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Effect of Harmonic Distortions on Energy Measurement by Smart Energy Meter: An Experimental Analysis

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Abstract

This study presents a comprehensive investigation into the effects of harmonic distortions on the energy measurement accuracy of smart electricity meters. Given the prevalence of non-linear loads in modern electrical systems, understanding the impact of harmonics on energy metering is crucial for ensuring accurate billing and system reliability. In the present work, experiments have been conducted on smart energy meters using, programmable power sources, to create a range of harmonic conditions and measurement of meter accuracy under the presence of harmonics disorders with two reference meters carried out for validation of the results. The experimental procedure involved generating pure sine waves and introducing various harmonics (3rd, 5th, 7th, 11th, etc.) in the supply system subsequently, measuring the resultant energy with the smart meters. Comparative analyses were performed against true RMS readings to evaluate the meters' accuracy under distorted waveforms. The results demonstrate a significant deviation in the meter readings with increasing harmonic frequency, amplitude, and phase angle underscoring the susceptibility of metering technology to harmonic distortion.

Keywords: Active Energy, Electrical Smart Meter, Power Quality, Reactive Energy, Total Harmonic Distortions

1. Introduction

The advent of sophisticated electronics and the ubiquity of power electronic devices have drastically altered the landscape of electrical loads on modern power systems. Such devices often introduce harmonics-frequencies that are multiples of the power system's fundamental frequency- resulting in non-sinusoidal current and voltage waveforms. These harmonic distortions are a growing concern for the integrity of energy metering, as they can lead to inaccuracies in energy measurement and consequently, in billing and energy management. The objective of this study is to systematically investigate the effect of harmonics on electrical energy measurement through smart energy meters through a series of controlled experiments. By simulating various harmonic conditions commonly encountered in power systems, this study aims to quantify the extent to which harmonic frequencies and amplitudes can influence the accuracy of energy meter readings.

The experimental setup, at CPRI Bhopal, is designed to reflect realistic conditions and incorporates smart meters, a programmable power source to emulate harmonic distortion, and two numbers of substandard meters for validation of results to ensure a thorough evaluation of meter performance. This work outlines the significance of the study in the context of a power-dense electronic age and sets the stage for detailed exploration into harmonics and their implications on electrical energy metering. The research aims to provide valuable insights that will help improve metering technology and ensure its dependability while dealing with non-linear loads. This study aims to examine the impact of harmonics on the measurement of electricity via the use of a smart electronic energy meter. Furthermore, the research seeks to determine the precise attributes of harmonics and the extent of distortions that

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have the greatest impact on the measurement imprecision for both active and reactive energies.

The remaining material is organized into five primary sections. The second section addresses the literature review, the third section gives the research methods, and the fourth section presents experimental studies. The fifth section presents findings and comments, and the sixth section concludes the study.

2. Literature Review

Rind *et al.*, Smart energy meters have significant progress throughout time, including several interconnected sectors like electricity and smart grid. To address global concerns, various areas are interconnected by communication technologies and processed on the cloud. Advancements in sensor, communication, and processing technologies have enabled the enhancement of capabilities in smart energy systems. Due to technological improvements, sensing technologies have become more accurate and reliable, communication techniques have become faster and more flexible, and calculating methods have become more integrated and robust. Furthermore, the use of management, automation, and analytics has significantly facilitated the progress of system integration. Conversely, its level of complexity has notably increased. Smart meters, being a crucial element, must adapt to these enhancements. The presence of harmonics in the smart grid system has created many complications in energy measurements and billing. The complexity and functionality of metering technologies have increased, requiring the use of high-accuracy meters to fulfil their new responsibilities. This study investigates smart meters as integrated systems consisting of sensing, processing, and communication nodes, characterized by adaptable and advanced design paradigms. Additionally, it emphasizes any deficiencies and potential challenges in the design of the meters that might emerge in the future[1].

Bartolomei L *et al.*, focus on revenue-active electrical energy meters, which play a crucial role in energy billing and grid monitoring. These meters are essential for monitoring energy use. Standardization is crucial to achieving compliance with the European Directive 2014/32/EU (MID) for the law. Occasionally, it is necessary to provide old standards in device specifications, which entails the need to compare the latest standards. The objective of this study is to examine the impact of harmonic disturbances on the precision of energy meters, a matter of growing significance in modern power grids. The test findings indicate that some energy meters are susceptible to genuine harmonic disruptions, underscoring the need to factor in such scenarios during the development of standards[2].

Feng X *et al.*, ultimately, it is crucial to attain a power grid operation with minimal carbon emissions and maximise the utilisation of renewable energy sources to provide energy security and meet carbon neutrality objectives. The introduction of more energy into the power grid brings about a substantial presence of harmonic content, which poses a challenge to conventional metering systems. A novel metering technique is suggested, which takes into consideration the presence of harmonics. This scheme enables the measurement of both the fundamental wave and harmonic energy. The research examines the remuneration of users, the imposition of harmonic penalties, and the computation of energy costs within this novel system, showcasing its advantages for both power supply companies and customers. The user's text is enclosed in tags[3].

Tari L *et al.*, explain that load profiling, within the framework of energy digitalization, assists in making informed decisions about electrical load utilization. It may be used for enhancing energy efficiency, analyzing system behaviour, making predictions, optimizing performance, and identifying issues. Essential for smart meters of the new generation that possess certain metrological features, such as Monitoring Quality (MQ) and Electrical Signature Quality (ESQ). This paper investigates the influence of MQ and ESQ on load profiling performance and concludes that load profiling often requires less stringent metrological criteria compared to energy billing, hence decreasing infrastructure expenses. Enhancing energy characteristics does not always improve reliability and accuracy, particularly when some features lack sensitivity. By using techniques such as Kernel Density Estimation (KDE) and threshold procedures, the reliability of load profiling may be enhanced by eliminating factors that have low sensitivity. This methodology may be used for additional measurable properties, simplifying the establishment of desired standards for monitoring and the identification of crucial characteristics[4].

Stanko P *et al.*, demonstrate that railways have the potential to enhance transportation efficiency while simultaneously mitigating their environmental footprint. Electric train systems deteriorate power quality at the grid connection because of significant harmonic distortion induced by traction converters. This distortion may impact the accuracy of energy consumption measurement. The study examines several sets of electric locomotives, evaluating their harmonic current spectra obtained from actual measurements at a power transformer plant. Additionally, it uses distorted current waveforms to validate the accuracy of energy meters via calibration[5].

Masri *et al.,* this study gives empirical findings on the influence of Total current Harmonic Distortion (THDi) on the measurements of a digital energy meter (kWh) used by residential customers. The research adheres to the guidelines of IEEE-159 standard and investigates the impact of THDi % from non-linear loads on the performance of EDS2560 and Fluke-43B electronic energy meters when subjected to sinusoidal voltage supply circumstances without harmonics. Both meters function well when subjected to linear load circumstances but display notable discrepancies when confronted with high levels of THDi[6].

Rodríguez-Pajarón P *et al.,* during this research, a method for predicting the THD of voltage at low voltage bus bars in residential distribution feeders is presented. The strategy makes use of information that is gathered from a selective group of smart meters. This technique makes use of the existing monitoring infrastructure for demand response operations to provide system operators with data about the quality of the delivered electricity. The construction, testing, and comparison of several different systems for forecasting voltage THD were carried out. Some of these techniques include artificial neural networks. Calculations have been made to determine the required coverage of smart meters to obtain accurate THD measurements. During the validation process, a probabilistic demand load model is used. This model is dependent on the harmonic injections of typical home equipment as well as from a European low-voltage test-feeder that has 471 household customers[7].

Have T *et al.*, presented that the shift towards sustainable power use has resulted in a move from linear to non-linear time-variant demands in connected devices, which are frequently more energy-efficient. Therefore, there have been instances of electromagnetic interference problems, particularly with static energy meters. This may lead to increased energy costs for customers when they connect strongly pulsed loads. This article examines the interference waveforms about key directives and standards. It concludes that the current test standards primarily concentrate on frequency domain testing and do not include the diverse range of waveforms seen in home contexts where static energy meters are mounted[8].

Abas N *et al.* focused on the challenges of selecting an appropriate lighting solution in regions facing power and energy shortages. An instance of such a geographical area is Pakistan, where there is extensive use of electric lighting. The selection of lighting source is based on several aspects, such as conversion efficiencies, efficacies, operation hours, lifespan, harmonics, and power factors, among other considerations. A study was conducted to measure the voltage and current harmonic distortions generated by several types of commercial fluorescent tubes, Compact Fluorescent Lamps (CFL), and LED lights. This specific study was conducted with the use of both a conventional utility power supply and an independent generator set to provide the lighting. Based on the data, power losses resulting from distorted power factors varied from 30% to 35% for CFLs, 1.5% to 28% for tube lights, and 1.1% to 5% for LED lamps. LED lights have become the optimal choice for environmental preservation and power saving. This emphasizes the need to implement energy conservation techniques with advancements in efficiency[9].

Zhou M *et al.,* discussed that the Smart Energy Meter (SEM) is of great importance in the smart grid, attracting considerable interest from power supply companies and consumers in terms of its lifespan. Due to its direct integration into the power grid, the smart energy meter is susceptible to significant levels of harmonic pollution. Conventional approaches for predicting the lifespan of SEMs have failed to include the impact of harmonic effects on the dependability of SEMs. This research presents a novel approach for predicting the lifespan of SEM that considers harmonic variables. By using the reliability of harmonic test data, the meter life prediction model is enhanced with the integration of the harmonic components, resulting in improved forecast accuracy. The comparison between SEM prediction models and accelerated life testing results validates the method's high level of accuracy[10].

Khazaee A *et al.,* suggested that transformers are often designed to operate efficiently under specified settings with ideal sinusoidal loads. Nevertheless, the introduction of non-sinusoidal loads results in the inclusion of harmonic elements that hurt the performance of transformers. This leads to elevated losses, temperature elevation, insulation difficulties, decreased lifetime of the transformer, and the occurrence of undesired neutral currents. Distribution firms provide energy to end-users with consistent power quality. This research provides a comprehensive analysis of THD using data obtained from smart metres. This research examines the influence of THD on the reduction of transformer capacity under different load circumstances in different regions[11].

Bernieri A *et al.,* explored the impact shift towards Directive on Measurement Instrument (MID) compliance has refocused discussions on issues like the metrological characterization of meters. The study scrutinizes the test configurations specified in existing harmonized standards for electric energy metering under the MID. The goal is to identify any variables in these test conditions that could affect the reliability of results and determine whether a particular device meets or fails to meet the MID requirements[12].

Sheng Q *et al.*, this paper examines the methodologies used to evaluate the electrical performance of single-phase smart meters, focusing on their technical characteristics. It evaluates the precision, reliability, and security of these intelligent meters by verifying the data and considering their basic electrical properties. Precise operational data is gathered from intelligent electric energy meters to correctly measure their properties and assess their electrical performance. The study also examines the influence of harmonic components in the power system on measurements taken by electric energy meters. It analyses the power consumption, accuracy, and stability of these meters throughout operation[13].

Haddouk A *et al.*, research presents a technique for quantifying and discerning characteristics of nonlinear loads via the use of an SEM. When linked to the electrical network, many contemporary loads generate harmonics. Although contemporary electricity meters try to include these harmonics in their calculations, their algorithms have some limits. The suggested system substitutes conventional meters with the utilization of the Node MCU ESP8266 WiFi module, a PIC18F4550 microcontroller, and LabView to exhibit and visually illustrate outcomes such as active power (P), distortion factor (D), and active energy (Wh). An LCD provides precise numerical numbers indicating power and energy[14].

Shklyarskiy Y *et al.*, examined how harmonics affect electrical energy meter accuracy in nonlinear load networks. The study notes that although electronic static meters for active energy are evaluated for distortion, reactive energy accuracy requirements do not account for harmonics. The research reveals that harmonic number and intensity drive active energy measurement inaccuracy. Phase angle affects reactive energy measurement accuracy at fundamental and harmonic frequencies. Researchers tested how capacitor banks affect reactive energy measurements in nonlinear load networks. Measurement error and phase shift angle fluctuations increased significantly. Additionally, the research studies reactive power measurement computational errors using several equations. It finds that acceptable distortion keeps the error margin between 5-7 %[15].

3. Methodology

3.1 Influence of Harmonic Distortions on Energy Measurement by Smart Energy Meter

The influence of harmonic parameters on energy measurement by electricity meters is a complex and critical issue in modern power systems. Harmonic distortion, caused by non-linear loads like electronic devices and LED lighting, creates deviations from the ideal sinusoidal waveform of electrical current or voltage. These distortions can significantly affect the accuracy of energy measurements. Smart meters, which use digital technology to measure and record energy usage, are designed to be more accurate than their electromechanical predecessors. However, the presence of harmonics can lead to inaccuracies, especially if the meter is calibrated for a pure sinusoidal waveform. Harmonics alter the phase angle between voltage and current, affecting the measurement of reactive and apparent power and, consequently, the power factor. The design of the meter plays a crucial role, as some are better equipped to handle harmonic distortions with specialized components for compensation. Regulatory standards, such as IEC 61000-4-30, also dictate the quality of power and measurement standards, including considerations for harmonics. Addressing these influences is essential for ensuring accurate billing and maintaining the overall quality and reliability of the electrical system. The meaning of the important terms related to this work are as follows:

a. **Harmonic distortions:** Power systems often have distortions in the waveform of the electrical current or voltage. These are generally caused by non-linear loads such as electronic devices, LED lighting, and variable frequency drives. Harmonics are integer multiples of the fundamental frequency (e.g., 50 Hz in India) and can significantly affect the accuracy of energy measurements.

b. **Smart electricity meters:** Modern smart meters are designed to measure energy usage more accurately and efficiently than older electromechanical meters. They use digital technology to measure current and voltage, calculate power, and record energy usage. They have inbuilt or plug-in type communication circuitry to transmit the recorded electrical parameters to the utility data centre. Also, smart meters have load switches to connect/disconnect them from the supply system. These special features make their function smarter as compared to the traditional meters.

c. **Influence on energy measurement:**

- Accuracy: Harmonics can lead to inaccuracies in energy measurements. Meters calibrated for a pure sinusoidal waveform might not measure the real energy correctly when harmonics are present.
- Phase Angle: Harmonics can change the phasor relationship between voltage and current, affecting the power factor and thus the measurement of reactive and apparent energy.
- Meter Design: Modern meters are designed to withstand certain levels of harmonic distortion, but still, they are not capable of fully ignoring the presence of harmonic distortions and may give incorrect readings. Advanced meters might include algorithms to compensate for these distortions.

4. Experiment

An experimental investigation of the harmonic effects on electrical energy metering would involve several steps to systematically explore how different harmonic frequencies and magnitudes affect the accuracy of energy measurement by smart energy meter. Here's an outline of what such an experiment might entail:

a. Objective definition:
  - To determine the impact of harmonic distortions, present in current and voltage on the accuracy of energy measurement by electronic smart electricity meter.

b. Hypothesis formulation:
  - The presence of harmonics in the electrical system will lead to inaccuracies in energy meter readings.

c. Equipment setup:
  - Smart electronic electricity meter capable of measuring power under harmonic conditions.
  - A programmable power source fits with the six-position test bench to generate pure and harmonic-distorted waveforms.
  - A high-accuracy substandard reference meter fit with the power source cabinet and a movable reference meter to calculate the energy measurement accuracy in the percentage of the smart energy meter due to the harmonic distorted waveforms at different phase angles.

4.1 Constructional Details of the Test Bench

1. **Meter test system:** The three-phase meter test system is used for simultaneous testing, adjustment and calibration of up to six electricity meters with the meter monitoring system of the same numbering. The meter test system contains the source and one test bench with six test positions. Figure 1 shows the six-position meter test bench at CPRI Bhopal.

Figure 1. Six-position meter test system.

The testing system integrates a fully electronic method for generating test current and test voltage. The working standard is a subpar meter with a broad measurement range that is directly linked to the test circuit.

2. **Phantom power source:** The three-phase phantom power source generates the test voltage and currents which are used to energize the electric meters. Figure 2 shows the power source cabinet.

Figure 2. Power source cabinet.

The power source cabinet has the following components:

- Frequency generator: The frequency generator serves as the core component for generating synthetic waveforms. The system creates the desired values for the digital control of the power amplifier units, performs the closed-loop management of the test settings, and manages the switching operations throughout the test process.
- Substandard meter: The wide-range substandard meter is directly connected to the primary circuit; the accuracy of the working standard is also the total accuracy of the test equipment. The substandard meter is equipped with a power-proportional pulse frequency output. The substandard meter is designed to measure the actual values for test voltage, test current, and test power per phase as well as the phase angle. These values are sent to the frequency generator for regulation and actual value indication. The measurement accuracy of the substandard meter is 0.01%. The active and reactive energy accuracies obtained by this substandard meter are denoted by P1 and Q1 respectively in this work.
- Current amplifier: The amplifier is required to generate test current. This digital switch mode amplifier meets all the requirements of modern static power supply units. Current range 1 mA ... 120 A. The source cabinet has three current amplifiers to generate R, Y, and B phase currents respectively.
- Voltage Amplifier: The amplifier generates the required test voltages in all three phases. This digital switch mode amplifier meets all the requirements of modern static power supply units. Voltage range 40 ... 320 V.

4.2 Portable Reference Meter

Apart from the six-position test bench system we have measured active and reactive energy accuracies of the smart energy meter through a movable portable reference meter simultaneously for validation of the results. The details of the portable reference meter are as follows:

The wide-range portable reference meter is connected to the meter current supply cables through current clamps. The voltage circuit of the smart energy meter under study is connected in parallel with the portable reference meter voltage circuit. The portable reference meter is equipped with a power-proportional pulse frequency output. The portable reference meter is designed to measure the actual values for test voltage, test current, and test power per phase as well as the phase angle. Figure 3 shows the portable reference meter used for this study.

Figure 3. Portable reference meter for the experiment.

The portable reference meter is capable of recording harmonics waveforms applied to the smart energy meters through the test bench. The measurement accuracy of the portable reference meter is 0.1%. The active and reactive energy accuracies obtained by this portable reference meter are denoted by P2 and Q2 respectively in this work.

4.3 Smart Energy Meter

The smart energy meter taken for this study is a 3-phase 4-wire CT/PT operated meter having a voltage rating of 3x63.5V, current rating is -/5A, Imax is 10A, 50Hz with meter constant of 16000 impulse/unit. The smart energy meter used for the study is shown in Figure 4.

Figure 4. 3 phase 4 wire CT/PT operated smart energy meter.

The meter can measure active and reactive energies and has respective registers to store these values. For data communication, the meter has cellular technology.

As per the Government of India norms, all traditional energy meters are now replaced by smart energy meters, hence we have performed our experiments on smart energy meters at Energy Meter Testing Laboratory, CPRI Bhopal.

4.4 The Test Set-Up Arranged for the Experimental Work

The purpose of setting up of the experimental setup is to find out the effect of harmonic distortions on the measurement of active and reactive energies by the smart energy meter and to find out the effect of different harmonic component angles on the measurement accuracy of the meter for reactive and active energies. Figure 5 represents the experimental setup for the study.

Figure 5. Experimental setup for harmonic distortion study.

The experimental setup consists of a test bench with a power source to generate harmonics in the meter supply system, a substandard reference meter, a movable reference meter, a smart energy meter and one PC with bench software installed in it to run the bench. Figure 6 represents the schematic diagram of the test setup in the laboratory. The diagram represents the interconnection of all the equipment and their inter-dependability for testing the energy meter for harmonic purposes.

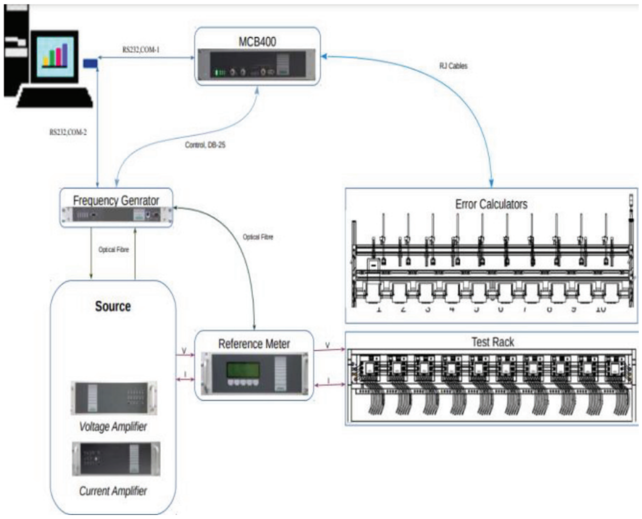

Figure 6. Schematic diagram of test setup in laboratory.

4.5 The Program of Experimental Study

The harmonics and their phase angles, applied to the smart energy meter for study purposes are mentioned in Table 1. Values of harmonic voltage, current and phase angles will be changed to find out the relative accuracy of energy measurements for both active and reactive energies of the smart energy meter. Here the harmonic amplitude is presented as the percentage value of the fundamental value of voltage and current and the values of harmonic phase angles are denoted in degrees. The program of experimental study in the energy meter testing laboratory, as outlined in this paper, involves a series of experiments to investigate various harmonic parameters and their influence on energy measurement.

Table 1. The harmonics parameters applied during the study

Experiment No.	Φ1	U3	I3	Φ3	U5	I5	Φ5	U7	I7	Φ7	U11	I11	Φ11
1	40	30	10	80	-	-	-	-	-	-	-	-	-
2	40	30	20	100	20	25	13	-	-	-	-	-	-
3	40	30	30	150	20	25	13	21	17	10			
4	40	30	40	180	20	25	13	21	17	10	18	15	10

4.6 Experimental Procedure

- Check the calibration of all the equipment to ensure accurate readings.
- Generate a pure sinusoidal waveform and take the accuracy of the smart meters at fundamental frequency (50Hz).
- Introduce harmonics into the supply system, starting with lower harmonics components (e.g., 3rd harmonic) in the supply voltage and current to the smart energy meter and progressively moving to higher frequencies (e.g., 5th, 7th, 11th, etc.).
- Vary the amplitude of the harmonic components to assess the effect of different levels of harmonic distortions.
- Phase shift angle at the fundamental frequency (φ_1): The phase shift angle at the fundamental frequency for each experiment is fixed at 40 degrees during the study.
- 3rd harmonic voltage and current (U_3, I_3) and phase angle (φ_3): The amplitude of the 3rd harmonic voltage is mostly set at 30%, and 3rd harmonic current amplitude varies between 10-40% of its fundamental current value, and their phase shift angle Φ_3 varies between the ranges from 80 to 180 degrees.
- 5th, 7th, and 11th harmonic parameters (U_5, I_5, φ_5, U_7, I_7, φ_7, U_{11}, I_{11}, φ_{11}): Like the 3rd harmonic, these voltage and current amplitudes and phase shift angles for the 5th, 7th, and 11th harmonics varies between 10% and 40%, and the phase shift angles range from 10 to 180 degrees respectively.

The output waveforms of voltage and currents without and with harmonics are shown in Figure 7 to Figure 13.

Figure 7 represents the sinusoidal supply current wave with fundamental frequency applied to the smart energy meter without any harmonics.

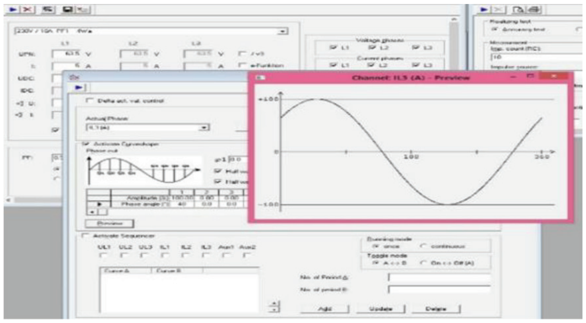

Figure 7. Current waveform without any harmonics.

The output of the experiment of the harmonics effect on the smart meter is shown on the screen when the phase angle changes. When φ_1(40), U_3(30), I_3(10), φ_3 (80) is shown in Figure 8.

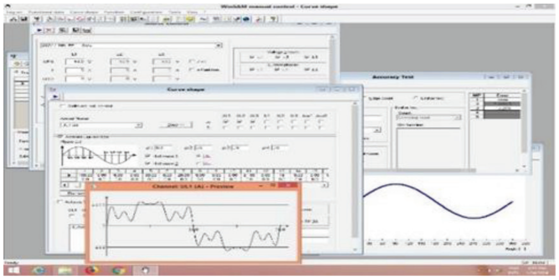

Figure 8. Voltage waveform with harmonics.

The output of the experiment of the harmonics effect on the smart meter is shown on the screen when the phase angle changes. When φ_1(40), U_3(30), I_3(20), φ_3 (100), U_5 (20), I_5 (25), φ_5(13) is shown in Figure 9.

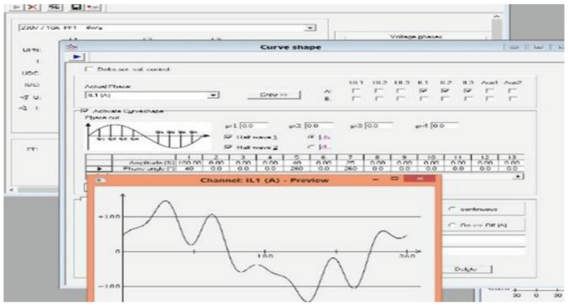

Figure 9. Current waveform with harmonics.

The output of the experiment of the harmonics effect on the smart meter is shown on the screen when the phase angle changes. When for φ_1, the value is 40, followed by U_3 at 30, and I_3 at 30, φ_3 is 150, U_5 is 20, and I_5 is 25, φ_5 is 13, U_7 is 21, and I_7 is 17, φ_7 is 10 degrees. Figure 10 shows the output waveform.

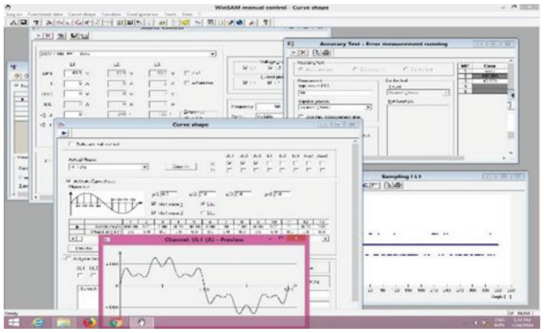

Figure 10. Current waveform with harmonics.

The output of the experiment of the harmonics effect on the smart meter is shown on the screen when the phase angle changes, when φ_1 is 40, U_3 is 30, I_3 is 40, φ_3 is 180 degrees, U_5 is 20, I_5 is 25, φ_5 is 13 degree, U_7 is 21, I_7 is 17, φ_7 is 10 degree, U_{11} is 18, I_{11} is 15, and φ_{11} is 10. Figure 11 shows the waveform.

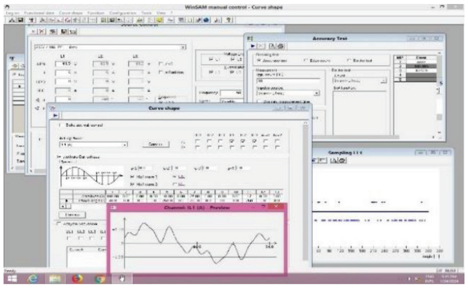

Figure 11. Current waveform with harmonics.

Similarly, another output of the experiment of the harmonic effect on the smart meter shown on the screen when the phase angle changes. When the variables φ_1, U_3, I_3, and φ_3 are assigned the following values: When φ_1 is 40, U_3 is 30, I_3 is 40, φ_3 is 180 degrees, U_5 is 20, I_5 is 25, φ_5 is 120 degrees, U_7 is 21, I_7 is 17, φ_7 is 10 degree, U_{11} is 18, I_{11} is 15, and φ_{11} is 10. Figure 12 shows the waveform.

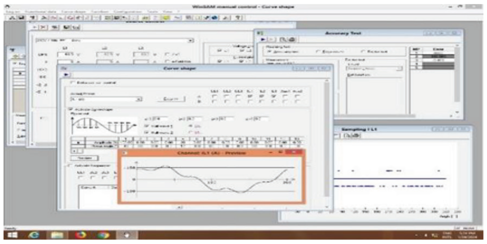

Figure 12. Current waveform with harmonics.

The output of the experiment of the harmonics effect on the smart meter is shown on the screen when the phase angle changes. When φ_1 is 40, U_3 is 30, I_3 is 40, φ_3 is 180 degrees, U_5 is 20, I_5 is 25, φ_5 is 150 degrees, U_7 is 21, I_7 is 17, φ_7 is 10 degrees, U_{11} is 18, I_{11} is 15, and φ_{11} is 10. Figure 13 shows the waveform.

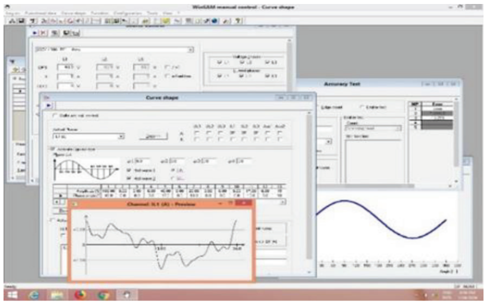

Figure 13. Current waveform with harmonics.

The output of the experiment of the harmonics effect on the smart meter is shown on the screen when the phase angle changes. When the variables φ_1, U_5, I_5, $\varphi5$, U_7, I_7, φ_7, U_{11}, I_{11}, and φ_{11} are assigned respective values: When φ_1 is 40, U_3 is 30, I_3 is 40, φ_3 is 180 degrees, U_5 is 20, I_5 is 25, φ_5 is 180 degrees, U_7 is 21, I_7 is 17, φ_7 is 10 degrees, U_{11} is 18, I_{11} is 15, and φ_{11} is 10. Figure 14 shows the waveform.

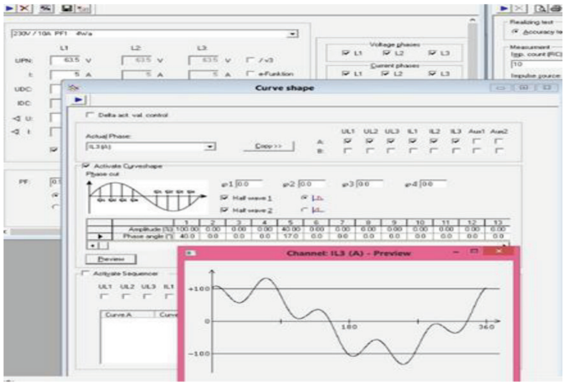

Figure 14. Current waveform with harmonics.

4.7 Data Analysis

- Compare the active and reactive energy measurement accuracies of the smart meter with the reference accuracies and note down the relative accuracy errors against reference and distorted waveforms to evaluate the variations in the accuracy.
- Analyze the waveform data to understand the relationship between harmonic distortion and meter readings.
- Use statistical methods to determine the significance of the results.

5. Results and Discussion

The study of the harmonic distortion effect on electrical smart meters via experiments likely aimed to understand how non-linear loads and the resulting harmonic currents and voltages affect the accuracy of electrical smart meters.

5.1 Influence of Harmonic Parameters on Power Measurement

In the first phase of the study, using the data provided in Table 1, we produced different current and voltage signals for the reference meters. The parameters that were modified include the amplitude and phase angle of the harmonic current, the phase shift angle at various frequencies, and the composition of the harmonic spectrum. The magnitude of the phase voltages at the output is 63.5 volts. The reference meters use computational models to determine the measurements of active power in the tested devices, specifically:

$$P = P_1 + P_H \tag{1}$$

$$P_1 = U_1.I_1.cos\phi_1, P_H = \sum_{h\neq 1}^{\infty} U_h.I_h.cos\phi_h, \tag{2}$$

The variables U_h, I_h, and φ_h represent the Root Mean Square (RMS) value of voltage harmonic h, current harmonic h, and the phase shift angle between voltage and current harmonic h, respectively. The calculation of reactive power measurements is performed as follows:

$$Q = \sqrt{S^2 - P^2}, S = \sqrt{\sum_{h=1}^{\infty} U_h^2} \cdot \sqrt{\sum_{h=1}^{\infty} I_h^2} \tag{3}$$

The study yielded the spectrum, amplitude, and phase angle of harmonics in the error of active and reactive energies. The findings of the investigation have been compiled in Table 2.

Table 2. The results of the study

Exp. No.	Φ1	U3	I3	Φ3	U5	I5	Φ5	U7	I7	Φ7	U11	I11	Φ11	Accuracy % Active Power		Accuracy % Reactive Power	
														P1	P2	Q1	Q2
1	40	30	40	80	-	-	-	-	-	-	-	-	-	+9.87%	+10.05%	-0.99%	-1.10%
2	40	30	40	100	20	25	13	-	-	-	-	-	-	+10.12%	+10.83%	-1.04%	-1.39%
3	40	30	40	150	20	25	13	21	17	10	-	-	-	+10.38%	+10.90%	-1.16%	-1.80%
4	40	30	40	180	20	25	13	21	17	10	18	15	10	+10.41%	+10.78%	-1.21%	-1.85%

Figure 15 in the study presents a visual representation of the relationship between metering accuracies and the number of harmonics, with a specific focus on a scenario where the phase shift angle at the fundamental frequency (φ_1) is set at 40 degrees. In this scenario, the amplitudes of harmonic current and voltage are constant, and the number of harmonics is changing. The addition of more harmonics in the supply system will increase the values of active energy measurement errors and the reactive energy measurement errors are not much affected.

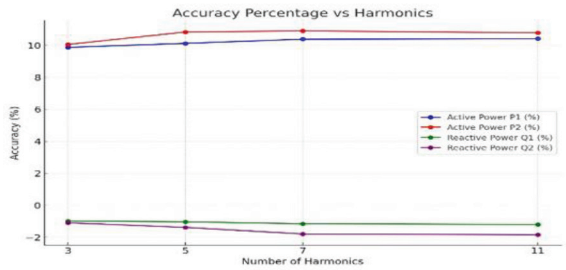

Figure 15. Relative metering error vs number of harmonics.

The blue line represents active energy P1, the red line represents active energy P2, the green line represents reactive energy Q1, and the purple line represents reactive energy Q2.

Figure 16 illustrates the dependencies of the relative metering errors on the amplitude of 3rd harmonics.

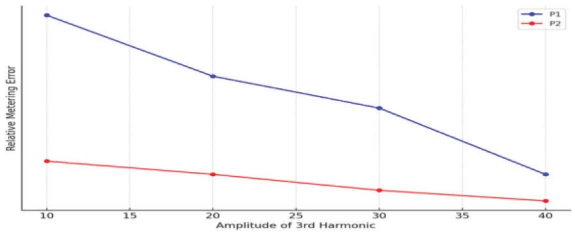

Figure 16. Relative metering error for active energy vs amplitude of 3rd harmonic current.

Figure 16 illustrates "Amplitude of 3rd Harmonic", displaying the values 10, 20, 30, and 40 percent of the fundamental current. The blue and red lines represent the values of the active power measurement accuracies P1 and P2 respectively.

Figure 17 illustrates the study that depicts the relationship between the relative metering error for both active and reactive energy and the phase shift angle, focusing particularly on the 5th harmonic. As the phase shift angle of the harmonics is varied, resulting in changes to the active and reactive power associated with these harmonics. The graph illustrates how these variations in the phase shift angles of the harmonics, while keeping their amplitudes constant, impact the accuracy of metering, particularly highlighting the changes in active power due to these phase shifts. This figure is crucial for understanding how different harmonic conditions affect the precision of electrical energy meters.

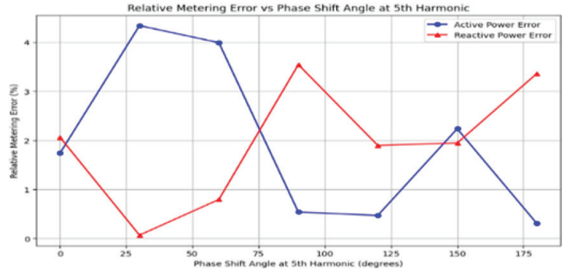

Figure 17. Relative metering error vs phase shift angle at 5th harmonic.

This graph is essential for understanding how the phase shift at this specific harmonic frequency influences the accuracy of metering in active and reactive energy measurements. The graph shows how the error in metering varies with changes in the phase shift angle at the 5th harmonic, providing insights into the impacts of harmonic distortions on energy meter accuracy.

The blue line (active energy error) shows how the relative metering error for active energy varies with the phase shift angle at the 5th harmonic.

The red line (reactive energy error) indicates the variation in the relative metering error for reactive energy under the same conditions. Each point on these lines represents the error percentage at a specific phase shift angle, ranging from 30° to 180°. This data suggests that both active and reactive energy measurements are affected by the phase shift angle of the harmonic, which is a common issue in power systems with significant harmonic content.

In real-world scenarios, the actual impact on metering accuracy would depend on the specific characteristics and design of the smart energy meter, as well as the nature of the harmonics in the system. The relationships might be more complex and require detailed analysis to understand fully.

6. Conclusion

The harmonic effect on electrical smart meters, as studied in this paper, reveals that harmonic distortions in voltage and current indeed influence the accuracy of energy meters. The study underscores that different methods of computing active and reactive energies when harmonics are present, yield varying levels of computational error. Furthermore, it highlights that the THD in both voltage (THDv) and current (THDi) can significantly affect these errors. The effectiveness of different computational methods is dependent on the unique characteristics of the smart energy meter and the specific nature of the harmonics within the power system. These findings are critical as they suggest that metering technology must be adaptive to the complexities introduced by harmonics to ensure accurate energy measurement and billing.

7. References

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