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Impact of charging a large number of electric vehicles on the power system voltage stability

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Abstract. In this paper, the impact of charging a large number of electric vehicles (EV) on the power system voltage stability is investigated on an example of a real power transmission system. First, the maximum load factors for different states in a selected part of the power system are determined using the continuation power flow (CPF) calculations and PV curves. The approach provides information about the active power limit value prior to the voltage collapse. Second, different daily load diagrams for the current load and the load expected in 2025 and 2030 together with the impact of charging 5 % and 10% of the electric vehicles in the analyzed region are constructed and voltage variations at 110 kV buses for different scenarios are analyzed. The results show that the foreseen future charging of a large number of EVs during the peak load intervals combined with the expected increase in power consumption can significantly affect the voltage profiles in the power transmission grid.

Keywords: power system, voltage stability, electric vehicles charging, continuation power flow

Vpliv polnjenja velikega števila električnih vozil na stabilnost električnega omrežja

V članku obravnavamo vpliv priključitve in polnjenja akumulatorjev električnih vozil na stabilnost električnega omrežja. Najprej so podani izračuni za različne obremenitve električnega omrežja z uporabo stalnega pretoka moči in krivulj PV. Na ta način dobimo podatke o aktivni moči pred točko kritične napetosti. Nato smo obravnavali različne pričakovane diagrame dnevne obremenitve električnega omrežja v letih 2025 in 2030 ob upoštevanju polnjenja 5 % do 10 % električnih vozil na določenem območju. Rezultati potrjujejo, da bo imelo polnjenje akumulatorjev električnih vozil velik vpliv na napetostni profil v električnem omrežju.

1 INTRODUCTION

The different processes, such as deregulation of the electricity market, integration of a large number of power plants exploiting renewable energy sources, implementation of new technologies, etc., have made the power systems worldwide to go through a process of significant changes. One of the fields attracting attention of the researchers is the analysis of different technical aspects of the impact of charging a large number of electric vehicles (EV) on the power systems. A significant increase in the EV sales in the last few years and the expected future mass sales will be keeping this topic in the focus of researchers for a long period in the future. Controlled EV charging and different control strategies are studied in [1], [2], [3], [4]. It has been concluded that controlled EV charging can reduce the voltage variations that could take place at certain times if charging is left uncontrolled, minimize the power losses, reduce charging costs and allow for a far greater EV penetration. The impact of EV charging on the power distribution grid (voltage variations and losses) is analyzed in [5], [6], [7], [8], [9] where it is concluded that EVs can significantly affect the power distribution grid. Refs. [10] and [11] analyze the EV impact on the power quality and [12], [13] analyze their impact on the power system stability. A voltage sensitivity analysis based method is proposed in [14] to determine the best location for a EV charging station.

In this paper, voltage stability is analyzed by using the PV curves on an example of a real power system. Using this approach, the maximum power transfer before the occurrence of the voltage collapse in the analyzed system is determined for different network states. Also, the buses where the most significant voltage variations can be expected as a consequence of the load increase are identified. By using the measured time series of the active and reactive power consumption, a daily load profile with the maximum peak load is identified. Based on [15] and [16], the expected daily load profiles for 2025 and 2030 are constructed taking into account a 3% annual increase in power consumption. Also, according to [17], it is assumed that 5% and 10% of the total vehicles are EVs in 2025 and 2030, respectively. All the EV are being charged during the daily peak (around 6 p.m.) with the charging power of 3.7 kW ($\cos\varphi = 0.98$) and the total

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assumed time of charging of six hours. The results show that charging of a large number of EVs, with the expected future increase in power consumption, can at certain states of the power transmission network lead to significant variations in the voltage profiles. This ultimately requires adoption of some control strategy actions or additional investments in the transmission network assets (new lines, transformers, reactive power compensation, etc.). Also, in this analysis, conclusion is drawn that EV charging should be regulated. In this way, the operating limits would remain within the set limits.

The paper is organised as follows. Section 2 briefly explains voltage stability, the methodology used in the practical analysis and shows a test example (western part of Bosnia and Herzegovina, e.g. the Una-Sana region). The results of the analysis and a discussion are presented in Section 3. Section 4 draws conclusions of the paper.

2 THEORETICAL BACKGROUND AND SELECTED POWER SYSTEM

2.1 Basics about the voltage stability

In this subsection based on [18], [19] and [20], basics about the voltage stability are presented. Generally, the power system stability or instability can be manifested in several ways, depending on the characteristics and configuration of the power system, operating state and nature and location of the disturbance. Voltage stability is a subset of the global power system stability and presents the ability of a power system to maintain steady acceptable voltage values at all buses under normal operating states and after being subjected to a disturbance [18]. Voltage stability is usually a local phenomenon but its consequences may have a widespread impact [18]. For a practical illustration of the basic theory of voltage stability, the two-bus Thevenin equivalent system is usually used. The system consists of the Z_{Th} Thevenin equivalent impedance with a three phase source with constant voltage E_{Th} and the load represented with impedance Z_L. Voltage instability occurs when the power consumption is greater than the limit power transfer, i.e. for the simplest model of the system it occurs when $|Z_L| = |Z_{Th}|$. A large number of different indicators is used to asses voltage stability. Quite practical approaches to the voltage stability analysis are the PV and QV curves. The PV curve describes variations in the node voltages in dependence of the active power consumption. The power system is stable in all the points in the upper part of the curve and unstable in the lower part of the curve. The nose of the curve represents the limit power transfer point for the analyzed network. The purpose of the PV and QV curves is to determine the capacity of the system to maintain the voltage stable at all the buses in the system. These curves are suitable for detection of the point of the voltage collapse and maximum power transfer capacity between the buses before the voltage collapse, the need for the reactive power compensation in order to prevent the voltage collapse, etc. The PV and QV curves are obtained with a series of power flow calculations, and a rather practical approach is the continuation power flow (CPF) technique.

2.2 Analyzed area of the power system

For our practical analysis we selected the part of the power system supplying Bosnia and Herzegovina in its western part, i.e. in the Una-Sana region. This region covers some 4.125 km^2, has eight municipalities and some 300.000 inhabitants. The maximum power load is some 93 MW and 30 MVAr. The total number of electricity consumers is some 100.000. The number of the registered vehicles in 2012 was 67.000. The number was split to fit the areas of individual 110/x kV transformer substations (TS). The part of the analyzed power transmission system is shown in Fig. 1. In the central part of the city of Bihać (administrative center of the region), there are one 220/110 kV TS and two 110/x kV TSs. The other 110/x kV TSs are on two 110 kV rings and are located mostly in the centers of smaller towns in the region. The majority of the 110/x kV TSs supply the consumers in the regional corresponding municipalities while the 110/x kV TS EVP K.Vakuf is the only TS supplying the railroad network. The data about the modelled system shown in Fig. 1 are given in Tables 1-3. This part of the power system does not contain some large generating units.

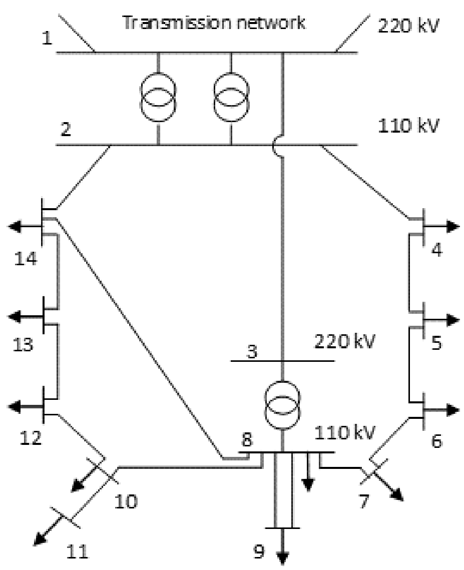

Figure 1. Single-line diagram of the analysed power transmission system

Table 1: Load data

Bus no.	Name	Un (kV)	P (MW)	Q (MVAr)
4	S. Most	110	11.33	2.23
5	Kljuc	110	4.99	1.06
6	B. Petrovac	110	3.82	1.03
7	EVP K.Vakuf	110	0.07	0.02
8	Bihac 1	110	14.00	3.57
9	Bihac 2	110	11.07	1.82
10	Cazin 1	110	16.13	4.01
11	Cazin 2	110	4.72	1.04
12	V. Kladusa	110	9.77	2.14
13	Vrnograc	110	7.94	2.26
14	B. Krupa	110	8.62	2.44

Table 2: Line data

From Bus	To Bus	R (p.u)	L(p.u)	C (p.u)
1	3	0.012	0.00019	0.000292
2	14	0.079	0.00054	0.000052
2	4	0.034	0.00023	0.000022
8	14	0.049	0.00035	0.000033
8	9	0.004	0.00005	0.000005
8	9	0.004	0.00005	0.000005
8	10	0.016	0.00018	0.000018
10	11	0.010	0.00011	0.000011
10	12	0.026	0.00028	0.000028
6	7	0.027	0.00029	0.000029
12	13	0.013	0.00014	0.000014
5	6	0.043	0.00047	0.000046
4	5	0.029	0.00031	0.000031
7	8	0.037	0.00041	0.000029
13	14	0.032	0.00035	0.000008

Table 3. Transformer data

From Bus	To Bus	kV/kV	R (p.u.)	X (p.u.)
1	2	220/110	0.0027	0.109
1	2	220/110	0.0024	0.109
3	8	220/110	0.0018	0.105

3 Results and discussion

This chapter presents results of our analysis and the appropriate discussion. For each analyzed case, the nominal voltage value of 1 p.u. for the Prijedor 220 kV bus was used in the calculations. The current voltage variations at this bus are not taken into consideration.

3.1 PV analysis

Based on the model presented in Fig. 1 and loads measured at individual TSs, the PV analysis was conducted for four cases using the CPF calculations. The loads were modelled as constant PQ loads with their increase for every node defined as $P_L = P_{L0}(1+\lambda)$ and $Q_L = Q_{L0}(1+\lambda)$, with a constant rate of the increase. The CPF calculations were done using the PSAT toolbox and Matlab software [20].

For the basic case (case C1 - all the power lines and transformers are in operation) the voltage collapse occurs at the maximum load factor of 7.18. p.u. Also, in this point, the Jacobian matrix becomes singular. In this case, the most significant changes in the voltage value resulting from the increase in power consumption are identified on the 12, 11, 10 and 13 buses, respectively. Similar results, but with a significantly lower load factor, are identified for the second case (case C2 - power line 1-3 outage). For C2, the maximum load factor is 3.84. The most significant voltage variations are identified for the same buses as in the basic case (12, 11, 10 and 13 buses). Third analyzed case is the case when the power line 2-4 is in outage (case C3), and the maximum load factor is 4.39. p.u. For case C3 the most significant voltage variations are identified for the 4, 5 and 6 buses. The fourth analysed case is the case when the power line 2-14 is in outage (case C4). The results of the analysis for this case show that the maximum load factor is 4.53. p.u. and the most significant voltage variations are on the 13, 12, 10 and 14 buses.

Judging from the current power consumption, there is a relatively high reserve in the transmission capacities of the analyzed power system, which can reliably supply the consumers in this region even in cases of some network elements unavailability. This type of the analysis can provide very important information about the transmission capacity availability. The QV curves, which are not presented in this paper because of the high number of figures, indicate the need for an additional reactive power in some of the nodes and eventually also the need for the reactive power compensation.

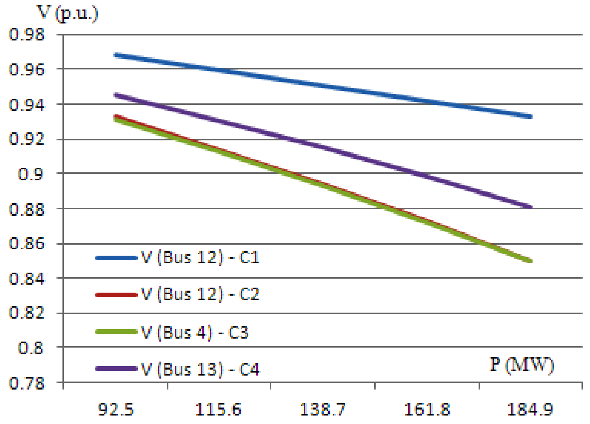

Figure 2. PV curves for critical 12, 4 and 13 buses and four different cases from the tested power transmission system

The PV curves for some of the buses of the analyzed cases are shown in Fig. 2. The voltage values are given to the point of the total active power consumption of 185 MW. This value is chosen to reflect the expected increase in electricity consumption due to both the annual power consumption increase and the expected EV charging in the peak time, for the EV penetration rate of 10 % expected by 2030.

From Fig. 2 it can be concluded that for the analyzed increase in power consumption, the voltage values are within the limit of –10 % Un for all the buses only for the basic C1 case. It should be noted that according to the national Grid Code limit voltage variation in the 110 kV network is ±10 % Un. For the other three cases at the buses with the most significant voltage variations identified, the voltage value drops below -10 %.

3.2 Daily load profile, increase in power consumption and EV charging

As stated in Section 1, the current daily load diagram, expected daily load diagrams for 2025 and 2030 (3 % annual increase in power consumption), and daily load diagrams for 2025 and 2030 together with the expected EV charging (5 % and 10 %) are shown in Fig. 3. S1 represents the current power consumption for which the daily load profile and hourly values were obtained with measurements made in the analyzed system. S2 represents the expected power consumption in 2025 while S3 adds up the additional load from the EV charging in 2025 for a 5 % EV penetration rate. The total number of EVs in the analyzed area for the 5 % EV penetration rate is 3355 and the additional load they represent is around 12.4 MW. S4 represents the expected daily diagram resulting from the increase in power consumption in 2030 while S5 adds up the additional load from EV charging for a 10 % EV penetration rate in 2030. The total number of EVs for a 10 % EV penetration rate is 6711 and the resulting additional load is around 24.8 MW. For S3 and S5 it is assumed that EVs are charged from 5 p.m. – 11 p.m. For the analyzed scenarios, the maximum load is in 2030 with a 10 % EV penetration rate (around 180 MW).

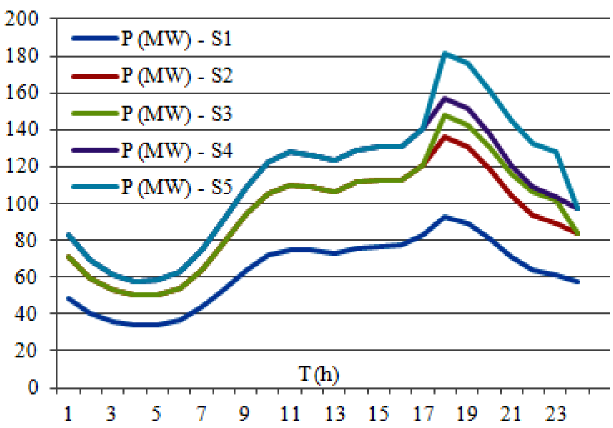

Figure 3. Daily load profile for the current state and expected power consumption in 2025. and 2030. with a 5 % and 10 % EV penetration respectively

For this reason, the PV curves shown in Fig. 2 are also constructed up to the point of around 180 MW. The load flow calculations are made for every hour of each of the analyzed scenarios. For all the scenarios, the load flow calculations are made for the four cases presented in previous chapter (C1, C2, C3 and C4). All the calculations are made using the PSAT toolbox and Matlab software [21].

Results of the voltage variations for C1 case at bus 12 for all the analyzed scenarios are shown in Fig. 4. As seen, the daily voltage variations do not fall below the lower limit of –10 %. The basic configuration of the network can keep the voltage value within the set limits for all the analyzed scenarios. On the other hand, for C2 and S2, S3, S4 and S5, violations of the voltage limits are identified, especially in the periods of the daily peak consumption. For S4 and S5, violations are identified for a long period during the day (Fig. 5).

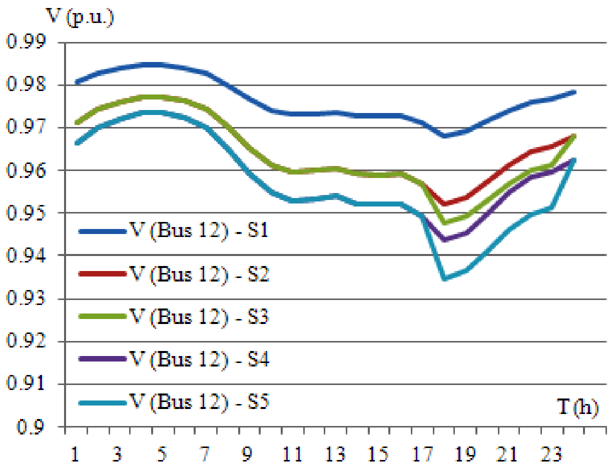

Figure 4. Voltage variations at bus 12 for C1 for all the five analysed scenarios

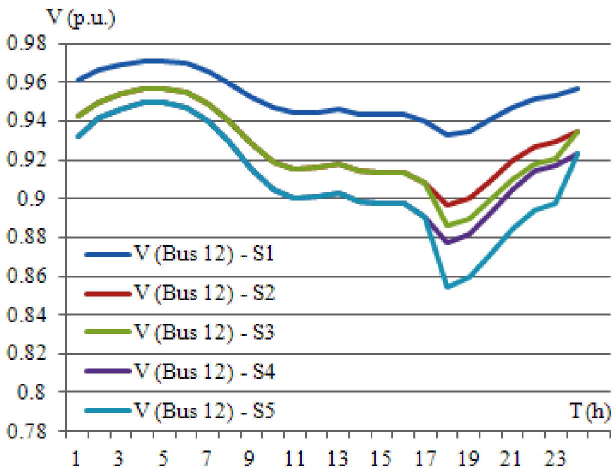

Figure 5. Voltage variations at bus 12 for C2 (line 1-3 outage) for all the five analysed scenarios

Similar results can also be observed for C3 and bus 4 where the violations of the voltage limits are identified in the transmission network (Fig. 6). For C4, the voltage limits are violated only for S5 at bus 13 (Fig.7). In other words, if in 2030 10% of vehicles are EVs, their charging for the case of outage of the 2-14 power line would violate the voltage limits.

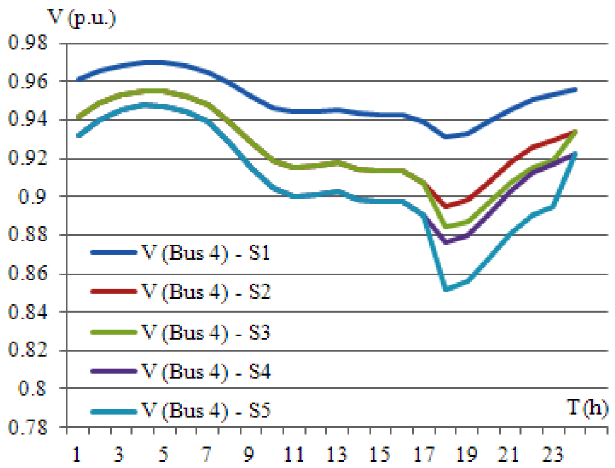

Figure 6. Voltage variations at bus 4 for C3 (line 2-4 outage) for all the five analysed scenarios

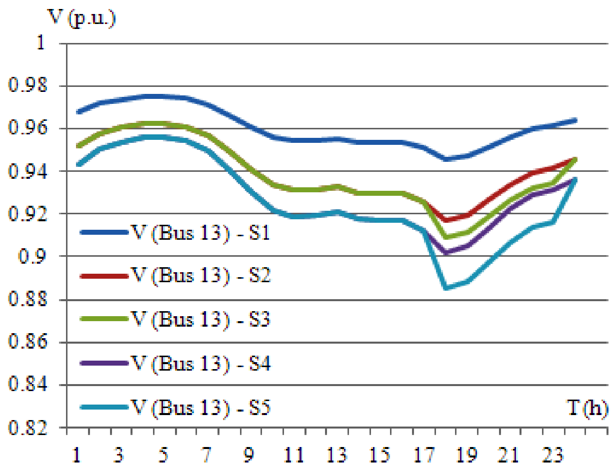

Figure 7. Voltage variations at bus 13 for C4 (line 2-14 outage) for all the five analysed scenarios

From the presented analysis it is clear that integration of a large number of EVs in the power system is not going to be easy and that the impact on the transmission system is expected to be significant. This of course confirms the conclusions of the research of many authors regarding the necessity for controlled EV charging, which would according to the system capacity allow charging to be done at the time when it is minimally affecting the system. On the other hand, voltage stability is only one of the technical aspects that needs to be analyzed. For the cases and scenarios analyzed in this paper, it is clear that there will be no voltage collapse. However, what can be expected are violations of the voltage limits in the power transmission network, which for the transmission system operator means that certain operating actions or investments in the transmission network need to be done.

4 Conclusion

The paper presents results of a voltage stability analysis made on an example of a real power transmission system for an expected increase in power consumption resulting from an expected increase in the EV penetration rate. By applying the CPF calculations, the maximum load factors prior to the voltage collapse are calculated and the buses where such event is expected to take place are identified. It is shown that for the analyzed area there is a big reserve in the current transmission network capacities and that for the expected increase in power consumption until 2030 with a 10 % EV penetration rate there will be no voltage collapse. However, in cases of unavailability of some of the network elements, unacceptably low voltage values can be expected. This indicates that penetration of a large number of EVs will not be simple and can lead to unwanted impacts on the power system and to violations of the adopted operational limits. Following the above, the issue should be paid special attention and the EV charging strategy should be clearly defined.

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