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Impact of Household PV Generation on the Voltage Quality in 0.4 kV Electric Grid—Case Study

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Abstract: This article (case study) discusses the influence of household photovoltaic generation on the voltage quality in a three-phase 0.4 kV grid. The research analyzes remotely acquired data from two specially designed three-phase Y-connected power meters to understand the PV system's influence on the grid. The values of the voltages, currents, THD, individual harmonics, power factor, and K-factor are obtained every 200 ms over several months, creating more than 20 GB of data. The loads are typical household electrical appliances and EV portable chargers. The main conclusion after analyzing the measurements is that three-phase PV generation in the presence of household loads can create or increase grid unbalance; important current values into the neutral wire and THD and K-factor increase in some cases. The results also uncovered that without current sensing at the household connection point to the three-phase grid to control the PV inverter, the balanced phase output power of the grid-tied inverter is harmful to the 0.4 kV grid balance.

Keywords: solar energy; photovoltaic; power quality; harmonics; THD; inverters

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1. Introduction

Photovoltaic (PV) installations in households spread rapidly all over the world. Technology Report, September 2021, shows that "Of the 1 TW installed, roughly 40% represents distributed PV installations out of which more than one-third are in the residential sector. Around 130 GW of PV systems are deployed in households, which account for approximately 25 million units" [1].

At the same time, there is little information about household PV inverter's influence on the voltage quality in three-phase low-voltage (0.4 kV) electric grids with neutral [2–4].

The primary discussion concerns low-voltage grid balancing by theoretical or simulation means and does not include whole household loads. Due to the complexity and not determining the nature of household loads (on–off time, power variations), the theoretical approach is practically very complex or even impossible. As described below, actual field measurements give information and knowledge about processes and electrical parameter values.

On the contrary, the impact on the electric grid from medium or large PV plants is assessed widely, e.g., in the review [5].

The current article is a case study and discusses the PV setup's influence on the electric grid in households.

Over a five-month (mid-April to mid-August) period in 2022 in Latvia, each three-phase system voltage and current was measured over ten periods of the 50 Hz mains by acquiring instant values based on a 5 kHz sampling frequency. The measurement-taking point is near the household's connection to the grid.

The available recorded dataset [6] (683 views) reflects a household's grid power profile (16 April 2022–5 May 2022). However, in this case, the study analyzes recorded data on the 30 April 2022 from 15:00 to 16:00—a typical situation occurring on practically every sunny day.

Based on sampled values over a 0.2 s period, the following calculations for each phase have been carried out:

- Active power;
- Voltage RMS;
- Current RMS;
- Voltage and current harmonics (up to 15th harmonic).

In this case study, we do not look at grid impedance evaluation, which recently gained importance [7]. Additionally, harmonics evaluation is approximate, "just to know", omitting the interharmonics calculation or estimation [8,9] due to a lack of necessary measurement equipment.

The household power profile under consideration includes the following typical appliances: a 2.2 kW electric oven and 1.7 kW induction hob, two 0.22–1.55 kW air-to-air heat pumps for air conditioning, a three-phase 18 kW through-flow water heater, 6 kW solar panels with a 6 kW three-phase inverter and a 2.3–2.8 kW portable charger for an electric car.

2. Materials and Methods

The overall household electric grid installation diagram is shown in Figure 1.

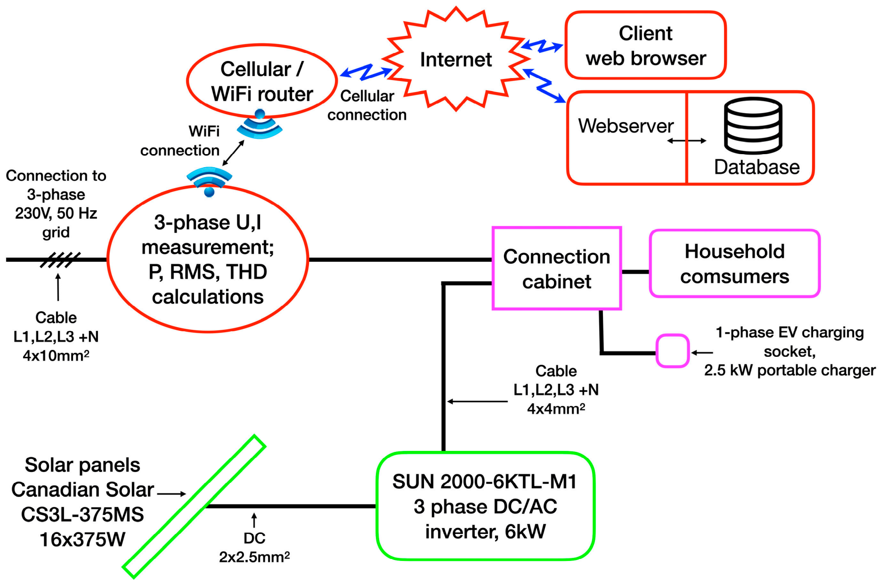


Figure 1. Household measurement system installation diagram.

2.1. Measurement System

The measurement and calculation system employed upgraded the in-house designed power meter (Figure 2a). The primary device contained:

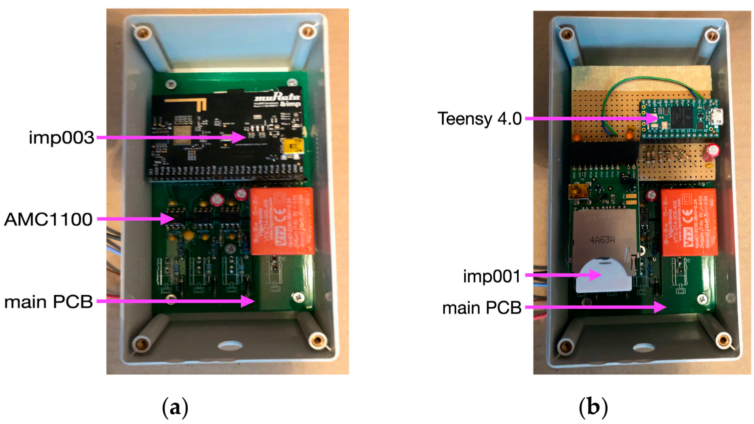


Figure 2. (**a**) Basic power meter (imp003); (**b**) upgraded power meter (Teensy 4.0 and imp001).

- Three galvanically isolated voltage sensors—isolated amplifiers AMC1100 [10];
- Three Hall-effect-based galvanically isolated current sensors HSTS 016L-10A [11];
- Twilio electric imp Murata imp module (imp003 LBWA1ZV1CD) [12].

Initially, module imp003 was employed utilizing an IEEE 802.11 b/g/n 2.4 GHz Wireless LAN IC BCM43362 and STM32 ARM Cortex-M4 micro-controller STM32F405 running 32-bit computation at a 72 MHz clock frequency. Imp003 module programming and communication were carried out wirelessly via Wi-Fi. The design allowed the setting of 1.8 kHz voltage and current waveform sampling rate on six inputs, acceptable in most cases.

At the same time, the 72 MHz clock frequency proved to be too low. It was insufficient for the harmonic component calculation of each voltage and current waveform.

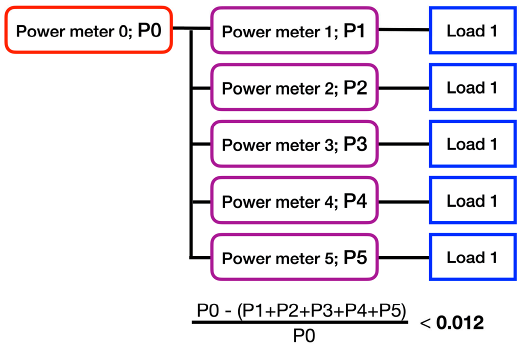
In order to increase the computation power of the power meter, the imp003 module was replaced with an NXP IMXRT1062DVL6 microcontroller running 32/64 bit at 600 MHz included in the Teensy 4.0 development board [13] (Figure 2b). Another Twilio electric imp imp001 module was employed to provide Wi-Fi communication.

Implementing the Goertzel algorithm [14] for harmonic component detection in relative scale eliminates the necessity for narrow fast Fourier transformation (FFT) bins. Additionally, for FFT, achieving the desired bin central frequencies is problematic and requires manipulation with the micro-controller clock frequency and frequency dividers.

The main drawback of implementing the Goertzel algorithm is a requirement of low deviation from a 50 Hz mains frequency in the grid frequency.

All these power meters have been verified and tuned using a three-phase calibrated adjustable power source MTE PCS400.3 (Figure 3a) according to the standard IEC 61000-4-30.

(**a**)



(**b**)

Figure 3. (**a**) Three-phase adjustable power source MTE PCS400; (**b**) accuracy field test diagram.

Power meter precision depends on the Hall current sensor accuracy (1%) and linearity (better than 1%).

Accuracy field tests, provided by a schematic diagram shown in Figure 3b, demonstrated overall accuracy below ±1.2%.

2.2. Communication, Data Storage, and Visualization

Measured and calculated data were stored in the database every 0.2 s, creating a block of ten CSV-like lines to be sent to the server, bulk occurring every 2 s.

On the server side, information was decoded accordingly and stored in the MySQL database. The data amount was enormous: the published dataset was 2.89 GB, but the database table size on the server was more than 20 GB (1 GB = 1,073,741,824 bytes). The table row count was more than 70 million rows.

Recorded data visualization is a web page containing interactive graphs. Interactive graphs designed for a computer screen are challenging to represent on printed paper or in a PDF. A larger size is available on the indicated website https://remotelab.lv/power/powerD2.php or https://remotelab.lv/power/powerD2_THD.php (accessed on 1 March 2023).

2.3. PV and Inverter

The solar PV system under consideration comprised 16 375 W Canadian Solar CS3L-375MS solar panels and a three-phase grid-tied inverter Huawei SUN 2000-6KTL-M1. The planned first-year system average efficiency was 80.77%, without solar tracking.

3. Results and Explanation

The PV system power profile shows the recorded data from 30 April 2022, selected from the five-month data period recorded (Figure 4). Positive power values on charts are shown in Figure 4; the mean energy consumption from the grid, and negative power value mean energy is fed into the grid. The generated energy profile to the left is a screenshot from the solar inverter's smartphone application. The power profile reflects the measured values.

30 April 2022

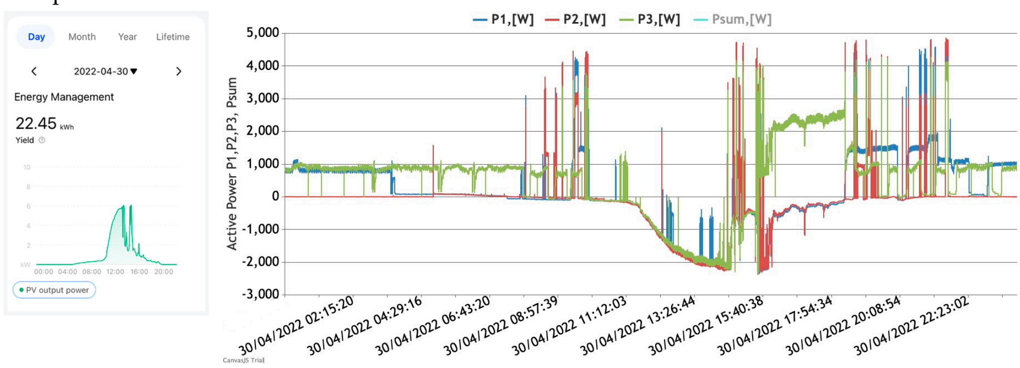


Figure 4. Generated energy profile (**left**) and registered power profile (**right**).

The analysis discussed below relates to the period from 15:00 to 16:00 (GMT+3) on the 30 April 2022.

Figure 5 (also https://remotelab.lv/power/powerD2.php (accessed on 1 March 2023)) reflects measured voltage, current, power, and power factor curves for each phase in the three-phase Y system at the measurement point (Figure 1).

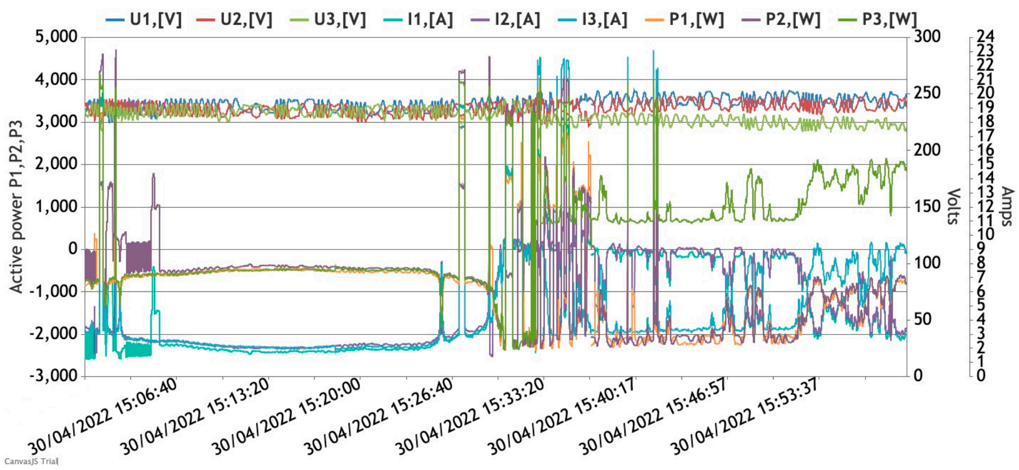


Figure 5. Measured voltage V, current I, power P, and power factor PF curves for each mains phase.

As mentioned above, the graphical representation of the recorded data uses an interactive web page with an option to toggle on–off each parameter values curve. Such an approach is unsuitable for presentation in the paper, so a separate analysis for voltages, currents, and power takes place.

Voltage and current analysis based on the standard IEEE Std 519TM-2022 [15] approximation (harmonics up to the 15th, no 50 as required) include the total harmonic distortion (THD) calculation by the well-known Expression (1):

$$THD = \frac{\sqrt{h_2^2 + h_3^2 + \ldots + h_n^2}}{h_1} \tag{1}$$

where the h-harmonic value in the waveform, n is the harmonic number.

THD characterizes how much the waveform deviates from a sinusoidal form but does not say anything about each particular harmonic value in the spectrum. A deeper analysis takes into account the percentage of each harmonic value of the sum of all 15 harmonic values, according to Expression (2):

$$h_{percentage} = \frac{h_n}{\sum_1^n h_n} \times 100\% \tag{2}$$

where the h-harmonic value in the waveform, n is the harmonic number.

3.1. Voltage and Current Profile Analysis

Figure 6 (also https://remotelab.lv/power/powerD2_THD.php (accessed on 1 March 2023)); please note that the webpage is slow to load) shows the registered voltage, current profiles, and corresponding THDs (in %) and the first harmonic value against the sum of all harmonic values.

Voltage values are in standardized limits −15% . . . +10% and the calculated THD is less than 5%. Additionally, the 1st harmonic (50 Hz) values are in the range of 85% . . . 94% of the spectrum up to the 15th harmonic.

The three-phase Y connection voltage profile does not show any non-typical values during the 1 h of observation.

Figure 6c,e show the presence of significant harmonic distortion in the current waveforms—up to 20%, occasionally even more.

K-factor is a weighting of the harmonic load currents according to their effects on transformer heating, as derived from ANSI/IEEE C57.110. To determine the possible influence on the 0.4 kV transformer, the K-factor was also calculated according to IEEE Std 1100-1992-2005 [16]. The higher the K-factor, the greater the harmonic heating effects. The equation to calculate the K-factor is as follows:

$$Kfactor = \frac{\sum_1^n (i_n \times n)^2}{\sum_1^n {i_n}^2} \tag{3}$$

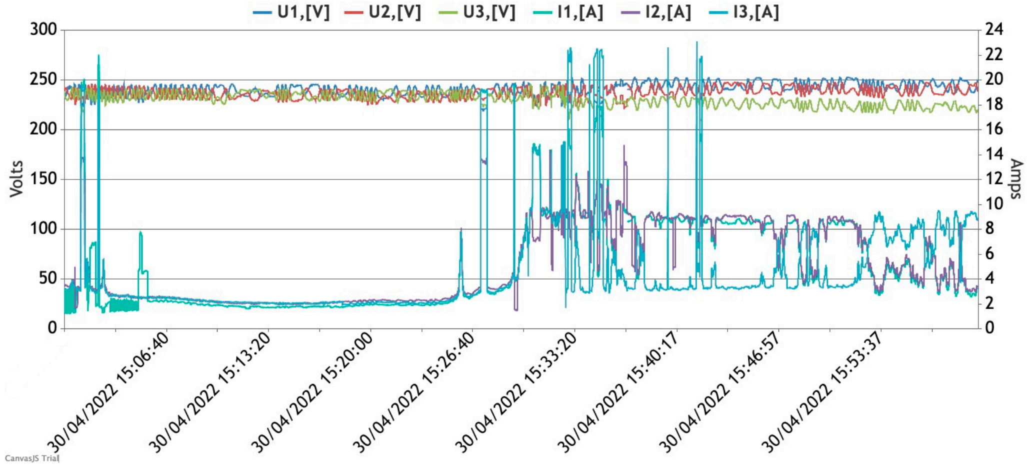
where the i_n is the current harmonic value in the waveform and n is the harmonic number.

The results show (Figure 7, also https://remotelab.lv/power/powerD2_Kf.php (accessed on 1 March 2023) that the K-factor is less than 8—an acceptable value for household consumers.

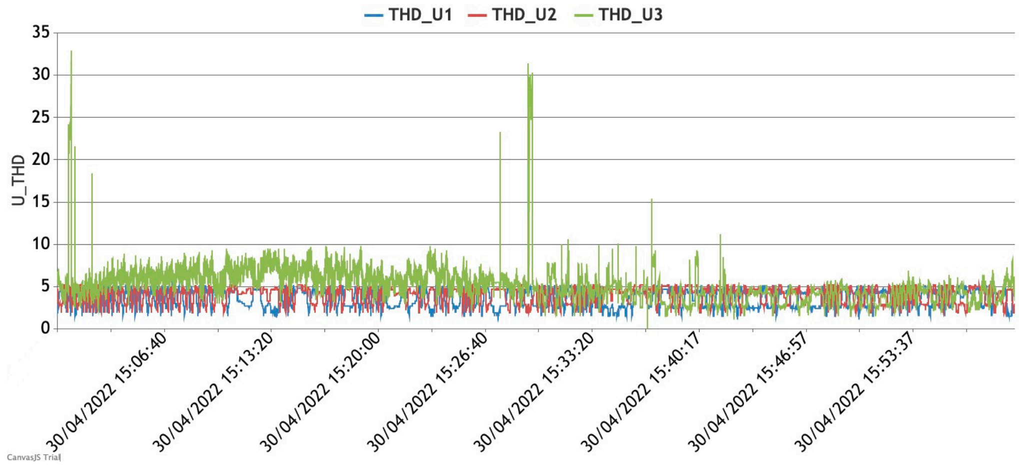
The source of the high THD values could be due to the solar inverter or household consumers or interference between them.

A non-linear load has an influence not only on the grid but also on the solar panel's inverter. Load or inverter nonlinearity or non-sinusoidal inverter output voltage causes interharmonics, which is not discussed here.

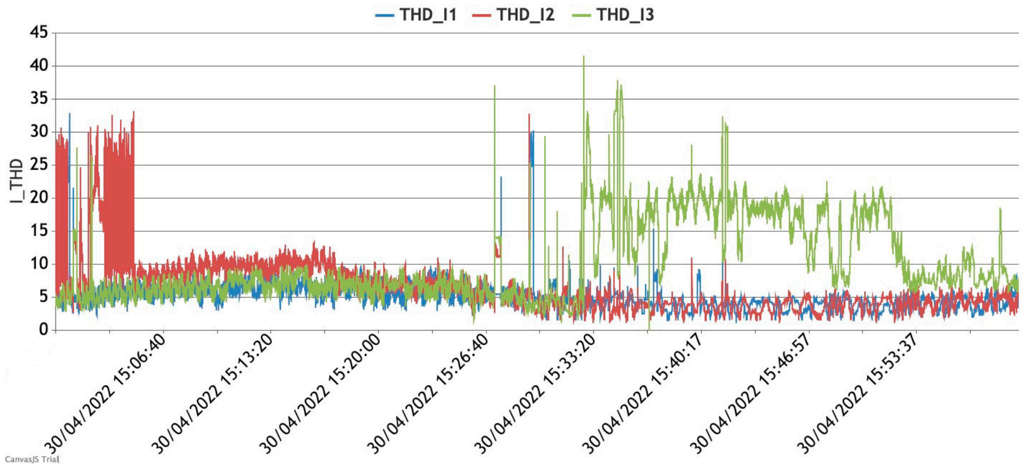
To detect the source of harmonics, the measurement system was updated (Figure 8) with an additional second identical power meter directly at the grid-tied inverter's output.



(**a**)

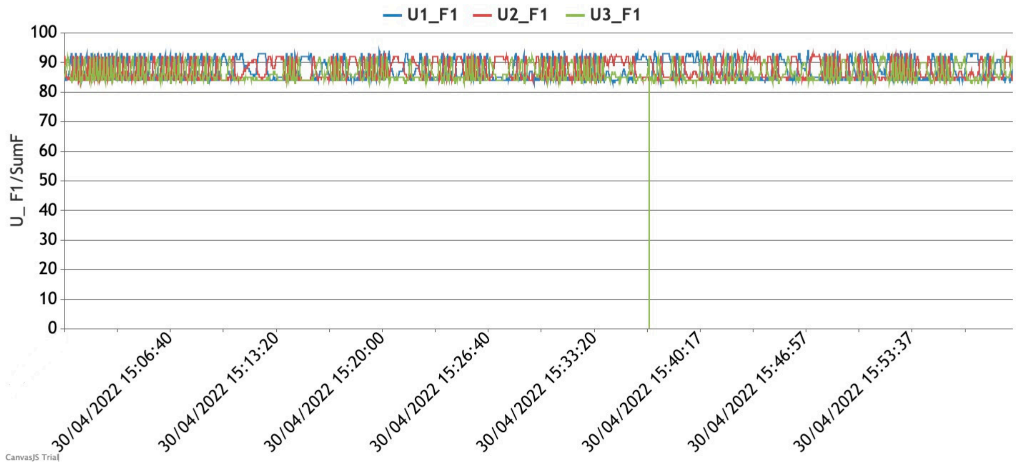


(**b**)



(**c**)

Figure 6. *Cont.*



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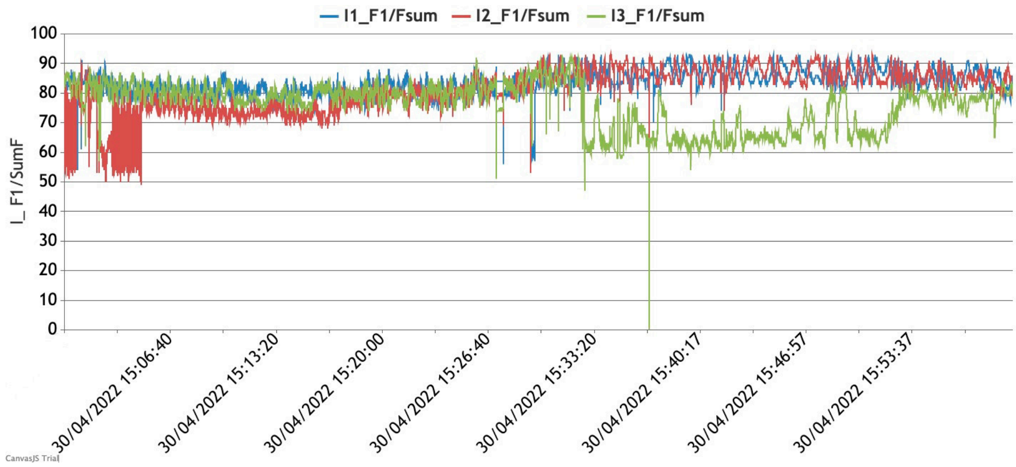

(**e**)

Figure 6. (**a**) Registered voltages and currents; (**b**) calculated THD for phases U1, U2, and U3; (**c**) calculated 1st harmonic value against the sum of all harmonic values for phases U1, U2, U3; (**d**) calculated THD for phases I1, I2, and I3; (**e**) calculated 1st harmonic value against the sum of all harmonics values for phases I1, I2, and I3; (see also https://remotelab.lv/power/powerD2_THD.php (accessed on 1 March 2023); please note that the webpage is slow to load).

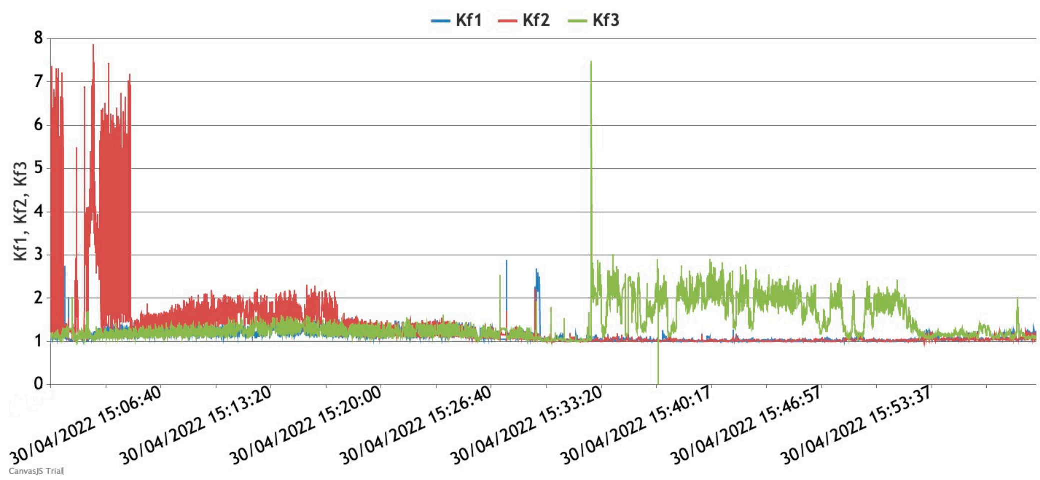

Figure 7. Calculated K-factor Kf1, Kf2, Kf3 graph for phase currents I1, I2, I3 accordingly.

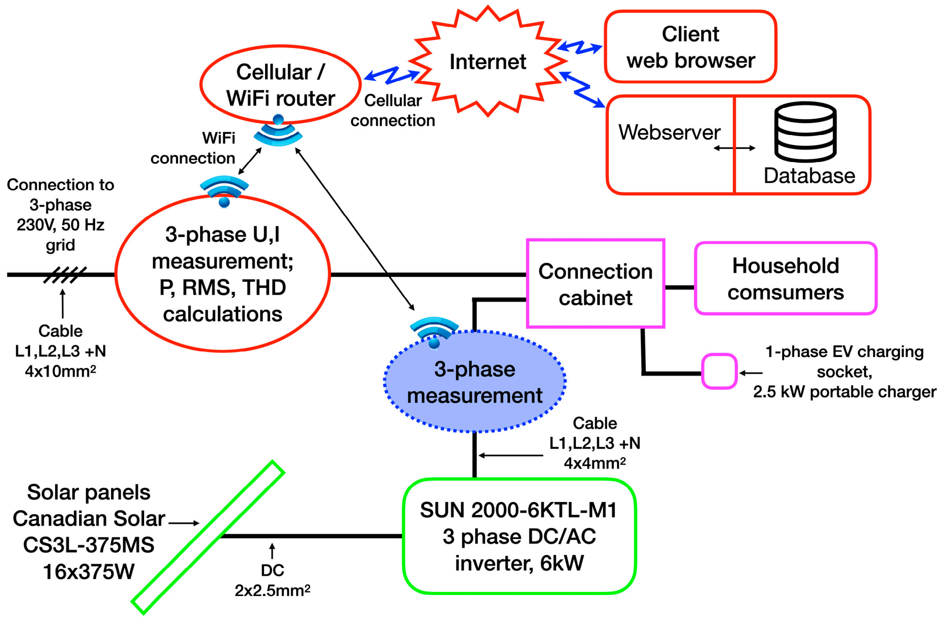

Figure 8. Upgraded measurement setup by the installation of an additional power meter.

As can be observed in the results from the measurements taken directly at the inverter's output (values not reflected in this paper due to inaccurate results), the voltage THD does not exceed 5%, and the current THD is less than 6.3%.

Therefore, household electrical appliances are the primary source of increased current THD.

The portable charger for the electric car could also have an influence.

3.2. Power Profile Analysis

Figure 9 reflects the active power profiles registered at each phase separately—at the grid connection and at the inverter's output.

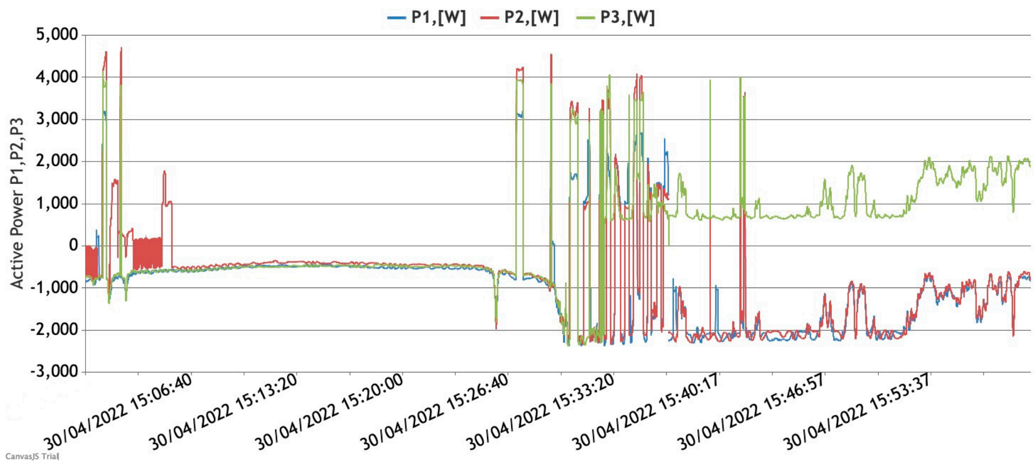

Figure 9. Power profile at connection point to the grid.

Usually, based on historical terms, the discussion also includes the power factor or cos ϕ.

Today's power factor is not so important due to the impressive number of digital converters connected to the grid, but this parameter is also shown here. Figure 10 (also https://remotelab.lv/power/powerD2.php (accessed on 1 March 2023)) shows the power factor's graph.

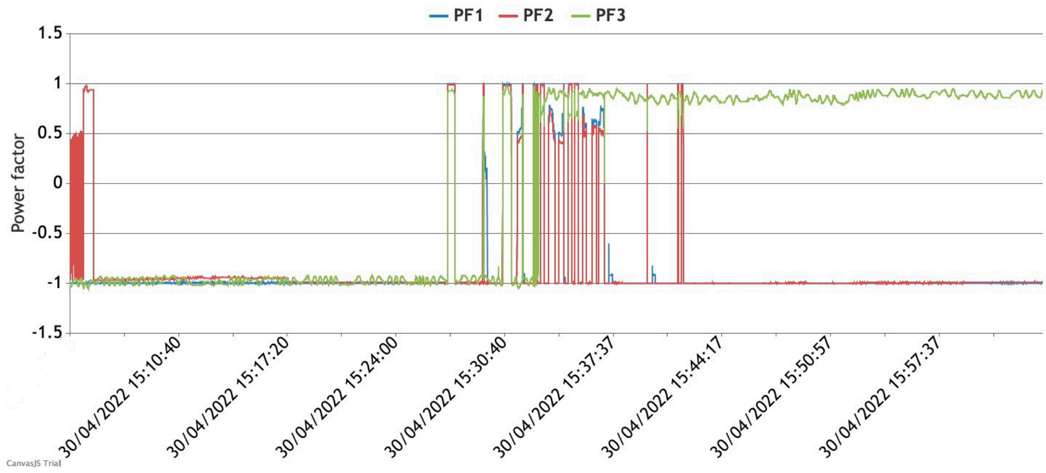

Figure 10. Calculated each phase power factor PF1, PF2, PF3 at the grid connection point.

The power factor values in Figure 10 are positive or negative depending on the direction of energy flow. The power factor values are mainly close to 1. The exception is when the water pump's motor periodically starts and stops, or other load transients occur, causing the power factor to drop below 1.

The inverter's output power values on all phases are negative—the energy flow is from the inverter to the household connection cabinet (Figure 8), consumers, and grid. The picture is quite different for the household connection to the grid.

At this point, the grid is unbalanced: one phase (P3) consumes energy, but two other phases (P1, P2) feed energy into the grid.

The mentioned situation occurs because P3 includes a 2.6–2.8 kW portable electric vehicle charger. The charger's power is higher than the solar inverter can provide for a single phase, so the necessary supply power difference comes from the grid.

An unbalanced three-phase system is a much bigger problem than a high THD or low power factor. As a quick illustration, let us take a look at Figure 11.

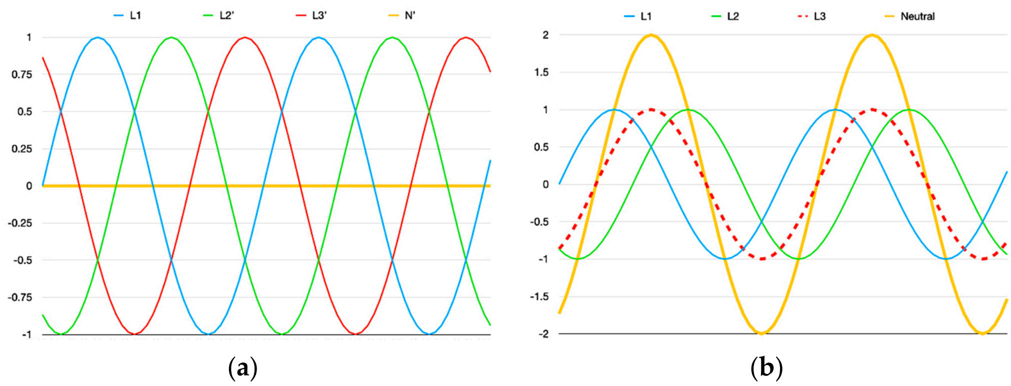

Figure 11. Balanced Y grid neutral current (**a**) and case in which in two phases energy is fed into the grid and in one phase energy is consumed from the grid (**b**).

In an unbalanced three-phase Y system, the current in the neutral wire is not zero but could be more than the phase current. In this condition, the cross-section of the neutral wire must be more significant than the line cables; the cross-section must be more extensive, or two (or three) conductors can be used in parallel formation to carry the high amount of generated unbalanced currents.

In cases wherein PV systems are just an add-on to existing household infeed wiring, the National Electrical Code (NEC) Article 310, "Conductors for General Wiring" [17], and other regulations are not always considered due to financial and practical reasons to change or replace cabling.

Moreover, the unbalanced three-phase Y system increases power losses I^2R and can reduce the lifetime of distribution power transformers by increased heat.

4. Discussion

A considerable part of the publicly available information about PV system commissioning is straightforward and one-sided—install the PV panels and inverter and connect the system to the grid. Very little information is available on the potential problems PV inverters can cause, such as grid distortion or unbalancing.

As discussed above, a solar panel inverter connected to the 0.4 kV grid can cause or increase the three-phase Y system unbalance and, in interaction with various household loads, can increase THD and K-factor values in some cases.

Due to unbalance and weak 0.4 kV grids, some grid operators continue the discussion about limiting the PV-generated power.

Such an idea is inappropriate from the economic, regional energy independency, and environmental points of view—nowadays, it is not acceptable to limit the generation of green energy.

There are several options to avoid creating grid unbalance in household PV systems.

The first would be adapting the inverter's control algorithm. According to measurement data discussed in this article, the PV system generates enough power than is necessary for one-phase loads, but the loads are not the same in all Y system phases. Still, the inverter distributes PV power symmetrically in all phases, acting like a classical three-phase generator. Thus, PV inverters cause unbalance. The control algorithm could be used to try to balance the system by distributing the available PV power asymmetrically instead, controlling the power and energy flow at the point of the PV inverter and grid coupling. This solution requires an additional inverter sensor installed at the household connection point to the grid.

The second option is using a dual output or "grid-tied/off-grid" inverter, which is complicated since such inverters are mostly single-phase.

The third approach would be using grid balancers between the household and the load. Nevertheless, even the simplest grid balancer is a bidirectional AC/DC/AC converter, which is not commonly available and is expensive.

If the household utilizes just a one-phase connection to the grid, the influence of PV generation on the three-phase grid could be lower from a grid symmetry point of view.

Comparison between the one-phase and three-phase PV system's influence on a 0.4 kV grid must be researched.

There are no such problems at large PV farms. From the grid perspective, issues in the grid mainly arise during low-power grid-tied PV generation.

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Conflicts of Interest: The authors declare no conflict of interest.

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