# Harmonic Distortion in Low Voltage Grid with Grid-Connected Photovoltaic

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***Abstract*—Power electronic converters are being introduced in low voltage (LV) grids at an increasingly rapid rate due to the growing adoption of power electronic-based home appliances in residential grid. Photovoltaic (PV) systems are considered one of the potential installed renewable energy sources in distribution power systems. This trend has led to high distortion in the supply voltage which consequently produces harmonic currents in the network and causes an inherent voltage unbalance. In this study, a typical low voltage grid with high penetration of 3- phase and single-phase PV from southern Germany was modelled using MATLAB/Simulink environment. The characteristics of the load-side harmonic impedances were analyzed, and their harmonic contributions were evaluated for different distortion levels. The effect of the high penetration of PV on the harmonic distortion of both positive and negative sequences was also investigated.**

***Index Terms*—harmonic distortion analysis, PV systems, power quality, residential distribution system**

## I. Introduction

In the recent years, the use of power electronics in residential appliances has been significantly increasing owing to their importance and numerous advantages. Whether for control, protection or filtering, electronic components are not to be waived in the electronic-based modern devices, which are extensively used in a broad variety of industrial, commercial and domestic applications. Owing to their nonlinear characteristics, power electronic-based loads generate harmonic currents in the supply system, which in turn cause high voltage distortion as they interact with the distribution grid [1].

It has been established in the literature that the harmonics injected from individual residential loads can collectively increase feeder harmonic current distortion levels compared to commercial and industrial loads [2]. The typical nonlinear household loads usually consist of two types of power electronic front ends −diode-based rectifier like electronic ballasts for compact fluorescent lamp (CFL) [3] or thyristor/triac (SCR) -based rectifier like dimmers [4]. Despite the new generation of home appliances with PWM (pulse-width modulation) -switching rectifier are being increasingly introduced in the market, diode/thyristor-based loads are still commonly used in the LV residential distribution systems.

Furthermore, due to the raising concerns on environmental pollution and the decreasing costs of the PV modules which was strongly supported by the government policies around the world, additional grid-connected PV systems are being progressively connected to the distribution network [5]. In fact, the substantial percentage of installed PV systems is dominated by residential areas with low rated power. Consequently, the high penetration levels of PV systems, which are connected to the distribution grid through PV inverters, inject additional harmonic currents to the LV grid level [6]. Since PV inverters use self-commutating technologies, the harmonic current is basically dependent on the switching frequency of the PWM as well as the bandwidth of the measurement filters.

In order to investigate the effect of harmonic distortions, a case study of a typical LV grid configuration with high penetration of 3-phase and 1-phase rooftop mounted PV from southern Germany was first considered. EMT simulations were then carried out under the MATLAB/Simulink environment which contain detailed models for power electronic-based loads, ohmic-based loads as well as 1- and 3-phase PV. Note that, the switching patterns of the power electronic circuits were considered in this study. Measurements were eventually performed to analyze the distortion levels during the day.

## II. Effects of Harmonic Distortion on LV Grids

As a result of the proliferation of power electronic-based residential loads and distributed generation systems (DGs), higher harmonic current magnitudes have been extensively introduced, in particular odd harmonics with low-order such as $3^{rd}$, $5^{th}$, $7^{th}$, $9^{th}$ and $11^{th}$ [7], [8]. Moreover, the increased penetration of single-phase rooftop mounted PVs resulted in a significant increase in the voltage unbalance factor as well as the magnitude of the $3^{rd}$ harmonic current and its multiples, which may cause an excessive loading of the neutral conductor [9].

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The injection of harmonic current in distribution networks was found to reduce the power quality and also cause major economic and technical setbacks. Such distortions may result in an overheating of the connected loads, generators and conductors and hasten the thermal aging process [10]. Additionally, the capacitors used for power factor correction and harmonic filtering of the nonlinear loads may generate parallel resonance with the harmonic source at certain frequencies. This in turn may lead to excessive capacitor currents and voltage distortions [11]. When different converters are parallelly connected to the distribution grid, harmonic interaction effects may occur between individual converters which result in either resonance, control interaction or protection interference [13].

The harmonic content does not only depend on the amplitudes of the harmonic, but also on the phase angles. As a result, the harmonics from individual appliances and PVs can add together producing unexpected current distortion levels at the point of common coupling (PCC). In order to keep the harmonic propagation within prescribed limits, the PV integration must comply with the currently relevant standards and guidelines for the interconnection of DGs [14]–[17]. These standards provide the specific recommendations for the PV system operation, particularly with the factors related to utility system operation and power quality parameters (such as frequency, flicker and harmonics).

The terms used to quantify the harmonic voltage/current distortion limits are the individual harmonic distortion and the total harmonic distortion (THD). The latter is defined as:

$$THD_v(\%) = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1} \times 100 \qquad (1)$$

where $V_1$ is the fundamental component of the voltage and $V_h$ is the $h^{\text{th}}$ component of the harmonic voltage up to the order $H$.

Among these standards, the European Standard EN 50160 requires that the voltage THD at the PCC (up to the order 40) must not exceed 8 % in normal operation mode to minimize the adverse voltage effects on other equipment connected to the grid [18]. This limit conforms with the IEEE Standard 519 that specifies a maximum contribution of 5% for individual harmonic component [19]. In the IEEE Standard 1547, the current THD must be less than 5% of the fundamental frequency current at rated inverter output [15].

This issue imposes nowadays a major challenge for researchers and system operators, especially with the increased penetration of PV in LV networks (around 85% of the total PV power installed in Germany). Within this framework, various studies have been published to analyze and address this issue. [2] presented the harmonic current characteristics of residential distribution systems. [6]–[12] investigated the harmonic impact of residential loads and DGs on LV networks. In [13], an experimental analysis is carried out to assess the harmonic interaction of PV inverters with the LV network.

## III. Test Grid Configuration

The LV grid model contains 114 mixed 3-phase loads (linear and nonlinear) with a total peak demand of 340 kW and 27 grid-connected PV plants, from which 5 are 3-phase and the rest are single-phase. The total peak generation of PV plants is 234.6 kW. The LV grid is connected via three winding transformer of vector group Dyn5 to an independent feeder of 16 MVA short-circuit power and 0.1 R/X ratio. The feeder cables (L6:L9) type is NA2XRY with 300 A rating, while the type of cable extensions from the feeder to loads or PVs is NA2XY-J with 150 A rating. The grid forms a radial network, which is typical for Germany low density areas. An overview illustration of the LV grid with typical line lengths, distribution of loads and PVs and their connections are shown in Fig. 1.

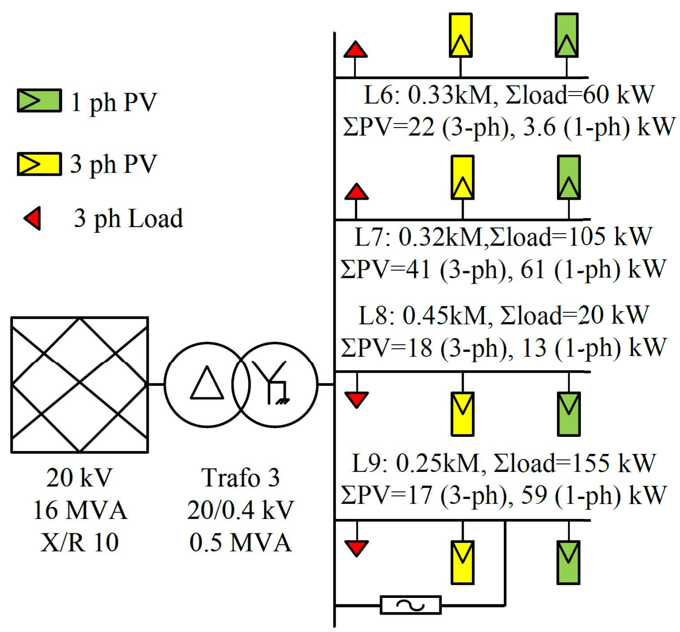


Fig. 1. Schematic diagram of LV grid from Germany

The PV plants as well as the loads are fed with PV and load profiles based on realistic measurements of the PV power and consumption behaviors in southern Germany. Each day is represented by 144 measuring points, where a measuring point is recorded every 10 minutes. Fig. 2 shows a sample of the PV and load profiles of one day during summer normalized on their maximum peaks. It should be emphasised that the profiles shown in Fig. 2 are for demonstration and not assigned for all the PVs and loads. The maximum generation existed for 3-phase and single-phase PV are 43 kW and 5 kW respectively while the maximum single-phase load demand is 1 kW. In such scenario, the grid exhibits a highly nonlinear behavior.

This model was successfully tested in [21] as this was adopted in this work. However, it should be noted that only the feeder cables L6, L7, L8 and L9 were examined, due to the huge computational requirements. This drawback by harmonics transient simulations can be alleviated using improved harmonic domain models based on alternative modeling techniques [22].

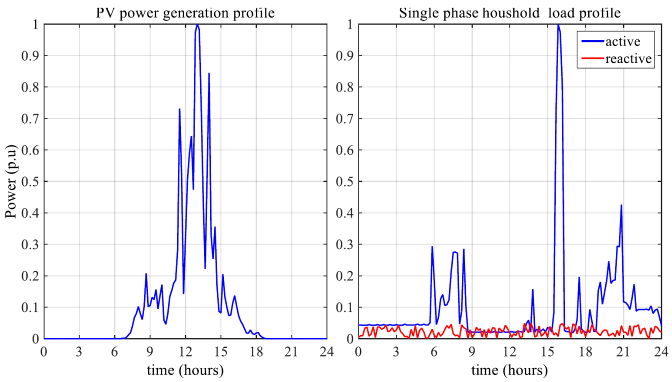


Fig. 2. Sample of PV and load profiles

### A. Load modeling

The developed loads are generally categorized into two types −Type 1 which is modeled as a set of three independent single-phase loads composed of RL-load, single-phase diode-based and SCR-based rectifier loads and Type 2 which is modeled as a 3-phase RL-load, 3-phase diode-based and SCR-based rectifier loads. These types represent a typical device combination applied in households. Due to the absence of information regarding the nature of the load, the loads were distributed stochastically in the network over various residential areas through the distribution cables.

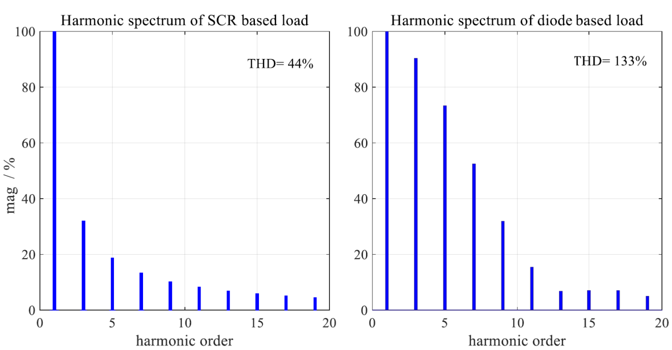


Fig. 3. Harmonic current spectrum for the used load types

In order to identify their individual harmonic emission characteristics, measurements have been conducted for each load type under clean grid conditions. It is obvious that the diode-based and SCR-based rectifier loads produces high level harmonic currents because of synergic effect action [7]. Therefore, the THD of the currents for SCR and diode-based loads are 44% and 133% respectively as shown in Fig. 3. As stated above, the magnitude of harmonics for both loads are more significant up to the $11^{th}$ order and decrease for larger order. Accordingly, the loads are equipped with harmonic filter, which is designed to limit the THD of the current in compliance with the requirements in [20].

### B. PV modeling

Owing to its simple topology structure, grid-connected PV systems become more popular at LV distribution grid. The circuit diagram of a 3-phase and single-phase grid-connected PV inverter, excluding the filters, is presented in Fig. 4. The objective of the line side converter (LSC) is to ensure that the DC link voltage is always close to its predefined nominal value in order to allow the power flow to the grid. Additionally, LSC provides voltage support capability through reactive power provision.

The high active power injection from the PV results with high voltages at the feed in point due to the ohmic nature of the LV cables. Additionally, in case of long feeders, the voltage at the transformers should be increased in order to ensure the minimum voltage threshold at the consumer. The new grid codes regarding small and medium sized PV plants require the capability of the grid-connected PV to feed in reactive power with PF up to 0.95 lagging/leading from PV power up to 3.68 kVA and PF up to 0.9 lagging/leading from PV power higher than 13.8 kVA [17]. Accordingly, a proportional controller is implemented to produce the required reactive power for grid voltage support. The required reactive power is limited according to the maximum power factor and the maximum allowed value with the priority set to the positive sequence active current as shown in Fig. 5.

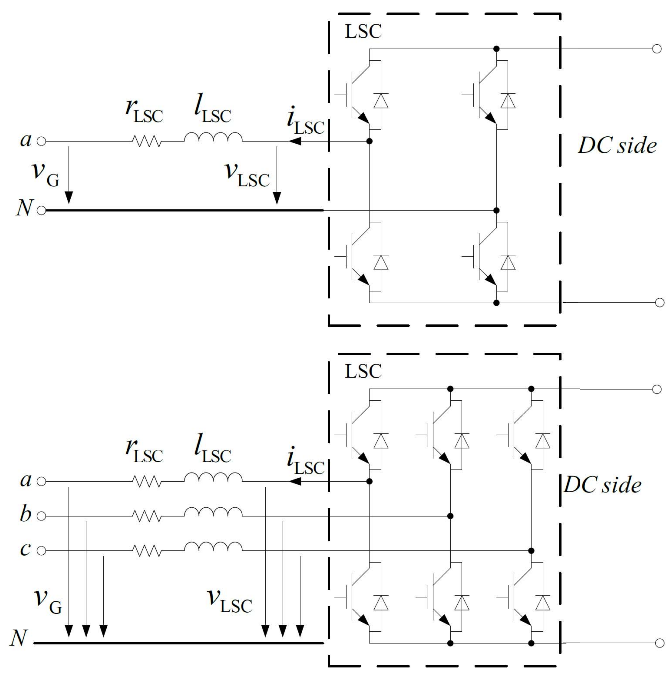


Fig. 4. 3-phase and 1-phase grid-connected PV inverter circuit diagram

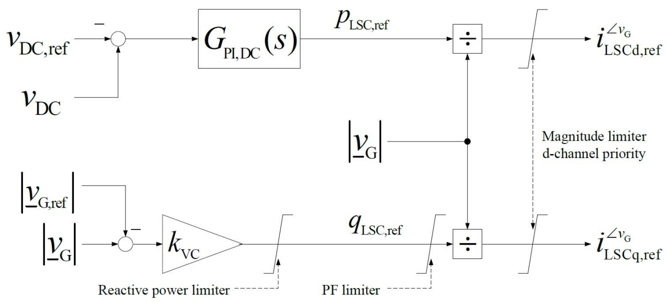


Fig. 5. Outer control loop of PV positive sequence controller

The harmonic frequencies, produced by the pulse width modulated (PWM) inverter, are related to the carrier frequency as follow:

$$f_h = m.f_C \pm n.f_{fund} \tag{2}$$

where $m$ and $n$ are positive integers and $f_C$ and $f_{fund}$ are the carrier and the fundamental frequency, respectively.

To ensure an efficient modulation, the switching frequency was set at 16 kHz. In addition, the inverter was equipped with filters in order to attenuate the injected harmonics and keep the THD in the predefined limits in accordance to [20].

## IV. Harmonic Analysis in the Test Grid

The configuration and the size of the grid requires high computational effort. Therefore, only the results of a single mid-summer day, which represents a critical period where the demand and generation of power reach substantial levels, were analyzed. Test cases were carried out considering two different system scenarios. In the first case, it was assumed that no PV systems were connected to the grid. In the second case scenario however, the simulations were performed with the addition of PVs. The measurements were taken at the low voltage side of the feeders transformer.

The total active power in the grid with no connected PVs is always positive during the day (consumer oriented). However, when the PVs are connected, the active power reverses and reaches its maximum value during mid-day time, as shown in Fig. 6. As already mentioned, the transformer terminal voltage increases in response to the high active power feed-in from the PVs, as depicted in Fig. 7. Due to the increased voltage magnitude, the PV controllers was found to absorb the reactive power in order to restore the voltage to its nominal value, as shown in Fig. 6. Nevertheless, the reactive power compensation was found to cease when the voltage magnitude exceeded the 110%, in agreement with the regulation in [17].

The stochastic distribution of the loads in addition to the high penetration of the single-phase PVs was found to generate unbalanced harmonic currents. This imbalance would be minimal without PVs, as all the loads have the same demand's peak. However, the behavior of each individual load remained stochastic which resulted in unbalanced harmonic currents with small magnitudes, as displayed in Fig. 8.

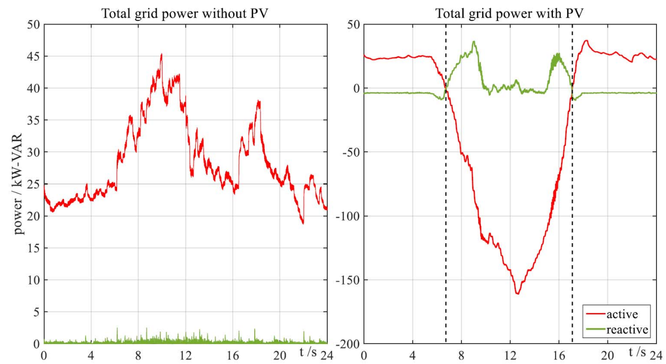


Fig. 6. Total power in the grid


Fig. 7. Transformer low side terminal voltage profile

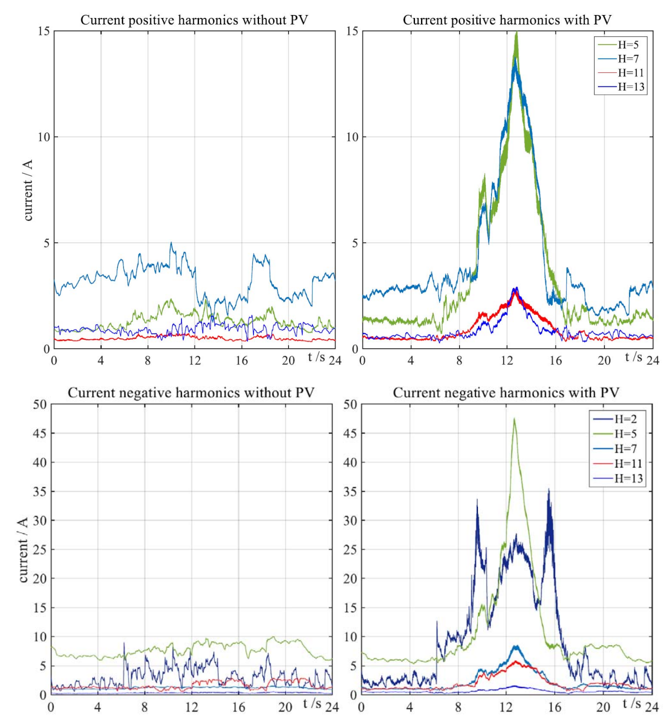


Fig. 8. Harmonic contents of the current flowing through the transformer

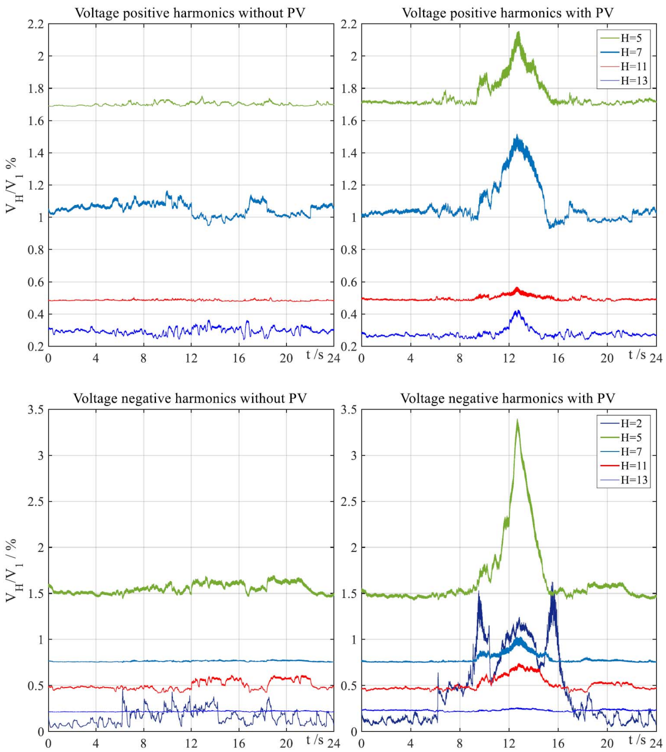


Fig. 9. Harmonic contents of the transformer low terminal voltage

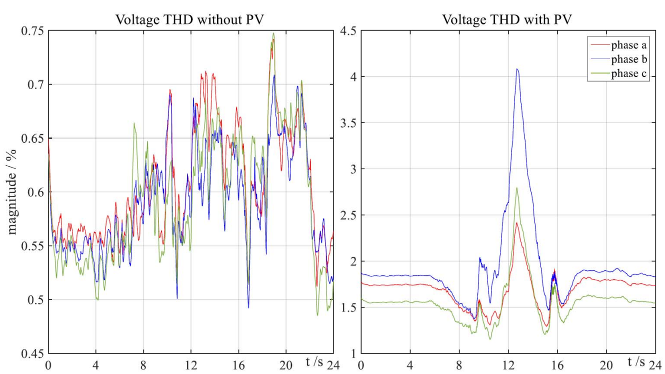


Fig. 10. THD of the voltage at the transformer low side terminals

Despite the low harmonic currents generation as well as the low THD of individual PVs in comparison to the power electronic-based loads, the high penetration of the PVs, in particular single-phase, may cause high unbalanced harmonic currents especially the 2$^{nd}$, the 5$^{th}$ and the 7$^{th}$.

The unbalanced harmonic currents had consequently given rise to unbalanced harmonic voltages. The imbalance in the harmonic voltages was found to be minimal without PVs. However, when the PVs are connected, the magnitude of the unbalanced harmonic voltages increased, in particular the 2$^{nd}$ and the 5$^{th}$ harmonic, as shown in Fig. 9. As an end effect, the THD of the voltage was found to be low without PVs, which was attributed to the low load demand and the low magnitudes of the harmonic currents. On the other hand, the THD of the voltage increased when the PVs were considered, particularly at mid-day when the voltage and current magnitudes reach their maximum values. Additionally, the THD value can be different from one phase to the other, as illustrated in Fig 10.

## V. Conclusion

In this paper, we investigated the influence of high penetration of 3-phase and single-phase rooftop mounted PVs in distribution network as well as the increase of power electronic-based loads on the harmonic distortion. Detailed models of different types of loads as well as for the PVs were developed considering the switching patterns of the power electronic circuits. The loads as well as the PVs were equipped with harmonic filters designed to limit the THD of the current in accordance to the limits specified in the standards. Afterward, an EMT simulation was carried out for a typical real LV grid configuration from southern Germany using the developed detailed models, where each load and PV was fed by a typical load and generation profile respectively based on realistic measurements.

The simulation results showed that the stochastic nature of the loads results in unbalanced harmonic currents, which consequently produce unbalanced harmonic voltages and different THD of each phase voltages. However, the magnitude of the harmonic currents as well as the harmonic voltages are low as the load demand did not reach its peak value during the simulated period of one day. Although the harmonic contents of the generated currents from the PVs are too low, the high penetration results in high magnitudes of harmonic currents especially, the 5$^{th}$ and the 7$^{th}$ order harmonic currents. Additionally, the single-phase PVs give rise to high unbalanced harmonic currents especially the 2$^{nd}$ and the 5$^{th}$ harmonic currents. The high harmonic currents magnitudes produce high harmonic voltages at the transformer terminals especially the 2$^{nd}$ and the 5$^{th}$ order harmonics and lead to an unequal THD values for each phase voltages.

The unbalanced harmonic currents lead to unequal power distribution off the lines which give rise to unequal thermal distribution. Additionally, the unbalanced harmonic currents and voltages will increase the core losses of the transformer and increase heat production. Although the power limits of the transformer were not exceeded, the future increase of the PVs inside the grid may lead to thermal break down of the insulation or faster aging of the equipment due to the increased harmonic currents especially the 2$^{nd}$ and the 5$^{th}$ order harmonics, which attained high values as shown from the simulation results. The results shown in this work call for introduction of new stipulation regarding limits of harmonic current injection from PVs, especially considering not only their individual generation capacity but additionally the total generation capacity inside the grid.

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