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THE USE OF SAMPLED VALUES FOR POWER TRANSFER ANALYSIS AT DISTRIBUTION LEVEL

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Abstract: The expansion of renewable energy sources, battery energy storage systems, electric vehicles charging stations, power electronics interfaced loads and the integration of microgrids operating in connected or island modes have caused voltage and current signals to be distorted from their conventional sinusoidal model [1]. The transient phenomena over short timeframes (less than 1s) cannot be detected by conventional means of measurement devices, which focuses more on information concentrators of electric quantities, rather than analyzing the entire variation of the signal. Therefore, new methods of measuring and modelling energy transfer are needed to understand these phenomena in detail and to adapt electric networks to the new requirements of the energy transition. This paper proposes a new method for monitoring the deviation of the current signal from the sinusoidal model at low voltage distribution level through sampled values [2]. A system composed of a sampling unit and an edge computing capacity is proposed to receive the aggregated current signal from multiple loads and analyze its deviation from the sinusoidal model over a predefined timeframe. The deviation from the sinusoidal model is quantified using two statistical indicators, Root Mean Square Deviation (RMSD) and Goodness of Fit (GoF), which provide a different view about the deviation of the signal. This way, the Distribution System Operator (DSO) can receive aggregated information about the degree of distortion of current signals in a system node.

Keywords: Sampled values, current signal deviation from sinusoidal model, high reporting rate measurements

INTRODUCTION

In recent decades, power systems have undergone significant transformations, shifting from a centralized model based on conventional energy producers to an increasingly decentralized landscape. The growing use of renewable energy sources, such as photovoltaic panels and wind turbines, along with the massive integration of loads and other electronic devices connected through static converters, has radically changed the way energy is generated, transfered, and used. Additionally, the emergence of new applications, such as electric vehicles charging stations, energy storage systems, heat pumps, data centers, and so on introduces new challenges to distribution networks, leading to significant deviations of current signals from the traditional sinusoidal model.

These fundamental changes put increasing pressure on traditional monitoring and energy transfer analysis methods, which wrongly assumes the current signal as an ideal sinusoid and therefore exclude the consequences that this deformation of signal has on the state of health of equipment and devices, on the energy losses, on the opperation of protection and automation systems and even on the stability of power systems. In the current context, where distribution networks must respond quickly to voltage and current fluctuations caused by distributed sources and dynamic loads, conventional measurement methods are no longer sufficient. Traditional measurement systems based on RMS and average values over relative long time periods (over 1 min) cannot capture the fast and complex behavior of modern grids. Moreover, as these new real-time (less than 1 s) applications are integrated into the distribution network, the necessary data flow for their management and operations rise drastically. This increasing data flow can no longer be efficiently managed in a centralized manner, requiring a shift towards decentralized and distributed processing methods. The traditional approach of collecting and analyzing data in a central location is becoming impractical due to latency and storage constraints and the need for immediate response in dynamic grid conditions [3].

To address these challenges, it is essential to adopt measurement and monitoring methods that enable real-time (less than 1 s) and decentralized analysis of power flow at the distribution level. The use of sampled values represents a promising solution, as it provides high temporal resolution and allows for precise monitoring of electrical signals in the network. By utilizing these techniques, system operators can gain more detailed

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and faster insights into the grid's state, facilitating the optimization of power flows and ensuring the stable and efficient operation of the modern power system.

1. EXPERIMENTAL SETUP

The experimental setup consists of an ELSPEC G4430 power quality analyzer [4], a computer with PQSCADA Sapphire software installed [5], a Rasberry PI 3 unit with Linux operating system [6], and various electrical loads whose current signals were studied: laptop charger, 12 V vehicle battery, power drill, refrigerator, and microwave oven. Through experimental setup in laboratory conditions, the aim was to replicate the process of measurement information and processing, that can be performed at a low voltage distribution substation (Figure 1).

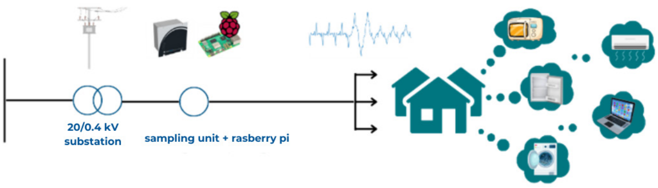

Figure 1: Schematical representation of the on-site measurement infrastructure replicated in the laboratory

Thus, the ELSPEC G4430 power quality analyzer acts as a sampling unit, while the Raspberry Pi is used as an edge computing solution for analyzing the distortion of the current signal at the transformer level. PQSCADA Sapphire software was used as the primary interface for data visualization and pre-processing. The software enabled monitoring of recorded signals, facilitating the identification of power quality events and trends. In Figure 2, the laboratory experimental setup is presented with highlighted elements.

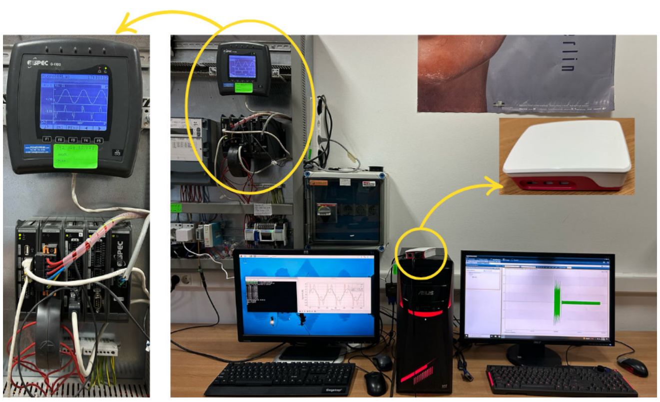

Figure 2: Experimental setup consisting of: ELSPEC G4430, Rasberry Pi 5 and its human machine interface, and PC with PQSCADA Sapphire software

2. METHODOLOGY

In this study, the experimental setup was used to analyze the current signal deviations from the sinusoidal model under different load conditions. The current signal was sampled for various individual loads (laptop charger, 12 V vehicle battery, power drill, refrigerator, and microwave oven), as well as for the aggregated current signal when all loads were operating simultaneously. The sampling was conducted at a frequency of 51.2 kHz (1024 samples per cycle) using the ELSPEC G4430 power quality analyzer. The recorded data were accessed through the PQSCADA Sapphire application, which allowed us to study different signal characteristics and subsequently export the data for further analysis.

The main objective of this process was to determine the deviation of the current signal from the ideal sinusoidal waveform. To achieve this, a script was implemented on the Raspberry Pi unit, designed to read data files and compute two specific indicators that highlight the signal distortion relative to the sinusoidal model: Root Mean Square Deviation (RMSD) and Goodness of Fit (GoF). Additionally, the algorithm provides a graphical representation of the deviation (Figure 3). The sinusoidal model corresponding to the distorted current signal is represented by the fundamental component of the signal, whose parameters were determined by applying the Discrete-Fourier-Transform (DFT) analysis and then computed the ideal sinusoidal signal. The timeframe for computing RMSD and GoF indices, and consequently the reporting rate at which the script returns the computed values, could be adjusted as needed, allowing for flexible analysis of signal distortion over varying timeframes.

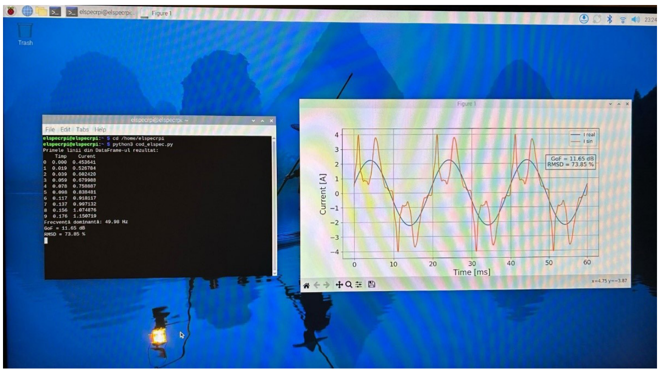

Figure 3: Rasberry PI 3 interface

The following equations were used to determine the deviation of the current signal from the sinusoidal model using $RMSD$ and GoF indices:

$$GoF = 20\lg \frac{A}{\sqrt{\frac{1}{N}\sum_{k-1}^{N}\left(w_k - v_k\right)^2}} [dB] \tag{1}$$

$$RMSD = 100 \frac{\sqrt{\frac{1}{N}\sum_{k-1}^{N}\left(w_k - v_k\right)^2}}{\frac{1}{N}\sum_{k-1}^{N}\left|v_k\right|} [\%] \tag{2}$$

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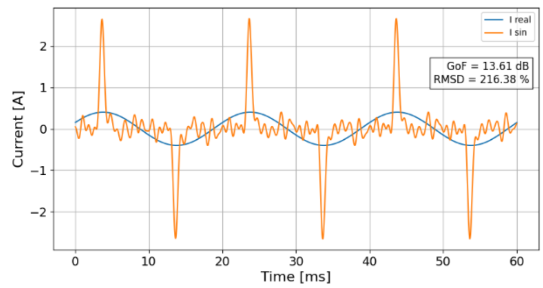
For the above equations, A represents the amplitude of the sinusoidal signal, N represents the total number of samples, k represents the sample index, w_k represents the k-sample value of the distorted signal, and v_k represents the k-sample value of the sinusoidal signal.

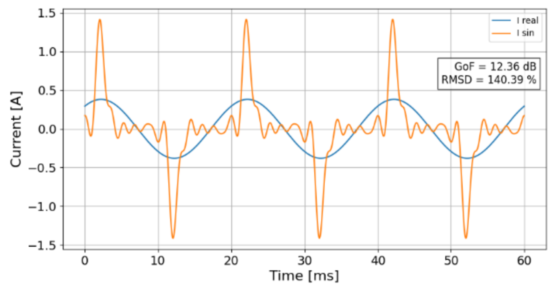
GoF indicator is defined as the normalized reciprocal value of the fit standard error [7] and evaluates how well the current signal fits the sinusoidal model [8]. On the other hand, $RMSD$ quantifies the average difference between the two signals and represents a measure of how much the current signal deviates from the sinusoidal model [9].

3. RESULTS AND DISCUSSION

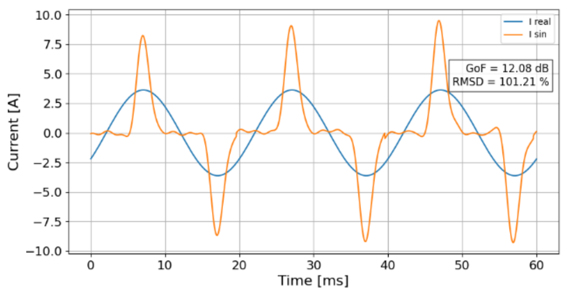
Below are presented the graphical representation of the deviation of current signals from the sinusoidal model over 3 periods together with the values for GoF and $RMSD$. The current profiles were sampled at a frequency of 51.2 kHz (corresponding to 1024 samples per cycle) using the ELSPEC G4430 power quality analyzer and correspond to different loads (laptop charger, 12 V vehicle battery, power drill, refrigerator, and microwave oven) functioning individually and also simultaneously.



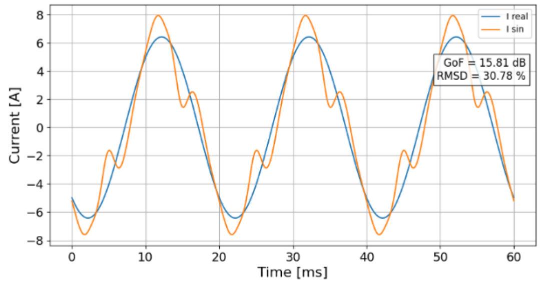
a)



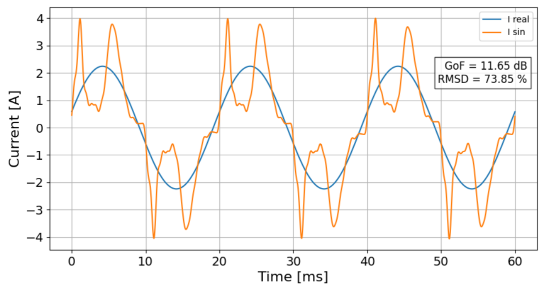
b)



c)



d)



e)

Figure 4: Comparasion between the real current signal and its sinusoidal correspondand model for: a) laptop charger; b) 12 V vehicle battery; c) power drill; d) microwave oven; e) aggregated vehicle battery + laptop charger + power drill + refrigerator)

In the table below are presented and evaluated the values obtained for GoF and $RMSD$ indicators for the current profiles above:

Table I: $RMSD$ and GoF values for the analyzed current signals

Load	RMSD [%]	GoF [dB]
laptop charger	216.4	13.6
12 V vehicle battery	140.4	12.4
power drill	101.2	12.1
microwave oven	30.8	15.8
laptop charger + 12 V vehicle battery + power drill + refrigerator	73.9	11.7

Based on the results, it can be observed that the loads under analysis have a significant impact on the distortion of the current signal compared to the sinusoidal model. The highest levels of distortion were recorded for the laptop charger (Figure 4-a) and the 12V vehicle battery (Figure 4-b). These results are proof that new measurement methods at low voltage distribution level are needed in the context of high-share usage of modern loads (interfaced with power electronics) connected to the network and especially of electric vehicles charging stations.

In contrast, the current profile corresponding to the microwave oven (Figure 4-d) exhibits a waveform that is closer to the sinusoidal shape when analyzed on a time scale of tens of milliseconds. However, when the time scale is extended to the order of hundreds of milliseconds, it becomes evident that the current profiles of the microwave oven undergo significant variations both in amplitude and in signal profile (Figure 5). This suggests that while this kind of appliance may appear to have a relatively stable waveform over short periods, their behavior introduces notable deviations that must be considered in power quality assessments [10].

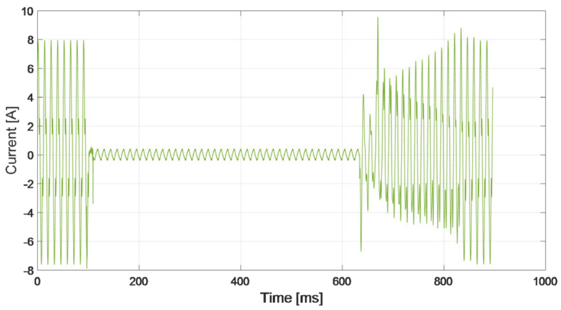


Figure 5: Current profile of microwave oven during 1 s

4. CONCLUSION

The objective of this study was to propose a first stage of novel method for monitoring and analysis of the energy transfer at the distribution level using the deviation of the current signal from the sinusoidal model. To achieve this, a laboratory setup was in place consisting of a sampling unit represented by an ELSPEC G4430 power quality analyzer, a PC with the PQSCADA Sapphire application installed and a Raspberry Pi 3 unit as an edge computing solution for calculating the GoF and RMSD indicators. The setup was used to analyze various loads based on their specific current signal under operation.

The results demonstrated that the analyzed loads exhibit current profiles with significant deviations from the sinusoidal waveform and/or large and abrupt amplitude variations. These phenomena cannot be accurately identified using traditional measurement techniques. Therefore, this edge computing-based solution for monitoring and analyzing the energy transfer in the distribution network paves the way towards new measurement methods tailored to present and future needs.

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BIOGRAPHY

Radu Opreanu works as Protection and Automation System Engineer at CNTEE Transelectrica SA, Bucharest Branch. He graduated with a Bachelor’s and a Master’s degree from the Faculty of Energy Engineering, Power System Engineering Specialization at National University of Science and Technology POLITEHNICA Bucharest. He is currently PhD student at Faculty of Electrical Engineering with his research focused on real-time estimation methods for power system inertia.

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Dr. Radu Plămănescu holds a PhD on synchronized measurements and high-reporting rate PQ equipment to develop new protection and control algorithms for microgrids, from University POLITEHNICA of Bucharest. Radu is an Assistant Professor at UNST Politehnica Bucharest with more than 7 years of experience as Research and Innovation Expert (as part of MicroDERLab Group at University “Politehnica” of Bucharest, Politecnico di Torino, Dipartamento di Energia, Torino, Italy, G2Elab, INP Grenoble, France, CEZ Group, Romania and Institute for Nuclear Research Pitesti). Radu also spend a leave in 2019 at Colorado State University as a Fulbright Visiting Scholar. He is also an IEEE (the Institute of Electronic and Electric Engineers), member (since 2016), also member of the IEEE Instrumentation and Measurement Society and member of the IEEE Power & Energy Society, and member of the Steering Committee for the Microgrid Symposium Series.