On-site Waveform Characterization at Static Meters
Loaded with Electrical Vehicle Chargers

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Abstract—For assessing the underlying problem behind the static meter misreadings, a measurement technique must be developed for characterizing the currents that static meters are usually exposed to. In previous studies it was shown that misreadings of the static meters occur when impulsive currents are drawn from the net, even with standalone commercial off the shelf equipment. Time domain electromagnetic interference (EMI) measurements create a novel opportunity for analyzing these noisy waveforms and identifying their fundamental parameters. The next step is extending this measurement approach to on-site scenarios in which these kind of waveforms coexist in superposition with other components that are properly measured by the static meter when they occur alone. This especially holds for up and coming technologies like electric vehicle (EV) charging stations. The characterization is intended in the future for describing realistic waveforms that can be used as new standardized type-testing signals, which will be employed to produce novel standards. Time Domain Electromagnetic Interference Measurement and Post-processing System (TEMPS) software is used in conjunction with a low cost baseband digitizer to measure the waveforms of EV chargers on four different lines, that is the three phases (L1, L2, and L3) and the neutral line (N) simultaneously. To distinguish the impulsive nature of the waveforms a statistical approach is performed in the form of an amplitude probability distribution (APD) diagram. Furthermore the multichannel capability of the low cost digitizer is utilized to achieve a frequency range extension by using two probes simultaneously with different frequency ranges.

I. INTRODUCTION

In modern household situations the energy consumption is measured using static energy meters [1], [2], which are called smart meters if a communication link is added. These smart electricity meters are currently widely being deployed by utilities across Europe. Major deviations in some meter readings have been reported in recent studies.

In this regard, it has been shown that significant errors occur when the meters are exposed to interference caused by home appliances. For photo voltaic (PV) systems, errors on the meters were caused by either the active infeed converters [3], [4] or the power drives of fans [5]. In these studies lower readings of the meters were encountered. Higher energy meter readings were also found when having pulsed currents. In the latest study energy reading deviations between -61\% and +2675\% were found when using a standard commercial off the shelf available water pump [6].

Considering energy meters are being deployed across Europe, it is important to determine the actual extent of the problem described above. In fact, a joint task force of Universities and National Metrology Institutes across five European countries, namely, Czech Republic, Norway, The Netherlands, Spain and the United Kingdom is working towards a more complete understanding of the reported energy metering error problem as part of the MeterEMI European research project [7]. The main objective of this project is to develop new standards to analyze the performance of the smart meters with the identified critical waveforms.

Therefore, the first important task is to perform on-site interference measurements at a representative set of static meter installations and electrical products. In that sense, one of the selected test sites are the Electrical Vehicles (EV) Charging Stations. This is because of the rising number of EV in Europe points to the proliferation of EV charging stations, which in turn might be associated to an increase in conducted Electromagnetic Interference (EMI) of impulsive behaviour.

Subsequently, a measurement technique must be developed for characterizing the waveforms which static meters are typically exposed in operando. Previously, baseband digitizers and time domain EMI measurements have been used to evaluate conducted and radiated emissions on-site in complex scenarios such as fixed installations and railway applications [8], [9]. On this subject, analyzing noisy waveforms and identifying their fundamental parameters, like their di/dt, based on time domain EMI measurements offers a novel turnaround that is suitable for addressing power quality concerns under an approach formerly validated in the field of electromagnetic compatibility.

Finally, the former waveform characterization is intended to distinguish a set of parameters that describe realistic current waveforms that can be used as new standardized type-testing signals.

This paper starts off with an elaboration on the methodology behind the waveform characterization in section II, where the focus lies on the TEMPS software and the statistical approach used to identify the impulsive nature of the waveforms. This is then followed up by a short section about the measurement equipment in section III, after which the results of these measurements are presented in section IV. In section V a conclusion to the paper is given.
II. WAVEFORM CHARACTERIZATION

Previously, static meter misreadings have been shown to exist, even with commercial off the shelf equipment. Experiments suggest that waveforms with a high di/dt seem to cause the misreading of static meters [10], [11]. One possible reason could be the saturation of the current sensing element of static meters due to impulsive interferences, resulting into significant measurement errors. Consequently, the static meter measures more energy than what is actually being consumed.

To get a clear understanding of the problem at hand, first, waveforms that static meters are usually exposed to should be captured and then characterized. To capture such impulsive interferences, a high resolution (high dynamic range) and a high sample rate (high frequency) is required. Once captured, one should be able to identify the critical parameters that distinguishes the waveforms that cause the misreadings of static meters.

For instance, an experiment showed that the impulsive current of a standalone water pump causes faulty readings in static meters. In Fig. 1 the current waveforms for different settings of the water pump are plotted against the voltage. In [11] it was shown that as the phase with respect to the voltage, of the impulsive waveforms, increases, the errors in the static meter readings also increase. The figure presents the currents measured with a base band digitizer which allowed retaining the complete magnitude and phase information, which was fundamental for characterizing such a representative waveform. Therefore, the next step is extending this measurement approach to on-site scenarios in which these kind of waveforms coexist in superposition with other components that are properly measured by the static meters when they are alone.

A. Time Domain Electromagnetic Interference Measurement and Post-processing System

Waveform measurements should be carried out in the time domain. For that purpose, a Time Domain Electromagnetic Interference Measurement and Post-processing System (TEMPS) was used. In several preceding publications, the advantages of TEMPS were evidenced for on-site EMI assessments in comparison with frequency-swept receivers [12], [13]. In summary, TEMPS allows to reduce the effective measurement time, perform full-spectrum measurements, parallelize acquisitions through multi-channel capabilities. Moreover, other advanced processing functions are possible because time domain data is available.

Furthermore, the advantages above allow improved EMI measurement insights such as the agile identification of characteristic emissions spectrum associated to changes in the EUT’s functional modes and the mitigation of the influence of background noise variations in EMI measurements. Also, since the measurement system hardware consists of a USB powered oscilloscope connected to a general purpose laptop, there are several other practical benefits. For instance, the measurement system is battery powered (it does not requires to be plugged to the mains network), it is more robust to DC and transients and it is a cost effective software based solution that relies on inexpensive hardware. Finally, the possibility of obtaining at the same time the frequency and the time data permits us to compute statistical data of the measured signals that can be especially significant for impulsive noise identification.

A basic block diagram of TEMPS is shown in Fig. 2. TEMPS transducers are the typical ones of EMI testing, including the LISN, antennas, RF current probes, voltage probes, near E-field and/or H-field probes, etc. Moreover, other compatible oscilloscope probes, such as current clamps, can be used as well. Regarding the data processing, TEMPS optimizes the oversampling rate and dwell time for maximizing the dynamic range and the EMI measurement accuracy as a function of the memory depth. Thereafter, windowing and spectral estimation, based on Welch’s method according to the desired equivalent resolution bandwidth, are performed to obtain the results in the frequency domain in compliance with the standard weighting detectors.

B. Amplitude Probability Distribution measuring function

As time domain data is available with TEMPS, it is used to characterize the waveforms with a statistical approach. With the aim to identify the possible impulsive waveforms that can produce errors to the static meters, the Amplitude Probability Distribution (APD) of the time domain measured data is computed. APD has been employed in previous publications to compute and evaluate the degradation caused to digital
TABLE I: Measurement specifications

<table>
<thead>
<tr>
<th>Reference</th>
<th>Car type</th>
<th>Charging State</th>
<th>sample rate</th>
<th>Dwell time</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Type 1</td>
<td>No Charging</td>
<td>500 kSa/s</td>
<td>200 ms</td>
</tr>
<tr>
<td>M2</td>
<td>Type 1</td>
<td>Charging</td>
<td>500 kSa/s</td>
<td>200 ms</td>
</tr>
<tr>
<td>M3</td>
<td>Type 2</td>
<td>Charging</td>
<td>500 kSa/s</td>
<td>200 ms</td>
</tr>
<tr>
<td>M4</td>
<td>Type 1</td>
<td>Charging</td>
<td>62.5 MSa/s</td>
<td>30 ms</td>
</tr>
</tbody>
</table>

IV. RESULTS

In this section, on-site measurement results are shown for the different measured cases defined in Table I, where different vehicles are charging at different times at the same EV charging station. The waveform characterization was done in presence of an EV charging its batteries at the same time that other unknown devices were consuming current. I.e., the measured waveforms are the superposition of the current consumption produced by the unknown devices and the EV charger. Such results of the superposition are important for characterizing the waveforms which static meters are typically exposed to.

A. Time Domain Measurements

In Fig. 4 the currents for the three-phases and the neutral are given when no car is charging, referred to as M1. A clearly impulsive current can be identified when looking at the time domain signal at the different phases. As the vehicle is not charging its batteries, the measurement is the characterization of the current produced by the unknown devices, which are connected at the same network as the EV charger. It is important to highlight that in L1 the 50 Hz component has an amplitude of around 3.5 A, while the spikes raise the signal up to around 5 A. Otherwise, in L3, the 50 Hz component has the same value but the impulsive current reaches a value higher than 6.5 A. Therefore, it is important to emphasize the importance of obtaining the data simultaneously from all the phases, as relatively high amplitude variations exist between the different lines.

According to the levels measured, it seems that the measured impulsive currents will not cause saturation or errors in this situation due to the overall relatively low amplitudes. Nevertheless, if these relatively low-amplitude impulsive currents occur with higher amplitudes, they could be able to cause errors to the smart meters. This impulsive nature, within the superposition situations where 50 Hz currents are present, is harder to measure and identify. Therefore it is essential to use the measurement technique presented in this paper to measure these scenarios which are the most plausible to exist at on-site locations.

In Fig. 5, the waveform obtained when charging a car, M2 according to Table I, is plotted. This measurement is performed within a minute after the results shown in Fig. 4, so it is expected that the other devices connected at the network will still be present. When looking at results of the measurement M2 the impulsive behavior of the net is still present on top of the higher charging signal. Hence, this is an example of the previously mentioned superposition,
Fig. 4: Time domain data of not charging (M1)

Fig. 5: Time domain data of charging an EV (M2)

Fig. 6: Time domain data of charging an EV (M3)

where the extra current spikes on top of the charging current are even harder to identify and measure. Nevertheless, the available time-domain data also enables us to compute the empirical mode decomposition, which is capable of splitting the impulsive current from the main 50 Hz component [17]. Afterwards the impulsive component can be identified by applying the APD diagram.

On the other hand, when looking at Fig. 6, the impulsive noise behavior is not observed at the high amplitude of the main 50 Hz current. It is important to note that the measurement in Fig. 5 and Fig. 6 were measured with a two-hour difference, meaning that the unknown devices causing the impulsive behavior at the network, shown in Fig. 4, are not present anymore at this time.

Even though the impulsive nature is clearly recognizable from some of the results as in Fig. 4, the time domain data is not suitable for an automatic triggering function. The reason is that the values of the current are constantly changing over time according to the consumption of the different devices connected to the network and the status of the EV batteries. With the aim to obtain more information from the measured scenarios, that can help us to identify critical current waveforms, a statistical approach is performed in the next section.

B. Amplitude Probability Distribution

With the purpose to evaluate whether we are capable to distinguish scenarios where impulsive currents are present, we use the previously acquired time domain data. We analyze the statistics of the time domain data by computing the APD diagram when an EV is charging or not. In Fig. 7, we observe the APD diagram when the EV is charging in red color and in blue color when the charger is not charging the batteries of the EV. A clear variation in the shape of the APD diagram is noticeable for the M1. When the impulsive current is not clearly identified in the time domain, an APD diagram...
From the APD diagram, we can easily identify measured data where impulsive currents can cause errors to the smart-meter readings. Therefore, it is recommended to employ APD diagrams to trigger measurements to detect impulsive currents. For M2 an APD diagram could be used after the empirical mode decomposition.

C. Frequency Range Extension

As it has been stated before, with TEMPS it is feasible to measure an extended frequency range using different current probes synchronously. In Fig. 8, the spectral content of the current when a vehicle is charging is observed. With the low-frequency probe, we can compute the spectrum from DC up to 20 kHz, while with the RF probe we can compute the spectrum from 10 kHz up to 30 MHz. At frequencies between 10 kHz and 20 kHz, we observe an overlapping response of the current probes, obtaining the same values at the spectral domain. Moreover, this extension at the observable frequency range shows data up to 30 MHz, which can be used to obtain more information from the impulsive currents that can produce reading errors of the static meters.

V. Conclusion

With the use of TEMPS in conjunction with a digitizer the waveforms of an EV charger with two different types of cars have been measured. The data obtained measuring the three phases (L1, L2, and L3) and the neutral line (N) simultaneously, with four identical current probes, can be used in later research to test possible misreadings of static meters. As it can be stated from the results, since relatively high amplitude variations can exist between the different lines, it is important to highlight the capability of TEMPS to obtain the data synchronously. Moreover, the methodology proposed in this paper is capable of measuring and identifying impulsive currents at on-site scenarios, where superposition of different devices can occur. This superposition is the case when technologies like EV charging stations produce a relatively high 50 Hz component while there are other sources producing impulsive currents at the same time. For this reason, it is important to use a methodology like APD, which is capable of still identifying meaningful impulsive currents. Finally, due to the multichannel capabilities of the digitizer a frequency extension has also been achieved by using two probes with different frequency ranges. The extended measurement at the frequency domain allows the user to observe possible effects at the high frequency range and at the same time have a good accuracy at the main components of the current consumption.

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