HARMONIC ANALYSIS AND MITIGATION IN DISTRIBUTION GRIDS WITH HIGH PENETRATION OF POWER INVERTERS

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ABSTRACT

Inverters of large heat pumps in an urban low voltage grid generate current harmonics and cause consequently significant variations of the respective voltage harmonics. The voltage level at each grid point is not only influenced by the operation of such inverters, but higher harmonic voltage amplitudes can be expected, caused by the sum of all loads in the grid. The paper provides a comprehensive harmonic analysis of a typical urban distribution grid including heat pumps and presents insights on the variations and impact on the voltage profile of the 15th harmonic currents. An active harmonic filter was installed to enhance the power quality, by compensating the harmonic currents and by improving the voltage profile at grid points close-by the heat pumps.

INTRODUCTION

The expansion of renewables and the increased use of heat pumps in Switzerland and Germany lead to a growing number of power electronics conversion stages in the distribution grid. Due to their electronic design, power supplies, batteries and solar inverters as well as frequency inverters inject in the grid a non-sinusoidal current and influence the frequency-dependent grid impedance (fGI). As a consequence, resonance effects can occur, which highly distort the voltage and can even lead to instabilities.

The project OptiQ

Power quality (PQ) parameters can be strongly influenced by the increased use of power electronics and by the change of the frequency-dependent grid impedance. Actual grid planning concepts of the grid operators do not consider these issues sufficiently. In the project OptiQ which stands for “Optimization of planning and operation of distribution grids taking into account the power quality phenomena”, measurements and simulations are performed to develop guidelines as well as tools for the target grid planning [1].

HARMONICS IN DISTRIBUTION GRIDS

Maximum levels of voltage harmonics are specified in the EN 50160 [2]. The permissible level of the 15th harmonic is 0.5 % of the fundamental and will be increased to 1 % according to EN 50160/prA3.
Current harmonics are mainly generated by non-linear loads as single-phase appliances equipped with power electronic conversion stages which are ubiquitous in households and commercial buildings [3][4]. Critical levels occur mainly in electric grid areas with a high number or high power of non-linear electronic converters. The quality of voltage and current of such an area in the city of Zurich (Figure 1) was analysed by the Bern University of Applied Sciences BFH, the company Schaffner and the electric utility of the city of Zurich, ewz. The area hosts a residential building complex where the heat is generated by two heat pumps: a large one, powered by a 150 kW inverter and a small heat pump driven by a 35 kW inverter. During operation of the large heat pump, significant voltage amplitude variations of the 15th harmonic were registered. In two measurement campaigns, six grid nodes were monitored with fifteen PQ measuring devices (PQ-Box 100/150/200, a-eberle). Additionally, the fGI was measured and analysed. The transformer station, house 1 and house 2, belong to the building complex where the heat pumps are installed. The remote cabinets 1 and 2 are connected to the transformer station by long cables of 300 m and 160 m. In the standard situation, there was no active filter (corresponding to the node RLC in Figure 1) installed.

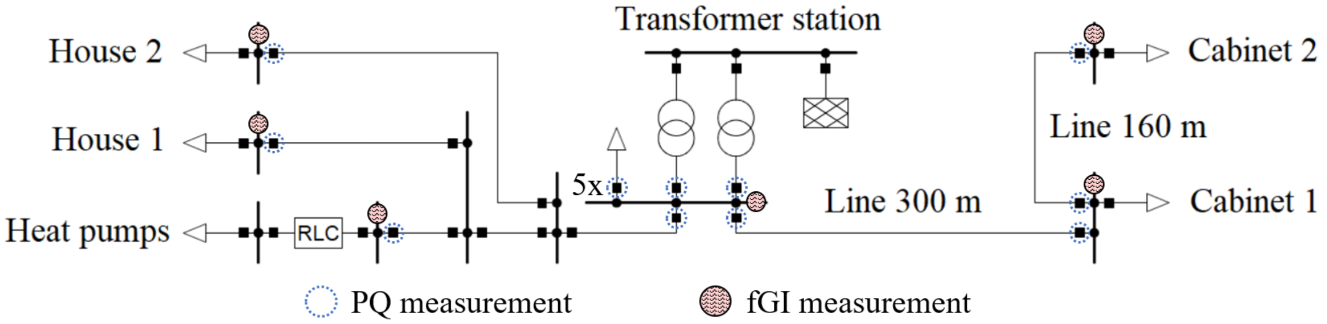

Figure 1: Simplified line diagram of the analysed grid in the software PowerFactory with marked measuring points

PQ measurements

To measure PQ parameters, voltage sensors were connected to the three phases L1 to L3, to neutral N and to protective earth PE (Figure 2), corresponding to measurement category CAT IV. The terminals of voltage probes connected to the feeders are equipped with fuses. The current sensing was performed by Rogowski coils or current clamps. The neutral conductor current was measured. Measurement data were saved as RMS values in 1-minute intervals with Class A devices to achieve sufficient accuracy.

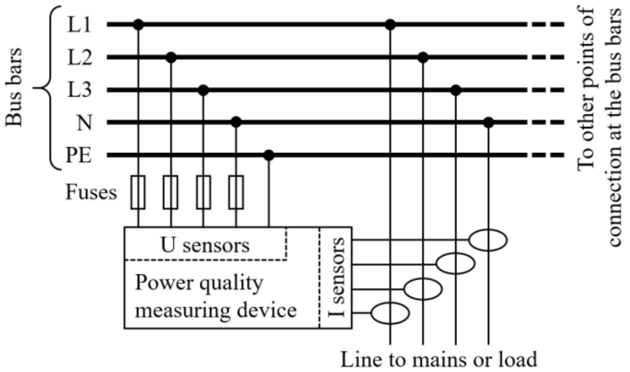

Figure 2: Connection of a PQ measuring device

VARIATION OF THE 15TH HARMONIC CAUSED BY POWER INVERTERS

Three main operating states of the heat pumps were analysed: Operation of the large heat pump, operation of the small heat pump and off-state of both heat pumps. The simultaneous operation of both heat pumps never occurs. The heating power of both heat pumps depends on the outside temperature and it is limited by their maximum power rating of 150 kW and 35 kW, respectively.

The operation of the heat pumps results in a higher 15th harmonic current amplitude which influences the voltage drop for the 15th voltage harmonic across the grid impedance. The measurements at the connection point of the heat pumps revealed that the large heat pump has stronger influence on the voltage level, particularly when operating at maximum power (Figure 3). In contrast, the small heat pump led to voltage variations not proportional to the voltage changes induced by the larger heat pump. The variation of the current amplitude was not affecting the voltage magnitude in both cases, but rather the variation of current angle and the fGI.

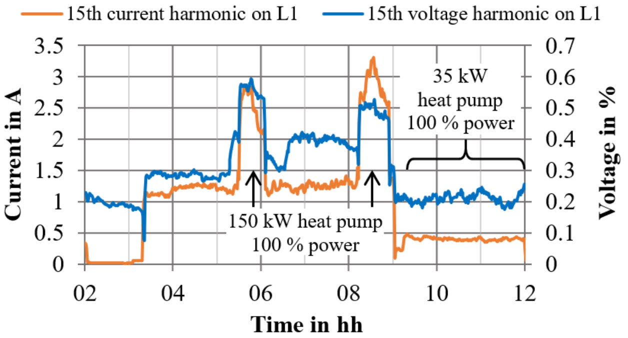

Figure 3: Measured 15th current and voltage harmonic on phase L1 during operation of the heat pumps at the heat pumps' point of connection without active filter

A similar behaviour as at the connection point of the heat pumps also occurred for all phases at the other measuring points of the building complex (transformer station, house 1 and house 2). The lowest amplitudes were measured at the transformer station.

Contrary to the results in the building complex, a different behaviour of the three phase voltages was recognized at the distribution cabinets 1 and 2 which are connected with the transformer station by long cables. The 15th voltage harmonic level at both remote cabinets was higher at L2 and L3 when only the small or no heat pump was in operation. For each measuring point, the voltage levels of the three phases are plotted in Figure 4 for the following three operating states:

- Power peak of the large heat pump;
- Power peak of the small heat pump;
- Both heat pumps OFF.

The sum of all other loads in the grid led to an elevated voltage level at cabinet 1 and 2. Furthermore, the current angles were changing for different operating states and consequently also the angles of the voltage drop across the long lines, which can lead to different phenomena on the three phases.

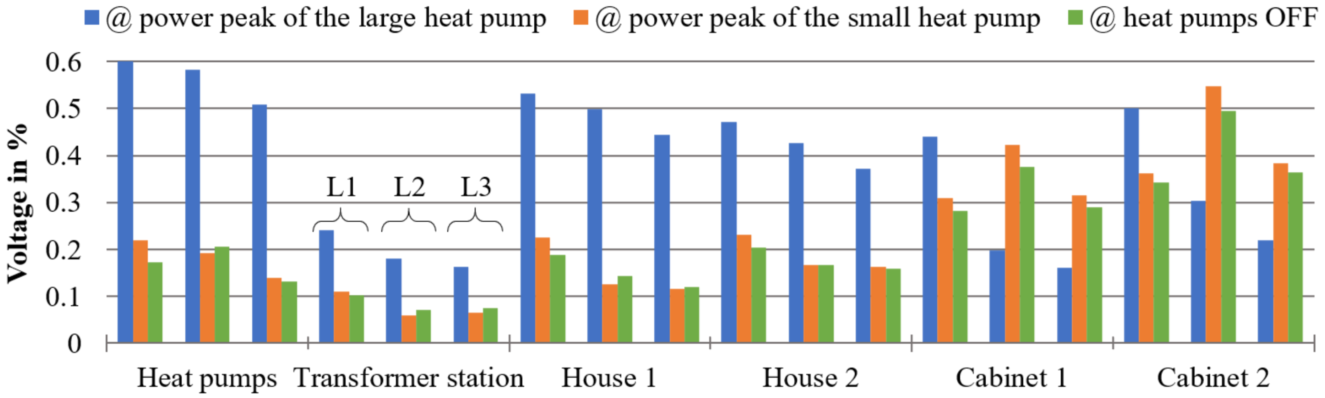

Figure 4: Measured voltage amplitudes of the 15th harmonic for phase L1 to L3 during three different operating states without active filter

COMPENSATION OF HARMONICS WITH AN ACTIVE HARMONIC FILTER

Because the inverters of the large heat pump cause significant variations of the 15th order harmonic at each analysed grid point, an active harmonic filter (AHF) was installed to actively compensate the 15th harmonic currents and thus as consequence also to improve the quality of the voltage by reducing the variation of the 15th voltage harmonic. In the analysed grid, a 4-wire active harmonic filter Ecosine Sync FN 3541 by Schaffner [5] was connected at the connection point of the heat pumps according to Figure 5.

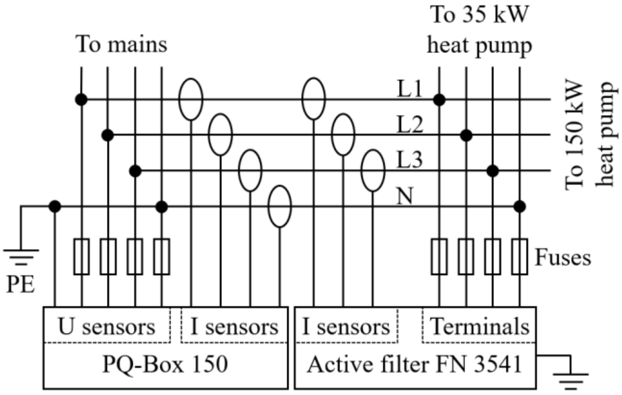

Figure 5: Schematic of the active filter connection

The current sensors of the active filter were installed on the mains side of the filter, upstream the filter connection point. This corresponds to a closed-loop control which typically leads to more accurate results than a current measurement after the filter connection point. The active filter was parametrized to compensate the harmonic currents of the 15th, 21st, 27th and 33rd order, based on the PQ measurements without filter which showed that the amplitudes of these harmonics were relatively close to the limits according to EN 50160. As an example, Figure 6 shows the influence of the 15th harmonic current on phase L1 and on neutral currents. With AHF in operation, the selected harmonic currents in all phases were significantly reduced. During the operation of the small heat pump, the injected current of each compensated harmonic order was reduced to values lower than 100 mA on the phases L1 to L3. In the neutral, the current is increased slightly by the filter. During the off-state of the heat pumps, the AHF was drawing phase currents of about 50 mA of amplitude which yielded to 100 mA in the neutral for the 15th harmonic. During the on-state of the large heat pump, the variation of the current on neutral was higher than without filter. The filter was intentionally not compensating the entire harmonic current amplitudes during operation of the large heat pump, because the filter compensation current was parametrized and limited corresponding to a medium power operation rather than to high (maximum) power state.

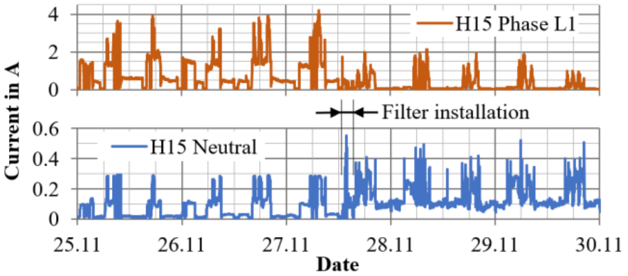

Figure 6: Measured influence of the active filter on the currents of the 15th harmonic at the connection point of the heat pumps

The voltage level of the 15th harmonic is clearly reduced at the connection point of the heat pumps and the 0.5 % level is exceeded less frequently.

It must be considered that the discussed measuring values are logged as 1-minute RMS values. According to EN 50160, 10-minutes RMS values must be respected. It was defined to sample more frequently because the heat pumps' duty may be only for a few minutes and the 10-minutes values would show less accurate results.

The maximum amplitudes of the 15th harmonic at each measuring point, with and without compensation of the AHF, are compared in Figure 7. At each measuring point of the building complex, the maximum voltage amplitude on each phase L1 to L3 was reduced by the filter. At the cabinets 1 and 2, phase L1 voltage was also positively influenced. But the phases L2 and L3, which behaved already differently than L1 when the on- and off-state of the heat pumps without AHF installed are compared (Figure 4), show again a different behaviour than L1. The maximum level on L3 (Cabinet 1 and 2) is higher when the active filter is running. On phase L2, the maximum level remains almost equal.

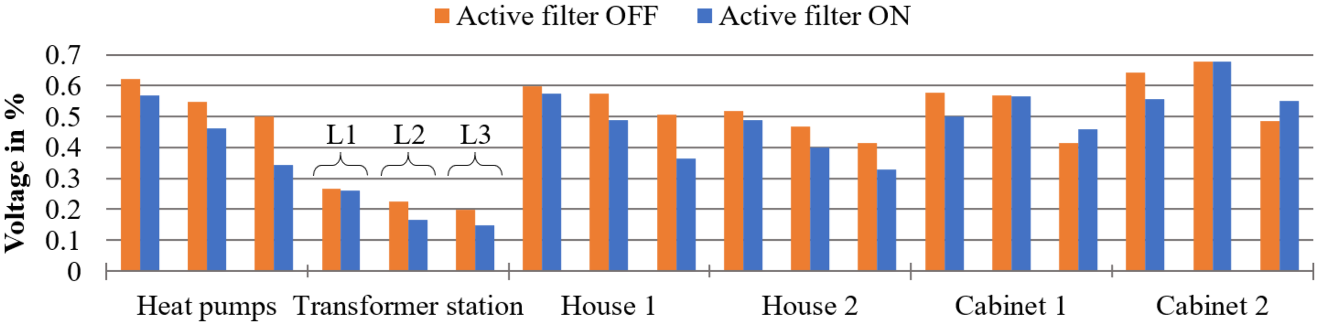

Figure 7: Maximum amplitude of the 15th harmonic for L1 to L3 with/without active filtering during 12 days

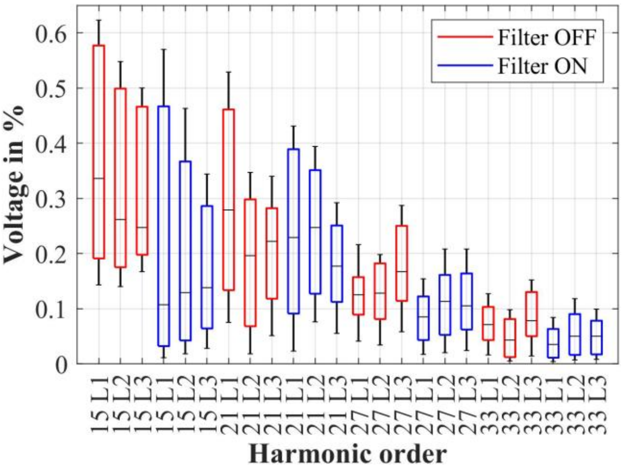

Figure 8: Measured voltage ranges of the 15th, 21st, 27th and 33rd harmonic with active filter ON/OFF at the connection point of the heat pumps during operation of the large heat pump

At the connection point of the heat pumps the harmonics of the 15th, 27th and 33rd order were clearly reduced by the AHF during the operation of the large heat pump (Figure 8). Also, the maximum levels of the 21st harmonic were reduced on the phases L1 and L3. This positive effect was also measured at other grid points of the building complex, e.g. in the transformer station. At the remote cabinets 1 and 2, the voltage amplitudes of the 15th and 21st order were not affected by the AHF whilst the amplitudes of the 27th and 33rd order showed a small improvement. The voltage amplitude variations at the remote cabinets were not susceptible to the operation of the heat pumps at the same way in each case. Hence, these voltage variations were consequently not susceptible to the compensation by the AHF but rather to the general loading structure dictated by the topology of the distribution grid.

While the smaller heat pump was running, a different effect on the voltage levels of the targeted harmonics at the heat pumps' connection point was registered with AHF in operation. As earlier presented, the AHF was compensating the harmonics to zero by injecting compensating currents during operation of the small heat pump. Even though almost no harmonic currents were injected in the grid, the respective harmonic voltage level was higher with operating both AHF and small heat pump. Since the resulting current was negligible, potential positive compensation effects of the small heat pump were eliminated and hence the voltage was only influenced by the dispersed grid load. Accordingly, the filter had the positive effect on the voltage harmonics when the large heat pump was operating. The effect on the voltage of remote grid points was only marginally measurable and the influence with operating small heat pump was negligible. But in none of the cases, disturbances of devices in the low voltage grid occurred.

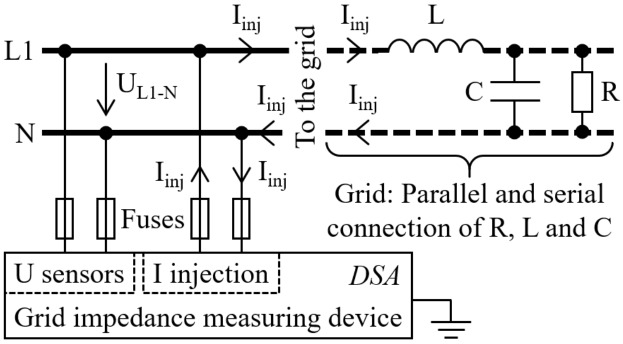

Figure 9: Schematic of a grid impedance measurement

ANALYSIS OF THE FREQUENCY-DEPENDENT GRID IMPEDANCE

The fGI in distribution grids is dominated by locally connected devices and can vary strongly between two measuring points. The closer to a device the measuring equipment is connected, the better the influence of this device can be observed. The potential influence of the connected device is damped by the line impedance between the measuring device and the device under investigation. Devices which are connected to the distribution grid influence the fGI at their point of connection. In some cases, the power line communication (PLC) can be disturbed due to very low impedances at the frequency bandwidth of communication [6]. To analyse the influence of the AHF, the fGI was measured at the filter's connection point with the device DSA ("Digitaler Spannungsanalysator") by MICHELS (Figure 9). A measuring current was injected in the distribution grid and the voltage variation detected through this current. Grid impedance measurements can be performed from phase to neutral (L-N) and from phase to phase (L-L).

The measured fGI during operation of the large heat pump are plotted in Figure 10. The PLC frequency and the parametrized frequencies of the filter are marked with dotted lines. The fGI presents no critical values, only a light resonance impedance at 850 Hz. With the AHF connected, the impedance is lower in the range between 500 and 1300 Hz. The impedance values at the marked frequencies are not critical or there are no strong resonance effects. The most significant change is observed in the angle at 750 Hz (15th harmonic): With active filter ON, the impedance is almost pure ohmic and shows only very little inductive behaviour.

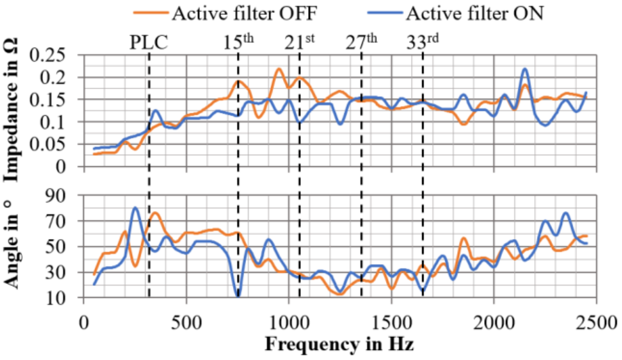

Figure 10: Measured grid impedance with/without active filter, 150 kW heat pump ON and 35 kW heat pump OFF

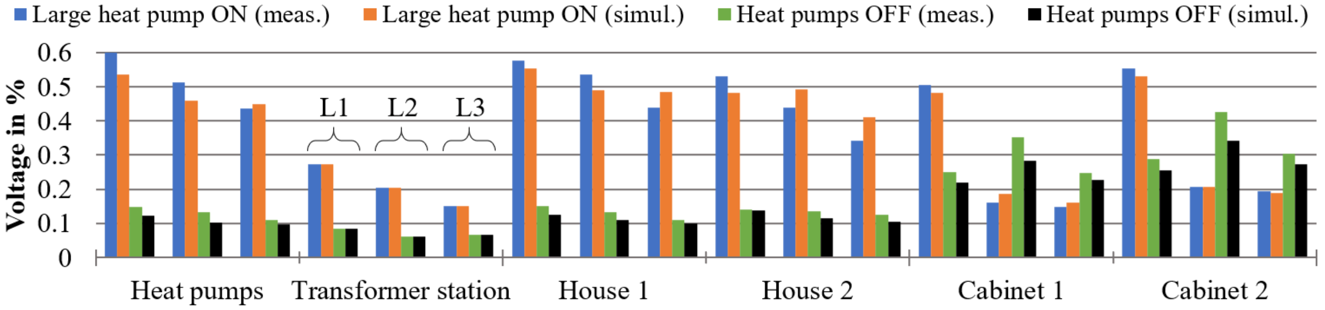

Figure 11: Comparison of measured and simulated voltage levels (15th harmonic voltage) at each measuring point. Two operating states are shown: on-state and off-state of the large heat pump. The small heat pump is always in the off-state.

MODELLING OF THE 15TH HARMONIC

The investigated grid without AHF was modelled and simulated using the software PowerFactory. The measured harmonic current amplitudes and angles were set at the modelled loads. At the transformer station a voltage source with the measured voltage was modelled. A comparison of the simulated and measured amplitudes is given in Figure 11. The model allowed to investigate why the voltage levels of the 15th harmonic behave differently on the three phases at the remote cabinets 1 and 2. Figure 12 shows for phase L3 that the voltage angle at the transformer station is changing about 180 degrees when the large heat pump is turned on (black vectors) or off (grey vectors), caused by the changed current flow through the transformer. The voltage at the transformer station and the voltage drops across the lines to cabinet 1 and 2 were smaller when the large heat pump was not running. But the voltages at the cabinets 1 and 2 were higher during the large heat pump's off-state, dependent on the angles of the line currents and thus of the voltages. In off-state, the voltages and voltage drops add almost arithmetically, which leads to higher voltages at the remote points.

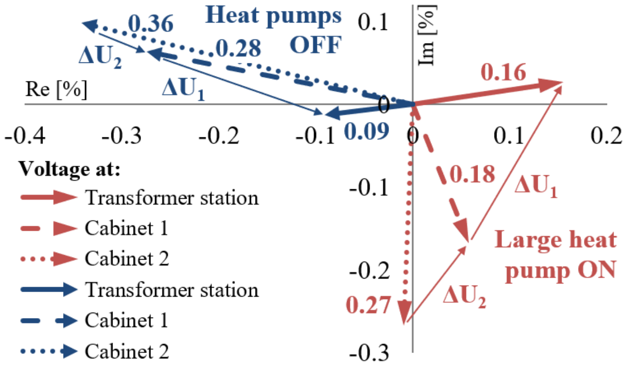

Figure 12: Modelled voltage vectors of the 15th harmonic at ON/OFF-state of the large heat pump without active filtering

CONCLUSIONS

Power inverters can influence harmonic voltage levels significantly on all points of a distribution grid. Critical harmonic amplitudes are induced by power inverters with a high-power rating and by the sum of many different non-ideal loads, connected at different grid points of common coupling (PCC). The described measurements at remote nodes and simulations under unbalanced grid conditions illustrate the dependencies very well. To draw precise predictions and conclusions, current amplitudes and angles shall be measured accurately. Active harmonic filters are able to compensate the harmonic currents generate by the non-linear loads and improve the local voltage profile. If the grid presents multiple non-linear loads injecting current harmonics in the grid, the corrective effect of an active harmonic filter is limited at remote grid points. To decrease the amplitudes of the investigated harmonics in the entire analysed grid, actively harmonic filtering at each node with compensation of relevant harmonic currents would be needed to prevent major grid disturbances.

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