On-Site Waveform Survey in LV Distribution Network using a Photovoltaic Installation

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Abstract—Conducted electromagnetic interference has shown to result in misreadings of static energy meters due to non-linear current waveforms. Based on these findings it is of interest to survey waveforms that occur in typical low voltage distribution networks, and to which static energy meters are exposed to. Therefore, complex waveforms in a domestic photovoltaic installation are identified. Furthermore, discrepancies between the generated power, consumed power by the loads and drawn power from the grid are found. This paper aims to correlate these waveforms to the observed discrepancies in the power consumption data and survey the waveforms that occur in these modern installations.

Index Terms—Conducted electromagnetic interference, Distribution network, Non-linear, Photovoltaic installation, Static energy meter

I. INTRODUCTION

Static energy meters are used in modern low voltage (LV) distribution networks to measure the consumption in residential situations for billing purposes [1]. These meters are widely deployed by utilities throughout Europe. It was already shown that harmonic disturbances can result in static meter errors outside the limits declared by the manufacturer, and their relationship with $\sin \varphi$ (or power factor) [2]. More recent studies show that the non-linear behavior of modern appliances can generate conducted electromagnetic interference (EMI) problems, resulting in misreadings of these static energy meters [3]. Misreadings have found to be due to dimmed lighting equipment of light emitting diode (LED) and compact fluorescent lighting (CFL) technology [4], or because of a speed controlled water pump [5]. The last case was reported by consumers observing an extreme high energy meter reading. In this regard, the energy consumption of the above mentioned

water pump was measured in laboratory conditions using ten different static meters. The experiments found errors in meter reading between -61% and +2675% [5]. These findings were confirmed by independent research centers within the framework of the MeterEMI project [6], [7].

An analysis of the waveforms drawn in these situations, showed that impulsive currents were generated with a high peak value and low root mean square value, and thus a high crest factor [8]. Furthermore, the existence of more household appliances with high crest factor and fast current slope, and their relationship with metering errors was shown in [9].

Based upon these studies, it is of interest to survey the signals to which the installed static meters are exposed to in realistic (on-site) conditions. Such a survey was performed in [10], which showed the existence of high current slopes at LV customer terminals and thus the relevance of previously performed lab experiments. Further examples of such representative situations are LV distribution networks connected to photovoltaic (PV) installations and electric vehicle (EV) charging stations. An EV charging station was already investigated and the results were reported in [11].

For instance, Fig. 1 shows a discrepancy between the generated power by a PV installation (area below the solid black line), the consumed power of the premises (red area combined), and the drawn power from the grid (red area). From the consumption data it is clear that at some moments, in between 11.00 and 14.00 hour, power is drawn from the grid, while the PV installation generates enough power to supply the power consumed by the loads in the system.

The power consumption readings were taken from a domestic PV installation located in Catalonia, Spain. For the Spanish consumer this is a problem, because the power that is delivered back to the grid is not refunded. Moreover, it is not clear if the static meter readings plotted in Fig. 1 may be erroneous due to the influence of current waveforms such as those identified in the previous studies.

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Fig. 1: Discrepancy in consumption data from a consumer in Spain. The area below the black line is the power generated by the PV installation, the grey area is the power consumed from the PV installation and the red area is the power drawn from the grid.

In this paper, a case study is developed in the domestic PV installation where the previously mentioned energy metering behaviour was observed. There, a survey of the current waveforms is done in time domain, and the results are analyzed to identify complex waveforms that could be related to metering errors.

The rest of this paper is organized as follows: Section II presents an overview of the interfering current waveforms along with examples taken from laboratory experiments. Then, the methodology used to perform the on-site measurements in this survey is described in Section III. Section IV comprises the on-site measurements results and shows their comparability with waveforms from previous laboratory experiments. Finally, a conclusion is made about the identification of complex waveforms in a domestic PV installation, and this section comments on the relation with respect to the discrepancies found in the consumption data.

II. INTERFERING WAVEFORMS FOR STATIC METERS

The waveforms that have been associated with large deviation in the static energy meters are, in general, non-linear pulsed currents, with a high crest factor, relatively high peak amplitude, and a short rise time (in the microsecond range).

As an example, Fig. 2 shows several current waveforms that are drawn by modern appliances and resulted in EMI and large errors in static energy meters [8]. These waveforms are produced by LED and CFL technology and a water pump, in all cases combined with a commercial of the shelf dimmer. In [8] it is shown that the short rise time has a big influence on the interference cases. The critical interfering current waveforms that are analyzed all have current slopes higher than $0.1 \text{ A}/\mu\text{s}$, and the corresponding critical rise times are in between $2 \mu\text{s}$ and $150 \mu\text{s}$.

From these waveforms multiple different types can be obtained, based on the short rise time of the signal. Those signals with a single rise edge will be referred to as signal type 1, so rise to the maximum value at once, see the blue

Fig. 2: Interfering current waveforms for static energy meters, based on lab experiments [8].

and purple signals in Fig. 2. Alternatively, the signals that have multiple rising edges, creating a superposition of multiple type 1 signals, are referred to as signal type 2, see the yellow and orange signals in Fig. 2.

The complexity and diversity of the interfering waveforms measured during the experiments makes it challenging to develop an univocal model that clearly states its behavior. But, the interfering waveforms that are available from the laboratory experiments can be used to analyze the on-site scenarios.

III. METHODOLOGY

A. Measurement setup

Measurements are performed at the meter connection point of a consumer, and thus measures the complete residential system. This includes the combination of the generated energy by the PV installation and the consumed energy by the loads in the system. The line and neutral current are measured, using flexible current probes model TA325 from Pico Technology, and these were set to measure up to 30 A peak current, and have a frequency range up to 20 kHz. The transducers are connected to a 5444B Picoscope digitizer from the same manufacturer. The Time-Domain EMI Measurement and Processing System (TEMPS) software [12] is controlling the digitizer via a laptop connected to it. The measurement setup is shown in Fig. 3, and Fig. 4 shows the installed measurement setup at the consumers meter connection point.

B. Measurement settings

The current waveforms were monitored during an interval of ten days. The acquired waveforms were analyzed in order to preselect and store only meaningful data. For that purpose, specific triggering settings were used based upon the impulsive interfering waveforms that are known from laboratory experiments. Triggers that are used to detect the signals of interest are amplitude probability distribution (APD)

Fig. 3: Schematic overview of the measurement setup.

Fig. 4: Installed measurement setup at the consumers meter connection point.

[13] and wavelets [14]. The wavelet trigger is a discrete wavelet transform (DWT) using the Daubechies wavelet with two filter coefficients (db2) as mother wavelet. As indicator wavelet coefficient 4 is used, representing the frequency range from 31.25 kHz to 62.5 kHz. This DWT trigger was shown to be a strong indicator for the type of signals to be triggered in this research [14]. Furthermore, a snapshots is made every ten minutes (free-run). In this way, we expect to gather a representative set of waveforms in PV installations.

The measurement time for each triggered acquisition was ten cycles at mains frequency, which is equivalent to 200 ms. The waveform sampling rate was set to 1 MS/s.

IV. RESULTS

In this section the results obtained in course of the on-site measurements at the residential system containing a PV installation are presented. It is important to highlight that, as part of the experiment conditions, there was neither prior knowledge on which appliances were turned-on nor control on how the loads changed over time.

A total of 1253 measurements were triggered during the ten days measurement campaign. The triggered current waveforms can roughly be subdivided into three different classes: typical occurring (in 74% of the cases), harmonic distorted (18%), and transient waveforms (8%). In the first two classes the waveform was triggered by either APD, wavelet, or free-run. In the last class the waveforms were only triggered by

wavelets. It is interesting to note that most of the harmonic distorted waveforms occur during daytime, so when the PV installation is active. Whereas during nighttime a clear 50 Hz component can be seen, and the waveform can be classified as a typical occurring waveform.

The results are correlated to the discrepant consumption data in Fig. 1 and the discrepancy in consumption data from the consumer roughly occurs between 11.00 and 14.00 hour, therefore the data in this period is considered as relevant for this case study and is analyzed hereafter.

Fig. 5: Typically occurring current waveform.

Fig. 6: Amplitude spectrum of a typical occurring current waveform in the frequency range from 0 to 2500 Hz.

A. Typical occurring current waveform

Most of the current waveforms that are observed in this study contain the fundamental frequency clearly, and have higher order frequency components at the top of the sinusoidal wave, Fig. 5 shows five periods of such a waveform. The amplitude spectrum is visualized in Fig. 6, it is shown

in the frequency range until 2500Hz which corresponds to the 50th frequency harmonic. This figure shows a dominant fundamental harmonic at 50Hz, as was also clear from the time-domain plot.

Fig. 7: Filtered version of a typical occurring current waveform.

In order to analyze the impulsive higher order frequency components at the top of the sinusoidal wave, the frequency content below 60Hz is filtered using a high-pass filter during processing of the signal. For the line current waveform the resulting time-domain waveform is shown in Fig. 7. This waveform shows an impulsive behavior which looks similar to the interfering waveforms showed in Section II. Therefore, it is of interest to analyze the rise and fall times of these pulses. The time and corresponding slopes to rise or fall from 10% to 90% of the peak value are determined, as this is a measure for fast rise or fall times in electronics [15]. The highest rising slope found in this signal is $0.01 \text{ A}/\mu\text{s}$, which is a factor ten times lower compared to the critical rising slopes found in the previous found interference cases [8].

B. Harmonic distorted current waveform

Interestingly, also current waveforms occurred that have a high harmonic distortion. An example is shown in Fig. 8, where five periods of the line current are showed. However the waveform looks quite impulsive, the highest slope is $0.01 \text{ A}/\mu\text{s}$, so this is not considered as harmful based on previous interference cases [8]. On the other hand, in this waveform a repetition pattern with a frequency of 50Hz can be recognized, however this is not very clear and a 150Hz component is better visible. This can also be seen in the plot of the amplitude spectrum in Fig. 9. The 150Hz frequency component (or 3rd harmonic) is higher than the fundamental frequency at 50Hz. This shows that the system has a high harmonic distortion and reacts non-linearly. Moreover, this high harmonic distortion could result in static meter errors as was shown before in [2]. And this could possibly be a reason for the observed power consumption discrepancies.

Fig. 8: Harmonic distorted current waveform.

Fig. 9: Amplitude spectrum of a harmonic distorted current waveform in the frequency range from 0 to 2500Hz.

C. Current waveform with a transient

Another current waveform of interest is shown in Fig. 10. In this figure the line current for ten periods of the waveform is shown. This waveform is of interest because of a transient that occurred at 0.025s. For this transient the time and corresponding slope to rise or fall from 10% to 90% of the peak value is calculated. The fall time of the transient is $27 \mu\text{s}$ and the corresponding falling slope is $0.6 \text{ A}/\mu\text{s}$. The rise time of the transient is $38 \mu\text{s}$ and the corresponding rising slope is $0.4 \text{ A}/\mu\text{s}$. These times and slopes have similar values compared to the earlier mentioned critical interfering waveforms for static meters [8].

Fig. 10: Current waveform with a transient.

Fig. 11: Amplitude probability distribution of the analyzed waveforms.

Fig. 12: Wavelet coefficient 4, using db2 as mother wavelet, of the analyzed waveforms.

Although this transient has a quite short rise and fall time, it does not occur often. The transient is only observed in one of the ten periods captured in this event. This is also the case for similar waveforms exhibiting current transients. Therefore, it is questionable if this type of current transient could result in significant misreadings of static energy meters, and if it is a cause of the observed discrepancies.

The waveforms that are analyzed in this section are triggered by either APD or wavelet. The amplitude probability distribution of the analyzed waveforms is shown in Fig. 11. A variation in the distribution is noticeable and a heavy tail distribution can be recognized for the harmonic distorted and transient waveform. This indicates the impulsive nature of these waveforms. From the wavelet coefficient plot in Fig. 12 it is clear that the harmonic distorted and transient waveform exceed the wavelet limit. Whereas the typical waveform does not exceed this limit, and is not considered as impulsive based on wavelets.

This section gives an overview of the signals found in only a small time instance within the measurement interval of several days. However, the signals that are shown resemble the signals that are found in the complete measurement interval, in the rest of the measurement interval no other notable signals are found. Therefore, the analyzed signals give a complete overview of the waveforms that can be found in LV distribution networks using a PV installation.

V. CONCLUSION

During the on-site measurement campaign different kind of complex current waveforms are identified in a domestic PV installation. Most of the captured waveforms show a clear fundamental frequency, and have higher order frequency components, or pulses, at the top of the sine wave. The slope of these pulses is way lower than current pulses found in earlier research resulting in EMI issues. However, also harmonic distorted waveforms that show a higher third order harmonic compared to the fundamental frequency are observed. This shows that the behavior of the system is not nearly linear, and the effect of non-linear effects in modern low-voltage distribution networks is huge. Furthermore, current transients with short rise times in the microsecond range were observed.

The current waveforms showed in this study were captured during discrepancies in the power consumption readings of a consumer. At some moments in time power was drawn from the grid, while the PV installation provided enough power to supply this demand. The analyzed current waveforms may be the cause of these observed discrepancies, because of the pulsating nature of the waveforms, the high harmonic distorted currents, and current transients with short rise and fall times. Therefore, more analysis to identify critical on-site waveforms that cause EMI need to be done for further research.

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