Bachelor Thesis

Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids

By

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angefertigt am
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Betreuer: Dipl.-Ing. Simon Wenig

April 2015
I guarantee hereby, that I have done my Project Work by myself, and under consideration of the scientific rules of the Karlsruhe Institute of Technology (KIT). I have not used more sources or help than the ones specified in the project.

Karlsruhe, the August 28th 2015.

Guillermo Moraleda.
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1 Introduction

Electric mobility relates to the electrification of the power train. In this thesis we will refer to EVs (Electric Vehicles) as all the vehicles for which an electric motor is their main source of propulsion. All these EVs will be assumed as wired charging vehicles: we differ between plug in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).

1.1 Motivation

In the past years, Europe has gone through an initial adoption phase of electric mobility. The gradually increasing momentum behind EV adoption, both from the side of the consumer and the automotive industry, suggests that EV will play an important role in Europe’s mobility in the future. The main reasons to think that e-mobility will eventually play an important role in a future scenario are:

- Environmental consciousness
- Oil price increase
- Battery price decrease due to economy of scale
According to Figure 1.1 the number of EVs in Germany increased by 70.87% between years 2013 and 2014 and by 55.87% between 2014 and 2015. Although the actual number represents only a 0.0423% share of all the personal vehicles, if the actual sales growth keeps on this tendency, in a few years it will become a direct competitor of Internal Combustion Engine (ICE) vehicles.

The next few years will be a period for further maturation of the existing technology supported by government initiatives. In result, a new charging infrastructure will be developed to provide charging points to the users. The upcoming spread of charging stations could represent a challenge for the actual power grids. Grid operators will have to deal not only with an increase in the total energy demand, but also with eventual demand peaks due to the simultaneous characteristic of the charging procedures.

Like in other north European countries, in Germany the electric power demand curve shows a peak during evening hours, which is the time where most electric vehicles are expected to be charged.

In order to predict possible issues coming along with the new automotive car reality it is necessary to carry out studies which can simulate the grid response to an e-mobility fleet introduction. This will provide precious information to grid operators which could plan the needed strategies in order to provide reliable and more efficiently generated electricity.

1.2 Task Description

This Project Work will handle the issue of electro mobility integration in the grid by simulating the charging of a certain number of electric vehicles in two medium-voltage networks. These simulations will also show the fluctuating infeed of renewable energies.

During the simulations different EV and time scenarios will be studied in order to discuss the upcoming problems which may appear. Therefore the goal of the Thesis is to provide a good view of the main challenges that the grid operators will have to face in the following years to maintain a safe operation and assure the energy provision in a medium-voltage grid.

In order to achieve this goal two medium-voltage electrical networks are available. These grids are of great value due to their loads characteristics. They both have residential and industrial areas as well as conventional and renewable infeed. All these characteristics will be found in typical future grids.

The definition of the conventional load (household and industry load) as well as the infeed and the new generated e-mobility loads, will be included in the network for the power flow simulations. The conventional load values will depend on the season se-
lected according to meteorological considerations which will also have to be consid-
ered when generating the photovoltaic infeed.

The e-mobility loads will be introduced by generating a charging infrastructure that
will supply two different electric car scenarios. One of them will represent the possible
case in the year 2020, with 1 million EVs in Germany, and the other case will repre-
sent the year 2030, with 6 million cars using electric propulsion.

Once the simulations are carried out, different diagrams of both grids will be studied.
The most important parameters are considered to be the Grade of Utilization (GoU)
of the charging infrastructure and the different load values in the grid. In attempt to
obtaining reliable results, a comparison between both grids as well as both e-mobility
scenarios is carried out.

1.3 Methodology

The information related to the grid was given by means of two POWERFACTORY
networks as well as an Excel sheet specifying the number of households in the se-
cond grid. First of all, the data related to the power generation and consumption
(nominal values and power factors) as well as the zone distribution is obtained from
the POWERFACTORY files and introduced into an Excel sheet. The second step is to
import the data into MATLAB. MATLAB functions will:

- generate the household and industry conventional loads
- generate the conventional and renewable energy generation
- introduce an e-mobility charging infrastructure
- generate the EV aggregated loads
- export the MATLAB data into an Excel sheet

This MATLAB functions are obtained from [1], however the given functions had to be
slightly modified as a new function was introduced. The new function developed is
called Diagram_V3.m and it generates two different graphs which will show both the
Grade of Utilization (GoU) of the charging infrastructure and a boxplot diagram for the
given time and number of simulations.

This procedure will be repeated in each grid for both the 1 and the 6 Million Scena-
io. The complete simulations have to be carefully chosen so that the most interesting
time periods are shown.

Figure 1.2 shows the methodology followed in this Thesis to obtain a complete view
of the e-mobility impact on the given electric networks.
Figure 1.2: Load Flow Structure
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids
2 Background Framework

In order to run the power flow simulations, different MATLAB tools developed in previous projects have been used. The use of these tools enables the user to generate:

- Household and industry loads
- Conventional and renewable infeed
- Charging infrastructure with its corresponding e-mobility loads.

2.1 Effects of EM Loads on a Medium-Voltage Network

Due to the previous simulations made on MS_Clusterntz_1 under the influence of EVs; a extended explanation of the previous project will be carried on, in order to understand the different functionalities.

In [1], MATLAB tools were developed to prepare the grid data in six different steps:

![Figure 2.1: Thesis Structure according to [1]]

2.1.1 Grid Data Management

In [1], new e-mobility loads were generated in MS Clusternetz 1; this will be one of the two networks which will be studied. The grid consist of a radial network, this is means that in normal conditions, the grid will be connected with the high-voltage level by means of one transformer station. However, in case of grid failure it can also be supplied by two other transformer stations placed at both sides of the grid.
This distribution network holds a total of 119 loads. 82 of them are household loads while the other 37 substations are considered industrial loads. In order to generate time-dependent load values the standard profiles are used. (H0: Standard Household) and (G0: Standard Industry).

There is one load with a given nominal apparent power per node. All these loads have a 0.9 inductive power factor. Apart from the domestic and industrial loads, also renewable infeed can be found at the substations. There are a total of 88 renewable generators, where 83 of them are solar panels and the other 5 are biogas- or combined heat and power plants. 23 of the plants feed in at a medium-voltage level while the other 65 supply at a low-voltage level.

A power factor of $\cos \varphi = 1$ is applied for the biogas- or combined heat and power plants, as well as for 75 solar generators. From the other eight, seven of them have a $\cos \varphi = 0.95$ and one a $\cos \varphi = 0.9$.

There is a total of 286 cables connecting the low-voltage networks among each other and to the transformer station. A great number of them (247) are underground cables, while the 39 others are overhead transmission lines. Table 2.2 shows the different cables used as well as the maximum current rating of the conductors.
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids

### Table 2.1: Medium-Voltage Underground Conductors

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Current [kA]</th>
<th>n° of Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2XHGY 150</td>
<td>0.367</td>
<td>3</td>
</tr>
<tr>
<td>N2XSXY 3x1x95</td>
<td>0.323</td>
<td>5</td>
</tr>
<tr>
<td>NA2XS2Y 3x1x150</td>
<td>0.319</td>
<td>156</td>
</tr>
<tr>
<td>NA2XS2Y 3x1x150 RE/25</td>
<td>0.319</td>
<td>9</td>
</tr>
<tr>
<td>NA2XS2Y 3x1x185</td>
<td>0.361</td>
<td>7</td>
</tr>
<tr>
<td>NA2XS2Y 3x1x240</td>
<td>0.417</td>
<td>10</td>
</tr>
<tr>
<td>NA2XS2Y 3x1x300</td>
<td>0.471</td>
<td>10</td>
</tr>
<tr>
<td>NA2XSY 3x1x150</td>
<td>0.319</td>
<td>4</td>
</tr>
<tr>
<td>NA2YSY 3x150 RM/25</td>
<td>0.296</td>
<td>3</td>
</tr>
<tr>
<td>NAKLEY 3x1x70</td>
<td>0.183</td>
<td>10</td>
</tr>
<tr>
<td>NAKLEY 3x1x95 RM</td>
<td>0.219</td>
<td>5</td>
</tr>
<tr>
<td>NAKLEY 3x150</td>
<td>0.277</td>
<td>17</td>
</tr>
<tr>
<td>NEKBA 3x80</td>
<td>0.185</td>
<td>6</td>
</tr>
<tr>
<td>NEKBA 3x95</td>
<td>0.274</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 2.2: Medium-Voltage Overhead Conductors

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Current [kA]</th>
<th>n° of Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL/ST 35/5</td>
<td>0.17</td>
<td>2</td>
</tr>
<tr>
<td>AL/ST 50/8</td>
<td>0.21</td>
<td>20</td>
</tr>
<tr>
<td>AL/ST 95/15</td>
<td>0.35</td>
<td>16</td>
</tr>
<tr>
<td>AL/ST 120/20</td>
<td>0.41</td>
<td>1</td>
</tr>
</tbody>
</table>

In order to proceed with the simulations, the POWERFACTORY data is introduced into an EXCEL Grid Data document, this file will contain the following information:

![EXCEL Grid Data](image)
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2.1.2 Generation of Grid Loads and Infeed

In this paragraph the conventional load and infeed as well as the renewable infeed generation will be handled. In order to shape the ‘conventional load’, load profiles obtained from BDEW are applied [2]. These provide daily, weekly or even annual information about the load profiles of different demanding groups.

Given the lack of additional information just two kinds of loads are assumed. These are ‘G0: Standard Industry’ and ‘H0: Standard Household’. Different load characteristics are given depending the time of the year:

- Winter: 01.11. until 20.03.
- Summer: 15.05. until 14.09.
- Transitional Period: 21.03. until 14.05. and 15.09. until 31.10.

Additionally each week is divided into three types of days:

- Workday
- Saturday
- Sunday

Figure 2.4: Day type

The tool Photovoltaic Geographical Informational System (PVGIS) will provide the required data to generate the photovoltaic infeed profiles. This software calculates the solar radiation every 15 minute for the whole month given a certain location. The results are used to generate a daily solar radiation profile. With these values and the given nominal power of the panels the PV infeed is generated. On the other hand all the conventional generators will be feed the grid at nominal power.

Figure 2.5: Screenshot of the PVGIS
Both the conventional load and the renewable infeed are generated by Complete_Scaling_V4 in two different steps: Load_Scaling and EEG_Scaling; the third function included is the EM_Load_SELECTOR, related to the e-mobility load generation explained in the following paragraph.

2.1.3 Electromobility Load Generation

The electric vehicle loads are implemented in two steps:

1. Generation of a charging infrastructure
2. Generation of the e-mobility load profiles

The charging infrastructure generation is accomplished by the MATLAB script: Grid_Data_Generator_V5.m. In order to fulfill the task the script has to cover the following points:

First, the number of EVs in the Grid are obtained. In order to determine this value two different scenarios are proposed. The first scenario (1 Million EVs in Germany) assumes that by the year 2020, 2.28% of all the vehicles will have electric propulsion. The second option which predicts a scenario by the year 2030, assumes that 13.68% of all vehicles are electric (6 Million EV in Germany).

According to the previous information, once that the total vehicle number in the grid is determined the estimation of the number of EVs can be calculated. In the case of MS_Clusternetz_1, given that the exact location of the grid is known, the number of inhabitants can be easily obtained. The vehicle number was established applying the ratio one vehicle each 1.6 inhabitants which was established in [6].

The e-mobility technology definition was carried out in [5]. Here, the EV distribution was determined for both the 1 and the 6 million scenario. This distribution is considered to be accurate enough in order to study the e-mobility load impact.

Now that the number and the characteristics of the EVs are known, it is possible to establish the number and the maximum power of the charging stations. Each EV will have its corresponding private charging station. Also for every 10 EVs one public charging station will be added. For private charging stations the maximum power will be the corresponding charging power of the EV; on the other hand of public stations each car will be charged at its maximum power. An efficiency of 90% and an inductive power factor of 0.97 are assumed for the charging procedure.
In [1] a matrix for each grid substation is created, this matrix needs the aggregated charging profile of the charging stations to generate the EV Loads. The final values show all the necessary information including the charging stations ID number and the type of station.

For public charging stations different locations are described: work, shopping, recreation or other. Due to the lack of information these stations are distributed equally.

The generation of the e-mobility load profiles is carried out by the script *Pelican_9.m*. This tool generates an aggregated load profile by using charging load profiles obtained from [5]. *Pelican_9.m* allows the user to:

- select the precise grid
- choose the EV scenario
- choose the simulation length, selecting the starting weekday
- determine the number of simulations

This tool requires both the charging infrastructure and the charging profile data as inputs. This second file is obtained from [5], which implements the charging strategy *Load50* to determine the user behavior.

![Pelican_9.m interface](image-url)


2.1.4 Grid Simulation

After all the data obtained from the MATLAB tools is generated and analyzed, a power flow simulation can be executed. For the power flow simulation [1] chose to simulate different day types (Workday, Saturday and Sundays) of May and November during midday and after work hours. The obtained results showed that the point with the highest load values corresponds to a workday in November. This case was studied with great detail.

The point of maximal conventional load with a maximum value of 7.202 MW was found at 12:00. However, at this time the generation reached its peak value with a total infeed of 6.460 MW. This means that at this time the load was balanced by the grid generation.

During this day an evening peak appears at 18:00 o’clock. At this time the e-mobility load presents its maximum values. An example of load profiles is shown in Figure 2.7.

![Figure 2.7: Total Load November MS_Clusternetz_1](image-url)
2.2 EV Charging Characteristic

The information about the charging profiles and the probabilistic behavior of the charging processes is obtained from the Master Thesis ‘Modeling of the driving and charging behavior of the Electric Vehicles’ [4] and the Bachelor Thesis: ‘Simulation and Analysis from probabilistic Electromobility Load Profile’ [5].

2.2.1 EV Driving and Charging Behavior Model

The EV driver behavior is specified in [4]. In order to accomplish this task, a java-model is created. The first target of the project is to model the driving behavior. Therefore the study ‘Mobility in Germany’ is used as a pattern [6]. This study handles with information related to the driving behavior of the German population. Due to the extension of the sample and the relative up-to-date information (2008), the survey can be considered as valid for predicting the charging procedures.

This survey allows the user to obtain the information of a specific region as well as the type of urban settlement. More than 190.000 trips with the corresponding information about purpose of the travel, length, vehicle type and departure time are registered. All this information is reflected in [4] in terms of a probability density functions.

In this Thesis various assumptions were made: first of all an EV type distribution is applied (see table 2.4), second, the availability of the charging stations depends on the destination of the travel.
Finally, a State of Charge (SOC) is given for every EV. As expected, the SOC will decrease during the driving times and will increase during the charging periods. For the generation of the final output two different charging strategies are implemented:

- Charging after the last ride of the day
- Charging after every ride

### 2.2.2 Simulation of EM Load Profiles

The previously explained Thesis is followed by [5]. In this Thesis, a new charging strategy called \( \text{Load50} \) is introduced. With the new strategy, the e-mobility users will charge their vehicles after a drive if:

- The SOC is below 50%
- It was the last drive of the day.

This strategy assumes a total charging availability.

In [5] a new EV distribution is proposed (see table 2.5). This distribution was used in [1] and will also be used in this thesis; therefore the EVs distributions of the two future e-mobility scenarios (1 and 6 million EV in Germany) are estimated. In the 1 million EV scenario the distribution adopted shows today's e-mobility state of art, while in the 6 million EV scenario two more EV types with larger battery capacity and higher charging power are introduced.
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Given the limited range of EV, the maximum drive length will be assumed to be 100 km. This means that for all travels which covered longer distances 100 km value will be assigned.

With this data, charging profiles of 10,000 vehicles during duration of one week were generated. In Figure 2.8 the output information is described. This information will also be obtained from these project’s simulations.

![Figure 2.8: Output Information Gebel](image)

During later work, an update was introduced to simulate the constant current/constant voltage charging characteristics. This strategy is used by most EVs manufactures in order to achieve rapid charging of Li-Ion batteries without reaching current or voltage overloads. This means that the EVs are not charged at a constant power anymore. As we can see in Figure 2.9, the power load will be diminished once a certain SOC is reached.

![Figure 2.9: Charging Characteristic according to [5]](image)
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids
3 Realization

The study of the impact that e-mobility fleets may have on medium-voltage electric networks requires a full grid behavior understanding, which will be obtained through:

- Grid data analysis
- Aggregated e-mobility load generation
- Grade of Utilization (GoU) analysis
- Power flow simulations

3.1 Net Data

In order to realize the e-mobility load simulations, two medium-voltage grids are given: MS_Clusternetz_1 and MS_Clusternetz_3, both of them are 20 kV grids. The first task of the project is to analyze the new grid MS_Clusternetz_3 and then import the data in MATLAB.

MS_Clusternetz_3 consist of a radial medium-voltage distribution network. The customers are supplied by one central transformer station which includes two transformers, each one with a nominal power of 40 MVA each. Additionally, other possible spare transformer stations can be connected in case of failure. This represents the typical configuration for rural or suburban areas.

Figure 3.1: MS_Clusternetz_3 node example
The grid contains a total of 304 loads. From these loads, 200 represent household loads (defined as H0: Standard Household) and 104 are industrial loads (defined as G0: Standard Industry). The distinction between the two types of loads was not obtained from the POWERFACTORY data but from the Zuordnung_MSClusternetz_3Extern EXCEL sheet given.

From the 304 loads 298 have a power factor of $\cos \varphi = 0.95$; 5 of them have a power factor of $\cos \varphi = 0.9$ and one of them was assigned $\cos \varphi = 0.712$.

It was observed, that in the initial POWERFACTORY grid two scaling factors are applied to the loads. One of them, the Area Scaling Factor, is applied to both active and reactive power of the grid elements, while the other one, the Grid Scenario Factor, is just applied to the active Power of the loads. This second factor represents the grid status, which can be Low Load, High Load and Maximum Load with values of 0.3, 0.8 and 1 respectively; due to its characteristics, this factor will change the power factor of the loads.

Renewable infeed is also connected to the grid. There is total number of 57 generators. From these generators, 34 are photovoltaic generators, 19 are renewable generation, 3 are static generators and there is also one wind turbine. All the infeed is connected at the medium-voltage level. Due to their generation characteristics, the generators are divided in two groups: the first group is defined as the fixed generators, it consists of the 22 renewable and of the 3 static generators, while the other group, defined as the variable generators includes the 34 photovoltaic panels and the wind turbine.

There are a total number of 628 conductors. 465 from these conductors are underground, while the 163 resting are overhead lines. The conductor’s distributions are shown in Tables 3.1 and 3.2.

<table>
<thead>
<tr>
<th>Medium Voltage Overhead Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>AL/ST 50/8</td>
</tr>
<tr>
<td>AL/ST 35/6</td>
</tr>
<tr>
<td>AL/ST 25/4</td>
</tr>
</tbody>
</table>

Table 3.1: MS_Clusternetz_3 overhead lines
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids

<table>
<thead>
<tr>
<th>Medium Voltage Underground Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>NEKBA 3x95</td>
</tr>
<tr>
<td>NEKBA 3x50</td>
</tr>
<tr>
<td>NEKBA 3x35</td>
</tr>
<tr>
<td>NAKLEY 3x1x95 RM</td>
</tr>
<tr>
<td>NAKLEY 3x1x70</td>
</tr>
<tr>
<td>NAKLEY 3x1x240 RM</td>
</tr>
<tr>
<td>NAKLEY 3x1x150</td>
</tr>
<tr>
<td>NA2XS Y 3x1x50</td>
</tr>
<tr>
<td>NA2XS Y 3x1x240</td>
</tr>
<tr>
<td>NA2XS Y 3x1x185</td>
</tr>
<tr>
<td>NA2XS Y 3x1x150</td>
</tr>
<tr>
<td>NA2XS Y 3x1x300</td>
</tr>
<tr>
<td>NA2XS Y 3x1x240</td>
</tr>
<tr>
<td>NA2XS Y 3x1x185</td>
</tr>
<tr>
<td>NA2XS Y 3x1x150</td>
</tr>
<tr>
<td>NA2XS Y 3x1x300</td>
</tr>
<tr>
<td>N2XS Y 3x1x240</td>
</tr>
</tbody>
</table>

Table 3.2: *MS_Clusternetz_3* underground cables

As explained before, the number of the grid households is given in the Excel sheet. Once that the household number is known the number of inhabitants can be determined by applying a ratio of 2.47 inhabitants per household, these ratio is explained in [9]. With the previous information, a total number of 19.157 Inhabitants were assigned to the grid. Known the population in the area we can determine the number of vehicles by applying the ratios described in [6]. With this relationship we obtain a total number of 11.925 vehicles.

### 3.2 Electromobility

After analyzing the main grid features all the data can be introduced in an EXCEL sheet. This will allow the introduction of the e-mobility loads as well as generating the conventional load and the power infeed corresponding to a specific time period. This will be done by the MATLAB tools developed in [1].

Once the vehicle number estimation is completed, it is possible to introduce the EV number. This value will depend on the scenario chosen and will follow the percentages given in [5].
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<table>
<thead>
<tr>
<th>EV Number</th>
<th>MS_Clusternetz_1</th>
<th>MS Clusternetz 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mio. Scenario</td>
<td>171</td>
<td>266</td>
</tr>
<tr>
<td>6 Mio. Scenario</td>
<td>1032</td>
<td>1630</td>
</tr>
</tbody>
</table>

Table 3.3: EV number

The number of charging stations depends on the number of EVs defined in the area. The charging stations distribution was defined in [5]:

- One private charging station per EV
- One public charging station every 10 EVs

<table>
<thead>
<tr>
<th>Charging Stations nº</th>
<th>MS_Clusternetz_1</th>
<th>MS Clusternetz 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mio. Scenario</td>
<td>205</td>
<td>293</td>
</tr>
<tr>
<td>6 Mio. Scenario</td>
<td>1238</td>
<td>1793</td>
</tr>
</tbody>
</table>

Table 3.4: Charging Stations number

Now that the number of charging stations is known, the EM loads are introduced. As explained before, this is done by the MATLAB script *Pelican_9.m*. In order to obtain a full knowledge about the grid’s behavior, different EV simulations were completed.

Figure 3.2: EV simulations

The name of the file refers to the following information:

- Grid nº: 1 stands for *MS_Clusternetz_1* while 3 stands for *MS_Clusternetz_3*
- Scenario: 1 million or 6 million EV scenarios
- Simulation length: number of days simulated
- Nº of simulations

The simulation length chosen is seven days so the characteristic of a whole week can be analyzed. Actually, in the *Pelican_9.m* tool a total number of 8 days will be chosen, however the first day will be omitted as it is considered as a transient period.
In order to have a reasonable number of results, a large number of simulations were performed. The number of simulation chosen were 50 for the 1 Million Scenario and 20 for the 6 Million one. These simulations provide enough data to proceed with a complete impact study.

3.2.1 Grade of Utilization of the Charging Infrastructure

The Grade of Utilization (GoU) determines the level of usage of the charging infrastructure for all the given simulations. These values are obtained to study the generated charging network behavior.

In order to estimate the total GoU new MATLAB functions were developed. First of all, the version Grid_Data_Generator_V6.m was updated to create an output file, called Diagram Data, with information related to the charging infrastructure:

- Number of charging stations
- Number of EV
- EV type distribution.

Once that all the input information is created the function GoU_Data_Generator.m can be used. The input used by the function will not only be the Diagram Data, but also the grid with the introduced charging infrastructure (generated by Grid_Data_Generator_V6.m) and the aggregated e-mobility loads (generated by Pelican_9.m).

In order to run GoU_Data_Generator.m a time period has to be selected. This time period can either be a day of the week (from Monday to Sunday) or the whole week. Once that all the inputs are correctly defined the function will generate a Grade of Utilization matrix. This matrix will contain the GoU values for each minute of the selected period for all the simulations considered (defined in Pelican_9.m). In Figure 3.3 an example of GoU_Data_Generator.m called is shown.

\[ f_x > > \text{GoU
data
generator}('Mon') \]

Figure 3.3: GoU_Data_Generator call
The Grade of Utilization is obtained by the equation described in Figure 3.4:

\[ \text{GoU} = \frac{\sum P_{ev}}{P_{ci}} \]

Equation 1: Grade of Utilization

In the previous equation, ‘\( P_{ev} \)’ represents the total sum of e-mobility loads at a specific time period (in this case a minute) and ‘\( P_{ci} \)’ will represent the total charging infrastructure active power. For the analysis of the medium-voltage grid only the active power will be considered. This is due to the fact that an inductive power factor of 0.97 is applied to the charging procedure making the consumed reactive power negligible.

Once the GoU data has been generated, the two plots can be reproduced. This task is accomplished by GoU_Plot.m. The function will receive the previously generated Grade of Utilization matrix as well as certain simulation characteristics of the corresponding simulation:

- The selected time period
- The EV scenario

Finally an interval length is assigned; this value will be used in the box plot diagrams. As shown in Figure 3.5 this will be done when calling the function.

\[ f_x \gg GoU\_Plot(3) \]

Figure 3.5: GoU_Plot call

Once that the input has been defined, the function will generate a plot of all the grade of utilization values obtained. However, due the size and dispersion of the data, a box plot will be generated for a better understanding of the results. The box and whiskers plot definition is described in Figure 3.6.
A box plot distribution is used to study the data distribution. In the previous figure, IR represents the Interquartile Range (75 percentile minus 25 percentile). The outlier points present the extreme values of the sample.

By changing the length interval of the box plot (which is defined in hours), it is possible to obtain a good overview of: the dispersion of the generated data (interquartile range); the value of the outlier points; and the charging behavior by analyzing the median values of the different time intervals. Finally the sequence to obtain the Grade of Utilization plots is described in Figure 3.7.

3.3 Power Flow Simulation

Finally, the medium-voltage grid response to the new EM loads is analyzed through a power flow simulation executed in POWERFACTORY software. In order to achieve an accurate simulation the following steps are carried out.
The first step consists on the introduction of the new electromobility loads. Every single low-voltage load will be assigned an EM load, this means that every industrial and household low-voltage load will have its corresponding EM load.

Once that the EM loads are introduced, it is necessary to select one specific day of the year to be studied. Both the conventional load and the infeed are generated by the function Complete_Scaling_V4.m and will depend on the day chosen.

In the second step the new generated MATLAB values are introduced in the POWERFACTORY grid. These final values are obtained by the MATLAB script Data_Export_V4.m developed in [1].

The task of Data_Export_V4.m is to select a minute of the day and create an EXCEL sheet following POWERFACTORY data structure. Once all the new data is stored, it can be manually copied from the EXCEL sheet columns to POWERFACTORY.

The last step is to run the power flow simulation. Simulations of the most interesting time periods (at load and infeed peaks) are executed. Three different EVs scenarios are executed, first one without e-mobility loads and then introducing the 1 and the 6 Million EV scenario. After the power flow simulations a profound analysis of the results are made to determine the highest loaded grid components and how the introduction of e-mobility will affect these values. The technical data of the power flow simulation is shown in Table 3.5.

<table>
<thead>
<tr>
<th>Power Flow Simulation</th>
<th>AC-Symmetrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Standard Newton-Raphson</td>
</tr>
<tr>
<td>Numerical Method</td>
<td>Automatic Load Tap Changer</td>
</tr>
<tr>
<td>Reactive Power Control</td>
<td>25</td>
</tr>
<tr>
<td>Max n° Iterations</td>
<td>0.01 kVA per Node</td>
</tr>
</tbody>
</table>

Table 3.5: Power Flow Characteristics
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids
4 Result Analysis

The impact of e-mobility fleets on the given grids is estimated following the next steps:

1. Import of the POWERFACTORY grid data to MATLAB.
2. Introduction of the new e-mobility charging infrastructure
3. Simulation of power infeed and conventional loads
4. Generation of the e-mobility aggregated loads
5. Study of the charging infrastructure Grade of Utilization
6. Export of selected scenarios from MATLAB data to POWERFACTORY
7. Run the power flow with the new data

This process has been applied to both MS_Clusternetz_1 and MS_Clusternetz_3. During this paragraph the given grid data as well as the obtained results are analyzed. The different scenarios simulated give a complete overview of the e-mobility loads impact.

4.1 Grid Comparison

The first step of the result analysis consists on a description of the given electric networks.

Both grids are medium-voltage grids of 20kV which feed both industries and households low-voltage networks. They include infeed coming from different renewable sources. The structure of both grids is radial, with just one transformer station operating but with auxiliary transformer stations which could be connected to the grid in case of fault. This arrangement is commonly used in rural and suburban areas.
The most representative features of both grids are showed in Table 4.1:

<table>
<thead>
<tr>
<th>Grid Comparison</th>
<th>MS Clusternetz 1</th>
<th>MS Clusternetz 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Users</td>
<td>12.119</td>
<td>19.157</td>
</tr>
<tr>
<td>Load nº</td>
<td>119</td>
<td>304</td>
</tr>
<tr>
<td>Industry Load</td>
<td>31,1%</td>
<td>34,21%</td>
</tr>
<tr>
<td>Household Load</td>
<td>68,1%</td>
<td>65,79%</td>
</tr>
<tr>
<td>Generators nº</td>
<td>103</td>
<td>60</td>
</tr>
<tr>
<td>Fixed Generation</td>
<td>6,80%</td>
<td>41,67%</td>
</tr>
<tr>
<td>Variable Generation</td>
<td>93,1%</td>
<td>58,33%</td>
</tr>
<tr>
<td>EV 1 Mio. Scenario</td>
<td>171</td>
<td>266</td>
</tr>
<tr>
<td>EV 6 Mio. Scenario</td>
<td>1.032</td>
<td>1.630</td>
</tr>
</tbody>
</table>

Table 4.1: Grid Comparison

A distinction between variable and fixed generation is made. The variable generators are the PV and the wind infeed while the rest of technologies correspond to the fixed generation.

Out of the previous information it can be concluded that the second grid covers a more widely-spread and less-populated area than the first grid. It can also be established that the impact of a fluctuating power infeed will be bigger on the first grid than on the second one. This is reflected in Figure 4.1.
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids

Figure 4.1: Conventional Load Comparison

In *MS_Clusternetz_1* an inductive power factor of 0.9 for every conventional load is given, while in *MS_Clusternetz_3* the Power Factors are defined as 0.95 inductive. On the other hand the generation distribution is shown in Figure 4.2.

![Generation Comparison](image)

Figure 4.2: Generation Comparison

The Power Factor of the photovoltaic and wind generators is 1 for most the generators while big solar farm generates with a Power Factor of 0.95. Other conventional generators present a power factor of 0.95.

In the previous figure, a distinction between variable infeed (which represent photovoltaic and wind generation) and fixed infeed is made. The graphic shows that the dependency of both grids on fluctuating infeed is considerably large and therefore, it should be taken into account when studying the grid response to the generated EM loads.

### 4.2 Charging Infrastructure

EV charging has some marked differences from conventional ICE refueling, and as a result, drivers show a different charging behavior. In this paragraph the main tasks are:

- Charging infrastructure analysis
- Charging behavior overview

In approach to fulfill the given tasks, the Grade of Utilization (GoU) of the charging infrastructure will be studied showing both the percentage of usage of the installed charging infrastructure and charging behavior of e-mobility users.
In *MS_Clusternetz_1* a total of 205 charging stations were installed for the 1 Million Scenario. This meant an average of 1.74 stations per low-voltage grid with an average consumed power of 44.66 kW per grid. The total installed power was 5.262 MW.

For the 6 Million Scenario, this grid holds a total of 1238 charging points with an average of 10.49 charging points and an average installed power of 367.913 kW per low-voltage connection. The total installed power raises to 43.420 MW.

On the other hand, for the 1 Million Scenario, *MS_Clusternetz_3* holds a total of 294 charging stations with a total power of 6.912 MW. The average stations number per low-voltage connection is 1.01 with an average installed power of 23.75 kW.

For the 6 Million Scenario the number of charging points equals 1,793. This means an average of 6.16 stations with an average power of 207.94 kW per connection. In this case, the total installed power is of 60.505 MW.

Two graphs are generated per grid showing the results from the 1 and the 6 Million Scenario Grade of Utilization. The next four figures show the GoU of the Charging Infrastructure of both grids for the 1 and the 6 Million Scenario.
In these four graphs the Grade of Utilization (GoU) of a whole week is shown for the two scenarios on both grids. The number of simulations for both grids was:

- 50 Simulations for the 1 million EV scenario
- 20 Simulations for the 6 million EV scenario

Table 4.2 and 4.3 show the most important features of the Grade of Utilization:

<table>
<thead>
<tr>
<th>MS Clusternetz 1</th>
<th>EV nº</th>
<th>Charging Station nº</th>
<th>Installed Power</th>
<th>GoU Average</th>
<th>GoU Maximum</th>
<th>GoU Interquartile</th>
</tr>
</thead>
</table>
The previous values show that the charging infrastructure installed can handle the charging of the introduced electric vehicles. Furthermore, it might be determined that this infrastructure is oversized. The maximum GoU obtained is 11.35%, while the average values are always below 1%. On the other side, no important differences were observed between the two electric networks.

The different EV technologies used in the 1 and the 6 Million Scenario have a strong effect on the GoU behavior. Both distributions are shown in Table 2.5. The two magnitudes which change with the distribution applied are the battery capacity and the maximum charging power; these factors directly affect the GoU values.

In the 6 Million Scenario the charging procedures will demand a higher power, however these procedures will last shorter and take place less often due to a larger battery capacity. This will conclude on a smaller GoU of the charging infrastructure, which average value is reduced by a 40.23% on MS_Clusternetz_1 and 29.89% on MS_Clusternetz_3.

Due to the use of a probabilistic charging behavior, an increase in the number of EVs is followed by a lower divergence. This explains why with a 6 million scenario the interquartile range is reduced. According to previous research, the application of standard load profiles for e-mobility will be valid for more than 1,000 electric vehicles [7]. Although in this case, the artificial coincident factor of 1 introduces inaccuracies.

When observing the day behavior, it can be concluded that the period with the highest values of utilization appear from 18:00 to 20:00. This corresponds to the time when the electric vehicle users arrive at their houses and begin to charge the batteries. This time concurs with the conventional load peak, which increases the instantaneous demand of electric energy. This may be an issue for the Transmission System

<table>
<thead>
<tr>
<th>MS Clusternetz</th>
<th>EV nº</th>
<th>Charging Station nº</th>
<th>Installed Power</th>
<th>GoU Average</th>
<th>GoU Maximum</th>
<th>GoU Interquartile range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mio. Scenario</td>
<td>266</td>
<td>294</td>
<td>6.912 MW</td>
<td>0.92%</td>
<td>9.13%</td>
<td>0.074%-2.24%</td>
</tr>
<tr>
<td>6 Mio. Scenario</td>
<td>1630</td>
<td>1793</td>
<td>60.505 MW</td>
<td>0.42%</td>
<td>3.42%</td>
<td>0.045%-1.35%</td>
</tr>
</tbody>
</table>

Table 4.3: MS_Clusternetz_3 GoU values
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids

Operators (TSO) as the total load peak might produce overload in some distribution lines; therefore, this will be a topic of discussion on further paragraphs.

The following box plot shows a day distribution of the GoU every hour. It shows a Wednesday with a 1 Million Scenario EVs on MS_Clusternetz_1. As it can be observed the average GoU value at 20:00 is 3.96%; a value much higher than the average week value, 0.87%. In this case the GoU of the charging infrastructure is always under 9%.

![GoU Box Plot Simulation](image)

**Figure 4.7: GoU Box Plot Simulation**
4.3 Aggregated Load

Once that all the new MATLAB data is generated a POWERFACTORY analysis can be completed. However, it is important to choose the right time periods for the power flow simulations. Therefore, in this paragraph both the infeed and the aggregated load (conventional and e-mobility) will be represented so that the right time scenarios are chosen for further analysis.

In order to obtain feasible results, different seasons and different EV scenarios have been simulated. For each time period simulation, three different e-mobility scenarios will be studied. By actual scenario we took the actual load values with a negligible charging power.

The conventional load curve includes the industry and the household loads. It has been observed that there is a change in the daily load curve for different year seasons as well as for different day types. Three day types have been defined: Weekdays, Saturday and Sunday. Figure 4.9 shows the load behavior for the different day types on a winter period.

![Figure 4.8: Simulation Scenarios](image)

![Figure 4.9: Day Type Comparison](image)
The previous graph shows the day type comparison of a transitional month for MS_Clusternetz_1. In this case the highest value is obtained at a Saturday at midday; this is due to a household load increase during the weekend. On the other side, Sunday shows lower load values explained by a sharp decrease in the industry load.

As explained before, three different time periods have been defined: winter, summer and transitional. During the winter months a load peak appears during the evening hours when an increase in the household power demand takes place. However for transitional and especially for summer months the load maximum peak is higher at midday time. Figures 4.10 and 4.11 show the load behavior for both grids:

Figure 4.10: MS_Clusternetz_1 Conventional Load Comparison

Figure 4.11: MS_Clusternetz_3 Conventional Load Comparison
It is possible to derive some conclusions from the previous two graphs.

- First, the behavior of the two grids is slightly different. It can be observed that the evening peak in MS_Clusternetz_1 is less important than in MS_Clusternetz_3; this is due to the bigger share of household load in the second network.

- Second, during midday a load peak also takes place, this peak mostly represents the industry loads which have a stronger impact on the first grid. However, this peak might be balanced by the PV infeed, which will show its generation peak around 12:00.

There are also differences between the power generation on both grids. As shown in previous paragraphs, the PV infeed has a greater impact on MS_Clusternetz_1. This means that the infeed fluctuation will also be bigger on the first grid. Due to its relatively high nominal power, the influence of the wind turbine operating on MS_Clusternetz_3 will also be analyzed. The Infeed behaviors are shown in Figures 4.12 and 4.13.

![Infeed Comparison](image.png)

*Figure 4.12: MS_Clusternetz_1 Perfect Conditions Infeed Comparison*
Once that the conventional load, the infeed and the e-mobility load distribution are known, it is possible to determine the most critical grid time periods. These time periods are searched in order to study possible overloads on the grid transformers or the conductors. Figure 4.14 shows the distribution of the three values.

This comparison shows that there will be two main critical time periods: midday and evening hours. Around 12:00 the grid shows a peak not only of load power, but also of generation maximum, which appears due to a maximum PV generation. Therefore a low transformer load but high line currents are expected around this time of the day.
On the other hand during after work hours (between 18:00 and 20:00) the conventional load shows a peak due to a household power demand increase. At this time, only the conventional generators will be feeding the grid, this result in a decrease in the power generation. Therefore this time will be especially interesting to study the impact of e-mobility in the grids as the aggregated e-mobility profiles will reach their maximum value between 18:00 to 20:00.

For all of these reasons the selected simulation times will be:

- Evening in winter
- Evening in transitional months
- Midday in summer

### 4.4 Power Flow Simulations

The power flow analysis of the previously defined time periods provides a good overview of the grid behavior: the influence of the solar and wind energy infeed and specially the impact of future e-mobility fleets.

From the power flow simulations of MS_Clusternetz_1, the following points can be concluded:

On one hand, the consumption of electric power will be much higher than its generation in the case of a winter day during the evening hours. This is due to three facts: First, during the winter months a conventional load peak will occur between 18:00 and 20:00 hours; second, at this time the infeed will be exclusively fixed generation (and wind generation in the case of MS_Clusternetz_3); third, the e-mobility load reaches its peak values. These conditions provoke relatively high transformer and line loads.

On the other hand, the midday summer scenario shows a different behavior. In this case, although the load values are high, the power infeed is even higher due to the PV generation. This means that the energy flows from the medium-voltage to the high-voltage level. Also the impact of e-mobility is relatively low according to the charging behavior. It has been observed that the power exchange correspond to low values, this situation results on a low transformer load value, however some lines can show high loads, due to the high load and generation inside the grid.

During the simulations a ‘worst case scenario’ was identified, this finally consisted of a Saturday evening during a transitional season period. This case showed the highest transformer station load as well as the highest line load. After the introduction of the electromobility loads the transformer load raised up to 21.094%. While the maximum line load value raised to 43.42%. All the load values obtained were below nominal values.
In this paragraph only the worst case scenario is shown, the other power flow simulations will be attach in Appendix B.3.

**October’s Saturday at 19:00**

<table>
<thead>
<tr>
<th></th>
<th>MS Clusternetz 1</th>
<th>Without EM</th>
<th>1 Mio. EM</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged Power [kW]</td>
<td>6742</td>
<td>7115,9</td>
<td>8211,2</td>
<td></td>
</tr>
<tr>
<td>Transformer Load</td>
<td>17,318%</td>
<td>18,278%</td>
<td>21,094%</td>
<td></td>
</tr>
<tr>
<td>Generated Power [kW]</td>
<td>1105</td>
<td>1105</td>
<td>1105</td>
<td></td>
</tr>
<tr>
<td>Consumed Power [kW]</td>
<td>7765,96</td>
<td>8133,02</td>
<td>9211,07</td>
<td></td>
</tr>
<tr>
<td>Critical Line Load</td>
<td>39,67%</td>
<td>41,37%</td>
<td>43,42%</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.4: MS_Clusternetz_1 Worst Case Scenario*

On the other hand, *MS_Clusternetz_3* simulations show the following characteristics:

The exchanged power is bigger than in *MS_Clusternetz_1*. The power flow direction is from high-voltage to the medium-voltage level for all simulated scenarios. On the other side, as it was expected, the PV infeed has a much smaller impact on the grid, this means that the generated power remains within stable values.

As previously explained, this grid presents a wind generator with a nominal power of 850 kW. This generator represents a fluctuating infeed which can affect the transformer load in more than 8% in some cases.

It is also important to notice that the impact of the household loads is bigger in this grid. This means that the evening hours show a greater peak. Therefore the ‘worst case scenario’ is considered to be a Saturday evening in January. Once that the 6 million scenario load is introduced the transformer load goes up to 20.69%, which was the highest value obtained in the simulations. The critical line load rose up to 27.83%. It can be concluded that all the values obtained are kept under critical loads.
January’s Saturday at 19:00

<table>
<thead>
<tr>
<th></th>
<th>MS Clusternetz 3</th>
<th>Without EM</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exchanged Power [kW]</strong></td>
<td>14420,5</td>
<td>14870,07</td>
<td>16185,51</td>
<td></td>
</tr>
<tr>
<td><strong>Transformer Load</strong></td>
<td>18,52%</td>
<td>19,07%</td>
<td>20,69%</td>
<td></td>
</tr>
<tr>
<td><strong>Generated Power [kW]</strong></td>
<td>11043,37</td>
<td>11043,37</td>
<td>11043,37</td>
<td></td>
</tr>
<tr>
<td><strong>Consumed Power [kW]</strong></td>
<td>25293,61</td>
<td>25739,9</td>
<td>27041,01</td>
<td></td>
</tr>
<tr>
<td><strong>Critical Line Load</strong></td>
<td>27,16%</td>
<td>27,25%</td>
<td>27,83%</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.5: MS_Clusternetz_3 Worst Case Scenario**
Impact of Future E-Mobility Fleets on suburban Medium-Voltage Grids
5 Conclusion

5.1 Future EV Scenario

Research made on the actual e-mobility state of art demonstrate that charging procedures in private charging stations will not take place at the maximum charging power of the vehicles, but at lower power levels (around 7 kW).

On the other hand, public charging stations will reach these maximum values (up to 120 kW for DC charging stations [10]). It is concluded, that the private station charging power should be reconsidered in further studies.

5.2 Grid impact results

Table 5.2 shows the maximal percentage of load increase due to the introduction of electric vehicles in the grids, these values are obtained by aggregating the e-mobility load to the conventional load values. These percentages are calculated for the worst case scenarios.

<table>
<thead>
<tr>
<th>Load Increase</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS Clusternetz 1</td>
<td>5,69%</td>
<td>22,41%</td>
</tr>
<tr>
<td>MS Clusternetz 3</td>
<td>1,90%</td>
<td>7,66%</td>
</tr>
</tbody>
</table>

Table 5.1: Maximum load increase due to e-mobility loads

The previous table shows that in the year 2030 the grid load might increase a 22.41% in MS_Clusternetz_1, if no further strategies are applied. In spite of this increase and due to the distributions of the loads and the oversized infrastructure of the electric networks, no overload is expected.

In MS_Clusternetz_3 the obtained values were also below critical limits. The maximum transformer load was 20.69% and the line loads were not higher than 28%. Given the results we can conclude that, in the medium term, the introduction of e-
mobility loads will not disturb the operation of the two analyzed medium-voltage networks.

On the other hand, it was observed that different e-mobility load values were obtained from both grids. It can be concluded that the impact of e-mobility fleets will be higher on MS_Clusternetz_1. This is due to the fact that MS_Clusternetz_3 represents an area with lower density of inhabitants and higher power consumption per household. Table 5.3 shows the installed power per inhabitant for both grids.

<table>
<thead>
<tr>
<th>Household Installed Power</th>
<th>MS Clusternetz 1</th>
<th>MS Clusternetz 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power per Inhabitant</td>
<td>1,239 kW</td>
<td>2,519 kW</td>
</tr>
</tbody>
</table>

Table 5.2: Household Installed Power per Inhabitant

Given that the EV number will depend on the number of inhabitants, the total charging infrastructure installed power will represent a lower share of the total installed household power in MS_Clusternetz_3 (14.32% and 125.4% for the 1 and 6 million scenarios) than in MS_Clusternetz_1 (30% and 180% for the same scenarios).

MS_Clusternetz_3 shows a relatively low share of variable infeed, this value rises to 7.81 MW when the PV and the wind power reach their maximum values. However, even at this scenario, this infeed will just represent a 28% of the conventional load. This means, that the grid operation will remain reasonably stable during different scenarios.

The characteristics of MS_Clusternetz_1 are considerably different. Here, the PV infeed can reach values of 10.41 MW. This represents more than a 90% of the total generation, and exceeds the grid load values. Therefore, due to meteorological variations, important power fluctuations are expected in this grid.
5.3 Consequences for Future Grid Planning

Over the longer term, EVs will reach a large scale market penetration. Therefore, some charging strategies are proposed in order to optimize the grid response. The following strategies can be included in what is called Smart Grid Initiatives:

- **Load Shifting:** As shown in previous paragraphs, the charging frequency reaches the maximum values at after work hours. As seen before, this will be a time period of a high household load. A load management system could be installed to delay the charging procedures if possible.

- **Vehicle to Grid (V2G):** One step further, EVs will be providing electricity to the grid. The EVs could be charged at low demand and high generation time periods and release the stored energy during peaks of demand with lower infeed.

- **Vehicle to Building (V2B):** The battery capacity of the EVs could also be used to reduce the electricity costs of the grid users. Households could eventually consume their whole day energy demand (around 10 kWh per day) at low tariff stages and charge the EVs for a future consumption.

The previous initiatives will definitely suit to the given medium-voltage networks. They will help to balance the electric power demand making it easier to provide a more sustainable energy mix as well as increasing the grid reliability. Electric vehicles implementation could therefore lead to a cleaner, more efficient and more reliable energy scenario.
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¡Error! Utilice la ficha Inicio para aplicar Überschrift 1 al texto que desea que aparezca aquí.
Appendix A

Box Plot Distribution

Figure A.1: Boxplot MS Clusternetz 1 Scenario 1 Mio.

Figure A.2: Boxplot MS Clusternetz 1 Scenario 6 Mio.
Figure A.3: Boxplot MS Clusternetz 3 Scenario 1 Mio.

Figure A.4: Boxplot MS Clusternetz 3 Scenario 6 Mio.
Appendix B

Infeed and Load Day Distribution

Figure B.1: MS Clusternetz 1 Graph Comparison

Figure B.2: MS Clusternetz 3 Graph Comparison
Appendix C

Power Flow Analysis

MS Clusternetz 1

1. January 15th at 19:00

<table>
<thead>
<tr>
<th>MS Clusternetz 1</th>
<th>Without EM</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged Power [kW]</td>
<td>5397,3</td>
<td>5698,6</td>
<td>6795,4</td>
</tr>
<tr>
<td>Transformer Load</td>
<td>13,635%</td>
<td>14,406%</td>
<td>17,212%</td>
</tr>
<tr>
<td>Generated Power [kW]</td>
<td>1105</td>
<td>1105</td>
<td>1105</td>
</tr>
<tr>
<td>Consumed Power [kW]</td>
<td>6447,29</td>
<td>6743,98</td>
<td>7828,12</td>
</tr>
<tr>
<td>Critical Line Load</td>
<td>28,37%</td>
<td>29,68%</td>
<td>30,99%</td>
</tr>
</tbody>
</table>

Figure C.1: MS Clusternetz 1 Jan. Power Flow Sim.

2. July 15th at 13:00

<table>
<thead>
<tr>
<th>MS Clusternetz 1</th>
<th>Without EM</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged Power [kW]</td>
<td>-3234,8</td>
<td>-3085</td>
<td>-2879,5</td>
</tr>
<tr>
<td>Transformer Load</td>
<td>8,689%</td>
<td>8,36%</td>
<td>7,916%</td>
</tr>
<tr>
<td>Generated Power [kW]</td>
<td>10575,83</td>
<td>10575,83</td>
<td>10575,83</td>
</tr>
<tr>
<td>Consumed Power [kW]</td>
<td>7298,53</td>
<td>7448,9</td>
<td>7655,08</td>
</tr>
<tr>
<td>Critical Line Load</td>
<td>32,39%</td>
<td>33,4%</td>
<td>32,45%</td>
</tr>
</tbody>
</table>

Figure C.2: MS Clusternetz 1 Jul. Power Flow Sim.
3. October Saturday at 19:00

<table>
<thead>
<tr>
<th>MS Clusternetz 1</th>
<th>Without EM</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged Power (kW)</td>
<td>6742</td>
<td>7115,9</td>
<td>8211,2</td>
</tr>
<tr>
<td>Transformer Load</td>
<td>17,318%</td>
<td>18,278%</td>
<td>21,094%</td>
</tr>
<tr>
<td>Generated Power (kW)</td>
<td>1105</td>
<td>1105</td>
<td>1105</td>
</tr>
<tr>
<td>Consumed Power (kW)</td>
<td>7765,96</td>
<td>8133,02</td>
<td>9211,07</td>
</tr>
<tr>
<td>Critical Line Load</td>
<td>39,67%</td>
<td>41,37%</td>
<td>43,42%</td>
</tr>
</tbody>
</table>

Figure C.3: MS Clusternetz 1 Worst Case Scenario
MS_Clusternetz_3

1. January 15th at 19:00

<table>
<thead>
<tr>
<th>MS Clusternetz 3</th>
<th>Without EM</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged Power [kW]</td>
<td>11754,77</td>
<td>12135,74</td>
<td>13571,71</td>
</tr>
<tr>
<td>Transformer Load</td>
<td>15,18%</td>
<td>15,64%</td>
<td>17,4%</td>
</tr>
<tr>
<td>Generated Power [kW]</td>
<td>11893,37</td>
<td>11893,37</td>
<td>11893,37</td>
</tr>
<tr>
<td>Consumed Power [kW]</td>
<td>23513,39</td>
<td>23890,62</td>
<td>25313,3</td>
</tr>
<tr>
<td>Critical Line Load</td>
<td>23,64%</td>
<td>23,7%</td>
<td>23,43%</td>
</tr>
</tbody>
</table>

Figure C.4: MS_Clusternetz_3 Jan. Power Flow Sim.

2. July 15th at 13:00

<table>
<thead>
<tr>
<th>MS Clusternetz 3</th>
<th>Without EM</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged Power [kW]</td>
<td>4786,41</td>
<td>4939,29</td>
<td>5192,32</td>
</tr>
<tr>
<td>Transformer Load</td>
<td>6,69%</td>
<td>6,85%</td>
<td>7,12%</td>
</tr>
<tr>
<td>Generated Power [kW]</td>
<td>18206,37</td>
<td>18206,37</td>
<td>18206,37</td>
</tr>
<tr>
<td>Consumed Power [kW]</td>
<td>22881,83</td>
<td>23034,31</td>
<td>23286,28</td>
</tr>
<tr>
<td>Critical Line Load</td>
<td>21,24%</td>
<td>20,8%</td>
<td>21,11%</td>
</tr>
</tbody>
</table>

Figure C.5: MS_Clusternetz_3 Jul. Power Flow Sim.
3. January Saturday at 19:00

<table>
<thead>
<tr>
<th>MS Clusternetz 3</th>
<th>Without EM</th>
<th>1 Mio. Scenario</th>
<th>6 Mio. Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged Power [kW]</td>
<td>14420,5</td>
<td>14870,07</td>
<td>16185,51</td>
</tr>
<tr>
<td>Transformer Load</td>
<td>18,52%</td>
<td>19,07%</td>
<td>20,69%</td>
</tr>
<tr>
<td>Generated Power [kW]</td>
<td>11043,37</td>
<td>11043,37</td>
<td>11043,37</td>
</tr>
<tr>
<td>Consumed Power [kW]</td>
<td>25293,61</td>
<td>25739,9</td>
<td>27041,01</td>
</tr>
<tr>
<td>Critical Line Load</td>
<td>27,16%</td>
<td>27,25%</td>
<td>27,83%</td>
</tr>
</tbody>
</table>

Figure C.6: MS_Clusternetz_3 Worst Case Scenario
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