AALBORG UNIVERSITY
DENMARK

COORDINATED CHARGING OF ELECTRIC VEHICLES THROUGH DEMAND RESPONSE IN DISTRIBUTION GRIDS

MASTER'S THESIS

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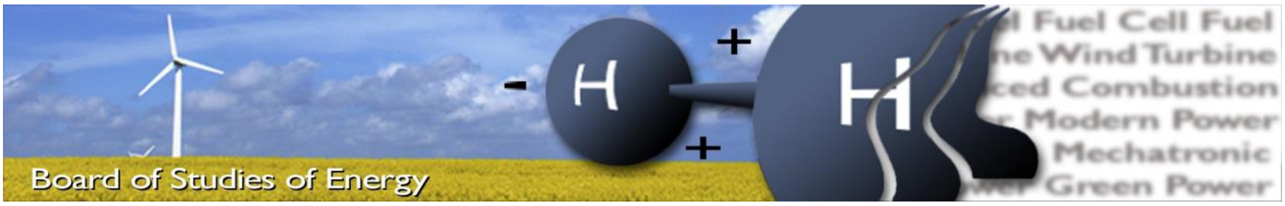

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SYNOPSIS:

The increased integration of large energy storage devices and loads into the distribution system causes several issues along with the increased renewable energy generations which are also very uncertain. In this project, the ability of electric vehicles to participate in providing flexibility to the distribution systems through demand response management is analyzed. For this reason, electric vehicles are integrated to the grid and two different coordinated charging control strategies are applied in order to provide flexibility to the distribution system and create no voltage or congestion issues.

Pages: 67

Appendix: A & B

Supplements: -

LIST OF FIGURES

LIST OF TABLES

Contents

Coordinated charging of electric vehicles through demand response in distribution grids

CHAPTER-1

In this chapter, an investigation and motivation, scope, objectives, and methodology of the project are contextualized. The relevance of the project topic as part of the current sustainable energy targets and developments in the Danish power system with its increasing renewable energy sources are analyzed.

1.1 Background and motivation

Denmark, being one of the pioneers in wind power technologies, stands upfront in developing renewable energy sources as a concern to increased environmental exploitations and energy security. Like, several other countries in the world, Denmark has set a national target for electricity production from Renewable energy sources and completely getting rid of burning fossil fuels by 2050 [1].

In the roadmap to 2050 target, one of the mid term goal set by the Danish government is to generate enough energy from wind turbines to meet half of its annual electricity consumption by 2020 [2], which is also evident from the Figure 1.1. In 2017, it was recorded that 46% of the annual electricity consumption was supplied by the renewable energy sources and of which wind turbines contributed about 44% and shows how near it is from the national target set for 2020 [3].

Figure 1. 1: Wind power and consumption profile over few weeks of 2013 and for 2050 [2].

Over the years, the Danish power system has evolved from having large share of generation from fossil fuel-fired central power plants with synchronous generators to distributed generators like wind turbines, solar PVs, and other Renewable energy sources. Corresponding to the development in the variable and fluctuating Renewable energy generation trends, the interconnector capacities with the neighboring countries like Sweden, Norway and Germany has also been increased and developed over the years, which almost equals the installed capacity of RESs in Denmark, as seen in Figure 1.2 [4].

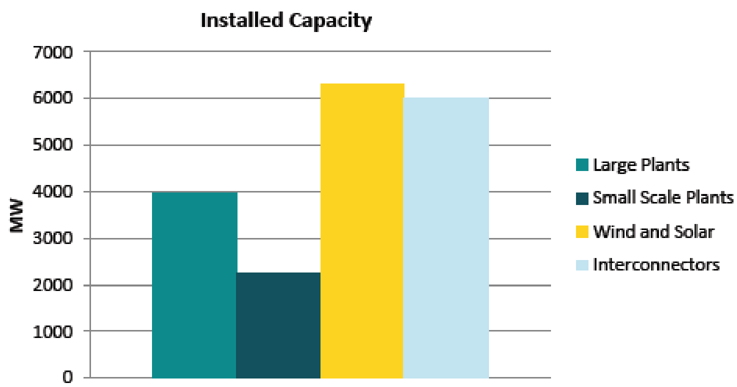

Figure 1. 2: Installed capacity Of Danish power system [13].

As of May 2018, the Danish power generation capacity records 5GW from wind turbines, close to 1GW from solar PVs and 6.3GW from local and central thermal units to meet the consumption peak of 6.5GW. Then, the Danish power system interconnector capacity with Norway, Sweden and Germany is reported to be 6.5GW altogether. Also, it has been proposed to establish new interconnections to England and Netherlands for 1400MW and 700MW respectively. These rapid developments and future proposals towards the green energy generation and flexible interconnector capacities has shown a vibrant decrease in thermal capacities up to 30% in the recent years [4].

Further looking forward in the Danish national targets, it is proposed to meet the complete electricity and heating needs from RESs by 2035 and to cover all the energy needs (heat, electricity,transport, gas and industry) from RESs within 2050 [3]. With regard to this on 2nd October 2018, the Danish parliament has decided to terminate the sale of new cars with conventional internal combustion engines by 2030 and comission only electric cars or cars with zero-emission capability by 2035. Along with electric vehicles, new generation technologies like individual heat pumps, electric cartridges in district heating and household battery storage also hold equally higher potential in achieving the national targets [2]. Thus it is evident that Denmark has a very good platform to experiment the integration of flexible generation and consumption technologies both politically and technically. The stochastic growth in the flexible consumption pattern towards 2035 is depicted below in Figure 1.3.

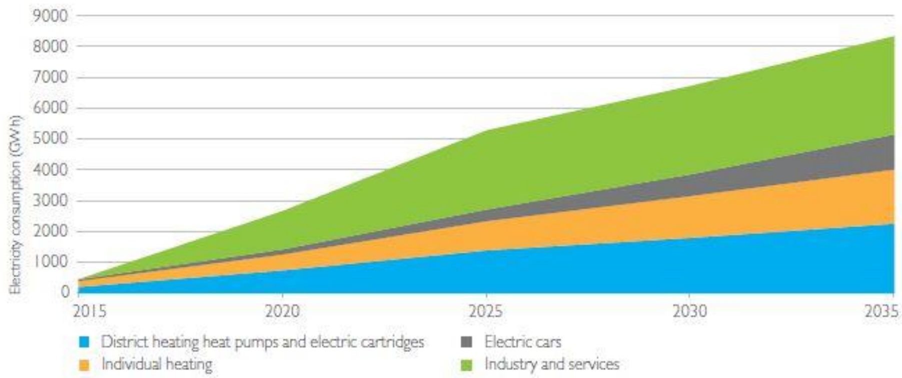

Figure 1.3: Expected pattern of growth in electricity consumption [2].

Several research studies justify the integration of more variable distributed generators like wind turbines and solar PVs provide not only diversity and security of supply but also contribute substantial impacts and repercussions to the distribution grid which is convetionally radial and designed to operate with no generation. Impacts would be like, reversing the power flow direction supplying the external grid, creating bottlenecks and overloading the lines and transformers which in turn would increase the power losses, detiorating the power quality and voltage regulations, on the whole it claims to weaken the reinforcement of distribution grid [5].

On the other hand, higher dependancy over the wind turbines and solar PVs, which during uncertain weather conditions would create potential disturbance to the system equilibrium. In addition, the continuous decommissioning of large scale power plants due to their CO2 emissions might decrease the rotational inertia for the power system and gradually become a threat to system stability and security [6]. Upon which there have been a lot measures taken to modify the grid topologies and operations, still studies are being carried out to ensure protection and reinforcement to the grid in higher level.

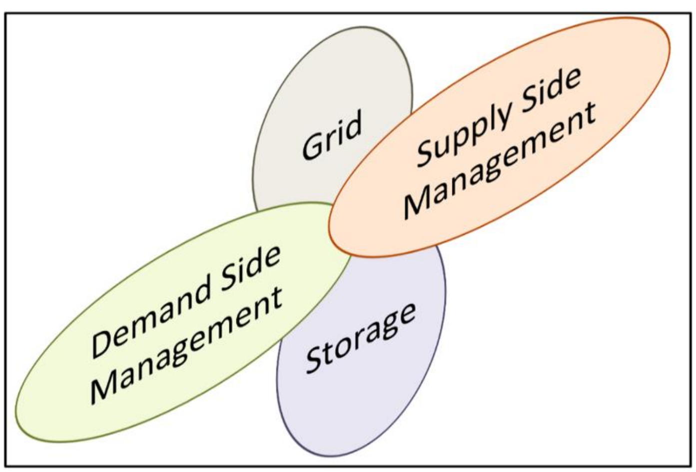

Figure 1. 3: Considerable Solutions for integration RE resources [7]

To elaborate Figure 1.3, Supply side management is ensuring the availability of enough spinning and capacity reserves for frequent start-up, shut down and fast response and subside the disturbances. Currently, the main source of supply side management in Denmark is large and small-scale CHPs, with a total installed capacity of 6.3GW which can be referred in Figure 1.2. Out of 6.3GW capacity, about 4GW is based on burning fossil fuel in forms of coal and oil which highly contradicts with the motivation of 2050 strategy. So, supply side management option contracts to depend only on gas-fired small-scale CHPs. However, it requires a huge investment in building new or upgrading the existing prime-movers to run on gas.

Expanding or reinforcement of transmission grid can yield reduction in electricity prices by reducing the existing line congestions and losses. While strengthening the distribution grids can reduce the loading of the lines and transformers and mitigate the power losses and voltage deviations. But this does not alone provides a unique solution to mitigate or overcome the operational challenges in the transmission and distribution grids currently being faced and predicted for the future. However, this requires a huge capital investment, planning and longer time to be established.

Other means of ensuring security of supply would be devising and establishing bigger storage capacities to offer regulation during the contingencies or bad weather conditions and to reserve energy during excess generation. They are a great source of offering flexibility to the system and are highly being stressed in the development schemes of FLECH (Flexibility clearing house), a market-oriented platform for trading anciallary services between DSOs and aggregated distributed energy resources [8]. Although, like the other solution explained above, it also requires bigger investment, planning and modifications in the grid.

Demand side management or Demand response management is a kind of solution that alters the energy consumption pattern of the end-users based on algorithms where, the optimal running condition of the distribution grids or providing ancillary services to the system will be the prime objective. Say, load shifting is a type of demand response management where the load consumption during the peak demand periods are shifted to the off- peak periods or to the periods where there is excess generation from the renewables. This in other means can utilise the supply and demand capablity of the system in the most effective manner such that the grid conditions are optimally met. There are different kinds of demand side management strategies depending on the application or the ancillary services needed, which are later introduced in the chapter-2. The highest share of investments on adopting demand response programs would probably be on developing suitable control strategies, installing smart-meters, control and tele-communication devices, which seems to be the cheapest of all the above mentioned possible solutions while drawing potential benefits and developments to the system.

[1] and [2] also states that there are new generation appliances like Electric vehicles, individual heat pumps, electric boilers that will gain interest among the people in the future which are not as popular now in Denmark due to their costs. If seen on DSO and TSO point of view, these appliances are basically loads with bigger ratings and thus they would bring in potential increase in the annual average energy consumption. In the context of this project, new generation loads are a great source of providing flexibility to the demand and thereby having the annual energy consumption on track. These appliances would not

not always be connected to the grid and would not also follow any regular consumption pattern since it completely depends on the customer's convenience who are not aware of the grid conditions and regulations. When these appliances are set to operate based on certain consumption fashion to help the grid to run optimally, they become flexible loads and thereby explaining the benefit of demand response programs to the system operators. This also will bring in potential benefits to the customers by getting incentives or saving the energy bills.

Adoption of electric vehicles are considered to be one of the most promising approach to electrify and develop emission-free transportation sector which could offer potential socio-economic benefits. Though providing benefits, it cannot overshadow the impacts on the distribution grid and its components when adopted on a large scale [9]. EVs are comparatively larger consumer loads and the main challenge to be addressed upon large scale adoption would be grid congestion and voltage regulation issues [10]. But it is also said that EVs possess a greater potential to contribute demand response (DR) and offer flexibility to the consumption by adopting certain patterns of charging instants. Like, plugging off not to charge when the demand or price for electricity is high, and plugging in to charge when the demand or price of electricity is low and also when there is a need to utilise the excess generation from the variable RES. This characteristic behavior of EVs when aggregated can be seen as a flexible capacity resource which could also aid maintaing balance in the system during contingencies and reduce the urging necessity to expand the grid and interconnection capacities [2].

1.2 Problem formulation

As mentioned in the previous sections, power generation will be highly dominated by renewable sources in order to minimize burning of fossil fuels in the near future. Supply side management through large conventional CHPs running on fossil fuels will not exist in harmony with the 2050 energy target, which will further make the system dependent on the interconnections with the neighboring countries during contingencies and disturbances due to poor or high wind conditions. Also, import-export of power with the neighboring countries may always not be profitable and cost-effective since the market is dynamic and volatile. Hence, there will be a strong need for ensuring the regulation of energy resources within Denmark.

As mentioned in the previous sections, household demands will also be dominated by large energy storage devices/appliances and electric vehicles in the near future. And these devices and vehicles help achieving the Denmark's clean energy goals. But considering that the generation is going to be highly variable and electricity demand on the other hand is also going to increase rapidly, managing the equilibrium at system level and congestion/voltage related issues in the distribution grid is going to get tougher. Hence, the conventional supply side management alone will not be enough to maintain a balanced system, but the demand side management should also be tuned in a manner that it supports the system by offering flexibility.

1.3 Objective

The aim of this project is to study the impact of large-scale integration of electric vehicles in the low voltage distribution grid and develop relevant control schemes for the charging, so as to provide demand flexibility and manage the impacts caused. To realize the above aim, the following objectives are conducted through this project:

- Theoretical review on electric vehicles and demand response management.
- Modelling of a low voltage distribution network with flexible electric vehicle units.
- Developing relevant incentive-based and price-based demand response control schemes for charging the electric vehicles
- Analyze the operation and performance of the developed control schemes in the low voltage distribution grid.

1.4 Methodology

DIgSILENT PowerFactory is the main software tool used for all the simulations in this project. The electric vehicle model was developed using DPL (DIgSILENT programming language) and QDSL (Quasi-dynamic simulation) modelling toolbox. The demand profiles for the households are accessed from CREST demand model, which is an open-source platform for real-time household demand data. The price profile for the price-based control scheme is accessed from Nordpool day-ahead (Elspot) market.

Following is the methodology that is followed in this project:

- Demand models for residential loads and electric vehicles are developed.
- Dynamic model for electric vehicle is developed.
- Developed models are tested in the LV distribution grid and reference case is derived.
- Simulations for price-based and incentive-based controlled charging are carried out.

1.5 Limitations

The common limitations considered through out this project are specified below:

- The distribution grid is assumed to be balanced 3-phase and single phasing is neglected.
- Power electronic components and power quality are not considered while modelling the electric vehicle battery.
- Electric vehicle battery is assumed to absorb only active power.
- One random day in winter was chosen for generating the demand profile for the households and obtaining price profile. And for simplicity, system prices are used and not retail prices.
- Degradation of the battery is neglected.
- All the electric vehicles are assumed to be charged only once per day.

1.6 Outline of the thesis

Chapter 1: Background, motivation, objectives, methodology and limitations are explained.

Chapter 2: A state of the art review on the demand response management and participation of electric vehicles in offering flexibility.

Chapter 3: Grid description, residential demand model, electric vehicle demand model and electric vehicle dynamic model are presented along with steady state studies.

Chapter 4: Operation of price-based demand response control scheme and performance of the grid are illustrated

Chapter 5: Operation of Incentive-based demand response control scheme and performance of the grid are illustrated

Chapter 6: Comparative study of the two implemented control schemes along with conclusions and future work.

CHAPTER-2

In this chapter, introduction of Danish distribution system and energy markets have been summarized in relation to this project. A short literature review on deployment of demand response program has been presented and the ability of Electric vehicles to offer flexibility has been quantified through some of the relevant previous work that are reported.

2.1 Distribution system

Over the last decade, the Danish power system has transformed from having big central power plants with large synchronous generators to integrating multiple distributed generation sources. The share of renewable energy has increased over the years and is still increasing with a large focus on wind power in Denmark.

The distribution system is a medium through which the end-user of electricity and the transmission system along with the generators interact. In other words, any grid that provides connection to a customer is a distribution grid [11]. There are 49 Distribution system operators in Denmark [12] and they operate at different voltage levels between 60kV and 400V depending on the geographical feasibilities and the consumer requirements. The chief responsibility of the DSO will be to provide electricity to the end-user and ensure that they meet the supply standards for quality and protection.

In Denmark, the architecture of the distribution network is getting modified over the years from place to place and time to time in order to host the evolving wind turbines, solar PVs and local thermal units. Accommodating more DGs does not easily benefit the society and economy but also creates operational problems in the distribution grids which are conventionally meant to follow the load and not to host generations. Repercussions are seen in form of grid congestion, voltage deviations, increased power losses and back-feeding [12]. Among which congestion management and voltage control are addressed all through this project.

2.2 Electricity markets in Denmark

The wholesale and retail electricity markets in Denmark are de-regulated since 1999 and 2003 respectively which means, the market players are liberated to buy and sell power between themselves. The market players in Denmark, Norway and Sweden make agreements through the Nord Pool market which exist as two submarkets based on the duration left before bidding, day-ahead basis (ELSPOT) and intra-day (ELBAS) markets [13]. The Nordic regulating power market is meant for selling and purchasing of regulation power necessary to balance the system during uncertainties, where the regulating power can also be obtained through bilateral agreements between the market players directly [14].

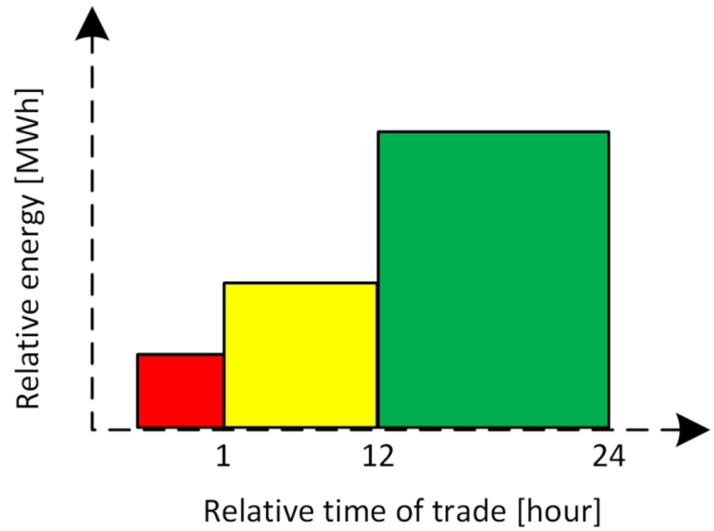

Figure 2. 1: Time frame of operation for markets [12]

The Elspot market operates on a day-ahead basis which involves three factors, the demand bid by an aggregator/retailer, available generation from a producer and the capacity available within the TSO control area. The producer decides the price and amount of power that is available to sell for the forthcoming day, based on their forecasts. The retailers also forecast their demand and price for every hour in the next day. And the actual price for the power trade in every hour is decided by demand and generation or purchase and sale curve example of which is shown in Figure 2.2.

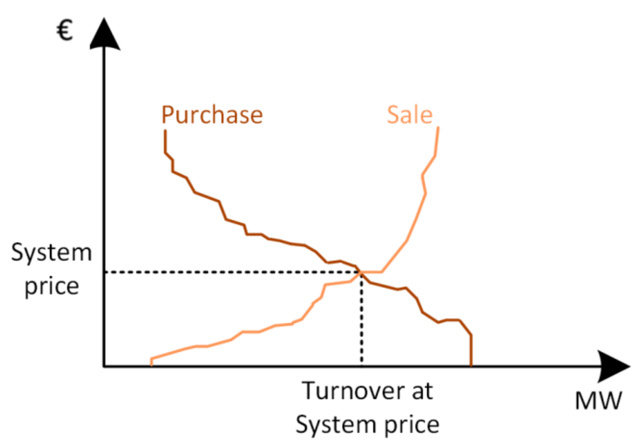

Figure 2. 2: Elspot price calculation for every hour.

The point of intersection of the price from the demand and generation curves will mean to be the market clearing price for the particular hour in the day next. But the clearing price may vary depending on the availability of free capacity under the respective TSO. When the power has to be transported to an area with higher available capacity, the price may be lower than to an area with heavily loaded grid. So, responsibility of the TSO in the Elspot market is to report the free capacity for every hour [11].

It is clear that the Nord Pool Elspot market operates based on the day-ahead forecasts and stochastic data and hence, it is not certain that there will not be any intermittency between the time of trade and the time of delivery. Here is why the placement of Elbas intra-day market is. In the Elbas market, the power required to equate the production and consumption in case an agreed producer falls out or able to produce excess power due to unpredicted weather conditions is traded. The trade in this market is meant to happen until an hour before time of delivery based on the hourly forecast [11]. Hence, the time of delivery for the power traded in this market will be lagging by an hour for the consumption. Also, the clearing price in the market comparatively is higher than in the Elspot day-ahead market.

The regulating power market is meant for buying and selling of regulating power to deal with the imbalances in the system within the time of delivery of the power traded in the Elbas market or due maloperation of any equipment. The balance responsible parties (BRP) can directly trade power to the TSO with bilateral agreements and are available in three levels of control. Hence, the BRPs become responsible depending on the type of necessity, whether to increase or reduce production and consumption and thereby, involving in up/down regulation [12].

The primary control or the frequency control is activated when the system frequency varies more than $\pm 20mHz$ from the nominal frequency of 50Hz and within 30 seconds of realization. The secondary or load frequency control is activated after the 30 seconds of the disturbance and has to balance it no later than 15 minutes. If the system still runs out of secondary control, then the spinning reserves in form of tertiary control has to be activated [15].

There has already been research to design DR programs to potentially aid frequency regulation and other ancillary services to the TSO, thereby ensuring the system reliability at a low cost. Where, the loads are considered as a virtual spinning reserve to absorb less power during frequency drop [15]. So, Demand response programs tend to be a potential resource to alter the market structure and to implement a new flexible market in the future, where the commercial players will be able to trade flexibility as a commodity, Figure2.3.

Figure 2. 3: Flexibility Market [16]

2.3 Demand response

Demand response is referred as *"the changes in electricity usage by end-use consumers from their normal consumption pattern in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized",* according to the U.S. Department of Energy, 2006. In other words, Demand response is a temporary adjustment of electricity consumption in response to a reliability-based signal or price signal.

Conventionally, DR was practiced in the form of Demand-side management (DSM) activities that are carried out by the electric utilities to consume electricity more efficiently. Figure 2.4 classifies the DSM techniques by peak clipping, load shifting, load shaping, night-valley filling, strategic load growth, energy efficiency etc., to alter the electricity consumption and ensure the system reliability on a bigger time frame [17].

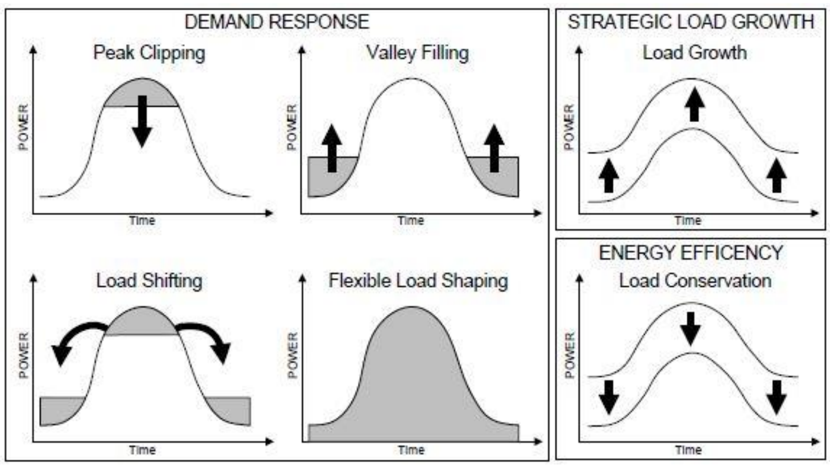

Figure 2. 4 Classification of DSM activities [17]

The prime idea of implementing DR program through this project could be to temporarily disconnect the load, or shift the time of its use, or reduce the consumption to maintain the generation and demand equilibrium and thereby managing the congestion in the network and support voltage deviations.

2.3.1 Types of DR programs

There can be three basic actions that an end-user can do to participate in DR programs. First, customer can reduce the usage of electricity during the critical peak period when the prices are high without altering the consumption patterns in other periods. Example for this type of response can be adjusting the thermostat settings of heat pump or an air-conditioner, which includes a temporary loss of comfort. Second, customers can respond to the high electricity prices by shifting the peak demand household activities (eg. Charging EVs, Dishwashers) to off-peak periods, where this bears no loss or subjects to any cost. Thirdly, the customers may respond for higher prices by using their storage units or local generation. Through this customer experiences very little or no changes in their consumption pattern but will be a significant change in the total demand when aggregated for a utility [18]. The existing DR programs can broadly be classified in to two types, IBP (Incentive-based program) and PBP (Price-based DR program). Depending on the applications, type of loads and consumer preference each of the two programs are further classified in Figure 2.4.

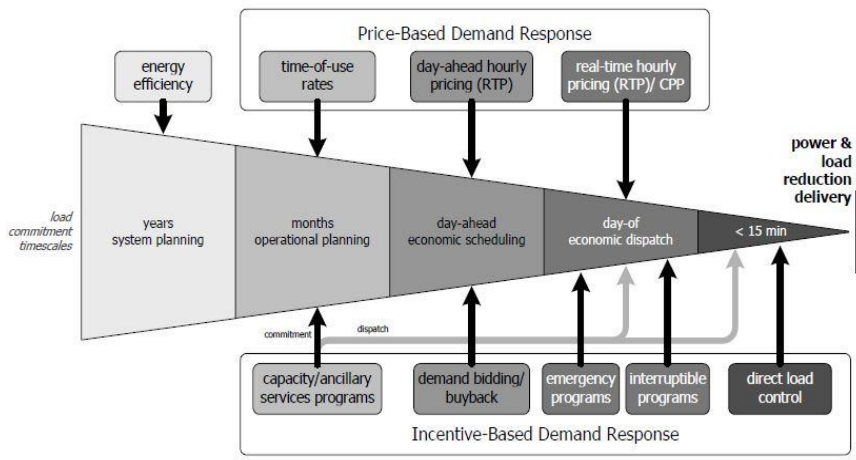

Figure 2. 5: Timescale of Planning and Operation of DR programs [19].

2.3.2 Incentive-based Program

In IBP, the DSOs make a contractual agreement with the customers to extract demand reductions during the events of higher prices or contingencies that threaten the system operation and reliability. The customers that are enrolled to the IBPs are paid incentives for reducing the load, additionally or separately from the fixed retail electricity tariff [20].

In Direct load control programs, the DSO will remotely have the authority to disconnect the customers' equipment on a short notice. Similarly, in Interruptible/curtailable programs, the customers will respond by reducing the loads to predefined setpoints for which they will be provided discounts and additional payments and on failing to respond, the customers will face penalties depending on the terms and conditions [21].

Market based IBP is where the customers directly lie in connection to the different types of markets based on the kind of program they are committed to [19]. Demand bidding, also known as buyback program, is where the customers bid their specific load curtailments in the wholesale electricity market. If the bid is accepted, customer will have to reduce the load as specified in the bid. In capacity market programs, the customers commit to provide pre-specified load curtailments on a day-ahead notice. This program in other way can help reducing the loading of the network and thereby lower the market clearing prices.

Ancillary services market program is similar to the demand bidding program, where the demand reductions are bid as operating reserves in the intra-day spot market. Market based IBPs earn customers the incentives for their specified response and penalties for failing to respond as committed in the bids or contracts [19].

2.3.3 Price-based Program

In Price based demand response program, the end-user of electricity is offered dynamically varying tariffs based on the market clearing price unlike IBP and with which the utility can indirectly control the load [17]. In simple means, customers are charged high prices for consuming electricity during peak periods and cheaper prices during off-peak periods. Peak and off-peak periods are defined based the application and the type PBP adopted. In general, Peak periods are when the cost of generation is higher, the total demand of the system is higher, or the network is overloaded; off-peak periods are when the total demand of the system is very low, or generation is higher and cheaper.

Time of use (ToU) program is the simplest and commonly used PBP, where the customers are charged different tariffs during different blocks of time in a day; in simple means, higher prices during peak demand and lower price during off peak demand periods [18]. Critical peak pricing (CPP) rates may be pre-specified additional tariff over the flat rate prices or ToU rates, charged during contingencies and price spikes in the wholesale electricity markets which may last for few hours in a day. Extreme day pricing (EDP) is similar to CPP, where the CPP may last for a whole day until the next day-ahead market clearing time. Real-time pricing (RTP) is the most advanced, economical but complex program where the end-user is charged based on the hourly-varying real cost of electricity in the wholesale market [22].

2.3.4 Benefits of DR program

The potential benefits of adopting DR programs can be realized in customers and all the entities of power system and energy market. First, the customers get economically benefitted by saving their electricity bills, incentives and for getting able to bid their flexibility offers in the market. This does not only benefit the participants of the DR programs but also the other customers by reducing the overall cost of the electricity indirectly [17].

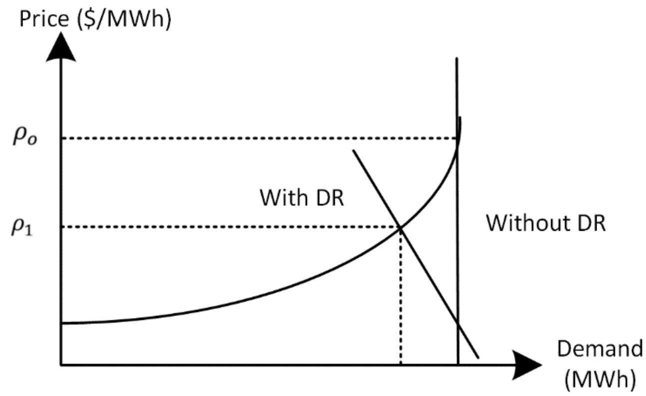

Figure 2. 6: Effect of DR on the market clearing prices [17].

Secondly, the TSO can efficiently utilize the DR programs to maintain the equilibrium between the generation and the demand which in turn reduces the need for expensive operating or capacity reserves and thereby aids reducing the price volatility in the wholesale market [27].

Demand Response Benefits

- Participant
  - Incentive payments
  - Bill savings
- Market-Wide
  - Price reduction
  - Capacity increase
  - Avoided/deferred infrastructure costs
- Reliability
  - Reduced outages
  - Customer participation
  - Diversified resources
- Market performance
  - Reduces market power
  - Options to customers
  - Reduces price volatility

Figure 2. 7: Potential benefits of DR programs [22].

Thirdly, the DSO will be able to manage the congestion and acquire consistent voltage support for the LV and MV distribution grids from deploying the DR programs at the domestic level. This in other way helps the DSO to delay or avoid the need for grid expansion to maintain reliability and reinforcement [28].

DR can eventually be realized from various types of flexible sources including, dispatchable loads, storages and other resources that are capable of modifying their consumption or generation. In the context of this project, Plug-in Electric vehicle being a dispatchable flexible load with storage capability is the prime focus.

2.4 Electric vehicles

According to [29], 20% of the total emissions in Denmark is estimated from the transportation sector and of which 50% is from the passenger vehicles. Although, the Danish government has plans to achieve zero-emission from the transportation sector by 2050 [2] and it is said that there will be no sale of conventional cars that run on IC engines by 2030 and every new car sold in Demark will be an Electric car or other Zero-emission cars aftermath. This transformation in the transportation sector also has another major benefit apart from reducing greenhouse gas emissions in the country; it reduces the quantity of petroleum imported and provides customers a cheaper alternative to the petrol and diesel.

In the power system perspective, EV is considered as a battery or storage device which behaves as a load while charging and as a source when it discharges back to the grid. So, the performance and characteristics of the EV differs from one another and it depends on the battery technology that is used to enhance the parameters like cycle life, power and energy density, energy efficiency and so on [32]. A brief classification on battery technologies can be seen from the table 2.1.

Type	Energy efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Life cycle (cycles)	Self-Discharge
Pb-Acid	70-80	20-35	25	200-2000	Low
Ni-Cd	60-90	40-60	104-180	500-2000	Low
Ni-MH	50-80	60-80	220	< 3000	high
Li-Ion	70-85	100-200	360	500-2000	Med
Li-Polymer	70	200	250-1000	> 1200	Med
NaS	70	120	120	2000	-

Table 2. 1: Battery technologies [32].

The electrification of transportation sector on the other hand, develops many operational challenges to the distribution system when integrated on a large scale. Due to the larger ratings of the EV, on large scale penetration the distribution system easily gets affected to face, overloading of cables and transformers, voltage unbalances and voltage deviation problems [30]. Switching on/off EV charging leads to voltage flickers and uncontrolled charging of EV during peak periods shows increased voltage drop and power losses in the LV grid [31]. So, it becomes important to study the impacts of large-scale integration of EVs into the local grid from the DSO perspective.

A distributed congestion price-based DR program has been implemented to relieve the congestion in the 60/10.5 KV Danish distribution grid by proposing a locational marginal pricing model in [34]. Thereby, reflecting the real price of congestion in the day ahead Nordpool spot market and scheduling the household loads through the interactions with the aggregators and DSO.

In [33], Vehicle to grid (V2G) concept has been investigated from the DR perspective and quantified the amount of flexibility it can offer in balancing the supply and demand. Complex network synchronization method is applied considering the dynamic behavior of the EV mobility to achieve synchronous stability and system balance.

In [35], demand shaping problem has been presented and an algorithm for distributed DR control of EVs to minimize the peak demand and smoothen the aggregated daily demand profile has been proposed. And it has been proved that it is possible for all the customers to accommodate EVs in their household and match the same peak demand without EVs.

[36] proposes a decentralized DR control method for an aggregator to optimally manage charging and discharging of EVs to not only maximize its profit by establishing real-time pricing to the customers but also maintain the distribution grid within its operational limits. And it has been proved that a large-scale integration of EVs can be adopted without violating the operational limits.

In [37], an integrated evaluation of dynamic pricing and peak clipping-based DR control for utilizing the bi-directional power capability EVs and Battery energy storage systems (BESS) has been presented. Mixed-integer linear programming has been used to model a home energy management system to enable vehicle-to-home and vehicle-to-grid capabilities of the EV. Two-way energy trading capabilities of the EV and BESS has been studied considering the availability and preferences of the consumer.

From the above presented literature review, it is obvious that interaction of EVs on a large scale with the distribution grid would result in line congestion and voltage drops. While, implementing DR control schemes along with aggregated EVs can help DSOs to avoid voltage deviations and manage congestion problems; provide ancillary services to the TSOs, especially when there is high/low wind power penetration; benefit the EV customers in saving the electricity bills; provide an option for the aggregator to trade flexibility in case of future flexibility market.

2.5 Demand response control methods

Over the years, there have been several research and studies carried out to develop control strategies to manage the high penetration of EVs, especially in the LV distribution grids. In [40], price based EV charging schemes have been proposed with simple control techniques, where customers typically reduce the consumptions for the high price periods and shift it to lower price periods. In [42] [43], optimum charging algorithms for EVs have been proposed based on the similar approach. However, adoption of purely price-based control techniques may necessarily not consider the network constraints and may lead to creating peak demands during the low-price periods. In this project, the possibility of involving DSO in means of providing the constraints and limits were also discussed. Figure 2.7 depicts the way different market players and stakeholders were involved for establishing price-based demand response program in this project.

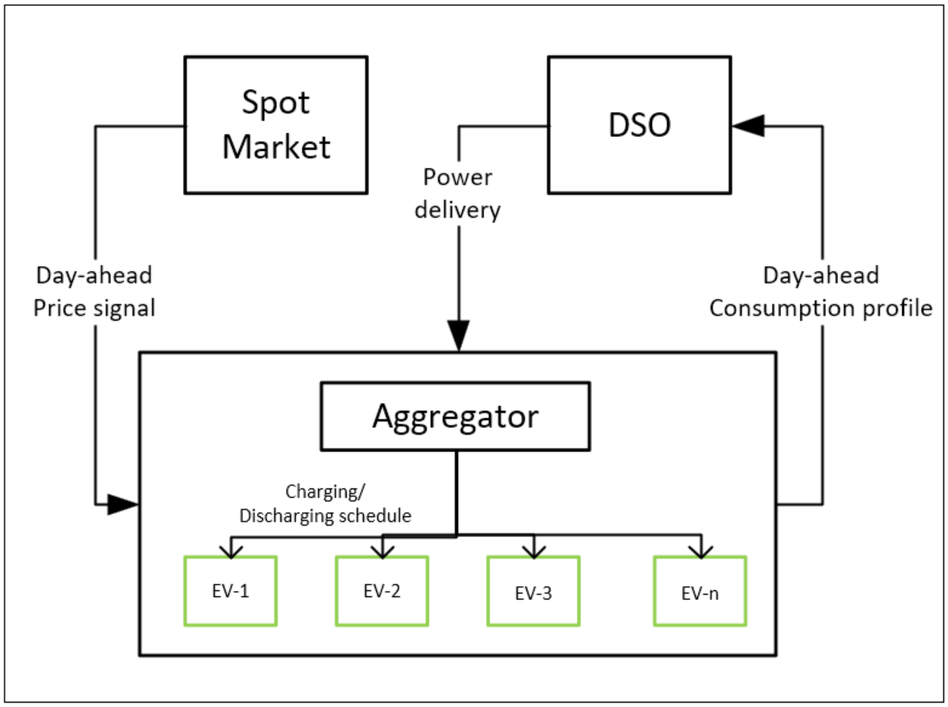

Figure 2. 8: Price-based Demand response program.

On the other hand, in [42] control algorithm for optimized charging of EVs has been proposed considering the voltage and thermal loadings as the network constraints. In [43], using a reference demand curve, a flexible EV charging optimization technique considering the thermal loading as the network constraint is proposed. In incentive-based demand response programs, the DSO is believed to have direct control over the charging/discharging of electric vehicles. Where, if the electric vehicle users respond to the notifications of DSO based on a Day-ahead consumption forecast, they will be paid incentives by the DSO. In this way, a DSO can benefit from managing the distribution system run under optimal conditions while the electric vehicle users might benefit by getting paid the incentives. Figure 2.8 represents the involvement of DSO and an electric car owner in the incentive-based demand response program implemented in this project.

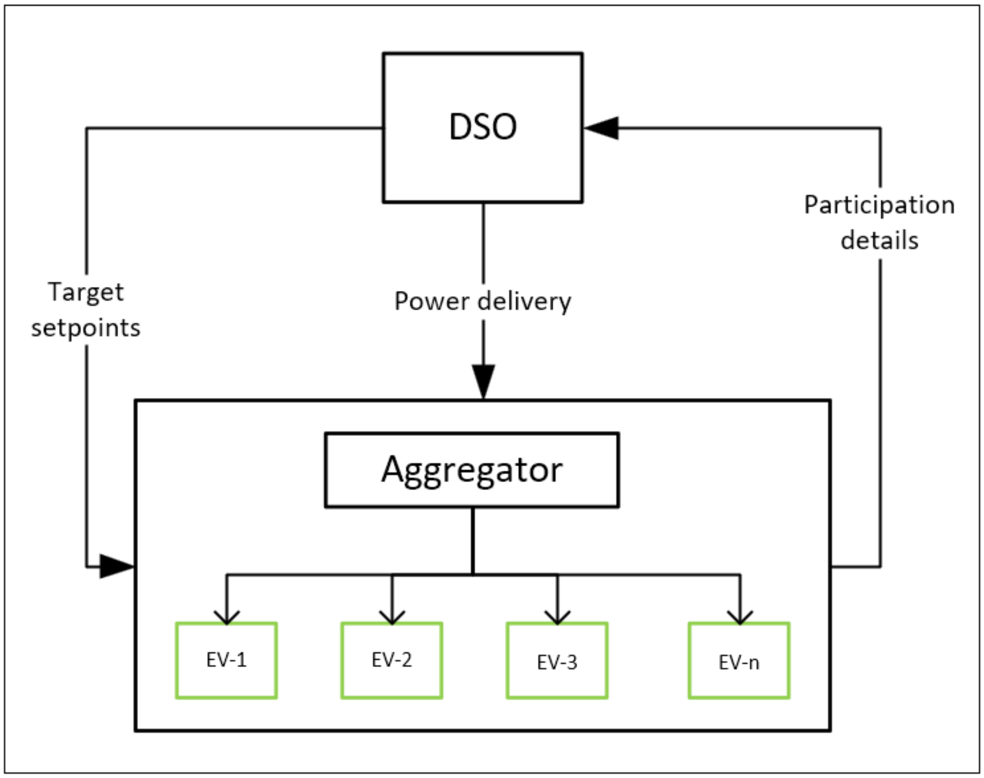

Figure 2. 9: Incentive-based Demand response program

2.6 Chapter summary

The previous sections in this chapter builds up the state of art that addresses both deployment of demand response strategies and integrating EVs from technical and socio-economical perspectives that are still under research and developmental stages in Denmark. It also clarifies that with the existing direct/indirect load control methods, there can always be high uncertainties in the load response and participation of the customers. Also, there is no specific measure or standard developed to deploy different types of DR and quantify the responsiveness of customers to manage the congestion and control the voltage in the LV distribution grid which, this project will try to address in the forthcoming chapters.

CHAPTER-3

Introduction

In this chapter, the low voltage grid used throughout this project along with the details of equipment used are explained; namely loads, transformers, electric vehicles and distribution lines. Then the steady state analysis is carried out under different levels of load demand conditions to evaluate the impact of the Electric vehicles on the distribution grid. To be noted, this chapter does not involve any kind of dynamic behavior of loads and electric vehicles.

3.1 Grid description

The objective of the project is to implement coordinated charging for electric vehicles in distribution grid. For this purpose, residential feeder from the CIGRE benchmark model of a 400V distribution grid is used [51]. In the Figure 3.1 as it can been, the residential feeder is supplied through a 20/0.4kV transformer and the feeder include several nodes with loads that depict the aggregated low voltage residential distribution grid.

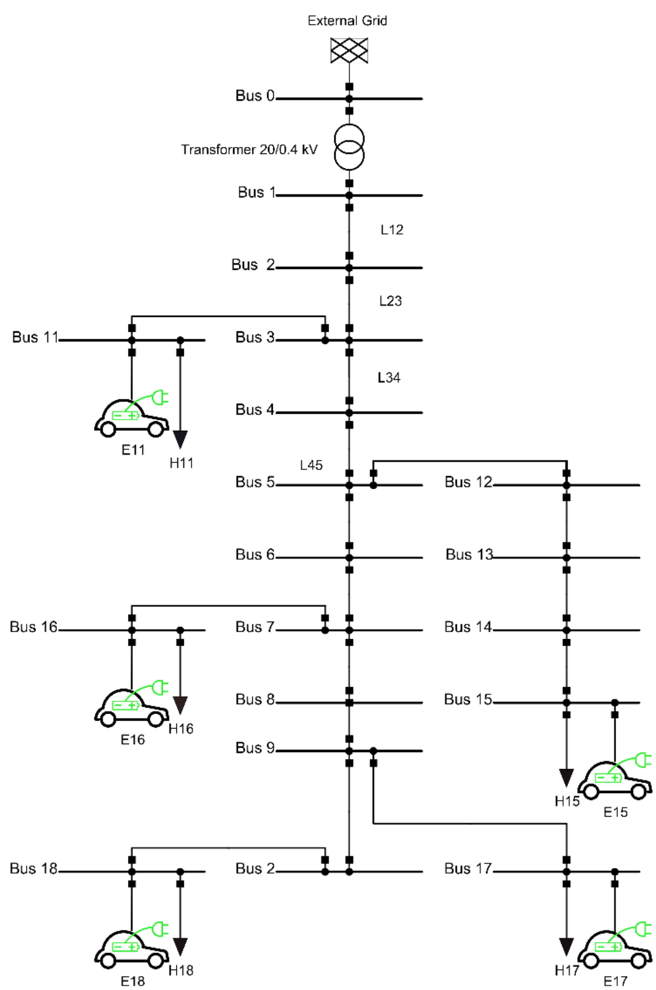

Figure 3. 1: Single-line diagram of the Residential feeder.

The table 3.1 summarizes the maximum capacity of the residential loads connected to the grid. And the housing loads demand models are explained in the section 3.2. The ratings and placement of the elements in the grid are completely based on [50], except the ratings and placement of Electric vehicle loads. The EV loads has been sized according to the currently available electric car models and also has been discussed in the section 3.3.

Installed capacity of the loads		
Residential loads	Bus: 11, 15, 16, 17 and 18	Total capacity: 200kVA

Table 3. 1: Summary of residential loads in the grid.

3.2 Residential load model

The data and ratings of all the other components in the grid can be found in the appendix-A. In order to represent the housing behavior realistically, CREST demand model published by the Loughborough university has been adopted to the residential loads [45]. This model comprises of electrical demand profile which was recorded from a household in one-minute resolution for any day in a year and of which a winter day has been chosen to be used. Figure 3.2 represents the housing demand model proposed by the CREST.

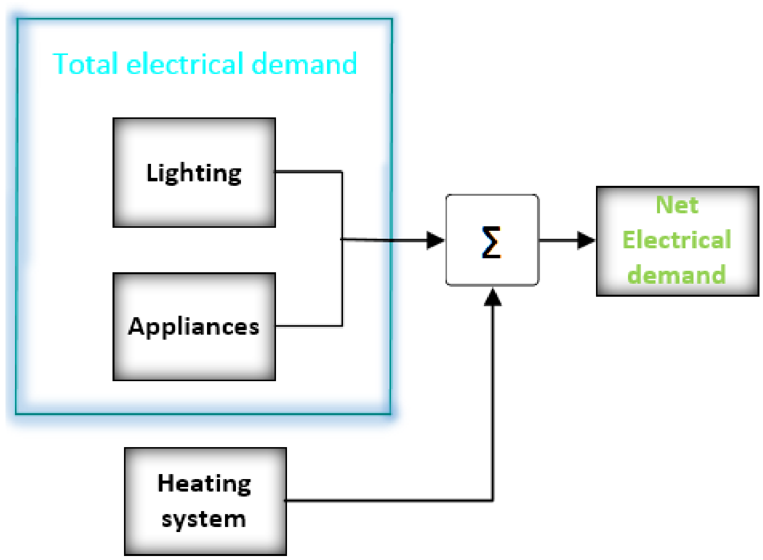

Figure 3. 2: Housing demand model [45].

Figure 3.3 represents the demand profile used for all the residential loads on a winter day of the year where heating demand is considerably higher than the other usages. In the residential consumption load profile in Figure 3.3, a morning 72% peak can be seen which may seem a little unusual and it is because of the hot water demands in the mornings which is also integrated within the heating systems of the house. The evening 100% peaks can be clarified to be the combined demand of heating and other electrical demand of the house.

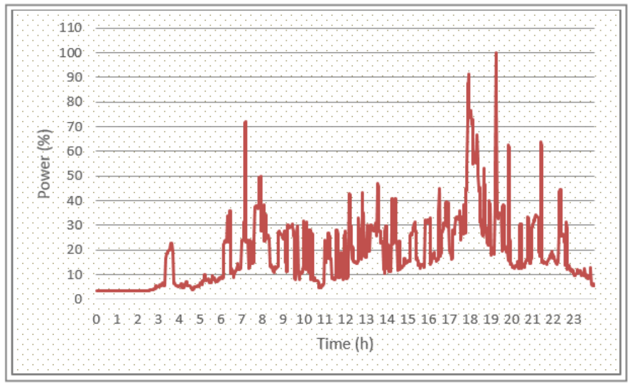

Figure 3. 3: Residential load profile on a winter day.

3.1.2 Load flow study

As it is said in earlier sections, the complete modelling of the network and analyses are carried out in Digsilent Power factory software. In such a way, Load flow was performed in the residential feeder with the consumption load profile for the loads varying every minute in duration of 24 hours, for which the results have been discussed in this section.

In his project, Newton-Raphson load flow method has been used to analyze the node voltages and the loading of the lines and transformers which are the basic factors of network congestions. The limits for the bus voltages and line/transformer loading are chosen randomly based on assumptions as in Table 3.2.

Permissible Limits	
Bus Voltages	**+5% p.u.** **-10% p.u.**
Transformer Loadings	**<80%**
Line Loading	**<80%**

Table 3. 2: Grid codes

By Newton-Raphson load flow method the apparent power flowing through any node in a network of n number of nodes can be given as,

$$S_i = P_i + jQ_i = V_i I_i^*$$

When, i and j are taken as adjacent nodes, active power flowing through the i^{th} node,

$$P_i = V_i \sum_{j=1}^{n} (G_{ij} V_j \cos\theta_{ij} + B_{ij} V_j \sin\theta_{ij})$$

And reactive power flowing through the node,

$$Q_i = V_i \sum_{j=1}^{n} \left(G_{ij} V_j \sin\theta_{ij} - B_{ij} V_j \cos\theta_{ij}\right)$$

Where, Current flowing through the any node,

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j$$

And branch admittance,

$$Y_{ij} = G_{ij} + jB_{ij}$$

θ_{ij} in the above equations will stand for the difference in voltage angles of two nodes.

Therefore, depending on the type of buses say, load, generator or a slack bus the unknown variable can be determined through any kind of power flow solutions, but Newton-Raphson load flow methods stands more powerful than the others due to its nature of attaining convergence faster and being independent about the size of the system in order to attain convergence. And same iterative method is used in Digsilent Powerfactory to calculate the nodal voltages and line currents for every component in the residential feeder.

The % Loading of the transformer is calculated by,

$$T_{loading} = \frac{|I|}{I_{rated}} * 100\%$$

Where, the rated current of the transformer,

$$I_{rated} = \frac{S_{rated}}{\sqrt{3} * V_n}$$

S_{rated} refers to the rated apparent power of the transformer.

% Loading of any line can be determined by computing the maximum of the following factors between any two nodes.

$$L_{loading} = Max\ of\ \left\{ \left(\frac{I_{bus,i}}{I_{rated}} \right) * 100\% \middle| \left(\frac{I_{bus,j}}{I_{rated}} \right) * 100\% \right\}$$

This load flow method was applied to the residential network for the maximum capacity of the loads in order to know the reaction of the feeder for the consumption peak. In the Figure 3.4 represents the bus voltages of the terminals where residential connections are present. Throughout this project, the bus voltages are represented in per unit values.

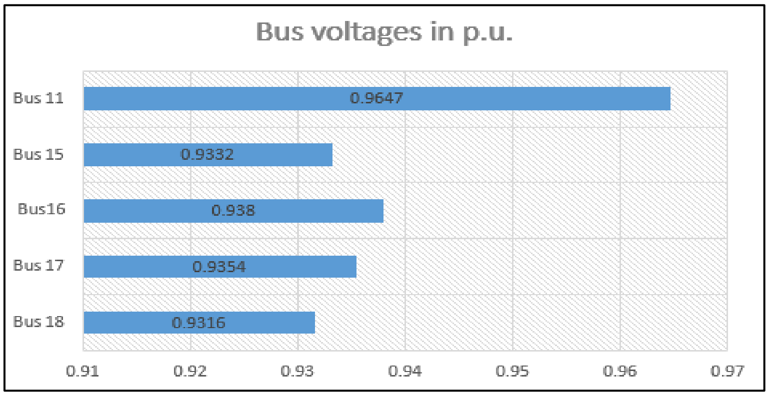

Figure 3. 4: Bus voltages for max capacity of the loads.

As it can been seen in the Figure above, the voltages at the buses 15, 16, 17, and 18 are nearly 3% lower than the bus 11. The residential feeder is radial by nature and the buses where reduced voltages are seen, are located far away from the distribution transformer and during the peak consumption, voltage drops across the lines and transformer will be higher; so the buses that are located far away will have to experience reduced voltages but there are several other measures normally DSOs carry out to mitigate this problems say, installing capacitor banks, capacitive filters, etc.,

In the Figure 3.5, loading of the lines and the transformer during the peak residential consumption is represented. And throughout this project, loading of the lines and transformer are always realised in % values.

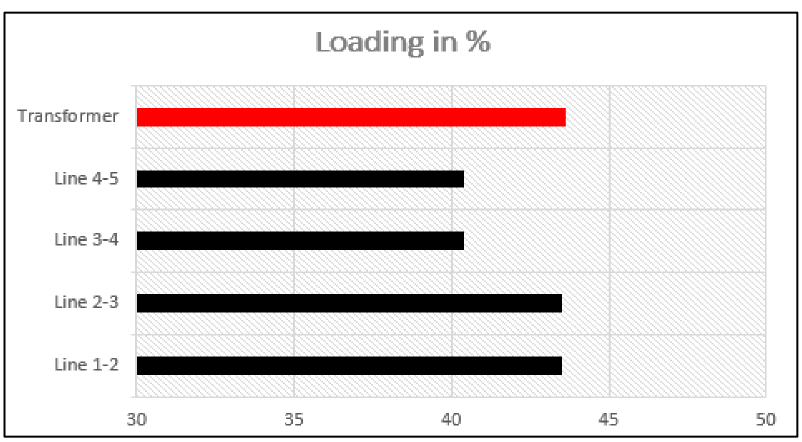

Figure 3. 5: Loading of the distribution transformer and the cables.

Lines 1-2, 2-3 and the transformer are very near to the connection point and they naturally will have to host the rest of the lines, nodes and loads in the radial feeder. Hence these two lines and transformer tend to withstand higher percentage of loading during the peak consumption period. Normally, the DSOs while laying the feeder, considering the overloading issues, use higher rating of cables for the lines near to the connection point. And to overcome the transformer overloading, DSOs install parallelly distributed transformers rather than installing one transformer of bigger power ratings.

From looking at the bus voltages, transformer and line loadings, it can be concluded that customers at the terminals of the feeder experience reduced voltage levels during the peak hours. Also, the Maximum % loading was observed at the transformer, lines 1-2 and 2-3 as 43.5%. But with regard to the grid codes adopted for this project as stated in Table 3.2, bus voltages and loadings seem to be under the capability limits. So, in the later sections, the condition of the grid when the electric cars are also introduced into the houses will be analysed.

3.3 Electric Vehicle demand model

Electric vehicles are believed to be really good source of providing flexibility and recognised to participate in DR applications in two ways by charging (EV) and discharging (Vehicle-to-Grid) with a common feature, battery storage. In this section, only the charging (EV) is considered in order to realise the impact of uncontrolled charging in the distribution network.

The charging fashion of an electric vehicle depends on several social factors and changes from user to user, like daily driving pattern, arrival and leaving time, individual comfort factor, etc., These characteristics of any EV users, determine the start charging time and initial state of charge (SoC) of the EV which in turn would determine the time taken to complete charging and the amount of energy consumed. Hence the charging demand from the electric vehicles can only be adapted and scaled based on the real-time surveys recorded or approximated from probabilistic distributions available for the different characteristics mentioned above.

In the Figure 3.6, normalized histogram for the probability of start charging events happening in every 15-minutes on a day is represented. This histogram was obtained from a real-time based project called “My electric avenue” which was carried out in the UK in the year 2018 and that project studied and surveyed 200 EV users’ charging behaviour and driving patterns in more than 85000 instants over a year of time [46]. There are two congested time periods that can be noted from the histogram in the Figure 3.6, but the morning consumption peak that is depicted in dark blue shade doesn’t cause much of a problem since it doesn’t last longer as that of evening peak.

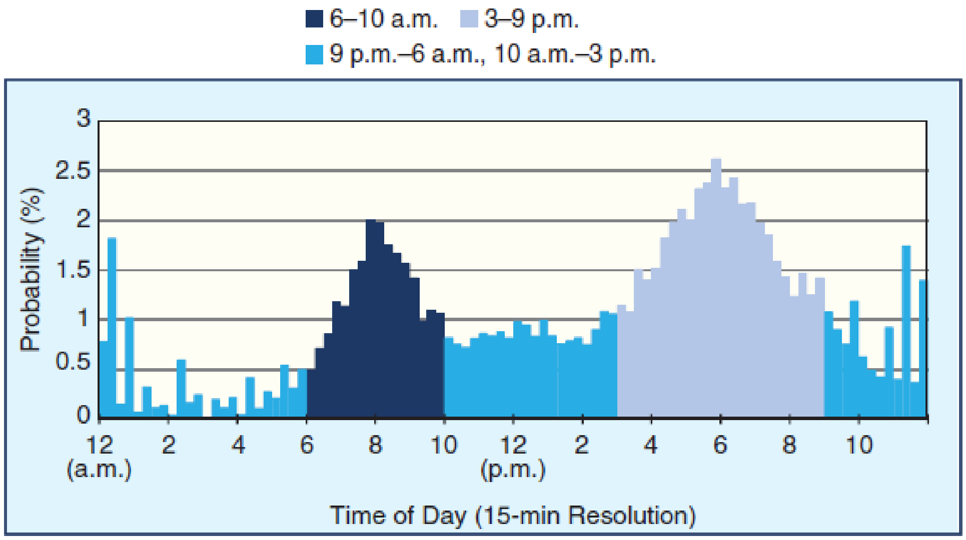

Figure 3. 6: Start-charging time of EVs [46].

Next, important factor that would help determining the time taken to complete charging would either be the initial state of charge during the time of connection or the distance driven by the user since the last time of charging. In the Figure 3.7, probability of initial SoC of the battery being in different levels is represented. From the Figure below, it can be observed that at least 95% of the users maintain a minimum SoC of 16.6% hence to be noted that, minimum possible initial SoC is considered as 17% throughout this project. Later in the Figure 3.8, the probability of Soc of the battery being in different levels during the time of disconnection is shown.

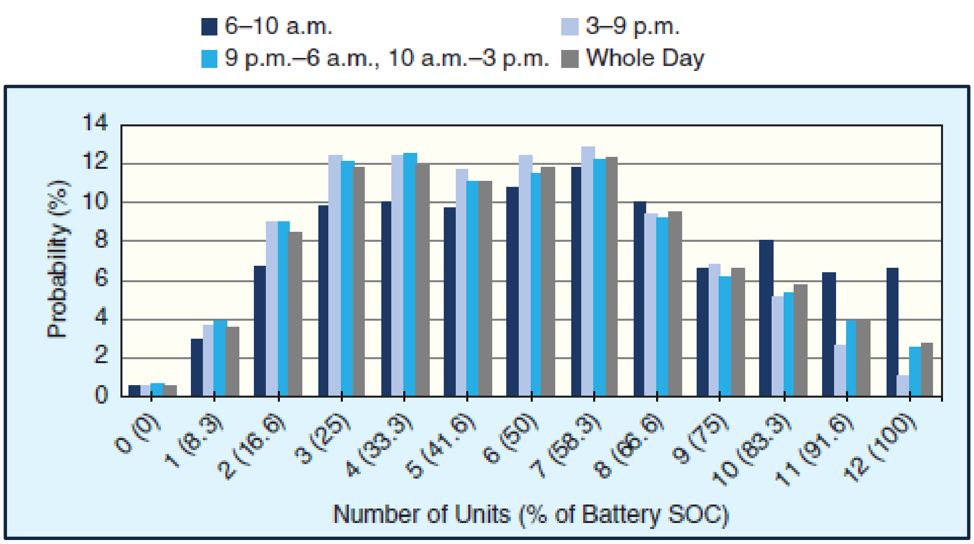

Figure 3. 7: Battery SoC at Start charging events [46].

From the Figure 3.8, it can be understood that there was about 75% probability of reaching a full charge between 3-9 p.m. To be noted, all these data and surveys from the 'MEA project' were not completely adopted in the reference cases. There are more data available regarding the users' charging behaviors during weekdays and weekends or having one or more charging events, etc., which will be discussed in the upcoming chapters. But for the reference case simplicity purposes, EV owners were considered to drive the same distance on both weekdays and weekends. Like, on the weekdays they drive from home to work and on the weekends, they drive to the city center. And since 95% of the users had only one or less charging events on a day, second charging events were neglected.

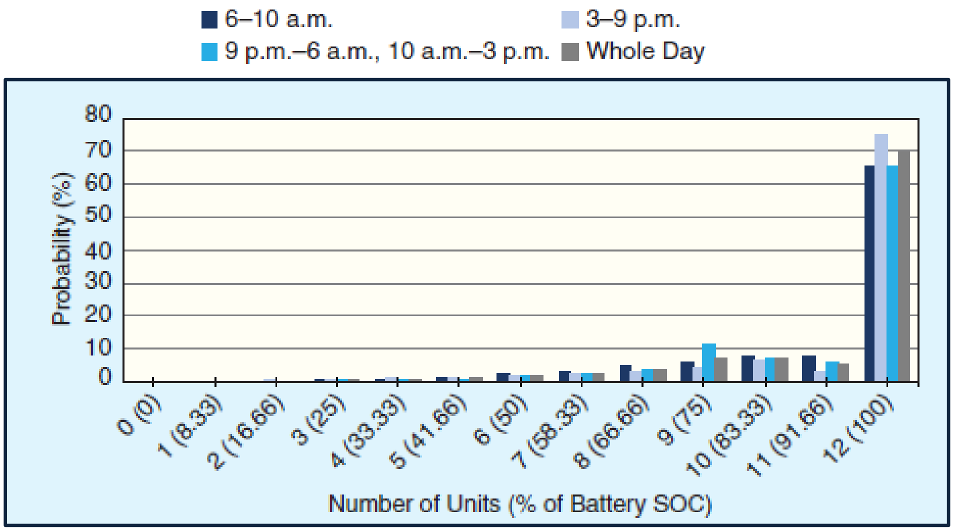

Figure 3. 8: Battery SoC at finish charging events [46]

As stated in previous sections, there are forty housings in this residential feeder and each of them are considered to own an electric vehicle. Among them, 15 houses own Tesla model S type of car and 25 of them own Nissan Leaf type of car. These two models of electric cars are very popular in the market and are believed to be the most sold electric cars so far. Also, both the cars come with different charging power, energy capacities and driving ranges which may take this project near to very realistic scenarios. Table 3.3 provides a brief description about the electrical characteristics of both the electric cars discussed above.

DESCRIPTION	DETAILS	
MANUFACTURER-MODEL	TESLA-MODEL S	NISSAN-LEAF
BATTERY CAPACITY	60 kWh	40Kwh
BATTERY WEIGHT	2090 kg	1640 kg
MAXIMUM RANGE	335 km	243 km
ENERGY CONSUMPTION	0.179 kWh/km	0.15 kWh/km
EFFICIENCY	80%	80%
CHARGING POWER	11 kW	7 kW
CHARGER TYPE	3- Ø/400V	3-Ø/ 400V

Table 3. 3: Electrical characteristics of the Electric vehicles [47] [48].

According to the electrical characteristics of the chosen electric cars they of 60kWh and 40kWh energy storage capacity and they charge at 11kW and 7kW at constant power respectively. Hence, it takes 5 hours 27 minutes for the Tesla model S and 5 hours 42 minutes for the Nissan Leaf cars to charge from 0 to 100% charging and it is portrayed in the Figure 3.9.

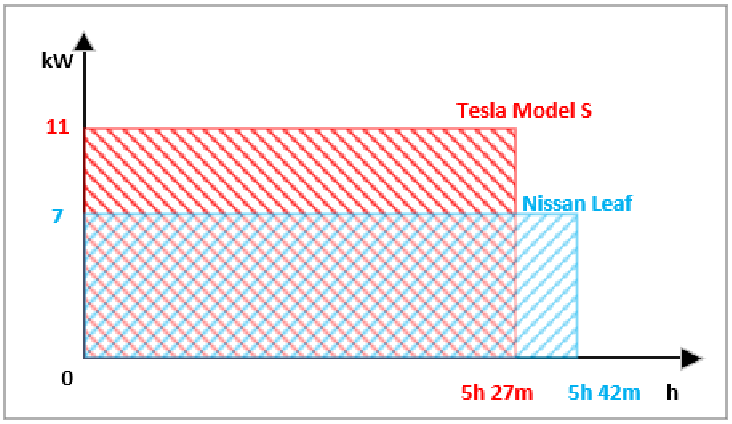

Figure 3. 9: EV charging characteristics.

Considering all the distributions and charging time picturized in the previous sections, an average charging demand chart for all the electric vehicles throughout a day of time can be obtained from a convolution. The average charging demand profile is depicted in Figure 3.10.

The average charging demand of EV for a day is obtained by convoluting the functions as mentioned in the previous sections and it is shown in the Figure 3.8. The peak demand from the EV is observed between 7pm. and 9pm., where maximum number of EVs charge at the same time. This is the common demand profile used for all the EVs connected to the grid in the following sub-sections 3.4.1 and 3.4.2.

Figure 3. 10: EV demand profile for whole day.

3.4 Impacts of integrating Electric Vehicles on the LV distribution grid.

In this section, two scenarios are presented depending upon the different penetration levels of Electric vehicles. Then the impacts of the electric vehicles during the consumption peak hours are studied, and a relevant case is taken forward to be improved through this project.

As stated in the previous sections of this chapter, from the 40 electric vehicles connected to the residential feeder, 15 electric vehicles are assumed to be 60kWh Tesla Model S and charge at 11kW of power, while the rest 25 electric vehicles are assumed to be 40kWh Nissan Leaf and charge at 7kW of power. Table 3.4 below gives a brief description about the nodes in the feeder where the loads are connected, total loading at each nodes and number EVs at every node.

Node	No. of EVs connected	Max. Charging Power (kW)	Total load of EV at node (kW)	Total housing load at node (kW)	Total load at node (kW)
Bus 11	14	7	98	68.4	166.4
Bus 15	11	7	77	52.25	129.25
Bus 16	3	11	33	44.65	77.65
Bus 17	9	11	99	14.25	113.25
Bus 18	3	11	33	14.25	47.25

Table 3. 4: Description of loads included.

In the following two cases, the residential load profile is not altered and are fixed based on the demand curve presented in Figure 3.3. But the percentage of penetration electric cars are changed; 100% and 50% of the average charging demand profile shown in Figure 3.10.

3.4.1 Case-1: 100% Penetration

In this case, 100% of all the loads including the electric vehicles specified in the table 3.4 were involved and a steady state analysis through the ‘quasi-dynamic simulation’ module in Digsilent powerfactory was carried out. This study was conducted over a 24-hour period on a winter day with residential peaks between 6:00-10:00 AM and 5:00-8:00 AM along with electric cars charging peak between 4:00-9:00PM. The residential and electric vehicles charging profiles are depicted in Figures 3.3 and 3.10 respectively.

Firstly, all the bus voltages were looked upon and bus voltages of the buses with load connection points are presented in the Figure 3.11. It was observed that bus voltages were the least during the evening peak load instant where the conventional residential peak happens along with the charging events of electric cars. Bus 18, 17, 16, and 15 as seen in the Figure 3.1 are located far away from the connection point. Therefore, the voltage drop increases when the length of the line increases since the cumulative impedance also increases. Along with the distance, the lines have to experience increased power losses during the peak load instants which causes the voltage drop across the lines and that's why the buses at the feeder terminals have to experience undervoltage.

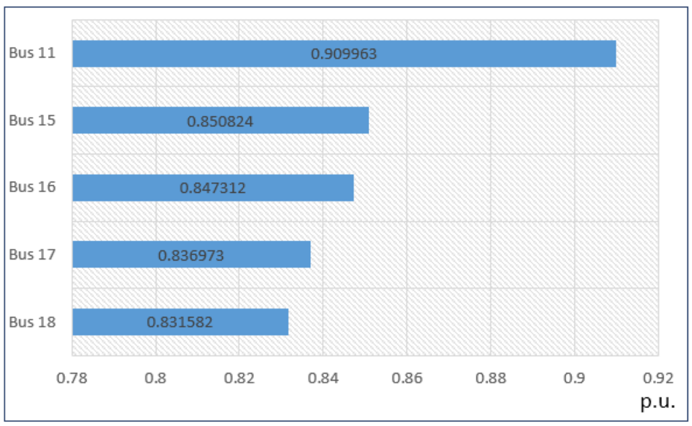

Figure 3. 11: Bus voltage at peak load instant.

Secondly, transformer and line loadings were studied throughout the 24-hour period and the maximum loading percentage was seen around the evening peak instant. During the peak load instant, the transformer is forced to generate high current in order to cater the loads, the constant power. As stated in the previous section, the buses with load connections experience undervoltage issues during the peak load instant. Hence, due to the increased current, overloading was experienced in the transformer and lines L12, L23, L34 and L45 as shown in the Figure 3.12. Ideally it is considered as overloading when the current flowing through a transformer or a line exceeds their rated current and, in this project, the permissible limits were considered 80% as maximum which can be seen in table 3.2. The maximum loading was observed at the lines L12, L23 and the transformer as 118% loading which is 38% high than the allowable limits.

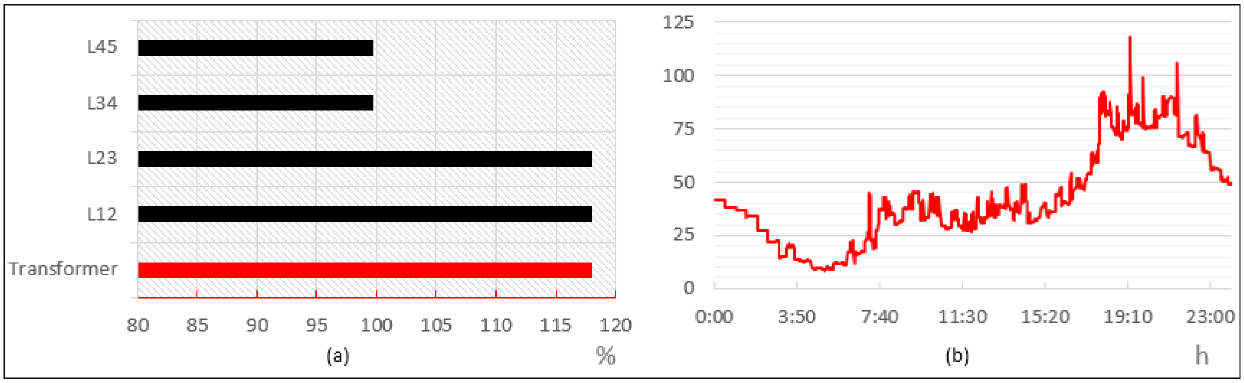

Figure 3. 12: (a) Loading of lines and transformer at peak load instant. (b) Transformer loading throughout a 24-hour period.

From this case study, it can be concluded that the grid cannot withstand or host uncontrolled charging events of 40 electric vehicles. In the later cases, studies will be presented from reducing the number of electric cars integrated into the grid by means of penetration levels.

3.4.2 Case-2: 50% Penetration

In this case, the residential loads were set to operate 100% to their capacities and the charging of electric cars were controlled to operate only 50% of their maximum capacity. In other words, the connected capacity of electric cars at each node was reduced to half of its maximum which was intended to refer charging of 20 electric cars; it was 40 electric cars in the previous case.

As it can be seen from the Figure 3.13, the minimum voltages at the buses to which loads are connected are represented. For 50% penetration the difference can be seen from the previous case but the voltage in most of the buses still prove that they are affected by undervoltage for the controlled charging of electric cars.

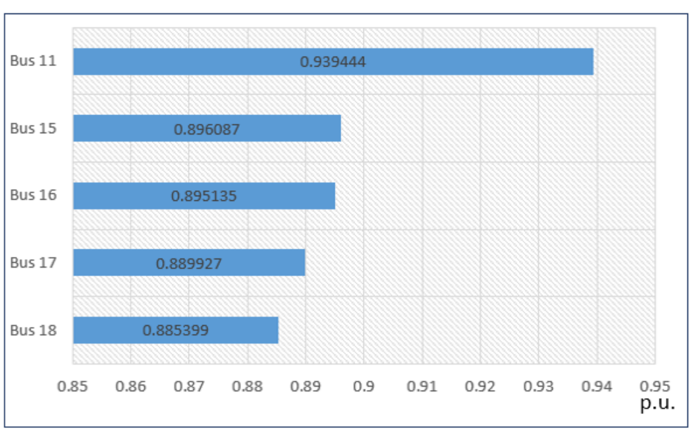

Figure 3. 13: Bus voltage at peak load instant.

On the other hand, the lines and transformer loading were also seen reduced and are marginally under permissible limits where, the transformer was observed as 78% which is 2% less than the permissible limit. In the Figure 3.14, the loading of the transformer and lines are presented along with the variation of transformer loading throughout the day.

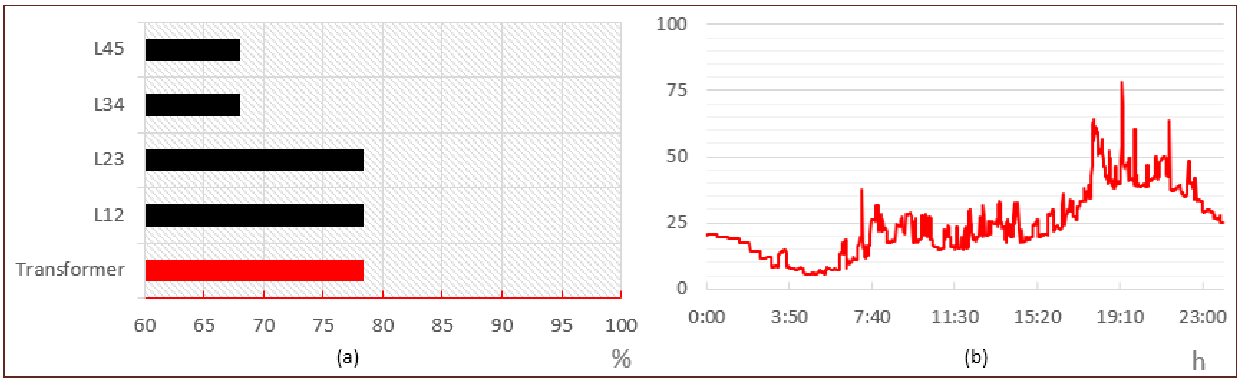

Figure 3. 14: (a) Loading of lines and transformer at peak load instant. (b) Transformer loading throughout a 24-hour period.

From this case, it can be concluded that transformer and line loadings are under control marginally, but bus voltages still appear to be slightly below the permissible limits.

3.5 Electric vehicle Time-dependent model

This electric vehicle model is developed in the Quasi-Dynamic Simulation (QDSL) toolbox in DIgSILENT PowerFactory, which can be used for long term load flow simulation studies. Quasi-Dynamic simulation basically refers to carrying out a series of load flow simulations spaced in time and involving time-dependent models [51]. Block diagram describing the sequence of events during this simulation the procedure ae explained in Appendix-B. This model was developed in order to introduce the time dependent character of the electric vehicles, which could not be realized through the demand model in the previous section. Although the results obtained in the previous section using the data from [46] have been really useful for understanding the impacts of integrating electric vehicles to the distribution grid. Also [46] have laid the base for obtaining the parameters for this dynamic electric vehicle model.

3.5.1 Model Description

The Following equation is derived from [51], to represent the charging of the electric vehicle in this model.

$$SoC = SoC_{initial} + \frac{Pt * 100}{E * 3600}$$

Where, Pt is the charging power of the battery and E is the maximum capacity of the battery. And this equation forms the base for this electric vehicle model.

All the electric vehicles are assumed to be aggregated by summing up the charging power and battery capacity of all the electric vehicles at each of the 5 different nodes as shown in the Table 3.5 based on the residential location. Also, the initial SoC preferences has been set for each of the electric vehicles based on a condition which can be understood from the later chapters. The parameters represented in the Table 3.5 will remain the same throughout this project in all the following chapters and the results from this section will be regarded as the reference for the rest of the studies.

The arrival time of the electric vehicles are chosen based on Figure 3.6, such that the users arrive at home after work between 15:00 hours and 21:00 hours and connect the battery for charging. In this case, there is no control involved in charging of electric vehicles. Hence, the users start charging the electric vehicles as soon as the arrive at home when the state of charge is below their limits. The results from uncontrolled charging of electric vehicles are explained in the next sub-section.

Node	No. of EVs connected (No.)	Arrival time (h)	Aggregated Charging Power (kW)	Aggregated Battery capacity (kWh)	Preferred min Initial SoC (%)
Bus 11	14	15:00	98	560	20
Bus 15	11	15:00	77	440	35
Bus 16	3	16:00	33	180	45
Bus 17	9	17:00	99	540	20
Bus 18	3	18:00	33	180	20

Table 3. 5: Parameters for electric vehicle QDSL model.

3.5.2 Base case

In this section, the impacts of uncontrolled charging of electric vehicles are studied and documented for further references within this project. As a part of this work, dynamic load flow simulation was carried out for a span of 24 hours in a day from 10:00 hours to 10:00 hours the next day. All the electric vehicles engage in charging as specified by the parameters in the Table 3.5.

Figure 3.15 illustrates the results obtained from the load flow simulations after integrating this electric vehicle model.

Charging of the electric vehicles can be observed from plot (a) through the output state of charge. As there is no control over charging, all the electric vehicles start charging immediately upon their arrival.

In the plot (b), the voltage behavior of the most critical buses (Bus 11, 15, 16, 17 and 18) where the loads are connected can be seen. It is clearly visible that when all the electric vehicles charge simultaneously, under voltage problem is experienced very severely. With reference to the grid codes in Table 3.2, this appears to be a serious issue since the minimum permissible limit for any bus voltage is 0.9 p.u. Here in this case, buses 15, 16, 17, and 18 experience undervoltage at some level except the bus 11 which is located very closer to the distribution transformer. Bus 17 records the lowest voltage during the peak period at 0.862 p.u. and bus 15, 16, and 18 records 0.866, 0.875 and 0.864, respectively.

Finally, loading of the transformer in plot (c) reflects the situation when all the electric vehicles are simultaneously being charged and when they are not. The maximum observed transformer loading is 111% around 18:00 hours while the electric vehicles are parallelly charging and around the same instances where bus voltages are also recorded minimum.

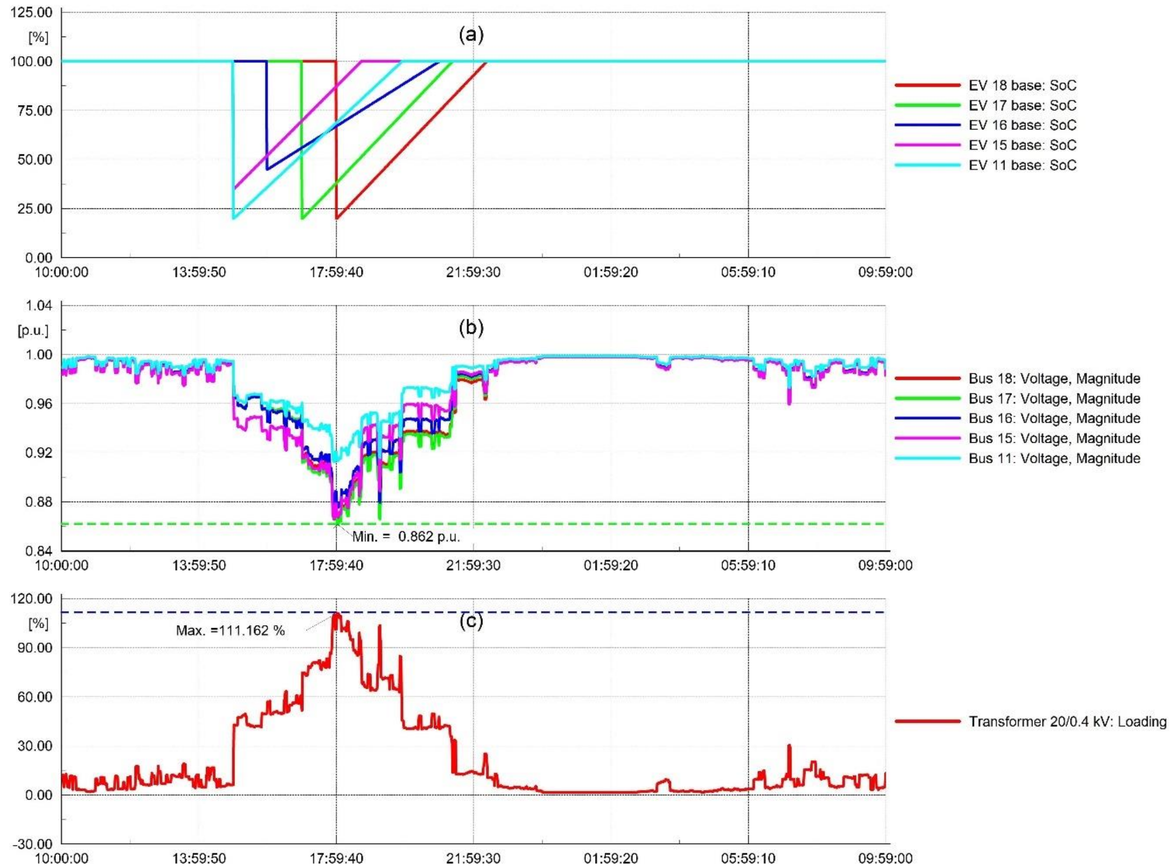

Figure 3. 15: (a) State of charge (b) Bus voltages and (c) Transformer loading.

3.6 Chapter summary

The modelling of residential feeder and descriptions of housing loads along with the load flow methods adopted for steady state studies were explained in the earlier sections of this chapter. Later, a demand model representing the consumption pattern of electric vehicle users was modelled and studied through different levels of penetration. Then understanding the limitations of using the demand model, a time-dependent electric vehicle model was designed in the quasi-dynamic toolbox of DIgSILENT PowerFactory. Finally, in the section 3.5.2, the dynamic electric vehicle model was tested by integrating to the grid and load flow was carried out. The results from this section will be playing an important role throughout the later chapters, being the base case to which further results will be compared with. And it can be inferred that the grid experiences severe problems through undervoltage and over loading when the charging of electric vehicles is uncontrolled. Hence in the next chapter, one of the two measures proposed to overcome this problem is presented in the next chapter.

CHAPTER-4

In this chapter, studies regarding the controlled charging of electric vehicles based on the day-ahead electricity prices are presented along with the operation and results.

4.1 Price based demand response model

As stated in the section 2.5, the objective of price-based demand response control is to economically benefit the electric vehicles user, aggregator and indirectly benefit the distribution system operator by offering flexibility in the consumption. The price-based model used in this project aims to benefit the user by reducing the electricity tariffs. From Figure 2.7, the aggregator will have the control over the number of electric vehicle users based on contracts/agreements and provide them with the day-ahead electricity prices and monitor consumptions every day. Also, the aggregator helps the DSO with the forecasted consumption patterns, so that the DSO can plan their operations. the block diagram for the performing the control operation in the DIgSILENT PowerFactory modelling environment QDSL is depicted in Figure 4.1.

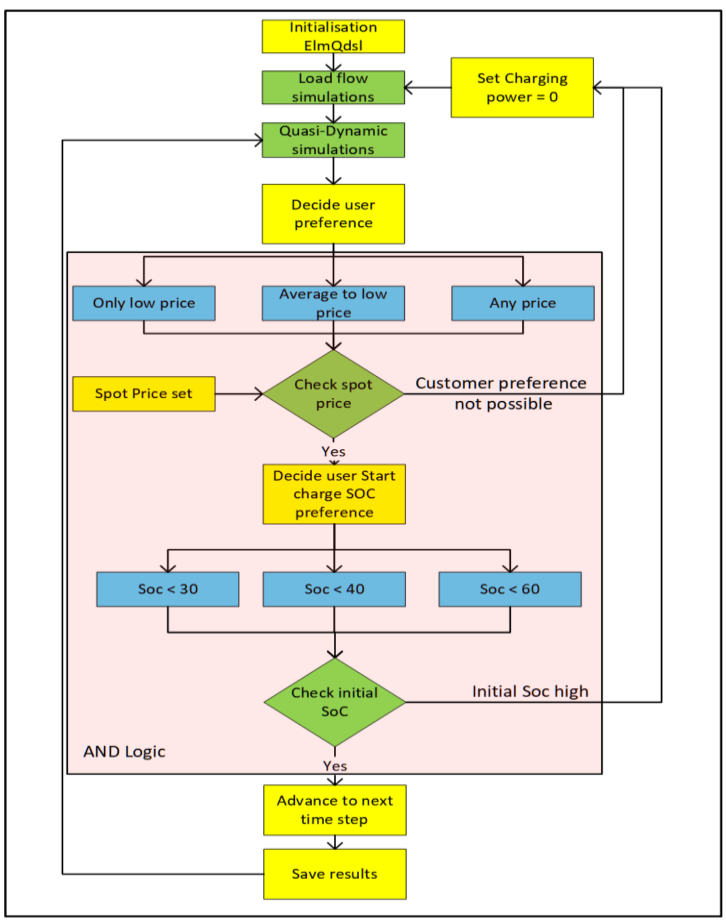

Figure 4. 1: Price-based demand response control operation.

The control algorithm considers the minimum allowed initial state of charge (SoC) and maximum allowed price to charge the electric vehicle upon arrival. The electric vehicle user receives the electricity pricing for every hour of the next day in advance and chooses the maximum price until which the vehicle can charge. So, when the price of the specific hour is higher than the user specified limit, the charging is switched off until the next instant where the price is below the user specified limit. Similarly, the user specifies the minimum SoC at which the electric vehicle charging can be started depending on the distance travelled after the last instant of full charging and until the time of arrival. When the SoC at the instant of start charging is higher than the user specified limit, the charging will not start and be skipped for the day. In order to check both of these conditions simultaneously before start charging, AND logic is used. Validating these conditions and managing the charging events of the number of electric vehicles adds up to the responsibility of an aggregator and marks them as a different player than a conventional electricity retailer.

4.2 Model Description

In this section, the input parameters involved in operating the electric vehicle in the grid through price-based demand response control are explained along with few assumptions and limitations. The demand curve for the residential houses is not changed from the base case and can be referred to Figure 3.3. In this case, electric vehicles are divided in groups based on their users' preference for price limit and start charging SoC level. In this case, the user's preference towards the cost of electricity and start charging SoC level are considered and that marks its difference from the base case operation in 3.5.2. It can be observed from the Table 4.1, there ae 5 different price levels which are chosen randomly to represent the users' nature to prefer low price, average price, and high price.

Node	Arrival time (h)	Aggregated Charging Power (kW)	Battery capacity (kWh)	Preferred min Initial SoC (%)	Preferred max price limit (DKK/MWh)
Bus 11	15:00	98	560	20	148
Bus 15	15:00	77	440	35	190
Bus 16	16:00	33	180	45	170
Bus 17	17:00	99	540	20	156
Bus 18	18:00	33	14.25	20	152

Table 4. 1: Parameters for Price-based demand response control.

So, the electric vehicles at bus 11, 17 and 18 are believed to charge during the low-price periods, while the ones at Bus 16 and 15 are believed to charge when the price is in average level and high level respectively and this is depicted in Table 4.2. When it is said high price, this group of electric vehicles prefer to charge at any time and do not care about what the price is. The categorization of price groups below was done based only the day-ahead price depicted in Figure 4.2

Low Price	Average Price	High price
<160 DKK/kWh	<180 DKK/kWh	>180 DKK/kWh

Table 4. 2: Categorization of electric vehicles.

4.2.1 Price profile

In order to implement price-based demand response control, a price profile is required based on which the users can choose their time to start charging. The price profile used in this case can be observed from the Figure 4.2. This price profile represents a real time day-ahead system price. A random winter day was chosen in that matter, where the wind power production had a serious impact in pricing. That is, more the wind power generation on that particular day, the lower was the system price. The price in the Figure 4.2 varies every hour for a span of 1 day and was accessed from Nordpool day-ahead market. The retail electricity pricing was not used in this case considering the simplicity purposes.

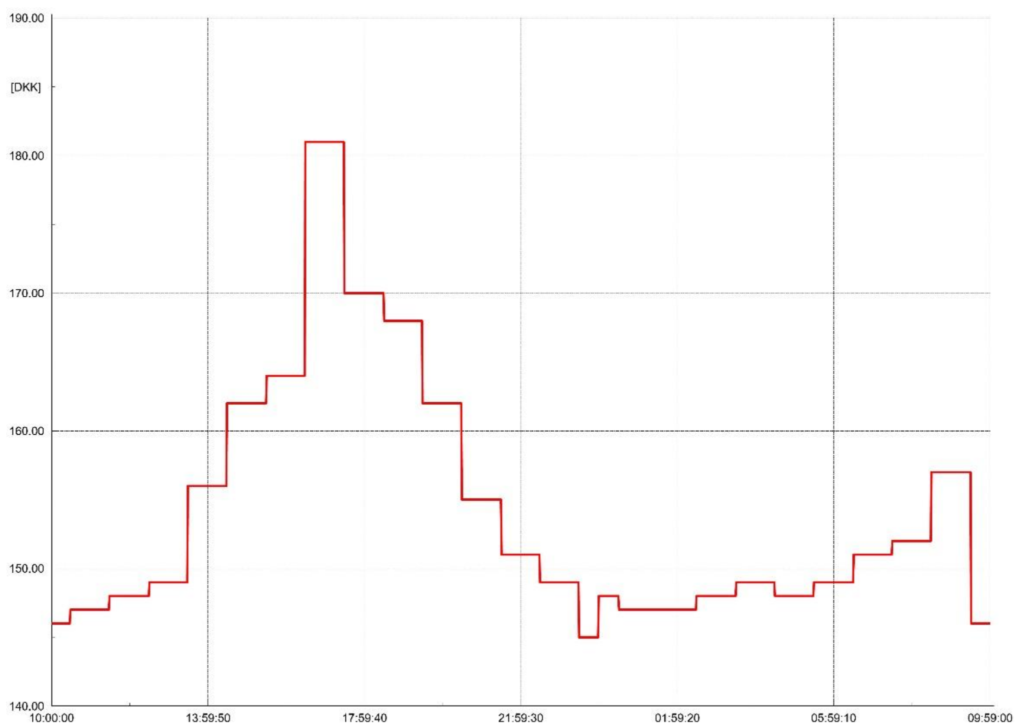

Figure 4. 2: Price profile on a winter day [52].

4.3 Price based demand response control

In this section, the condition of the grid is analyzed after implementing price-based demand response control scheme for the electric vehicles. In the further sections, the behavior of the grid is illustrated in terms of obtained results for bus voltages, transformer loading and state of charge of the electric vehicles.

4.3.1 State of charge

In this section, the state of charge profile for the electric vehicle is obtained from executing the load flow simulations for the price-based control operation and compared with base case. In Figure 4.3, state of charge profile of uncontrolled charging of electric vehicles and price-based controlled charging of electric vehicles are depicted. It can be observed from the Figure 4.3 that the electric vehicles at bus 15 (EV15) is charging in same fashion in both cases since that user has opted to charge at even high prices. It can be noticed that charging of electric vehicles at buses 11, 17 and 18 (EV 11, EV 17, EV 18) are delayed though their arrival time is earlier, because the price of electricity during those hours seem to be high and they do no want to charge in that period. Also, EV15 at bus 15 stops charging only for the peak price period since that user has opted for charging only during below average price periods.

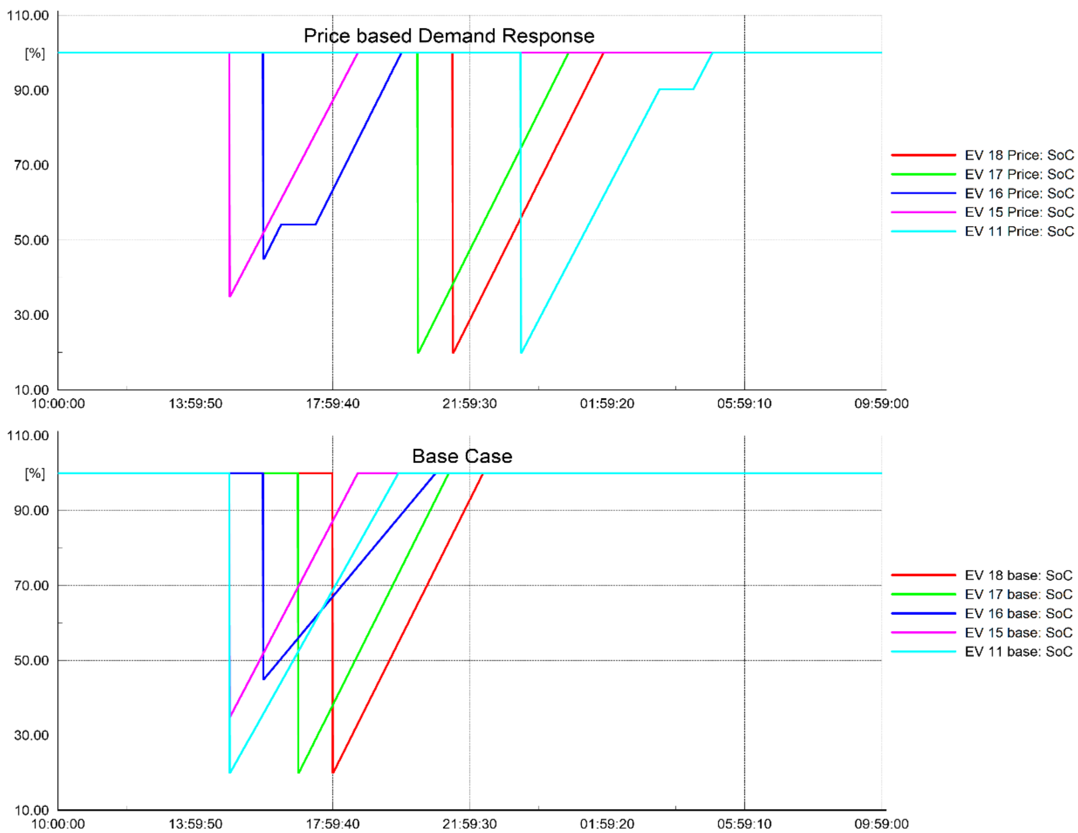

Figure 4. 3: State of charge profile for Price-based demand response control vs Base case

4.3.2 Bus voltage

In this section, voltages of the most critical buses in the grid are analyzed. Figure 4.3 depicts the plots of voltage in most critical buses, obtained from implementing the price-based demand response control and base case.

Firstly, in the base case, buses 15, 16, 17 and 18 experienced undervoltage issues during the uncontrolled charging of electric vehicles. Bus 17 recorded the minimum voltage of 0.862 p.u. in the base case which is highlighted in the Figure 4.4.

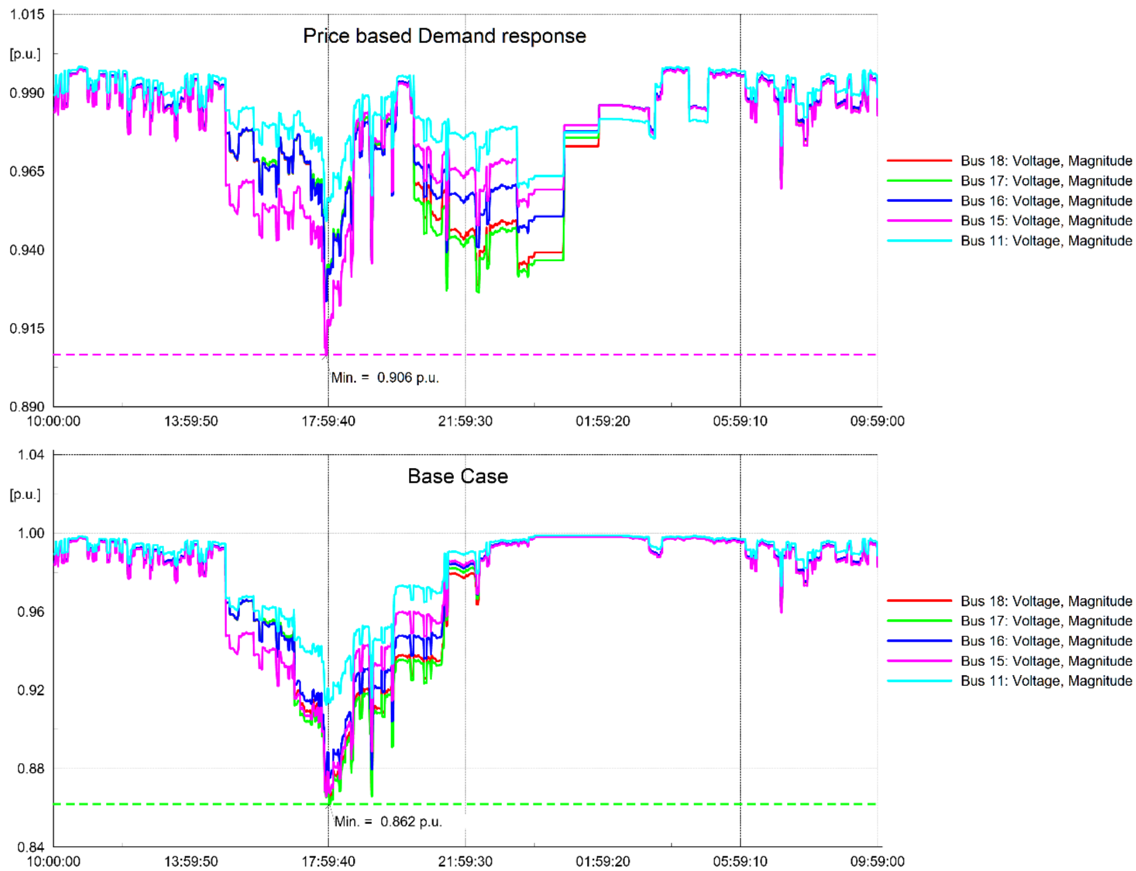

Figure 4. 4: Bus voltages profile for price-based control vs Base case.

Secondly, it is clearly observed that there is no undervoltage issues existing in any of the buses in the grid after implementing price-based demand response control scheme, with reference to the grid codes mentioned in the Table 3.2. The lowest recorded voltage in this case is 0.906 p.u. at the bus 15. It is to be noticed that bus 15 is one among the three buses containing households and electric vehicles and that are located far away from the distribution transformer. And the electric vehicle connected to this bus (EV15) prefers to charge for any price and extends the consumption peak created by the residential households. Otherwise, price-based demand response control scheme seems to be effective in managing the undervoltage problem in rest of the critical buses.

4.3.3 Transformer loading

In the Figure 4.5, transformer loading obtained after implementing the price-based control is depicted along with the transformer loading from the base case.

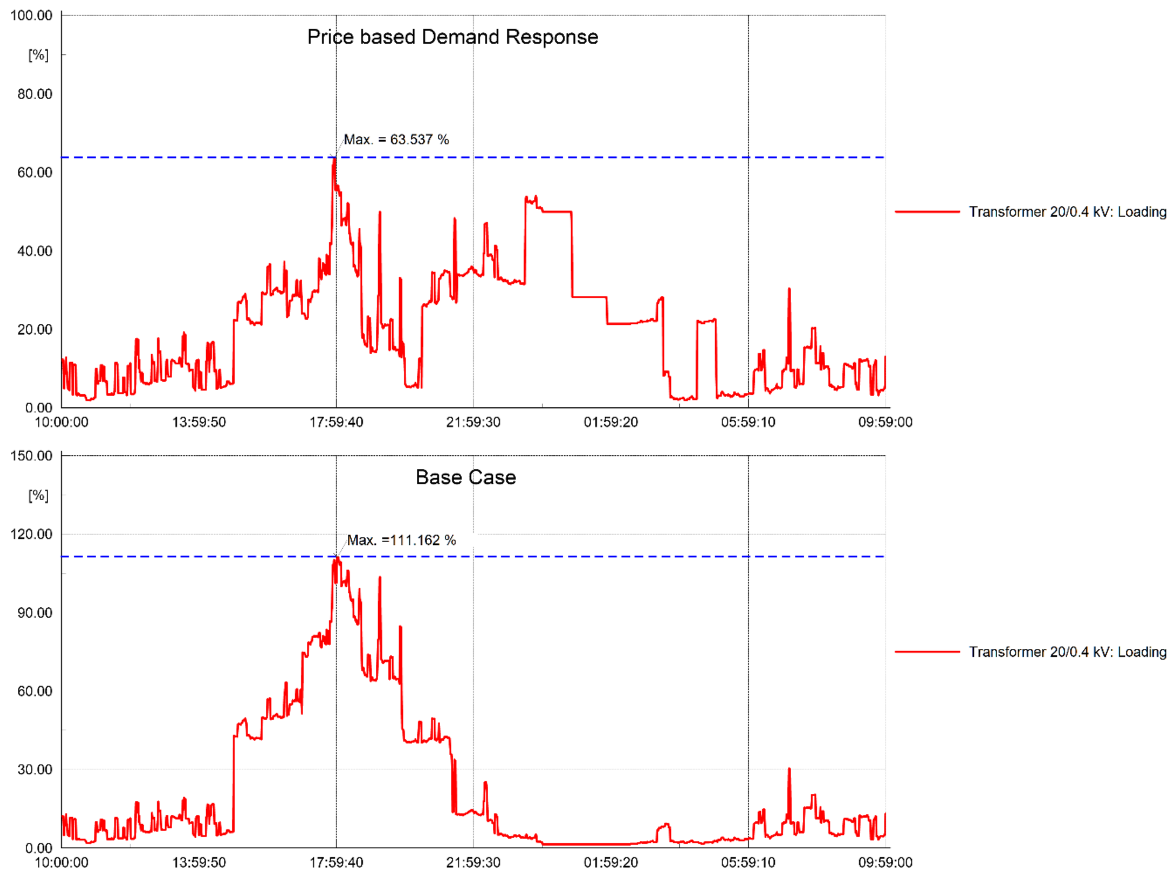

Figure 4. 5: Transformer loading for price-based control vs base case.

The loading of the transformer in the Figure, completely reflects the situation where the loads are being shifted to the low-price periods through price-based control of electric vehicles charging. The maximum loading of the transformer for price-based control is 63.5% while that of base case where there is no control involved is 111%. The reduction in the maximum transformer loading between controlled and uncontrolled is 47 %. Also, the maximum permissible limit for the transformer loading mentioned in the Table 3.2 is 80%, which is still satisfied through this control methodology.

4.3.4 Price-based charging

In this section, prime reason to implement the price-based demand response control scheme is explained. In the Figure 4.6, charging profile of the electric vehicles are represented against hourly varying electricity prices. Comparing the results in the both the plots below and referring to the input parameters in Table 4.1, it can be inferred that the price-based control of electric vehicles works as expected.

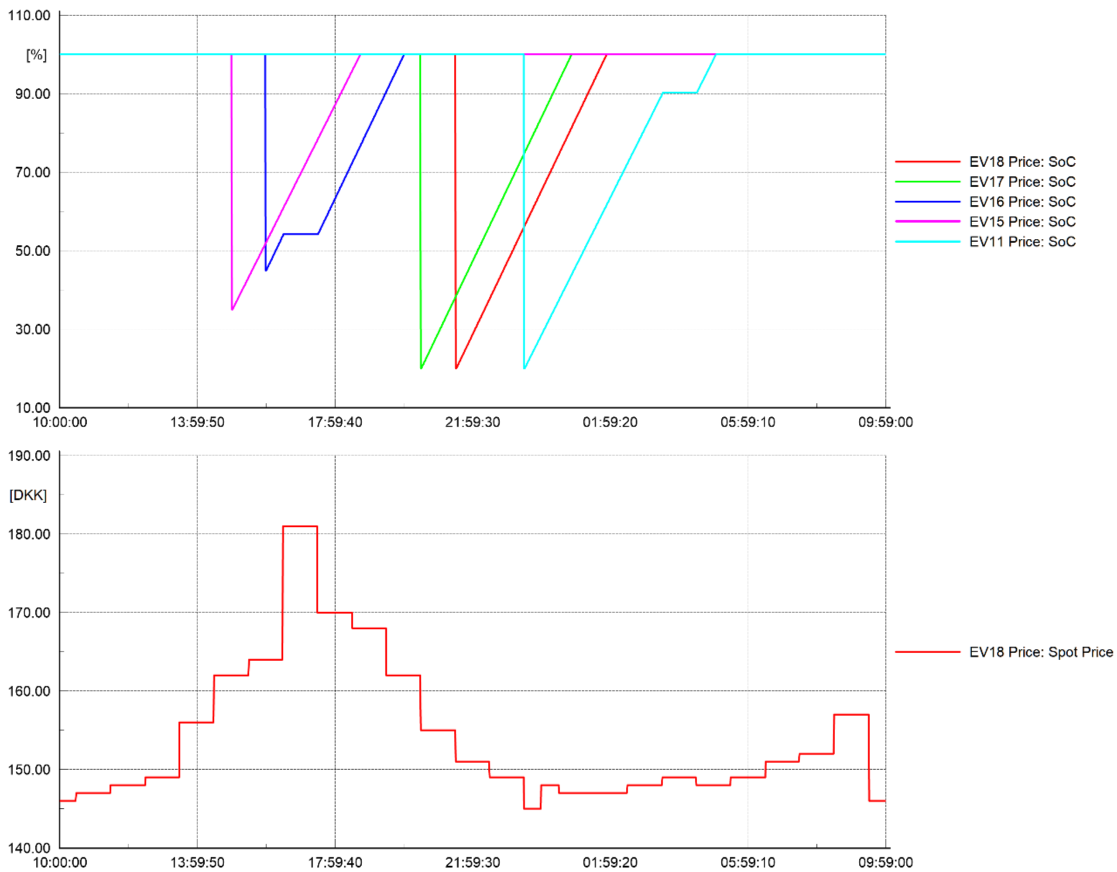

Figure 4. 6: State of charge vs day-ahead price.

The arrival time of EV11 is 15:00 hours, EV17 is 17:00 hours, and EV18 is 18:00 hours but due to the higher rates of electricity prices, start charging only at 00:00 hours, 21:00 hours and 22 hours, respectively.

4.4 Chapter summary

In this chapter, Price-based demand response management was implemented for the electric vehicles. The results are evident that this control method is profitable to electric vehicle user directly by reducing the electricity tariffs. This method also indirectly controls the electric vehicles to reduce the congestion in the grid and avoid the undervoltage issues. Although this method seems to be highly beneficial for the electric vehicle users, this indirect load control method as the name states, do not directly or completely control the charging of electric vehicles. This is one of the reasons that in section 4.3.2, one of the buses show an instance were the undervoltage issue is marginally under control. Hence, a direct control method is necessary to yield better benefits, for the distribution system operator.

CHAPTER-5

In this chapter, studies regarding the incentive-based demand response control is presented along with the operation and results.

5.1 Incentive based Demand response Model

As mentioned previously in the section 2.5, the objective of the incentive-based demand response control scheme in this project is to directly control the charging of electric vehicles by providing charging power set points to the users. Through implementing this control method, a distribution system operator will get benefitted by yielding flexibility from large consumers (electric vehicle users in this case) and actively manage the grid congestion and voltage issues. In Figure 5.1, control operation for incentive-based demand response management is explained.

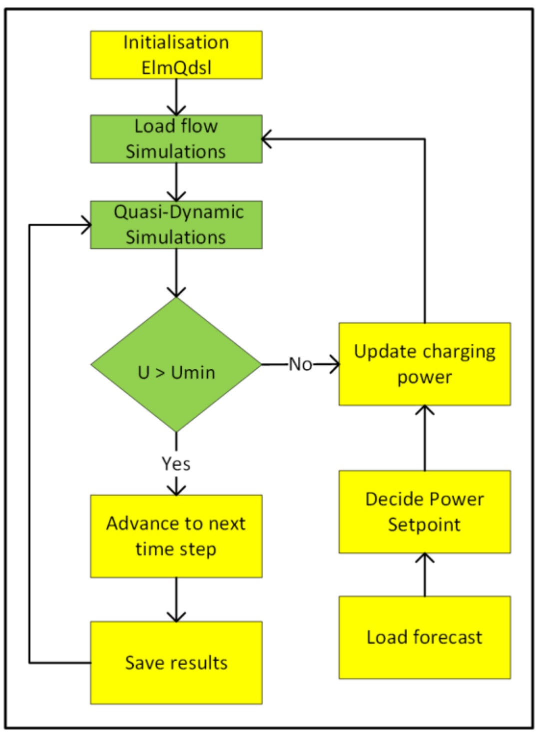

Figure 5. 1: Incentive-based demand response control operation.

The users are benefitted by receiving incentives from the DSO for actively supporting them by responding to their power setpoint signals or by charging only when the DSO advises to. There are two types of control that can be implemented through this method, either by providing power setpoints for the users or by providing time slots when to charge and when not to charge, on a day-ahead basis by forecasting the consumption or congestion pattern. The operation of electric vehicles through incentive-based control method is further explain in the next section.

5.2 Model Operation

In this section, the input parameters involved in operating the electric vehicle model in the grid through incentive-based demand response control are explained along with few assumptions and limitations. The demand profile for the residential houses is not changed from the base case and can be referred to Figure 3.3. In this case, electric vehicles are considered to be in groups based on their location in the grid. Also, user's comfort related factor is neither used in any calculations nor considered while choosing values for the parameters. Table 5.1 features the parameters used to execute incentive-based control method for electric vehicles.

Node	**No. of EVs connected (No.)**	**Arrival time (h)**	**Aggregated Charging Power (kW)**	**Battery capacity (kWh)**	**Preferred min Initial SoC (%)**	**U_{min} (p.u.)**
Bus 11	14	15:00	98	560	20	0.96
Bus 15	11	15:00	77	440	35	0.92
Bus 16	3	16:00	33	180	45	0.95
Bus 17	9	17:00	99	540	20	0.93
Bus 18	3	18:00	33	14.25	20	0.93

Table 5. 1: based demand response control.

U_{min} in the Table 5.1 represents the voltage below which the electric vehicle will not charge, and the user might be penalized, if the command was not obeyed. This value is determined based on the location of the electric vehicles on the grid. Say, electric vehicles connected to bus 11 enjoy the benefit of staying closer to the distribution transformer and do not share the congestion and undervoltage issues. Hence, U_{min} (minimum permissible voltage) is chosen as 0.96 p.u. and if the bus voltage goes below this value, the charging of electric vehicle will be stopped until the voltage rises above U_{min}. Similarly, bus 15 in the grid is located far away from the distribution transformer and it will be the first bus to experience the undervoltage or congestion problems. Hence, it has been given a slack and U_{min} value for this bus is chosen as 0.92. In the further sections the results obtained by implementing this control method will be discussed.

5.3 Incentive-based demand response control

In this section, the condition of the grid is analyzed after implementing incentive-based demand response control scheme for the electric vehicles. In the further sections, the behavior of the grid is illustrated in terms of obtained results for bus voltages, transformer loading and state of charge of the electric vehicles.

5.3.1 State of charge

In this section, the state of charge profile for the electric vehicle is obtained from executing the load flow simulations for the incentive-based control operation and compared with base case. In Figure 5.2, state of charge profile of uncontrolled charging of electric vehicles and price-based controlled charging of electric vehicles are depicted.

It can be observed from the Figure 5.2 that the electric vehicles do not charge for the periods where the congestion was forecasted and undervoltage was expected. This control method in other words will fall under the category of peak clipping and load shifting as explained in the section 2.3.

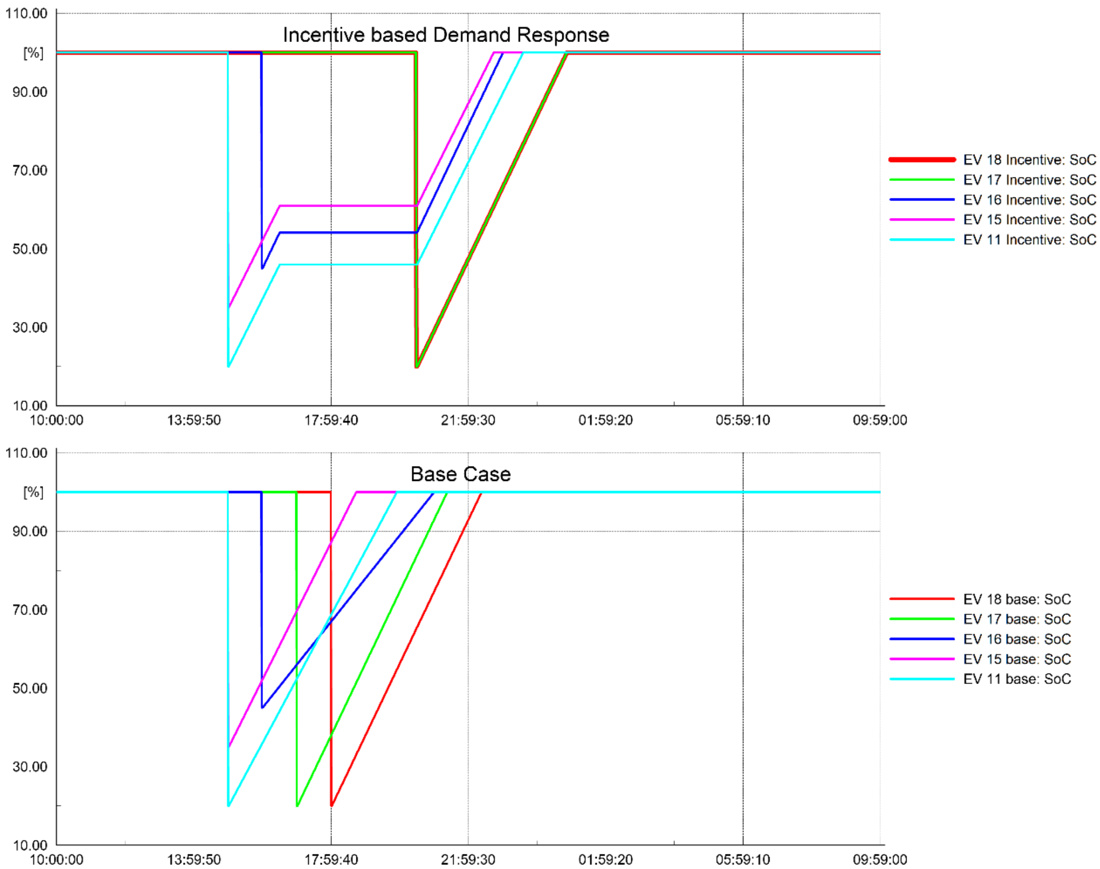

Figure 5. 2: State of charge profile for incentive-based demand response control vs Base case.

5.3.2 Bus voltage

In this section, voltages of the most critical buses in the grid are analyzed. Figure 5.3 depicts the voltage profiles of most critical buses, obtained from implementing the incentive-based demand response control and base case.

After implementing this control method, the minimum recorded voltage in the bus 15 is 0.943 p.u. and this the lowest bus voltage in the whole grid. While the minimum recorded voltage for the bus 17 in the base case is 0.862 p.u. and is highlighted in the Figure 5.3. And the minimum recorded voltage in the section 4.3.2 was 0.906 p.u. which proves incentive-based control method is much more effective in terms of handling the undervoltage issue. These scenarios will be further discussed in the later sections.

Figure 5. 3: Bus voltages profile for incentive-based demand response control vs Base case.

5.3.3 Transformer loading

In this section, loading of the transformer in the grid is analyzed. In the Figure 5.4, loading profile of the transformer obtained from implementing the incentive-based demand response control scheme and base case.

Incentive-based control has reduced maximum loading of the transformer to 42.9% which was recorded to be 111% for the uncontrolled charging of electric vehicles and the difference between them marks to be 68%. It can be observed from the Figure 5.4 that the consumption during the peak hours is completely cut off and distributed to the off-peak hours (20:00-10:00 hours) and the household loads are solely responsible for the existing peak that is seen around the peak hours (16:00-20:00 hours).

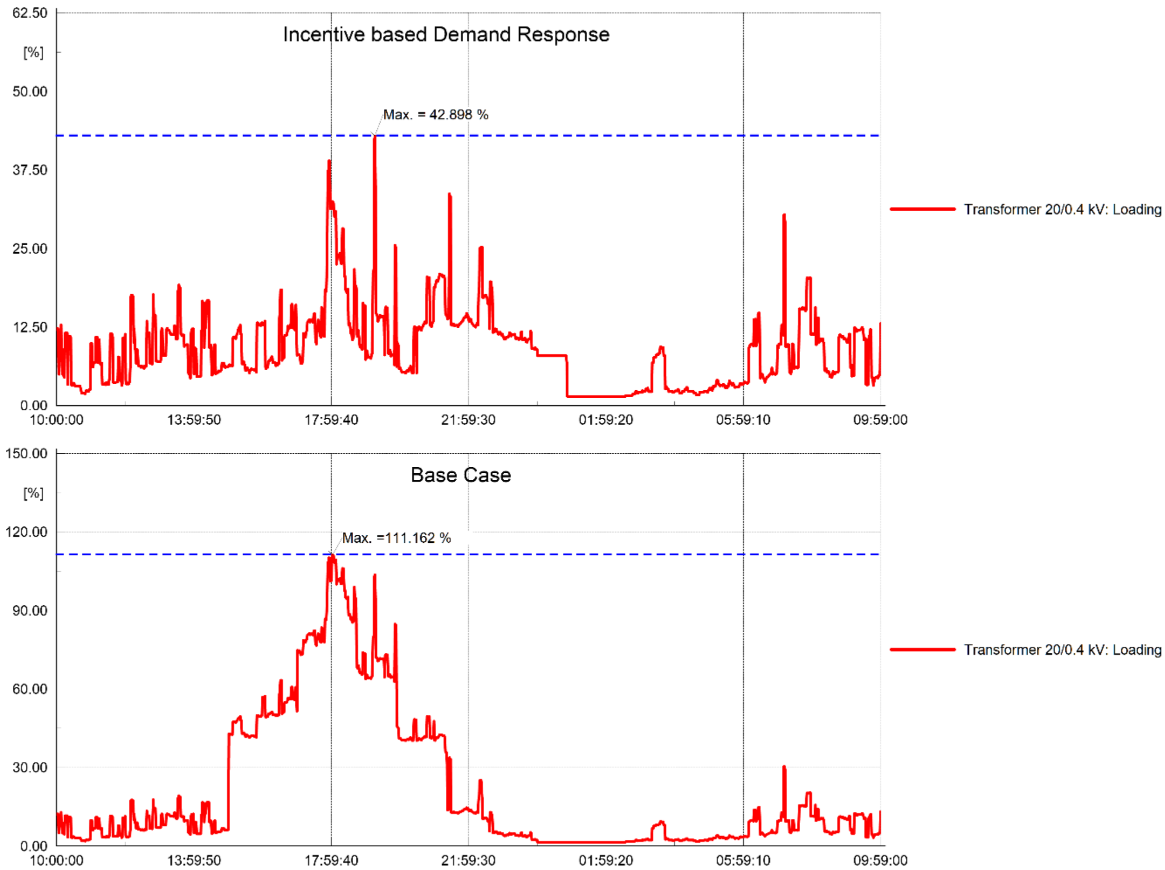

Figure 5. 4: Transformer loading for incentive-based demand response control vs Base case.

5.4 Chapter Summary

In this chapter, incentive-based demand response control method was developed and implemented. The results obtained from implementing this scheme are evident that this method provide better benefits to the distribution system operator by means of flexibility in charging of electric vehicles. Meanwhile, the electric vehicle user also gets benefitted by receiving incentives from the distribution system operator. In the next chapter, results obtained from the chapter 4 and 5 are analyzed together and discussed.

CHAPTER-6

6.1 Discussion of results

In this section, the results obtained from the price-based and incentive-based demand response control methods are studied and compared together.

In the Figure 6.1, voltages of the most critical buses after implementing both the control methods are presented. Comparing the results, incentive-based approach has produced better result than the price-based approach, but it is also to be noted, the difference in the level of control both the approaches had over the electric vehicles. Outputs of both the approaches clearly reflect the level of control involved, incentive-based approach has managed the undervoltage problem better than the price-based approach because it has complete control over the charging of electric vehicles and neglects the user preferences completely. Where, the lowest voltage recorded by the incentive-based approach is 0.943p.u. and by the price-based approach is 0.906p.u.

Figure 6. 1: Discussion of bus voltage profiles.

In the Figure 6.2, the transformer loading from the both the control methods are presented. The maximum recorded transformer loading from the incentive-based approach is 42.9% and from the price-based approach is 63.5%. Again, incentive-based approach has provided a better demand response control in managing the congestion in the grid. Also, it can be observed that the transformer is in better condition evidently in the controlled charging than uncontrolled charging of electric vehicles. Hence, it can be inferred that as the level of control over charging of electric vehicles increase, the level of congestion management also increases.

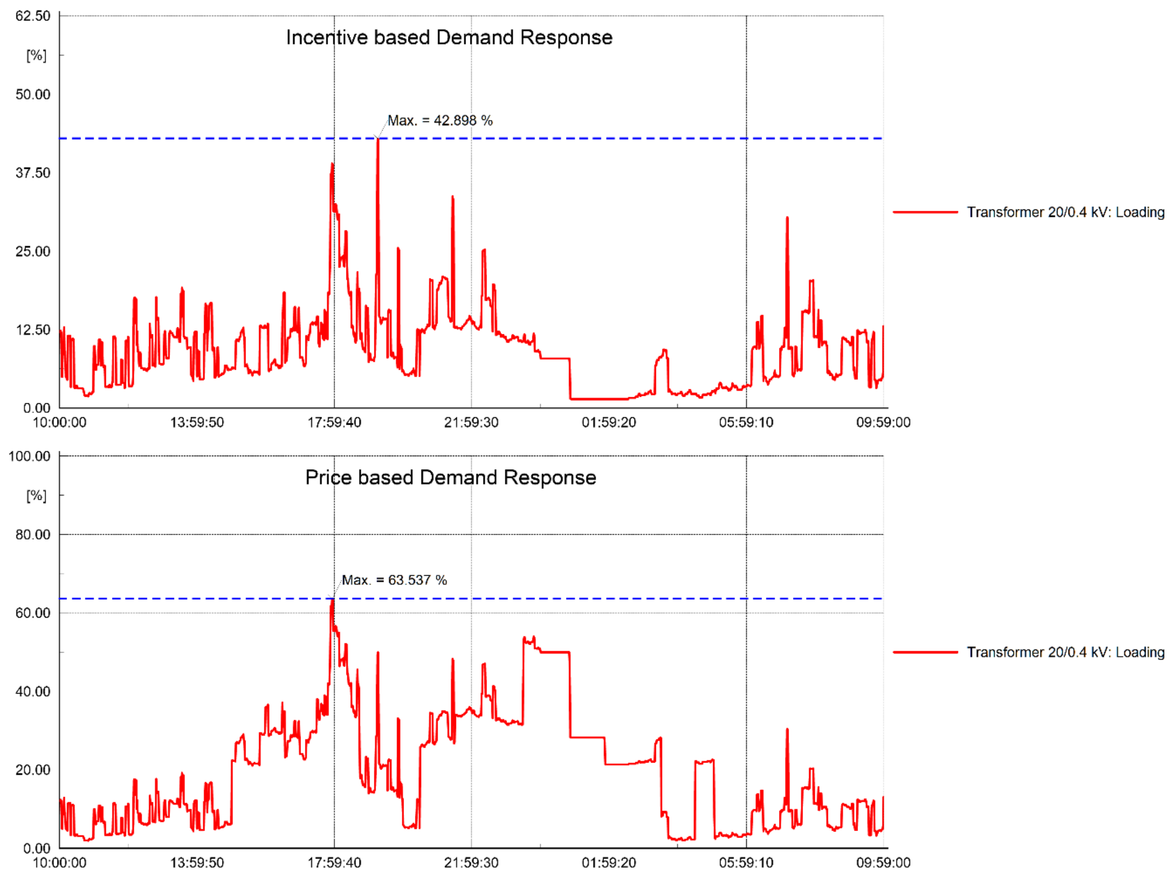

Figure 6. 2: Discussion of Transformer loadings.

6.2 General conclusions and discussion

The aim of this project was to study the impact of integrating electric vehicles on a large scale and quantify the demand flexibility that they can offer to mitigate those repercussions. A benchmark 20kV distribution grid was modeled and analyzed in the DIgSILENT PowerFactory simulation software. The grid comprises of single feeder containing several buses with aggregated loads. The feeder is connected to a 20kV medium voltage grid through a 500kVA distribution transformer. Electric vehicle loads were further incorporated to the buses consisting of aggregated household loads.

Firstly, a residential demand model was derived for the aggregated household from a real-time demand survey called CREST. Then, a charging demand curve was obtained for the aggregated electric vehicles, again from a real time survey conducted and documented in England for over a year, called the MEA project. A steady state analysis was carried out to understand the basic behavior of the grid upon challenging congestion and undervoltage problems.

Secondly, understanding the limitations of utilizing a time-invariant electric vehicle demand model, a time-dependent quasi-dynamic electric vehicle model was developed in DIgSILENT Programming Language (DPL). Then, all the electric vehicle demand models were replaced by this model and a steady state analysis was carried out again without the involvement of any type of control. The results obtained from this steady state analysis were documented and marked as the reference case throughout the project. The transformer was highly overloaded, and all the critical buses were experiencing undervoltage issues.

In order to have a regulation over the charging of electric vehicles, a centralized price-based control scheme was developed and implemented in all the electric vehicles. In this control scheme, all the electric vehicles are assumed to be in contracts with an aggregator who is a third-party market player that owns control over the charging of electric vehicles. in this control method the users will be provided with the day-ahead prices for every hour and they can choose the price and minimum state of charge at which the vehicle needs to be charged. And the price-based control approach yields the electric vehicle user, reduction in the electricity tariffs while the DSO indirectly benefits by enjoying the flexibility extracted from the aggregator. While the aggregator benefits from trading this flexibility in the market or directly with the DSO. It was observed that there were several improvements in bus voltages and transformer loading when compared to the uncontrolled charging in the reference case and were satisfying the grid codes. But there were a few instances where one of the critical buses was marginally under control and might easily slip into undervoltage issue for unforeseen contingencies.

Later, in order to have a better control over the charging of electric vehicles, and to extract flexibility in an efficient manner, incentive-based demand response control scheme was developed. This is a local level control scheme where the users will be provided with power setpoints and based on the day-ahead congestion forecast and the users receive incentives for obeying the setpoints and receive penalties for not following the commands from the DSO. This type of demand response control owns a direct control over the electric vehicles and executes peak-shaving or peak-clipping method. The results obtained from this method of control seemed to be much more stable and promising. Hence, it can be inferred that when the degree of control increases, the degree of demand responsiveness and flexibility extracted are higher and efficient.

6.3 Future work

In this section, some of the relevant ideas that can be explored around this domain are as follows:

- Implementing a photovoltaic generation system along with the electric vehicles and vehicle-to-grid system can be much more beneficial to the local grid.
- Implementation of both the centralized and local control together can fade away the disadvantages that are seen when they are enacted separately.
- Using optimization methods in formulating the rules for the control schemes can be more efficient.
- A clear strategy for profit sharing between the different market players upon implementing smart charging can be devised.
- More rules can be added to the existing control schemes to add diversity to the charging preferences.
- A centralized control that includes communication between different units to improve the performance of the local/individual control.

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APPENDIX-A

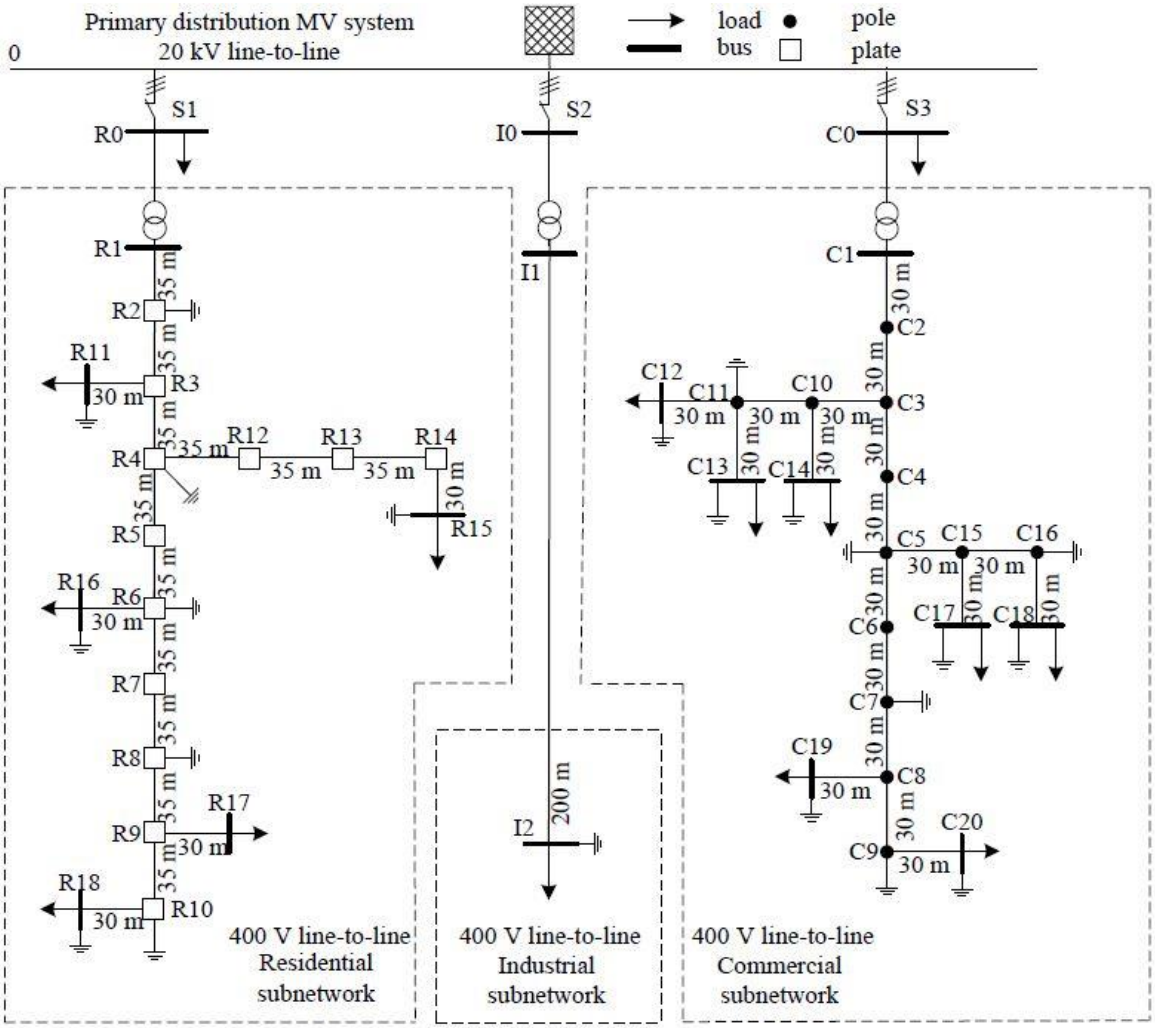

Figure:1 CIGRE Benchmark LV grid.

Conductor ID	Type	Cross-sectional Area	Number of strands	R'_{ph}	d_c	GMR	t_i	t_{ts}	d_{ov}	a
		[mm^2]		[Ω/km]	[cm]	[cm]	[mm]	[mm]	[mm]	[m]
UG1	NA2XY	240	37	0.162	1.75	0.671	1.7	2.8	52	0.1
UG2	NA2XY	150	37	0.265	1.38	0.531	1.4	2.4	42	0.1
UG3	NA2XY	120	37	0.325	1.24	0.475	1.2	2.3	39	0.1
UG4	NA2XY	25	1	1.54	0.564	0.220	0.9	1.8	24	0.1
UG5	NA2XY	35	1	1.11	0.668	0.260	0.9	1.8	26	0.1
UG6	NA2XY	70	1	0.568	0.944	0.368	1.1	2.0	32	0.1

Figure: 2 Cable Geometry.

Line segment	Node from	Node to	Conductor ID	R'_{ph}	X'_{ph}	R'_0	X'_0	l	Installation
				[Ω/km]	[Ω/km]	[Ω/km]	[Ω/km]	[m]	
1	R1	R2	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
2	R2	R3	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
3	R3	R4	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
4	R4	R5	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
5	R5	R6	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
6	R6	R7	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
7	R7	R8	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
8	R8	R9	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
9	R9	R10	UG1	0.163	0.136	0.490	0.471	35	UG 3-ph
10	R3	R11	UG4	1.541	0.206	2.334	1.454	30	UG 3-ph
11	R4	R12	UG2	0.266	0.151	0.733	0.570	35	UG 3-ph
12	R12	R13	UG2	0.266	0.151	0.733	0.570	35	UG 3-ph
13	R13	R14	UG2	0.266	0.151	0.733	0.570	35	UG 3-ph
14	R14	R15	UG2	0.266	0.151	0.733	0.570	30	UG 3-ph
15	R6	R16	UG6	0.569	0.174	1.285	0.865	30	UG 3-ph
16	R9	R17	UG4	1.541	0.206	2.334	1.454	30	UG 3-ph
17	R10	R18	UG5	1.111	0.195	1.926	1.265	30	UG 3-ph

Figure: 3 Cable data.

Node from	Node to	Connection	V_1	V_2	Z_{tr}†	S_{rated}
			[kV]	[kV]	[Ω]	[kVA]
R0	R1	3-ph Δ-Y grounded	20	0.4	0.0032+j0.0128	500

Figure: 4 Transformer data.

Node	Apparent Power, S [kVA]	Power Factor
	[kVA]	
R1	200	0.95
R11	15	0.95
R15	72	0.95
R16	55	0.95
R17	15	0.95
R18	47	0.95

Figure: 5 Load data.

APPENDIX-B

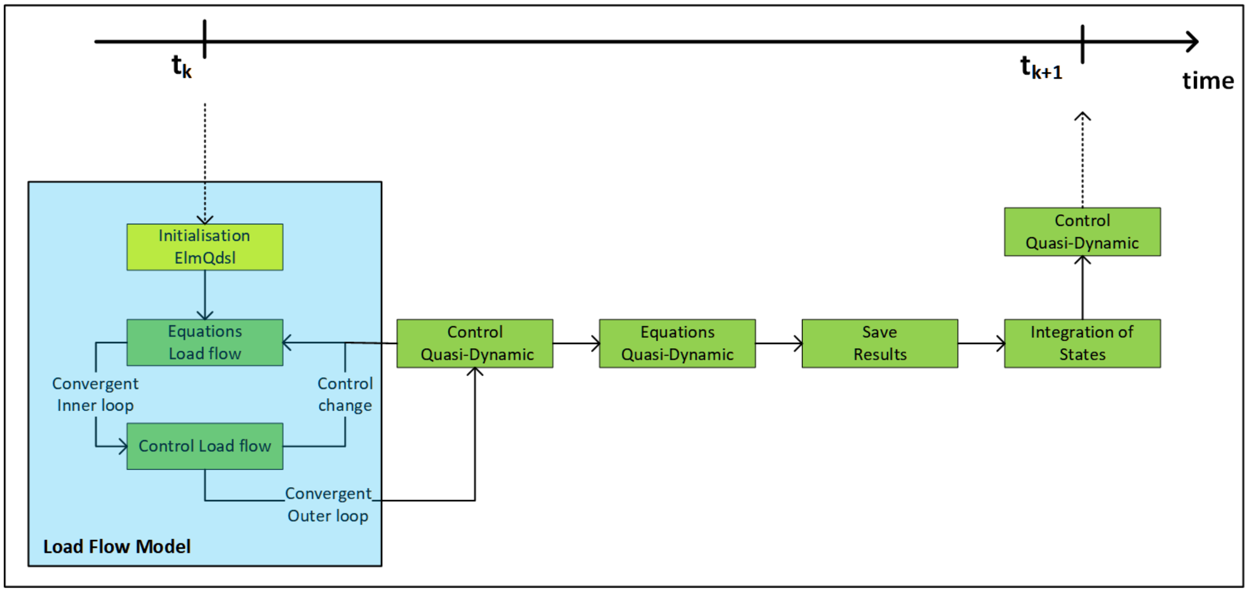

Figure 1: Quasi-Dynamic Simulation Algorithm.