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Analysis of the Impact of Electric Vehicle Charging on Harmonic Voltages in a Low-Voltage Distribution Network

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Abstract. Electric vehicles (EVs) retain the focus of the public attention because of the constant development and promotion of their technology and global warming awareness. Their integration is expected to experience an exponential rise along with new challenges for the existing networks. Simultaneous and unregulated charging of a large fleet of EVs increasingly burdens the power system and negatively affects the power quality parameters, especially during the daily peak-period. The paper analyses the power quality analysis of a low-voltage distribution network in Bosnia and Herzegovina. Different EV types are investigated, such as Mitsubishi i-MiEV, Renault ZOE, Volkswagen e-Golf, and Tesla X, to determine their impact on harmonic voltages impact for three EV penetration levels: 10%, 20% and 50%. Wallbox charging mode is also investigated. The results are evaluated compliably with the European power-quality standard EN 50160. Results show that none of the analyzed EV penetration scenarios violate the permissible harmonic voltage limits, except for the 50% EV penetration scenario with wallbox charging.

Keywords: Distribution network, electric vehicles, harmonic voltages, low voltage, power quality, unregulated charging.

Analiza vpliva polnjenja električnih vozil na harmonične napetosti v nizkonapetostnem električnem omrežju

Električna vozila ostajajo v središču pozornosti z nenehnim razvojem in promocijo te tehnologije, ki jo spremlja ozaveščenost o globalnem segrevanju. Pričakuje se, da bo njihova uporaba vedno bolj množična,
kar predstavlja nove izzive za obstoječa električna omrežja. Hkratno in neregulirano polnjenje velikega števila vozil povzroča dodatne obremenitve, zlasti v dnevnem času največjih obremenitev. Prispevek temelji na analizi kakovosti električne energije nizkonapetostnega (NN) elektroenergetskega omrežja v Bosni in Hercegovini. Analiza je upoštevala različne znamke električnih vozil ter njihov vpliv na električno omrežje. Dobljene rezultate smo analizirali v skladu z evropsko normo za kakovost električne energije EN 50160. Rezultati so pokazali, da je le v enem primeru prišlo do prekoračitve mejnih vrednosti parametrov harmonskih napetosti.

1 INTRODUCTION

The society's desire to participate in the mitigation of greenhouse gas emissions and global-warming effects has motivated the popularity of electric vehicles (EVs), followed by their increasing technological development. However, the large-scale implementation of EVs and their simultaneous, unregulated charging introduces various power-quality issues including voltage unbalance, voltage oscillations, and harmonic distortion [1, 2].

It is important to note that the extent of the EVs negative effect on global warming and emissions depends highly on the type of the network EVs are connected to as well as on the of the source that feeds the network, meaning that the feeding source should be primarily based on renewable energy. A positive EVs effect can be expected with adoption of regulated charging and when EVs switch to a Vehicle-to-Grid (V2G) mode to act as small, distributed generators [3,4].

Harmonics are integer multiples of the fundamental frequency waveform. They are the main source of the sinusoidal wave distortion caused by nonlinear loads. Harmonic voltages and currents introduce a deteriorating effect on equipment, such as overheating of transformers, cables, motors, thus reducing the life span of equipment as well as causing power-quality issues. To prevent such occurrences, it is important to analyze the network prior to adding new EVs.

The paper extends our previous study [5], by providing a harmonic analysis of charging several EV types in a Grid-to-Vehicle (G2V) mode, at various penetration levels. The contribution of the paper is its analyzing a real LV network with real in-field measurements of four most sold EV types, for several EV penetration levels The rest of the paper is organized as follows. Section 2 is the literature review, Section 3 describes the modeled network, data and scenarios. Section 4 presents the results of our work and Section 5 draws conclusions.

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2 LITERATURE REVIEW

Over the past years, several studies have been conducted to analyze the impact of harmonic distortion in power distribution systems. A combination of distributed generators, storage systems and EVs directly connected to a low-voltage distribution system, increases the existing harmonic distortion originating from the end-user nonlinear loads [6].

Paper [7] analyzes the impact of EVs on voltage sags and harmonic voltages using MATLAB. Results of testing a distribution network in Bangladesh show that for one EV connected, the total harmonic distortion (THD) of voltage is around 4.82% while the allowed limit is 5%. There is a difference detected in the voltage profile before and after connecting an EV charger due to the related sags and harmonic disturbances. The analysis promotes renewable-energy-source-charged EVs because of their impact on pollution decreasing.

In [8] a residential LV distribution network is tested to determine the impact of three different EV charging scenarios. Uncontrolled EV charging, tariff-based EV charging, and controlled EV charging are analyzed for three EV penetration levels: 30%, 45%, and 60%. The results indicate that for an EV penetration level of 45%, the voltage THD violates the limit of 8%, as THD of heavy loads increases up to 14.2%.

Paper [9] identifies THD in a three-phase LV distribution network for three EV penetration levels and an equal load distribution per phase. It considers only a single-phase charging at a 45%, 65% and 90% EV penetration level and both the linear and non-linear residential loads. Two worst scenarios in terms of the phase angle are considered: EV current harmonics being in phase or in an opposite phase of the harmonic current introduced by other loads. Significant current harmonics are expected in rural networks with long feeders and depend on cable impedance.

Study in [10] analyzes the impact of fast charging method of EVs on THD with respect to the IEEE519, IEC 61000/ EN 50160 standards. Four measurements were performed using the Volkswagen e-Up! charging process. Two vehicles are connected to the same feeder to analyze their harmonic phase angle. Results show that the more vehicles connected to the same feeder the higher are their harmonic amplitudes. Individual harmonics such as 11^{th} and 13^{th} order exceed the Standard limits.

Four types of EV charging were analyzed in [11] for several power quality parameters, including harmonic and inter-harmonic voltages. The power quality at a 380 V bus of an EV charging station is investigated. Results show that each charger complies with the Standard limits except for an off-board quick charger, where the 5^{th} order harmonic value exceeds the limit.

Authors of [12] study a total of four EV types in a LV distribution network and their uncontrolled charging impact on harmonic distortion rate, for the harmonics of the 3^{rd} and 5^{th} order. Their measurements are taken during the winter period, with a heavier load case and higher harmonic emissions compared to that of the summer period. Results do not exceed any Standard limit even for the case of a 100% EV penetration level.

A study [13] analyzes the impact of several plug-in EVs and an electric bus fleet on the harmonic distortion of a distribution network operating in Brazil. Four charging modes of different input voltages, currents, and power values, as well as four different technical specifications, such as battery range, capacity, and battery type are analyzed in this paper. The network experiences no violation of the harmonic voltage limit.

Work done in [14] measures the effect of EV charging on voltage and current harmonics in an LV network. Measurements were taken during the charging period including two charging modes: constant current and constant voltage. Results show the voltage THD remains within the permissible limits, and the current THD exceeds the limit, implying a significant disturbance resulting in cable overheating.

3 MATERIALS AND METHODS

3.1 Analyzed network

Our investigation conducted on a rural LV distribution network focuses on three EV penetration levels, 10%, 20% and 50%, with an equal load distribution per phase. The network operates in the town of Zavidovići, Bosnia and Herzegovina, and is supplied by a single 10/0.4 kV distribution transformer of the installed power of 160 kVA. A total of 63 loads are distributed along the main 915-meter-long feeder. The used educational version of DIgSILENT enables modeling 38 loads, so that the remaining 25 are represented in a form of a lumped load, i.e., equivalent. Table 1 lists basic transformer parameters and Table 2 provides with the information of power distribution across the network. Table 3 presents the type and length of overhead power lines.

Table 1. Transformer parameters

TS 10/0.4 kV	
Rated power [kVA]	160
Total energy [kWh]	1229.6287
Total peak power [kW]	124.2720
Reactive power [kVAr]	0.1963
Total power for modeled area [kW]	40.7938
Power factor	0.9999 ≈ 1

Table 2. Network power distribution

NNO Šehići	
Total load active power	**Total load reactive power**
40.7938 kW	0.645 kVAr
Power of the modeled loads	

23.1508 kW	0.0366 kVAr
Power in the equivalent	
17.6431 kW	0.0279 kVAr

Table 3. Line type and length

Line type	Total line length [m]
X00/0 A 4x16 16mm2	529
X00/0 A 3x35+71.5 35mm2	211
X00/0 A 2x16 16mm2	117
NA2XRY 4x70sm 0.6/1kV	1119
NA2XRY 4x150sm 0.6/1kV	14
Main feeder	915

The first scenario considers an equal load distribution per phase and the network is therefore modeled as balanced. Figure 1 shows the network topology and Figure 2 presents the methodology flow chart.

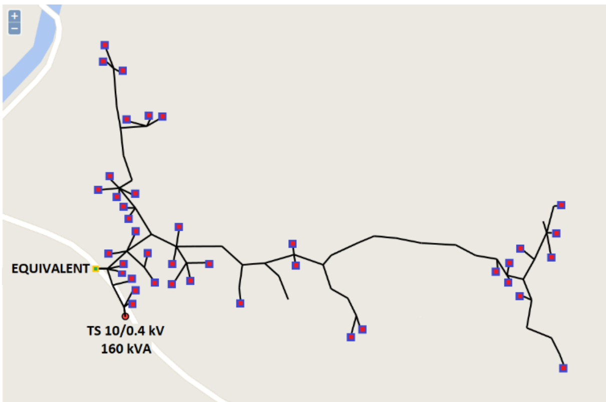

Figure 1. Network topology [5]

3.2 *Input data*

The measuring data, used in our simulations include transformer and smart meter readings as well as EV power quality measurements. The transformer meter readings are taken at a 15-minute interval in a one-year period. The peak consumption on the 5th of August is analyzed. The LV network fed by the analyzed transformer originally consisted of several feeders. In our investigation, only one feeder is modeled and analyzed due to the number of busbars limited by the used educational of DIgSILENT Power Factory license, which required representing a part of the network in a form of a lumped load. Smart meters record the daily energy consumption per load. The daily consumption is calculated by multiplying the energy percentage per load at the transformer peak power of the transformer [5].

The analyzed part of the network consumes about 32.83% of the peak power, and the total of 40.79 kWs are distributed along the main feeder. The 38 modeled loads consume 23.1508 kW, and 25 lumped loads consume 17.6431 kW [5]. The values for the 5th and 7th harmonic current emission of the residential loads are taken from [15]. The background harmonic value, defined in the external grid element as a voltage source, is taken as 1% of Un for the 5th and 1.5% of Un for the 7th harmonic, where Un is the voltage level of the 10kV medium-voltage (MV) network. Household load emissions for the 5th harmonic are taken as 8.392%, and for 7th harmonic as 2.480%.

The power quality measuring data of the four EVs are provided by Elektroprivreda Power Utility and include the data for Mitsubishi i-MiEV, Renault ZOE, Volkswagen e-Golf and Tesla X. In the EV charging process, the 5th and 7th harmonic are measured, to be further used in our simulations and analysis. The measurements provide data for all the three phases, but our study involves only the single-phase charging, so the values for 5^{th} and 7^{th} harmonic of the three phases for Renault ZOE and Tesla X are averaged in our model. Volkswagen e-Golf charging is a two-phase charging, therefore values of 5^{th} and 7^{th} harmonic of those two phases are also averaged. The Mitsubishi i-MiEV is the only EV type whose original single-phase charging measurements are used in this analysis. The EV harmonic current values for the four types of EV are shown in Table 4.

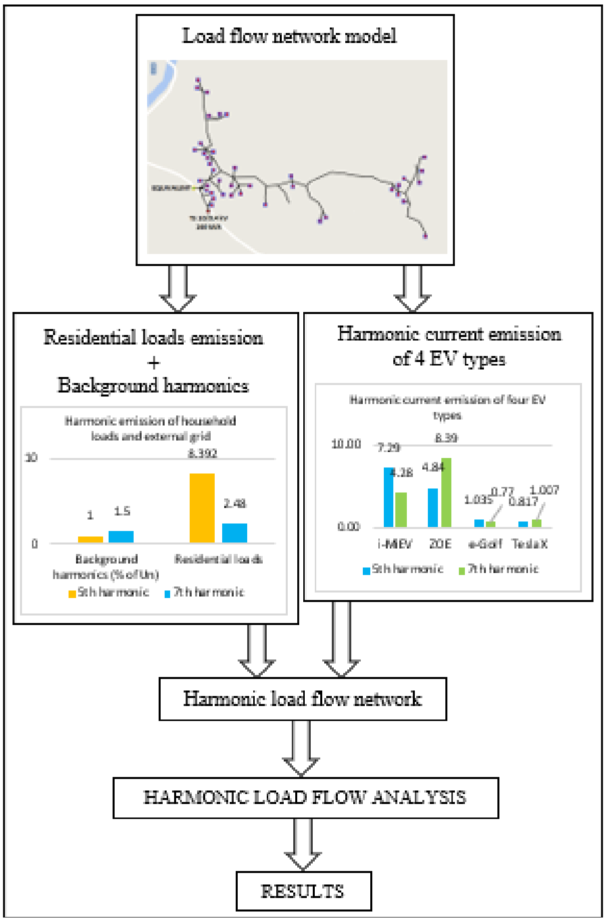

Figure 2. Methodology flow chart of approach

Table 4. Harmonic current emissions for the four EV types

Harmonic order	Mitsubishi i-MiEV	Renault ZOE	Volkswagen e-Golf	Tesla X
5th	7.290%	4.840%	1.035%	0.817%
7th	4.280%	8.393%	0.770%	1.007%

3.3 Harmonic voltages

The network harmonic distortion with only the background and household load emissions and no EVs connected is studied. The results are then used as a reference value for comparison of the harmonic emissions introduced by connecting different EV penetration levels.

The two harmonic sources analyzed in the network model are the loads and the external grid. The loads are modeled as harmonic current sources and the external grid as a background harmonic with harmonic voltage values. In calculating the harmonic load flow, the modeled harmonic sources are treated according to the IEC 61000 Standard, which applies the second summation law to both the voltage and current [16].

4 Results and Discussion

4.1 First scenario with 10% of EV penetration

The first scenario with 10% penetration level involves 6 EVs. To make a realistic analysis, the EV type distribution was done according to the EV prices, obtained from [17]. The most common EV type is thus the cheapest one, and the least common is the most expensive one. Table 5 shows the distribution of EV types in the network. Figure 3 shows results of the harmonic load flow for the 5th harmonic, and Figure 4 shows results for the 7th harmonic.

Table 5. Number of EV types in the network

EV type	Mitsubishi i-MiEV	Renault ZOE	Volkswagen e-Golf	Tesla X
No. of connections	2	2	1	1

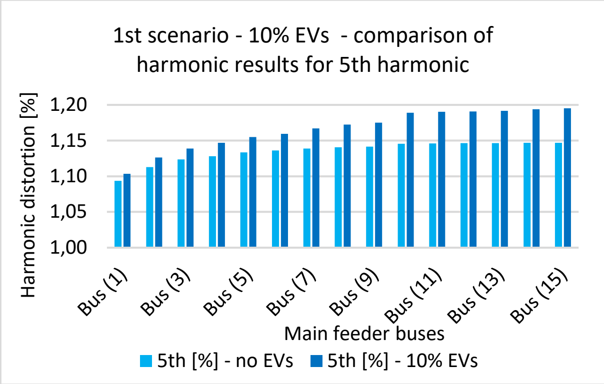

Figure 3. HVD, 1st scenario with no EV penetration vs. with 10% EV penetration, the 5th harmonic

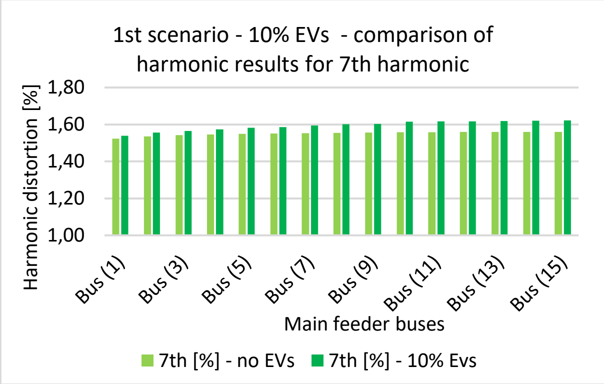

Figure 4. HVD, 1st scenario with no EV penetration vs. with 10% EV penetration, the 7th harmonic

Both the 5th and the 7th harmonic values are well within the limits of 6% and 5%, respectively, of the values defined in EN 50160 Standard.

4.2 First scenario with 20% of EV penetration

The first scenario with a 20% EV penetration level involves 12 EVs, scattered along the main feeder. Three EVs are connected to the equivalent including Renault ZOE, Volkswagen e-Golf and Tesla X. Their harmonic emissions are averaged since they are presented in the form of a lumped load, connected to the equivalent. Table 6 presents the distribution of individual EV types. Figure 5 shows results of the harmonic load flow for the 5th harmonic and Figure 6 for the 7th harmonic.

Table 6. Number of EV types in the network

EV type	Mitsubishi i-MiEV	Renault ZOE	Volkswagen e-Golf	Tesla X
No. of connections	4	4	2	2

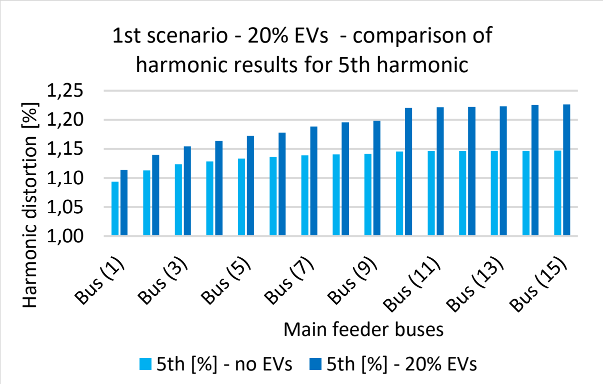

Figure 5. HVD, 1st scenario with no EV penetration vs. with 20% EV penetration, the 5th harmonic

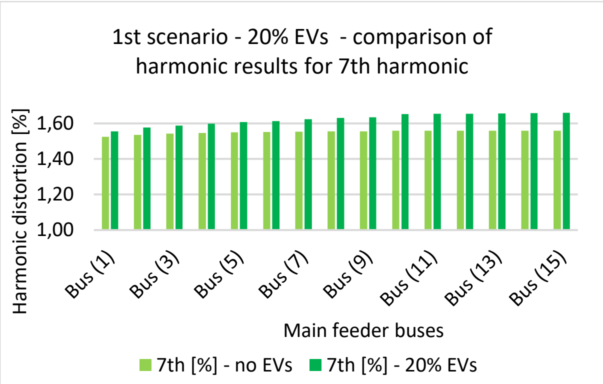

Figure 6. HVD, 1st scenario with no EV penetration vs. with 20% EV penetration, the 7th harmonic

The values of the 5th and 7th harmonic are increased compared to those of the 20% EV penetration, however theyremained within the Standard limits.

4.3 *First scenario with 50% of EV penetration*

First scenario with 50% EV penetration includes 30 EVs, distributed along the main feeder. Nine EVs are put in the equivalent. Their harmonic emissions are averaged since they are presented in the form of a lumped load, connected to equivalent. Table 7 shows the EV type distribution in the network and Table 8 provides with EV types in the equivalent. Results of the harmonic load flow are shown in Figure 7 for the 5th harmonic and in Figure 8 for the 7th harmonic.

Table 7. Number of EV types in the network

EV type	Mitsubishi i-MiEV	Renault ZOE	Volkswagen e-Golf	Tesla X
No. of connections	10	10	5	5

Table 8. Number of EV types in equivalent

EV type	Mitsubishi i-MiEV	Renault ZOE	Volkswagen e-Golf	Tesla X
No. of connect ions	3	3	2	1

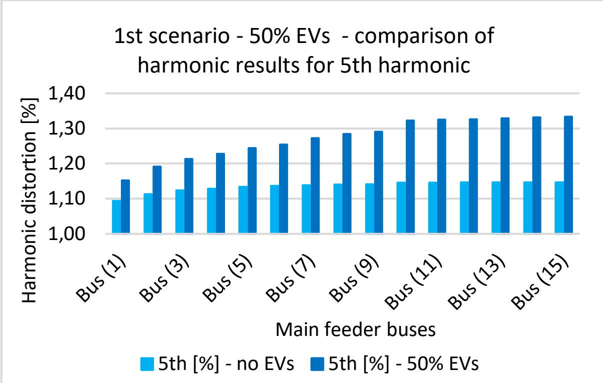

Figure 7. HVD, 1st scenario with no EV penetration vs. with 50% EV penetration, the 5th harmonic

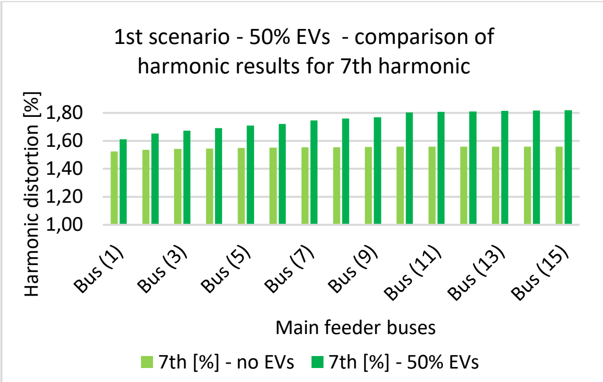

Figure 8. HVD, 1st scenario with no EV penetration vs. with 50% EV penetration, the 7th harmonic

The graphs show taht the harmonic distortion is the greatest in the case of 50% EV penetration level. The values of the 5th and the 7th harmonic remain within the limits of distortion, as the 5th harmonic has the greatest value of 1.3699% and the 7th harmonic the value of 1.8587%, both at the feeder end. The results imply that the harmonic voltage limit values are not violated in either case of the EV penetration level and that the network is capable of supporting half of the households having an EV, without disturbing the power quality parameter.

4.4 First scenario with 10% of EVs – Wallbox charging

The wallbox EV charging is made with the same EV penetration levels previously introduced above. In the studied rural LV network, there is no perspective for neither the public AC nor DC charging stations. Table 9 presents the charging power of four EV types in the analysis. Figures 9 and 10 show the resulting 5th and 7th harmonics, respectively.

Table 9. Charging power of four EV types – Wallbox

EV type	Charging power [kW]
Mitsubishi i-MiEV	3.7
Renault ZOE	22
Volkswagen e-Golf	7.1
Tesla model X	16.5

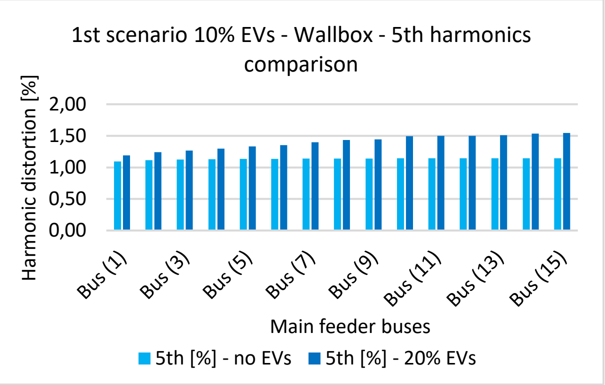

Figure 9. HVD, wallbox charging, 1st scenario with no EV penetration vs. 10% EV penetration, the 5th harmonic

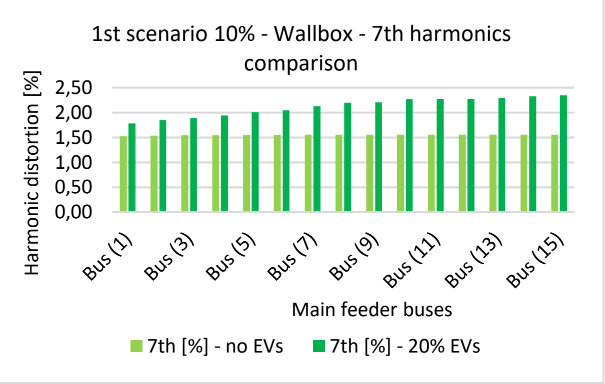

Figure 10. HVD, wallbox charging, 1st scenario with no EV penetration vs. 10% EV penetration, the 7th harmonic

The first scenario with 10% EV penetration supports the six modelled vehicles, simultaneously charged by a wallbox charger, compliably with the values defined in EN 50160. The results show that neither the 5th nor the 7th harmonic violates the limit values. The highest value for the 5th harmonic is 1.546% and for the 7th is 2.344%.

4.5 First scenario with 20% of EVs – Wallbox charging

The EV distribution across the network is the same as in the scenario with standard household plug charging, given in Table 3. Results of harmonic load flow for the 5th harmonic are shown in Figure 11 and for the 7th harmonic in Figure 12.

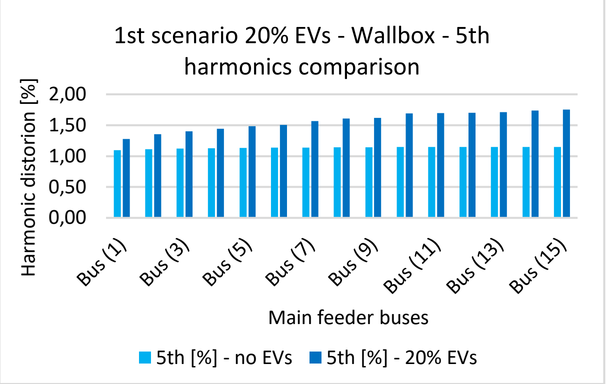

Figure 11. HVD, wallbox charging, 1st scenario with no EV penetration vs. 20% EV penetration, the 5th harmonic

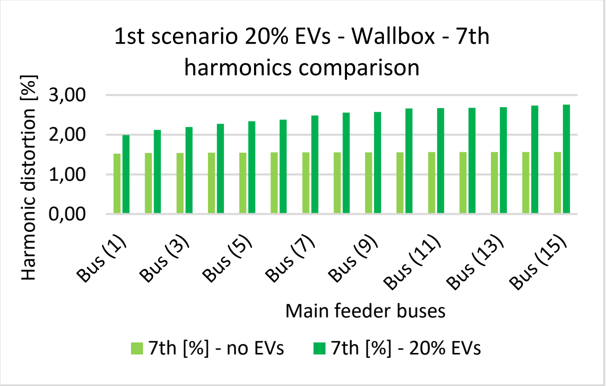

Figure 12. HVD, wallbox charging, 1st scenario with no EV penetration vs. 20% EV penetration, the 7th harmonic

The EV penetration of 20% increases the HVD without violating the Standard limits. Figure 11 and Figure 1 show the highest distortion for 5th harmonic and 7th harmonic as 1.755% and 2.756%, respectively.

4.6 First scenario with 50% of EVs – Wallbox charging

The first scenario with 50% EV penetration level could not handle wallbox charging. It was found that there was no load flow convergence in the network therefore the analysis could not have been completed. The lowest voltage value recorded before the load flow convergence is lost, is 91.868 V at the very end of the main feeder. This value isobtained by decreasing the charging value of a single Mitsubishi i-MiEV from 3.7 kW to 2.3 kW, while the remaining 29 vehicles keep the values defined in Table 8, for wallbox charging. Other voltage values for the three EV penetration levels are shown in Figure 13.

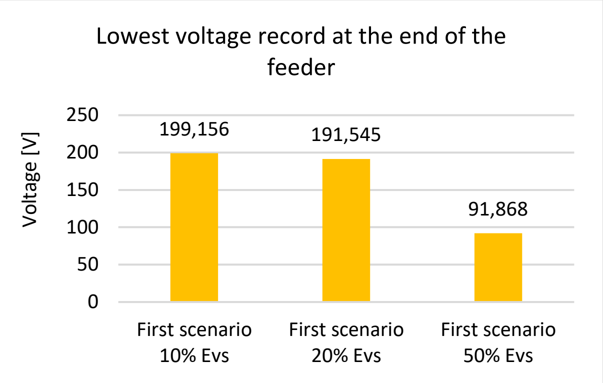

Figure 13. Voltage values at the end of the main feeder for the three EV penetration levels

According to the EN 50160 Standard and voltage-variation parameter, none of the scenarios with wallbox charging is acceptable, as they all violate the voltage-variation limit of -10% Un, that is, 207 V. This parameter is analyzed in more detail in [5]. The network does not support wallbox charging due to low voltage profiles, when the limit is set to 207 V, that is, -10% of the nominal voltage.

5 Conclusion

The paper investigates the harmonic distortion effects four EV types (Mitsubishi i-MiEV, Renault ZOE, Volkswagen e-Golf and Tesla X), during a simultaneous charging process. In its first part it analyzes the effects of only household and background harmonic emissions. The obtained results are then used as reference values when comparing results of scenarios with three EV penetration levels. None of the scenarios violates the EN 50160 limit of 5th and 7th harmonic emission, of 6% and 5%, respectively, implying that this network topology withstands the harmonic distortion introduced by EVs. Results may vary for networks of different voltage levels, network configurations and for different three-phase short circuit power values.

6 Appendix

Table 10. Modelled loads

Load name	No. of phases	Power of load [kW]
Load 1	1	0.0459
Load 2	1	0.0867
Load 3	1	0.2487
Load 4	3	0.6175

Table 11. Modelled loads (cont'd)

Load 5	**3**	**0**
Load 6	3	0.5889
Load 7	3	0
Load 8	1	0.2578
Load 9	1	0.2357
Load 10	3	0.6062
Load 11	3	0.5323
Load 12	3	0.092
Load 13	3	1.2339
Load 14	3	1.1108
Load 15	3	0.0058
Load 16	3	1.9588
Load 17	3	0.2745
Load 18	3	0.6577
Load 19	1	0.96
Load 20	3	0.0685
Load 21	3	1.5999
Load 22	3	1.0511
Load 23	3	0.7561
Load 24	3	1.0171
Load 25	3	0.9469
Load 26	1	0.3715
Load 27	1	0.6587
Load 28	1	0.6815
Load 29	1	1.1281
Load 30	3	0.8113
Load 31	1	1.5125
Load 32	3	0.2115
Load 33	3	1.8006
Load 34	3	0.5432
Load 35	3	0.0614
Load 36	3	0
Load 37	1	0.1819
Load 38	1	0.2357

Table 12. Lumped loads data

Equivalent		
Load name	No. of phases	Power of load [kW]
Load 39	3	0.4512
Load 40	3	0.0627
Load 41	3	1.1923
Load 42	3	0

Table 13. Lumped loads data (cont'd)

Load 43	**3**	**0.3627**
Load 44	3	1.2978
Load 45	3	0.6277
Load 46	3	0.0001
Load 47	3	1.3197
Load 48	3	2.1367
Load 49	3	0.1984
Load 50	3	1.7126
Load 51	3	0
load 52	3	1.341
Load 53	3	0.6441
Load 54	3	0.8007
Load 55	3	0
Load 56	3	1.0814
Load 57	3	1.7813
Load 58	3	0.5806
Load 59	3	0.9789
Load 60	3	0.7673
Load 61	3	0.0026
Load 62	3	0
Load 63	3	0.3033

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