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Impact of Plug-in Electric Vehicles and Photovoltaic Technologies on the Power Distribution Network (case-study of a suburban medium-voltage network)

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Abstract. Many recent studies have dealt with the future of the power distribution system, and there are different technologies which will facilitate the development towards the smart power distribution grid vision. Plug-in electric vehicles (PEV) and distributed generation (DG) technologies will become integral part of this vision. PEVs are specific because they can act both as a load and as a source of energy in a concept known as Vehicle-to-Grid (V2G). This paper analyses the impact of these technologies on an example of a real medium-voltage distribution network operating in Bosnia and Herzegovina. The impact of each technology and in combination with another technology is analyzed. It is shown that the impact of PEVs may be negative in terms of the increase in the peak load and power losses as well as transformer overloading for scenarios of a high-penetration level and uncontrolled charging. However, controlled charging and regulated implementation of V2G can be beneficial in certain terms. The Photovoltaic (PV) technology can reduce the power losses, but will violate voltage-limitations in periods of high solar insolation, especially for a high-penetration level. By controlling the new emerging technologies, many of the negative impacts can be reduced and even turned into positive effects.

Keywords: smart grid, electric vehicle, distributed generation, photovoltaic system, vehicle-to-grid

Vpliv priključnih električnih vozil in fotovoltaične tehnologije na distribucijsko omrežje

V zadnjem času zasledimo številna dela s področja elektroenergetskih distribucijskih omrežij prihodnosti. Pri snovanju omrežij je treba upoštevati tudi vedno bolj aktualna in številna priključna električna vozila (PEV), ki imajo lahko vlogo porabnika ali vira električne energije. V prispevku obravnavamo vpliv PEV na srednjenapetostno omrežje v Bosni in Hercegovini. Analize so pokazale, da uporaba PEV povečuje porabo električne energije v konicah in izgubo moči, kot tudi preobremenitev transformatorjev pri veliki in nenadzorovani vključitvi PEV v električno omrežje. V delu smo pokazali, da je lahko v določenih okoliščinah nadzorovana vključitev PEV v omrežje koristna. Fotovoltaična tehnologija lahko v ugodnih vremenskih razmerah zmanjša izgubo moči zaradi povečanja vključitve PEV v omrežje in z nadzorovano uporabo novih tehnologij lahko zmanjšamo njihove negativne vplive.

1 INTRODUCTION

A smart grid is a power network that uses digital and other advanced technologies to monitor and manage the power transport from all generation sources to meet the varying power demands of end users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity-market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing the system reliability, resilience and stability [1].

In order to achieve the expected results and features of a smart distribution grid, it is important to analyze different and various impacts of different technologies on the smart distribution grid. One of the important technologies for smart distribution grids are plug-in electric vehicles (PEV) that can be charged by the power network. Several car manufacturers have recently begun to roll out PEVs. The main reason for this is the fact that the transportation system is currently highly relying on petrol-powered vehicles releasing high CO_2 emissions. The passenger car is a major energy consumer, accounting for more than half of the total transportation energy [2]. Because of the phenomenon of global warming, a great number of studies and research are being performed in order to find different solutions to reduce and minimize emissions. Car manufacturers and drivers have recognized the importance of PEVs in reducing the CO_2 emissions of

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the transport sector, so mass production and demand for them have increased in the course of years. The integration of PEVs in the power distribution system asks for the analysis of their impacts. Hence, this paper presents an analysis of PEV charging on an example of a part of a real medium-voltage (MV) power distribution network operating in Bosnia and Herzegovina. This study also analyzes the impact of the Vehicle-to-Grid (V2G) approach, in which PEVs, such as battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), communicate with the power grid to sell demand-response services by returning electricity to the grid, as well as reducing their charging rate [3]. This represents the way of energy storing, which is a solution that may solve many problems and find numerous applications. This stored energy can be used at peak hours to reduce the peak load, mitigate overloading of the transmission and distribution networks, delay the need of additional peak-power plants, facilitate a higher integration of renewable generation etc.

Another important technology for the smart distribution grids are photovoltaic (PV) systems, designed to supply electricity by means of PV panels that utilize the solar energy. The solar energy has the highest potential among all renewable energy sources. The PV technology is very attractive considering its relatively easy implementation and construction on already existing facilities such as rooftops. That power can be consumed locally, with all the surplus power injected to the grid. As the PV system peak-production period partially coincides with the peak demand period of the consumers in the network, the usage of the solar PV systems mitigates the peak demand, which is an important positive effect.

The paper analyzes residential 3 kW PV systems connected to a particular distribution network. Different scenarios with different penetration levels are analyzed. Their impact is analyzed both individually and combined with scenarios of PEVs existing in the power distribution network.

In Section 2, the related literature is reviewed. Section 3 presents a case study-network. In section 4, the methodology proposed in this paper is described. Section 5 presents the results. Section 6 draws conclusions.

2 LITERATURE REVIEW

The impact of PEV charging in a real distribution network is analyzed in [4] for two different charging strategies and for different scenarios each with different PEV penetration levels. It is shown that the negative impact of PEV charging, i.e. overloading the distribution transformers, conductors and cables and violation of voltage limits, can be expected even with a small PEV percentage in case of uncontrolled charging [4]. Most of the negative impacts can be solved by scheduling the time and duration of charging, i.e. by regulated charging of PEV [5]. The impact of PEV charging on the investment costs and power losses is analyzed in [6]. The results show that for the scenario of 60% of all vehicles being PEV, depending of the way of charging, the investment costs in the distribution networks can be increased by 15%, where the power losses can be increased by 40% in the off-peak hours [6]. In [7], it is advised to regulate PEV charging, in order to avoid overloading the distribution network and the need of new investments. In [8] it is shown that charging of many PEVs in a scenario of a significant PEV penetration, can violate the set voltage limits. In certain circumstances, PEV charging can violate some other power quality parameters and lead to voltage unbalance [8]. If PEVs are uniformly placed through phases, voltage asymmetry is unlike to exceed the set limits [8]. Considering the impact on the distribution transformers, each charging strategy causes new load peaks, which in turn decreases the efficiency of the distribution transformers and in some cases overloads the distribution transformers [9]. However, the distribution system can handle unregulated charging of a smaller number of PEVs [10]. PEV charging affects the power losses, overloading and voltage limit values [10]. The adopted dual tariff for PEV charging can increase the network capacity to accept PEV by 14%, while the implemented strategy of smart charging leads to a 52% increase in the network capacity [10].

The planning tools for evaluating the sizing and system economy for individual PV systems are given in [11,12]. In [13], the authors analyze the impact of a large-scale PV system integration in the power distribution network and draw the conclusion that small PV penetration levels can reduce the power and can have a positive effect. Higher penetration levels can overload power transformers and increase the voltage levels if they cannot adapt themselves to voltage variations caused by DG. Typically, conventional distribution transformers cannot adapt to voltage variations because they do not have on-load tap changers (OLTC), meaning that only a moderate level of voltage variation. On the other hand, for a dynamic response in the range of ±2.5%, the voltage may fluctuate and higher penetration levels are possible. [14] evaluates the feasibility, potential and global benefits of very large-scale PV power generation systems deployed in desert areas and each generating from 10MW to several gigawatts.

3 Analysis of a Real Distribution Network

A case-study of a part of a real MV distribution network is presented. It supplies a sub-urban part of the city of Tuzla situated in the north-eastern part of Bosnia and Herzegovina. A georeferenced scheme and a single-line diagram are shown in Figs. 1 and 2, respectively.

The network can serve as an example of a typical MV network operating in Bosnia and Herzegovina. It is supplied by a 35/10.5 kV transformer of a 4 MVA installed power. It consists of 59 overhead MV lines and 20 cable lines on six feeders. It supplies a total of 3992 consumers. 3812 of them are residential and 180 are of other types. This network is already analyzed in [4], using a different methodology.

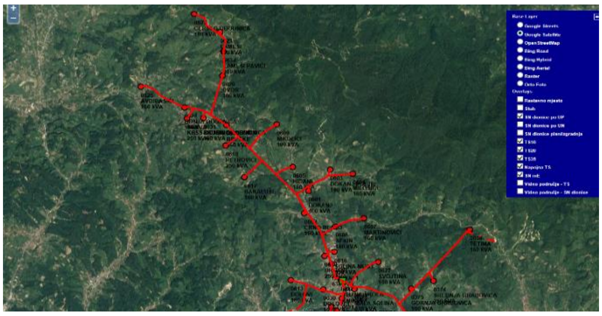

Figure 1. Georeferenced scheme of the analyzed network

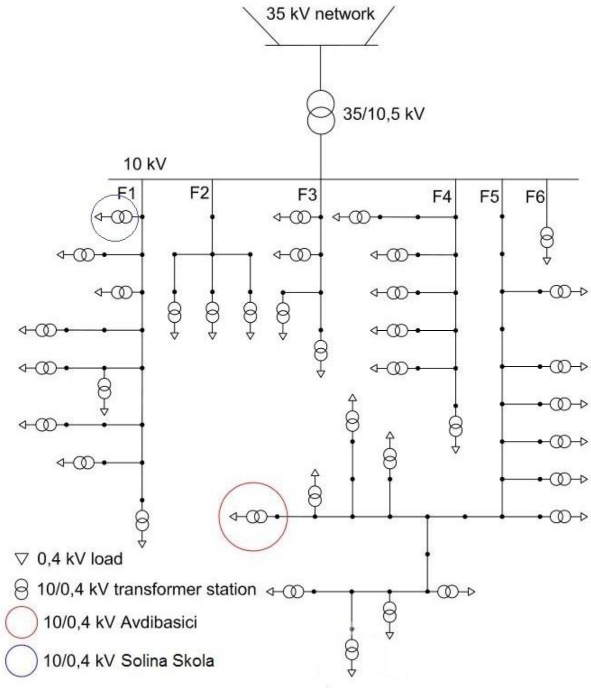

Figure 2. Single-line diagram of the analyzed network

In our case-study the network is modelled in the Power System Analysis Toolbox (PSAT), which is an open-source toolbox for the Matlab software. Each of the 37 transformer loads are modelled on 0.4 kV buses. The PEV charging load from each low voltage (LV) network is modelled as an addition to the existing loads on the 0.4 kV buses of the 10/0.4 kV transformers. The V2G power from PEVs is for each LV network modelled as a PQ generation on the 0.4 kV buses of the 10/0.4 kV transformers. DG is modelled in the same way as the V2G power.

In Fig. 3, active-power load profiles of five analyzed feeders are shown.

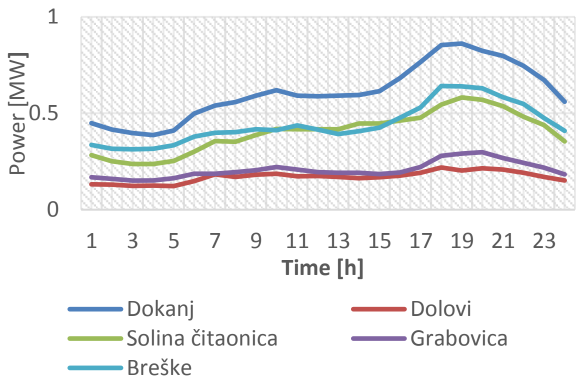

Figure 3. Active-power load profiles of five analyzed feeders

4 Methodology

The methodology used in our case-study is a significant improvement of the methodology used in [4]. The load-flows are calculated in the Matlab software (PSAT Toolbox) using the Newton-Raphson method.

4.1 Methodology for analyzing the PEV impact

In the model, PEVs are assumed to use a BMW i3 (24 kWh) battery.

PEVs are charged from a 220 V home outlet, by 3.7 kW home chargers. Statistically, in the course of a year, drivers drive approximately 13.000 km, which is some 35 kilometers a day. Table 1 provides a specification for the car used in our calculation.

The impact of slow charging is analyzed and modelled. The batteries are assumed to be charged once a day for some two hours. The charging power is 3.7 kW and the daily consumption is 6.2 kWh. PEVs are charged with the power factor of 0.99.

Table 1. Electric-car specification

Car Model	Battery Capacity	Range	Specific Consumption	Daily Consumption
BMW i3	24 kWh	135 km	0.169 kWh/km	6.2 kWh

4.1.1 Scenarios

To analyze the PEV impact, different scenarios are created based on different assumptions. Firstly, a 20% and 50% vehicle penetration are analyzed. Secondly, an unregulated and regulated slow-charging strategies are modelled. The number of PEV charging is calculated based on the number of consumers. It is assumed that 70% of consumers have a car. This was used as a baseline for calculating the number of PEVs in different scenarios and penetration percentages.

Table 2. Different scenarios for analyzing the PEV impact

Scenario	Percentage	Charging Strategy
S0	0	n/a
S1	20	Unregulated
S2	50	Unregulated
S3	20	Regulated
S4	50	Regulated

Charging diagram of unregulated slow charging used for the calculations is shown in Fig. 4. It is based on the graph for Germany from [15]. Since there is no such diagram for Bosnia and Herzegovina, we use the graph for Germany, showing daily charging of a large number of PEVs scaled down to the power of a single vehicle. As this is a graph for unregulated charging, one can notice an increase in consumption at 4 p.m., which is the time when the majority of drivers come home from work and start charging their vehicles.

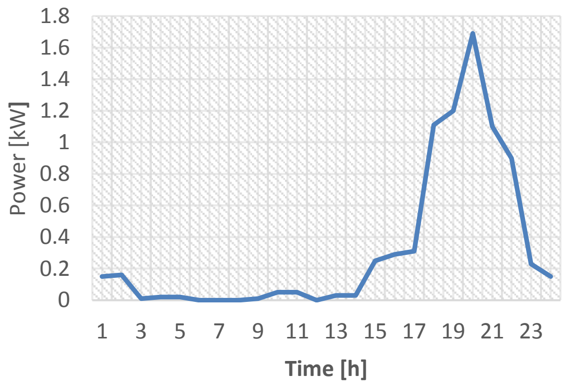

Figure 4. Unregulated slow charging scaled down to a single vehicle

In our case-study, the impact of regulated charging is analyzed as well [4]. In Fig. 5, a diagram of the active power for two analyzed scenarios is shown. The diagram represents average regulated charging for all the vehicles scaled down to the power of a single vehicle. (S3 stands for the scenario of a 20% vehicle penetration, while S4 for the 50% case).

4.2 Methodology for analyzing the impact of PV systems

The PVs power is assumed to be about 3 kW and the area is 20 m^2. To calculate the hourly PV output, irradiation data measured in Mostar in 2011 are used with the position of 43.342˚N 17.810˚E. Fig. 6 shows a daily irradiation graph transformed into kW for a particular solar panel (module).

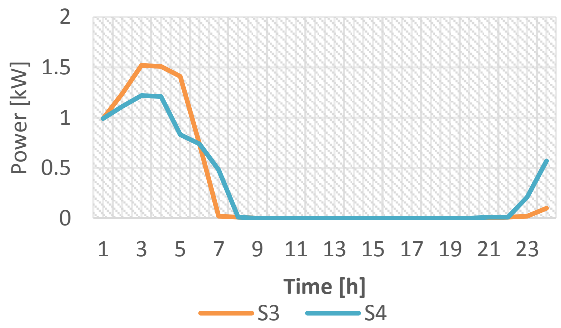

Figure 5. Regulated slow charging scaled down to a single vehicle for two different scenarios

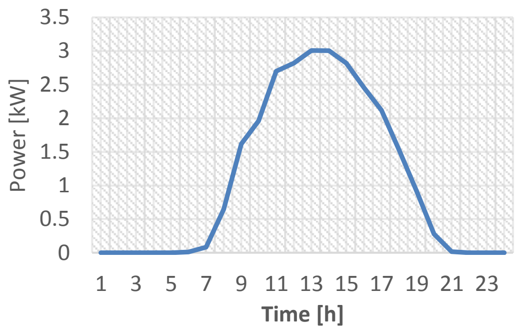

Figure 6. Power diagram of a solar module (used at home) of one consumer. It is used as a nominal approach for calculating power generation for every consumer

To analyze the impact of the PV usage, two scenarios presented in Table 3 are analyzed. The PV S1 scenario is used for the case of the 20% of PV consumers and the PV S2 for the case of the 50% of PV consumers.

Table 3. Different scenarios for analyzing the PV impact

Scenario	Penetration level
PV S1	20%
PV S2	50%

4.3 Methodology for analyzing the impact of vehicle-to-grid technology individually and combined with PV systems

When investigating the PEV impact on smart grids it is important to analyze V2G. As stated above, mass production and mass usage of PEVs means that a great amount of energy shall be available from the vehicles connected to the charging station. The available PEVs are assumed to return the power to the grid at 8 p.m. during the peak-load time. At that hour, PEVs provide 10 kW per vehicle, which is reasonable since the battery capacity is 24 kWh and there is still energy left in the PEV battery after returning from work. Of course, the V2G functionality of EV charging stations is necessary. The reactive power generated by the batteries is calculated according to the power factor of 0.99. Table 4 shows the V2G impact for individual scenarios.

Table 4. Different scenarios for analyzing the V2G impact

Scenario	Penetration level	Returning the power to the grid
V2G-1	20%	All
V2G-2	50%	40%

In the V2G-1 scenario, the active and reactive power from PEVs is generated at 8 p.m. and the vehicles are charged according to the regulated charging strategy during the night. The PEV percentage penetration is 20% and all vehicles provide V2G services. In the V2G-2 scenario, power is generated at the same time with the same amount, but for the 50% share penetration. Only 40% of PEVs return the power back to the grid through V2G, since at this time all vehicle batteries and all charging stations will not be available.

The second approach combines V2G and PV contributions to the power grid. For this approach, only V2G-2 + PV S1 scenario is analyzed in which 20% of the consumers use mini solar facilities (roof panels), and 50% of them have PEVs according to the regulated strategy, but only 40% of PEVs return the power back to the grid as V2G at 8 p.m.

Table 5. Scenario for analyzing the impact of V2G combined with PV

Scenario	PV penetration level	PEV penetration level	Returning the power to the grid
V2G-2 + PV S1	20%	50%	40%

5 Results and Discussion

Fig. 7 shows the voltage drop on the *10 kV Breške* feeder, from starting the feeder to the furthest point *Cerik* in the network, as used in the S0 baseline scenario with no consideration of the smart grid technology.

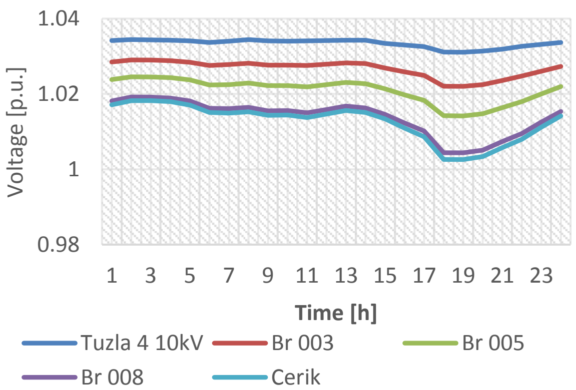

Figure 7. Voltage drop along points on the longest feeder in the network

It is important to note the voltage drop at 4 p.m. due to the peak load, since it plays a significant role in the analysis of the impact of unregulated PEV charging which takes place at the same time.

Figs. 8 and 9 show the impact of the voltage drop in case of unregulated and regulated charging respectively, for different scenarios for the *10/0,4 kV Avdibašići* transformer station where the voltage values are the lowest.

As seen, in case of unregulated charging, voltage drop is near the voltage limit, because of the high load at PEV charging. This is very typical for the higher PEV penetration scenarios, where the voltage limit of ±10% U_n, defined by EN 50160, is exceeded.

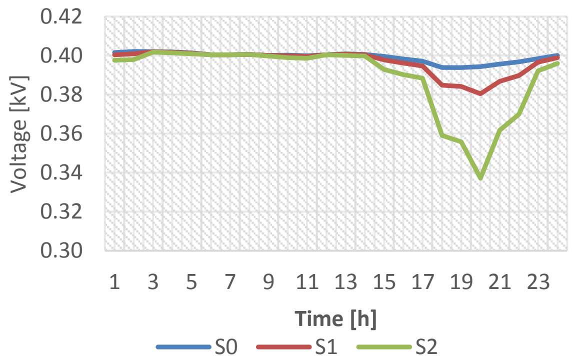

Figure 8. Voltage drop at Avdibašići in the unregulated charging strategy.

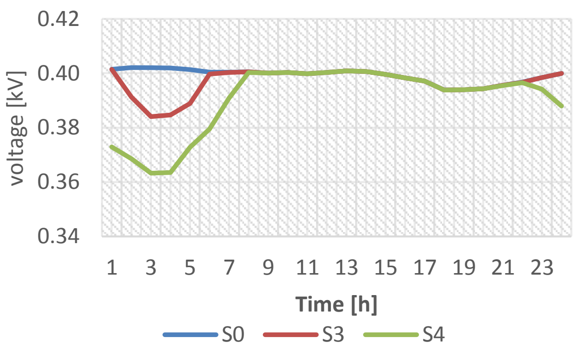

Figure 9. Voltage drop at Avdibašići in the regulated charging strategy

Regulated charging, helps maintaining satisfiable voltage profiles, particularly in the low penetration scenario, i.e. S3.

Figs. 10 and 11 show the network active power observed at the Tuzla IV 35/10 kV transformer station for all scenarios. As seen, unregulated charging leads to an increase in the daily peak power, which is especially high in the high PEV penetration scenario, i.e. S2. This can be avoided by using regulated charging strategy, especially for lower PEV penetration levels, i.e. S1, in which vehicles are charged at night during moderate power consumption. This regulated charging approach can be improved by carefully analyzing the load diagrams and power flows and accordingly scheduling the vehicle charging. Also, regulated charging positively affects the network and power system by decreasing the risk of network-components overloading, better exploiting the power-generation facilities during the night, decreasing the need for new peak-generation facilities and positively impacting the voltage profiles.

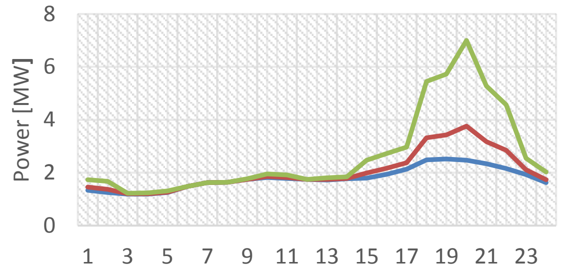

Figure 10. Total active-power consumption in unregulated charging

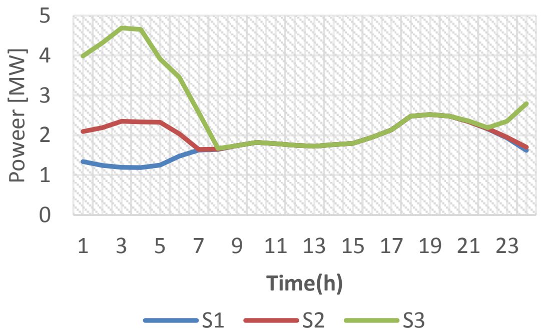

Figure 11. Total active-power consumption in regulated charging

Fig. 12 shows the active-power losses during one day for each scenario for unregulated and regulated charging. We can see that by increasing the number of PEV vehicles, the losses increase, too. It is also important to note that regulated charging leads to lower power losses than unregulated.

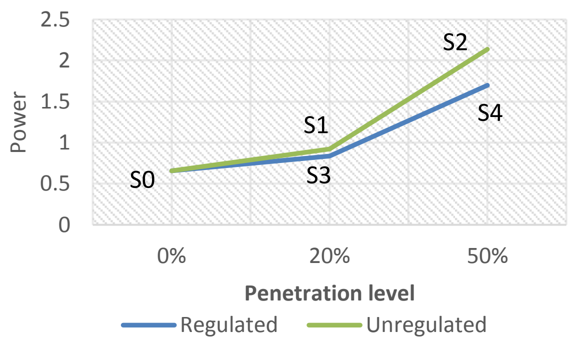

Figure 12. Daily active-power losses for different PEV charging scenarios

The following graph in Fig. 13 shows the voltage-limit violation and thermal limit violations of network elements. The voltage limits are violated only at 17% of the total network buses in scenario S2. These violations took place at voltage drops of less than 0.36 kV (0.9 p.u.) at the time of the daily peak load when a lot of consumers charge their PEVs.

In the V2G-1 scenario, 20% of the total vehicle owners use PEV. They all of return the power back to the grid at 8 p.m., after charging by the regulated strategy during the night. In the V2G-2 scenario, 50% of the total vehicle owners use PEVs, but only 20% of them (40% of the PEVs' owners) return the power back to the grid at 8 p.m. Fig. 14 shows the generated and consumed power for both V2G scenarios.

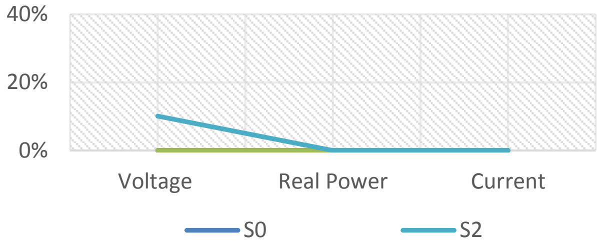

Figure 13. Voltage-limit violations

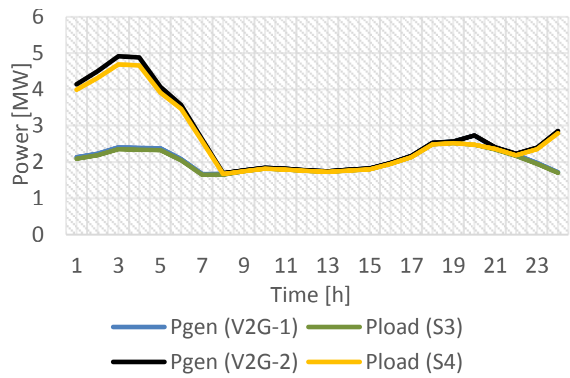

Figure 14. Total generated and consumed active power for both V2G scenarios

Analyzing the diagrams one can see that using the V2G scenarios can be very beneficial for the grid. The generated peak power in the V2G scenario in the above graph can be regulated at almost any time. This means that if additional power is needed in the network, it is already available in the PEVs. By applying different tariff strategies, this can be beneficial for the distribution system operators, suppliers and consumers owning PEVs.

Fig. 15 presents results of the analysis of the impact of distributed generation in form of PV. The active-power generation with no PV generation is shown, too.

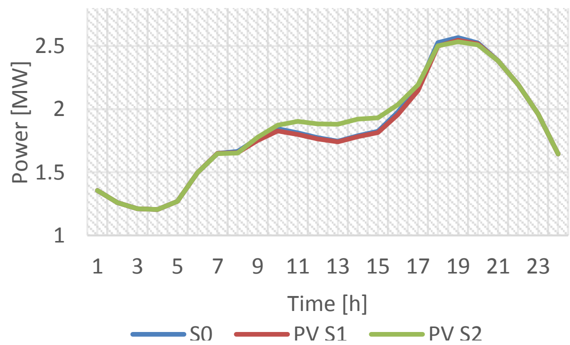

Figure 15. Total active-power generation in terms of PV by scenarios.

Fig. 16 presents results of a combined approach with the impact of DG and V2G: 20% of consumers with installed PV systems in combination with 50% of consumers having PEVs charged at night (regulated strategy), and 40% of the consumers with PEVs connected as V2G. Though the PV effect can be seen in Fig. 15, PV systems for such low penetration level increase the power generation only slightly compared to the number and power of PEVs, and therefore it is hard to observe it in Fig. 16. As the PV systems are modelled as small-capacity systems with the power of 3kW per consumer compared to V2G with 10 kW per consumer, whose impact on the graph can be more easily seen.

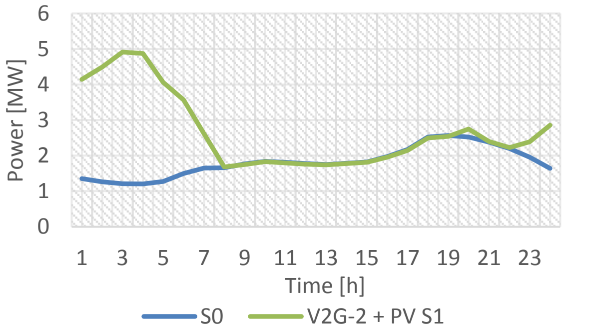

Figure 16. Total active generated power for the combined approach with the existing DG and V2G for defined penetration levels, with all PEVs using regulated charging strategy

Fig. 17 shows the voltage profiles for the *10/0.4 Solina school TS* for different scenarios. Analyzing this figure makes it easier to understand the impacts of different technologies. Fig. 18 shows the total power losses during one day.

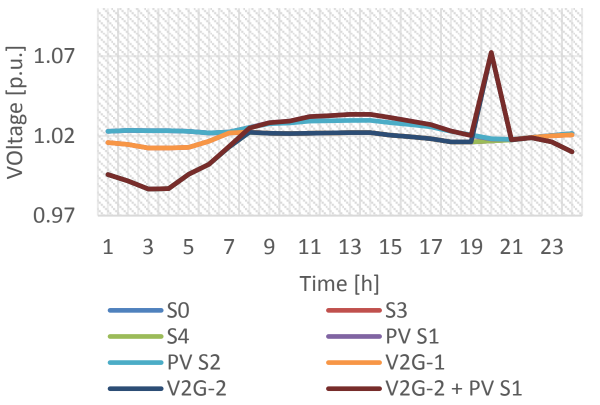

Figure 17. Voltage profiles at the Solina school TS for all scenarios

Fig. 19 shows a diagram for certain limit violations (voltage, power overload and maximum current) for different network elements expressed in percentages for the total number of network elements.

The limits are violated only in the PV S2, S2 and V2G-2 + PV S1 scenarios. In each of them the voltage limits are violated. In PV S2, the voltage limit is exceeded because of the PV production on certain buses. In S2, the voltage level is lower than permissible because of the high increase in the power consumption (due to high PEV penetration). In V2G-2 + PV S1 the voltage limits are exceeded at 8 p.m. when 20% of the vehicles are V2G connected.

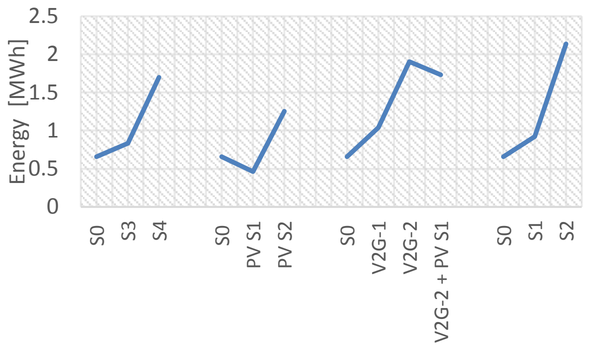

Figure 18. Active-power losses for each scenario during one day

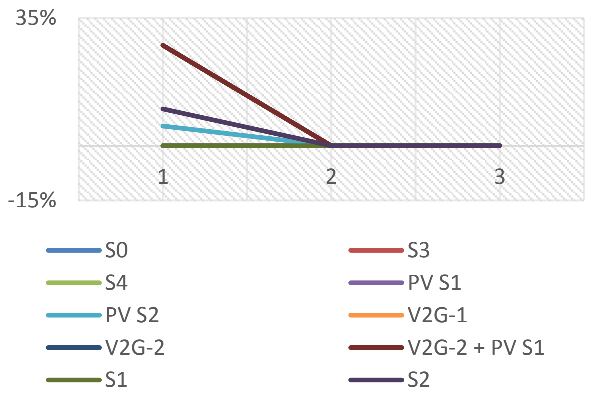

Figure 19. Limit violations

6 CONCLUSION

The impact of different smart-grid technologies is analyzed by using different simulation scenarios and investigating different possible solutions and approaches.

PEV charging affects the MV network by increasing the daily peak load, and active-power losses, particularly in case of the unregulated charging strategy, which even can result in voltage-limit violation (in the range from 0.9 to 1.1 p.u.). The impact depends on the PEV penetration rate. By regulating PEV charging, i.e. adopting a regulated-charging strategy, the power distribution system can operate well, even better than without PEVs, as a result of improved and flattened load profiles, thus also increasing the utilization of the base-load power plants.

The DG impact in a form of small solar systems (photovoltaic) on the power network is significant. When their penetration level is small, the network supports their integration without consequences. When their penetration level is high, the voltage limits can be violated as observed from our model simulation results. Regardless of that, installing PV systems positively affects the power system especially in the period of high consumption, when the power production from PV systems decreases the network load. Moreover, the energy can be stored in PEV batteries and to be later utilized for various network purposes like peak load shaving.

The conclusion drawn from our study is that using PEV, PV and V2G can positively affect the power distribution networks as it decreases their peak load.

Those different smart grid technologies have specific and different impact, yet careful and professional approach in their operation could lead to better conditions in distribution grids and greater satisfaction of all active and passive users of the network.

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