A, 32 A and 63 A outlets, which can deliver power amounts of 11 kW, 22 kW and 43 kW separately. In this work, the charging power is limited to a maximum amount of 4 kW to prevent the need for strengthening conventional wiring in the house and furthermore it is available as a single-phase outlet. Although the fast charging EVs were also introduced as very challenging loads in section 2, however as their plug in times to the power network are very short due to their fast charging, they are not a suitable EV group to be controlled through the proposed SCRM system. The EVs have to be available for a longer time to be managed by the aggregators in the control centers regarding their charging and discharging procedures. In addition to this, based on reference [119], a vast majority of EVs’ driving profiles will be covered with single phase home-charging, both in Germany and the US so that high shares of EVs can be operated in the grid, using home charging only.

The results of the simulation of a standard distribution network are conducted in controlled and uncontrolled charging mode at different penetration levels of EVs and at different priority groups. These results showed that utilizing this method improves the system operation in many aspects in terms of economy, efficiency, reliability and system security. A pricing and priority scheme for operational time periods of EVs for coordinating the charging procedure, in the form of an effective smart load management has been shown. EV owners can define priorities for charging based on smart load management to reduce their energy costs and system losses and also be involved in maintaining frequency regulation.

The proposed smart charging and regulation management (SCRM) system is trying to respect the car owner’s determined charging time periods if the system constraints are not violated. This method can’t perform fast charging of the EVs, due to the limitation of both, network constraints and home wiring. The reactive power exchange capacity of the charger is useless in this method. The simulation was applied in one node of the test-system including 53 households and was run for two different scenarios based on performed studies to see the positive impact of the proposed SCRM system in decreasing the charging energy costs and receiving extra payments for the offered power regulation services (primary/secondary control power services). The results were extrapolated to the other nodes of the test system considering similar condition. Furthermore, the situation of Germany 2030 has been investigated and the future benefits for Germany, applying the proposed SCRM method, are highlighted.

6.2 Scenario definition

To show the feasibility of this SCRM system for the situation of Germany regarding the relation between the number of EVs and available smart homes in 2030, two different scenarios are defined. For running the SCRM system as a central control method, it is necessary for homes to be equipped with smart home capabilities, so that they could be controlled and managed online and remotely. Smart homes have the adequate infrastructures for charging the EVs, which can be managed remotely and furthermore, the number of available smart homes in 2030 in Germany could be applied in the simulations according to [14]. Due to the Deloitte study [14], there will be 6.3 million and 15.2 million smart homes in Germany, considering a conservative and a progressive scenario respectively. It is known that the main objective of the

German government is to apply 6 million EVs till 2030. Due to the EWI study [12], just the number of 2.8 million EVs will be realistic. Therefore, regarding these studies, two different scenarios are simulated considering the proportion of the EVs to smart homes in Germany in the year of 2030. Two simulation scenarios will be defined as follows:

- Scenario A1:

The number of 6 million EVs and 6.3 million smart homes are assumed, so the EVs have a penetration level of 95%. This means that almost all of the smart homes apply an EV.

- Scenario A2:

The number of 2.8 million EVs and 6.3 million smart homes are considered. Thus, the penetration level of EVs for this scenario is 44%. Therefore, less than the half of the smart homes use an EV due to this scenario.

6.3 Energy request of the EVs for scenario A1

Table 6.1 demonstrates the requested amount of energy of the EVs in one node of the simulated distribution system for scenario A1 for a typical summer work day. Likewise, the EVs energy request for a typical winter work day in December 2015 is presented in Table 6.2. Regarding the proportion between EV and smart homes in scenario A1, 95% of the homes have an electric vehicle. There are three different charging priority groups that are named with the numbers 1, 2, and 3. The number 1 is for “urgent charging” without any considerations, 2 for “flexible charging” and 3 is for “normal charging” in specific times and medium energy prices. The amount of the requested energy and priority group are resulted from the first step of the SCRM system applying the fuzzy controllers (introduced and explained in section 5). For example, EV number 26 in Table 6.1 is requesting 8 kWh of energy with an urgent charging priority. Due to Table 6.1, 12% are requesting 12 kWh charging energy, 36% need 4 kWh of energy and 52% of the EVs request 8 kWh energy. Regarding Table 6.2, only 6% of the EVs request 12kWh charging energy, more than the half (54%) need 8 kWh and 40% of the EVs ask for 4 kWh energy. In both tables, there are no EVs requesting energy at home number 46, 50 and 51, according to the simulated scenario.

Table 6.1: Requested energy by the EVs of one node of the distribution network resulting from the SCRM system for a typical summer work day (Scenario A1)

Smart home no.	***EV energy request of 4 kWh***	***EV energy request of 8 kWh***	***EV energy request of 12 kWh***
1	0	0	**2**
2	0	0	**2**
3	0	0	**2**
4	**2**	0	0
5	**2**	0	0
6	**2**	0	0
7	**2**	0	0
8	**2**	0	0
9	0	**2**	0
10	0	0	**2**
11	0	0	**2**
12	0	0	**2**
13	0	**2**	0
14	0	**2**	0
15	**2**	0	0
16	**2**	0	0
17	**2**	0	0
18	0	**2**	0
19	0	**2**	0
20	0	**2**	0
21	0	**2**	0
22	0	**2**	0
23	0	**2**	0
24	0	**2**	0
25	0	**2**	0
26	0	**1**	0
27	0	**2**	0
28	0	**2**	0
29	0	**2**	0
30	0	**2**	0
31	0	**2**	0
32	0	**2**	0
33	0	**2**	0
34	0	**2**	0
35	0	**2**	0
36	0	**2**	0
37	**2**	0	0
38	**3**	0	0
39	**2**	0	0
40	**2**	0	0
41	**2**	0	0
42	0	**2**	0
43	**2**	0	0
44	**2**	0	0
45	**2**	0	0
47	0	**2**	0
48	**3**	0	0
49	0	**2**	0
52	0	**2**	0
53	**1**	0	0

Table 6.2: Requested energy by the EVs of one node of the distribution network resulting from the SCRM system for a typical winter work day (Scenario A1)

Smart home no.	*EV energy request of 4 kWh*	*EV energy request of 8 kWh*	*EV energy request of 12 kWh*
1	0	**2**	0
2	0	**2**	0
3	0	**2**	0
4	0	**2**	0
5	0	**2**	0
6	0	**2**	0
7	0	**2**	0
8	0	**2**	0
9	0	**2**	0
10	0	0	**2**
11	0	0	**2**
12	0	0	**2**
13	0	**2**	0
14	0	**2**	0
15	**2**	0	0
16	**2**	0	0
17	**2**	0	0
18	**2**	0	0
19	**2**	0	0
20	0	**2**	0
21	0	**2**	0
22	0	**2**	0
23	0	**2**	0
24	0	**2**	0
25	0	**2**	0
26	0	**1**	0
27	**2**	0	0
28	**2**	0	0
29	**3**	0	0
30	**3**	0	0
31	**3**	0	0
32	**3**	0	0
33	**3**	0	0
34	**3**	0	0
35	**3**	0	0
36	**3**	0	0
37	**2**	0	0
38	**2**	0	0
39	0	**3**	0
40	0	**1**	0
41	0	**3**	0
42	**2**	0	0
43	**2**	0	0
44	**2**	0	0
45	0	**1**	0
47	0	**3**	0
48	0	**1**	0
49	0	**3**	0
52	0	**3**	0
53	0	**3**	0

6.4 Results for scenario A1

The simulation is applied for a whole year considering the energy prices in Germany from December 2015 to December 2016 (derived from the EEX platform [15]) and the seasonal German load curve regarding the H0 standard load profile adapted from reference [118]. The H0 standard load profile is according to the German association of the electricity industry (VDEW) and presents the representative consumption behavior of household electricity customers on different days of the week in Germany. Because of the large amount number of results, a demonstrative work day from 15th May to 14th June 2016 in summer and in December 2015 in winter, are presented in the following pages. A complete set of data for the other months of the year including the simulation results of the EV's charging requests is presented in Appendix B. The load curve of the simulated distribution network with 1378 smart homes in a typical summer work day without EVs is shown in Figure 6.1 and respectively, the system load curve for winter work days is presented in Figure 6.2. These load curves are adapted equally for each household based on [118].

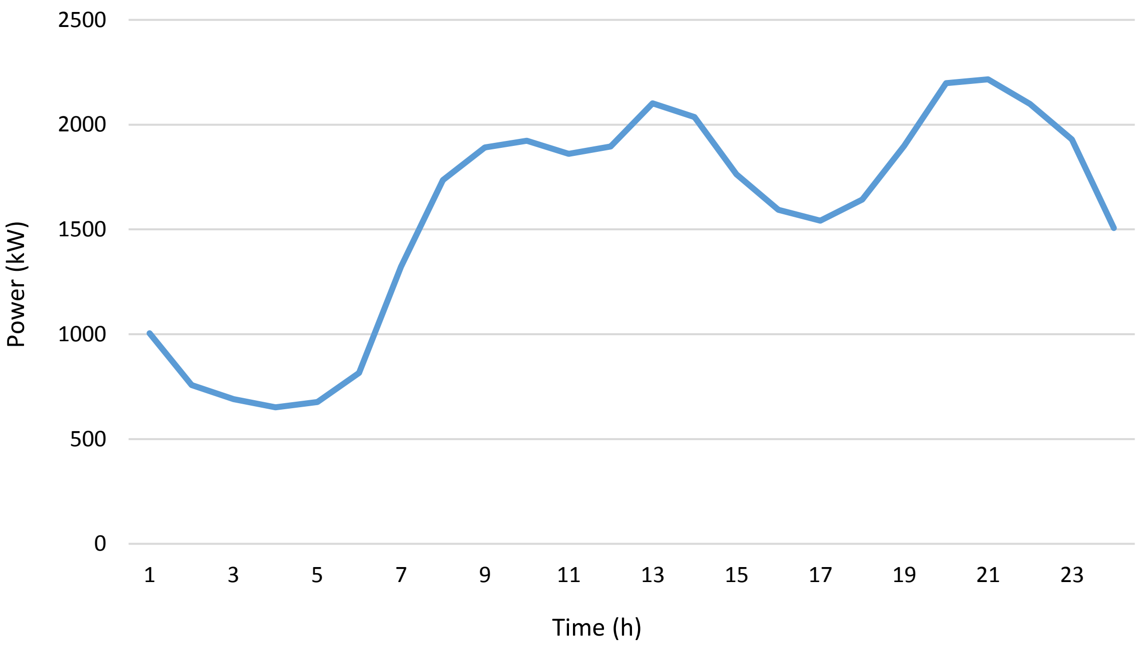


Figure 6.1: Applied load curve of the distribution network with about 1400 smart homes for a typical summer work day

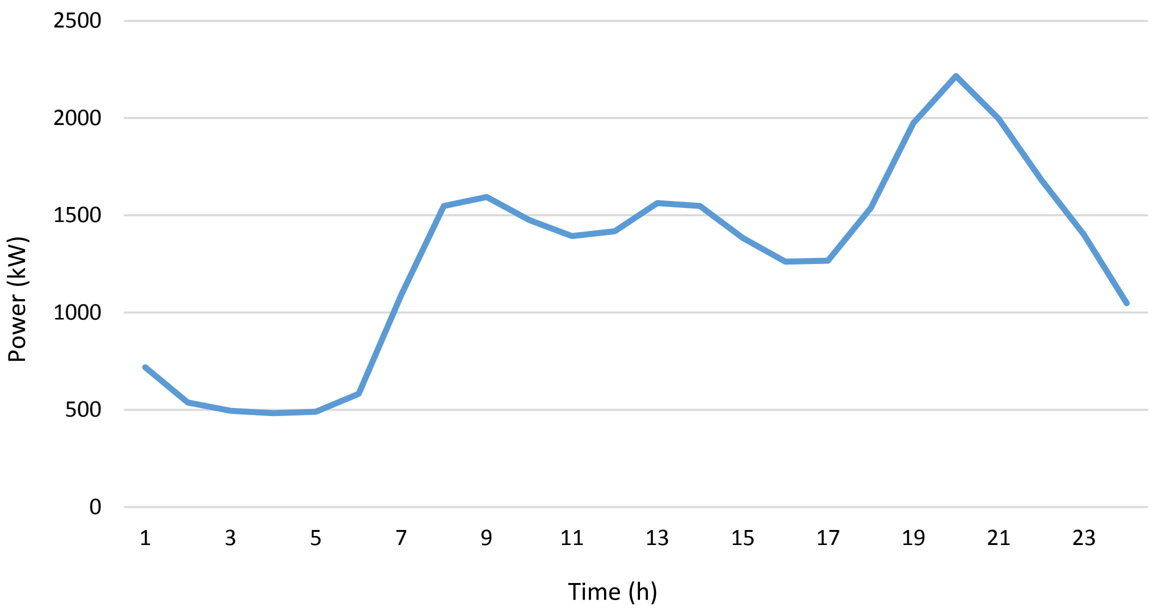


Figure 6.2: Applied load curve of the distribution network with about 1400 smart homes for a typical winter work day

For Germany 2030, the possible load curve for 6.3 million smart homes without EVs could be assumed as shown in Figure 6.3 and Figure 6.4 for summer and winter work days respectively.

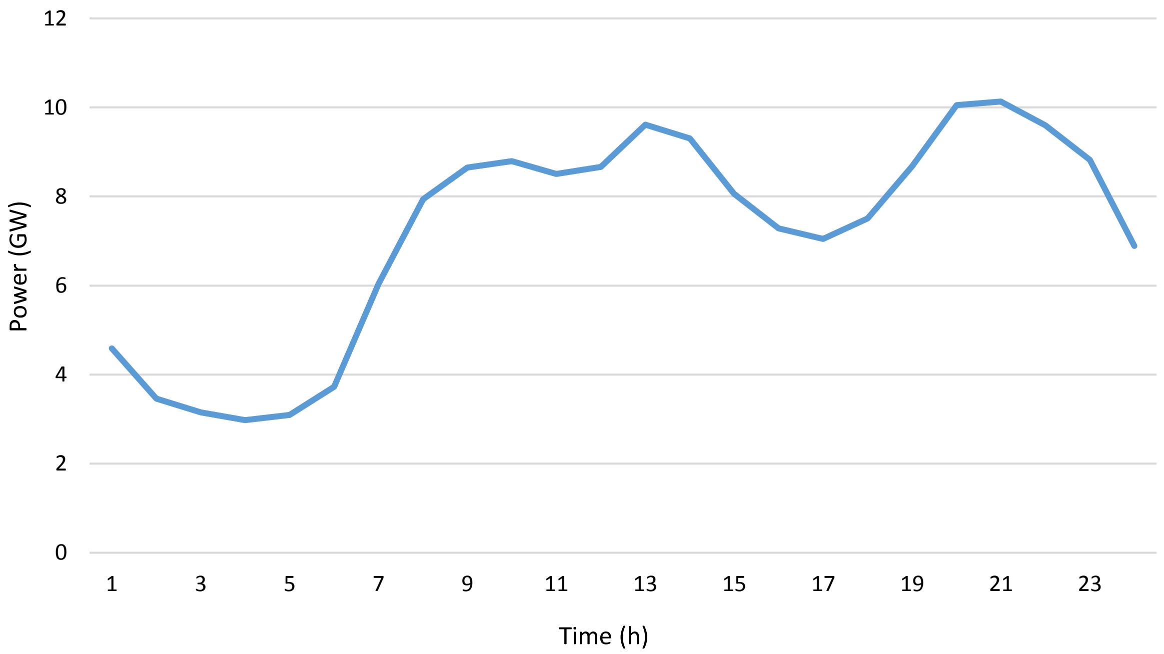


Figure 6.3: Possible load curve for a typical summer work day for Germany 2030 assuming of 6.3 million smart homes

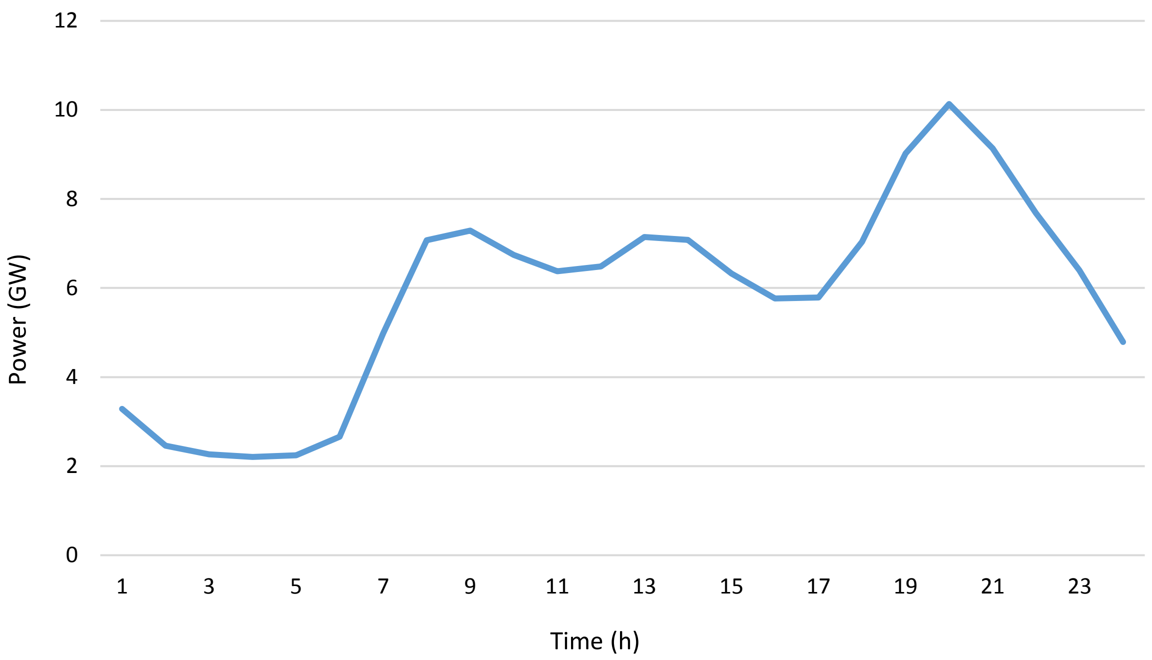


Figure 6.4: Possible load curve for a typical winter work day for Germany 2030 assuming of 6.3 million smart homes

The resulted charging hours regarding the type of energy request of the EVs in summer is presented in Table 6.3. For example, the EV at the smart home no.26 starts charging at 7 am until 9 am in an urgent charging priority group as requested (see Table 6.1). Also, regarding Table 6.4, the EV no.10 had requested 12 kWh in the flexible energy group (due to Table 6.2) and is charging for 3 hours from 2 am till 5 am due to the SCRM system results. In both tables, “flexible 8”,” flexible 4” and “flexible 12” stands for 8 kWh, 4 kWh and 12 kWh requested energy in the flexible charging group respectively. Likewise, “normal 4” and “normal 8” defines the EV groups that requested 4 kWh and 8 kWh of normal charging and so, “urgent 4” and “urgent 8”, are the EV groups in urgent need of charging. If all these EVs would start charging right after arriving their homes or their charging places without any consideration, a great amount of load demand would be inevitable. This is assumed as the uncontrolled charging of the EVs, which happens after they arrived home at 6:00 p.m. (i.e., the highest arrival probability based on [5]) on a work day in Germany. Although, all the EVs could start charging at the same time as a worst case scenario of uncontrolled charging, but a normalized charging start time of the EVs with two different penetration levels (scenario A1 and A2) is assumed in this research as more realistic uncontrolled charging scenarios. The resulted load curves will be shown later in this section.

Table 6.3: Resulting charging hours of the EVs of one node of the distribution network for a typical summer work day (Scenario A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 8 ch. Start hour***	***urgent 4 ch. start hour***
35	5					
20	2					
21	4					
36	2					
18	4					
42	1					
23	3					
25	1					
27	5					
19	3					
9	1					
13	5					
47	3					
22	1					
28	5					
31	3					
32	1					
30	5					
49	3					
34	1					
24	5					
29	3					
14	1					
52	5					
33	3					
16		6				
39		6				
40		6				
17		6				
4		1				
37		16				
6		6				
44		5				
8		2				
7		1				
45		16				
41		6				
5		3				
15		4				
43		5				
1			4			
2			3			
12			2			
3			4			
11			2			
10			4			
38				17		
48				17		
26					7	
53						7

Table 6.4: Resulting charging hours of the EVs of one node of the distribution network for a typical winter work day (Scenario A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. Start hour*	*normal 8 ch. Start hour*	*urgent 8 ch. start hour*
1	5					
20	5					
2	2					
21	4					
4	1					
23	4					
6	3					
25	1					
8	3					
7	5					
9	1					
3	3					
13	5					
22	1					
5	3					
24	5					
14	1					
16		6				
17		6				
37		24				
18		3				
42		6				
44		5				
27		4				
38		24				
19		1				
28		2				
15		3				
43		6				
12			4			
11			3			
10			2			
35				7		
36				7		
31				7		
32				7		
30				7		
34				15		
29				7		
33				15		
39					11	
41					11	
47					10	
49					14	
53					10	
52					13	
40						16
26						16
45						16
48						16

As can be seen from Figure 6.1, there are two peak hours in the system which makes the condition in maintaining its stability after the additional load caused by the EVs, very hard. Figure 6.5 and Figure 6.6, show the impact of the uncontrolled charging of the EVs due to scenario A1 for a typical summer and winter work day respectively.

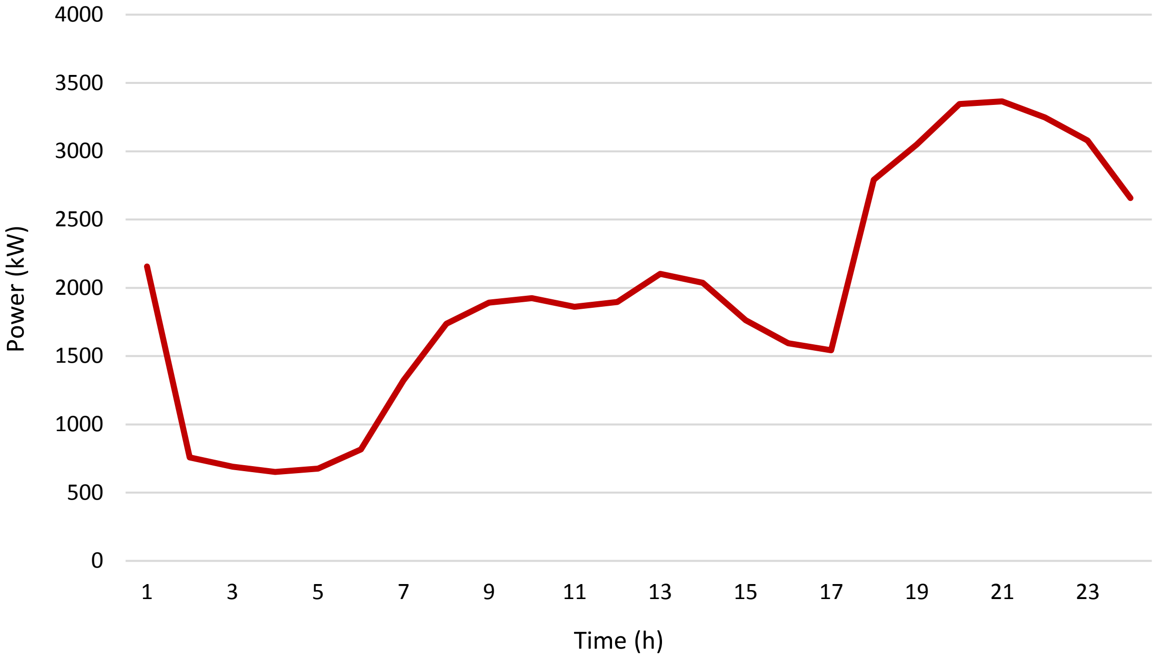


Figure 6.5: Load curve of the system at uncontrolled charging of the EVs of the distribution network in a typical summer work day (Scenario A1)

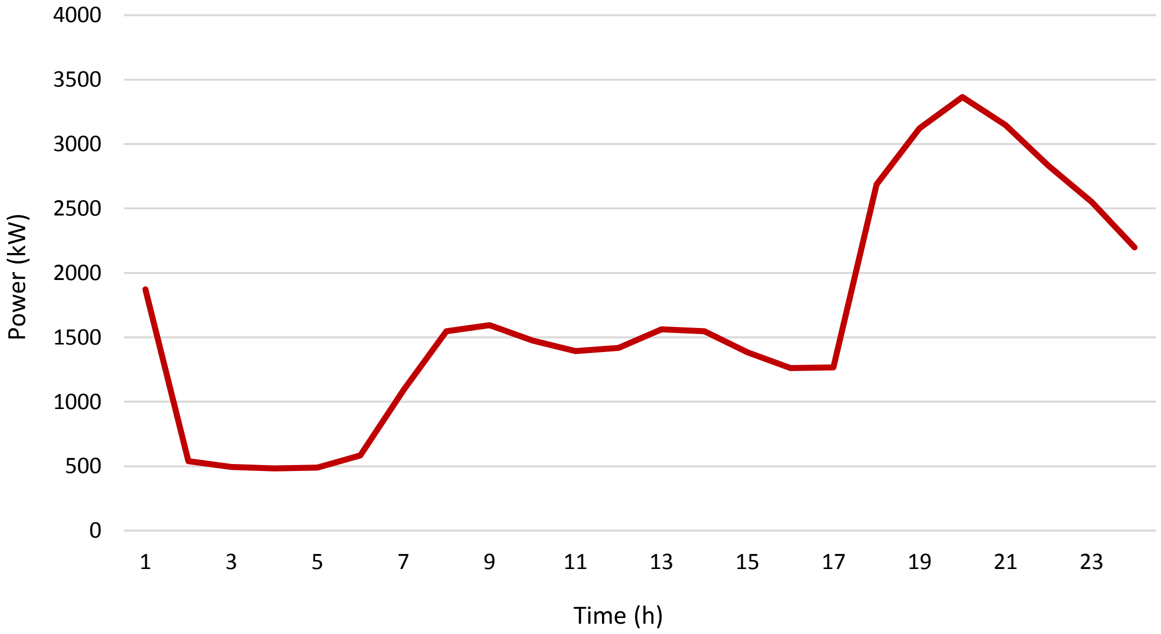


Figure 6.6: Load curve of the system at uncontrolled charging of the EVs of the distribution network in a typical winter work day (Scenario A1)

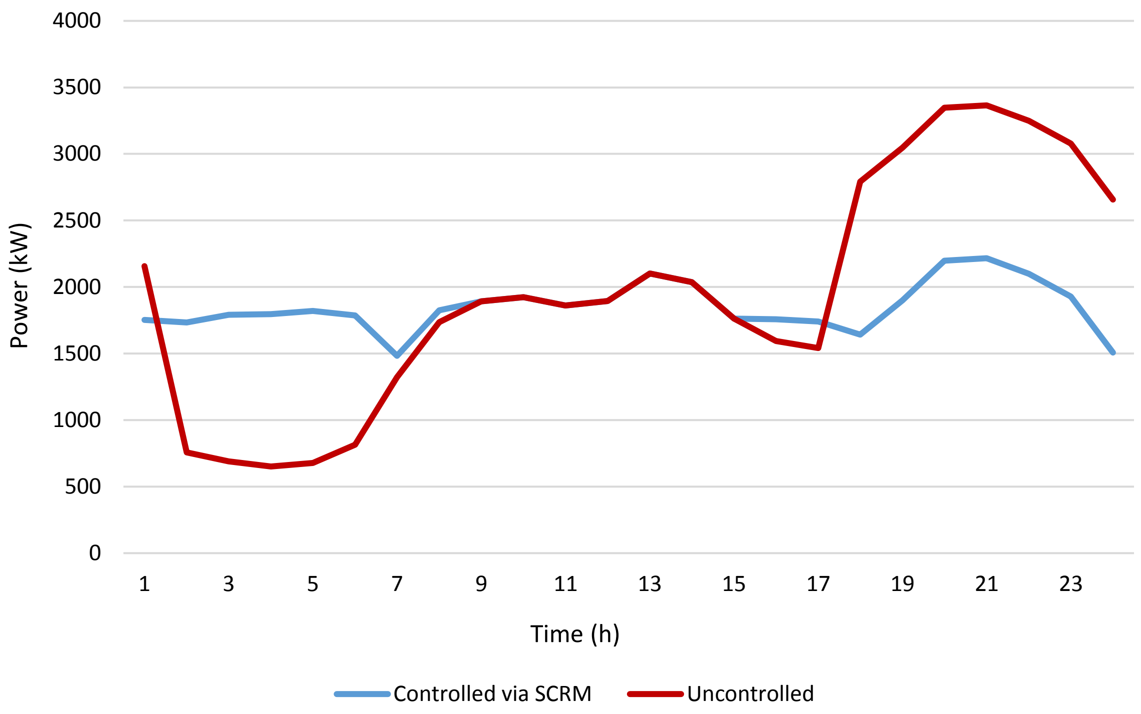


Figure 6.7: Load curve comparison of the system with controlled and uncontrolled charging in the distribution network for a typical summer work day (Scenario A1)

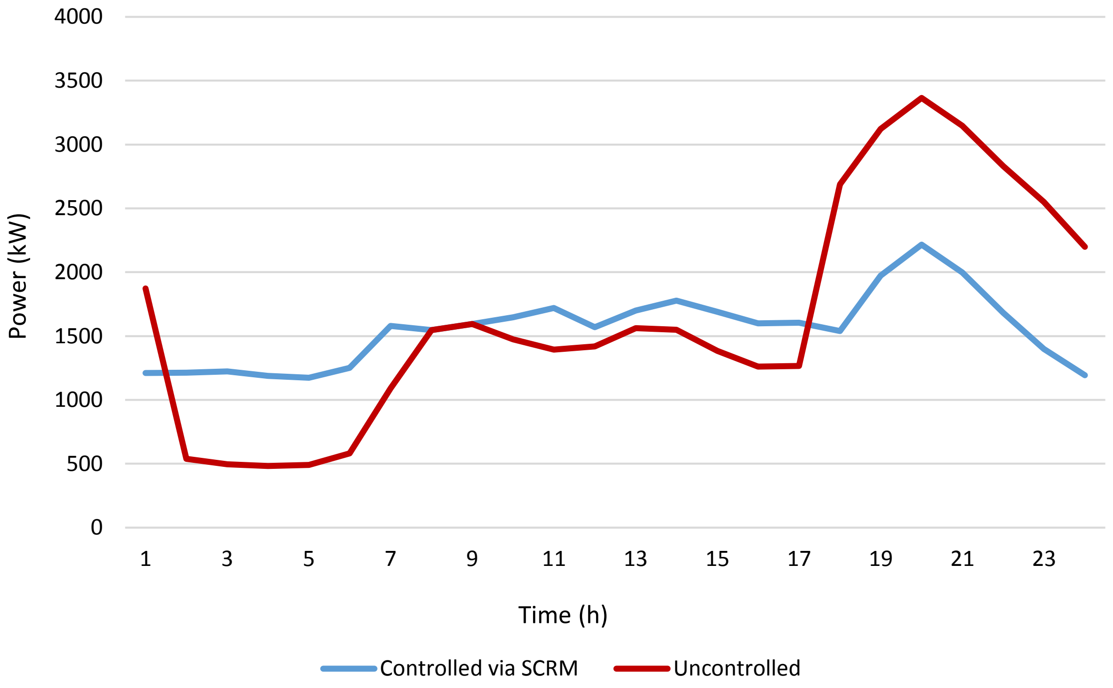


Figure 6.8: Load curve comparison of the system with controlled and uncontrolled charging in the distribution network for a typical winter work day (Scenario A1)

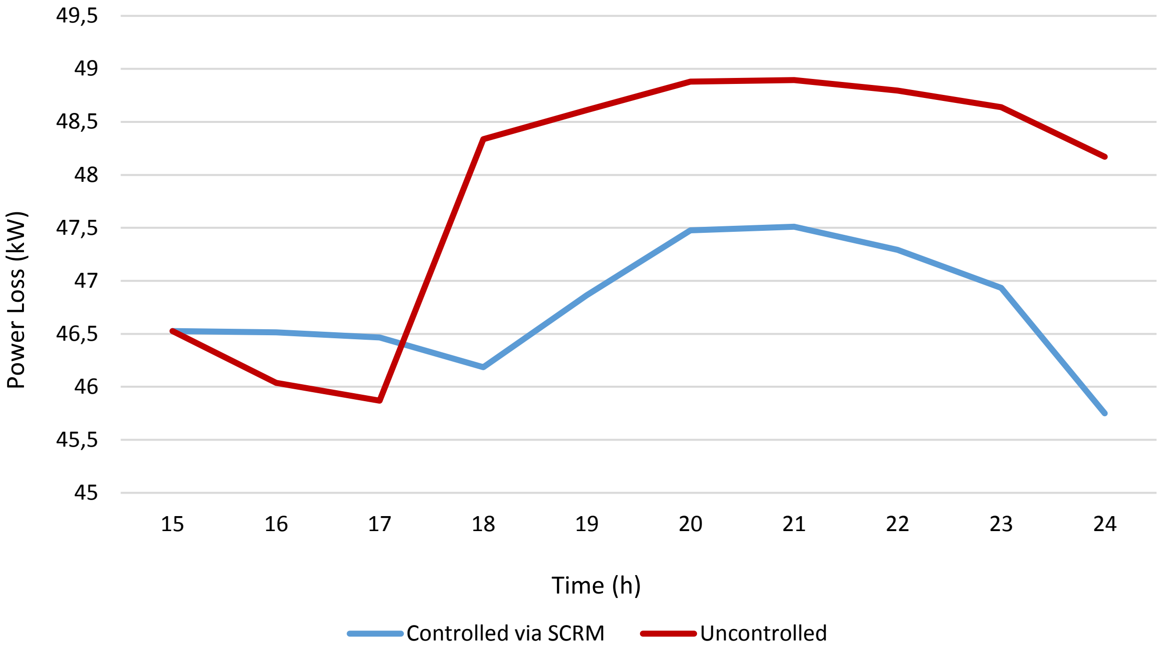


Figure 6.9: Power loss comparison of the distribution network with controlled and uncontrolled charging for a typical summer work day (Scenario A1)

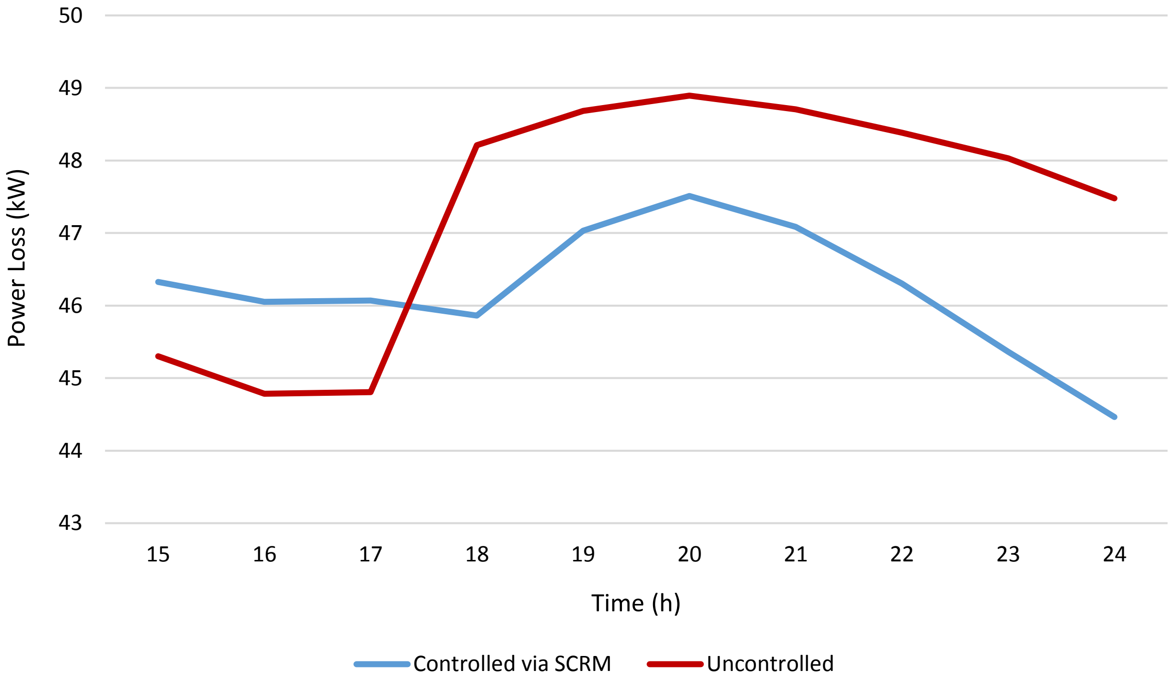


Figure 6.10: Power loss comparison of the distribution network with controlled and uncontrolled charging for a typical winter work day (Scenario A1)

After controlling and managing the EVs charging procedure, it can be seen in both cases that an impressive peak of about 3.4 MW could be avoided applying the SCRM system in the simulated distribution network. This means that the system could be operated without additional grid expansion costs using available infrastructures. Furthermore comparing the Figure 6.7 with Figure 6.1 as well as Figure 6.8 with Figure 6.2, the maximum demand of the system is not exceeded and the load curve peak remains the same as before using EVs, which is realizing one the aims of the proposed SCRM system. It can also be seen in Figure 6.9 and Figure 6.10 that the maximum loss of the system decreases after applying the SCRM system for a typical summer and winter work day. In addition to this, the voltage of the system remains within the expected limits (0.9 pu and 1.1 pu [1]) as another objective of the proposed system. The voltage magnitude of bus number 15, which has the lowest voltage compared to other buses of the system can be observed in Figures 6.11 and 6.12 for the summer and winter work month, respectively. Applying the SCRM system the voltage remains almost constant and the significant voltage drop which would have been occurred due to uncontrolled charging of the EVs is avoided. A set of data related to the hourly voltage magnitude of all buses of the 31-bus test system in a summer and winter work day in two controlled and uncontrolled mode for scenario A1 is available in Appendix C.

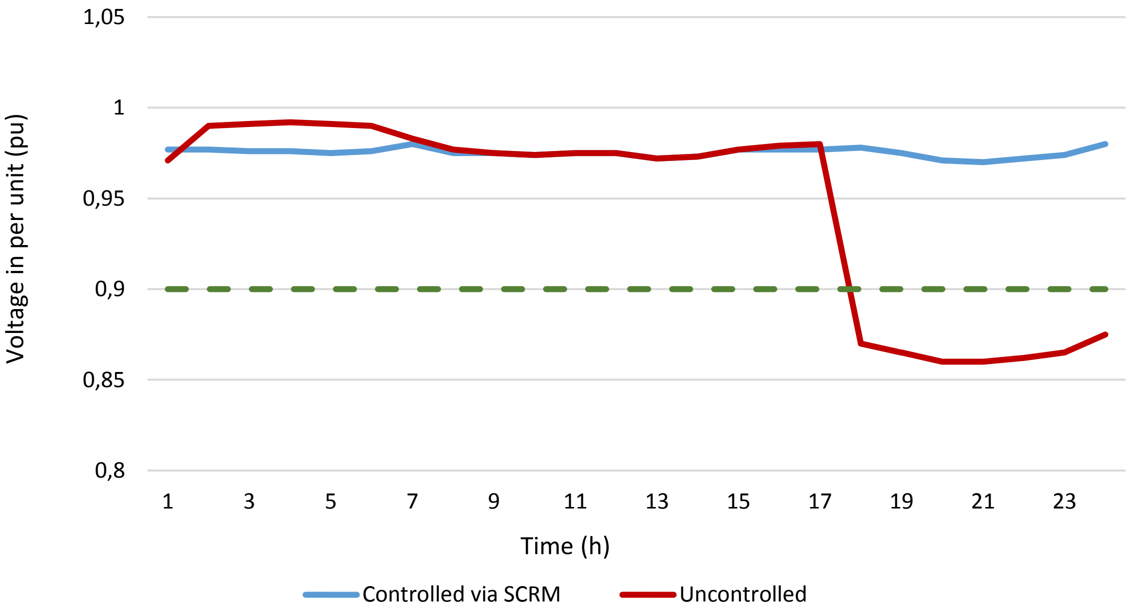


Figure 6.11: Voltage deviation comparison of bus no.15 of the distribution network with controlled and uncontrolled charging for a typical summer work day (Scenario A1)

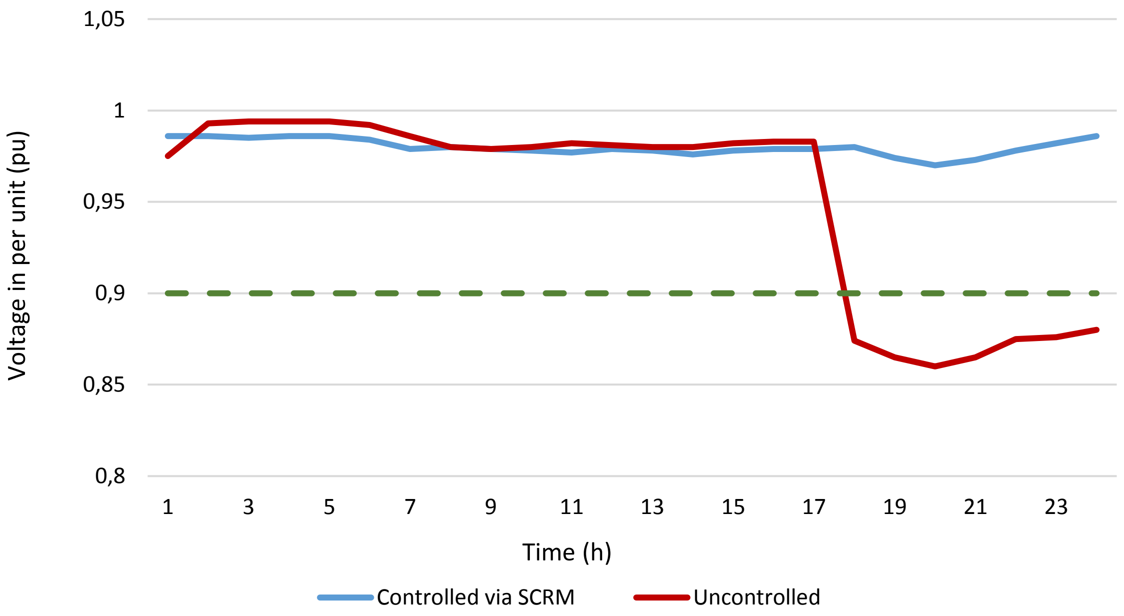


Figure 6.12: Voltage deviation comparison of bus no.15 of the distribution network with controlled and uncontrolled charging for a typical winter work day (Scenario A1)

The value of system peak in Figure 6.6 will be high, assuming the whole German distribution system in 2030 due to scenario A1. A possible peak increase of about 5.2 GW will be inevitable in a typical summer work day as shown in Figure 6.13.

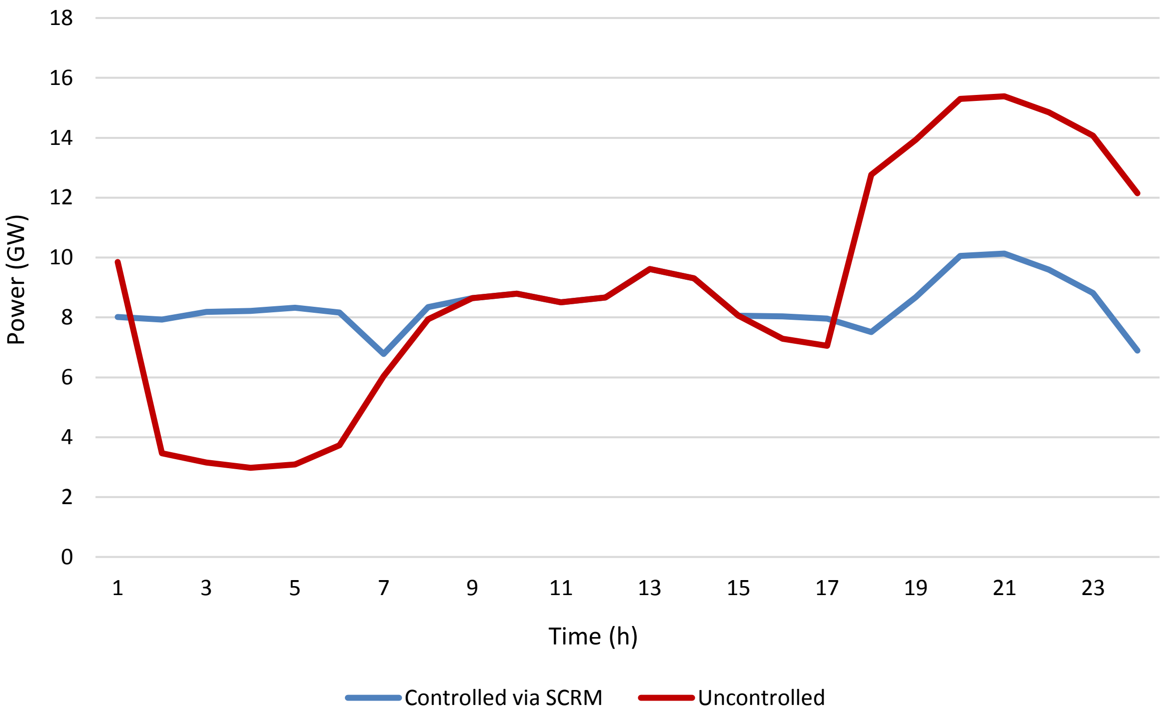


Figure 6.13: Possible load curve comparison of Germany in 2030 assuming of 6.3 million smart homes with controlled and uncontrolled charging of 6 million EVs for a typical summer work day (A1)

The same happens in winter due to Figure 6.14, where a possible peak increase has been avoided, applying the proposed SCRM system. Furthermore, according to the equations (5.15) and (5.16), the calculated LoLE and LoLP system security indices are changing from 7 to 0 and from 0.29 to 0, respectively. This indicates that the system is able to provide the requested energy in both typical summer and winter work days in Scenario A1, using the SCRM system.

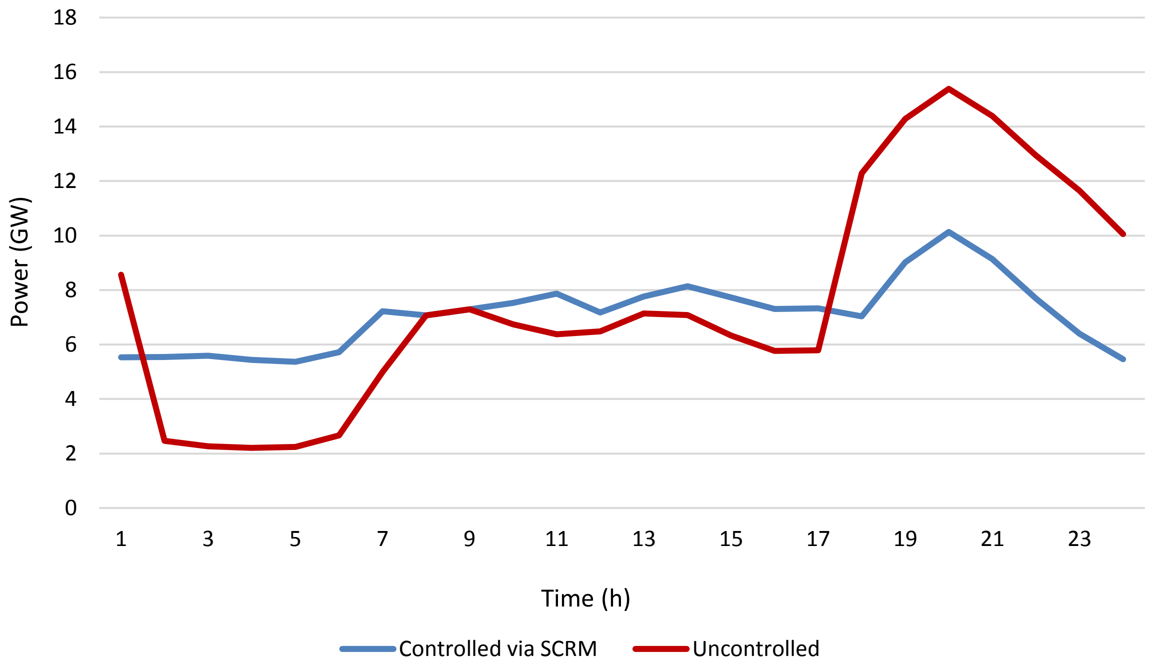


Figure 6.14: Possible load curve comparison of Germany in 2030 assuming of 6.3 million smart homes with controlled and uncontrolled charging of 6 million EVs for a typical winter work day (A1)

So far, the grid operational benefits were presented in the previous figures. The economic benefit of this managing method in the simulated distribution network for a summer and winter month is shown in Figure 6.15.

There will be a charging cost saving of about €2500 in the simulated distribution system in this summer month and €2800 in this winter month. Considering the amount of available EVs in 2030, regarding scenario A1, there could be a possible saving of up to €11.6 million for 6 million EVs in Germany in a typical summer work month and similar €13.7 million saving in a typical winter work month (See Figure 6.16).

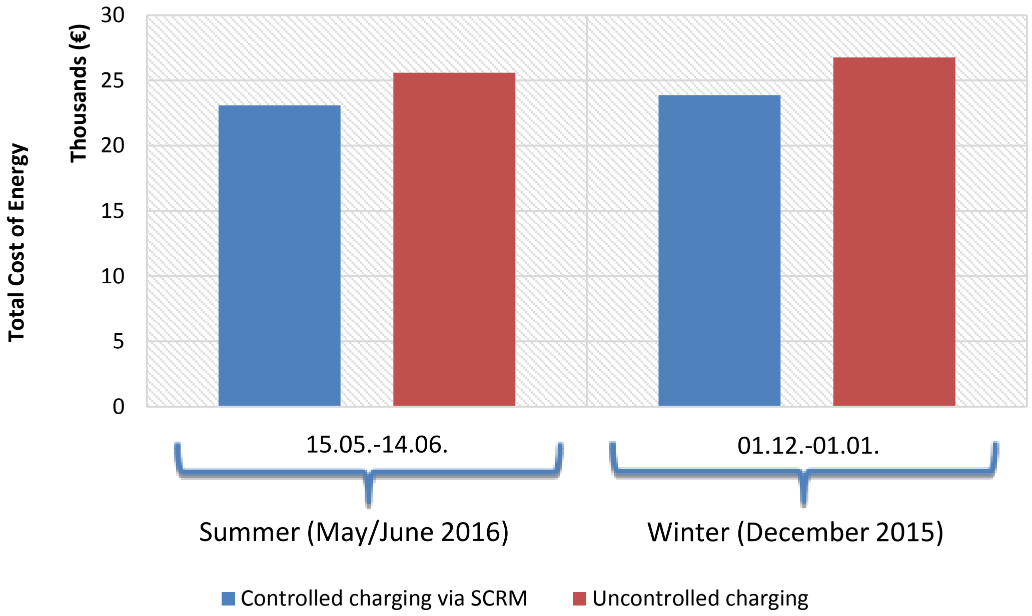


Figure 6.15: Comparison of the total cost of energy of the distribution network from 15th of May to 14th of June and during December applying SCRM (Scenario A1)

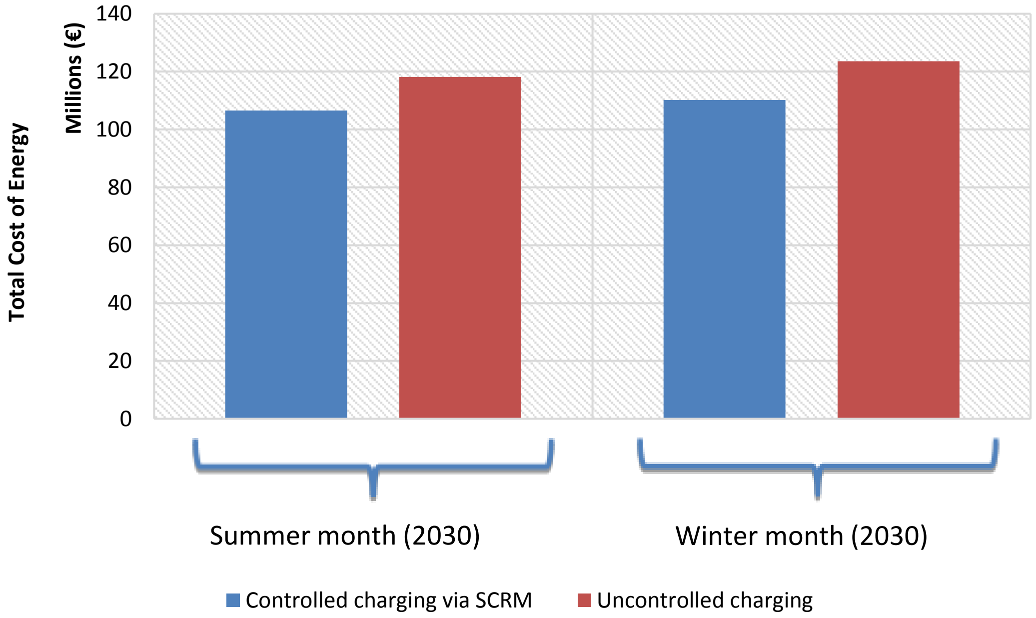


Figure 6.16: Possible savings in the total cost of energy in a typical summer month in 2030 and winter month in 2030, applying SCRM for 6.3 million smart homes and 6 million EVs (Scenario A1)

6.5 Energy request of the EVs for scenario A2

The requested amount of energy of the EVs in one node of the simulated distribution system for a typical summer work day for scenario A2 is presented in Table 6.5. Regarding the proportion between EV and smart homes in scenario A2, 44% of the homes have an electric vehicle. Compared to Table 6.1 of scenario A1, a lower amount of EVs is requesting energy. The same summer month as in scenario A1 is presented in the detailed results.

Due to the SCRM first step results, around 26% of the EVs are requesting 12kWh energy, likewise 26% need 4kWh of energy and 48% request 8 kWh of energy mostly in the flexible charging priority level. Regarding Table 6.6, 13% of the EVs request 12kWh charging energy, most of them (74%) needs 8 kWh and 13% of the EVs ask for 4 kWh energy in the same winter month as in scenario A1.

Table 6.5: Requested energy by the EVs of one node of the distribution network resulting from the SCRM system for a typical summer work day (Scenario A2)

Smart home no.	*EV energy request of 4 kWh*	*EV energy request of 8 kWh*	*EV energy request of 12 kWh*
1	0	0	**2**
4	0	0	**2**
6	0	0	**2**
10	0	0	**2**
12	0	0	**2**
18	0	0	**2**
21	0	**2**	0
24	0	**2**	0
26	0	**2**	0
28	0	**2**	0
29	0	**2**	0
31	0	**2**	0
33	0	**2**	0
35	**3**	0	0
37	**2**	0	0
38	**2**	0	0
40	**2**	0	0
41	**2**	0	0
42	**2**	0	0
43	0	**2**	0
46	0	**2**	0
49	0	**2**	0
52	0	**1**	0

Table 6.6: Requested energy by the EVs of one node of the distribution network resulting from the SCRM system for a typical winter work day (Scenario A2)

Smart home no.	***EV energy request of 4 kWh***	***EV energy request of 8 kWh***	***EV energy request of 12 kWh***
1	0	**2**	0
2	0	**2**	0
4	0	**2**	0
9	0	**2**	0
10	0	0	**2**
12	0	0	**2**
18	0	0	**2**
20	0	**2**	0
21	0	**2**	0
26	0	**2**	0
28	0	**2**	0
29	0	**3**	0
32	0	**3**	0
35	0	**2**	0
37	0	**2**	0
38	0	**2**	0
40	**2**	0	0
41	**2**	0	0
42	**2**	0	0
43	0	**2**	0
46	0	**2**	0
49	0	**2**	0
52	0	**1**	0

6.6 Results for scenario A2

Like scenario A1, the resulted charging hours regarding the type of energy request of the EVs are shown in Table 6.7. As an example, EV no.4 starts charging at 3 am- 6 am with a flexible charging priority group as requested in Table 6.5. Also, regarding Table 6.8, the EV at smart home no.29 had requested 8 kWh energy with normal charging priority (due to Table 6.6) and is charging for 2 hours from 10 am till 12 am due to the SCRM system results. All the definitions in the Tables 6.3 and 6.4 are also valid for the following tables.

Table 6.7: Resulting charging hours of the EVs of one node of the distribution network for a typical summer work day (Scenario A2)

Bus no. of EV	***flexible 8 charging start hour***	***flexible 4 charging start hour***	***flexible 12 charging start hour***	***normal 4 charging start hour***	***urgent 8 charging start hour***
20	5				
46	2				
26	4				
28	2				
31	4				
49	1				
43	4				
24	3				
29	1				
33	3				
40		6			
37		6			
42		6			
38		6			
41		6			
1			4		
4			3		
18			2		
6			4		
12			2		
10			4		
35				17	
52					7

Table 6.8: Resulting charging hours of the EVs of one node of the distribution network for a typical winter work day (Scenario A2)

Bus no. of EV	***flexible 8 charging start hour***	***flexible 4 charging start hour***	***flexible 12 charging start hour***	***normal 8 charging start hour***	***urgent 12 charging start hour***
1	5				
35	5				
20	2				
2	4				
21	1				
4	4				
37	3				
46	1				
9	3				
26	5				
38	1				
28	3				
49	5				
43	1				
40		6			
42		6			
41		3			
18			4		
12			3		
10			2		
32				11	
29				10	
52					16

An uncontrolled charging of the EVs could also cause a huge peak demand of almost 3 MW to the grid as shown in Figure 6.17 and 6.18 in a typical summer and winter work day respectively. After managing the charging process of the EVs, there will be a remarkable peak reduction, valley filling and load shifting which is demonstrated in Figure 6.19 and 6.20.

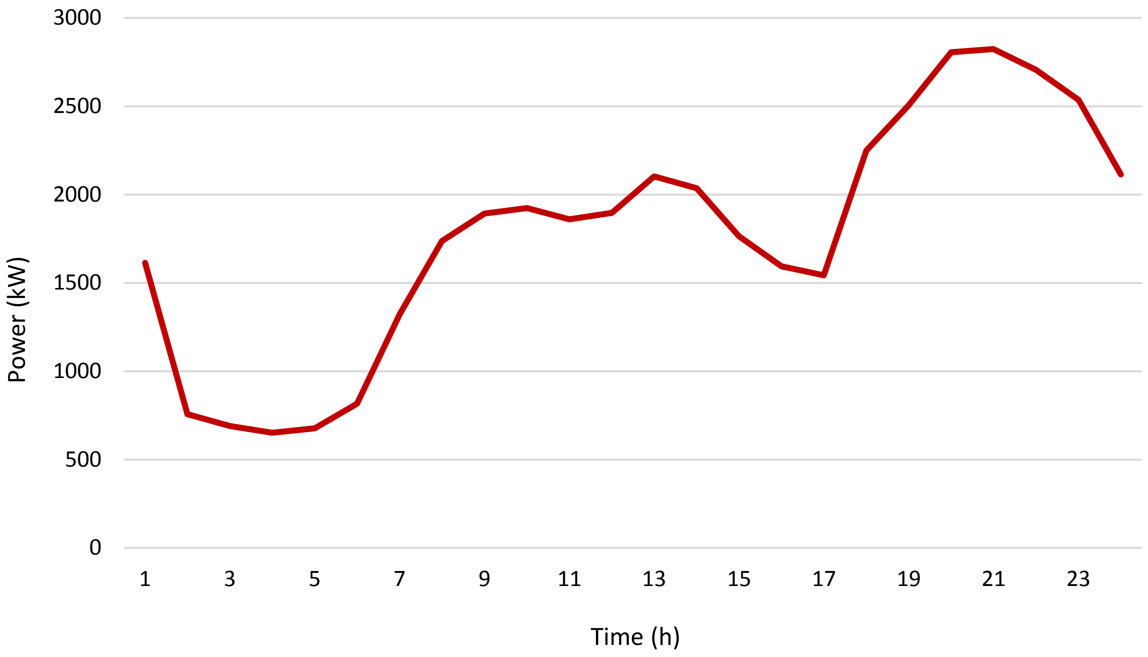


Figure 6.17: Load curve of the system at uncontrolled charging of the EVs of the distribution network in a typical summer work day (Scenario A2)

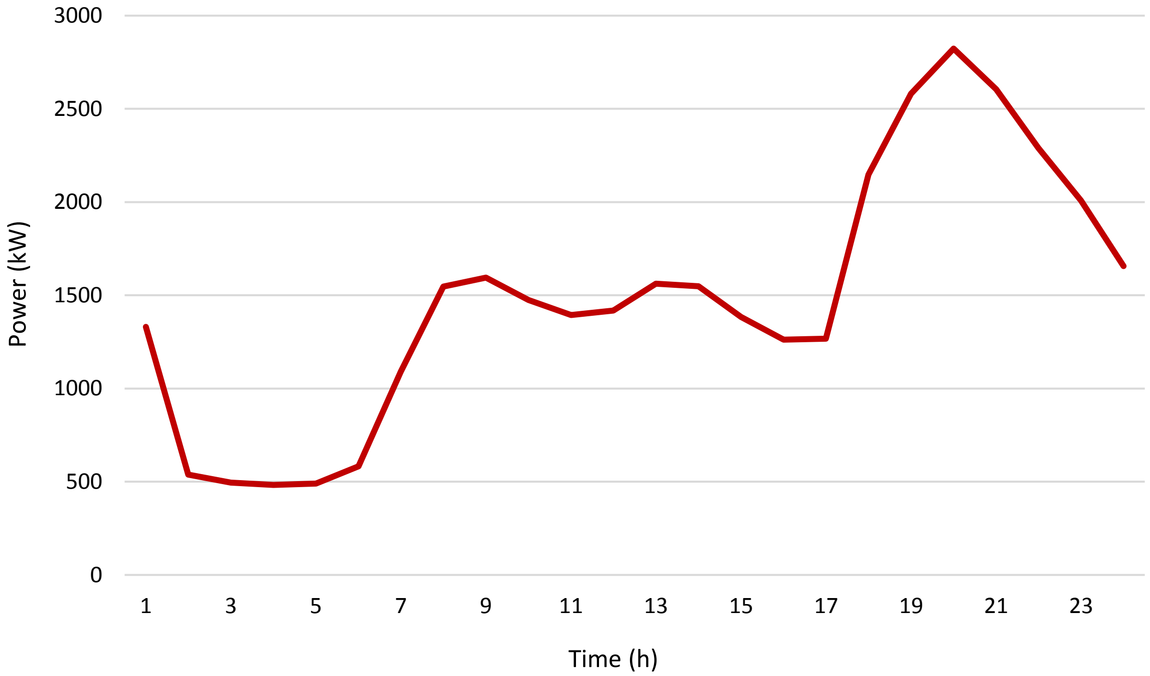


Figure 6.18: Load curve of the system at uncontrolled charging of the EVs of the distribution network in a typical winter work day (Scenario A2)

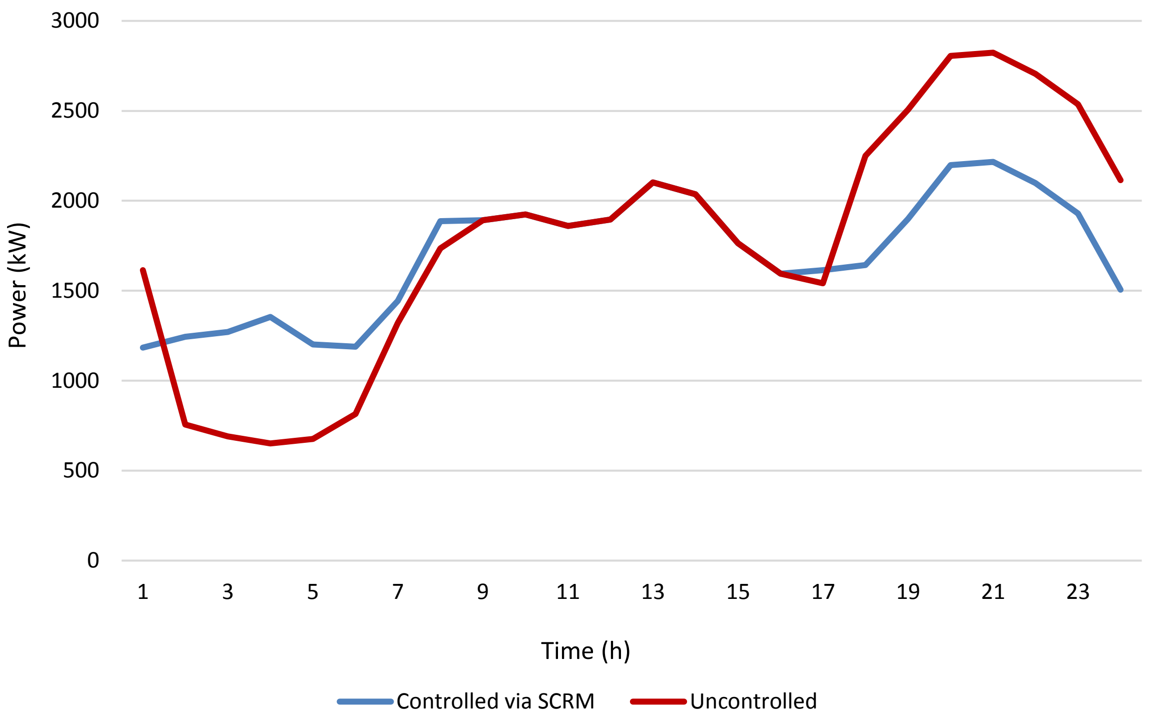


Figure 6.19: Load curve comparison of the system with controlled and uncontrolled charging of the distribution network for a typical summer work day (Scenario A2)

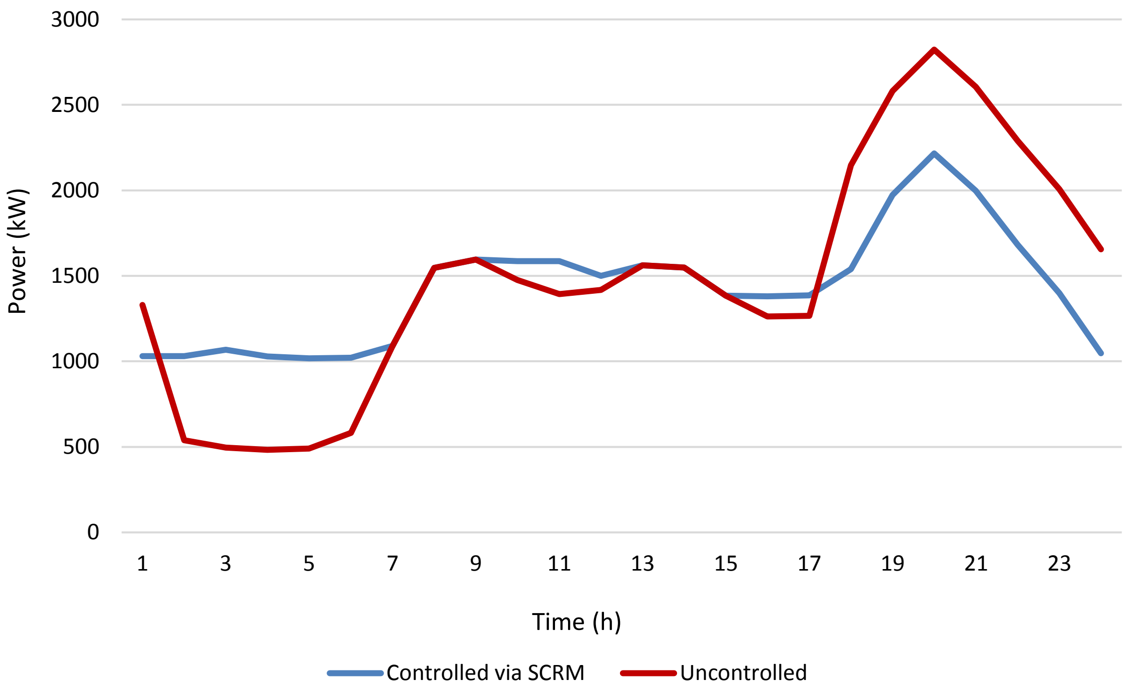


Figure 6.20: Load curve comparison of the system with controlled and uncontrolled charging of the distribution network for a typical winter work day (Scenario A2)

There is also a maximum loss reduction after applying the SCRM system for scenario A2 as it is shown in Figure 6.21 and 6.22 for a typical summer and winter work day separately.

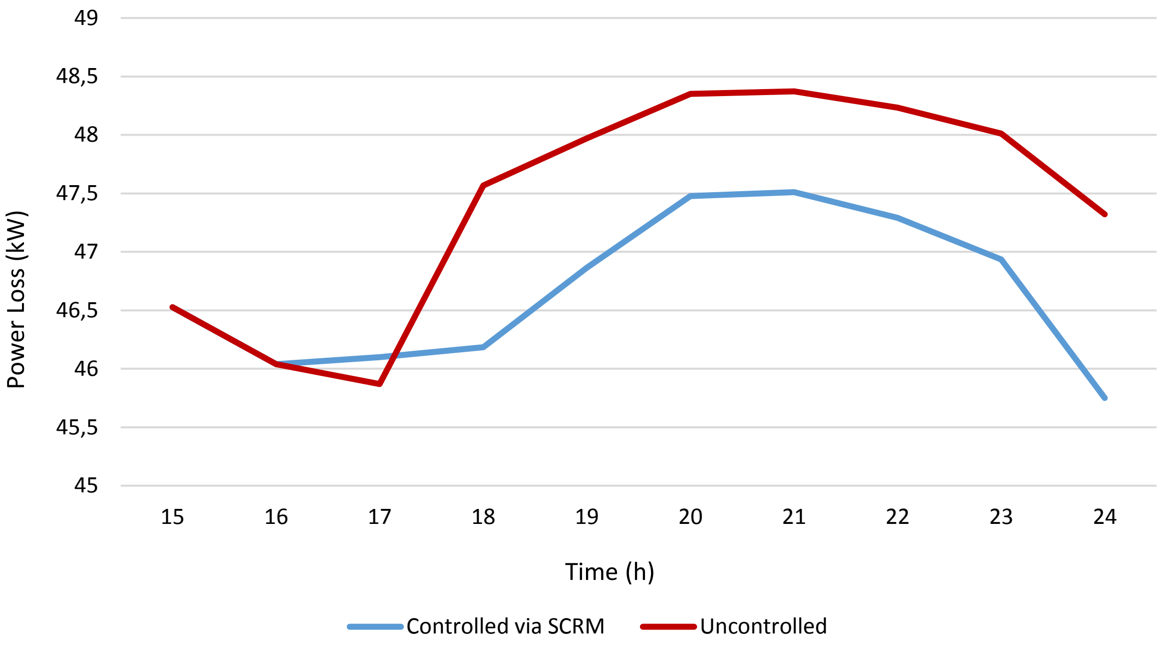


Figure 6.21: Power loss comparison of the distribution network with controlled and uncontrolled charging for a typical summer work day (Scenario A2)

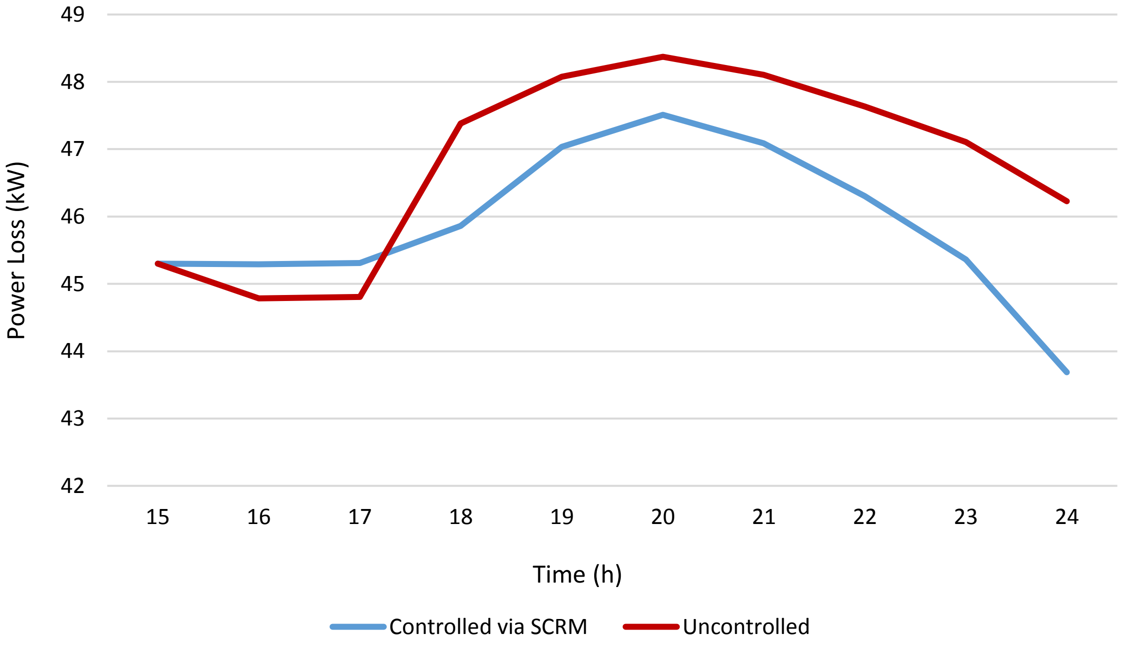


Figure 6.22: Power loss comparison of the distribution network with controlled and uncontrolled charging for a typical winter work day (Scenario A2)

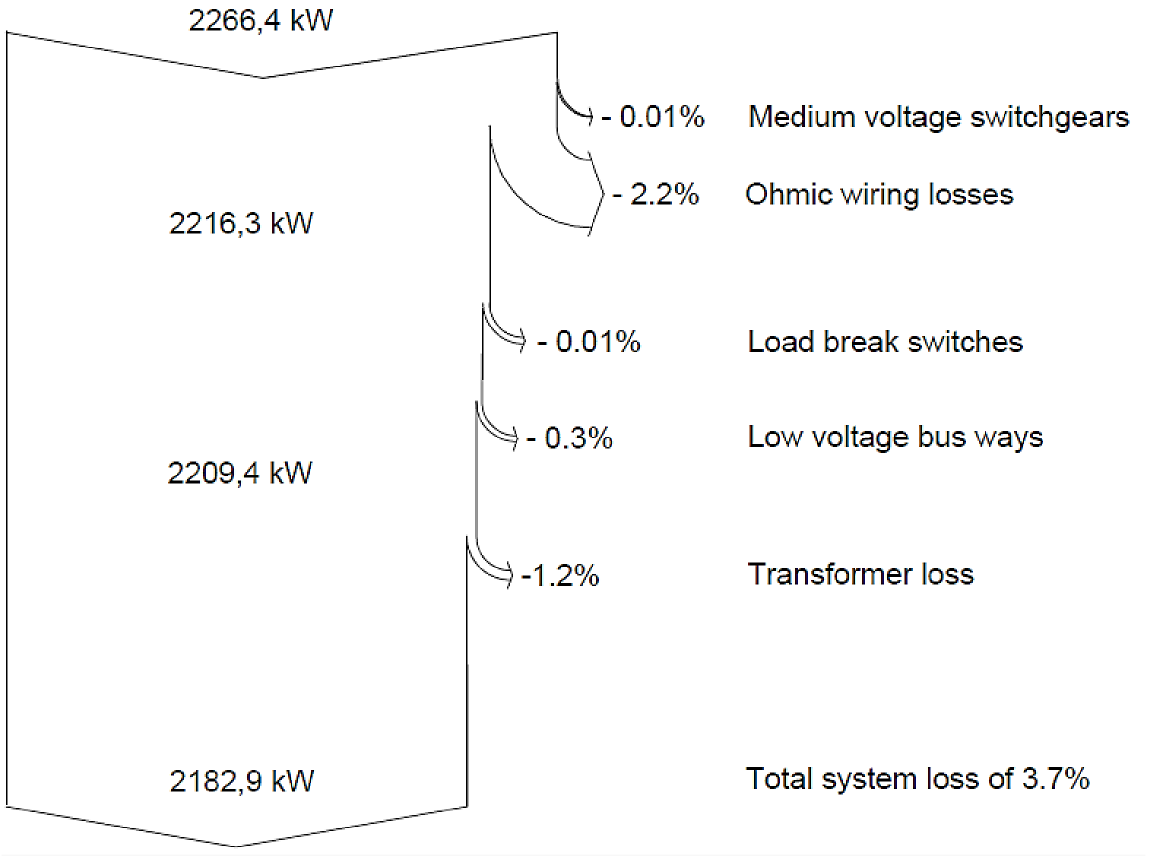


Figure 6.23: Sankey diagram of the total loss of the distribution network at maximum load

The transformer loss of the distribution network was not included in the displayed diagrams in the Figures 6.9, 6.10 and likewise the Figures 6.21 and 6.22. As it can be seen in Figure 6.23, a Sankey diagram is presented for the whole losses of the distribution network at the maximum load of the load curve at controlled charging. Considering an average transformer loss of about 1.2%, and other losses of about 0.32% [109], leads to a total system loss of about 3.7%.

Same as in scenario A1, by applying the SCRM system in scenario A2, the voltage magnitude remains within the desired limits and a high voltage drop has been avoided in both summer and winter work days (Figures 6.24 and 6.25).

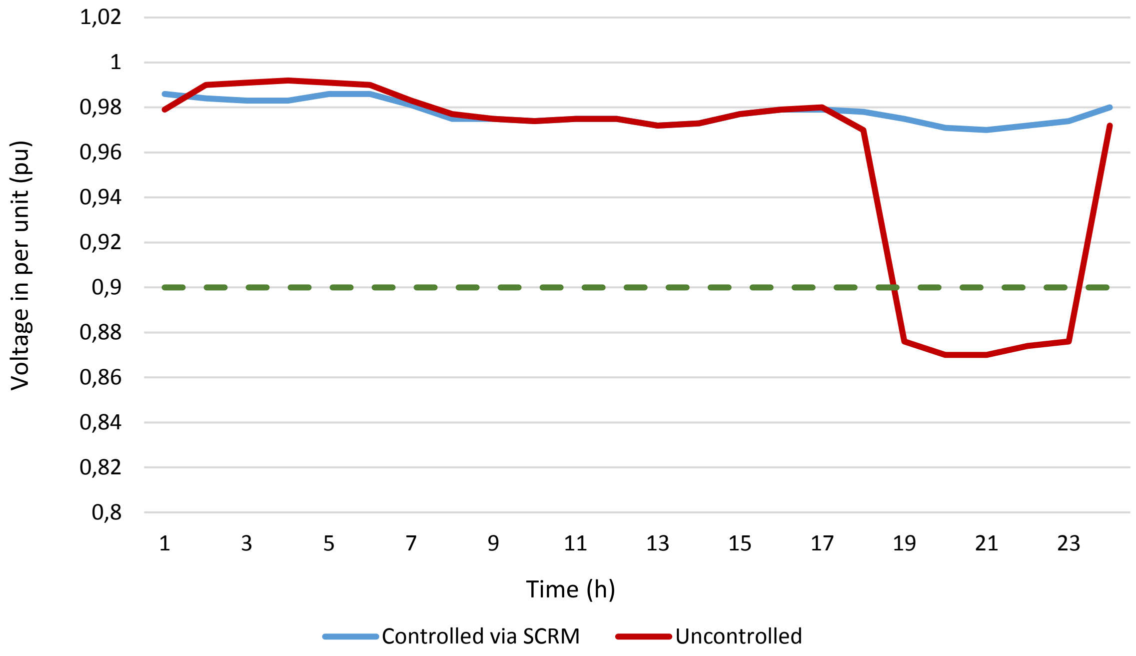


Figure 6.24: Voltage deviation comparison of bus no.15 of the distribution network with controlled and uncontrolled charging for a typical summer work day (Scenario A2)

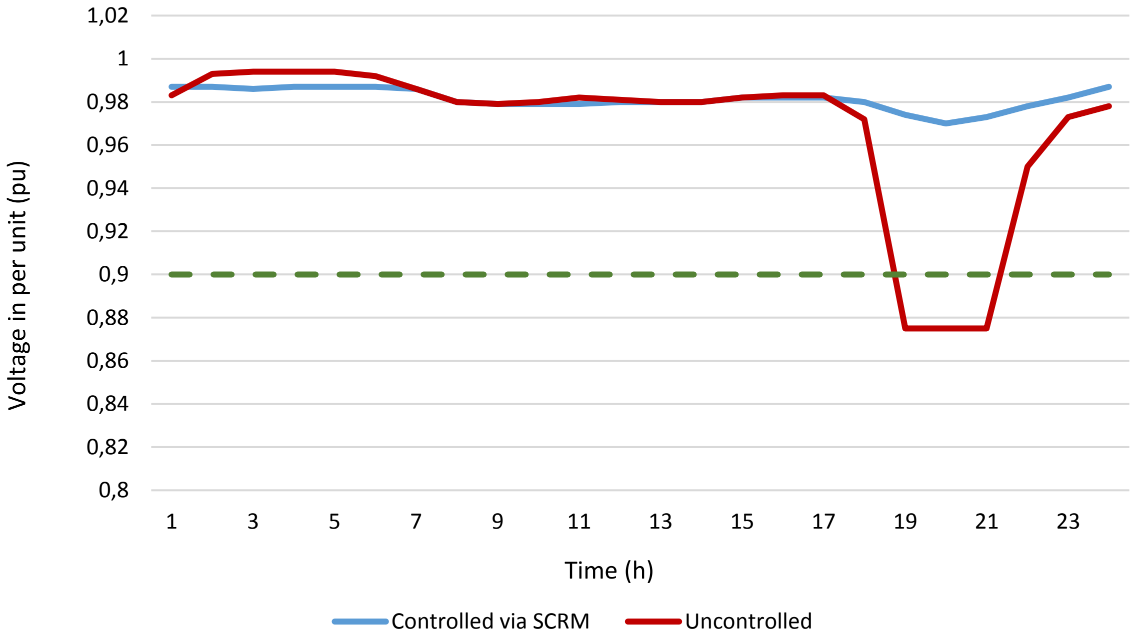


Figure 6.25: Voltage deviation comparison of bus no.15 of the distribution network with controlled and uncontrolled charging for a typical winter work day (Scenario A2)

Likewise to the previous part, there will be a possible peak increase of about 2.8 GW in Germany 2030, in a typical summer work day, as demonstrated in Figure 6.26. The same happens in winter due to Figure 6.27, where a possible peak increase has been avoided applying the proposed SCRM system. It can be concluded from these figures that also in this case, a noticeable peak reduction, valley filling and load shifting will lead to a more economical and cost-efficient car usage and system operation applying the proposed SCRM system. Similar to Scenario A1, the calculated LoLE and LoLP, become 0 in both typical summer and winter work days, thanks to the SCRM system.

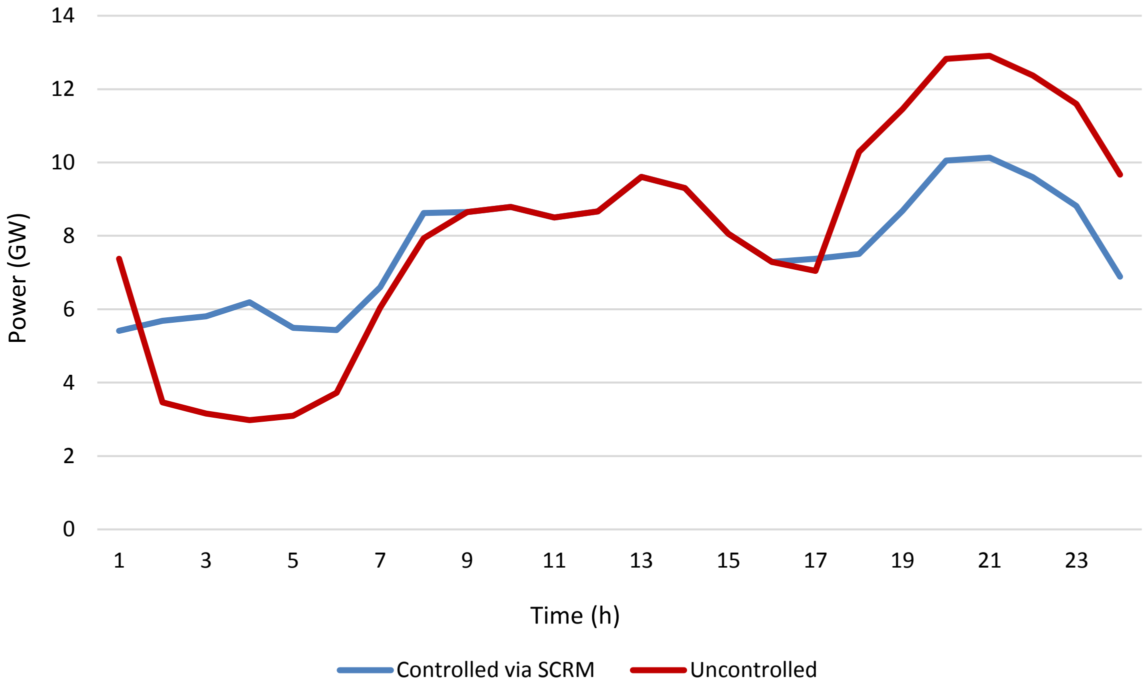


Figure 6.26: Possible load curve comparison of Germany in 2030 assuming of 6.3 million smart homes with controlled and uncontrolled charging of 2.8 million EVs for a typical summer work day (A2)

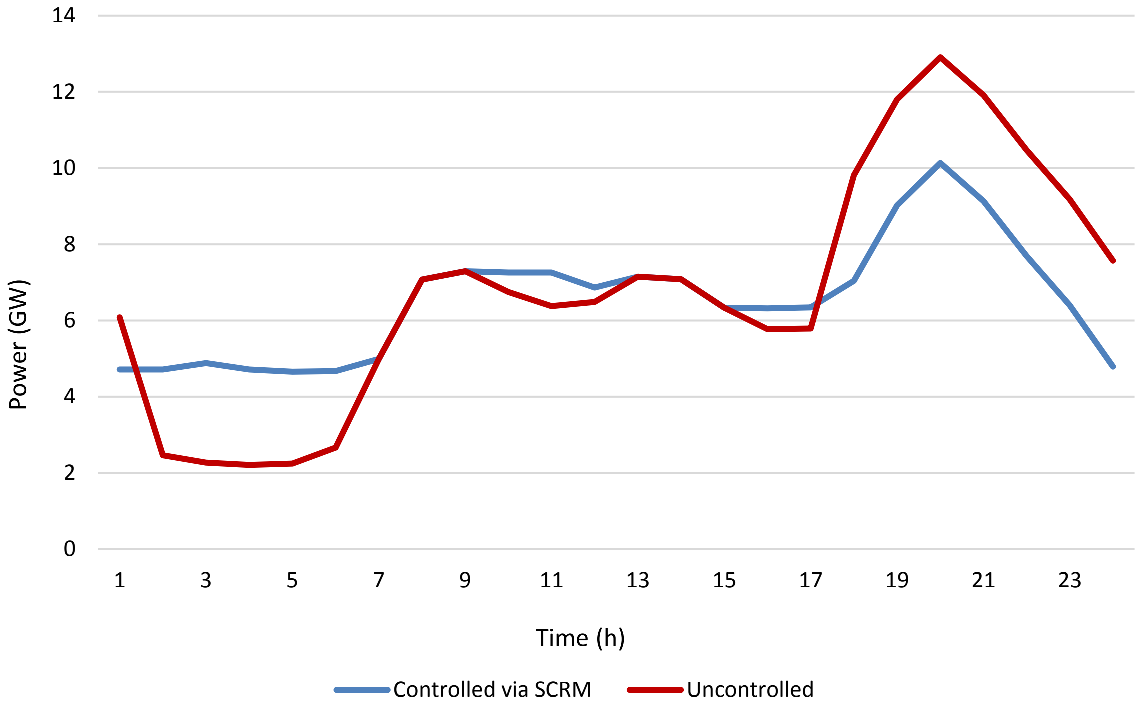


Figure 6.27: Possible load curve comparison of Germany in 2030 assuming of 6.3 million smart homes with controlled and uncontrolled charging of 2.8 million EVs for a typical winter work day (A2)

Same as in scenario A1, there will be a charging cost saving of about €1500 in the simulated distribution system for this month in summer. This amount of savings will be equal to about €1700 in the winter month. Considering 2.8 million EVs in 2030 regarding scenario A2, there could be a possible saving of up to €6.9 million and about €8 million for these EVs in Germany, respectively for a typical summer and winter work month (See Figures 6.28 and 6.29).

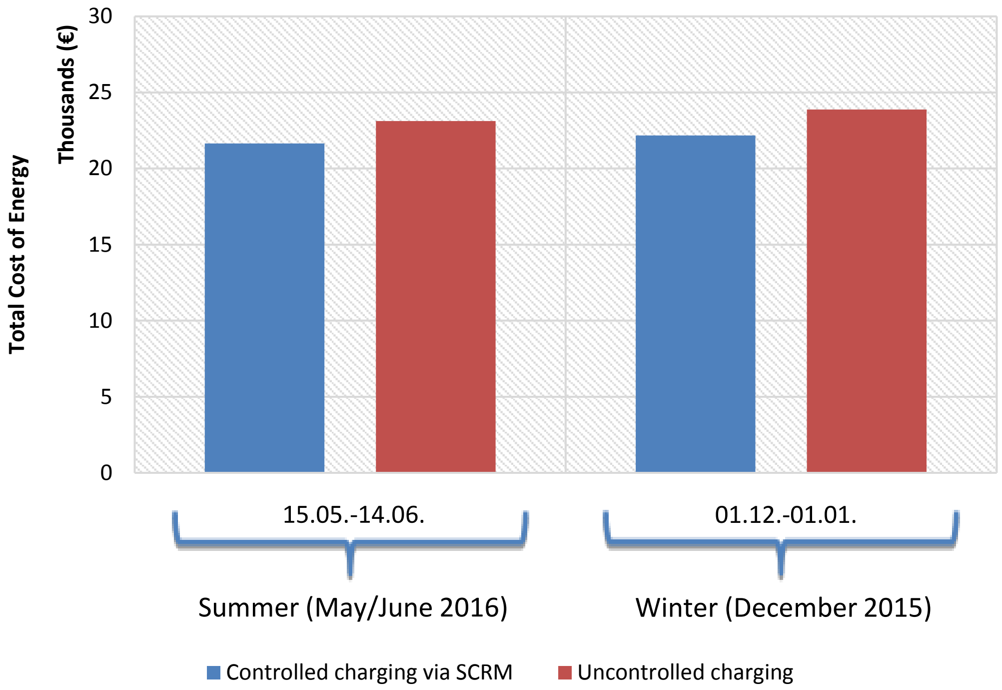


Figure 6.28: Comparison of the total cost of energy of the distribution network from 15th of May to 14th of June and during December applying SCRM (Scenario A2)

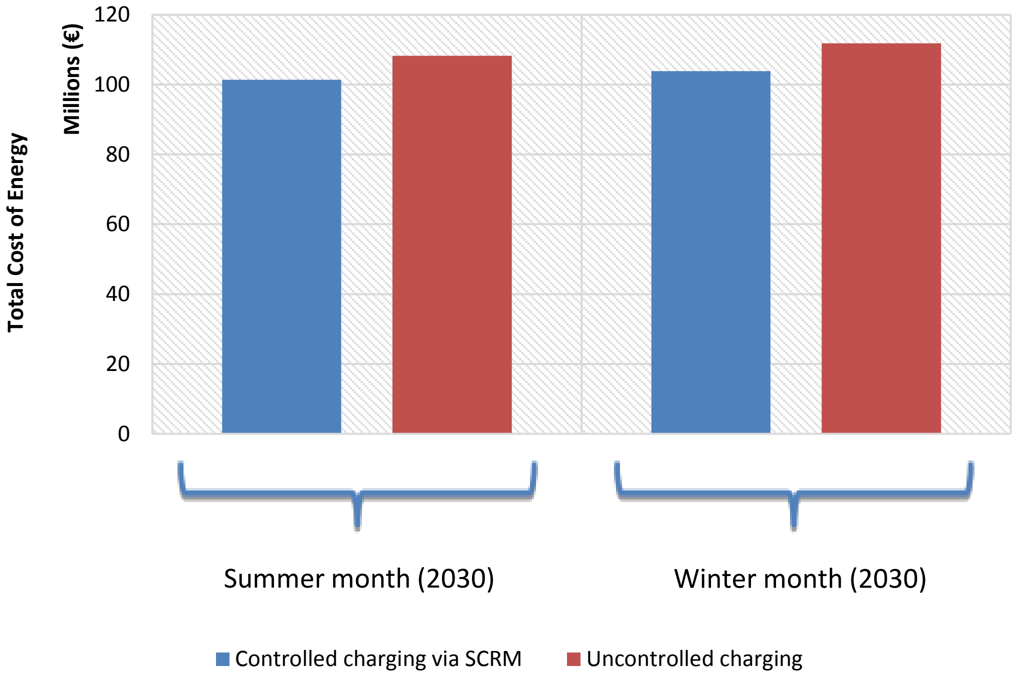
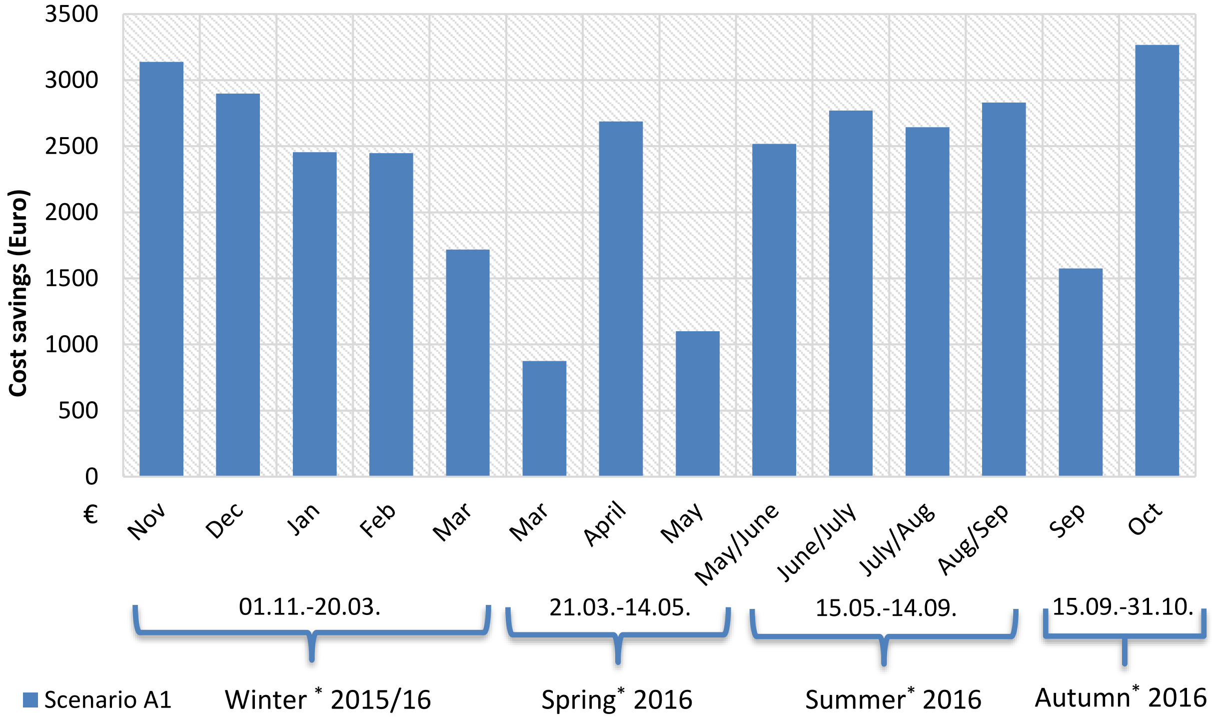


Figure 6.29: Possible savings in the total cost of energy in a typical summer month in 2030 and winter month in 2030, applying SCRM for 6.3 million smart homes and 2.8 million EVs (Scenario A2)

6.7 Results over the year for scenario A1 and A2

As it was mentioned before, just for one month in summer and one month in winter, results were presented in detail. In fact, the simulation has been run for every month of the year, in the same way. The savings in the total cost of energy will be presented for the whole year in Figures 6.30 and 6.31 for scenario A1 and A2, respectively. As mentioned before, the load curve for every month is adapted to the H0 Standard load profiles based on [118]. Due to this standard and the consuming patterns in Germany, the definition of season periods, differs from the astronomical and meteorological definition and are classified regarding their specific energy consumption profiles as follows: winter is from 01.11 to 20.03, summer is from 15.05 to 14.09, spring begins from 21.03 to 14.05 and autumn starts from 15.09 to 31.10. As observed in Figure 6.26, and due to the above definitions, for example the first half of September is categorized as summer and the other half as autumn. Likewise the days of March and May are spread between two different season.



* The season periods are defined due to the H0 standard regarding their specific consumption pattern

Figure 6.30: Savings of the total cost of energy in 2015/2016 in simulated distribution grid applying SCRM system (Scenario A1)

Now, some supplementary information on the cost saving difference of the seasons is presented:

- Summer 2016:

It can be observed, the highest savings in summer occurs during August/September. The reason is that we have more work days in this month (23 working days) compared to the others.

- Winter 2015/2016:

It is obvious that the highest savings in winter occurs during November. The reason is the higher difference between the minimum and maximum energy prices compared to other months. Furthermore, there are more hours available with reduced energy prices so that more EVs could be charged in the flexible charging priority group.

- Spring 2016:

It is good to mention that the big difference in April is because of the great number of work days. Due to the standard of energy months in Germany, just the last ten days of March will be assumed as spring and so, the first fifteen days of May.

- Autumn 2016:

Due to the energy cost savings in autumn 2016, the difference is like spring, because of the uneven number of work days in each month.

Likewise, the savings regarding scenario A2, are presented in Figure 6.31.

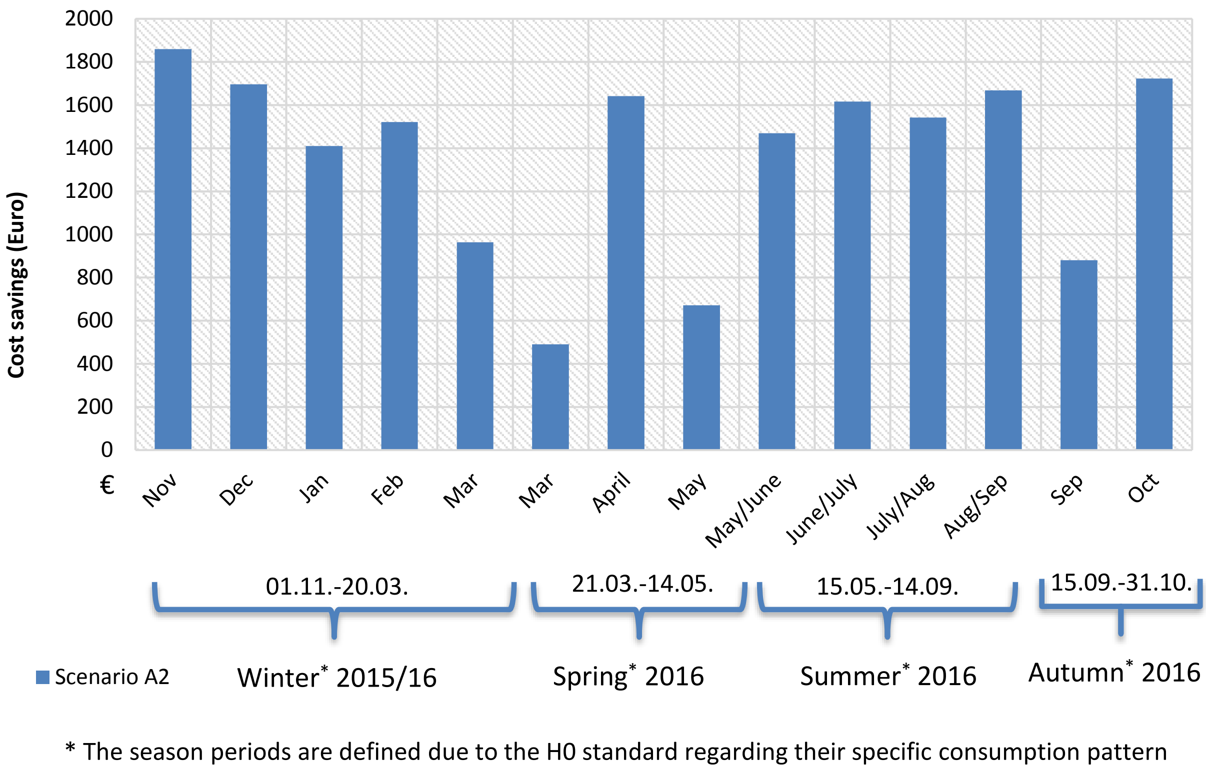


Figure 6.31: Savings of the total cost of energy in 2015/2016 in simulated distribution grid applying SCRM system (Scenario A2)

6.7.1 Possible energy cost savings in Germany 2030

Applying the proposed SCRM system from this research, there could be higher consumed energy cost savings for Germany in the year 2030. As it was mentioned before, 6 million EVs are expected in 2030 for scenario A1 and 2.8 million EVs for scenario A2. If this great number of EVs would start to charge uncontrolled, the German's power system would face serious operational problems. Figure 6.32 and Figure 6.33 shows the possible energy cost savings in Germany for any season and two simulated scenarios, just by coordinated charging of the EVs. As mentioned before, the season periods are defined according to the H0 standard regarding their specific consumption patterns.

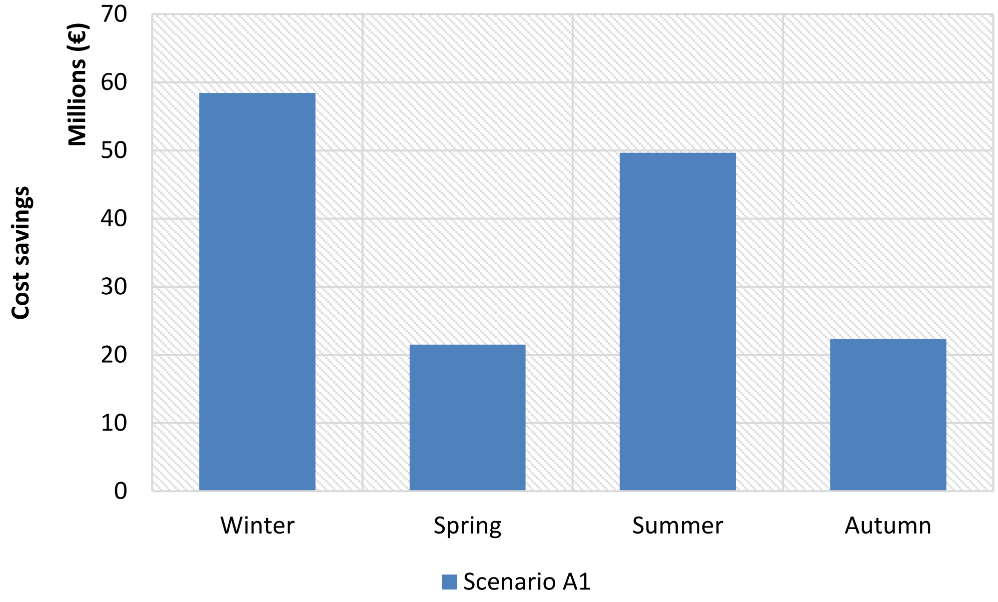


Figure 6.32: Possible savings in the total cost of consumed energy by the EVs in Germany 2030 for 6.3 million smart homes and 6 million EVs, applying SCRM (Scenario A1)

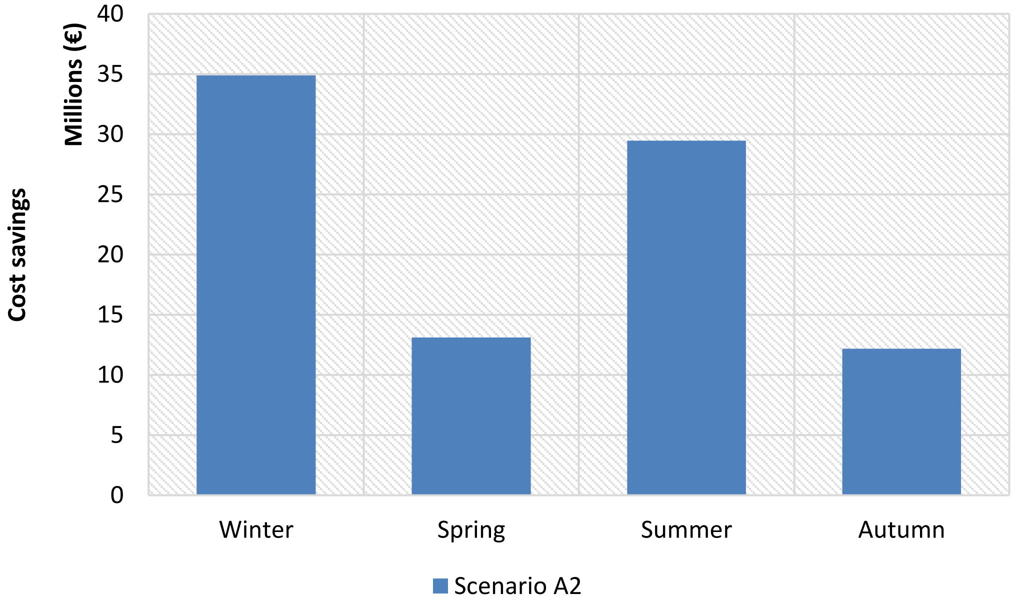


Figure 6.33: Possible savings in the total cost of consumed energy by the EVs in Germany 2030 for 6.3 million smart homes and 2.8 million EVs, applying SCRM (Scenario A2)

As it can be seen a saving up to €60 million could occur during winter for scenario A1. The reason that the highest savings will be in winter is the higher number of work days during this season compared to the others. There will be a total possible energy cost savings of up to €152 million annually in Germany 2030 as it is shown in Figure 6.34, which is a promising result.

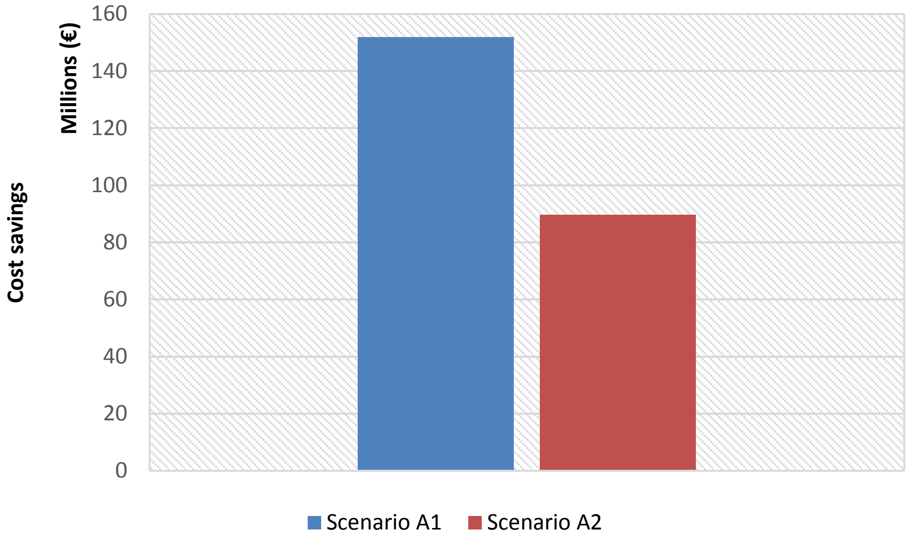


Figure 6.34: Possible annual savings in the cost of consumed energy by the EVs in Germany 2030 for 6 and 2.8 million EVs respectively applying SCRM system

6.8 Power regulation services by the EVs

As discussed in section 5, the SCRM system decides whether an EV offers a regulation services or not, due to the decision mechanism flowchart in Figure 5.9. If a failure happens in the distribution network, the SCRM system could define the amount of available regulation service, by mean of the transmitted input signals through the aggregator and EV owners. To show the EVs performance, while needing regulation power, an outage of about 4.8 MW of wind power at 22 pm, is assumed in the simulated distribution grid as a study case. As it can be observed in Figure 6.35, only 0.4 MW of the regulating power could be offered, due to the SCRM system considering the regulation signal as an input, in a typical summer work day, which is equal to 500 EVs considering 20% of DoD as discussed in section 3. This means, that not all the EVs could help to cover this fault and the activation of other regulation services, will be inevitable in this case to overcome the problem and maintaining the grid balance while bringing back the network frequency to its nominal value (in this case 50 Hz). In extremely critical grid operation situation, the EVs could also being disconnected from the grid as a load shedding action.

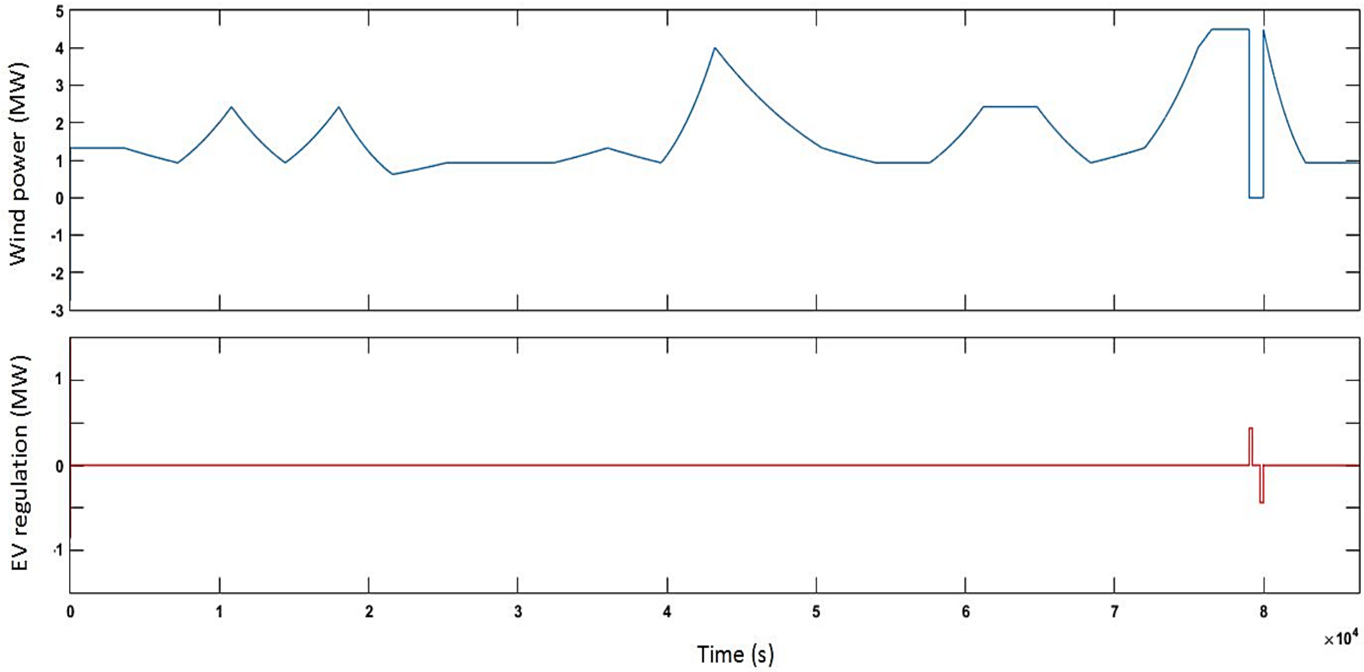


Figure 6.35: Offered regulation service of 500 EVs in the distribution network for a typical summer work day applying SCRM system

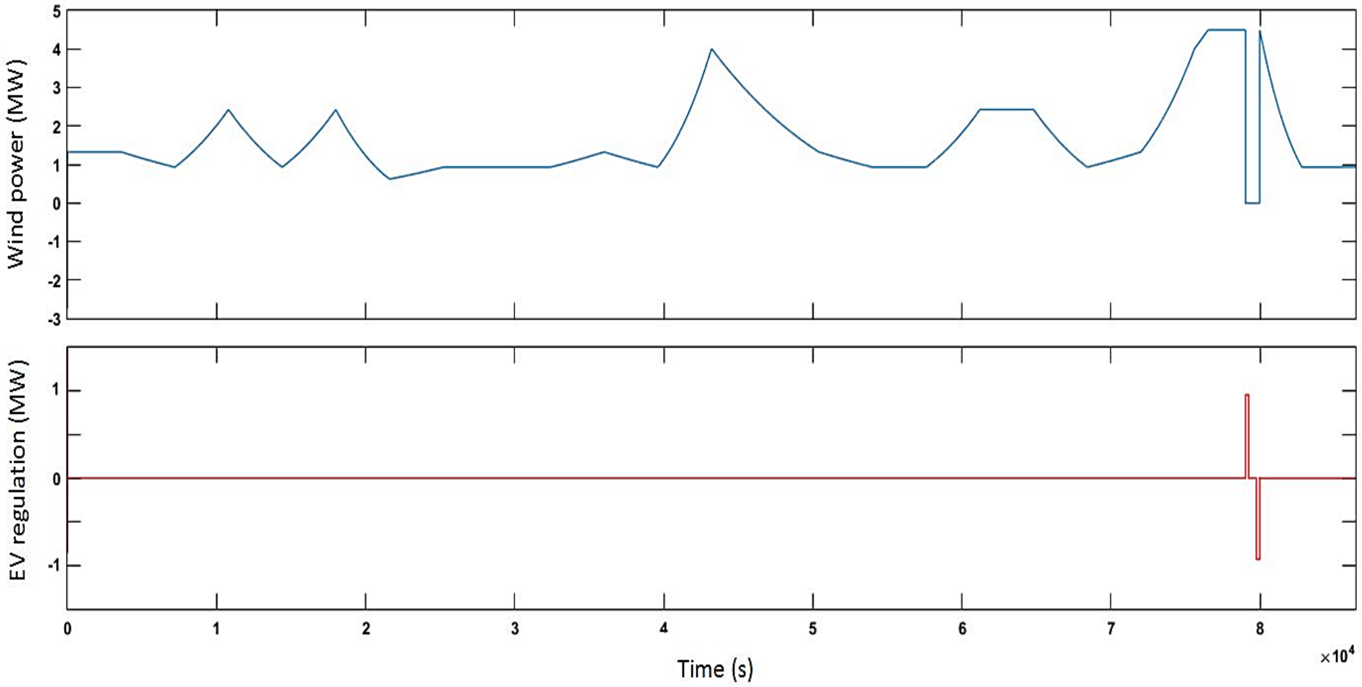


Figure 6.36: Offered regulation service of 1200 EVs in the distribution network for a typical winter work day applying SCRM system

The simulation results show more regulation power, in winter. It can be seen in Figure 6.36, that about 1 MW (1200 EVs) of the 4.8 MW power outage, could be covered by the connected EVs. A fleet of 6000 EVs would be needed to handle this amount of outage without the need of additional technologies. Therefore, due to the results of the SCRM system considering the regulation market status signal and the SoC and availability of the EVs, higher regulation power could be offered in winter compared to summer.

6.8.1 Economic calculation

The calculation of the related costs and gained profits, through participating in the described regulation-markets in section 3, has a high influence on the suitable regulation-market for the EVs. There are infrastructure costs, including charging and bidirectional connection equipment, and an estimation of the EVs' battery costs, because of their fast-developing technology [70]. These costs, contain degradation costs of the batteries related to their DoD, as discussed in section 3. Assuming a specific investment cost of 250 €/kWh for the batteries in 2030 and 20 % DoD (as discussed in section 3), a battery degradation cost of about 0.04 €/kWh can be concluded from Figure 3.9. In addition, an infrastructure cost of about 500 € can be considered, during the depreciation time of vehicle investment, which is equal to six years in Germany (85 €/a) [70]. Although this cost could be neglected, assuming a longer lifetime of the battery than the vehicle, in the future.

As the tertiary control reserve market is very small, just the participation in the primary and secondary regulation-markets are considered in the following calculation.

- Primary regulation:

There is an average weekly energy price of 2500 €/MW assumed for the positive and negative primary regulation service [16]. As it can be seen in Figures 6.29 and 6.30, a regulation service of about 0.4 MW is offered for both positive and negative reserve in a typical summer work day and the amount of 1 MW in a typical winter work day. It i#ts noticeable, that there is no additional cost for the negative service, as there is no extra infrastructure and battery degradation costs. Thus, the cost and revenues will be calculated as follows:

Positive for a typical summer work day:

$$Cost = (85\ \text{€} \times 500\ \text{EVs}) + \left(0.4\ \text{MWh} \times 40\frac{\text{€}}{\text{MWh}}\right) = 42{,}516\ \text{€/a}$$

$$Revenue = \left(0.4\ \text{MW} \times 2500\frac{\text{€}}{\text{MW}} \times \frac{365}{7}\right) = 52{,}000\ \text{€/a}$$

Negative for a typical summer work day:

$$Cost = 0$$

$$Revenue = \left(0.4\ \text{MW} \times 2500\frac{\text{€}}{\text{MW}} \times \frac{365}{7}\right) = 52{,}000\ \text{€/a}$$

In the same way, there will be a cost of about 102,000 €/a and a revenue of 130,000 €/a for a positive primary regulation service next to zero costs and the same amount of revenue for negative regulation in a typical winter work day. In follow, the calculations show the resulted cost and revenues, for the offered service in the secondary regulation-market, considering an average weekly procurement fee of 1000 €/MW along with an average energy price of 130 €/MWh. The average procurement fee for negative regulation service is lower and about 560 €/MW [16].

- Secondary regulation:

Positive for a typical summer work day:

$$Cost = (85\ \text{€} \times 500\ \text{EVs}) + \left(0.4\ \text{MWh} \times 40\frac{\text{€}}{\text{MWh}}\right) = 42{,}516\ \text{€/a}$$

$$\begin{aligned}Revenue = {} & \left(0.4\ \text{MWh} \times 130\frac{\text{€}}{\text{MWh}}\right) + \left(0.4\ \text{MW} \times 1000\frac{\text{€}}{\text{MW}} \times \frac{365}{7}\right)\\ & = 20{,}852\ \text{€/a}\end{aligned}$$

Negative for a typical summer work day:

$$Cost = 0$$

$$Revenue = \left(0.4\ \text{MWh} \times 130\frac{€}{\text{MWh}}\right) + \left(0.4\ \text{MW} \times 560\frac{€}{\text{MW}} \times \frac{365}{7}\right)$$
$$= 11{,}700\ €/\text{a}$$

Likewise, these calculations will result in a cost of about 102,000 €/a and revenue of 52,000 €/a for positive secondary regulation service in a typical winter work day. There will also be a revenue around 29,000 € annually in the winter.

The results show that offering both negative primary and secondary control reserve will be profitable. The positive primary control reserve is slightly profitable compared to the negative reserve. Although, participating in the positive secondary control market wouldn’t make any sense due to higher costs in comparison to the revenue earned. Generally, ignoring the low DoD of 20%, would change the results, so that all the regulation services would be profitable.

It is also good to mention, that neglecting the infrastructure investment costs in the future because of the fast battery technology development, and lower battery prices, will make also the positive control reserve markets interesting [70].

6.8.2 Regulation for Germany 2030 condition

Related to the previous part, the possible earnings from the offered regulation services, could also be calculated for both scenario A1 and A2 due to Germany 2030 condition. Assuming 6 million EVs for scenario A1 in Germany, and 4.8 GW supply (considering 20% DoD) with a demand of 1.8 TWh reserve energy per year could be calculated as follows:

- Primary regulation:

Positive:

$$Cost = (85\ € \times 6\ \text{million EVs}) + \left(1.8\ \text{TWh} \times 40\frac{€}{\text{MWh}}\right) = 582\ \text{million}\ €/\text{a}$$

$$Revenue = \left(4.8\ \text{GW} \times 2500\frac{€}{\text{MW}} \times \frac{365}{7}\right) = 624\ \text{million}\ €/a$$

Negative:

$$Cost = 0$$

$$Revenue = \left(4.8 \text{ GW} \times 2500 \frac{€}{\text{MW}} \times \frac{365}{7} \right) = 624 \text{ million } €/\text{a}$$

- Secondary regulation:

Positive:

$$Cost = (85\ € \times 6 \text{ million EVs}) + \left(1.8 \text{ TWh} \times 40 \frac{€}{\text{MWh}} \right) = 582 \text{ million } €/\text{a}$$

$$Revenue = \left(1.8 \text{ TWh} \times 130 \frac{€}{\text{MWh}} \right) + \left(4.8 \text{ GW} \times 1000 \frac{€}{\text{MW}} \times \frac{365}{7} \right)$$
$$= 483.6 \text{ million } €/\text{a}$$

Negative:

$$Cost = 0$$

$$Revenue = \left(1.8 \text{ TWh} \times 130 \frac{€}{\text{MWh}} \right) + \left(4.8 \text{ GW} \times 560 \frac{€}{\text{MW}} \times \frac{365}{7} \right)$$
$$= 373.8 \text{ million } €/\text{a}$$

Similarly, the results for scenario A2, assuming 2.8 million EVs, and 2.2 GW supply with an annual demand of around 0.84 TWh reserve energy, will lead to around 272 million €/a costs for positive primary regulation services, and 286 million €/a, income. The same earnings along with zero costs will be resulted in negative primary control service. The costs remain 272 million €/a, for the positive secondary service. There is an income of about 223.6 million €/a, for positive secondary control, and around 173.2 million €/a for negative secondary control service.

It can be concluded from the calculation results, that the primary control reserve market will be profitable for both negative and positive services for Germany 2030. The positive secondary control market seems not to be a suitable option, under current assumptions for 2030. Like the previous part, the negative secondary market will be interesting for the EVs. Figure 6.37, Figure 6.38 and Figure 6.39, compare the amount of gaining profits for scenario A1 and A2, due to different regulation types.

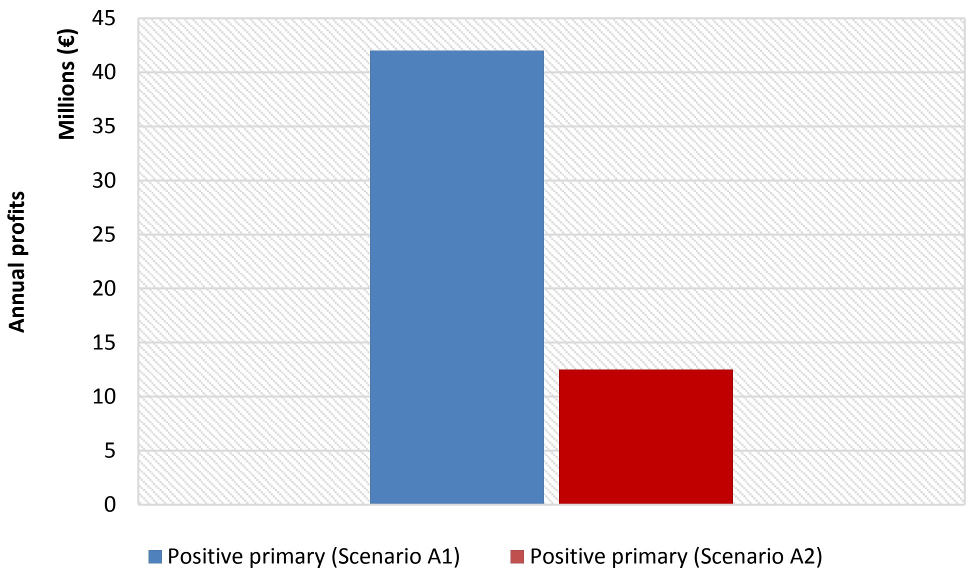


Figure 6.37: Comparison of possible annual profits of scenario A1 and A2 in positive primary control market for Germany 2030

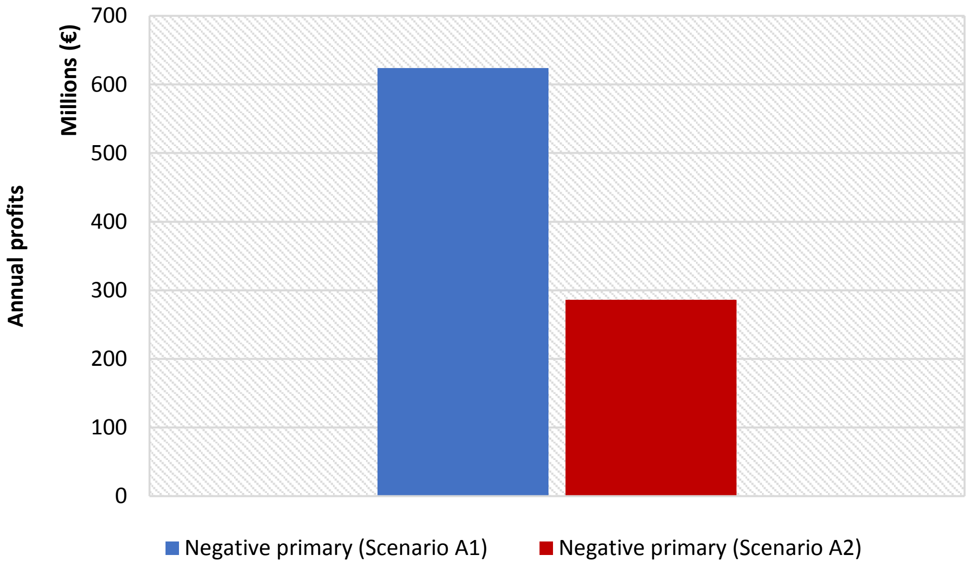


Figure 6.38: Comparison of possible annual profits of scenario A1 and A2 in negative primary control market for Germany 2030

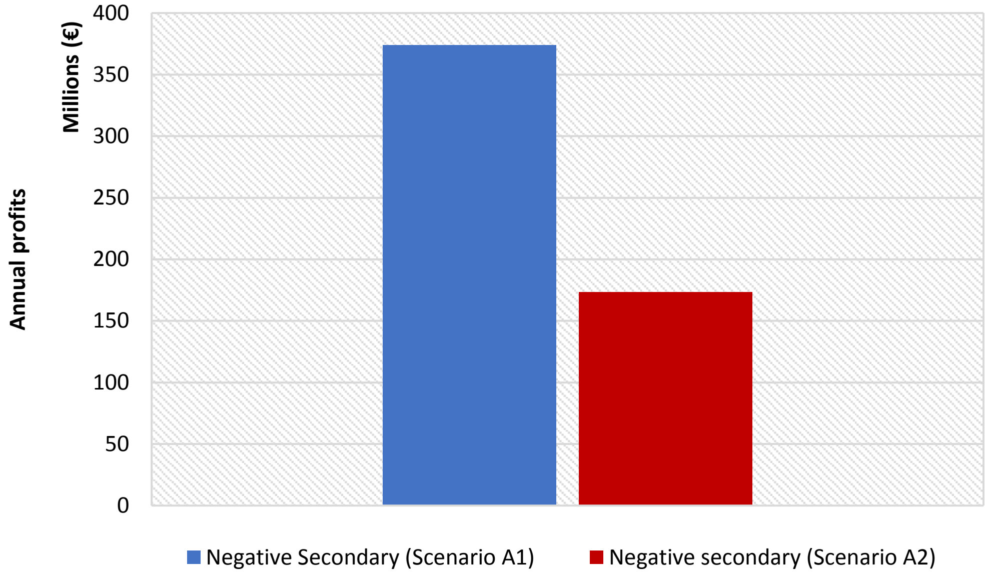


Figure 6.39: Comparison of possible annual profits of scenario A1 and A2 in negative secondary control market for Germany 2030

Obviously, there is no comparison demonstrated in the positive secondary control service. Because, as mentioned before, these kind of services, were unprofitable and thus, unsuitable for EVs under current assumptions.

Chapter 7

Conclusions and Summary of Achievements

7.1 Conclusions

This research proposes a smart charging and regulation management (SCRM) method, which controls and manages the probable high penetration level of EVs in the distribution grid. The simulation results verify the effectiveness of this methodology on energy cost reduction and optimal and secure operation of the grid along with additional income due to offered regulation services. In other words, in this work, a framework has been developed for optimal distribution network operation and planning, considering technical and economic facts. As mentioned before, there will be a 95 % penetration level of EVs in the governmental aim scenario (Scenario A1) and a 44% penetration of EVs for the realistic trend scenario (Scenario A2) in Germany 2030, in the smart residential sector.

The simulation results show the positive effect of applying the SCRM system in power grids. Through using this proposed smart system, the grid operator could avoid extra costs for new grid facilities and components for supplying the added EVs with energy due to the demonstrated valley filling, load shifting and peak shaving. Based on the simulation results, if the SCRM system wouldn’t come into action, the car holders would charge their cars immediately after they arrived home without considering essential grid and energy price constraints and would impose harmful effects to the operation of the grid, while facing higher energy costs. Furthermore, selected EVs by the SCRM system could also participate in control reserve markets and offer regulation services and earn additional income.

Therefore, this proposed smart charging and regulation management solution could be a fast, smart and practical solution for the future German grid.

In summary, the original contributions of this research are related to the development, analysis and quantification of the proposed models, methods and methodologies in the context of real-time smart charging and regulation management of EVs in distribution networks. These contributions are as follows:

- Real-time management of the charging procedure of the EVs, considering real driving patterns and flexibility of EV owners, while assuming grid operation limitation.

- Applying a smart data exchange system to be aware of the SoC of the batteries, charging priorities, plug-in state of the EVs, long distance travel plans, next travelling time, online energy market prices, regulation-market status for offering ancillary services and daily system peak hours.

- Offering a fast-uncomplicated method that avoids large mathematical calculation by mean of a fuzzy logic controller, which transforms the above-mentioned input data of the EVs and the power system, to simple digital signals, and decides the charging procedure and regulation participation of the EVs, applying practical fuzzy rules.

- An optimization problem based on the fuzzy logic results for charging requests and offered regulation services is taken into account, which applies AC optimal power flow to meet the grid operation limitations. In doing so, overloaded grid components could be prevented and the system power loss and consumed energy costs were minimized.

- Modelling real driving patterns of EV groups from studies, have also been utilized in the simulation to achieve realistic results that could be also applied in practice.

7.2 Summary of the achievements

7.2.1 Economic and technical aspects

- By implementing the SCRM system, the EV owners could save an annual charging cost of around €33 thousand in the simulated distribution system for around 1400 smart homes.

- This will lead to an annual €152 million savings in total cost of consumed energy by the EVs in Germany 2030, which could be a noticeable incentive for the owners to plug their cars to the grid anytime they arrive home or have a chance to, while becoming charged cars for the next trips.

- A peak reduction of 3.4 MW in the distribution system and a noticeable amount of 5.4 GW, in Germany, which will avoid a high part of grid expansion costs for the German operators.

- It can be concluded from the calculation results of the regulation subsection, that the primary control reserve market will be profitable for both negative and positive services for Germany 2030. The positive secondary control market seems not to be a suitable option, under current assumptions for 2030. The negative secondary market will also be interesting for the EVs' participation.

- There will be a possible annual profit of €42 million, in the positive primary control reserve market, and up to €624 million for the negative primary regulation service. The profits in the secondary control reserve market will be just for offering negative service and about €374 million, annually in Germany 2030.

- Generally, ignoring the low DoD of 20% (Fig. 3.9 in section 3), would change the results, so that all the regulation services would be profitable. Although, neglecting the infrastructure investment costs in the future, due to the fast-developing battery technology, and lower battery prices, will make also the negative markets highly profitable.

- In addition to the upper points, increased reserve demand in the regulation-market, due to the raise of uncontrollable electricity generation in the future in Germany, will lead to higher market prices and profits for the offered regulation services.

7.2.2 Reliability and system security aspects

Furthermore, the LoLP index of the system became 0 from 0.25 after applying the SCRM system and controlled charging of the EVs, which shows and proves a secure system. These plugged-in EVs could also be applied for grid regulation purposes which could help grid operators in saving regulation cost and maintaining a stable grid with existing infrastructures and bring additional income for the EV owners.

7.3 Future work

- It is needed to develop and adapt this proposed SCRM system as an extension to existing software and tools in the grid operators' control centers.

- The operation and planning of a distribution network depend on a detailed and precise modelling of uncertainties and random behaviors. However, it is tried to consider known uncertainties in this work, but in reality, EVs traveling plans, customers' flexibility, proposed optimization functions and demand level, are all under the influence of a certain degree of uncertainties, which may significantly change the operation and planning of the network. A more detailed formulation of the problem and simulation of model considering various possible scenarios, is required to cover more uncertainties.

- In this manner, further grid operation constraints could be considered in the optimization function next to environmental constraints like the amount of CO_2 emission. In general, it can be focused on environmental aspects and find suitable approaches to minimize the harmful effects.

- Other studies about the usage pattern of the EV owners could be taken into account to achieve a more generic usage pattern for the EVs to minimize the available uncertainties. In addition to this, the application of further mathematical formulations, optimization functions and decision-making methods can be investigated.

- Economic analysis could be executed in more detail while designing realistic market structures for the future power grids due to their smart structure. Fitting telecommunication methods and standards can also be investigated due to the future infrastructure of the smart power grids.

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List of Publications

Published:

A. Ameli, S. Krauter, and M.T. Ameli, “Smart Charging Management System of Plugged-in EVs Based on User Driving Patterns in Micro-Grids,*” International Journal of Engineering Research & Innovation (IJERI),* vol.10, no. 1, pp. 12-17, 2018.
(Nominated paper of the 5th IAJC/ISAM Conference on Engineering and related Technologies, Orlando, Florida, November 2016.)

A. Ameli, S. Krauter, M.T. Ameli, and H. Ameli, “Smart Charging Management System of Plugged-in EVs for Optimal Operation of Future Power Systems,” *NEIS Conference, Conference on sustainable energy supply and energy storage systems,* Hamburg, September 2017.

A. Ameli, H. Ameli, S. Krauter, and R. Hanitsch, “An Optimized Load Frequency Control of Decentralized Energy System Using Plug-in Electric Vehicle,” *In Proceedings of the International Conference: Innovating Energy Access for Remote Areas: Discovering Untapped Resources,* University of California, Berkeley, pp. 14-18, April 2014.

A. Ameli, S. Krauter, and R. Hanitsch, “Frequency Control Applying Plug-in Electric Vehicles Based on Costumer Behaviour in Electric Power Networks and Micro-Grids,” *In Proceedings of International Conference: Micro Perspectives for Decentralized Energy Supply,* TU Berlin, pp. 82-85, February 2013.

M.T. Ameli, A. Ameli, and H. Maleki, “Presenting Automatic Demand Control (ADC) as a new Frequency Control Method in Smart Grids,” *Micro Perspectives for Decentralized Energy Supply, International Conference,* TU Berlin, pp. 143-148, April 2011.

H.A. Shayanfar, G. Derakhshan, and A. Ameli, “Optimal Operation of Micro grids using Renewable Energy Resources,” *International Journal on Technical and Physical problems of Engineering (IJTPE),* pp. 97-102, February 2012.

To be submitted:

A. Ameli, S. Krauter, and M.T. Ameli, "A Novel Smart Charging and Regulating Management System for EVs Integration in Future Power Grids," *IEEE Transaction on Smart Grid,* 2019.

A. Ameli, S. Krauter, and M.T. Ameli, "Comparison of Different Artificial Intelligence Techniques for Smart Charging Management of EVs in Smart Grids," *IEEE Transaction on Smart Grid,* 2019.

Appendix A

Data of 31-Bus IEEE Distribution Network

Table A.1: Line parameters of each residential section containing 53 households in the 31-Bus IEEE distribution system [1]

Line		Line resistance *R*, V	Line reactance *X*, V	Line		Line resistance *R*, V	Line reactance *X*, V
From node	To node			From node	To node		
1	2	0.0415	0.0145	23	24	0.7763	0.0774
2	4	0.0424	0.0189	21	22	0.5977	0.0596
4	6	0.0444	0.0198	16	17	0.1423	0.0496
6	8	0.0369	0.0165	17	18	0.0837	0.0292
8	9	0.0520	0.0232	18	19	0.3124	0.0312
9	12	0.0524	0.0234	16	20	0.0163	0.0062
12	13	0.0005	0.0002	1	35	0.0163	0.0062
12	15	0.2002	0.0200	35	40	0.0415	0.0145
12	14	1.7340	0.1729	40	42	0.0424	0.0189
9	11	0.2607	0.0260	42	44	0.0444	0.0198
9	10	1.3605	0.1357	44	46	0.0369	0.0165
6	7	0.1402	0.0140	46	47	0.0520	0.0232
4	5	0.7763	0.0774	47	50	0.0524	0.0234
2	3	0.5977	0.0596	50	51	0.0005	0.0002
1	16	0.0163	0.0062	50	53	0.2002	0.0200
16	21	0.0415	0.0145	50	52	1.7340	0.1729
21	23	0.0424	0.0189	47	49	0.2607	0.0260
23	25	0.0444	0.0198	47	48	1.3605	0.1357
25	27	0.0369	0.0165	44	45	0.1402	0.0140
27	28	0.0520	0.0232	42	43	0.7763	0.0774
28	31	0.0524	0.0234	40	41	0.5977	0.0596
31	32	0.0005	0.0002	35	36	0.1423	0.0496
31	34	0.2002	0.0200	36	37	0.0837	0.0292
31	33	1.7340	0.1729	37	38	0.3124	0.0312
28	30	0.2607	0.0260	35	39	0.0163	0.0062
28	29	1.3605	0.1357	Distribution transformer reactance			0.0654
25	26	0.1402	0.0140				

Table A.2: Load type of each residential section

Linear and EV loads		Power	
Residential Nodes (Fig. 5.1)	Name	kW	kVAR
R1-R53	linear loads	1.5	0.5
	EV charger	4.0	0

Table A.3: Bus data of the 31-bus distribution system [113]

Feeder section	R (Ω)	X (Ω)	Feeder section	R (Ω)	X (Ω)
1-2	0.5096	1.7030	16-17	0.7282	0.4102
2-3	0.2191	0.0118	17-18	1.3053	0.7353
3-4	0.3485	0.3446	7-19	0.4838	0.4206
4-5	1.1750	1.0214	19-20	1.5898	1.3818
5-6	0.5530	0.4806	20-21	1.5389	0.8669
6-7	1.6625	0.9365	7-22	0.6048	0.5257
7-8	1.3506	0.7608	4-23	0.5639	0.5575
8-9	1.3506	0.7608	23-24	0.3432	0.3393
9-10	1.3259	0.7469	24-25	0.5728	0.4979
10-11	1.3259	0.7469	25-26	1.4602	1.2692
11-12	3.9709	2.2369	26-27	1.0627	0.9237
12-13	1.8549	1.0449	27-28	1.5114	0.8514
13-14	0.7557	0.4257	2-29	0.4659	0.0251
14-15	1.5389	0.8669	29-30	1.6351	0.9211
9-16	0.4752	0.4131	30-31	1.1143	0.6277

Appendix B

Data related to EVs' Charging Start Time

B.1 Winter 2015/2016

B.1.1 November 2015

Table B.1: Resulting charging hours of the EVs for a typical work day in November 2015 (A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*normal 8 ch. Start hour*	*urgent 8 ch. start hour*
1	5					
20	5					
2	2					
21	4					
4	1					
23	4					
6	3					
25	1					
8	3					
7	5					
9	1					
3	3					
13	5					
22	1					
5	3					
24	5					
14	1					
16		6				
17		6				
37		24				
18		3				
42		6				
44		5				
27		4				
38		24				
19		1				
28		2				
15		3				
43		6				
12			4			
11			3			
10			2			
35				15		
36				15		
31				10		
32				7		
30				11		
34				15		
29				12		
33				14		
39					7	
41					7	

47					7	
49					7	
53					7	
52					11	
40						16
26						16
45						16
48						16

Table B.2: Resulting charging hours of the EVs for a typical work day in November 2015 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 8 ch. start hour***	***urgent 12 ch. Start hour***
1	5				
35	5				
20	2				
2	4				
21	1				
4	4				
37	3				
46	1				
9	3				
26	5				
38	1				
28	3				
49	5				
43	1				
40		6			
42		6			
41		3			
18			4		
12			3		
10			2		
32				7	
29				7	
52					16

B.1.2 December 2015

Table B.3: Resulting charging hours of the EVs for a typical work day in December 2015 (A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***normal 8 ch. Start hour***	***urgent 8 ch. start hour***
1	5					
20	5					
2	2					
21	4					
4	1					
23	4					
6	3					
25	1					
8	3					
7	5					
9	1					
3	3					
13	5					
22	1					
5	3					
24	5					
14	1					
16		6				
17		6				
37		24				

18	3				
42	6				
44	5				
27	4				
38	24				
19	1				
28	2				
15	3				
43	6				
12		4			
11		3			
10		2			
35			7		
36			7		
31			7		
32			7		
30			7		
34			15		
29			7		
33			15		
39				11	
41				11	
47				10	
49				14	
53				10	
52				13	
40					16
26					16
45					16
48					16

Table B.4: Resulting charging hours of the EVs for a typical work day in December 2015 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 8 ch. start hour***	***urgent 12 ch. Start hour***
1	5				
35	5				
20	2				
2	4				
21	1				
4	4				
37	3				
46	1				
9	3				
26	5				
38	1				
28	3				
49	5				
43	1				
40		6			
42		6			
41		3			
18			4		
12			3		
10			2		
32				11	
29				10	
52					16

B.1.3 January 2016

Table B.5: Resulting charging hours of the EVs for a typical work day in January 2016 (A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*normal 8 ch. Start hour*	*urgent 8 ch. start hour*
1	5					
20	5					
2	2					
21	4					
4	1					
23	4					
6	3					
25	1					
8	3					
7	5					
9	1					
3	3					
13	5					
22	1					
5	3					
24	5					
14	1					
16		6				
17		6				
37		24				
18		3				
42		6				
44		5				
27		4				
38		24				
19		1				
28		2				
15		3				
43		6				
12			4			
11			3			
10			2			
35				7		
36				7		
31				7		
32				7		
30				7		
34				7		
29				16		
33				7		
39					15	
41					12	
47					15	
49					12	
53					15	
52					14	
40						17
26						17
45						17
48						10

Table B.6: Resulting charging hours of the EVs for a typical work day in January 2016 (A2)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 8 ch. start hour*	*urgent 12 ch. Start hour*
1	5				
35	5				
20	2				
2	4				
21	1				
4	4				
37	3				

46	1				
9	3				
26	5				
38	1				
28	3				
49	5				
43	1				
40		6			
42		6			
41		3			
18			4		
12			3		
10			2		
32				15	
29				12	
52					17

B.1.4 February 2016

Table B.7: Resulting charging hours of the EVs for a typical work day in February 2016 (A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*normal 8 ch. Start hour*	*urgent 8 ch. start hour*
20	5					
21	4					
23	4					
25	1					
26	3					
45	1					
13	3					
22	5					
24	1					
48	3					
14	5					
35		6				
16		6				
17		6				
36		6				
18		24				
42		1				
6		3				
44		6				
27		24				
19		2				
9		1				
28		5				
31		4				
32		3				
15		6				
30		24				
34		2				
43		1				
29		5				
33		4				
1			4			
2			3			
4			2			
12			4			
3			2			
11			4			
5			2			
10			1			
39					15	
37					11	
8					15	
7					11	
38					10	
41					15	
47					10	

49	12	
53	15	
52	10	
40		17

Table B.8: Resulting charging hours of the EVs for a typical work day in February 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***urgent 8 ch. Start hour***
35	2			
20	1			
37	5			
46	4			
26	1			
38	3			
28	1			
49	5			
43	3			
24	1			
40		6		
42		6		
31		6		
41		6		
29		5		
33		3		
1			4	
4			3	
18			2	
6			4	
12			2	
10			4	
52				17

B.1.5 March 2016

Table B.9: Resulting charging hours of the EVs for a typical work day in winter/ March 2016 (A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***
35	4		
20	4		
21	4		
36	1		
23	4		
25	3		
8	1		
7	3		
45	1		
13	3		
47	1		
22	3		
31	1		
32	3		
30	1		
34	3		
53	1		
24	15		
29	3		
14	12		
33	1		
52	15		
16		5	

39	5	
40	5	
17	5	
37	5	
18	5	
42	5	
6	5	
44	5	
19	23	
38	5	
27	16	
26	23	
9	5	
41	3	
28	12	
15	16	
49	14	
43	1	
48	4	
1		3
2		2
4		2
12		2
3		1
11		3
5		1
10		3

Table B.10: Resulting charging hours of the EVs for a typical work day in winter/ March 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***urgent 8 ch. Start hour***
20	4			
46	4			
26	4			
28	1			
31	4			
49	1			
24	3			
43	1			
29	3			
33	1			
35		5		
40		5		
37		5		
42		5		
38		3		
41		5		
1			3	
4			2	
18			2	
6			2	
12			1	
10			3	
52				7

B.2 Spring 2016

B.2.1 March 2016

Table B.11: Resulting charging hours of the EVs for a typical work day in spring/ March 2016 (A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***normal 8 ch. start hour***	***urgent 8 ch. Start hour***
35	6					
20	4					
21	6					
36	2					
18	4					
23	6					
42	1					
25	3					
19	6					
27	5					
9	1					
28	3					
13	5					
47	1					
22	3					
31	5					
32	1					
30	3					
49	5					
34	1					
24	3					
29	5					
14	1					
52	3					
33	5					
16		1				
39		2				
40		3				
17		4				
4		1				
37		16				
6		7				
44		2				
8		5				
7		3				
45		4				
41		1				
15		16				
5		7				
43		2				
1			4			
2			3			
12			5			
3			2			
11			4			
10			2			
53				18		
38					17	
48					17	
26						18

Table B.12: Resulting charging hours of the EVs for a typical work day in spring/ March 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 8 ch. Start hour***
20	6				
46	4				
26	6				
28	2				

31	4				
49	6				
24	1				
43	3				
29	6				
33	5				
40		1			
37		2			
42		3			
38		4			
41		1			
1			4		
4			3		
18			5		
6			2		
12			4		
10			2		
35				17	
52					18

B.2.2 April 2016

Table B.13: Resulting charging hours of the EVs for a typical work day in April 2016 (A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*urgent 4 ch. start hour*	*urgent 8 ch. Start hour*
35	4					
20	4					
21	4					
36	4					
18	1					
42	3					
23	1					
25	3					
27	1					
19	3					
9	1					
13	3					
22	1					
47	3					
28	1					
31	3					
32	1					
30	3					
49	16					
34	1					
24	3					
29	16					
14	1					
33	3					
52	15					
16		5				
39		5				
40		5				
17		5				
4		5				
37		5				
6		5				
44		5				
8		5				
7		5				
45		17				
41		5				
5		17				
15		5				
43		1				
48		12				
1			3			
2			2			

12			2		
3			2		
11			1		
10			3		
38				6	
53				6	
26					6

Table B.14: Resulting charging hours of the EVs for a typical work day in April 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 8 ch. Start hour***
20	4				
46	4				
26	4				
28	4				
31	1				
49	3				
43	1				
24	3				
29	1				
33	3				
40		5			
37		5			
42		5			
38		5			
41		5			
1			3		
4			2		
18			2		
6			2		
12			1		
10			3		
35				6	
52					6

B.2.3 May 2016

Table B.15: Resulting charging hours of the EVs for a typical work day in spring/ May 2016 (A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***urgent 4 ch. start hour***	***urgent 8 ch. Start hour***
35	4				
20	4				
21	4				
36	4				
18	1				
42	3				
23	1				
25	3				
27	1				
19	3				
9	1				
13	3				
22	1				
47	3				
28	1				
31	3				
32	17				
30	1				
49	3				
34	17				
24	16				
29	1				

14	3				
33	16				
52	1				
16		5			
39		5			
40		5			
17		5			
4		5			
37		5			
6		5			
44		5			
8		5			
7		5			
45		5			
41		15			
5		3			
15		4			
43		5			
48		18			
1			3		
2			2		
12			2		
3			2		
11			1		
10			3		
38				6	
53				6	
26					6

Table B.16: Resulting charging hours of the EVs for a typical work day in spring/ May 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 8 ch. Start hour***
20	4				
46	4				
26	4				
28	4				
31	1				
49	3				
43	1				
24	3				
29	1				
33	3				
40		5			
37		5			
42		5			
38		5			
41		5			
1			3		
4			2		
18			2		
6			2		
12			1		
10			3		
35				6	
52					6

B.3 Summer 2016

B.3.1 May/ June 2016

Table B.17: Resulting charging hours of the EVs for a typical work day in May/ June 2016 (A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*urgent 4 ch. start hour*	*urgent 8 ch. Start hour*
35	5					
20	2					
21	4					
36	2					
18	4					
42	1					
23	3					
25	1					
27	5					
19	3					
9	1					
13	5					
47	3					
22	1					
28	5					
31	3					
32	1					
30	5					
49	3					
34	1					
24	5					
29	3					
14	1					
52	5					
33	3					
16		6				
39		6				
40		6				
17		6				
4		1				
37		16				
6		6				
44		5				
8		2				
7		1				
45		16				
41		6				
5		3				
15		4				
43		5				
1			4			
2			3			
12			2			
3			4			
11			2			
10			4			
38				17		
48				17		
53					7	
26						7

Table B.18: Resulting charging hours of the EVs for a typical work day in May/ June 2016 (A2)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*urgent 8 ch. Start hour*
20	5				
46	2				
26	4				
28	2				

31	4				
49	1				
43	4				
24	3				
29	1				
33	3				
40		6			
37		6			
42		6			
38		6			
41		6			
1			4		
4			3		
18			2		
6			4		
12			2		
10			4		
35				17	
52					7

B.3.2 June/ July 2016

Table B.19: Resulting charging hours of the EVs for a typical work day in June/ July 2016 (A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 4 ch. start hour***	***urgent 8 ch. Start hour***
35	5					
20	2					
21	4					
36	2					
18	4					
42	1					
23	3					
25	1					
27	5					
19	3					
9	1					
13	5					
47	3					
22	1					
28	5					
31	3					
32	1					
30	5					
49	3					
34	1					
24	5					
29	3					
14	1					
52	5					
33	3					
16		6				
39		6				
40		6				
17		6				
4		1				
37		16				
6		6				
44		5				
8		2				
7		1				
45		16				
41		6				
5		3				
15		4				
43		5				
1			4			

12			3			
3			2			
11			4			
5			2			
10			4			
38				17		
48				17		
53					7	
26						7

Table B.20: Resulting charging hours of the EVs for a typical work day in June/July 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 8 ch. Start hour***
20	5				
46	2				
26	4				
28	2				
31	4				
49	1				
43	4				
24	3				
29	1				
33	3				
40		6			
37		6			
42		6			
38		6			
41		6			
1			4		
4			3		
18			2		
6			4		
12			2		
10			4		
35				17	
52					7

B.3.3 July/ August 2016

Table B.21: Resulting charging hours of the EVs for a typical work day in July/ August 2016 (A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 4 ch. start hour***	***urgent 8 ch. Start hour***
35	5					
20	2					
21	4					
36	2					
18	4					
42	1					
23	3					
25	1					
27	5					
19	3					
9	1					
13	5					
47	3					
22	1					
28	5					
31	3					
32	1					

30	5					
49	3					
34	1					
24	5					
29	3					
14	1					
52	5					
33	3					
16		6				
39		6				
40		6				
17		6				
4		1				
37		16				
6		6				
44		5				
8		2				
7		1				
45		16				
41		6				
5		3				
15		4				
43		5				
1			4			
2			3			
12			2			
3			4			
11			2			
10			4			
38				17		
48				17		
53					7	
26						7

Table B.22: Resulting charging hours of the EVs for a typical work day in July/ August 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 8 ch. Start hour***
20	5				
46	2				
26	4				
28	2				
31	4				
49	1				
43	4				
24	3				
29	1				
33	3				
40		6			
37		6			
42		6			
38		6			
41		6			
1			4		
4			3		
18			2		
6			4		
12			2		
10			4		
35				17	
52					7

B.3.4 August/ September 2016

Table B.23: Resulting charging hours of the EVs for a typical work day in August/ September 2016 (A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*urgent 4 ch. start hour*	*urgent 8 ch. Start hour*
35	5					
20	2					
21	4					
36	2					
18	4					
42	1					
23	3					
25	1					
27	5					
19	3					
9	1					
13	5					
47	3					
22	1					
28	5					
31	3					
32	1					
30	5					
49	3					
34	1					
24	5					
29	3					
14	1					
52	5					
33	3					
16		6				
39		6				
40		6				
17		6				
4		1				
37		16				
6		6				
44		5				
8		2				
7		1				
45		16				
41		6				
5		3				
15		4				
43		5				
1			4			
2			3			
12			2			
3			4			
11			2			
10			4			
38				10		
48				10		
53					7	
26						7

Table B.24: Resulting charging hours of the EVs for a typical work day in August/September 2016 (A2)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*normal 4 ch. start hour*	*urgent 8 ch. Start hour*
20	5				
46	2				
26	4				
28	2				
31	4				
49	1				
43	4				
24	3				
29	1				
33	3				
40		6			
37		6			
42		6			
38		6			
41		6			
1			4		
4			3		
18			2		
6			4		
12			2		
10			4		
35				10	
52					7

B.4 Autumn 2016

B.4.1 September 2016

Table B.25: Resulting charging hours of the EVs for a typical work day in September 2016 (A1)

Bus no. of EV	*flexible 8 ch. start hour*	*flexible 4 ch. start hour*	*flexible 12 ch. Start hour*	*urgent 4 ch. start hour*	*urgent 8 ch. Start hour*
20	4				
21	4				
18	4				
23	4				
42	3				
25	1				
19	3				
27	1				
9	3				
22	1				
13	3				
47	1				
28	3				
49	1				
24	3				
14	1				
52	3				
16		5			
39		5			
40		5			
17		5			
4		5			
37		5			
6		5			
44		5			
8		5			
7		16			

45		5			
41		16			
31		5			
32		16			
5		15			
15		5			
30		1			
43		2			
53		3			
29		12			
48		16			
1			3		
35			2		
2			2		
36			2		
12			1		
3			3		
11			3		
34			1		
10			3		
33			1		
38				7	
26					7

Table B.26: Resulting charging hours of the EVs for a typical work day in September 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***Urgent 4 ch. start hour***	***urgent 8 ch. Start hour***
20	4				
40	4				
37	4				
46	4				
26	1				
38	3				
28	1				
49	3				
24	1				
43	3				
42		5			
41		5			
31		5			
29		5			
33		1			
1			3		
4			2		
18			2		
6			2		
12			1		
10			3		
35				7	
52					7

B.4.2 October 2016

Table B.27: Resulting charging hours of the EVs for a typical work day in October 2016 (A1)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 4 ch. start hour***	***urgent 8 ch. Start hour***
20	3				
21	3				
18	1				
42	5				
23	3				
25	1				
27	5				
19	3				

9	1				
28	5				
13	3				
47	1				
22	5				
49	3				
24	1				
14	5				
52	3				
16		6			
39		6			
40		6			
17		6			
4		6			
37		1			
6		2			
44		6			
8		5			
7		1			
45		2			
41		6			
31		3			
32		5			
15		1			
5		2			
30		6			
53		3			
43		5			
29		4			
1			4		
35			3		
2			2		
36			4		
12			2		
3			4		
11			2		
34			4		
10			1		
33			4		
38				16	
48				16	
26					7

Table B.28: Resulting charging hours of the EVs for a typical work day in October 2016 (A2)

Bus no. of EV	***flexible 8 ch. start hour***	***flexible 4 ch. start hour***	***flexible 12 ch. Start hour***	***normal 8 ch. start hour***	***urgent 4 ch. Start hour***
20	2				
40	5				
37	4				
46	1				
26	3				
38	1				
28	5				
49	3				
24	1				
43	5				
42		6			
41		6			
31		6			
29		3			
33		4			
1			4		
4			3		
18			2		
6			4		
12			2		
10			4		
52				11	
35					7

Appendix C

Voltage Values of the Distribution System

C.1 Summer 2016

C.1.1 Controlled charging of the EVs with SCRM

Table C.1: Voltage magnitude of the system buses for a typical work day in summer after applying SCRM (A1)

Bus No.	***Voltage magnitude of the buses in per unit (pu)***									
#	***h = 1:00 a.m.***	***h = 2:00 a.m.***	***h = 3:00 a.m.***	***h = 4:00 a.m.***	***h = 5:00 a.m.***	***h = 6:00 a.m.***	***h = 7:00 a.m.***	***h = 8:00 a.m.***	***h = 4:00 p.m.***	***h = 5:00 p.m.***
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.997	0.997	0.996	0.996	0.996	0.996	0.997	0.996	0.997	0.997
3	0.996	0.997	0.996	0.996	0.996	0.996	0.997	0.996	0.996	0.997
4	0.995	0.995	0.994	0.994	0.994	0.994	0.996	0.994	0.995	0.995
5	0.992	0.992	0.991	0.991	0.991	0.991	0.993	0.991	0.992	0.992
6	0.991	0.991	0.990	0.990	0.990	0.990	0.992	0.990	0.991	0.991
7	0.987	0.987	0.986	0.986	0.986	0.986	0.989	0.986	0.987	0.987
8	0.985	0.985	0.984	0.984	0.984	0.984	0.987	0.984	0.985	0.985
9	0.983	0.983	0.981	0.981	0.981	0.981	0.985	0.981	0.983	0.983
10	0.982	0.982	0.980	0.980	0.980	0.980	0.984	0.980	0.982	0.982
11	0.981	0.981	0.979	0.979	0.979	0.979	0.984	0.979	0.981	0.981
12	0.978	0.978	0.977	0.977	0.977	0.977	0.982	0.977	0.978	0.978
13	0.977	0.977	0.976	0.976	0.976	0.976	0.981	0.976	0.977	0.977
14	0.977	0.977	0.975	0.975	0.975	0.975	0.981	0.975	0.977	0.977
15	0.977	0.977	0.976	0.976	0.975	0.976	0.980	0.975	0.977	0.977
16	0.983	0.983	0.981	0.981	0.981	0.981	0.985	0.981	0.983	0.983
17	0.983	0.983	0.981	0.981	0.981	0.981	0.985	0.981	0.983	0.983
18	0.982	0.982	0.981	0.981	0.981	0.981	0.985	0.981	0.982	0.982
19	0.987	0.987	0.986	0.986	0.986	0.986	0.989	0.986	0.987	0.987
20	0.986	0.987	0.985	0.985	0.985	0.985	0.988	0.985	0.986	0.987
21	0.986	0.986	0.985	0.985	0.985	0.985	0.988	0.985	0.986	0.986
22	0.987	0.987	0.986	0.986	0.986	0.986	0.989	0.986	0.987	0.987
23	0.995	0.995	0.994	0.994	0.994	0.994	0.995	0.994	0.995	0.995
24	0.994	0.995	0.993	0.993	0.993	0.993	0.995	0.993	0.994	0.995

25	0.994	0.994	0.993	0.993	0.993	0.993	0.995	0.993	0.994	0.994
26	0.993	0.993	0.992	0.992	0.992	0.992	0.994	0.992	0.993	0.993
27	0.993	0.993	0.992	0.992	0.992	0.992	0.994	0.992	0.993	0.993
28	0.993	0.993	0.992	0.992	0.992	0.992	0.993	0.992	0.993	0.993
29	0.997	0.997	0.996	0.996	0.996	0.996	0.997	0.996	0.997	0.997
30	0.996	0.997	0.996	0.996	0.996	0.996	0.997	0.996	0.996	0.997
31	*0.996*	*0.996*	*0.995*	*0.995*	*0.995*	*0.995*	*0.996*	*0.995*	*0.996*	*0.996*

C.1.2 Uncontrolled charging of the EVs

Table C.2: Voltage magnitude of the system buses for a typical work day in summer after uncontrolled charging (A1)

Bus no.	**Voltage magnitude of the buses in per unit (pu)**							
#	**h = 1:00 a.m.**	**h = 6:00 p.m.**	**h = 7:00 p.m.**	**h = 8:00 p.m.**	**h = 9:00 p.m.**	**h = 10:00 p.m.**	**h = 11:00 p.m.**	**h = 12:00 a.m.**
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.987	0.985	0.985	0.984	0.984	0.984	0.985	0.985
3	0.983	0.981	0.981	0.980	0.980	0.980	0.981	0.981
4	0.977	0.975	0.974	0.972	0.972	0.973	0.973	0.973
5	0.962	0.959	0.957	0.955	0.955	0.956	0.957	0.957
6	0.955	0.951	0.949	0.947	0.947	0.948	0.949	0.949
7	0.935	0.929	0.927	0.924	0.923	0.925	0.926	0.926
8	0.924	0.917	0.914	0.911	0.910	0.912	0.914	0.914
9	0.913	0.905	0.902	0.898	0.898	0.899	0.901	0.901
10	0.906	0.898	0.894	0.890	0.890	0.892	0.894	0.894
11	0.901	0.892	0.888	0.884	0.883	0.885	0.888	0.888
12	0.888	0.877	0.873	0.868	0.868	0.870	0.873	0.873
13	0.883	0.872	0.868	0.863	0.863	0.865	0.868	0.868
14	0.882	0.871	0.867	0.862	0.861	0.863	0.866	0.866
15	0.880	0.870	0.865	0.860	0.860	0.862	0.865	0.865
16	0.912	0.904	0.900	0.896	0.896	0.898	0.900	0.900
17	0.911	0.902	0.899	0.895	0.895	0.896	0.899	0.899
18	0.909	0.901	0.898	0.894	0.894	0.895	0.897	0.897
19	0.934	0.928	0.925	0.922	0.922	0.923	0.925	0.925
20	0.931	0.925	0.922	0.919	0.919	0.920	0.922	0.922
21	0.930	0.924	0.921	0.918	0.918	0.919	0.921	0.921
22	0.935	0.928	0.926	0.923	0.923	0.924	0.926	0.926
23	0.974	0.972	0.971	0.969	0.969	0.970	0.971	0.971
24	0.973	0.970	0.969	0.968	0.968	0.968	0.969	0.969
25	0.971	0.968	0.967	0.966	0.966	0.966	0.967	0.967
26	0.968	0.965	0.963	0.962	0.962	0.962	0.963	0.963
27	0.966	0.963	0.962	0.960	0.960	0.961	0.961	0.961
28	0.965	0.962	0.960	0.959	0.959	0.959	0.960	0.960

29	0.986	0.984	0.984	0.983	0.983	0.983	0.984	0.984
30	0.984	0.982	0.981	0.980	0.980	0.980	0.981	0.981
31	0.983	0.981	0.980	0.979	0.979	0.979	0.980	0.980

C.2 Winter 2015/2016

C.2.1 Controlled charging of the EVs with SCRM

Table C.3: Voltage magnitude of the system buses for a typical work day in winter after applying SCRM – Part 1 (A1)

Bus no.	***Voltage magnitude of the buses in per unit (pu)***									
#	***h = 1:00 a.m.***	***h = 2:00 a.m.***	***h = 3:00 a.m.***	***h = 4:00 a.m.***	***h = 5:00 a.m.***	***h = 6:00 a.m.***	***h = 7:00 a.m.***	***h = 10:00 a.m.***	***h = 11:00 p.m.***	**h = 12:00 a.m.**
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997
3	0.996	0.996	0.996	0.996	0.996	0.996	0.997	0.996	0.997	0.997
4	0.995	0.995	0.995	0.995	0.995	0.995	0.996	0.995	0.995	0.996
5	0.991	0.991	0.991	0.991	0.991	0.991	0.993	0.992	0.992	0.993
6	0.990	0.990	0.990	0.990	0.990	0.990	0.992	0.991	0.991	0.992
7	0.987	0.987	0.987	0.987	0.987	0.987	0.989	0.987	0.987	0.989
8	0.985	0.985	0.985	0.985	0.985	0.985	0.987	0.985	0.985	0.987
9	0.983	0.983	0.983	0.983	0.983	0.983	0.985	0.983	0.983	0.985
10	0.982	0.982	0.982	0.982	0.982	0.982	0.984	0.982	0.982	0.984
11	0.981	0.981	0.981	0.981	0.981	0.981	0.984	0.981	0.981	0.984
12	0.978	0.978	0.978	0.978	0.978	0.978	0.982	0.979	0.978	0.982
13	0.978	0.978	0.978	0.978	0.978	0.979	0.981	0.978	0.977	0.981
14	0.979	0.979	0.979	0.979	0.979	0.980	0.981	0.978	0.977	0.981
15	0.986	0.986	0.985	0.986	0.986	0.984	0.979	0.978	0.977	0.979
16	0.985	0.985	0.985	0.985	0.985	0.984	0.984	0.984	0.983	0.984
17	0.985	0.985	0.984	0.986	0.986	0.985	0.985	0.983	0.983	0.985
18	0.986	0.986	0.985	0.986	0.986	0.986	0.985	0.982	0.982	0.985
19	0.994	0.994	0.993	0.994	0.994	0.994	0.989	0.987	0.987	0.989
20	0.993	0.993	0.993	0.994	0.994	0.994	0.988	0.986	0.987	0.988
21	0.993	0.993	0.992	0.993	0.993	0.993	0.988	0.986	0.986	0.988
22	0.992	0.992	0.992	0.993	0.993	0.993	0.989	0.987	0.987	0.989
23	0.992	0.992	0.992	0.992	0.992	0.992	0.995	0.995	0.995	0.995
24	0.992	0.992	0.992	0.992	0.992	0.992	0.995	0.994	0.995	0.995
25	0.996	0.996	0.996	0.996	0.996	0.996	0.995	0.994	0.994	0.995
26	0.996	0.996	0.996	0.996	0.996	0.996	0.994	0.993	0.993	0.994
27	0.995	0.995	0.995	0.995	0.995	0.995	0.994	0.992	0.993	0.994
28	0.996	0.996	0.995	0.996	0.996	0.996	0.993	0.992	0.993	0.993

29	0.997	0.997	0.996	0.997	0.997	0.997	0.997	0.996	0.997	*0.997*
30	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.996	0.997	*0.997*
31	*0.996*	*0.996*	*0.996*	*0.996*	*0.996*	*0.996*	*0.996*	*0.995*	*0.996*	*0.996*

Table C.4: Voltage magnitude of the system buses for a typical work day in winter after applying SCRM – Part 2 (A1)

Bus no.	***Voltage magnitude of the buses in per unit (pu)***					
#	***h = 1:00 p.m.***	***h = 2:00 p.m.***	***h = 3:00 p.m.***	***h = 4:00 p.m.***	***h = 5:00 p.m.***	***h = 12:00 a.m.***
1	1.000	1.000	1.000	1.000	1.000	*1.000*
2	0.997	0.996	0.997	0.997	0.997	*0.997*
3	0.996	0.996	0.996	0.997	0.997	*0.996*
4	0.995	0.994	0.995	0.996	0.996	*0.995*
5	0.992	0.991	0.992	0.993	0.993	*0.991*
6	0.991	0.990	0.991	0.992	0.992	*0.990*
7	0.987	0.986	0.987	0.989	0.989	*0.987*
8	0.985	0.984	0.985	0.987	0.987	*0.985*
9	0.983	0.981	0.983	0.985	0.985	*0.983*
10	0.982	0.980	0.982	0.984	0.984	*0.982*
11	0.981	0.979	0.981	0.984	0.984	*0.981*
12	0.979	0.977	0.979	0.983	0.983	*0.978*
13	0.978	0.977	0.978	0.982	0.982	*0.978*
14	0.978	0.976	0.978	0.981	0.981	*0.979*
15	0.978	0.976	0.978	0.979	0.979	*0.986*
16	0.984	0.980	0.984	0.984	0.984	*0.985*
17	0.983	0.981	0.984	0.985	0.985	*0.985*
18	0.982	0.981	0.983	0.985	0.985	*0.986*
19	0.987	0.986	0.987	0.989	0.989	*0.994*
20	0.986	0.985	0.986	0.988	0.988	*0.993*
21	0.986	0.985	0.986	0.988	0.988	*0.993*
22	0.987	0.986	0.987	0.989	0.989	*0.992*
23	0.995	0.994	0.995	0.995	0.995	*0.992*
24	0.994	0.993	0.994	0.995	0.995	*0.992*
25	0.994	0.993	0.994	0.994	0.995	*0.996*
26	0.993	0.992	0.993	0.994	0.994	*0.996*
27	0.992	0.993	0.992	0.994	0.994	*0.995*
28	0.992	0.993	0.992	0.993	0.994	*0.996*
29	0.996	0.997	0.996	0.997	0.997	*0.997*
30	0.996	0.996	0.996	0.997	0.997	*0.997*
31	*0.995*	*0.996*	*0.995*	*0.996*	*0.996*	*0.996*

C.2.2 Uncontrolled charging of the EVs

Table C.5: Voltage magnitude of the system buses for a typical work day in winter after uncontrolled charging (A1)

Bus no.	***Voltage magnitude of the buses in per unit (pu)***							
#	***h = 1:00 a.m.***	***h = 6:00 p.m.***	***h = 7:00 p.m.***	***h = 8:00 p.m.***	***h = 9:00 p.m.***	***h = 10:00 p.m.***	***h = 11:00 p.m.***	***h = 12:00 a.m.***
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.996	0.985	0.985	0.984	0.985	0.985	0.985	0.987
3	0.996	0.981	0.981	0.980	0.981	0.981	0.981	0.983
4	0.994	0.975	0.974	0.972	0.973	0.975	0.975	0.977
5	0.991	0.959	0.957	0.955	0.957	0.959	0.959	0.962
6	0.990	0.951	0.949	0.947	0.949	0.951	0.951	0.955
7	0.986	0.929	0.927	0.923	0.926	0.929	0.929	0.935
8	0.984	0.917	0.914	0.910	0.914	0.917	0.917	0.924
9	0.981	0.905	0.902	0.898	0.901	0.905	0.905	0.913
10	0.980	0.898	0.894	0.890	0.894	0.898	0.898	0.906
11	0.979	0.892	0.888	0.883	0.888	0.892	0.892	0.901
12	0.977	0.877	0.873	0.868	0.873	0.877	0.877	0.888
13	0.976	0.877	0.868	0.863	0.868	0.877	0.877	0.883
14	0.975	0.875	0.867	0.861	0.866	0.876	0.877	0.882
15	0.975	0.874	0.865	0.860	0.865	0.875	0.876	0.880
16	0.981	0.904	0.900	0.896	0.900	0.904	0.905	0.912
17	0.981	0.902	0.899	0.895	0.899	0.902	0.903	0.911
18	0.981	0.901	0.899	0.894	0.897	0.901	0.902	0.909
19	0.986	0.928	0.925	0.922	0.925	0.928	0.928	0.934
20	0.985	0.925	0.922	0.919	0.922	0.926	0.926	0.931
21	0.985	0.924	0.921	0.918	0.921	0.924	0.924	0.930
22	0.986	0.928	0.926	0.923	0.926	0.928	0.928	0.935
23	0.994	0.972	0.971	0.969	0.971	0.972	0.972	0.974
24	0.993	0.970	0.969	0.968	0.969	0.970	0.970	0.973
25	0.993	0.968	0.967	0.966	0.967	0.968	0.968	0.971
26	0.992	0.965	0.964	0.962	0.963	0.966	0.966	0.968
27	0.993	0.963	0.963	0.960	0.961	0.963	0.964	0.966
28	0.993	0.962	0.960	0.959	0.960	0.963	0.963	0.965
29	0.997	0.984	0.984	0.983	0.984	0.984	0.984	0.986
30	0.996	0.982	0.981	0.980	0.981	0.982	0.982	0.984
31	0.996	0.981	0.980	0.979	0.980	0.981	0.981	0.983