Central Power Research Institute

Vol. 21(2)/127-134, December 2025
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v21i2.1215

Power Research

Experimental Studies on the Influence of Energy Injection on the Verification of Meter Constant

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Abstract

Energy meters are an important element in the modern electrical distribution system, ensuring accurate measurement. Meter constant is a crucial parameter in energy meters for enabling accurate billing. Indian Standards IS 13779:2020, and IS 14697:2021 for energy meters prescribe verification of the meter constant since it is one of the crucial parameters in the functioning of energy meter but provides flexibility in the level of energy to be injected while testing. This flexibility causes irregular testing protocols and extensive variations in the error measured, especially while testing for short durations. This paper experimentally examines the impact of variable energy injection levels—from 0.001 kWh to 5 kWh—on the accuracy of the meter constant in measurement. A variety of single-phase and three-phase static and smart meters were tested for meter constant accuracy in a controlled laboratory environment for this experiment.

Keywords: Energy Meter, Impulse Output, kWh/kVArh Measurement, Meter Accuracy Test, Meter Constant, Short Test Times, Smart Meter, Static Meter

1. Introduction

The Indian power sector has been significantly transformed over the past few decades by national initiatives such as Saubhagya: Pradhan Mantri Sahaj Bijli Har Ghar Yojana and the Smart Meter National Programme (SMNP). Universal household electrification is the aim, along with the vast deployment of Advanced Metering Infrastructure (AMI). The electrical distribution system of the nation has modernised exponentially. This modernisation in electrical distribution infrastructure aims to improve billing efficiency, reduce losses due to measurement, and empower consumers[1,2]. With millions of new smart meters being rolled out and installed for energy measurement, their accuracy and reliability are more crucial for retaining consumer confidence and fair billing.

The core of this modern distribution system infrastructure is the energy meter that measures the amount of electricity utilised by households and industries. These energy meters shall be highly accurate for fair billing of electricity consumption. Under the umbrella of static and smart meters in India, these meters measure active energy in kilowatt-hours (kWh) and reactive energy in kilovolt-ampere reactive hours (kVArh). A key parameter in the energy meters is the meter constant, which represents the number of countable optical pulses the meter generates per unit of energy consumed. For example, A meter rated at 3200 imp/kWh will produce 3200 optical pulses for every kilowatt-hour of energy consumed. The accuracy of these countable pulse emissions directly defines the accuracy of the meter.

Bureau of Indian Standards (BIS) provided a regulatory framework for testing and assessment of energy meter devices through standards, IS 13779:2020 for static watt-hour meters[3] and IS 14697:2021 for transformer-operated meters[4]. These standards specify detailed conditions for verifying a meter's accuracy, including the test method of the meter constant. BIS defined test conditions, such as meter constant, shall be measured at maximum current and unity power factor. However, the standard has not provided the exact amount of energy the test has to be performed, provide discretionary scope for the amount of energy to be injected during the test. Based on the laboratory standard practice,

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different laboratories perform a meter constant accuracy test by injecting different levels of energy. This discretionary scope provides a vast variation in the amount of accuracy measured during testing.

This flexibility allows significant non-uniformity while performing accuracy testing at laboratories.

A short-duration test, by definition involving a small amount of energy injection, may yield results that differ greatly from a longer energy injection test. The meter's internal design, firmware logic, test environment, and measurement conditions can impact its performance[5,6]. During testing, small deviations, i.e., differences in the number of pulses measured for given energy and pulses supposed to be emitted as per energy injected, may generate significant errors, especially when quantisation errors are present. Wang *et al.*[7] have described at low pulse counts the possibility of higher error due to the intrinsic property of the digital counting system.

This experimental study performed in this work addresses this procedural limitation by experimentally exploring how the measured accuracy of the meter constant changes with varying energy injections. The key goal is to measure this variation in optical pulse count at distinct levels of energy injection by keeping other parameters, viz., current, voltage and power factor, unaltered at each energy input to the energy meter from the MUT, connected to a high-speed digital counter to record the exact number of pulses. The resolution of the error display is 4½ decimal points. Uncertainty of switching edge detection for LED scanning: ± 1 μs.

2. Methodology

2.1 Test environment

The test procedure is repeatable and rigorous, such that the impact on the volume of energy injection alone is studied. Testing is performed in a temperature and humidity-controlled testing room, i.e. at 27°C ±2°C, RH < 60%, so that the effects of environmental factors were uniform[6].

2.2 Test Equipment and Experimental Setup

A high-accuracy automatic test bench used for measurement of pulse counts, it consists of a calibrated, more accurate three-phase reference standard (Six-position test bench, photograph of test bench is shown in Figure 1).

Programmable Power Source: A three-phase source capable of producing stable voltage and current with Total Harmonic Distortion (THD) below 1%, ensuring a pure sinusoidal supply is used during the experiment.

Reference Standard Equipment (RSE): A Class 0.02% reference equipment providing traceable, high-precision measurement of the true energy injected into the Me-ter Under Test (MUT). This equipment does not emit pulses; it is the reference module in the test bench. The uncertainty



Figure 1. Six position test bench is used for the accuracy measurement test.

and accuracy of the reference equipment are 0.0140% and 0.02%, respectively.

Pulse Scanning Head and Counter: A calibrated optical scanning head used to detect the LED pulse emitted. This highly accurate scanning head helps in testing energy meters efficiently without affecting the influence of scanner uncertainty in the meter constant testing.

Software: Automation software controls the process, ensuring the energy injection stops precisely when the RSE reaches the target value, while simultaneously gating the pulse counter to prevent unwanted pulse counts. The uncertainty of the software is 0.001%.

2.3 Meters Under Test (MUT)

Energy meters used in electrical distribution systems may vary based on their connection method, number of phases, operating voltages and current levels. Direct-connected meters, including single-phase and three-phase meters,

are designed to measure voltage and current directly from the supply, which are commonly used for low and medium-load applications. These meters operate within the rated voltage and current limits of the meter itself and do not require external instrument transformers.

For higher load conditions, Current Transformer (CT) and Potential Transformer (PT) operated meters are used to ensure safe and accurate measurement. LTCT meters are used in low-tension systems where the system voltage remains low, but the current exceeds the direct-connection capability of the meter. In such cases, the current is scaled using external CT, while the voltage is applied directly. HTCT meters are used in high-tension voltage systems, which receive both current and voltage inputs through external CT and PT. Using this arrangement allows meters to measure at high voltage and high current while maintaining electrical isolation and safety.

The use of CT and PT introduces scaling factors and phase shifts, which influence the effective meter constant and pulse output characteristics[4-6]. As a result, CT-and PT-operated meters generally have much higher declared meter constants compared to those of direct-connected meters, leading to differences in pulse resolution and test duration while performing tests for meter constant verification.

For our present experimental study, nine meters were selected to represent the broad spectrum of technologies and applications. Detailed specifications of the meter selected for this test are shown in Table 1. The meters selected for testing widely differ in their declared meter constants, operating current levels, and connection arrangements, which directly affect pulse generation during testing. Direct-connected meters generate a higher number of pulses for a given injected energy, typically due to their lower meter constants, making them suitable for verification at low energy levels accurately and requiring short test durations. In contrary, LTC and HTCT meters are designed for higher load applications and have higher meter constants, resulting in fewer pulses for the same injected energy (comparison is based on the declared meter constant).

Consequently, CT and PT-operated meters require higher energy injection or longer test durations to obtain sufficient

Error Calculation: Percentage error is calculated by comparing the MUT reading (E_{MUT}) with the RSE reference reading (E_{RSE}). The energy output recorded by the Meter under test (MUT) (E_{MUT}) is calculated based on the observed pulses during testing and the meter nameplate constant/ declared meter constant (K):

$$EMUT_ \frac{Npulses}{K} \quad (1)$$

pulse counts for reliable analysis. At very low energy levels, these meters are more sensitive to quantisation effects, which can lead to apparent variation in the observed meter constant. Therefore, the selection of test energy levels and duration plays a critical role in ensuring substantial comparison of meter constant behaviour across different meter types.

This diverse selection ensures that the findings are generally applicable, covering residential (LT), commercial (HT), and industrial metering (LTCT/HTCT).

For meters with higher declared meter constants, particularly LTCT and HTCT meters, e.g., 60000 imp/kWh or imp/kVArh, injecting energy equivalent to the full meter constant would result in excessively long test durations. Therefore, shorter energy injection levels were employed, and the resulting pulse counts were analysed to evaluate meter constant behaviour under practical laboratory conditions.

2.4 Test Procedure

A standardised and identical procedure was applied to all nine MUT for comparability. The test is performed using six position automated test bench, one after the other.

- **Pre-conditioning:** Each MUT was energised at its rated voltage and nominal load for at least 30 minutes to ensure thermal stability of its components.
- **Parameter Configuration:** As per IS 13779:2020[3] and IS 14697:202[4]:
  Active Energy (kWh) Test: Rated Voltage, Maximum Current, Unity Power Factor (UPF = 1.0)
  Reactive Energy (kVArh) Test: Rated Voltage, Maximum Current, Zero Power Factor Lagging (ZPF = 0.0)
- Iterative Energy Injection: To accurately understand the behaviour of meter constant accuracy with the varying energy input, a broad range of energy levels are injected to observe the change in meter constant percentage error, beginning at 0.001 kWh up to 5 kWh in the following sequence: 0.001, 0.002, 0.005, 0.008, 0.01, 0.05, 0.08, 0.1, 0.2, 0.5, 1, 1.5, 2, 2.5, and 5 kWh.
- Data Acquisition: Pulse counts from the MUT were recorded for each energy level.
  The percentage error calculation depends on matching the MUT registered energy to the reference standard reading:
- **Error Calculation:** Percentage error is calculated by comparing the MUT reading (EMUT) with the RSE

reference reading (ERSE). The energy output recorded by the Meter under test (MUT) (EMUT) is calculated based on the observed pulses during testing and the meter nameplate constant/declared meter constant (K):

$$EMUT = \frac{Npulses}{k} \quad (1)$$

$$\text{Percentage Error (\%)} = \frac{EMUT - ERSE}{ERSE} \times 100\% \quad (2)$$

E_{MUT} is the energy recorded in the MUT; E_{RSE} is the reference energy, which is given as input.

For Example 1, for a 3200 imp/kWh constant meter tested at an energy input of 0.001 kWh (E_{RSE}), the expected pulse count is 3.2 (=3200*0.001).

Case-1: If the meter shows 3 pulses, then E_{MUT} = 3 / 3200 = 0.0009375 kWh. The error would be ((0.0009375 - 0.001) / 0.001) x 100% = -6.25%.

Case-2: If the meter output shows 4 pulses, then E_{MUT} = 4 / 3200 = 0.00125 kWh. The error would be ((0.00125 - 0.001) / 0.001) x 100% = 25%.

For Example 2, for a 3200 imp/kWh meter being tested at an injection level of 2 kWh (E_{RSE}), the expected pulse count is 6400.

Case-1: If the meter outputs 6398 pulses, then E_{MUT} = 6398 / 3200 = 1.999375 kWh. The error would be ((1.999375-2) / 2) x 100% = -0.03%.

Case-2: If the meter outputs 6402 pulses, then E_{MUT} = 6402 / 3200 = 2.000625 kWh. The error would be ((2.000625 - 2) / 2) x 100% = 0.03%.

Repetition: Steps were repeated for 0.001, 0.002, 0.005, 0.008, 0.01, 0.05, 0.08, 0.1, 0.2, 0.5, 1, 1.5, 2, 2.5, and 5 kWh/kVArh.

3. Results - Measured Percentage Error of Different Energy Meters Selected

The empirical data from testing of all nine meters are summarised using the graph below. The percentage error observed for each meter varies with the level of injected

Table 1. Specifications of Meters Under Test — including type, phase, rating, and meter constant for each of the 9 meters

Meter Type	Phase	Connection	Accuracy Class	Rated Voltage (V)	Basic / Max Current (A)	CT / VT Ratio	Declared Meter Constant
Single-phase Static	1P	Direct	Class 1	240	5/30	–	3200 imp/kWh
Single-phase Static	1P	Direct	Class 1	240	5/30	–	3200 imp/kWh
Single-phase Static	1P	Direct	Class 1	240	5/30	–	3200 imp/kWh
Single-phase Smart	1P	Direct	Class 1	240	5/30	–	3200 imp/kWh
Single-phase Smart	1P	Direct	Class 1	240	5/30	–	3200 imp/kWh
Single-phase Smart	1P	Direct	Class 1	240	10/60	–	3200 imp/kWh
Three-phase Direct	3P	Direct	Class 1	3 × 240	10/60	–	1600 imp/kWh and 1600 imp/kVArh
Three-phase LTCT	3P	LTCT (CT)	Class 0.5S	3 × 240	5/10	1/1	12000 imp/kWh and
							12000 imp/kVArh
Three-phase HTCT	3P	HTCT (CT/ PT)	Class 0.5S	3 × 63.5	1/2	1/1	60000 imp/kWh and
							60000 imp/kVArh

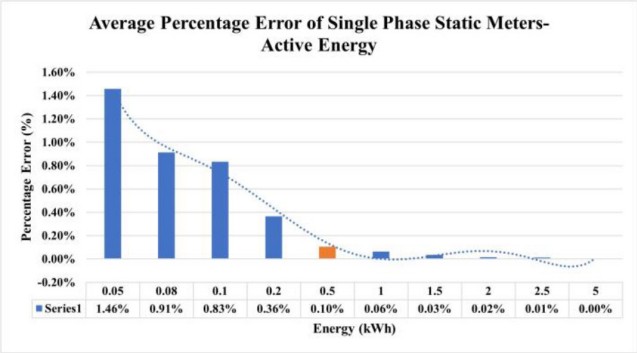


Figure 2. Single-phase static meters average deviation vs active energy.

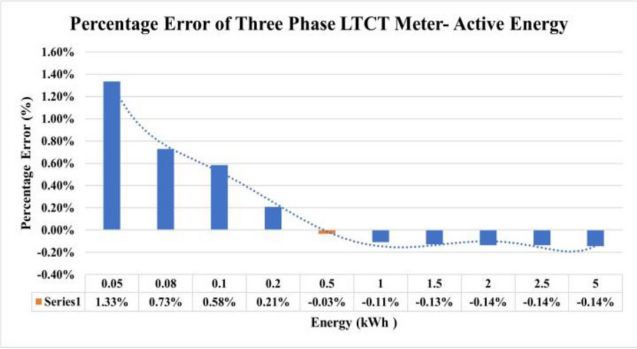


Figure 3. Single-phase smart meters average deviation vs active energy.

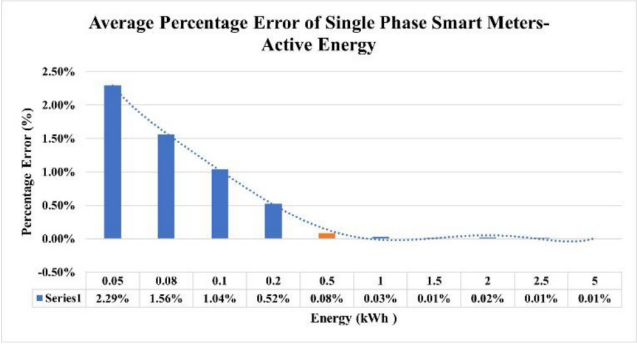


Figure 4. Three-phase direct meter deviation vs active energy.

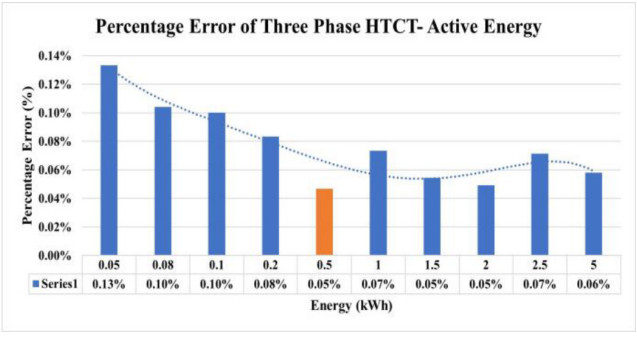


Figure 5. Three-phase LTCT meter deviation vs active energy.

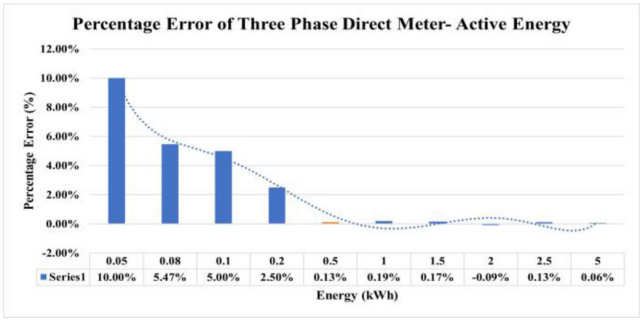


Figure 6. Three-phase HTCT meter deviation vs active energy.

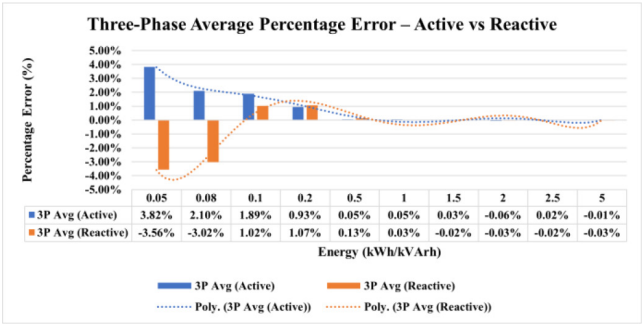


Figure 7. Three-phase meters average deviation – active vs reactive.

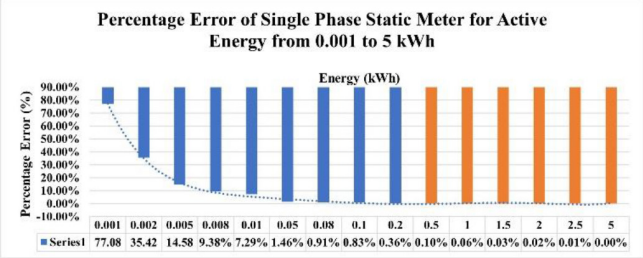


Figure 8. Percentage error of single-phase static meter for active energy from 0.001 to 5 kWh.

energy, reflecting differences in measurement behaviour across the tested energy input range. At low energy input, the percentage error is huge due to small pulse accumulation, whereas at higher energy input levels, the percentage error reduces significantly and stabilises. This shift indicates that the difference at low energy is primarily caused by pulse resolution and quantisation effects rather than by a change in the intrinsic accuracy of the meter.

For the three single-phase static meters and three single-phase smart meters, the percentage error is averaged across each energy level injected into the meter, and the same is represented in the graphical data below.

For better representation of Figure 8, the vertical axis (Percentage error %) is represented in the maximum axis value (Horizontal axis crosses).

From Figure 8, a consistent trend is observed wherein the Percentage error is significantly higher at very low injected energy levels (below 0.01 kWh/kVArh) and progressively reduces as the injected energy increases. This trend is similar for all other meter types. At low energy injection levels, the small amount of output pulses causes the measured percentage error to appear highly random and, in some cases, to exceed the nominal accuracy class limits.

However, this behaviour does not indicate a loss of intrinsic meter accuracy. Instead, it arises from the discrete nature of pulse-based energy measurement, where a meter can only output whole pulses. When the expected pulse count is small, even a ±1 pulse variation results in a large percentage error change. As the energy injection with input increases, the pulse count grows and the relative impact of a single pulse reduces, leading to a smooth reduction of percentage error and convergence towards the inherent accuracy of the meter as shown in the graphs (which can be observed in Figure 2-6) at 0.5 kWh, indicating convergence toward intrinsic accuracy.

4. Discussion

4.1 Quantisation error at low energy input levels

The percentage error recorded at low energy injection levels is huge, primarily due to quantisation error, which arises when continuous energy flow is represented by discrete output pulses (this is clearly visible in Figures 2-8 at low energy injection). As demonstrated by Wang *et al.*,[7] short measurement intervals or a small energy input window significantly increase the effect of quantisation, resulting in higher relative error.

From the graph in Figure 4, the declared meter constant is 1600 imp/kWh for the meter. The meter is expected to generate only a few pulses at very low injected energy, such as at 0.05 kWh energy injection. In such cases, a difference of one pulse corresponds to a large percentage error. As seen from the graph at 0.05 kWh energy input, the percentage error is found to be 10%, even though the underlying energy measurement algorithm remains accurate. This effect is therefore a consequence of pulse rounding and finite resolution rather than a true measurement inaccuracy of the meter.

4.2 Convergence to Intrinsic Accuracy

The pulse output count rises as the energy input increases, which results in the percentage error difference decreasing due to ±1 pulse. For better understanding, at 1 kWh injection (for 3200 pulses), ±1 pulse causes an insignificant error change. Hence, all error curves converge to a stable value representing the true intrinsic accuracy—an application of the Law of Large Numbers. From the graphical data in Figures 2-8 above, at energy levels ≥ 0.5 kWh/kVArh, the percentage error of the meters is in the range of the accuracy class of the meter, which is the requirement as per the standards.

4.3 Comparative Performance of Meter Technologies

Both static and smart meters (illustrated in Figures 2 and 3) show similar behaviour in the energy input vs percentage error graphs. Smart meters may stabilise faster due to advanced microprocessors and higher-resolution analogue-to-digital converters, enabling finer internal energy integration. However, this pattern indicates that quantisation errors at low pulse counts occur for different technologies of meter construction, making them improper short-duration tests, even for advanced meters.

4.4 Implications for Testing Standards

The findings reveal that Indian Standards are flexible regarding energy input injection specification. This flexibility results in unreliable test results, leading to:

Manufacturer vs. Utility Conflicts: Different tests with varying energy inputs will have varied accuracy outcomes.

Inter-Lab Discrepancies: Two accredited labs may report different results.

Inaccurate Field Audits: Portable short-duration tests may misclassify meter accuracy, class.

This procedural inconsistency undermines the goal of uniform accuracy verification, especially given India's vast Advanced Metering Infrastructure (AMI) rollout. Hence, it needs time to propose a energy level for testing, which may introduce less error due to pulse count. From the data acquired using this experiment (which is observed using representation in Figures 2-8), it is evident that the meter constant test conducted for energy level injected greater than 0.5 kWh/kVArh will have an accuracy of the meter within the specified bounds of BIS standards.

Table 2. Pulse count and percentage error at 0.5 kWh energy injection

Meter Type	Connection	Declared Constant (imp/ kWh)	Declared Pulses at 0.5 kWh	Observed Pulses at 0.5 kWh	Approx time to complete test (in minutes)	Percentage error (%)	Percentage error limit specified by the standard (%)
Single-phase Static	Direct	3200	1600	1602	4	0.1250	*±1*
Single-phase Static	Direct	3200	1600	1601	4	0.0625	*±1*
Single-phase Static	Direct	3200	1600	1602	4	0.1250	*±1*
Single-phase Smart	Direct	3200	1600	1602	4	0.1250	*±1*
Single-phase Smart	Direct	3200	1600	1599	4	-0.0625	*±1*
Single-phase Smart	Direct	3200	1600	1603	4	0.1875	*±1*
Three-phase Direct	Direct	1600	800	801	2	0.125	*±1*
Three-phase LTCT	CT-operated	12000	6000	5998	15	-0.0333	*±0.5*
Three-phase HTCT	CT/PT-operated	60000	30000	30014	75	0.0467	*±0.5*

The percentage deviation of all nine tested meters at 0.5 kWh energy injection is shown in Table 2. The uncertainty of the percentage error in Table 2 is 0.014%, considering the accuracy and uncertainty of reference equipment, the uncertainty of software and the uncertainty of the pulse scanner.

Table 2 shows that at an injected energy of 0.5 kWh, the percentage error of the meter constant for all tested meters converges within a narrow range, indicating stable meter constant behaviour once sufficient pulse accumulation is achieved.

4.5 Observations from the Graphical Data

The graphical results presented in Figures 2–6 and 8 illustrate the variation of percentage error with respect to injected energy and pulse count for different meter categories. Figure 7 indicates the percentage error on three-phase meters with active (kWh) and reactive (kVarh) energy measurements. When the injected energy increases, the number of output pulses increases as observed in Figures 2-7, resulting in better stabilisation of the measured error. Consequently, the percentage error gradually converges towards the true meter accuracy class. Consequently, the percentage error gradually converges toward the specified meter accuracy limits for both active and reactive energy measurements.

This behaviour is observed similarly for both high pulse and low pulse constant meters. However, meters with higher pulse constants generate more pulses for the same injected energy, thereby improving the resolution of error calculation and reducing quantisation effects at lower energy levels. The pulse constants listed in Table 1 directly influence the number of pulses generated during testing and therefore affect the resolution of error evaluation, as illustrated in Figures 2–7.

From the experimental observations, it is inferred that injecting a minimum energy of 0.5 kWh provides sufficient pulse accumulation for reliable error determination. Below this level, the limited pulse count results in significant deviations in the calculated percentage error.

5. Conclusion

It is found that tests involving lesser-energy injections result in extensive, unsustainable errors because of the

effects of quantization while the error is stable only for higher values of injected energy. The result points towards the importance of defining a minimum quantum of energy or a pulse number for the purpose of ensuring regular and consistent testing of the meters.

This experimental study computes the effect of energy injection levels on meter constant accuracy. Short-duration tests with few pulses count results in inaccurate, inconsistent results that do not represent meter performance accurately.

Key Findings:

- The percentage error in meter constant verification is inversely proportional to injected energy, especially below 0.2 kWh.
- Quantisation error results in a high percentage error at low pulse output.
- Percentage error settles only after sufficient pulses are output.
- The pattern holds across all meter types—static, smart, single-phase, and three-phase.
- The standard may be improved by recommending that meter constant tests shall be performed at the energy input of 0.5 kWh/kVArh or greater, ensuring reliability, uniformity, and integrity in meter testing nationwide.

6. Acknowledgment

The author is grateful to the management of Central Power Research Institute for their support to carrying out this experimental study.

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Author Contribution:

K.S.S, P.R : Conceptualization; K.S.S, P.R : Methodology and experimental design; K.S.S, A.A.B : Data Collection and Investigation; K.S.S, P.R : Writing- Original Draft Preparation ; P.R, K.D.R: Writing-Review and Editing; K.D.R: Supervision and Validation.