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Accuracy Testing of Three-Phase kWh Meters in Direct and Indirect Measurement APP Wiring

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Abstract: The reliability of electric power systems depends significantly on the accuracy of electrical energy metering instruments, as measurement errors directly influence consumption records and the fairness of transactions between utilities and customers. This study assesses the accuracy of kilowatt-hour (kWh) meters installed in three-phase Measuring and Limiting Devices (APP), considering both direct measurement configurations at low voltage (LV) and indirect measurement configurations at medium voltage (MV). The methodology includes field measurements of current, voltage, and power, followed by the calculation of kWh meter errors and Current Transformer (CT) errors using the collected data. The findings show that the kWh meter error is 0.27% for direct measurements and −1.78% for indirect measurements, with an average CT error of 1.97%. All measured error values are within the applicable standard tolerance limits; thus, the kWh meters are considered accurate, reliable, and suitable for operational use.
Keywords: kWh meter, energy metering accuracy, three-phase APP, direct metering, indirect metering

INTRODUCTION

Electrical energy is a fundamental requirement for modern society. It is utilized extensively in various sectors, such as lighting, communication, transportation, industry, heating, cooling, and other applications. Electrical energy generated by power plants is then transmitted and distributed through transmission and distribution networks to end consumers [1]. The reliability of electrical energy measurement systems is crucial because it directly impacts the accuracy of energy transactions, the efficiency of distribution systems, and fairness between electricity providers and customers [2].

Measuring and Limiting Devices (Alat Pengukur dan Pembatas, APP) are utilized in practical field operations to measure electrical energy and have kWh meters. Between the electricity provider and the energy consumer, the kWh meter is the primary transactional instrument. The installation of kWh meters is contingent on the power capacity of customers of Perusahaan Listrik Negara (PLN), the state-owned electric company. The accuracy and reliability of kWh meters are necessary to maintain consumer confidence and comply with utility regulations [3]. Based on the measurement method, kWh meters are classified into two types: direct measurement and indirect measurement [4], [5]. Although kWh meters are technically designed in accordance with applicable standards, various factors—such as load conditions, wiring configurations, and the characteristics of instrument transformers—can significantly influence measurement accuracy. Most previous studies have focused on laboratory-based testing of kWh meters or have examined only a single measurement configuration [6], [7].

This study presents a comparative analysis of kWh meter accuracy under two different system configurations: direct measurement at low voltage (LV) and indirect measurement at medium voltage (MV), both evaluated under real operational conditions. Furthermore, this research simultaneously integrates the evaluation of kWh meter errors and Current Transformer (CT) errors, providing a more comprehensive assessment of the performance of electrical energy measurement systems.

The objective of this study is to analyze the accuracy of three-phase kWh meters using both direct and indirect measurement methods. The focus of the investigation is the evaluation of each measurement configuration based on field measurement data obtained during system operation.

RESEARCHMETHOD

This study adopts an experimental approach to analyze the accuracy of electrical energy measurements using kWh meters in a three-phase system under two measurement methods, namely direct measurement and indirect measurement. The testing was conducted using a digital kWh meter type Edmi Mk10E for the direct measurement method and Edmi Mk6N for the indirect measurement method.

In the indirect measurement method, the measurement system is equipped with Current Transformers (CTs) and Potential Transformers (PTs) as additional components to step down current and voltage levels before being supplied to the kWh meter. All test configurations were assembled within a APP in accordance with standard electrical energy metering installation practices (Rudianta & Syakur, 2023). Supporting instruments used in this study include an AVO meter for voltage and current measurements, a clamp meter for non-intrusive current measurement, and a megger to verify that the insulation condition of the installation was satisfactory prior to testing.

The test design consists of two wiring configurations in a three-phase system. In the direct measurement method, the voltage and current sources are directly connected to the kWh meter without the use of CTs or PTs. In contrast, in the indirect measurement method, current and voltage from the network are first stepped down through CTs and PTs before being fed to the kWh meter. The testing procedure involved recording phase currents, phase-to-neutral voltages, and the electrical energy registered by the kWh meter over a specified time interval. The measured data were subsequently used to calculate kWh meter error and CT error, which serve as the basis for evaluating the accuracy of the electrical energy measurement system.

Accuracy Testing of kWh Meter in Three-Phase APP Direct Measurement Wiring (LV)

The accuracy testing of the kWh meter under the direct measurement system was performed using a three-phase APP wiring configuration applied to a low-voltage (LV) system. The wiring arrangement followed the standard LV APP installation guidelines established by PT PLN (Persero), in which the kWh meter is directly connected to the voltage source and load without the use of instrument transformers.

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In this configuration, phase conductors R, S, and T, as well as the neutral conductor, are directly connected to the kWh meter terminals according to the standard PLN wiring diagram. The test was conducted to observe the conformity between the electrical energy measured by the kWh meter and the calculated energy values derived from measured current and voltage parameters. The direct measurement wiring scheme is illustrated in Figure 1and Figure 2 Three-Phase APP Wiring Test , which was developed based on the technical guidelines for LV APP wiring issued by PT PLN (Persero)[17].

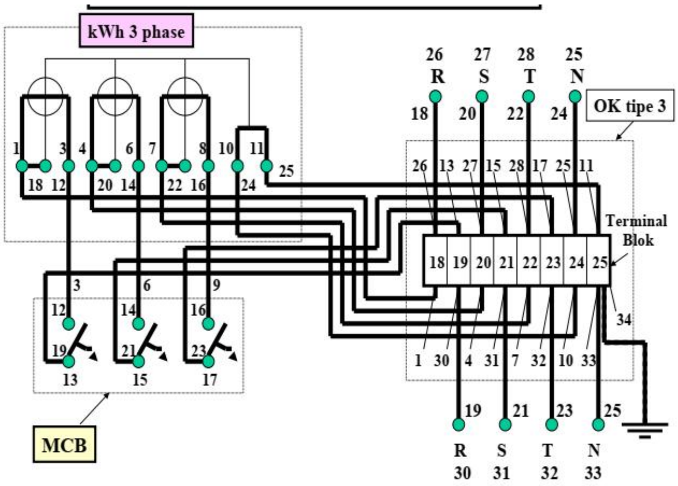

Figure 1. Wiring Scheme for a Three-Phase Four-Wire kWh Meter Using Direct Measurement [9]

Figure 2. Three-Phase APP Wiring Test Results Using Direct kWh Meter Measurement

Accuracy Testing of kWh Meter in Three-Phase APP Indirect Measurement Wiring (MV)
The accuracy testing of the kWh meter under the indirect measurement system was conducted using a three-phase APP wiring configuration applied to a medium-voltage (MV) system. The wiring arrangement refers to the standard MV APP installation guidelines of PT PLN (Persero), in which current and voltage are not measured directly by the kWh meter but through instrument transformers in the form of Current Transformers (CTs) and Potential Transformers (PTs).

In this configuration, the current from each phase (R, S, and T) is passed through CTs with specified ratios, while the voltage is stepped down via PTs before being supplied to the kWh meter terminals. The use of CTs and PTs aims to reduce current and voltage levels to safe limits and to enhance the safety of the measurement system. The indirect measurement wiring scheme is presented in Figure 3 and Figure 4 Three-Phase APP Wiring Test , which was prepared based on the standard MV APP wiring documentation issued by PT PLN (Persero)[17].

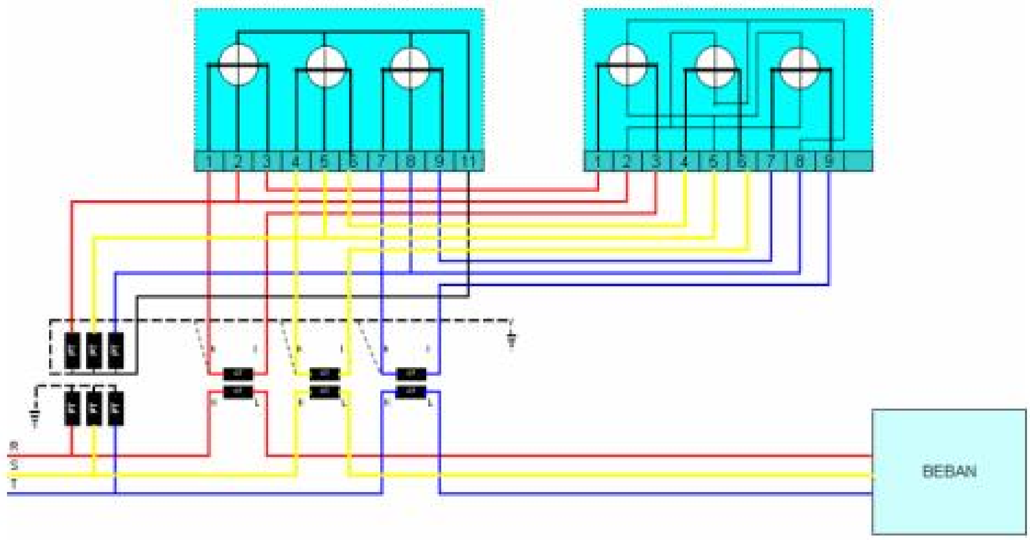

Figure 3. Wiring Scheme for a Three-Phase Four-Wire kWh Meter Using Indirect Measurement [9]

Figure 4. Three-Phase APP Wiring Test Results Using Indirect kWh Meter Measurement

RESULTS AND DISCUSSION

Direct Measurement kWh Meter Testing (LV)

Following the testing procedures, measurement data were obtained and used to compare and analyze the performance of the kWh meter against the applicable standards. The data were collected from experimental trials involving the installation of the Measuring and Limiting Device (APP) wiring in a direct measurement (low-voltage, LV) system under various load conditions using lamp loads. The experimental results are presented in Table 1, which summarize the outcomes of the conducted tests. Table 1 presents the measured current values for each phase, with average current values used as the basis for subsequent calculations. The parameters displayed on the kWh meter during the test, including measured electrical energy, line-to-line voltage, and phase-to-neutral voltage, are shown in Table 1.

Table 1. Experimental Data – Direct Measurement (LV)

Measurement Point	Current (A)	Phase-to-Phase Voltage (V)	Phase-to-Neutral Voltage (V)	Measured Energy (1 h) (kWh)
Phase R	0.25	385	224	0.25
Phase S	0.45	385	224	0.25
Phase T	0.25	385	224	0.25
Average	**0.32**	–	–	–

Based on the measured data, the electrical energy consumption was calculated using Equation (3), Substituting the measured values yields:

$E = 0{,}32\ .\ 385\ x\ \sqrt{3}\ x\ 0{,}92\ X\ 1$

$E = 196\ \text{Wh} = 0{,}196\ \text{kWh}$

The calculation shows that, under the applied load conditions, the theoretical energy is 0.196 kWh. This serves as the reference value for evaluating the accuracy of the kWh meter in the direct measurement setup.

The kWh meter error was then calculated using Equation (4):

$$\text{Error}_{kWh}(\%) = \frac{0{,}25 - 0{,}196}{0{,}196} \times 100\%$$

$$\text{Error}_{kWh}(\%) = 0{,}27\%$$

Based on the current and voltage measurements in the three-phase APP direct measurement system, the electrical energy recorded by the kWh meter was 0.25 kWh over a duration of one hour. The theoretical calculation yielded an energy value of 0.196 kWh, resulting in a kWh meter error of 0.27%.

A positive error value indicates that the energy recorded by the kWh meter is higher than the actual energy consumption. Under such conditions, the electricity provider (PLN) gains an advantage, while the customer experiences a financial disadvantage. Conversely, a negative error value indicates that the recorded energy is lower than the actual consumption, resulting in potential losses for the utility and benefits for the customer due to underbilling.

Indirect Measurement kWh Meter Testing (MV)

The kWh meter testing under the indirect measurement method was conducted using a three-phase Measuring and Limiting Device (APP) installed in a medium-voltage (MV) system, utilizing Current Transformers (CTs) and Potential Transformers (PTs). In this method, the current and voltage supplied to the kWh meter are first stepped down through CTs and PTs according to their nominal ratios before energy registration.

To evaluate kWh meter error and CT error, measurements of primary current and secondary current were performed using a CT with a nominal ratio of 40. The measured primary current (I_p) and secondary current (I_s) values are presented in Table 2, respectively.

Table 2. Experimental Data – Indirect Measurement (MV)

Phase	Primary Current (I_p) (A)	Secondary Current (I_s) (A)
R	77.6	1.97
S	72.9	1.85
T	77.4	1.99

Based on these measurements, the CT error was calculated using Equation (1). For Phase R, the CT error is calculated as follows:

$$\text{Error}_{CT} = \left(\frac{(40 \times 1{,}97) - 77{,}6}{77{,}6}\right) \times 100\% = 1{,}55\ \%$$

The CT error values for all phases are summarized in Table 3, yielding an average CT error of 1.97%. The CT error of 1.55% for Phase R indicates that the current transformer accurately scaled the primary current to the secondary side. Similar calculations for other phases yield an average CT error of 1.97%, confirming proper functioning of the CTs in the indirect measurement system.

Table 3. CT Error Calculation

Phase	CT Error (%)
R	1.55
S	1.51
T	2.84
Average	**1.97**

As a subsequent step, the kWh meter error was calculated based on secondary-side power ( ) and primaryside power ( ), derived from the energy readings displayed on the kWh meter, The calculation results are presented in Table 4 LCD. The secondary power was calculated using the following expression:

$$P_1 = P_{\text{LCD}} \times \text{CT ratio} \times \text{VT ratio}$$

$$P_1 = 1310 \times 40 \times 1 = 52.40\ \text{kW}$$

The secondary power represents the energy measured after scaling by the CT and PT. This value is critical for assessing the accuracy of the kWh meter after instrumentation transformation.
The primary power $P_2$was calculated as the sum of the power measured on each phase:

$$P_2 = P_R + P_S + P_T$$

$$P_2 = 17.42 + 17.62 + 18.31 = 53.35\ \text{kW}$$

Primary power represents the actual system load prior to measurement transformation. Comparing this value with secondary power allows evaluation of total system measurement error.
Using the calculated values of $P_1$and P_2, the kWh meter error was determined as follows:

$$\text{Error}_{\text{kWh}}(\%) = \frac{P_1 - P_2}{P_2} \times 100\%$$

$$\text{Error}_{\text{kWh}}(\%) = \frac{52.40 - 53.35}{53.35} \times 100\% = -1.78\%$$

The negative error indicates the meter slightly underestimated the energy consumption. Despite the deviation, the error remains within standard tolerance, demonstrating reliable performance under indirect measurement conditions.

Tabel 5. Power Calculations and kWh Meter Error

Parameter	Value
Secondary Power (P_1)	52.40 kW

Primary Power (P_2)	53.35 kW
kWh Meter Error (%)	−1.78%

In this indirect measurement test, the operating principle of the kWh meter is fundamentally similar to that of the direct measurement method. However, the key difference lies in the installation configuration. In indirect measurement systems, current and voltage are not measured directly but through instrument transformers, namely CTs and PTs.

The CT is used to reduce large alternating currents to smaller, standardized values suitable for kWh meter inputs and is connected in series with the load conductor. Meanwhile, the PT steps down the system voltage from 20 kV to 100 V, as the kWh meter used in this study operates within a voltage range below 400/250 V.

Transformer error—particularly CT error—is defined as the difference between the transformed secondary current and the actual primary current. A larger CT error leads to greater deviation between the recorded electrical energy and the actual energy consumed.

During data acquisition, power and current measurements were performed on both the primary and secondary sides. Primary power represents the power measured before the kWh meter, while secondary power corresponds to the power measured after passing through the CT and PT and entering the kWh meter. The same principle applies to current measurements, forming the basis for evaluating the overall accuracy of the energy measurement system.

CONCLUSION

Based on the experimental results and analysis, it can be concluded that the accuracy testing of three-phase kWh meters installed in Measuring and Limiting Devices (APPs) can be effectively conducted by comparing the energy recorded by the kWh meter with theoretically calculated energy values. The test results indicate that the kWh meter error under direct measurement is 0.27%, while under indirect measurement it is −1.78%. In addition, the average Current Transformer (CT) error of 1.97% demonstrates that the CT operates properly and remains within standard tolerance limits.

Overall, the tested three-phase APP energy measurement system exhibits satisfactory accuracy, indicating that the kWh meters used are feasible and reliable for application in electric power distribution systems.

For future work, it is recommended to conduct kWh meter accuracy testing under a wider range of load types and load levels, including unbalanced load conditions, to obtain a more comprehensive evaluation of system performance. Furthermore, future studies may compare measurement results with higher-accuracy reference instruments and investigate the influence of CT and PT ratios on energy measurement errors in medium-voltage systems.

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