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Analysis of installation errors of a low-voltage current transformer operated energy meter using in-service data

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Abstract

This study analyzed the installation errors associated with a low-voltage metering system with a focus on the reversal of secondary polarities of the current transformers (CT) and the mismatch of CT ratio and meter current ratio. This was achieved by introducing these errors into an existing 300/5A CT-operated metering system and computation of the energy estimated from the loads using the measurement carried out on-site. The largest energy loss (66.6%) occurred when the meter current ratio was greater than the CT ratio and the least energy loss (7.2%) occurred when the polarities of two CTs were reversed. This approach provides a cost-effective and quick estimate of energy loss in the event of any of these connection errors in the metering systems.

Keywords

Current transformer, energy meter, installation errors, losses, polarity.

1.0 Introduction

The electricity consumers on the estimated billing platform always allege some sort of extortion by the utility due to lack of adequate means to establish the quantum of energy utilized. Energy meters are installed to instil transparency and improve visibility in the billing process. They are integrating instruments that measure the product of instantaneous currents and voltages in a circuit over a certain period (Govindarajan et al., 2020).

The comprehensive trends of energy consumption which is fundamental in energy management can be provided through effective metering. To the utilities, effective metering provides the overall benefit of mitigation of technical, commercial, and collections losses (Dodo et al., 2020;

Nwohu et al., 2017). To curb these losses, the power utilities world over has deployed some sorts of programmes and interventions aimed at providing meters to the electricity consumers in their franchise areas. For instance, in Europe, the "Meter ON" was a project funded by the European Commission to support the development and deployment of advanced metering infrastructures (Enrico et al., 2018). In Nigeria, the Meter Assets Providers (MAP) scheme, the Credited Advanced Payment for Metering Implementation (CAPMI), and the "No Meter – No payment scheme" specifically for large power users were among the several regulatory interventions and initiatives to stimulate and accelerate metering across the country (Ehanmo & Onwuegbule, 2018; Olalere & Mathew, 2018; NBF News, 2013).

The procurement of these meters and consequent installations are expensive. In July 2018, the Abuja Electricity Distribution Company Plc, Nigeria acquired 222,728 low-voltage energy meters valued at ₦10 billion for customers in its franchise areas of Federal Capital Territory, Kogi, Nasarawa, and Niger states (Premium Times 2018; Guardian Nigeria, 2018). Unfortunately, such investments have always been marred with irregularities such as vandalism, meter tampering, and theft of energy through bypasses. The Jos Electricity Distribution Company Plc, Nigeria in February 2018 alone, lost revenue worth ₦3.5 billion to the theft of services (Sahara Reporters, 2018). In the United States, the annual losses through theft of energy are estimated at $6 billion (McLaughlin et al., 2014). The estimated world-wide loss of revenue figure is frightening. According to (Rong et al., 2014), at least $25 billion is lost every year to theft of electricity around the world. Meter tampering and bypass, fraudulent hook-ups to the line, anomalies in billing, and unpaid bills are the most common ways electricity can be accessed illegally (Tsado et al., 2017).

Another important threat to the billing process besides energy theft is errors in meter installation, especially when not noticed early or not even noticed at all. The meter installer or technician may by mistake introduces errors such as reversal of current transformer (CT) polarities, shorting of the phase conductors at the test terminal block (TTB), an asymmetrical connection of the potential cables, cross-connection or swapping of the current and potential cables, an incorrect connection of the neutral wire, and so on. Thus, it is essential that a three-phase energy meter line 1, line 2 and line 3 voltages and phase currents are identified and wired to the meter correctly in sequence. This is often not the case as the cable colours do not guarantee that the phases are in the correct order. The cable colours can be cross-connected and this will make them not in conformity with the phases leading to the energy meters performing poorly.

There are 287 modes of wrong installation of three-phase three-component energy meters, and 575 modes of wrong connection of three-phase three-wire energy meters (Quing et al., 2015). This study, however, failed to further present and analyse these errors. Jia et al. (2018) presented 12 cases of polarity reversal of voltage transformers (VT) in a three-phase three-wire energy meter. The analysis was performed in terms of the phasor relationships between currents and voltages of the VT. This approach is too analytical and cannot provide a bird-eye view of the energy and revenue loss resulting from the incorrect connections. A comparison of energy display with pulse output as an approach to determining the status and functionality of the energy meters is detailed in (GOSSEN, 2009). The basis of this method is that the energy meters are equipped with light-emitting diodes (LEDs) which flash according to the rate of energy consumption. For large energy consumption, the flashing intervals of the LEDs are usually in microseconds which can be difficult to analyse physically. An MT781 of class 0.1 and MT786 of class 0.05 Zera device is a state-of-the-art test system with an in-built voltage and current sources for analyzing complete metering installations, observations of the error limits in meters, and local mains conditions. This device is costly, apart from the skill requirements for its complex operations. Norrie (2017) estimated that more than 30% of energy meters are wrongly sized, connected, or installed. Therefore, for the various wrong connection modes of metering systems, it is necessary to establish what the measurement errors would be, the amount of energy the meter will record, and the resulting revenue losses that may occur if these oversights are not discovered quickly.

Therefore, this study aims to conduct an on-site analysis of installation errors of a low voltage CT-operated smart meter with a focus on reversed secondary polarities of the CTs, and mismatch in CT ratio and meter current ratio. This was achieved by introducing these errors into an existing metering system, and the energy consumption estimated from the loads and that registered by the meter for each error introduced into the system were analyzed. Apart from providing quick estimates on the quantum of energy loss in the event of any of these connection errors in the metering systems, this approach is cost-effective, simple, and will be useful when test sets malfunction or are not available.

2.0 Materials and Methods

The energy meter used for this research is A2000-T, 3X240/415 V, of MOJEC International Limited. It is a CT-operated meter that measures energy in 3-phase 4-wire networks with the following accuracy; active energy to IEC 62053-22 class 0.5S, and reactive energy to IEC 62053-23 class 0.2. The clamp meter used to measure loads for computation is of Fluke Company, with an accuracy class of 0.2. The set-up of the metering system for this study is shown in Figure 1.

Figure 1. CT-operated metering system

For the case of mismatched CT ratio and meter current ratio, the energy meter was reprogrammed to a higher (500/5A) and lower (200/5A) respectively, while the ratio of the CT in the circuit was not tampered with. That is, it was left as 300/5A.

A 3-phase 4-wire CT-operated energy meter has six input signals which must be present and connected in the right order for accurate measurement of energy. These signals include three voltage inputs that are tapped directly from the mains and three current inputs which are connected from the secondary terminals of the CT. Errors such as reversed polarities of at least one CT, and mismatch of CT and meter current ratios were deliberately introduced into an existing metering system with the assumption that they occurred during installation. Before introducing the errors, commissioning tests were carried out under normal operating conditions to serve as a reference point for other tests. For every error introduced into the system, tests were performed four times and their averages were taken. The difference between the estimated consumption and the meter reading in percentage is the losses that could occur when such installation errors were committed. Therefore, the error or loss in percentage (ε) for the various test cases was computed using:

$$\varepsilon = \left|\frac{e_2 - e_1}{e_2}\right| \times 100\% \qquad 1$$

Where e_1 represents the energy estimated from the load, and e_2 represents the energy recorded by the meter.

2.1 *Energy Meter*

An energy meter or a kilo-watt-hour meter is an electrical instrument for measuring and recording electrical energy consumed over a specified period. The computation that is performed by the energy meters regardless of the type is (Enokela, 2007; Gang et al., 2015):

$$E = \int_0^t i(t)v(t)dt \qquad 2$$

Where E is the energy consumed in Whr, t is the duration of energy consumption, i(t) and v(t) are the instantaneous values of current and voltage respectively.

The building blocks of all energy meters are sensors, multipliers, numerical conversion, and registers as shown in Figure 2, but the present-day meters comprise more complex components such as the microprocessors, analogue to digital converters, registers/displays, multiplexers, input/output communication ports, clock, etc (Smith & Rivers, 2006) as shown in Figure 2.

Figure 2. CT-operated metering system

The first generation of energy meters works on the principle of induction. That is, they operate on the principle that moving a magnet close to the periphery of an aluminium rotating disc causes the disc to rotate in the same direction as the magnet movement, due to the interaction of the magnetic field with the current (eddy current) generated by the disc (Nagashima et al., 2007). The energy meter shown in Figure 3 utilizes two types of technologies;

mechanical and electronic, and therefore is referred to as hybrid meters or electromechanical meters (Smith & Rivers, 2006).

An induction motor and a disc constitute the mechanical part, while a microprocessor-based register forms the electronic part of this type of meter. These meters dominated the metering of energy consumption because of their robustness. They can display only one type of energy and they also suffer from friction losses which make them require a definite starting current to effect the movement of the moving parts of the meters. Current below this level will certainly make it impossible to obtain any registration with the meter (Enokela, 2007).

Figure 3. Electromechanical meter (Smith & Rivers, 2006)

Solid-state, also called 'electronic' energy meters are based on one technology; electronic. These meters use a microprocessor with no induction motor and discs and can display more parameters compared to the induction meters (Zakariae et al., 2017). A single solid-state (electronic) meter can measure and display a multitude of billing functions and can be used for various billing applications and load monitoring purposes, and are effective in communication and programming (Smith & Rivers, 2006).

Another evolution of electronic meters is the "smart meters". They are digital energy meters with storage and communication interface, and commodity central processing units (Enrico et al., 2018). These smart meters and communication networks are the nervous system of Advanced Metering Infrastructure (AMI) services (McLaughlin et al., 2014). AMI provides several important functions that were not previously possible or had to be performed manually, such as the ability to automatically and remotely measure electricity use, connect and disconnect service, detect tampering, identify and isolate outages, and monitor voltages (US Department of Energy, 2016).

In electricity distribution, smart meters are available either as low voltage prepayment or credit meters and can be of single-phase (230/240V single phase voltage) or poly-phase (3x230V, whole current low-voltage, and current transformer operated low-voltage), while the high voltage poly-phase meters are available only as credit meters (AEDC Plc, 2017). Figure 4 shows a CT-operated prepayment smart meter.

Figure 4. Low-voltage CT-operated prepayment energy meter

A prepayment or prepaid electricity meter counts backward as the electricity is consumed and has a relay that disconnects the power when the kWh reading on the meter reaches zero. The credit meters register consumption continuously and do not have any relay for disconnection of power.

2.2 Commissioning of the metering system

Physical checks, CT burden checks, transformation tests, and meter register tests are the core of meter system commissioning.

(i) Physical checks

The physical checks were performed to make sure that;

- partial contacts and loose connections were avoided.

- the CT positions were in order; the side marked P1 faced the MAINS while the side marked P2 faced the LOADS.
- the cable connections of S1 and S2 of the CTs were connected the correct way.
- the meter was queried to ascertain that the display parameters conform with the requirements specified by the Nigerian Electricity Regulatory Commission (NERC, 2013).
- the date and time displayed by the meter synchronized with real-time.
- there was no meter current ratio and CT ratio mismatch.
- the programmed VT ratio was unity.
- the phasor display was in order and the phases were correctly in sequence (L_1- L_2- L_3).

(ii) Burden checks

The ohmic load connected to the secondary terminals of a CT is called its "burden", usually specified in VA (ABB, 2004; Siyakumar, 2007). This burden includes the energy meter burden and cable burden. For better performance of the CT, the burden imposed on it should not be higher than the rated value. According to ABB (2004) and Parmar (2011), the cable burden (Cb) is given by:

$$C_b = I^2 \times R \times 2L \quad (3)$$

Where R is the cable resistance per length, I is the secondary current of the CT, and 2L is the to and fro distance of cable length "L" from CT to the metering circuit. The cable resistance per length is further expressed as:

$$R = \frac{\rho \times L}{A} \quad (4)$$

Where, p is the resistivity of the conductor material (given typically at +20°C), and A is the conductor cross-sectional area (CSA). The resistivity of copper is given by 0.0178 μΩm at 20 °C.

From the manufacturer's catalogue, the burden of the meter is 1.825 VA. The CSA of the cable used is 2.5mm2. The length (L) of the cable was measured to be 2 m. Using equation (4), the resistance of the conductor was calculated as 0.01424Ω. From equation (3), the burden of the cable is determined as 1.424VA. The total burden imposed on the CT is the summation of the energy meter burden and the cable burden and this gives 3.249VA which is within the acceptable value of 5VA on the CT nameplate.

(iii) Current ratio error checks

It is dangerous to bring down high voltage lines directly to energy meters. This can compromise the operator's safety, and also increase the size and cost of the instruments. In such a case, instrument transformers can effectively solve these problems by stepping down these high quantities (voltage and current) to safer levels for measurement (Purkait et al., 2013; Marian et al., 2014). Instrument transformers are either voltage transformers (VT) or current transformers (CT). A CT is an instrument transformer used to supply a reduced value of current to meters, protective relays, and other instruments and to also insulate the protection relays and energy meters, by galvanic isolation from the high voltage on the primary system (Jackson & Chang, 2017; Rampersad, 2010). CTs are basically of two types - those that are used for power system relay protection and those that are used for metering. In protection applications, one is concerned about the performance and errors of the current transformers when fault currents occur and under normal conditions, the errors are of no significance. On the other hand, metering application errors are of concern under normal conditions and not of concern when a fault or abnormal condition occurs.

The current ratio expressed in percentage arises from the fact that the actual transformation ratio is not equal to the rated transformer ratio. This CT's ratio error (δ) in percentage is determined by (Bessolitsyn et al., 2017):

$$\delta = \frac{K_n I_S - I_P}{I_P} \times 100\% \quad 5$$

Where, Kn represents the rated transformation ratio, Ip and Is are the measured CT primary and secondary currents respectively.

If the measurements were performed more than once, the measured primary and secondary currents are expressed as:

$$I_P = \frac{\sum_{i=1}^{n} I_{Pi}}{n} \quad 6$$

$$I_S = \frac{\sum_{j=1}^{n} I_{Sj}}{n} \quad 7$$

Where I_Pi (i=1, 2, 3,4,....n) is the measured primary current of the CT, I_Sj (j=1, 2, 3,4,....n) is the measured secondary currents of the CT, and n is the number of times the measurements were performed. Hence, equation (5) becomes:

$$\delta = \frac{K_n\left(\sum_{j=1}^{n} I_{\mathrm{Sj}}\right) - \left(\sum_{i=1}^{n} I_{\mathrm{Pi}}\right)}{n\left(\sum_{i=1}^{n} I_{\mathrm{Pi}}\right)} \times 100\% \qquad 8$$

The calculated percentage errors of the CT on the red phase, yellow phase, and blue phases were 1.82%, 3.89%, and 2.19% respectively.

(iv) Energy meter register test

The essence of this test was to ensure that the energy meter is recording the energy consumption accordingly. It is used to compare the energy consumption recorded by the meter and that which was estimated from the loads. For a three-phase sinusoidal signal, the electrical energy (E) in kWh is expressed as:

$$E = \frac{\sqrt{3} \times I_{av} \times V_L \times \cos\theta \times \frac{t}{60}}{1000} \qquad 9$$

where, I_{av} is the average line current, V_L is the line voltage, Cos θ is the power factor, and t represents the duration of energy usage in minutes. When this test is performed more than once, the expressions for average line current and line voltage are given in equations (10) and (11) respectively.

$$I_{av} = {}^{1}\!/_{3}\left\{\frac{1}{n}\left(\sum_{i=1}^{n} I_{Ri} + \sum_{j=1}^{n} I_{Yj} + \sum_{k=1}^{n} I_{Bk}\right)\right\} \qquad 10$$

$$V_L = {}^{1}\!/_{3}\left\{\frac{1}{n}\left(\sum_{p=1}^{n} V_{(R-Y)p} + \sum_{q=1}^{n} V_{(Y-B)q} + \sum_{r=1}^{n} V_{(B-R)r}\right)\right\} \qquad 11$$

Where $I_{Ri}(i = 1,\ 2,\ 3\ldots.n)$,$I_{Yj}(j = 1,\ 2,\ 3\ldots.n)$, and $I_{Bk}(k = 1,\ 2,\ 3\ldots.n)$, are loads measured on red, yellow, and blue lines respectively. $V_{(Y-B)q}(q = 1,\ 2,\ 3\ldots.n)$, $V_{(R-Y)p}(p = 1,\ 2,\ 3\ldots.n)$, and $V_{(B-R)r}(r = 1,\ 2,\ 3\ldots.n)$ are voltages measured between red and yellow, yellow and blue, and blue and red lines respectively, while n represents the number of times measurements were carried out. For identification purposes, the nomenclatures "red, yellow, and blue" were used to describe lines 1, 2, and 3 of the transformer's secondary side.

Combining equations (9), (10), and (11), energy in kWh can be estimated using equation (12):

$$E = \frac{\frac{1}{\sqrt{3}\times n}\left\{\left(\sum_{i=1}^{n} I_{Ri}+\sum_{j=1}^{n} I_{Yj}+\sum_{k=1}^{n} I_{Bk}\right)\left(\sum_{p=1}^{n} V_{(R-Y)p}+\sum_{q=1}^{n} V_{(Y-B)q}+\sum_{r=1}^{n} V_{(B-R)r}\right)\right\}\times \cos\theta \times \frac{t}{60}}{1000} \qquad 12$$

The power factor, Cos θ displayed by the energy meter was 0.996 and this was adopted throughout this analysis.

2.3 Installation Errors

A 3-phase, 4 wire CT-operated energy meter has six different input signals in addition to a neutral termination and must be connected correctly to measure energy accurately. Thus, there are three voltage inputs (LR, LY, and LB) that are connected to the three "hot" wires of the power system to be metered, and three current inputs (CTR, CTY, and CTB) which are connected to the three current transformers (CT). In this study, a CT is assigned negative (-) when its polarities are in reversed connection, and positive when the connection of its polarities is in order. At each connection mode introduced, measurements were carried out, and energy estimated from loads was computed using equation (12). Tables 2 and 3 show the percentage energy loss as computed.

In the case of mismatched current transformer ratio and meter current ratio, the energy meter readings are usually multiplied by a certain factor, commonly referred to as the multiplying factor (MF) to arrive at the exact energy consumption. The MF is determined by:

$$MF = \omega \,/\, \mu \qquad 13$$

Where ω represents the CT ratio, and μ represents the meter current ratio. Therefore, for a CT ratio of 300/5A and meter current ratio of 500/5A and 200/5A, the MF is 0.6 and 1.5 respectively.

3.0 Results and Discussion

The results of the loads and line voltages measured at the primary sides of the CTs for cases of reversal of CT polarities are shown in Table 1. While the results of the computation of the estimated energy consumption for the reversed CT polarities and mismatch in CT ratio and meter current ratio are shown in Tables 2 and 3 respectively. It can be seen from Table 1 that the minimum and maximum loads occurred on the blue phase and red phase respectively. The loads on the three phases are not balanced and this resulted in the current flowing through the neutral cable. A graphical view of this variation is presented in Figure 5.

Table 1: Measurement of primary current and line voltages

Test Conditions	I_R (Amps)	I_Y (Amps)	I_B (Amps)	I_N (Amps)	V_{R-Y} (Volt)	V_{Y-B} (Volt)	V_{B-R} (Volt)
No reversal of CT polarities	48.0	26.1	22.1	23.3	373.3	378.8	372.8
	59.0	28.3	23.0	38.4	374.0	379.0	373.0
	57.2	27.8	28.6	38.6	373.0	378.0	372.6
	53.5	28.1	27.8	33.3	374.0	379.0	373.4
Reversal of one CT polarities	34.9	27.1	23.5	25.7	374.1	376.8	373.4
	44.6	21.5	23.2	30.5	374.0	378.6	373.0
	59.9	15.9	18.7	47.5	373.0	377.3	372.6
	59.3	16.3	22.6	46.8	373.3	378.0	372.8
Reversal of two CTs polarities	59.9	16.5	22.4	25.5	372.8	377.3	372.6
	50.5	16.2	17.6	40.0	373.1	378.0	372.8
	58.0	16.4	17.6	46.7	373.0	378.6	372.0
	49.4	15.8	17.9	39.2	374.1	376.8	373.0
Reversal of all CTs polarities	49.5	16.2	17.7	39.2	374.0	376.0	373.1
	52.4	16.3	18.6	43.3	373.2	378.0	372.0
	56.6	16.0	17.5	47.7	372.6	377.2	372.0
	62.0	22.2	21.8	47.1	373.0	379.0	372.1

The difference between the energy estimated from the load and the energy recorded by the energy meter under normal operating conditions (that is, when no polarity of the CTs was reversed) is insignificant. The difference in values is due to the dissimilarity in calibrations and accuracy classes of the clamp meter, CTs, and the energy meter on which the test was performed. When no polarity of the CTs was reversed, the energy estimated for 15 minutes was 5.97 kWh, while the energy meter registered 6.00 kWh leading to an absolute error of 0.005 kWh. The results of the computation of errors for reversed polarities of the CTs are shown in Table 2.

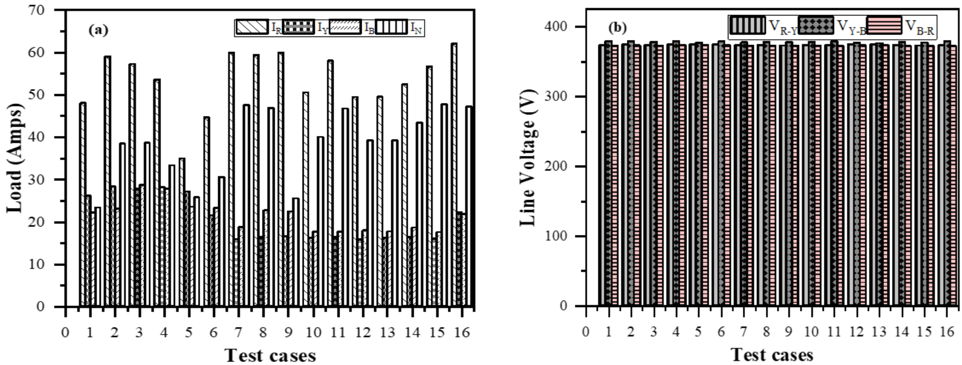

Figure 5. On-site measurement: (a) loads on each phase (b) Line voltages

Table 2: Computation of errors for reversal of CT polarities

Test scenario	Estimated energy (e_1) in kWh	Energy-meter reading (e_2) in kWh	$\boldsymbol{\varepsilon = \left\lvert \frac{e_2 - e_1}{e_2} \right\rvert \times 100\%}$
When one polarity of one CT was reversed	5.04	6.00	16.0
When polarities of two CTs were reversed	4.64	5.00	7.2
When polarities of all CTs were reversed	5.06	4.00	26.5

The results when the energy meter was reprogrammed to have current ratios of 500/5A and 200/5A respectively are shown in Table 3. With the CT ratio being greater than the meter current ratio, the energy meter registered a high reading and the reverse was the case when the CT ratio was less than the meter current ratio. Meanwhile, the relative error of a higher meter current ratio takes a negative sign, while a positive sign is obtained for the relative error of a higher CT ratio. This implied that, for a higher CT ratio compared to the meter current ratio, the customer will be under-billed by the power utility in converse to when the meter current ratio is greater than the CT ratio. In both cases, however, the multiplying factor expressed in equation (13) needs to be introduced to correct these anomalies.

Table 3: Computation of errors for mismatch of CT ratio and meter current ratio

Test scenario	Estimated energy (e_1) in kWh	Energy meter reading (e_2) in kWh	$\varepsilon = \left\|\frac{e_2 - e_1}{e_2}\right\| \times 100\%$
Meter current ratio of 500/5A	6.02	3.62	66.30
Meter current ratio of 200/5A	5.82	8.78	33.71

Figure 6 shows the graph of absolute percentage errors for the various connection modes. It can be seen that the conditions for mismatch in CT ratio and meter current ratio presented the largest energy loss in comparison with the conditions for reversal of CT polarities. An energy loss of 66.30% was recorded when the meter current ratio was 500/5A and the CT ratio was 300/5A. For a lower meter current ratio (200/5A), the loss of energy recorded was 33.71%. The largest energy loss recorded under the conditions of reversal of CT polarities was 26.5% and this occurred when all the CTs had their polarities reversed.

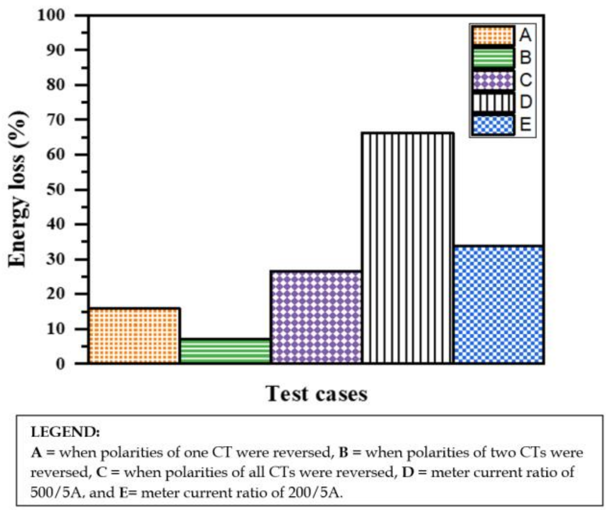

Figure 6. Absolute percentage errors for various connection modes

Hence, if the energy meter registers 2000 kWh in a month under the condition of a higher CT ratio compared to the meter current ratio, there is a tendency that 674.20 kWh of electricity will be lost. With the current electricity tariff of ₦69.70/kWh of the Abuja Electricity Distribution Company Plc for customers utilizing this category of energy meter on A-MD1, this is equivalent to losing about ₦46,991.74 in a month on one metering system.

4.0 Conclusion

In this study, mathematical models were used to determine the amount of energy loss under the conditions of reversed secondary polarities of the CTs, and the mismatch in CT ratio and meter current ratio of a low-voltage maximum demand energy meter. This analysis was conducted on a 300/5A CT-operated energy meter. The mismatch of CT ratio and meter current ratio presented the highest energy loss especially when the meter current ratio is greater than the CT ratio. The least energy loss was observed when the polarities of two CTs were reversed.

To curb these losses, it is vital for the meter installer and the power utility to ensure due diligence during the meter installations and also ensure that all the installed meters are commissioned instantly. Further studies could be concentrated on introducing more errors such as the cross-connection of the potential and current cables of the metering system to ascertain the magnitude of energy loss under such scenarios.

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