

Article



Demand-Side Management for Improvement of the Power Quality in Smart Homes Using Non-Intrusive Identification of Appliance Usage Patterns with the True Power Factor

Hari Prasad Devarapalli ^{1,2,*}, Venkata Samba Sesha Siva Sarma Dhanikonda ², and Sitarama Brahmam Gunturi ³

- ¹ Corporate Industry Forums and Standards Cell, A Unit of Corporate RnI, Tata Consultancy Services, Hyderabad T.S 500019, India
- ² Department of Electrical Engineering, National Institute of Technology Warangal, Warangal T.S 506004, India; sivasarma@gmail.com
- ³ Component Engineering Group, Tata Consultancy Services, Hyderabad T.S 500019, India; sitaramabrahmam.gunturi@tcs.com
- * Correspondence: hdevarapalli@ieee.org; Tel.: +91-94904-37035

Abstract: The proliferation of low-power consumer electronic appliances (LPCEAs) is on the rise in smart homes in order to save energy. On the flip side, the current harmonics induced due to these LPCEAs pollute low-voltage distribution systems' (LVDSs') supplies, leading to a poor power factor (PF). Further, the energy meters in an LVDS do not measure both the total harmonic distortion (THD) of the current and the PF, resulting in inaccurate billing for energy consumption. In addition, this impacts the useful lifetime of LPCEAs. A PF that takes the harmonic distortion into account is called the true power factor (TPF). It is imperative to measure it accurately. This article measures the TPF using a four-term minimal sidelobe cosine-windowed enhanced dual-spectrum line interpolated Fast Fourier Transform (FFT). The proposed method was used to measure the TPF with a National Instruments cRIO-9082 real-time (RT) system, and four different LPCEAs in a smart home were considered. The RT results exhibited that the TPF uniquely identified each usage pattern of the LPCEAs and could use them to improve the TPF by suggesting an alternative usage pattern to the consumer. A positive response behavior on the part of the consumer that is in their interest can improve the power quality in a demand-side management application.

Keywords: demand-side management; low-power consumer electronic appliances; low-voltage distribution system; non-intrusive identification of appliance usage patterns; power quality; smart home; true power factor; total harmonic distortion

1. Introduction

Clean and affordable energy—Goal no. 7 of United Nations' Sustainable Development Goals (SDGs)—is targeted for achievement by 2030. Demand-side management (DSM) plays a vital role in accomplishing this goal [1]. Clean energy is normally interpreted as green energy that is generated with renewable non-fossil fuels to reduce climate pollution. Interestingly, in its policies, the Government of India has articulated very well that both green energy and electrical power quality (PQ) are essential and need to be in balance without any ambiguity [2,3]. In this article, the authors consider the latter part of the interpretation of clean electrical energy.

1.1. Perspectives on Demand-Side Management

Consumers must be cognizant of unnecessary consumption and conscious of not polluting the power supply. To achieve the latter part of SDG 7—affordable energy—a wide range of technologies, such as compact fluorescent lamps (CFLs) and light-emitting diode



Citation: Devarapalli, H.P.; Dhanikonda, V.S.S.S.; Gunturi, S.B. Demand-Side Management for Improvement of the Power Quality in Smart Homes Using Non-Intrusive Identification of Appliance Usage Patterns with the True Power Factor. *Energies* 2021, 14, 4837. https://doi.org/10.3390/en14164837

Academic Editor: Surender Reddy Salkuti

Received: 13 July 2021 Accepted: 6 August 2021 Published: 8 August 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). (LED) lamps, have been deployed on a large scale by all nations across the globe, including India. This has led to indiscriminatory usage of consumer electronic appliances (smart TVs, smart phones, smart fridges, etc.) and computers with SMPS. This pervasive usage of low-power consumer electronic appliances (LPCEAs) is defeating the very purpose of SDG 7—clean energy with quality electric power. The traditional approach to DSM is primarily focused on energy conservation, and improvements in the true power factor (TPF) could effectively be achieved by way of a human-in-the-loop DSM [4]. The purpose of this paper is to ensure affordable power and to ensure that LPCEAs do not cause issues of poor PQ in low-voltage distribution system (LVDSs).

The PQ in an LVDS is multi-dimensional and includes both the current harmonics and the power factor (PF). The ill effects of current harmonics have been discussed in detail [5–7]. While current harmonics themselves are not healthy, they also result in a poor PF due to the bidirectional exchange of reactive power between the source and the load. The current harmonics and the poor PF negatively affect the accuracy of electricity meters and the PQ of the distribution system's supply [8–10]. The existing smart energy meters in our distribution systems are not designed to measure the TPF and reactive power; hence, they are not billed to the consumers. So, the need to bill consumers for poor PQ caused by their behavior is not recognized, and hence, the requirement of compensation of reactive power has gone unnoticed [11–13]. Therefore, the authors feel strongly that the DSM for the PQ is the need of the hour, and serious attention is required in order to measure and address issues of poor PQ in LVDSs and to meet SDG 7—affordable, clean, and quality energy for all.

1.2. Non-Intrusive Monitoring of the Usage of Appliances

While homes use several electric and electronic appliances, the energy consumption is measured at a single point of common coupling (PCC) of the supply mains from the distribution system. Several techniques have been explored by various researchers since G.W. Hart explored the idea of the disaggregation of electric loads and identified the usage of individual appliances in order to prompt responsible energy consumption and healthy consumer behavior [14]. A cooperative response from consumers to the insights from this critical objective analysis will help in achieving the energy conservation targets set by the United Nations. Hart's work was performed at a time when energy availability was not in abundance. With the advent of energy-efficient smart appliances, the average energy consumption has come down significantly. Yang H. et al. articulated in detail that the DSM in smart homes is focused on the PQ issues introduced by smart appliances, including power savers, in addition to energy conservation [15]. Due to harmonics, the displacement PF is not equal to the TPF. Because household appliances are considered to have low-power consumer electronic loads, their effect on the PQ will be significant when too many of them are in use [10]. The effects of harmonics on the displacement PF and %THD are not additive, so it is not right to ignore the effects of harmonic distortion when metering energy for both consumers and utilities [13].

A typical home uses multiple appliances at different times and for different durations, thus forming different load patterns; their usage is uniform neither over a day nor over a season. As a household might have numerous load points, there are unknown loads that could be connected in open sockets, and several load patterns could possibly reach an unwieldy number (factorial N; N is the number of loads, and some of the loads are unknown), but in practice, they would usually follow a very small number of appliance usage patterns. It is not common for a modern household to use single loads at any point in time [5]. Therefore, it is clear that the focus of DSM should be on appliance usage patterns (a combination of loads), and the usage of individual loads becomes irrelevant. The recommendation to the consumer should be to switch from an appliance usage pattern with a low PQ to an appliance usage pattern with a better PQ, thereby ensuring clean power in the LVDS.

1.3. Feature Selection for NILM

The harmonic interactions among several nonlinear appliances change the PQ indexes significantly. For instance, the PF, distortion factor (DF), and current THD are directly impacted; these indexes influence the billing of the electrical energy depending on the appliance usage patterns. Therefore, from the perspective of PQ, a combination of appliances that improve the PQ can determine the amount to be billed. Two different experiences were cited: One suggested the use of fundamental signals (displacement factor) to calculate the surplus of reactive power in electrical grids. Another suggested the use of the TPF. This fact shows that this work is important for the industry in the discussion of the problems caused by nonlinear appliances on electrical energy billing systems in order to rectify PQ issues [12].

R. Gopinath et al. researched the development of robust NILM techniques for the effective management of the energy of appliances in order to support reliable and sustainable DSM [16]. A significant improvement in the system efficiency can be realized if the improvement of the PF and the elimination of harmonics can be applied in the whole network [17].

Therefore, the authors proposed the use of aggregated measures of the PQ, such as the percentage of the total harmonic distortion (THD) and the TPF, in order to understand the appliance usage patterns and for consumers to adapt to PQ-sensitive behaviors. Devarapalli et al. discussed how the percentage THD can be applied in order to disaggregate load patterns and to suggest appropriate load patterns, thus reducing the harmonic pollution produced in the system [5].

This article presents the use of the TPF as a unique feature for identifying appliance usage patterns and for helping consumers by providing them with insights in order to switch from low-PF appliance usage patterns to high-PF appliance usage patterns and to become responsible consumers. The schematic of the non-intrusive identification of appliance usage patterns in smart homes with the TPF is depicted in Figure 1.



Figure 1. Schematic of demand-side management with the non-intrusive identification of appliance usage patterns in smart homes with the TPF.

1.4. The Major Contributions and Organization of the Article

- TPF measurement of real-world LPCEAs as per the IEEE 1459-2010 standard [18] by using the four-term minimal sidelobe cosine window (4MSCW)-based enhanced dual-spectrum line interpolated FFT (EDSLIFFT).
- Development of a virtual instrumentation-based measurement system for TPF measurements.
- Recommendation of appliance patterns for improvement of the TPF and DSM by using a lookup table in order to improve the utilization indexes of consumers.

This paper is organized into five sections; Section 2 describes the TPF measurement method. Section 3 elaborates on the real-time measurement of the TPF with the 4MCSWbased EDSLIFFT in the NI-cRIO (compact reconfigurable input–output)-based virtual instrumentation environment for various combinations of LPCEAs. Section 4 deliberates on the results and demonstrates that the TPF is a reliable single feature for identifying appliances' consumption patterns. Section 5 discusses the insights of the results, and Section 6 concludes with a summary of the proposed research work.

2. Measurement of the TPF Using the Four-Term MSCW-Based EDSLIFFT

In this section, the measurement of the TPF by using the 4-term MSCW-based ED-SLIFFT. The 4-term MSCW-based EDSLIFFT was proposed in [19] for the accurate estimation of the harmonics of LPCEAs. In this article, it is further extended for the computation of the TPF as per the IEEE 1459-2010 standard [18].

2.1. Overview of the Four-Term MSCW

Given the better main lobe, sidelobe, and sidelobe roll-off rate of the 4MSCW and the accuracy of the EDSLIFFT algorithm with the RT current harmonic signal analysis [19], they are further extended to measure the TPF in real time. Initially, the 4-term MSCW-based EDSLIFFT was used to measure the spectral amplitude and phase of an LPCEA's harmonic current signal. A brief overview of the 4MSCW is given in the following.

The discrete-time 4-term MSCW is expressed as:

$$w(n) = \sum_{m=0}^{M-1} (-1)^h a_h \cos\left(\frac{2\pi mn}{N}\right) \text{ for } n = 0, \ 1, \ \dots, \ N-1$$
(1)

where *n* denotes the sample index, *N* denotes the total number of samples, *m* represents the window item index, *M* is the maximum window item number, and a_h denotes the window coefficients.

The spectral window corresponding to the 4MSCW is written as:

$$W(n) = \sum_{m=0}^{M-1} \frac{a_h}{2} \left[e^{\frac{-j\pi(n-m)(N-1)}{N}} \frac{\sin(n-m)\pi}{\sin\left(\frac{(n-m)\pi}{N}\right)} + e^{\frac{-j\pi(n+m)(N-1)}{N}} \frac{\sin(n+m)\pi}{\sin\left(\frac{(n+m)\pi}{N}\right)} \right]$$
(2)
for $n = 0, 1, ..., N-1$

2.2. Processing with the 4MSCW-Based EDSLIFFT Algorithm

Generally, in digital signal processing, the harmonic signal is represented as [20]:

$$x(nT_s) = x(t) = \sum_{h=1}^{hmax} A_h \sin(2\pi f_h nT_s + \varphi_h)$$
 where $n = 0, 1, ..., N - 1$ (3)

where the signal amplitude is denoted as A_h , and the signal frequency and phase are represented by f_h and φ_h . The harmonic signal sampling time is denoted as T_s . The harmonic order is denoted as h, which starts from 1 and reaches the maximum harmonic order of *hmax*. The traditional FFT has the issue of spectral leakage due to non-synchronous sampling because of the unstable fundamental frequency. To mitigate the spectral leakage effect, the signal is weighted by window functions.

The mathematical representation of the windowed sample signal under non-synchronous sampling is given as:

$$X(k) = \sum_{h=1}^{hmax} \frac{A_h}{2j} \left[e^{j\varphi_h} W(k - k_h) - e^{j\varphi_h} W(k + k_h) \right]$$
(4)

where k = 0, 1, ..., (N - 1), W indicates the 4-term MSCW function, and k_h denotes the division factor of the signal frequency and the frequency resolution, which is expressed as:

$$k_h = \frac{f_h N}{f_s} = l_h + \xi_h \tag{5}$$

where f_s is the sampling frequency of the harmonic signal, l_h is an integer value, and ξ_h ($0 \le \xi_h \le 1$) is the fractional part caused by the non-synchronous sampling. The spectral line corresponding to the h_{th} harmonic lies between the two highest spectral lines—

explicitly, either the $l_{eng}{}^{th}$ and the $(l_h + 1)^{th}$ or the $l_h{}^{th}$ and the $(l_h - 1)^{th}$. The value of l_h is determined by the peak location index search algorithm, and the fractional part ξ_h is determined by using the EDSLIFFT algorithm, as shown in [19]. The computation process of the EDSLIFFT algorithm using 4MSCW is illustrated in Figure 2.



Figure 2. Computation process of the EDSLIFFT algorithm using 4MSCW.

The frequency spectrum expression used in the EDSLIFFT algorithm is given as follows:

$$X(\xi_h) = \frac{A_h}{2j} \left[e^{j\varphi_h} W(\xi_h - k_h) \right] \text{ for } \xi_h = 0, \ 1, \ \dots, \ N-1$$
 (6)

The two spectral lines represent the h^{th} harmonic amplitude, and they are represented by l_{h1} and l_{h2} (where $l_{h1} = I$, $l_{h2} = I + 1$, $l_{h1} < k_h < l_{h2}$). The peak locations of the harmonic amplitudes are obtained by using the peak location index search method described in [19]. Consider $y_1 = |X(I)|$ and $y_2 = |X(I + 1)|$; then, y_1 and y_2 are given as follows:

$$y_1 = |X(I)| = |A_h| \cdot |W(2\pi(I - k_h)/N|$$
(7)

$$y_2 = |X(I+1)| = |A_h| \cdot |W(2\pi((I+1) - k_h)/N|$$
(8)

The spectral amplitudes are determined with the least-square curve-fitting technique. The symmetrical coefficient α is considered in terms of l_h and k_h as follows:

$$\alpha = k_h - l_{h1} - 0.5 \text{ for } -0.5 \le \alpha \le 0.5 \tag{9}$$

The even spectral lines in EDSLIFFT, y_1 and y_2 , are represented as:

$$y_1 = |X(I)| = |A_h| \cdot |W(2\pi(-\alpha + 0.5)/N|$$
(10)

$$y_2 = |X(I+1)| = |A_h| \cdot |W(2\pi(-\alpha - 0.5)/N|$$
(11)

A symmetrical coefficient β in terms of α is considered in order to calculate the harmonic parameters; the expression of β is as follows:

$$\beta = g(\alpha) = \frac{(y_2 - y_1)}{(y_2 + y_1)} \tag{12}$$

From Equations (10) and (11), β can be represented as:

$$\beta = g(\alpha) = \frac{|W(2\pi(-\alpha - 0.5)/N)| - |W(2\pi(-\alpha + 0.5)/N)|}{|W(2\pi(-\alpha + 0.5)/N)| + |W(2\pi(-\alpha - 0.5)/N)|}$$
(13)

The value of α is determined with two maximum spectral lines and the fitting polynomial $g^{-1}(\alpha)$. Thereby, the amplitude, frequency, and phase values of the given signal are obtained based upon the following interpolated formulas:

$$k_h = \alpha + I + 0.5 \tag{14}$$

$$A_h = \frac{2y_1}{|W(2\pi(I - k_h))/N|}$$
(15)

$$f_h = \frac{k_h f_s}{N} \tag{16}$$

$$p_h = \arg(X(I)) - \arg\left[W\left(\frac{2\pi(I-k_h)}{N}\right)\right] + \frac{\pi}{2}$$
(17)

An LPCEA's input voltage, appliance current fundamental, and harmonic amplitudes are computed by using Equations (15)–(17). Under nonlinear loading conditions, it is necessary to measure the fundamental and harmonic content accurately; the conventional FFT has issues of spectral leakage and experiences the picket fence effect, and hence, the 4-term MSCW-based EDSLIFFT is adopted in this article. The measurement of the TPF by using the fundamental and harmonic amplitudes is discussed in Section 2.3.

2.3. TPF Measurement as per the IEEE 1459-2010 Standard

After measuring the fundamental and harmonic amplitudes of the voltage and current by using Equation (15) from the 4-term MSCW-based EDSLIFFT, the root mean square (RMS) values of the voltage and current are determined as follows:

$$V_{RMS} = \sqrt{V_{1RMS}^2 + V_{2RMS}^2 + V_{3RMS}^2 \dots + V_{hmaxRMS}^2}$$
(18)

$$I_{RMS} = \sqrt{I_{1RMS}^2 + I_{2RMS}^2 + I_{3RMS}^2 \dots + I_{hmaxRMS}^2}$$
(19)

The fundamental to higher-order harmonic voltages are represented by V_{1RMS} , V_{2RMS} , V_{3RMS} , ..., $V_{hmaxRMS}$ in Equation (18), and the fundamental and harmonic currents are denoted as I_{1RMS} , I_{2RMS} , I_{3RMS} , ..., $I_{hmaxRMS}$ in Equation (19). As per the IEEE 1459-2010 standard [18], the RMS of the voltage and current can be decomposed into fundamental and harmonic components as follows:

$$V_{RMS}^2 = V_{1RMS}^2 + \sum_{h>1}^{hmax} V_{hRMS}^2 = V_{1RMS}^2 + V_{HRMS}^2$$
(20)

$$I_{RMS}^2 = I_{1RMS}^2 + \sum_{h>1}^{hmax} I_{hRMS}^2 = I_{1RMS}^2 + I_{HRMS}^2$$
(21)

One of the most significant parameters for efficient power consumption with a good PQ is the PF. If the PF at the supply mains is at unity or close to unity, then it is designated as having a high PQ. On the contrary, a low PF means that the system is operating with a low efficiency and poor PQ. Under nonlinear appliance conditions, the PF is represented by the TPF, which is computed from the distortion factor and displacement PF. The distortion factor is determined from the current THD (THD_I).

The voltage and current THDs are determined with the following equations:

$$THD_V = \frac{\sqrt{\sum_{h>1}^{hmax} V_{hRMS}^2}}{V_{1RMS}}$$
(22)

$$THD_I = \frac{\sqrt{\sum_{h>1}^{hmax} I_{hRMS}^2}}{I_{1RMS}}$$
(23)

The voltage THD_V is negligible compared to the current THD_I ; hence, the current THD is considered in the distortion factor computation, as given below:

$$DF = \frac{1}{\sqrt{1 + THD_I^2}} = \frac{l_{1RMS}}{l_{RMS}}$$
(24)

The displacement factor is determined as follows:

$$DPF = \frac{P}{S} \tag{25}$$

where P represents the active power consumed by the LPCEAs and S denotes the total apparent power. The computation of the active, reactive, and apparent powers is discussed below.

The active power consumption of the LPCEAs given as:

$$P = V_{1RMS}I_{1RMS}\cos(\theta_1 - \delta_1) + \sum_{h>1}^{hmax} V_{hRMS}I_{hRMS}\cos(\theta_h - \delta_h)$$
(26)

The reactive power consumption of the LPCEAs is represented as:

$$Q = V_{1RMS}I_{1RMS}\sin(\theta_1 - \delta_1) + \sum_{h>1}^{hmax} V_{hRMS}I_{hRMS}\sin(\theta_h - \delta_h)$$
(27)

Based on the definitions of the voltage and current RMS values as functions of their fundamental and harmonic components, the total apparent power is expressed as:

$$S^{2} = (V_{RMS}I_{RMS})^{2} = \left(V_{1RMS}^{2} + V_{HRMS}^{2}\right)\left(I_{1RMS}^{2} + I_{HRMS}^{2}\right)$$
(28)

Using Equation (8), the fundamental and non-fundamental components of the apparent power are written as follows:

$$S^{2} = \left(V_{1RMS}^{2}I_{1RMS}^{2}\right) + \left(V_{1RMS}^{2}I_{HRMS}^{2}\right) + \left(V_{HRMS}^{2}I_{1RMS}^{2}\right) + \left(V_{HRMS}^{2}I_{HRMS}^{2}\right)$$
(29)

$$S^{2} = (V_{1RMS}I_{1RMS})^{2} + (V_{1RMS}I_{HRMS})^{2} + (V_{HRMS}I_{1RMS})^{2} + (V_{HRMS}I_{HRMS})^{2}$$
(30)
$$S^{2} = S_{1}^{2} + S_{2}^{2}$$
(31)

$$=S_1^2 + S_N^2 (31)$$

$$S = \sqrt{S_1^2 + S_N^2} \tag{32}$$

In Equation (31), S_N is the non-fundamental apparent power because of the occurrence of harmonic frequencies in the voltage or current waveforms. The fundamental apparent power S_1 is represented by:

$$S_1 = V_{1RMS} I_{1RMS} \tag{33}$$

The non-fundamental apparent power has three distinct terms, as shown in Equation (34).

$$S_N^2 = D_1^2 + D_V^2 + S_H^2 \tag{34}$$

The term D_1 denotes the current distortion power and comprises the fundamental voltage (V_{1RMS}) and the harmonic current (I_{HRMS}). It is determined as a function of the fundamental apparent power (S_1) and the current total harmonic distortion (*THD*_{*I*}):

$$D_I = V_{1RMS} I_{HRMS} = S_1(THD_I) \tag{35}$$

Similarly, the voltage distortion power, D_V , encompasses the harmonic voltage (V_{HRMS}) and the fundamental current (I_{1RMS}):

$$D_V = V_{HRMS} I_{1RMS} = S_1(THD_V) \tag{36}$$

Eventually, the harmonic apparent power, S_H , is determined from both the voltage and the current terms, and it contains the total harmonic distortion of the voltage and current, as given below:

$$S_H = V_{HRMS} I_{HRMS} = S_1(THD_V) (THD_I)$$
(37)

By substituting the active power given in Equation (26) and the total apparent power represented in (33), the displacement power factor is computed by using Equation (26). Then, the *TPF* is computed using the following equation:

$$TPF = DF \times DPF \tag{38}$$

Thus, the *TPF* is measured by using the 4-term MSCW-based EDLIFFT. The real-time (RT) validation of the proposed method of *TPF* measurement for identifying appliance usage patterns for DSM is presented in the next section.

3. Real-Time (RT) Measurement of the TPF

The real-time measurement of the TPF by using the 4-term MSCW-based EDSLIFFT for non-intrusive appliance usage pattern identification for DSM is described in this section. A compact reconfigurable input–output system (cRIO 9082)-based virtual instrumentation testbed from National Instruments (NI) was developed in order to deploy the proposed non-intrusive identification of appliance usage patterns. As per the authors' observation, it is prospective hardware for RT measurement of the TPF as per the requirements of international standards, such as IEEE 1459 [18], 1159 [21], and IEC 61000-4-60 [22]. Table 1. Summarizes the standards compliance of the proposed RT-based measurement method.

Table 1. Summary of the standards compliance of the proposed RT-based measurement method.

Standard	Electrical Parameters	Compliance
IEEE 1459-2010: Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Non-Sinusoidal, Balanced, or Unbalanced Conditions	Instantaneous Power, Active Power, Reactive Power, Apparent power, Non-Active Power, Voltage THD, Current THD, PF	Yes
IEEE 1159-2019: IEEE Recommended Practice for Monitoring Electric Power Quality	RMS voltage, RMS Current, Frequency	Yes
IEC 61000-4-60: Testing and measurement techniques—power quality measurement methods	Power Frequency, Flicker, Voltage Magnitude, Unbalance, Harmonics, Interharmonics	Yes

The NI-cRIO 9082 was equipped with a field-programmable gate array (FPGA) architecture, which was detailed in [23]. The voltage and current signals were acquired by the NI-cRIO 9082 with the NI-9225 (voltage) [24] and NI-9227 (current) modules [25]. Then, they were processed with the 4-term MSCW-based EDSLIFFT, which was deployed in a LabVIEW-configured desktop computer system. The desktop computer was interfaced with the NI-cRIO 9082 through a TCP/IP link, as depicted in Figure 3.



Figure 3. Hardware/lab setup for the measurement of the TPF.

CFLs, LEDs, exhaust fans, and SMPSs of personal computers are the LPCEAs that are most commonly used by consumers in developing countries; they were used here to showcase the severity of the problem for the readers, as every home that uses these appliances knowingly or unknowingly causes harmonic pollution.

The measurement hardware was coupled at the single-phase 230 V, 50 Hz utility supply mains for the TPF measurements. These TPF values were used for non-intrusive identification of appliance usage patterns. This non-intrusive appliance usage pattern identification approach took advantage of signal processing to reduce the hardware effort associated with systems intended for the identification of intrusive appliances with multiple dedicated sensors.

The TPFs of the different appliance usage patterns were measured by turning the connected appliances on or off, as shown in Figure 2. The detailed flowchart of the non-intrusive identification of appliance usage patterns with the TPF is shown in Figure 4.



Figure 4. Flowchart for the non-intrusive identification of appliance usage patterns with the TPF.

4. RT Results

The supply voltage and appliance current waveforms acquired with the NI-cRIO 9082 for various real-world appliance combinations are illustrated in Figures 5–8. The RT values of the average TPF, active, reactive, and apparent power, and percentage THD over 24 h that were obtained from NI-cRIO at 50 kS/s are tabulated in Tables 2 and 3. The figures depict the phase differences between the input voltage and the harmonic current. The RT data values for P, Q, S, S1, SN, TPF, and %THD were observed and are tabulated in Table 4.

0

Volta ne & Curren

89.5377

0 0.59887





0 8.74502

51 0 94.1348

0 116.165

Q -29.0642

%THD 123.402

00

S 149.51

Figure 5. The voltage and current waveforms of a single real-world appliance: (a) CFL, (b) LED, (c) exhaust fan, and (d) SMPS of a PC.

S.No	Combinations of Different Appliances	CODE	TPF
1	CFL	1000	0.59887
2	LED	0100	0.92228
3	Exhaust Fan	0010	0.97801
4	SMPS of PC	$0\ 0\ 0\ 1$	0.69738
5	CFL + LED	1100	0.63145
6	CFL + Exhaust Fan	$1 \ 0 \ 1 \ 0$	0.75781
7	CFL + SMPS of a PC	$1\ 0\ 0\ 1$	0.64612
8	LED + Exhaust Fan	0110	0.97925
9	LED + SMPS of a PC	0101	0.72841
10	Exhaust FAN + SMPS of a PC	0011	0.84232
11	CFL + LED + Exhaust Fan	1110	0.77422
12	CFL + LED + SMPS of a PC	1101	0.66289
13	LED + Exhaust Fan + SMPS of a PC	0111	0.85390
14	CFL + Exhaust Fan + SMPS of a PC	$1 \ 0 \ 1 \ 1$	0.73836
15	CFL + LED + Exhaust Fan + SMPS of a PC	1111	0.74947

Table 2. TPFs for all 15 appliance patterns in real time.



Figure 6. The voltage and current waveforms of combinations of two real-world appliances: (**a**) CFL and LED; (**b**) CFL and exhaust fan; (**c**) CFL and SMPS of a PC; (**d**) LED and exhaust fan; (**e**) LED and SMPS of a PC; (**f**) exhaust fan and SMPS of a PC.

The combinations of two real-world appliances were observed by turning on the combinations of the different two appliances. The voltage and current waveforms of the combinations of the two real-world appliances acquired with the NI-cRIO 9082 are depicted in Figure 6.



Figure 7. The voltage and current waveforms of combinations of three real-world appliances: (**a**) CFL + LED + exhaust fan; (**b**) CFL + LED + SMPS of a PC; (**c**) LED + exhaust fan + SMPS of a PC; (**d**) CFL + exhaust fan + SMPS of a PC.

(c)

The combinations of three real-world appliances were examined by turning on the combinations of three appliances; the corresponding voltage and current waveforms of the CFL, LED, exhaust fan, and SMPS of a PC are illustrated in Figure 7.

(d)



Figure 8. The voltage and current waveforms of the combination of the four real-world appliances: CFL + LED + exhaust fan + SMPS of a PC.

The voltage and current waveforms when all of the appliances were turned on are depicted in Figure 8.

Pertaining to the TPF values obtained from the operation of a single appliance to the operation of all four appliances, all were unique. Therefore, the TPF can be effectively used to identify appliance usage patterns. The TPFs measured with the four-term MSCW-based EDSLIFFT in the RT NI-cRIO 9082 system environment are depicted in Figure 4 and are tabulated in Table 2.

The performance of the experimentation demonstrated that the TPF could be uniquely identified for all combinations of the appliances. The standard deviation of the TPFs indicated that they were all unique and different. Hence, is the TPF can be used as a key feature of a lookup table in order to discern the appliances being operated.

Actionable Insights and Benefits							
Demand			d	Response		Benefits	
S.No	CODE	TPF	Actionable Insights	S.No	CODE	TPF	Change in TPF%
1	$1\ 0\ 0\ 0$	0.59887	Turn off CFL	2	0100	0.92228	-54.0033
2	0100	0.92228	NR ¹	NR	0100	0.92228	0
3	0010	0.97801	NR	NR	0010	0.97801	0
4	$0\ 0\ 0\ 1$	0.69738	Turn off LED for daytime	9	$0\ 0\ 0\ 1$	0.72841	-4.4495
5	1100	0.63145	Turn off CFL	2	0100	0.92228	-46.0574
6	$1 \ 0 \ 1 \ 0$	0.75781	Turn off CFL	8	0110	0.97925	-29.2210
7	$1\ 0\ 0\ 1$	0.64612	Turn off CFL for daytime	9	$0\ 0\ 0\ 1$	0.72841	-12.7360
8	0110	0.97925	Turn off LED for daytime	3	0010	0.97801	0.1266
9	0101	0.72841	NR	NR	$0\ 1\ 0\ 1$	0.72841	0
10	$0\ 0\ 1\ 1$	0.84232	NR	NR	$0\ 0\ 1\ 1$	0.84232	0
11	1110	0.77422	Turn off CFL	8	0110	0.97925	-26.4821
12	1101	0.66289	Turn off CFL	9	$0\ 1\ 0\ 1$	0.72841	-9.8839
13	$0\ 1\ 1\ 1$	0.85390	Turn off LED for daytime	10	0010	0.84232	1.3561
14	1101	0.73836	Turn off CFL	13	0111	0.85390	-15.6481
15	1111	0.74947	Turn off CFL	13	0111	0.85390	-13.9338
Standard	Deviation	0.1214		Standard	Deviation	0.099	

Table 3. Actionable insights for DR management using the TPF.

¹ NR = No recommendation.

The TPF variations of the appliance usage patterns according to demand are depicted in Figure 9a. The load patterns 1, 4, 5, 6, 7, 9, 12, 14, and 15 are in the region of poor TPF values. The TPFs of the appliance usage patterns after executing the recommendations given by the actionable insights in Table 3 are illustrated in Figure 9b, which demonstrates the improvement of the TPF. Further, it is necessary to adopt mitigation devices in order to improve the TPF as per the requirements of the IEEE 519-2014 standard [26].



Figure 9. The TPFs of appliance usage patterns according to: (a) demand; (b) responses to the insights.

	Actionable Insights and Benefits													
				Demand						Res	ponse			Benefits
S.No	CODE	P (Watts)	Q (VARs)	S (VAs)	S ₁ (VAs)	S _N (VAs)	Utilization Index = S ₁ /S	S.No	CODE	P (Watts)	Q (VARs)	S (VAs)	S ₁ / S	% Change in Utilization Index
1	$1\ 0\ 0\ 0$	89.5377	-29.0642	149.51	94.1348	116.165	0.6296	2	0100	8.74502	-3.1848	9.48195	0.9815	35.8531
2	$0\ 1\ 0\ 0$	8.74502	-3.1848	9.48195	9.30684	1.8162	0.9815	NR	0100	8.74502	-3.1848	9.48195	0.9815	0
3	0010	51.0239	-0.0008	52.1708	51.0239	10.882	0.9780	NR	0010	51.0239	-0.0008	52.1708	0.9780	0
4	$0\ 0\ 0\ 1$	80.2522	-26.0488	115.076	84.3726	78.2664	0.7331	9	$0\ 0\ 0\ 1$	88.9952	-29.233	122.176	0.7666	4.3703
5	1100	98.2871	-32.2501	155.651	103.447	116.3270	0.6646	2	0100	8.74502	-3.1848	9.48195	0.9815	32.2887
6	1010	140.558	-29.0638	185.479	143.53	117.481	0.7738	8	0110	59.7686	-3.18542	61.0348	0.9806	21.0892
7	$1\ 0\ 0\ 1$	169.803	-55.1164	262.805	178.522	192.914	0.6792	9	$0\ 0\ 0\ 1$	88.9952	-29.233	122.176	0.7666	11.3999
8	0110	59.7686	-3.18542	61.0348	59.8534	11.953	0.9806	3	0010	51.0239	-0.0008	52.1708	0.9780	-0.2686
9	0101	88.9952	-29.233	122.176	93.672	78.446	0.7666	NR	0101	88.9952	-29.233	122.176	0.7666	0
10	$0\ 0\ 1\ 1$	131.274	-26.0482	155.847	133.832	79.868	0.8587	NR	$0\ 0\ 1\ 1$	131.274	-26.0482	155.847	0.8587	0
11	1110	149.305	-32.2485	192.844	152.747	117.728	0.7920	8	0110	59.7686	-3.18542	61.0348	0.9806	19.2290
12	1101	178.533	-58.2972	269.323	187.807	193.052	0.6973	9	$0\ 1\ 0\ 1$	88.9952	-29.233	122.176	0.7666	9.0475
13	0111	140.016	-29.2325	163.971	143.034	80.1773	0.8723	10	0010	131.274	-26.0482	155.847	0.8587	-1.5806
14	1101	220.819	-55.1134	299.063	227.59	194.049	0.7610	13	0111	140.016	-29.2325	163.971	0.8723	12.7595
15	1111	229.565	-58.2983	306.302	236.849	194.263	0.7732	13	0111	140.016	-29.2325	163.971	0.8723	11.3560

Table 4. Actionable insights for the improvement of the utilization index.

NR = No recommendation.

The actionable insights for DR management are tabulated in Table 3, which establishes the opportunity to improve the TPFs in smart homes. Utilities can benefit from the reduced malfunctioning of the equipment in their distribution systems, and consumers can benefit from the enhanced lifetimes of their LPCEAs.

5. Discussion

This section discusses the analysis of the results and the scope of future research.

5.1. Analysis of the Results

- The harmonics are non-additive, and the cumulative TPF takes both the inductive and capacitive factors of various appliance combinations into consideration.
- Individual PFs are of no consequence, and the TPF is the value to consider in order to compare the impacts of appliance usage patterns with the impacts of individual appliances, as in our article. Therefore, the TPFs of appliance combinations are nonlinear, making the appliance patterns in use uniquely identifiable.
- The TPF can be improved by selecting alternative appliance patterns, as suggested in Table 4.
- Highly nonlinear appliances, such as CFLs, SMPSs, and their combinations, consume more reactive power, which results in a poor TPF.
- The standard deviation of the TPF from the experimental results was 0.1271 for the demand, and it was reduced to 0.099 according to the recommended consumer responses. Thus, the consumer utilization index improved, as illustrated in Table 4, and the quality of the power was enhanced.
- According to the results, it is necessary to adopt current harmonic mitigation devices, such as active power filters and PF correction devices in LVDSs, in order to minimize the malfunctioning of the utility equipment, such as failures of the transformers, false tripping of the circuit breakers, etc., as well as to safeguard LPCEAs from overheating.
- It is necessary to develop smart energy meters in order to measure the THD and TPF and to recommend PQ-sensitive measures, with a provision in the power tariffs for better consumer behavior.

The quantitative metrics tabulated in Table 5 demonstrate the efficacy of the proposed deterministic method over non-deterministic methods.

Quantitative Metric Category	Quantitative Metrics	TPF	Statistical Methods
Feature	Sampling rate	Medium	High
Method	Process of Execution	Experimental	Empirical
Accuracy	Disaggregation percentage (D)	100	<100
-	Disaggregation Error (DE)	0	>0
	Precision(P)—TP $^{1}/(TP + FP^{2})$	1	<1
	Recall (R)— $TP/TP + FN$	1	<1
	Accuracy = $(TP + TN^3)/(TP + TN + FP + FN^4)$	1	<1
	F-measure (f1) $2 \times P \times R/(P+R)$	1	<1
Training	User interface	Simple	Complex
Real-Time Implementation	Deployment capability	High	Low
Scalability	Pace of deployment	High	Low
Identification Factor	The standard deviation of the TPF	0.1271	NA
Generalization	Generalization over unseen homes	High	Medium

Table 5. Quantitative metrics for the non-intrusive identification of appliance usage patterns in comparison with those of statistical methods.

 1 TP = true positive; 2 FP = false positive; 3 TN = true; 4 FN = false negative.

5.2. Future Research

This paper offers a simple way of identifying appliance usage patterns, but there are a few challenges before taking this concept to market. The authors propose the following as the scope for future research.

- A smart home may have very sophisticated appliances that could be programmed and operated remotely or controlled through a mobile application. How demand-response systems can take advantage of appropriate communication is of practical interest to explore.
- The physical/thermal characteristics of electronic appliances may change over time and may, in turn, change the THD and TPF values. The accommodation of these adaptabilities in the demand-side management systems must be considered.
- The compensation of the reactive power must be studied so that a power factor at unity can be achieved at all times and all nodes in a distribution system.

6. Conclusions

The goal of this research was to save energy with good PQ in order to meet SDG 7. Due to the huge penetration of LPCEAs and their resultant current THD, the TPFs in LVDSs are poor, and consequently, the energy efficiency and PQ are heavily deteriorated. In LVDSs, poor PFs and LPCEAs are not penalized, which results in losses to the DISCOMs. This article illustrated a deterministic approach that uses the TPF in order to identify the consumption patterns of LPCEAs by using the 4-term MSCW-based EDSLIFFT in a virtual instrumentation environment for various combinations of LPCEAs in real time. It was depicted that the TPF values could be used to effectively identify various LPCEA combinations. This method of the non-intrusive identification of appliance usage patterns is essential for responsible electricity consumption with TPF that are close to unity. It is necessary to streamline the tariff structure based on the PQ. It is also necessary to mandate the correction of the PF to maintain PF that is at unity in an LVDS as per CEA regulations (2010) and to holistically comply with SDG 7. The standard deviation of the TPF is impressive, but is not sufficient to comply with the IEEE 519-2014 standard, which requires the installation of compensation devices in LVDSs when appropriate. The actionable insights recommended in this article highlight the reduction in the active power consumption and kVA requirement; they also demonstrate the improvements in the consumer utilization index. The Republic of India does not specify requirements for domestic requirements at the 230 V level, and hence, no PF penalties are imposed. Hence, the TPF is not even a concern of consumers at this moment. This work intends to highlight the deficiencies in the distribution system that must be fixed.

Author Contributions: Conceptualization, H.P.D.; Formal analysis, H.P.D. and S.B.G.; Investigation, H.P.D., and S.B.G.; Methodology, H.P.D.; Project administration, H.P.D.; Resources, V.S.S.S.D.; Supervision, V.S.S.S.S.D. and S.B.G.; Validation, H.P.D. and V.S.S.S.S.D.; Writing—original draft, H.P.D.; Writing—review and editing, V.S.S.S.D. and S.B.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors gratefully acknowledge the Department of Electrical Engineering of the National Institute of Technology Warangal for their support.

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

Nomenclature

п	Sample index
т	Window item index
M	Maximum window item number
h	Harmonic order
hmax	Maximum harmonic order
a_h	Minimal sidelobe cosine window (MSCW) coefficients
W	Four-term MSCW function
Ν	Total number of samples
T_s	Sampling time
t	Time period
A_h	Amplitude of the h_{th} harmonic component
f_h	Frequency of the h_{th} harmonic component
φ_h	Phase of the h_{th} harmonic component
k	Four-term MSCW sample points ($k = 0, 1,, N - 1$)
k_h	Division factor of signal frequency
f_s	Sampling frequency
l_h	Integer value of greatest spectral line
ξ_h	Fraction part of greatest spectral line
l_{h1}	Spectral line 1 representing the h^{th} harmonic amplitude
l_{h1}	Spectral line 2 representing the <i>h</i> th harmonic amplitude
Ι	Spectral line peak index location value
y_1	Amplitude of the spectral line 1
y_2	Amplitude of the spectral line 2
α	Symmetrical coefficient 1
β	Symmetrical coefficient 2
V_{RMS}	Total input voltage RMS value
I_{RMS}	Total load current RMS value
V_{1RMS}	Input fundamental Voltage RMS value
V_{hRMS}	<i>hth</i> order harmonic voltage RMS value
I_{1RMS}	Load fundamental current RMS value
I_{hRMS}	<i>h</i> th order harmonic load current RMS value
P	Active power consumed by the LPCEAs
Q	Reactive power consumed by the LPCEAs
θ_1	Fundamental voltage phase angle
δ_1	Fundamental load current phase angle
θ_h	<i>h</i> th order harmonic voltage phase angle
δ_h	h^{th} order harmonic load current phase angle
V_{HRMS}	Summation of all of the harmonic voltages
I _{HRMS}	Summation of all of the harmonic currents
S	Apparent power
S_1	Fundamental apparent power component
S_N	Non-fundamental apparent power component
D_1	Current distortion power
D_V	Voltage distortion power
S_H	Harmonic apparent power
THD_V	Voltage total harmonic distortion
THD_I	Current total harmonic distortion

Abbreviations

CEA	Central Electricity Authority
CFL	Compact fluorescent lamp
c-RIO	Compact reconfigurable input-output
DF	Distortion factor
DPF	Displacement power factor
DR	Demand response
DSM	Demand-side management
DSICOMs	Distribution companies
EDSLIFFT	Enhanced dual-spectrum line interpolated FFT
FFT	Fast Fourier transform
FPGA	Field-programmable gate array
IEEE	Institute of Electrical and Electronics Engineers
LED	Light-emitting diode
LPCEA	Low-power consumer electronic appliance
LVDS	Low-voltage distribution system
MSCW	Minimal sidelobe cosine window
NI	National Instruments
NILM	Non-intrusive load monitoring
PC	Personal computer
PCC	Point of common coupling
PF	Power factor
PQ	Power quality
RMS	Root mean square
RT	Real time
SDG 7	Sustainable Development Goal 7
SMPS	Switch-mode power supply
THD	Total harmonic distortion
TPF	True power factor

References

- Rahman, M.A.; Islam, R.; Sharif, K.F.; Aziz, T. Developing demand side management program for commercial customers: A case study. In Proceedings of the 2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT), Dhaka, Bangladesh, 22–24 September 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 1–6.
- 2. Srikanth, R. India's sustainable development goals–glide path for India's power sector. Energy Policy 2018, 123, 325–336. [CrossRef]
- Hazra, S.; Bhukta, A. Sustainable Development Goals. An Indian Perspective, 1st ed.; Springer Nature: Cham, Switzerland, 2020; pp. 107–127.
- 4. Verma, P.; Patel, N.; Nair, N.-K.C. Demand side management perspective on the interaction between a non-ideal grid and residential LED lamps. *Sustain. Energy Technol. Assess.* **2017**, *23*, 93–103. [CrossRef]
- 5. Devarapalli, H.P.; Dhanikonda, V.S.S.S.S.; Gunturi, S.B. Non-Intrusive Identification of Load Patterns in Smart Homes Using Percentage Total Harmonic Distortion. *Energies* **2020**, *13*, 4628. [CrossRef]
- 6. Oruganti, V.S.R.V.; Bubshait, A.S.; Dhanikonda, V.S.S.S.S.; Simões, M.G. Real-time control of hybrid active power filter using conservative power theory in industrial power system. *IET Power Electron.* **2017**, *10*, 196–207. [CrossRef]
- Jimenez, Y.; Cortes, J.; Duarte, C.; Petit, J.; Carrillo, G. Non-intrusive discriminant analysis of loads based on power quality data. In Proceedings of the 2019 IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA), Manizales, Colombia, 30–31 May 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 1–5.
- 8. Francisco, C. Harmonics, Power Systems, and Smart Grids, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2015; pp. 1–278.
- 9. Oruganti, V.S.R.V.; Dhanikonda, V.S.S.S.S.; Simões, M.G. Scalable single-phase multi-functional inverter for integration of rooftop solar-PV to low-voltage ideal and weak utility grid. *Electronics* **2019**, *8*, 302. [CrossRef]
- 10. Mageed, H.; Nada, A.S.; Abu-Zaid, S.; Eldeen, R.S.S. Effects of waveforms distortion for household appliances on power quality. *MAPAN* **2019**, *34*, 559–572. [CrossRef]
- 11. da Silva, R.P.B.; Quadros, R.; Shaker, H.R.; da Silva, L.C.P. Effects of mixed electronic loads on the electrical energy systems considering different loading conditions with focus on power quality and billing issues. *Appl. Energy* **2020**, 277, 115558. [CrossRef]
- da Silva, R.P.B.; Quadros, R.; Shaker, H.R.; da Silva, L.C.P. A Mixed of Nonlinear Loads and their Effects on the Electrical Energy Billing. In Proceedings of the 2020 IEEE 8th International Conference on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 12–14 August 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 116–120.
- da Silva, R.P.B.; Quadros, R.; Shaker, H.R.; da Silva, L.C.P. Harmonic Interaction among Electronic Loads and Its Effects on the Electrical Quantities and Billing: Case Study with Lighting Devices. In Proceedings of the 2020 7th International Conference on Electrical and Electronics Engineering (ICEEE), Antalya, Turkey, 14–16 April 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 53–60.

- 14. Ruano, A.; Hernandez, A.; Ureña, J.; Ruano, M.; Garcia, J. NILM techniques for intelligent home energy management and ambient assisted living: A review. *Energies* 2019, 12, 2203. [CrossRef]
- Yang, H.; Xue, Y.; Liu, S.; Gao, B.; Shu, Y.; Xu, Y.; Wang, J. A Judging Method of Electric Larceny in the Guise of Saving Electrical Energy. Application of Intelligent Systems in Multi-modal Information Analytics. MMIA 2019. In *Advances in Intelligent Systems and Computing*; Sugumaran, V., Xu, Z., Shankar, P., Zhou, H., Eds.; Springer: Cham, Switzerland, 2020; Volume 929, pp. 1029–1037.
- 16. Gopinath, R.; Kumar, M.; Joshua, C.P.C.; Srinivas, K. Energy management using non-intrusive load monitoring techniques-Stateof-the-art and future research directions. *Sustain. Cities Soc.* **2020**, *62*, 102411. [CrossRef]
- 17. Dlamini, F.M.; Nicolae, D.V. An approach to quantify the technical impact of power quality in medium voltage distribution systems. In Proceedings of the 2016 IEEE International Power Electronics and Motion Control Conference (PEMC), Varna, Bulgaria, 25–28 September 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 315–321.
- IEEE. Standard Definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions. In IEEE Std. 1459–2010 (Revision of IEEE Std. 1459–2000); IEEE: New York, NY, USA, 2010.
- Oruganti, V.S.R.V.; Dhanikonda, V.S.S.S.S.; Paredes, H.K.M.; Simões, M.G. Enhanced Dual-Spectrum Line Interpolated FFT with Four-Term Minimal Sidelobe Cosine Window for Real-Time Harmonic Estimation in Synchrophasor Smart-Grid Technology. *Electronics* 2019, 8, 191. [CrossRef]
- Varaprasad, O.V.S.R.; Sarma, D.S.; Panda, R.K. Advanced windowed interpolated FFT algorithms for harmonic analysis of electrical power system. In Proceedings of the 2014 Eighteenth National Power Systems Conference (NPSC), Guwahati, India, 18–20 December 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 1–6.
- 21. IEEE. Recommended Practice for Monitoring Electric Power Quality. In *IEEE Std.* 1159–2019 (*Revision of IEEE Std.* 1159–2009); IEEE: New York, NY, USA, 2014.
- 22. IEC 61000 4–30 Electromagnetic Compatibility (EMC)—Part 4–30: Testing and Measurement Techniques—Power Quality Measurement Methods; International Electrotechnical Commission: Geneva, Switzerland, 2015.
- 23. User Manual, NI cRIO-9082. Available online: http://www.ni.com/pdf/manuals/376904a_03.pdf (accessed on 16 June 2021).
- 24. Operating Instructions and Specifications, NI 9225. Available online: https://www.ni.com/pdf/manuals/374707e.pdf (accessed on 16 June 2021).
- 25. Operating Instructions and Specifications, NI 9227. Available online: https://www.ni.com/pdf/manuals/375101e.pdf (accessed on 16 June 2021).
- 26. IEEE. Recommended practices and requirements for harmonic control in electric power systems. In *IEEE Std.* 519–2014 (*Revision of IEEE Std.* 519–1992); IEEE: New York, NY, USA, 2014.