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Analyses and Evaluation of Power Quality Aspects in a Low-voltage Network with Regard to a High Penetration of Decentralized Generation and Charging Infrastructure

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Abstract — **The term "Power Quality" refers to the aspects of voltage quality such as a constant frequency, a perfect sinusoidal shape, a constant rms-value and the ideal symmetry of the three phases. The power electronics integrated in various consumers distort and interfere with them. This paper examines a public low-voltage network including households and electric vehicles as consumers. In addition, some photovoltaic systems feed into the grid. The scenario for the year 2030 illustrates the influence of increased penetration of electric vehicles and photovoltaic systems on power quality in a low-voltage grid. The distortion of the current is particularly high in some transformer outgoing circuits. Nevertheless, with the assumptions made, the limit values of the DIN EN 50160 standard for voltage distortion at the transformer can be respected.**

Keywords - electric mobility; harmonics; Power Quality; low voltage network; grid integration; impact of EV charging; Electric Vehicle

I. INTRODUCTION

The energy transition from centralized conventional power plants to renewable and decentralized generation (DG), in particular wind and photovoltaic, provides a number of challenges for transmission (TSO) and distribution system operators (DSO). Especially for DSO, with regard to the increase installation of household photovoltaic systems in low voltage network (LV) of house settlements (<1kV), the associated energy flow direction has changed from top-down to bottom-up. Beside the energy transition, converting transportation from internal combustion engines to electric vehicles (EV) represents an additional challenge for the network to reduce the CO_2-emissions in the transport sector.

Moreover, the registered numbers of EV in Germany show moreover an exponential increase (Figure 1) and will be further raised by new model campaigns of automotive manufactures in the future

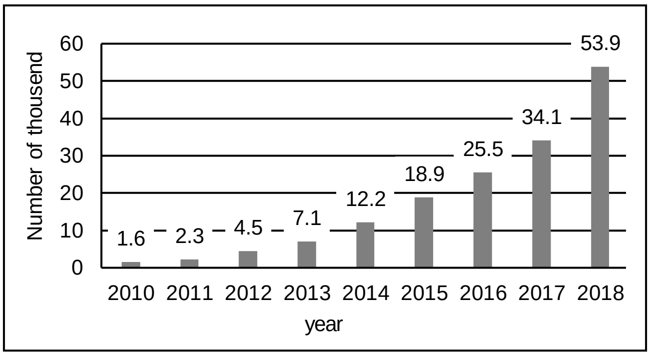


Figure 1. Registration numbers of EV in Germany [1]

The roll-out of fast charger (DC) and high-power charging infrastructure provide in public space the possibility to charge EVs. With regard to the user profile the introduction of charging infrastructure via home plug (AC, 3phase) turns the attention on residential low voltage networks. All charging modes are shown in Table 1. The charging via AC, 3phase (mode 2) represents the commonly used mode [2].

Due to the onboard charger of an EV equipped with power electronics as well as the relatively large loads connected to the LV, the share of converters is increasing in the LV system, in addition to converter loads such as photovoltaic systems and consumer electronics. These power electronic devices produce harmonics and their behavior should be analysed with respect to power quality. Harmonics have undesired effects, for instance like:

- network operation (e.g. earth fault compensation, ripple control signal)
- measurement and control devices (malfunction of protection devices, accuracy of electricity meter, voltage and current transformers)

- higher current and voltage loading of equipment (capacitors, motors, transformers, lamps) and accompanying reduced lifespan of components

Power quality standards have been developed such as the EN 50160 "Voltage characteristic of electricity supplied by public distribution system", to define the quality of power supply. Besides these, other standards define aspects of electromagnetic compatibility (EN 61000-3-2, EN 61000-3-12, EN 61000-3-3).

Table 1. Charging modes for EVs [3]

Charging mode	**1**	**2**	**3**	**4**
Max. current	16 A (one-phase)	16 A (one-phase) 32 A (3phase)	63 A (3phase)	
Max. power	3.68 kW (one-phase)	3.68 kW (one-phase) 22 kW (3phase)	43.5 kW (3phase)	38 kW or 170 kW possible
Connection to the network	Standard socket-outlet	Charger cable, wall charging station	Free charging station, wall charging station	External charging device with a fixed cable
feature	ELCB must exist	Charging device in the car, wall charging station	Charging device in the car, fast loading	DC-High-charging: ca. 30 minutes

This paper presents the analysis of power quality aspects in the public low voltage network, based on a selected network modelled in DIgSILENT PowerFactory. The network is characterised by a high share of DG and considered a medium forecast for the penetration of EV in the year 2030 [4].

II. GRID DETAILS AND FRAMEWORK CONDITIONS

Figure 2 shows a general schematic single diagram of the public low voltage network. The two transformers, with an apparent power of 0.63 MVA each, feed the households and EVs. The number of supplied loads is given in Paragraph II.B.

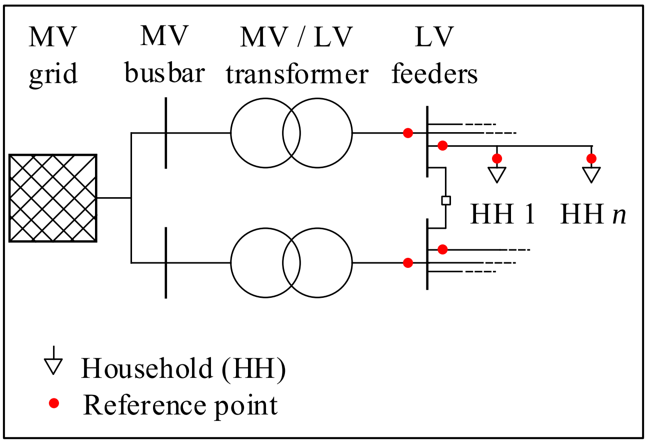


Figure 2. Single line diagram of the network

Table 2 lists the main characteristics of the LV network.

Table 2. Main components oft he LV network

Operating resources	***Type***	***Max. voltage/ power***	***Number***	***Additional information***
Transformer	Dyn5	0,63 MVA	2	
Cable	cable: NAYY 4x150SE 0,6	1 kV	598	length: 1 bis 297 m; I_N = 0,27 kA;
Households	Low voltage load	Load profile	292	Standard load profile

The network structure represents a new municipal residential suburb on the edge of a small city (20-50t residents) with good road links to a large city (100-500t residents) and industrial areas within a radius of 20 to 50 km. The following summarizes the assumptions for the network scenario 2030

A. *Renewables*

In total, 30 photovoltaic rooftop installations are considered with a capacity of 4 kWp each. The considered harmonic spectra are based on market available inverters, certified according to EN 61000-3-2.

B. *Household loads*

292 household loads are available in the network, using the standard load profile and having load increase factor of 1 % per year. The distribution and number of residents per household are based on [5] and allocated with 174 on transformer T1 and 118 on transformer T2 respectively.

The three persons household load profile on a workday during summer is shown in Figure 3.

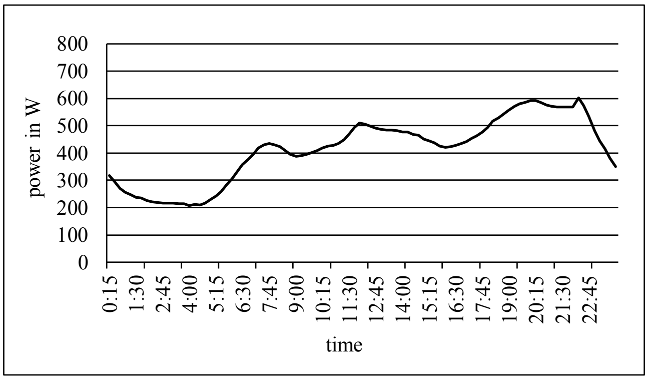


Figure 3. Load profile for a three-person household in the summer in 2030

The considered harmonic spectrum for the households is based on power quality measurements [6] and interpolated for each household, considering a conversion from conventional lamps to LED.

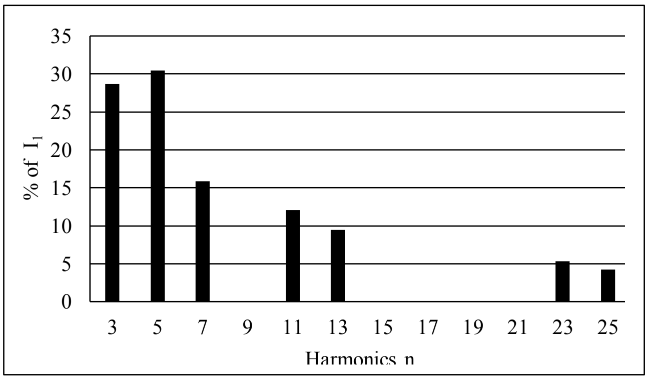


Figure 4. Harmonic spectrum of a household (2 pm)

C. EV in the network

Based on the households, the assumed number of EV is 44 which represents a medium forecast for the penetration of EV in the year 2030 [4].

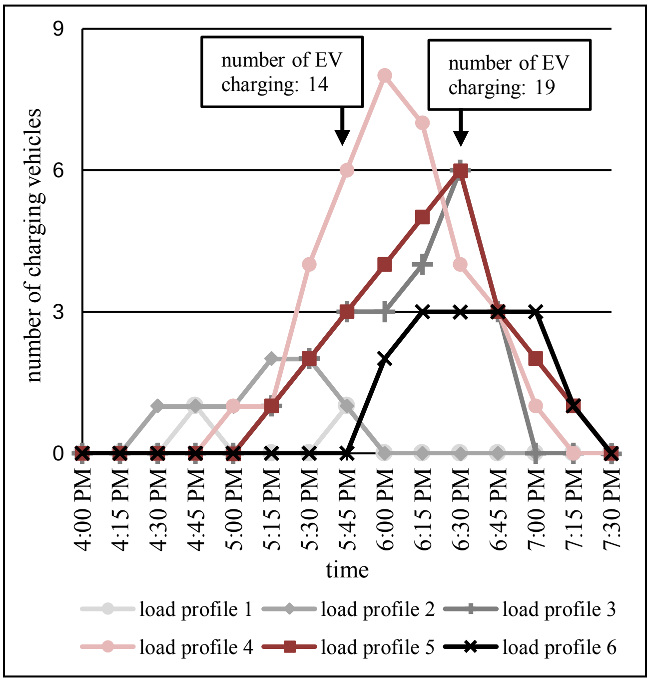
D. User and charging profile

The travel distances for the EV's are based on [7] and distributed as indicated in Table 3.

Table 3. EV user profile

Profile	***Distance [km]***	***Assumed covered distance in km/day***	***Numbers of persons out of 100 users***
1st profile	< 10	5	4
2nd profile	11-20	15	18
3rd profile	21-40	30	25
4th profile	41-65	53	28
5th profile	66-100	83	18
6th profile	> 100	110	7

The charging process of the EV´s occurs with a high probability between 4 pm and 7 pm and is indicated for each load profile in Figure 5 [7].



number of EV charging: 14

number of EV charging: 19

Figure 5. Loading EVs in the time period between 4 pm and 7:30 pm

III. SIMULATION RESULTS

The resulting loading profile for the LV network including household loads, charging EV and rooftop photovoltaic installation is indicated in Table 4. Based on the load profile, distinct times of the day have been selected, as follows:

- 2:00 pm: maximum power generation from photovoltaic
- 5:45 pm: more than 50% of the EVs are charging and still 50% generation from photovoltaic
- 6:30 pm: maximum number of charging EVs, low power generation from photovoltaic and higher household load

The load summary for the selected hours for each transformer feeder as well the number of charging EV is listed in Table 4 and Table 5. The maximum load demand is encountered at 6:30 pm.

Table 4. Loads at the transformers

Time	***P_{PV} 2030 [kW]***	***Loads of household [kw] on transformer***		***Total load [kW] on transformer***	
		T1	***T2***	***T1***	***T2***
2 pm	2.98	56.2	82.9	15.2	35.5
5:45 pm	1.44	56.4	83.1	169.3	242.5
6:30 pm	0.95	62.5	92.2	234.8	323.6

Table 5. Number of charging EVs and PV plant at the transformers

Time	*No. of charging EVs on transformer*		*No. of photovoltaic installations on*	
	T1	***T2***	***T1***	***T2***
2 pm	0	0	14	16
5:45 pm	6	8	14	16
6:30 pm	8	11	14	16

Transformer T2 faces the highest loading, due to household and number of charging EVs and at the same time a higher share of power generation from photovoltaic. A scenario without EVs and photovoltaic has been simulated, to evaluate the impact on the harmonic distortion, named as reference scenario and results are presented in the following figures and tables.

Figures 6 and 7 indicate the harmonic distortion on each MV/LV transformer incomer including the EN 50160 limits for the defined scenarios. Furthermore, the total harmonic distortion index (THD) (1) is indicated for each scenario.

$$\boldsymbol{THD_n = \frac{\sqrt{\sum_{n=2}^{n} I_n^2}}{I_1}} \qquad (1)$$

The harmonic distortion (HD) on the transformer feeders, represented for one phase for the selected times as well as the limits of the EN 50160, are shown in the following figures.

A. Scenario 2 pm

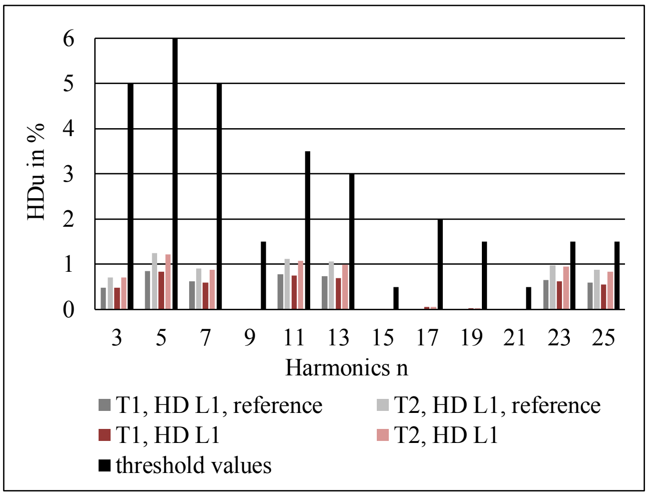


Figure 6. HDu at the transformers at 2 pm

The harmonic distortion at the transformers at 2 pm is nearly equal to the reference scenario. Each considered harmonic order is within the limits. The observed photovoltaic installations have only a minor impact and do not increase the HDu values of the households on the transformers. However, from the THDu perspective, the values decrease from 2.61 % (reference scenario) to 2.55 % on transformer T2. In this scenario, the voltage levels at all terminals/connection points are over 95 % of the rated voltage, as defined in the EN 50160. The scenario at 2 pm faces the highest voltage unbalance in the network caused by the photovoltaic power generation. In all other scenarios, namely 5:45 pm and 6.30 pm, this effect has only a minor influence, due to the increased 3-phase loads.

B. Scenario 5:45 pm

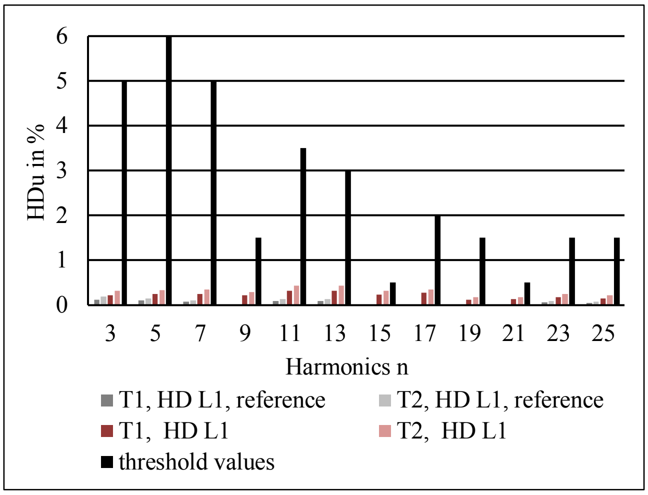


Figure 7. HDu at the transformers at 5:45 pm

Due to a lower harmonic distortion at 5.45 pm of the households (e.g. cooking instead of consumer electronics) the overall HDu is low. Moreover, the 14 EV charging have a lower impact than the households at 2 pm. Only the distortions on 15th to 21st harmonic orders are directly attributable to the EV and photovoltaic inverter. The values at 5:45 pm are all higher than in the reference scenario, but remain below the threshold values. The values on the 15th harmonic are close to the limits. From the THDu perspective the values rise from 0.34 % for the reference scenario to 1.16 %, on the transformer T2.
As before, the minimum voltage limit of 95 % of the rated voltage at all connection points is observed.

C. 6:30 pm

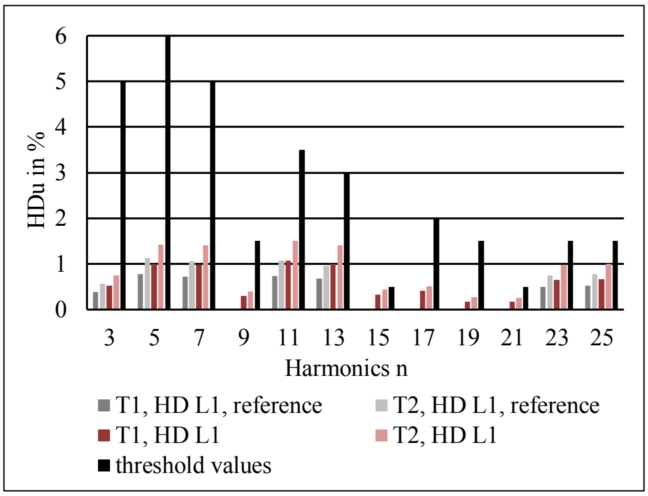


Figure 8. HDu at the transformer at 6:30 pm

The load scenario at 6:30 pm represents the worst scenario, since a high share of EV are still charging and a high share of harmonics from the household loads are encountered. Photovoltaic inverters are still online but producing at a low level. The harmonic distortion values are once again within the thresholds, nevertheless the harmonic orders of the 9th, 15th to 21st harmonic are noteworthy since the values are near to the limits and caused by EV and photovoltaic converters. The scenario is also underlined from the THDu perspective, since values up to 3.45% will be reached on the transformer T2. In this scenario, at two connection points located at the end of the feeders, the threshold minimum value of 95 % of the rated voltage is not kept. On both connection points EV and PV are supplied.

IV. CONCLUSION

Under the assumed conditions, the simulation indicates that, at some of the household loads, the voltage threshold of minimum 0.95 pu of the rated voltage is violated. These violations are caused by the high loads of the EV during the charging process and are also due to the location, at the edge of the LV network. The violations will be strengthened during the late afternoon due to the increasing number of charging EVs and lower power generation from the photovoltaic.

With regard to the harmonic distortion, the impact of consumer electronics in households is not insignificant on the power quality, besides a high amount of EVs on the LV network. Nevertheless, with the assumptions made, the limits of the DIN EN 50160 standard for voltage distortion at the transformer can be fulfilled. With the increase of the number of EV, the reserve margin for harmonic distortion decreases For the breakthrough of e-mobility and the subsequent changes in the low voltage network efforts from all stakeholders are necessary to ensure power quality aspects and to avoid bottlenecks.

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