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IMPACTS OF DEREGULATED AND REGULATED ELECTRIC VEHICLE CHARGING IN A DISTRIBUTION NETWORK

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The transportation sector contributes highly to environmental issues. With awareness of such issues, electric vehicles (EVs) have emerged as the solution in the transport sector. But at the same time, their higher penetration may cause grid issues since they are considered the additional load to the current grid. This paper presents the impact of deregulated and regulated electric vehicle (EV) charging scenarios on a real medium voltage (MV) grid in Gračanica. The grid modeling and quasi-dynamic simulation were done in DIgSILENT PowerFactory software. The analysis was done with data from Public Enterprise Elektroprivreda of Bosnia and Herzegovina. The regulation of charging was made by valley filling. This approach ensured the 100% penetration of EVs for the analyzed grid. Regulated EV charging scenarios impact the active power of the complete grid by shaving daily peaks compared to deregulated charging. All EV charging scenarios did not violate voltage limits defined by EN 50160.

1. INTRODUCTION

The global car market in 2022 provides more purchasing possibilities than in any previous year. These buying options mean cars of different styles, sizes, quality, *etc*. But what characterizes this era is the fuel these cars run on. Nowadays, electric cars are buying options as well, besides well-known diesel and gasoline-powered cars. The popularity of electric cars is increasing from day to day. It is pleasant to see that there are cars that are good for the environment and allow cleaner travel, but the cost of driving them sustainably is questionable [1,2].

It is anticipated that 500 million electric vehicles (EVs) will be driven by 2030. The technology and EV charging infrastructure are key factors for transitioning from cars with the internal combustion engine to EVs. EV charging infrastructure will be needed at households, workplaces, shopping centers, highways, etc. The power needed for EV charging should be provided by the distribution network at low prices, with minimum reinforcement, and at maximum reliability. Massive EV penetration can cause an increase in the peak demand on the network and possibly overloaded network components [3]. This paper compares the impact of deregulated and regulated EV charging on the real part of the medium voltage (MV) grid.

Work done in [4] focuses on coordinated and uncoordinated charging for 30 % and 100 % EV penetration. The analysis was performed on a benchmark (RBTS) test system and real distribution network located in Egypt for residential and non-residential customers. Results showed that uncoordinated EV charging might lead to feeders and transformers overload, higher charging and operational costs, higher system losses, and lower voltage profiles. The study showed that coordinated EV charging could significantly reduce the adverse effects caused by uncoordinated EV charging.

Authors in [5] investigated the impact of large integration of EVs on rural and urban distribution networks in Greece. The authors considered five different EV penetration levels and three charging strategies for both analyzed networks. The analysis showed that charging EVs causes voltage deviations in rural areas and overloading in urban areas. Regulated charging can reduce the problems caused by deregulated charging and allow higher EV penetration. Deregulated charging also negatively affects active power losses, while proposed smart charging strategies can reduce those losses.

The study in [6] assessed the impact of plug-in electric vehicles (PEVs) on the large residential urban area (low-voltage networks) and combined industrial and residential areas (medium-voltage and low-voltage networks). Three scenarios of PEV penetration were evaluated in the study. The study showed that the network would need reinforcement, but reinforcement costs could be decreased by about 70 % with smart charging strategies. These costs could also be lowered by 5 % to 35 % of the required investment if PEVs start charging off-peak hours instead of peak hours.

Authors in [7] analyzed the impact of EV charging on distribution networks with vehicle-to-grid (V2G) technology and without it. The analysis focused on the impact of EV charging on load active power and active and reactive power of the residential and industrial load. They showed that the V2G technology impact is not noticed with the low penetration levels of EVs, while the high penetration levels of EVs' supply a notable amount of power to the grid. The EV charging stations did not impact residential and industrial loads since charging stations were separated from both types of loads and were directly connected to the main distribution line.

Work done in [8] focuses on the impact of large-scale EV integration and fast chargers in the Norwegian distribution grid using real data from smart household meters. The goal of fast chargers' utilization and their optimal location is to reduce grid losses and voltage deviations. The authors also explored reactive power injection to minimize voltage deviations caused by fast chargers. The analysis showed that the Norwegian distribution grid could withstand 50 % EV penetration regarding voltage levels at all end-users and 20 % regarding the weakest power cable. The reactive power injection allowed the installation of fast or large EV household chargers at the weaker parts of the analyzed grid.

The authors investigated home-dominant and work-dominant EV charging scenarios on 10 actual distribution feeders with residential, commercial, and industrial loads [9]. The proposed EV charging scenarios impacted the mentioned

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three load profiles and the mixed-use load profile differently. The home-dominant charging scenario increased the peak load of all feeders. However, the impact of this charging scenario in terms of line loading and voltage was more noticeable on feeders with residential loads. The work-dominant charging scenario had a minor impact on residential and mixed-use feeders, while the impact on the commercial feeder was more significant. The charging also impacted the line loading of the commercial feeder in concentrated areas. The most significant rise in line loading was around 15%. The voltage deviations were extremely low since the feeder was robustly designed. The proposed charging scenarios moved the peak load for about 1h for residential and mixed feeders and 8h for commercial feeders. The peak load for the industrial feeder was not shifted.

The contribution of this paper is that it analyses a large real MV grid with a diverse mix of customers. Also, the methodology introduced for modeling diverse customers and EV charging at their locations is based on previous findings from the literature and real measurements. This work confirms the results of previous authors that regulated EV charging can help mitigate most of the problems resulting from deregulated EV charging.

2. **REAL DISTRIBUTION NETWORK**

2.1 GEOGRAPHICAL LOCATION AND ONE-LINE GRAPH

The case study of this paper is placed in Gračanica, Federation of Bosnia and Herzegovina. It is located at 44°41.5’N, 18°17.8’E. The analyzed network is a part of the real MV distribution network – 10 kV. The analysis was performed for Gračanica’s feeder Luke. The Luke feeder consists of 17 two-winding transformers and 2145 customers, and the 110/35/10 kV three-winding transformer supplies it. The length of the feeder is around seven kilometers. The network modeling has been done in DIgSILENT PowerFactory software. The georeferenced scheme of the analyzed network is shown in Fig. 1.

Fig. 1 – The georeferenced scheme of the analyzed network

2.2 CUSTOMERS

The analyzed part of the real MV network supplies 2145 customers. Of the 2145 customers, 1633 are registered as households, and 512 belong to the other types. Customers are represented as loads in DIgSILENT PowerFactory.

2.2.1 HOUSEHOLD CUSTOMERS

To input data for loads in DIgSILENT PowerFactory the average daily consumption per household and its peak had to be found. Due to the quasi-dynamic simulation, the daily consumption based on 15 minutes interval readings needed to be inserted into the software. Quasi-dynamic simulation performed 96 load flow calculations for one moment in time intervals of 15 minutes. The data for average daily consumption was taken from AMI readings for TS 10/0.4 kV Pišće for January 2018. TS Pišće is the substation in Gračanica, but it is located on a different feeder. The data is taken from this substation due to the better relevance. The average daily consumption of one household is calculated in two steps. The first step is taking 10 complete working days’ readings (96 readings per day) and adding them together. Then, the sum per 15-minute interval is divided by 10 (number of analyzed days) to get the average value of daily power consumption of the substation. The second step in calculating daily power consumption per household is dividing the average value of daily power consumption of the substation that we got in the first step by the number of households supplied by that substation. Fig. 2 illustrates the average daily consumption in kW. As seen from that figure, the consumption peak is at 20:00, and it is 0.568 kW.

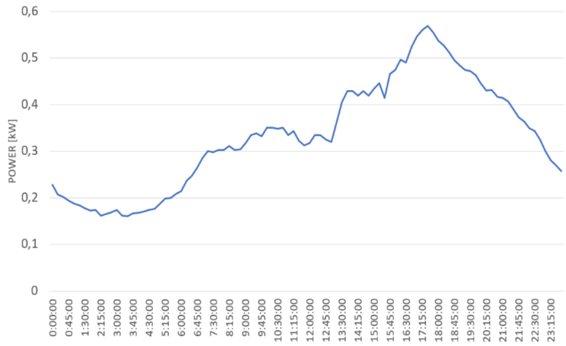

Fig. 2 – Daily power consumption per household

2.2.2 OTHER TYPES OF CUSTOMERS

Other types of customers can be classified into two classes:

1. Big customers
2. Other consumption

2.2.2.1 BIG CUSTOMERS

In this project, the biggest companies, 28 of them, are considered big customers. They are named because they have the most significant power consumption. For all big customers, smart meter readings are from January 2018.

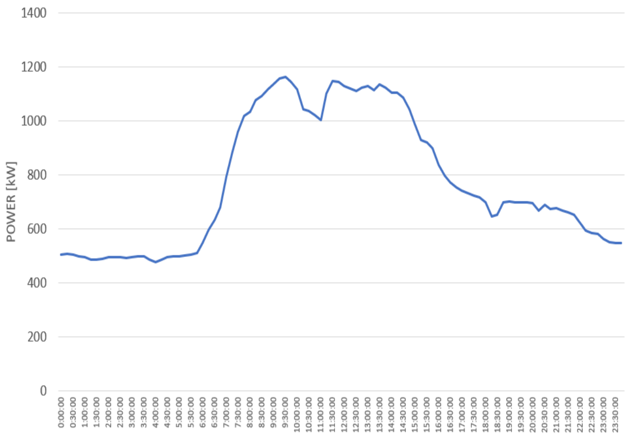

Fig. 3 – Summed daily power consumption per household

Each company has its graph and peak of daily consumption. Summed daily consumption for all 28 companies is presented in Fig. 3. The peak of summed daily consumption is at 09:30, and it is 1161.18 kW.

2.2.2.2 OTHER CONSUMPTION

The other consumption is calculated by subtracting the summed peaks of big customers and all households from the total power of loads given by the power utility company. The predicted power of loads is 2410.1 kW, while the summed peaks of big customers and all households are 1823.17 kW, which gives that the complete other consumption is 586.92 kW.

The graph for other consumption is taken from BDEW G0 standard load profiles whose 15-minute interval values were found in DIgSILENT PowerFactory. The graph is presented in Fig. 4.

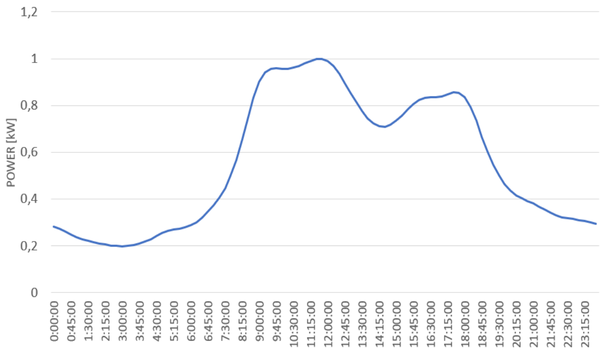

Fig. 4 – G0 standard load profile

The other consumption for an analyzed feeder is calculated by multiplying daily 15-minute readings of the G0 standard load profile with the value of the complete other consumption (586.92 kW). To get the value of the other consumption per customer, we needed to divide the other consumption of the analyzed feeder by the total number of customers of other consumption (484).

3. **METHODOLOGY**

This paper focuses on how deregulated and regulated EV charging impacts the grid for different charging scenarios. Each type of consumer (households, other consumers, and big customers) has its method of charging EVs.

3.1 DEREGULATED EV CHARGING

We analyzed five different scenarios for deregulated EV charging, and those scenarios are:

1. 0% penetration of EVs (no charging)
2. 5% penetration of EVs
3. 10% penetration of EVs
4. 20% penetration of EVs
5. 50% penetration of EVs

3.1.1 EV CHARGING AT HOUSEHOLDS

The graph for charging a huge number of electric vehicles in households in Bosnia and Herzegovina has still not been done. Therefore, the graph of slow unregulated charging is taken from [10]. That graph represents the actual graph of EV charging for Germany, which is made for MERGE project. Fig. 5 illustrates the daily graph of slow unregulated EV charging, representing the charging of one vehicle. Since charging is unregulated, EVs start charging immediately after coming home from the last trip. As seen in Fig. 5, most vehicles start charging after drivers return home from work. Not all EVs come home at the same time, therefore, the graph from Fig. 5 does not represent the real graph of charging one EV. Rather it illustrates a systematic graph of charging of all EVs, which can be used for this project since it incorporates a huge number of EVs [11]. The installed power of household chargers per substation is calculated by multiplying EV penetration percentage with the number of households per substation and 2.3 kW. This value is chosen because 2.3 kW is the charging rate for most EVs at home with a single-phase charger. The power consumed by charging EVs at households per substation is calculated by multiplying the percentage of penetration of EVs by the number of households per substation and 1,7 kW, which is the peak value taken from Fig. 5.

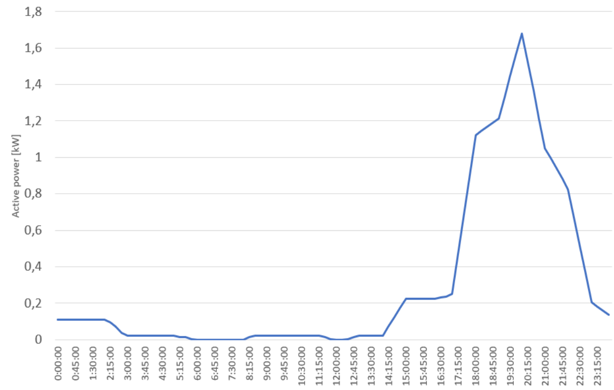

Fig. 5 – Active power of slow deregulated charging of one EV at households [10]

3.1.2 EV CHARGING AT OTHER TYPES OF CONSUMERS

The graph of charging a huge number of electric vehicles for other consumption and big customers for Bosnia and Herzegovina has still not been done. Therefore, the graph for fast, unregulated charging for other consumption and big companies is taken from [12]. EV chargers for other consumption customers and big consumers are 22 kW (ac).

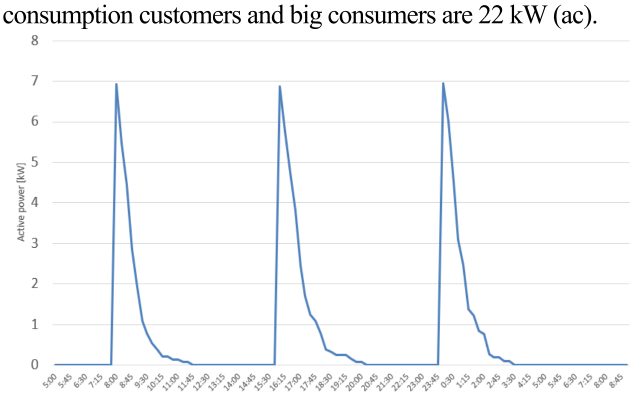

Fig. 6 – Charging of one EV for big customers – three shifts [12]

The graph, illustrated in Fig. 6, is made for one sugar factory in Portugal, which works in three shifts. The first shift starts at 08:00, the second shift at 16:00, and the third shift starts at 00:00. It is assumed that EVs start charging at the beginning of each shift.

3.1.2.1 EV CHARGING AT OTHER CONSUMPTION

For other consumption, in this paper, it was assigned that EVs are charging only in the first shift i.e. – EVs start charging at 08:00. The installed power of other consumption chargers per substation is calculated by multiplying the percentage of penetration of EVs by the number of other consumption customers per substation and 22 kW. The power consumed by charging one EV at another consumption customer is calculated by multiplying the percentage of penetration of EVs with the number of other consumption customers per substation and 7.1 kW, which is the peak value from Fig. 6.

3.1.2.2 EV CHARGING AT BIG CONSUMERS

We had 28 big consumers in this project for which we had smart meter readings, as it was mentioned in subsection 2.2.2.1, but not all of them were included in EV charging due to two reasons:

1. their consumption peak is lower than 7.1 kW;
2. the predicted number of cars for the company is zero.

For those consumers that were included in EV charging, the time of charging was set according to their working hours that we got after making graphs for their active power from smart meter readings. That means that some of them had to charge only in the first shift, some had EV charging in two shifts, and in some cases, had EV charging in all three shifts, as presented in Fig. 6. Big consumers have chargers for each car.

3.2 REGULATED EV CHARGING

We analyzed six different scenarios for regulated EV charging, and those scenarios are:

1. 0% penetration of EVs (no charging)
2. 5% penetration of EVs
3. 10% penetration of EVs
4. 20% penetration of EVs
5. 50% penetration of EVs
6. Maximum possible EV penetration with regulated charging

The regulation of charging was made by valley filling. The regulation was made for households and other consumption. Charging at big consumers did not change i.e., it has stayed deregulated. The process of EV charging regulation is described in the following section.

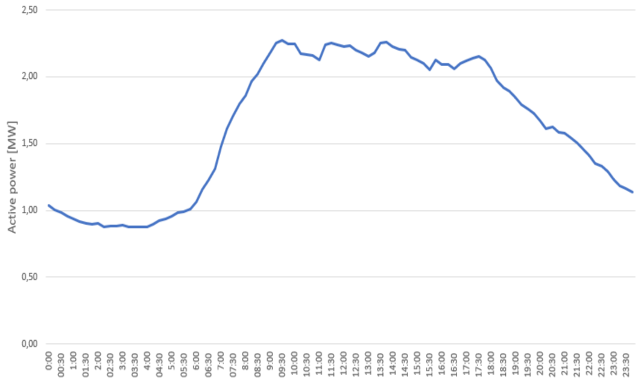

Fig. 7 – Graph of the daily power consumption of the Luke feeder

The first step in regulating EV charging is the summation of the total daily consumption of all the customers of the analyzed feeder. Figure 7 represents the daily graph of the Luke feeder.

Then the daily consumption is normalized by dividing every 96 readings by the peak of the daily consumption (2.27 MW). The third step in regulating EV charging is the subtraction of the normalized values of the daily consumption from one. The normalized peak (1) now becomes zero, and in that way, the valley filling is achieved. By doing so, the EV charging has been shifted to the night hours when there are no peak loads. Afterward, the energy was calculated. Then the readings of 1 – normalized daily power consumption are divided by the energy. That way, the 1 – normalized daily power consumption is normalized on 1 kWh. The last step in regulating EV charging is the multiplication of 96 readings from the daily consumption normalized on 1 kWh by 6.21 because 6.21 kWh is the average daily energy consumption based on the daily distance traveled by car in Bosnia and Herzegovina [11]. The 96 readings from the daily consumption normalized on 1 kWh are multiplied by 6.21. Now, these values represent the regulated charging of one EV. The graph of the regulated charging of one EV is shown in Fig. 8.

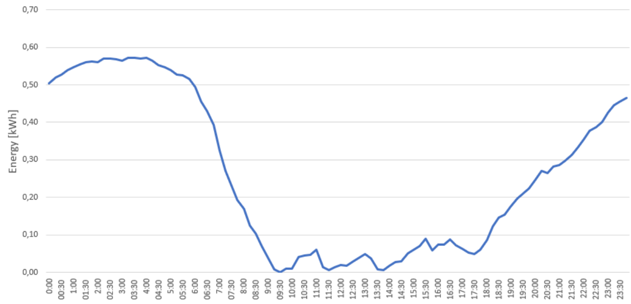

Fig. 8 – Graph of regulated charging of one EV

4. RESULTS AND DISCUSSION

In this section it will be discussed how different charging scenarios affect the grid in the following aspects:

1. Active power of complete grid
2. The voltage at 10 kV busbars
3. Loading of the lines
4. Loading of the transformers
5. Energy losses

4.1 IMPACT ON ACTIVE POWER OF COMPLETE GRID

Deregulated charging (Fig. 9) with 50 % of EV penetration exceeded the thermal capacity of the first cable sections at the beginning of the network, whose limit is 3.633 MW.

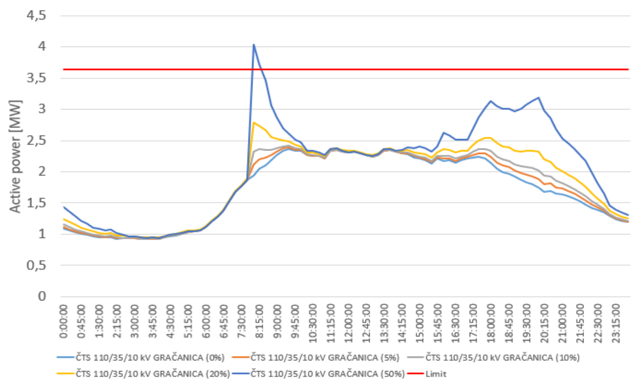

Fig. 9 – Total active power of the complete grid for deregulated EV charging scenarios

Figure 10 illustrates the impact of regulated EV charging of five penetration scenarios on the active power of the grid. For the 100% penetration scenario, the most significant increase of active power starts around 06:00. When the active power reaches its peak around 10:00 (~2.27 MW), it varies between 2.05 MW and 2.27 MW until 18:00. Then it starts decreasing until 04:00. The active power never reaches limit above of 3.633 MW. It is visible that the regulated EV charging shaved peaks that happened with deregulated EV charging at 08:00, 18:00, and 20:00.

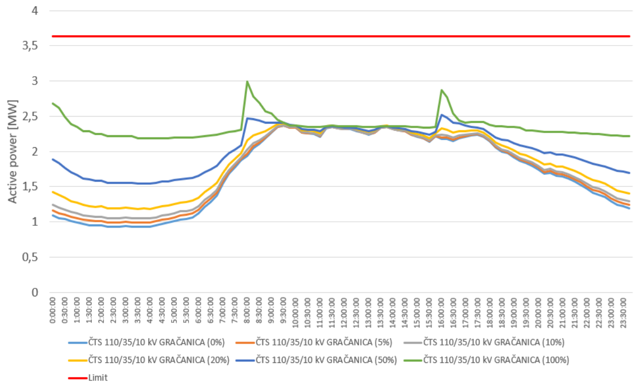

Fig. 10 – Total active power of the complete grid for regulated EV charging scenarios

4.2 IMPACT ON THE VOLTAGE OF THE 10 KV BUSBARS

Figure 11 represents 10 kV busbars at 50 % penetration of EVs for deregulated EV charging. The impact of deregulated charging at 50 % penetration of EVs on all 10 kV busbars is visible in voltage drops at 08:00 and in between 17:00 and 20:00. Figure 12 shows the voltage profile of regulated EV charging at 50% penetration with voltage drops around 08:00 and 16:30. For the analyzed charging scenarios the lowest voltage values are around 08:00. However, even though the voltage profiles for both scenarios are different neither of the charging scenarios did not violate the voltage limits of ±10 % of U_n.

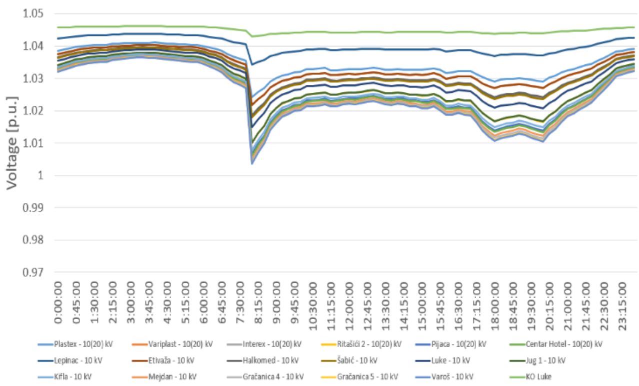

Fig. 11 – Daily voltage profile of 10 kV busbars for 50 % penetration of EVs (deregulated charging)

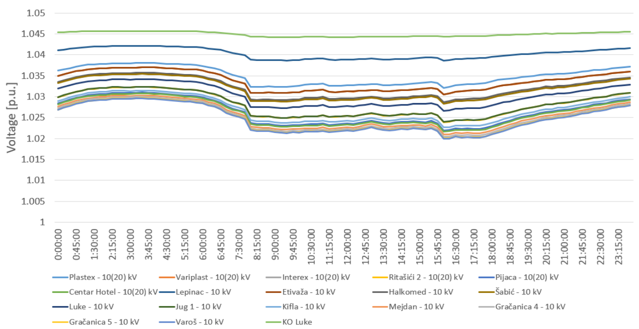

Fig. 12 – Daily voltage profile of 10 kV busbars for 50 % penetration of EVs (regulated charging)

4.3 IMPACT ON LOADING OF THE LINES

The line that was affected mainly by both EV charging scenarios is 730 meters long PHP 81 70 mm^2 line that goes from the KO Luke busbar to Lepinac 10 kV busbar. This line is overloaded at 50 % of EV penetration when it comes to deregulated charging, which is presented in Fig. 13. For that scenario, the line loading goes from around 32 % at 03:30 to over 110% at 08:00. As it can be seen from Fig. 14 the loading peaks happen at 08:00 and 16:00 for 100% EV penetration scenario. Still, even though the EV penetration is 100% the line is not overloaded. The line loading varies between 62% and 82% throughout the day.

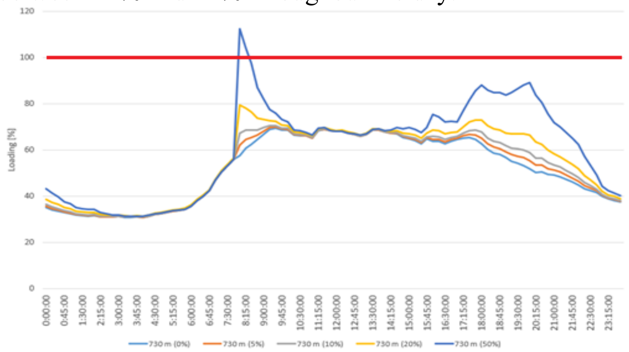

Fig. 13 – Loading of 730m PHP 81 70 mm^2 for deregulated EV charging scenarios

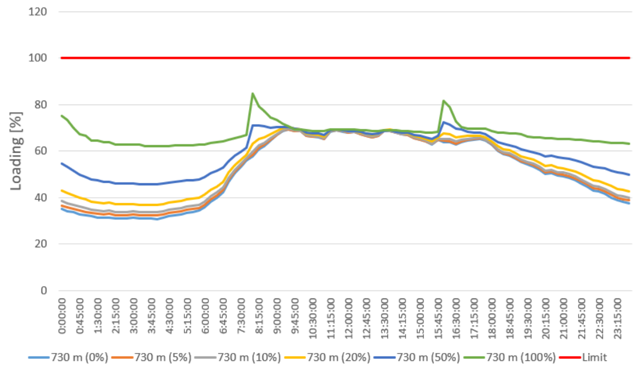

Fig. 14 – Loading of 730m PHP 81 70 mm2 for regulated EV charging scenarios

4.4 IMPACT ON LOADING OF THE TRANSFORMERS

Figure 15 shows the transformer loading from TS 10/0.4 kV Jug 1 for deregulated EV charging scenario. The nominal apparent power of this transformer is 250 kVA. This transformer represents the typical transformer of the substation on which households are the majority. The percentage of households as customers supplied by this substation is 94.95 (188 households out of 198 consumers).

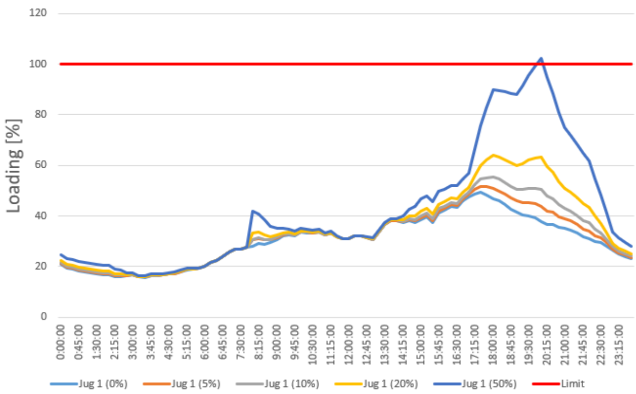

Fig. 15 – Daily graph of the apparent power of Jug 1 transformer for deregulated EV charging scenarios

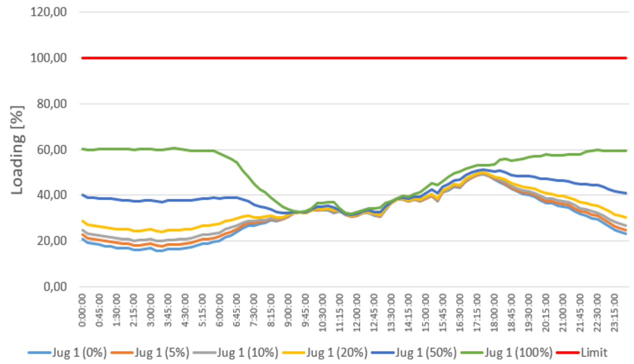

Fig. 16 – Daily graph of the apparent power of Jug 1 transformer for regulated EV charging scenarios

The deregulated charging with 50% EV penetration, presented in Fig. 15, exceeds the limit around 20:30. As can be seen from Fig. 16, the transformer does not exceed its nominal apparent power with the regulated charging at 100 % of EV penetration.

4.5 IMPACT ON ENERGY LOSSES

Figure 17 represents the energy losses for the analyzed scenarios of deregulated scenarios. Compared to the energy losses for the regulated EV charging scenarios presented in Fig. 18, regulated EV charging decreases the energy losses.

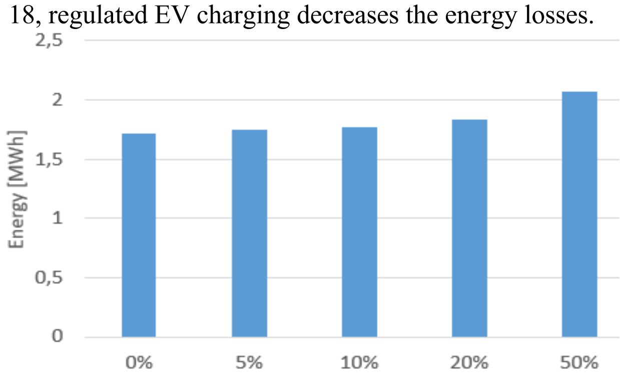

Fig. 17 – Energy losses for deregulated EV charging scenarios

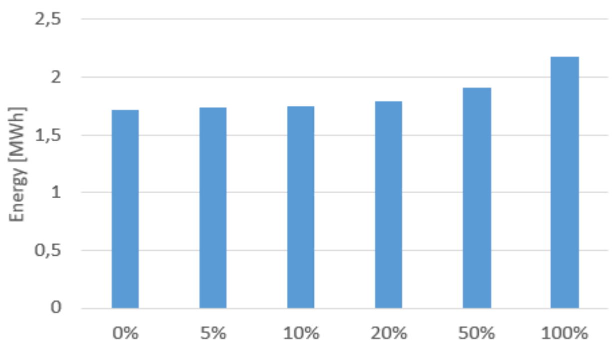

Fig. 18 – Energy losses for regulated EV charging scenarios

5. **CONCLUSION**

In this paper, we presented the impacts of deregulated and regulated EV charging on the part of the actual MV distribution grid. The valley filling method proved appropriate for regulating EV charging for the analyzed grid since it has allowed 100 % EV penetration. Neither of the analyzed (deregulated and regulated) charging scenarios makes the busbars' voltage below the lower voltage limit (0.9 p.u.). This is due to the analyzed grid since it is the shorter urban grid. The deregulated EV charging with 50% of EV penetration overloaded the grid's active power, line, and some transformers. The overloading of these components has been resolved with the proposed regulated EV charging. The regulated EV charging has shown that the current grid contains a large capacity reserve since the 100 % regulated EV penetration does not go beyond any voltage, power, transformer, and cable limit. Regulated EV charging reduces energy losses. The regulation of EV charging for big consumers would provide even better results, especially in loading transformers. The proposed EV charging regulation may impact grids with smaller capacity reserves differently.

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