Influence of Electric Vehicles, PV Systems, Home Storage Systems and Heat Pumps on the Voltage Quality in the Low-Voltage Grid

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Abstract

The German Mobilitätswende and Energiewende are leading to an increasing number of electric vehicles, PV systems, home storage systems and heat pumps in the low-voltage grid. In the future, the penetration of these components will continue to rise considerably. This can lead to a reduced voltage quality in low-voltage networks, as this is negatively influenced by the devices mentioned. Important characteristics of voltage quality are rapid voltage changes, harmonics, flicker and unbalance.

Against this background, single components such as electric vehicles, PV inverters, battery inverters and heat pumps are measured in a laboratory environment in the U-Quality research project in order to separately determine their effects on the voltage quality. This document shows results of measuring a single-phase battery inverter and a three-phase PV inverter. Additionally, the U-Quality research project determines the actual state of voltage quality in low-voltage networks with already high penetration of the above-mentioned components by means of measurements in selected networks. In the project, among other things, a suburban low-voltage grid is considered, in which the voltage quality is measured at different grid points in winter and summer in order to determine, for example, the different effects of heat pumps and PV systems. In this paper, results of the summer measurement are presented. Based on the measurements in the low-voltage network and in the laboratory, the influence on the different voltage quality characteristics is evaluated.

1 Introduction and Motivation

A significant increase in the penetration of PV systems, electric vehicles and heat pumps is expected in Germany in the future years. The *BEE Scenario 2030*, for example, predicts a number of 7 million heat pumps by 2030 [1]. In the study *Building sector Efficiency: A crucial Component of the Energy Transition*, a PV system capacity of 179 GW is expected by 2050 [2].

The components mentioned can have a negative influence on the voltage quality in low-voltage networks [3]. Compliance with DIN EN 50160 regarding the voltage quality characteristics is important to maintain the power quality [4]. Against this background, laboratory measurements and measurements in a low-voltage network are carried out in the U-Quality project in order to record the current state with regard to voltage quality and to determine the effects of single components. The focus is on the voltage quality characteristics *rapid voltage changes*, *flicker*, *unbalance* and *harmonics*.

This paper is structured as follows. Chapter 2 presents the standards relevant to voltage quality in the low-voltage level. Subsequently, Chapter 3 shows the investigations in the laboratory. In chapter 4, the investigations in a suburban low-voltage network are presented. The paper closes with a conclusion and an outlook.

2 Standards for Voltage Quality in Low-Voltage Grids

In the U-Quality project, the voltage quality in the low-voltage grid is investigated because the penetration of electric vehicles, PV systems, home storage systems and heat pumps will increase. In laboratory, single devices are examined to determine their effect on voltage quality and to check whether standard limits are violated. Against this background, low-voltage networks with high penetration of the mentioned devices are investigated as well.

The standards relevant for voltage quality in the low-voltage level are the DIN EN 50160 and the series IEC 61000-3. DIN EN 50160 defines limit values for public distribution networks subdivided according to voltage level, whereas the series IEC 61000-3 specifies limit values for devices. Voltage unbalance is defined in DIN EN 50160 as the ratio of the rms value of the negative sequence component of the fundamental to the positive sequence component of the fundamental. 95% of the 10-minute means of the voltage unbalance have to be in the range of 0% and 2%. Limits for voltage harmonics are defined in the DIN EN 50160 up to the 25th order. The limit value for short-term flicker is 1.0 according to IEC 61000-3-11.

With regard to rapid voltage changes (RVCs), the IEC 61000-3-11 defines limit values for several parameters. The limit for the voltage difference between the steady state before and after a RVC (d_c) is ±3,3% of the nominal voltage. In addition, the limit value for the maximum voltage difference from the steady state before the RVC (d_{max}) is ±4%. However, special conditions are defined for devices that allow higher maximum differences. In this paper, in addition to the calculation of the absolute values d_{max} and d_c, the direction of the voltage change is indicated by a sign. d_c and d_{max} refer to the steady state before the RVC. Therefore, a voltage increase results a negative value. Furthermore, voltage changes greater than ±3.3% compared to the steady state before the RVC may take a maximum of 0.5 s. [4], [5], [6], [7]

In addition to the presented standards, there are also the application rules VDE-AR-N 4100 and 4105 in Germany, which define requirements for the connection of loads and generators to the low-voltage network. [8], [9]

3 Investigations in Laboratory

In a laboratory environment, various devices are measured for their effect on the voltage quality. The following sections show the laboratory setup used and the results from measuring a single-phase battery inverter (maximum apparent power: 6 kVA) and a three-phase PV inverter (maximum apparent power: 20 kVA).

3.1 Experimental Setup

Figure 1 shows the laboratory setup. A grid simulator is used to create a three-phase network with a phase voltage of 230 V and a frequency of 50 Hz. Furthermore, a line impedance is realized with the grid simulator in order to investigate the worst-case scenario that the considered devices are connected at the end of a network line. The set resistance and reactance correspond approximately to a 1 km long NAYY 4x150SE 0.6/1kV line (resistance per unit length: 0.207 Ω/km, inductance per unit length: 0.08 Ω/km). The power analyzer measures the current and voltage values with a sampling rate of up to 1 MHz and calculates the different voltage quality characteristics and the power values. The device under test represents the different devices that are measured. [10]

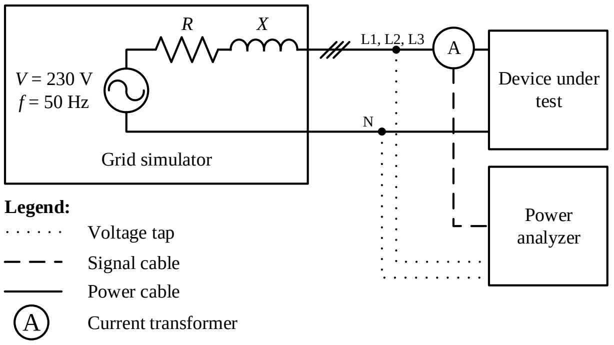

Figure 1 Schematic illustration of the laboratory setup for the investigation of single devices

3.2 Measurement Results Battery Inverter

The single-phase battery inverter under test is connected to phase L2 in the setup. The worst case is investigated that a generator at the end of the line feeds a high active power into the grid. For the considered case of active power feed-in, a constant under-excited cosφ of 0.95 is set for reactive power supply according to the VDE-AR-N 4105 [9].

Figure 2 shows the power values in the passive sign convention (PSC), the voltage and the voltage unbalance of the measurement. The active power increases from 0 to approximately -4 kW. A gradient of -48 kW/s occurs at the point with the highest slope. As a consequence of the rapid increase in active power, a RVC arises. At the point of the highest active power gradient, a voltage change of approximately 1 V per 50 Hz cycle occurs. This corresponds to 0.2% in relation to the nominal voltage. The difference between the steady state before and after the RVC (d_c) is -1.4% and consequently smaller than the limit value of the standard (in absolute values) [6]. The maximum voltage difference from the steady state (d_{max}) is -2% in relation to the nominal voltage and also below the limit value of ±4% (in absolute values) [6]. The reactive power in **Figure 2** corresponds to the set constant cosφ and reduces the voltage. Compared to the active power, the reactive power increase has a maximum gradient of about 1.9 kvar/s. The voltage unbalance caused by the single-phase battery inverter is 0.84% maximum.

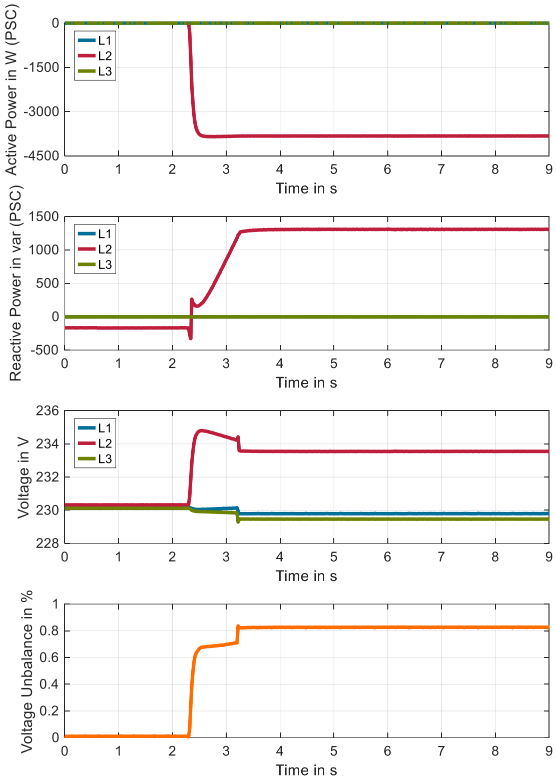

Figure 2 Active power, reactive power, voltage and voltage unbalance of the battery inverter measurement with cosφ of 0.95

Figure 3 is a spectrogram showing the voltage harmonics of phase L2 for the battery inverter measurement with constant cosφ. When the inverter provides power from about 3.5 s the voltage harmonics are increased at odd orders up to the 21st. However, they are only in the range of 0.1 V to 0.6 V. For example, the third harmonic is in the range of 0.2% relative to the fundamental. Above the 21st order, the voltage rms values are in the range up to a few 10 mV.

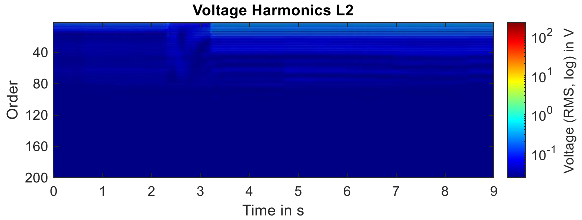

Figure 3 Voltage harmonics of the battery inverter measurement with cosφ of 0.95

The test with the battery inverter is also carried out without reactive power provision. **Figure 4** shows the measurement results of this experiment. The maximum active power is -4.3 kW compared to the previous test. Consequently, the maximum voltage difference (d_{max}) of -2,3 % is also higher (in absolute values). The voltage unbalance is in the range of 0.85% to 0.90% after the active power increase.

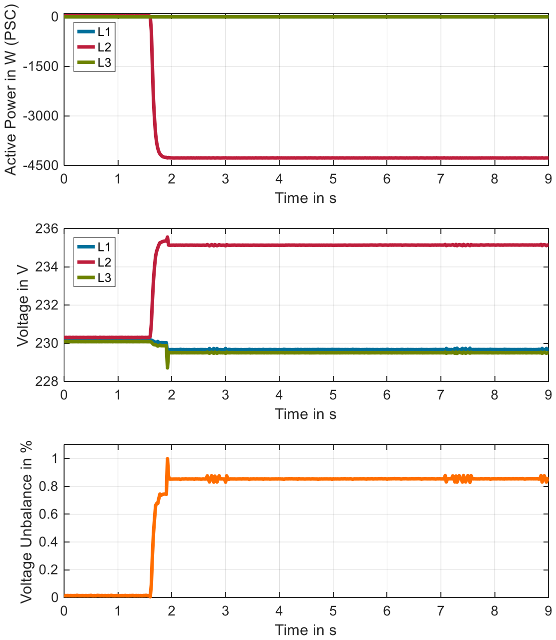

Figure 4 Active power, voltage and voltage unbalance of the battery inverter measurement without reactive power provision

3.3 Measurement Results PV Inverter

In the three-phase PV inverter, a constant under-excited cosφ is also used to provide reactive power. Since the maximum apparent power of the inverter is greater than 4.6 kVA, an effective factor of 0.9 is set in accordance with VDE-AR-N 4105 [9]. In the measurement, the worst case is considered that the inverter feeds maximum active power into the grid.

Figure 5 illustrates the results of the measurement, in which the power values again correspond to the PSC. The increase of the active power to the maximum value shows a maximum gradient of about -8.7 kW/s. This results in a maximum voltage change of 0.16 V per 50 Hz cycle. The lower active power gradient of the PV inverter compared to the battery inverter (in absolute values) consequently results in a lower voltage gradient. The difference between the steady states of the RVC is -1.8% (d_c) and the maximum voltage difference is -1.9% (d_{max}). Thus, the characteristic values of the RVC of the PV inverter measurement are also below the standard limits of IEC 61000-3-11 (in absolute values) [6]. The voltage unbalance caused by the PV inverter is negligible due to the three-phase feed-in.

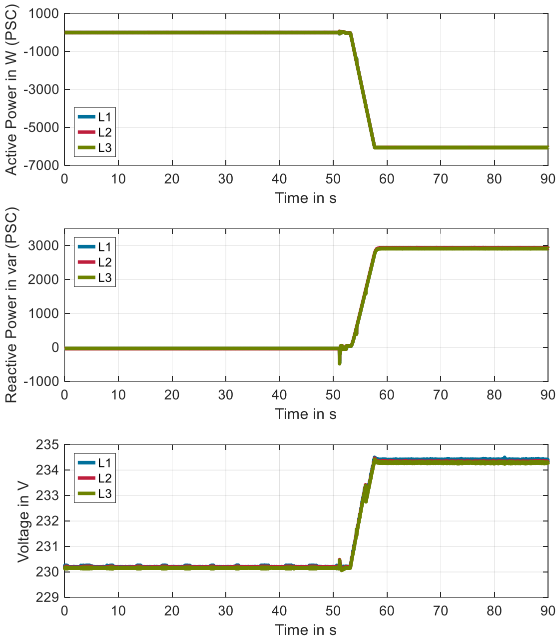

Figure 5 Active power, reactive power and voltage of the PV inverter measurement

4 Field Test

4.1 Measurements in a Low-Voltage Grid

The measurements for recording the actual state of the voltage quality in the low-voltage grid are carried out in a suburban development area with 96 households and a high penetration of heat pumps (33 systems) and PV systems (at least 8 systems) [10]. The penetration of battery electric vehicles is low with about three vehicles. The apparent power of the transformer is 400 kVA. In the network, measurements are carried out at different points over a period of two weeks. Measurements are taken in the distribution substation at 2 out of 7 feeders (marked in the paper as No. 1 and No. 2), in two cable distribution cabinets, at the end of a line, at a wastewater pump as well as at a house with PV system, heat pump, battery storage and electric vehicle. **Figure 6** shows the measurement setup at the distribution substation. The power analyzer calculates, among other things, voltage quality characteristics such as RVCs, harmonics, short-term flicker and unbalance. The measurement setups at the other measurement points are identical. In addition, weather data with a resolution of 10-minute averages are available for the measurement period.

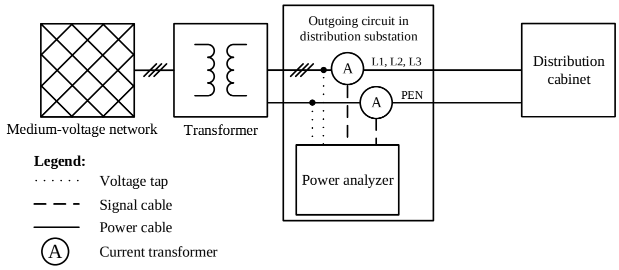

Figure 6 Block diagram of the measurement setup in the distribution substation for one feeder

4.2 Results

The measurement results are used to evaluate, among other things, the seasonal influences on the voltage quality. In the whole measurement period, the highest temperature is 32.6 °C, the lowest is 3.1 °C and the highest global radiation is 890 W/m². In the period of the highest global radiation, the voltage is around 232 V and the influence on the voltage quality characteristics is negligible (d_{max}. around -0.50% to 0.35% and d_c between -0.40% and 0.25%).

As shown in **Figure 7**, the maximum d_{max} values of 7.80% (L1) and 7.26% (L3) occur at 12:39 on August 21, when the temperature is about 29 °C. The d_{max} value of L2 is considerably smaller in this time range. Additionally, d_{max} of L2 has its maximum of 1.6% on another day at 6 o'clock. Compared to the maximum values on August 21, the mean values of d_{max} are low on this day. The means of the positive maximum voltage changes (d_{max}) defining voltage reductions are 0.08% (L1), 0.23% (L2) and 0.18% (L3). The means of the negative d_{max} values are -0.08% (L1), -0.16% (L2) and -0.16% (L3).

Other parameters of the voltage quality are shown in **Table 1**. The highest values of d_c (L1 to L3) are in the range of 1.43% to 1.46% and also occur on a different night.

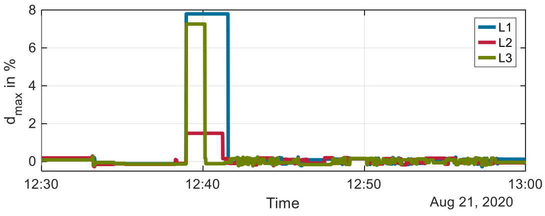

Figure 7 Maximum voltage changes (L1 to L3) at feeder No. 1 of the transformer at 12:39 on August 21, 2020

In comparison of the period with the highest d_{max} value, **Table 1** also shows other maxima and minima of the voltage quality in the entire measurement period at feeder No.1. The highest voltage with up to 243 V is not at the day of the highest d_{max} value. Additionally, the total harmonic distortion of the voltage (THDu) is also not the highest on August 21. In particular, the minimum d_{max} and d_c values on August 21 differs greatly from the minimum values of the entire measurement period.

Table 1 Voltage quality values at feeder No. 1 of the distribution substation (values of L1 to L3 do not have to be at the same time)

Parameter		**Period with maximum d_{max}**	**Overall measurement period at feeder No. 1**
Period		Aug. 21, 2020 12:00 till 18:00	Aug. 21,2020 10:24 till Sep. 4, 2020 9:30
Average temperature in °C		29.1	17.6
Maximum Voltage in V	L1 L2 L3	236.60 236.74 236.30	243.56 243.14 242.84
Minimum Voltage in V	L1 L2 L3	231.67 231.44 230.98	230.11 229.53 229.48
d_c maximum in %	L1 L2 L3	1.33 1.32 1.32	1.43 1.44 1.46
d_c minimum (neg.) in %	L1 L2 L3	-0.21 -0.23 -0.25	-1.54 -1.56 -1.51
d_{max} maximum in %	L1 L2 L3	7.80 1.49 7.26	7.80 1.61 7.26
d_{max} minimum (neg.) in %	L1 L2 L3	-0.29 -0.31 -0.30	-1.62 -1.63 -1.59
THDu maximum in %	L1 L2 L3	4.24 4.08 4.10	5.04 4.84 4.92

August 21 is a very warm period, however there is another warmer one. **Table 2** shows various voltage quality parameters for the coldest and the warmest period. There is almost no difference between most of the voltage quality characteristics. Only the minimum d_c and d_{max} values differ. For the purpose of comparing the warmest and the coldest period, the overall results at this feeder (No. 2) are presented as well. No value of the warmest and the coldest period appears in the overall results. Therefore, in this case, the temperature has no influence on the maximum voltage quality values. All maximum d_{max} values are significantly lower than the measured maxima on August 21.

Table 2 Voltage quality values at feeder No. 2 of the distribution substation in the coldest and the warmest period in the summer and over the entire measurement period (values of L1 to L3 do not have to be at the same time)

Parameter		Coldest period	Warmest period	Overall measurement period at feeder No. 2
Period		Sep. 18, 2020 00:00 till 6:00	Sep. 15, 2020 12:00 till 18:00	Sep. 4, 2020 12:42 till Sep. 23, 2020 9:06
Average temperature in °C		4.9	31.2	15.6
Maximum Voltage in V	L1	237.44	238.06	238.29
	L2	237.39	237.97	238.13
	L3	237.30	238.11	238.11
Minimum Voltage in V	L1	230.87	232.34	229.19
	L2	231.10	232.06	229.05
	L3	230.69	232.28	228.68
d_c maximum in %	L1	1.26	1.31	1.39
	L2	1.28	1.27	1.38
	L3	1.27	1.29	1.39
d_c minimum (neg.) in %	L1	-0.28	-0.85	-1.44
	L2	-0.46	-0.84	-1.52
	L3	-0.35	-0.84	-1.45
d_{max} maximum in %	L1	1.31	1.35	2.73
	L2	1.36	1.35	1.80
	L3	1.32	1.36	2.62
d_{max} minimum (neg.) in %	L1	-0.31	-1.10	-1.49
	L2	-0.47	-1.02	-1.55
	L3	-0.40	-1.10	-1.51
THDu maximum in %	L1	3.90	3.98	5.29
	L2	3.70	3.78	5.00
	L3	3.67	3.84	5.00

The measurement at the house connection box of the house take place in the same period as the measurement at feeder No. 1. At the house, the values of the highest short-term flicker are on different phases. High short-term flicker values that occur on different days are 0.409 (August 25) and 0.407 (August 31). The highest value is 1.326 which occur near the start of the measurement and could be a measurement error. The next highest short-term flicker value near the start time period is 0.436 (August 22). The voltage harmonics do not exceed the limits of the DIN EN 50160 at any time. The values of voltage harmonics at the house connection box are increased at odd orders up to the 23rd, similar to the battery inverter in the laboratory. In addition, some harmonics above the 23rd order are increased for some phases with values from 0.12 V to 0.19 V: 25th (L1, L2), 27th (L2, L3), 29th (L1) and 33th (L1). Compared to one battery inverter, the harmonics are higher in amplitudes and extend more to higher voltage harmonics. The voltage harmonics from the 3rd to the 7th order are in the range of 3 V to 9 V. Above the 7th order, the harmonics are in a range of 0.18 V to 2.6 V. Above the 33th order, the voltage values of the harmonics are in the range up to a few tens of millivolt up to a maximum of 0.07 V. The current harmonics are low over the whole measurement.

In all periods in which the unbalance is high, a high RMS value of the phase voltages also occur. Furthermore, each time the unbalance is high, one phase voltage is higher than 238 V. The one second mean values of the unbalance according to DIN EN 50160 have a maximum of 0.72% at the house. The second highest value is 0.63% and the third highest is 0.61%. In contrast, the 10-minute mean values of the unbalance at the house have a maximum value of 0.39%.

The maximum of the 10-minute mean values of the unbalance and the average of all measurement points are displayed in **Table 3** and **Table 4**. In the tables, the unbalance is distinguished between unbalance in the network according to DIN EN 50160 and unbalance at the feed-in point as shown by Meyer et al. [11]. The average unbalance (DIN EN 50160) is between 0.10% and 0.15%. The maximum at feeder No. 2 is 0.70 % and at feeder No. 1 0.41%. The unbalance (DIN EN 50160) at the wastewater pump, which is connected at the end of a line, is the highest. However, three-phase loads, such as wastewater pumps, are not relevant to the unbalance in the network under study, even at a feed-in point far away from the transformer. The unbalance (DIN EN 50160) is influenced by a maximum feed-in unbalance of the house of 0.26%. The unbalance of the house with PV system, electric vehicle, battery storage and heat pump is very low compared to the unbalance of the investigations in the laboratory and does not exceed the maximum unbalance limit of DIN EN 50160.

Table 3 Unbalance at measurement points in the field measurement at feeder No. 1 distinguished into feed-in unbalance [11] and unbalance according to DIN EN 50160

Measurement point	Feed-in unbalance of the system or measurement point in %	Unbalance according to DIN EN 50160 in %
Period	Aug. 21,2020 10:24 till Sep. 4, 2020 9:30	
Distribution substation feeder No. 1	Max.: 0.0940 Avg.: 0.0252	Max.: 0.3289 Avg.: 0.0986
Cable distribution cabinet (between substation and house)	Max.: 0.4326 Avg.: 0.0781	Max.: 0.4002 Avg.: 0.1059
House connection box	Max.: 0.2618 Avg.: 0.0481	Max.: 0.3900 Avg.: 0.1160
End of the line	Open network disconnecting point	Max.: 0.4138 Avg.: 0.0979

Table 4 Unbalance at measurement points in the field measurement at feeder No. 2 distinguished into feed-in unbalance [11] and unbalance according to DIN EN 50160

Measurement point	**Feed-in unbalance of the system or measurement point in %**	**Unbalance according to DIN EN 50160 in %**
Period	Sep. 4, 2020 12:42 till Sep. 23, 2020 9:06	
Distribution substation feeder No. 2	Max.: 0.1179 Avg.: 0.0374	Max.: 0.2778 Avg.: 0.1017
Cable distribution cabinet (between substation and wastewater pump)	Max.: 0.3963 Avg.: 0.0674	Max.: 0.4010 Avg.: 0.1097
Wastewater pump	Max.: 0.0252 Avg.: 0.0154	Max.: 0.6964 Avg.: 0.1541

5 Conclusion and Outlook

The actual state of the voltage quality is investigated in two ways in this publication. Measurements in a laboratory environment are used to investigate the effects of single devices and measurements in a low-voltage network are used to investigate real networks.

The laboratory measurements are used to investigate the worst-case scenario in which the devices under test are operated at the end of a line. The measured single-phase battery inverter causes RVCs due to high active power gradients and unbalance of up to 0.9%. However, the values are below the standard limits. The influence of the investigated PV inverter on the voltage quality also do not lead to any limit value violations. In comparison, the unbalance at a house with PV system, electric vehicle and battery storage and a heat pump is a maximum of 0.39% (according to DIN EN 50160) and consequently lower than that of a single device in the laboratory. In addition, the feed-in unbalance of the house is 0.26%. Furthermore, it is confirmed that a higher unbalance is measured at the end of a line. The temperature has no influence on the voltage quality in the low-voltage network under study in summer.

The measurement results allow a comprehensive evaluation of the voltage quality. Based on the results, simulations will be used to determine the effects of future increasing penetration of PV systems, home storage systems, power-to-heat applications and electric vehicles on the voltage quality in low-voltage networks. Furthermore, recommendations for action for the further development of standards and technical guidelines will be derived on the basis of the measurements.

6 Literature

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U-QUALITY

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