
A Technique for Electrical Energy Theft Detection and Location in Low Voltage Power Distribution Systems

Olusegun Mayowa Komolafe*, Kingsley Monday Udofia

Department of Electrical/Electronic and Computer Engineering, University of Uyo, Uyo, Nigeria

Email address:

segunkom@gmail.com (O. M. Komolafe), kingsleyudofia@uniuyo.edu.ng (K. M. Udofia)

*Corresponding author

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Abstract: In this work, we present a method for energy theft detection in power distribution networks—a problem in the Nigerian power system and an obstacle to national development—by network analysis. The focus was on radial systems with overhead distribution lines supported on poles. The power distribution network was modelled with typical parameters and consumer loads. In addition, a real network in Ekong Uko Street, Eket, Nigeria was surveyed and the physical structure modelled with simulated consumer and theft loads. The developed program was first initialized under conditions of no theft using the section line parameters and the actual voltage/current at each consumer node as would be reported by a smart tariff meter. The result of the initialization step is a matrix of consumer branch resistances which is stored for later use in the theft detection algorithm. Energy theft detection was achieved by comparing the actual voltages at each pole computed by propagation from all connected consumer nodes using the stored branch resistances. Differences were identified as indicators of theft and were further processed to estimate the power consumed. The result showed a dependence of detection accuracy on location of theft, relative magnitude of theft and network conditions. Minimum power theft that could be detected was between 10 W to 260 W and varied with the theft location. Accuracy in actual power consumed detection of 96% to 100% was obtained. Utility companies will find this work useful in detecting power theft in their secondary power distribution networks to arrest revenue loss.

Keywords: Power Distribution, Electric Energy Theft Detection, Non-Technical Loss, Power Losses, Power System Modelling, Power Theft Estimation

1. Introduction

In this modern world, energy has become a basic necessity for national development; its availability in the required quantity enables reduced work hours, better agricultural yield, optimized industrial production, superior health conditions, more reliable transportation infrastructure/machines and even more nourishing diets [1-2]. Different forms of energy exist but electrical energy is by far superior to other forms of energy due to its ease of conversion/control, lower cost, transmission efficiency and reduced pollution [3]. Generally, development indicators tend to increase with improved electric power availability [4]. For example, Figure 1 shows that there is a positive correlation between electric power consumption and Gross Domestic Product (GDP) in Nigeria; a similar connection exists at the individual level, hence the desire for more electricity is understood. However, some persons choose to meet this

need by pilfering electricity thereby creating a problem of non-technical losses in the power system.

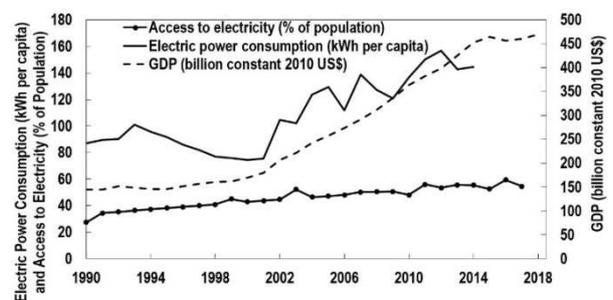


Figure 1. Correlation of electric power consumption with national development in Nigeria. Source: Developed by the researcher using data from [5].

Losses cannot be eliminated in the generation,

transmission and distribution of electric power since the very equipment used for this purpose are non-ideal [6-7]. For example, generators/transformers have losses due to their winding resistance, hysteresis and eddy current; transmission lines have corona losses at higher voltages; distribution lines have thermal (I^2R) losses; cables have dielectric losses and even tariff meters have associated losses [8]. These losses due to the non-ideal nature of the electrical equipment are known as technical losses; they can be estimated from the load flow study and minimized through the use of more efficient equipment/designs [9]. The other category of losses in electric power system is known as non-technical (or commercial) loss; this is the category to which energy theft belongs. Non-technical losses are generally external to the power utility; other sources include inaccurate billing, unpaid bills and defective metering equipment [10]. These losses, energy theft being the chief, cannot be readily computed and represent a major channel for revenue loss in power utilities. For example, in 2014, it cost the Malaysian utility \$229 million [10] and it is estimated that it costs the USA/global power industry \$6 billion/\$25 billion annually respectively [11]. In Nigeria, a composite term called the Aggregate Technical and Commercial Collection Losses (ATC&C) is used to quantify the total power system losses; a staggering 56% of the total electric power output was reported as lost in the period from January 2015 to May 2018 [12]. A study on a typical Nigerian power station [6] showed that non-technical losses far exceeded the technical losses; Port Harcourt Electricity Distribution Company in Nigeria reported a monthly loss of N233 million [13].

Electricity theft has been defined as the illegal use of electric power with the intent of evading tariff payment [13]. Illegal use of electricity is reckoned to have happened when: consumption is done without a contract, the metering equipment is bypassed or the meter is tampered with in order to alter the readings; the main objective being to save money [14]. Timely detection of ongoing energy theft is important not only for the purpose of punishing the offenders but also to immediately interrupt the illegal activity. Considering its enormity and global scale, a lot of research has been done towards automatic detection and location of electric energy theft.

In [15], having established that energy theft was responsible for about 20%–30% of the overall power utility loss in India, a solution was proposed by coupling a 150 kHz power line carrier signal into the distribution network at the sending end and monitoring the amplitude at different points along the distribution line; changes in amplitude between poles are attributed to energy theft. For each legitimate consumer, a filter circuit is applied to remove the high frequency signal before passing the low frequency power signal to the home; illegal consumers will not have this filter equipment and as such, according to the authors, will dissipate the high frequency signal, leading to attenuation and reduction in amplitude which is used to detect energy theft. The potential interference/noise issues

might be a challenge for this approach

Use of mobile wireless communication (GSM) in conjunction with smart meters with tamper detection hardware/software was proposed in [16]. The lack of utility control over the GSM network is a drawback of this solution.

The use of a master meter outside the reach of the consumer for the purpose of verification of either a single meter or a group of meters, is the subject of [8, 10, 17-19]. This method translates into increased cost and will not be able to detect energy theft through direct hook-up by illegal customers without meters.

The statistical data analysis approach proposed in [20] is based on the premise in [21] that electricity bills follow Benford's law. Combining this with a Stackelberg game model, the authors analyzed the consumption data logged from smart meters to detect compromised meters. A similar approach described in [22] uses linear regression while in [23], an advanced metering infrastructure intrusion detection system (AMIDS) that combines consumers' power consumption data with event/diagnostics data from the smart meters is used to detect energy theft by cyberattack. Illegal connections, which report no data, will go undetected by these methods.

The network analysis method adopted in [24] was applied only in determining technical losses with a reported error of $\pm 9\%$ for the LV feeder. Use of neural networks was explored in [25-27] but the approach has high deployment time because of the need to gather training data.

In this paper, we present a simple method of electricity theft detection and location in a smart grid using network analysis tools. The solution is specifically suited for the Nigerian radial residential low voltage distribution network where installation of additional transformers/transformer tap change is the generally adopted method of voltage control. Modelling/simulation was done with MATLAB.

The rest of this paper is organized as follows: in Section 2, we describe the network structure, model and parameters used for network analysis; Section 3 contains the theft detection model including the five unique cases that were analyzed; the results from a case study network is presented in Section 4 while conclusions and references make up Sections 5 and 6 respectively.

2. Distribution Network Structure and Model

An overhead radial network is selected for this work based on the typical installation in the Nigerian power distribution system as shown in Figure 2. The transformer is modelled in as an alternating current power source with unbounded capacity; this is because the reaction of the transformer is not of significance in this work. The distribution line conductors are made of bare aluminium; the impedance consists of the line resistance, which is obtained from manufacturers' data books as well as the inductance which is a function of the

conductors' physical dimensions and the geometrical

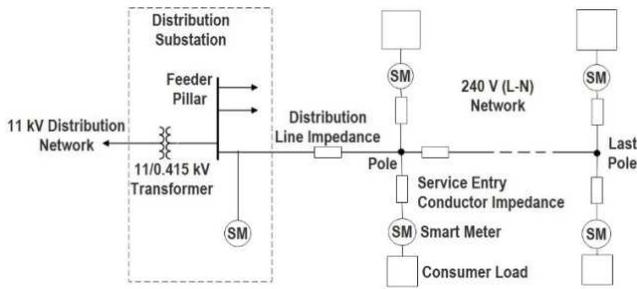


Figure 2. Distribution network structure.

layout (line capacitance is not generally considered for the overhead distribution lines [28]). Further, for the residential distribution network, non-inclusion of the line inductance does not significantly affect the results [29]; the distribution network was therefore modelled as a short line with the impedance computed for each section. The same treatment is applied to the service entry conductor although its impedance value is assumed to be unknown and is determined through the algorithm presented in this work. Consumer loads are connected to the network at poles; the loads are modelled as a mix of constant impedance and constant power loads. The smart meter for each consumer will transmit time-stamped values of the load current, voltage and other parameters to the central station for the network analysis; the meter at the distribution station transmits the total current drawn from the transformer and the terminal voltage

2.1. Parameters for Network Analysis

Figure 3 shows the network labelled with parameters to be used for the network analysis; a description of each parameter is provided in Table 1.

2.2. Description of the Algorithm

The approach is to detect the differential change in the pole node voltage caused by energy theft. For example, under no-theft conditions, projecting from node $N_{1,2}$ to obtain pole node voltage V_1 gives (1).

$$V_1 = V_{1,2} + I_{1,2}R_{b1,2} \tag{1}$$

Table 1. Network parameters naming nomenclature.

Parameter	Meaning
N_x	Node number x; the poles are identified as nodes and numbered serially
$N_{x,y}$	Consumer node number y connected to pole x.
$V_{x,y} / I_{x,y}$	Voltage / current at node x_y. Known for consumer nodes but calculated for pole nodes.
R_{pn}	Impedance between pole node n and node n-1. Value is known.
$R_{bx,y}$	Impedance of the service conductor from pole x to consumer node x_y. Value is unknown but calculated in the algorithm.

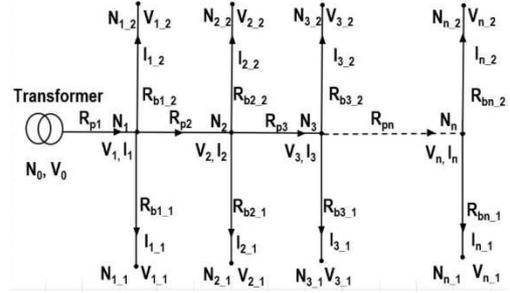


Figure 3. Network analysis diagram.

The same voltage can be projected from N_0 and $N_{1,1}$ to give (2) and (3) respectively.

$$V_1 = V_{1,1} + I_{1,1}R_{b1,1} \tag{2}$$

$$V_1 = V_0 - I_1R_{p1} \tag{3}$$

These computed pole node voltages will be equal except when there is energy theft through an unauthorized connection at one of the nodes

3. Energy Theft Detection Model

A pre-condition for energy theft detection is that a procedure which we have called initialization, is completed under conditions of no-theft. In the initialization process, the pole node voltages are computed using (3) and Kirchhoff's Current Law (KCL) repeatedly along the line. The consumer branch resistances are then computed using (1) or (2) and stored for use in the theft detection algorithm.

The first indication of energy theft is afforded by (4) after which the specific location is determined on the premise that there is one theft occurring at a time. Five unique theft connection cases were identified.

$$\sum_1^n \sum_1^m I_{n,m} \neq I_1. \tag{4}$$

3.1. Case 1—Theft at a Consumer Branch

Depicted in Figure 4; this also covers a case of partial or complete meter bypass. The unauthorized connection at point T results in an unknown current $I_{1,2T}$ being drawn; branch resistance up to point T is $R_{b1,2T}$. The pole node voltage, V'_1 calculated using (1) with the reported consumer current $I_{1,2}$ (without knowledge of theft) will differ from the true pole node voltage, V_1 (projected from other consumer nodes connected to the same pole) by a quantity $I_{1,2T}R_{b1,2T}$ (we will label this as V_t). If \mathbf{V} is the vector of computed voltages for a particular pole node, (5) to (10) enable theft location and estimation of power consumption; where $L_{1,2T}$ is the distance from the pole to the theft point and P_t is the estimated theft power.

$$V_t = \max(\mathbf{V}) - \min(\mathbf{V}) = I_{1,2T} R_{b1,2T} \tag{5}$$

$$I_2 = \frac{V_1 - V_2}{R_{p2}} \tag{6}$$

$$I_{1,2T} = I_1 - I_{1,2} - I_{1,1} - I_2 \tag{7}$$

$$R_{b1_2T} = \frac{V_t}{I_{1_2T}} \tag{8}$$

$$L_{1_2T} = \left(\frac{R_{b1_2T}}{R_{D1_2}}\right) L_{1_2} \tag{9}$$

$$P_t = I_{1_2T} (V_1 - (I_{1_2} + I_{1_2T}) R_{b1_2T}) \tag{10}$$

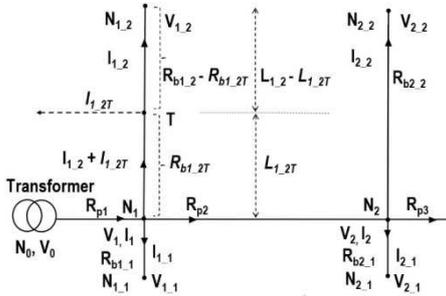


Figure 4. Distribution line with theft at a consumer branch.

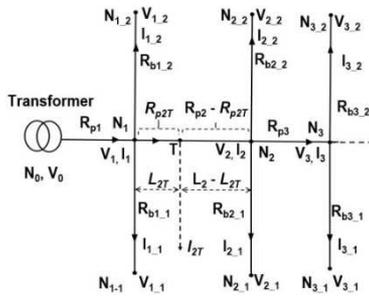


Figure 5. Distribution line with theft between pole nodes.

3.2. Case 2—Theft at a Singly-Connected Branch

This covers cases where only one consumer is connected to a pole node; we simply propagate from the succeeding or previous pole node to obtain additional pole node voltages for comparison and proceed as in Case 1.

3.3. Case 3—Theft Between Pole Nodes

This is illustrated in Figure 5; energy theft at point T, which is at a distance of L_{2T} from pole node N_1 , results in flow of unknown theft current I_{2T} . The length of the section N_1 - N_2 is L_2 and the resistance of the conductor between N_1 and theft point T is R_{p2T} . Let the calculated current flowing in the section N_1 - N_2 (using the reported consumer load currents with no knowledge of energy theft) and entering the node N_2 be I_2' and the associated node voltage at node N_2 be V_2' . The actual current reaching N_2 is still I_2 (though $I_2 + I_{2T}$ is leaving N_1) and the actual node voltage is still V_2 . Detection and location of the theft is accomplished by application of (11) to (15).

$$V_t = V_2 - V_2' = I_{2T} (R_{p2} - R_{p2T}) \tag{11}$$

$$I_{2T} = I_1 - I_{1_1} - I_{1_2} - I_{2_1} - I_{2_2} - I_3 \tag{12}$$

$$R_{p2T} = R_{p2} - \frac{V_t}{I_{2T}} \tag{13}$$

$$L_{2T} = \left(\frac{R_{p2T}}{R_{p2}}\right) L_2 \tag{14}$$

$$P_t = I_{2T} (V_1 - (I_2 + I_{2T}) R_{2T}) \tag{15}$$

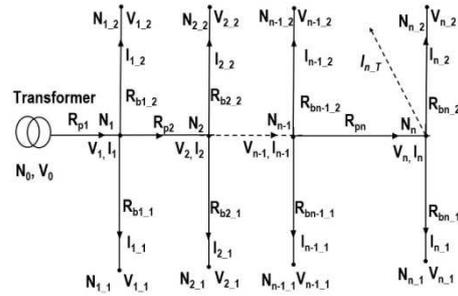


Figure 6. Distribution line with theft at the last pole node.

3.4. Case 4—Theft at a Pole Node

It is treated as a special instance of Case 3 with L_{2T} and R_{2T} being zero; the algorithm described for Case 3 is sufficient for detection and location of this theft.

3.5. Case 5—Theft at the Last Pole Node of the Network

The theft current I_{n_T} (see Figure 6) cannot be detected using the methods described in the previous section because there is no succeeding pole at which to evaluate the node voltage for comparison. Since this is the last pole of the network and all preceding quantities are known, we proceed using (16) and (17).

$$I_{n_T} = \frac{V_{n-1} - V_n}{R_{pn}} - I_{n-1} - I_{n-2} \tag{16}$$

$$P_t = I_{n_T} V_n \tag{17}$$

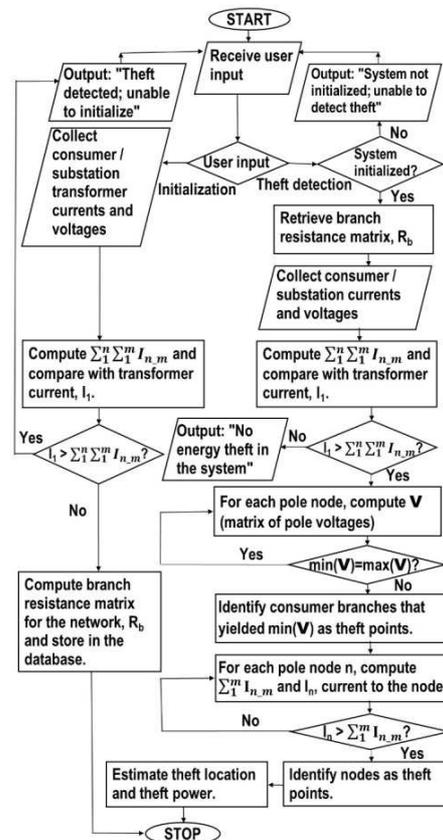


Figure 7. Flowchart of the theft detection algorithm.

Pole	Branch 1			Branch 2			Branch 3			Branch 4		
	Load (kW)	L (m)	R (mΩ)	Load (kW)	L (m)	R (mΩ)	Load (kW)	L (m)	R (mΩ)	Load (kW)	L (m)	R (mΩ)
25	0.85	10	19.10	2.7	12	36.96	-	-	-	-	-	-
26	1.9	10	19.10	-	-	-	-	-	-	-	-	-
27	4.2	11	21.01	0.9	13	40.04	-	-	-	-	-	-
28	1.2	13	24.83	3	12	36.96	3.5	18	82.98	-	-	-

The system was modelled in MATLAB (Simulink) on a balanced system basis (Figure 9); no physical construction was done. Subsequently, the initialization program was customized for the network configuration and run to obtain the branch resistance matrix. The result, as shown in Figure 10 and Figure 11, indicates a 100% accuracy in branch resistance calculation (the values in the model are labelled as “actual values” while the values returned by the theft detection algorithm are labelled as “calculated values”).

4.2. Energy Theft Detection and Location

In the next step, synthesized theft loads were connected to different points of the modelled network and the theft detection program was run to detect and locate the theft points. The theft loads inserted in the model are labelled as “actual

theft” while the values detected independently by the theft detection algorithm are labelled as “detected theft”. As seen in Figure 12 and Figure 13, theft location accuracy greater than 94% was obtained. Note that the only input to the theft detection algorithm is the matrix of consumer/transformer currents and voltages as would be reported by smart tariff meters.

4.3. Sensitivity Analysis

With all other conditions maintained constant, the theft load at each theft location was reduced in steps in order to estimate the minimum value that can be detected. The result as presented in the presented in Figure 15 shows a variation in the minimum detectable theft power from 10 W to 260 W.

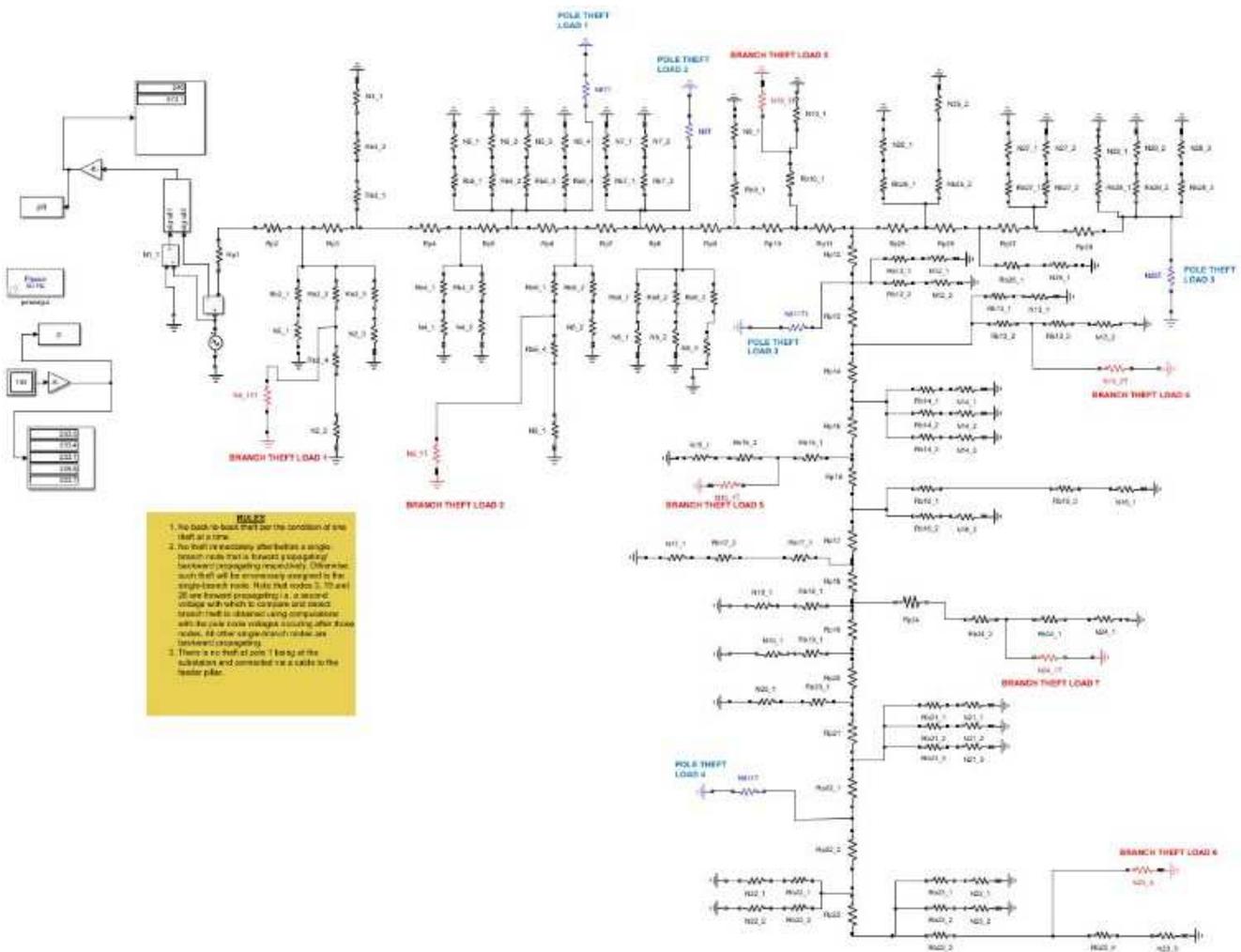


Figure 9. MATLAB model of Ekong Uko distribution network.

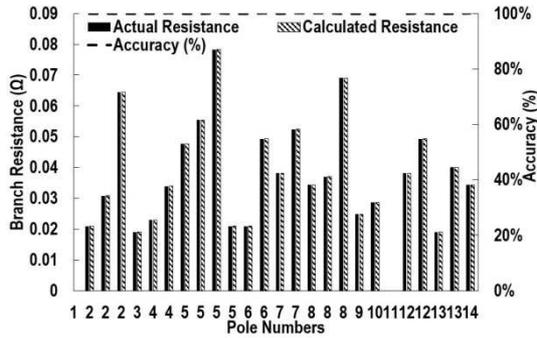


Figure 10. Plot of actual vs calculated branch resistances (consumer nodes 1 of 25). Note that some poles have no connected consumers.

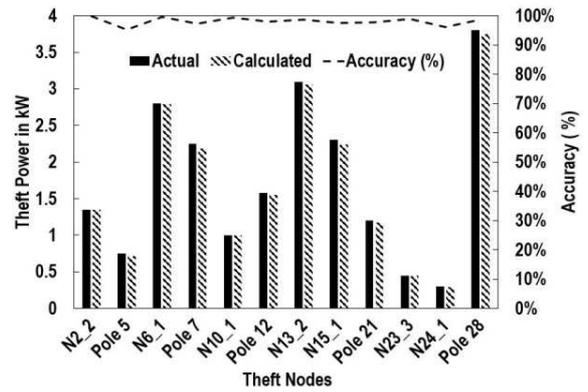


Figure 14. Estimate of theft power.

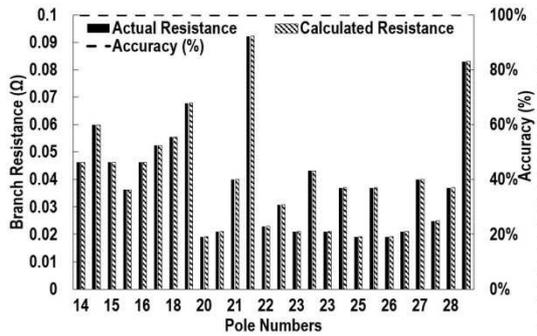


Figure 11. Plot of actual vs calculated branch resistances (consumer nodes 25 to 50).

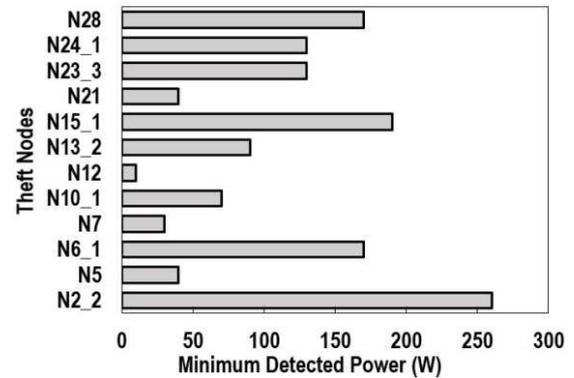


Figure 15. Minimum detected power at theft locations.

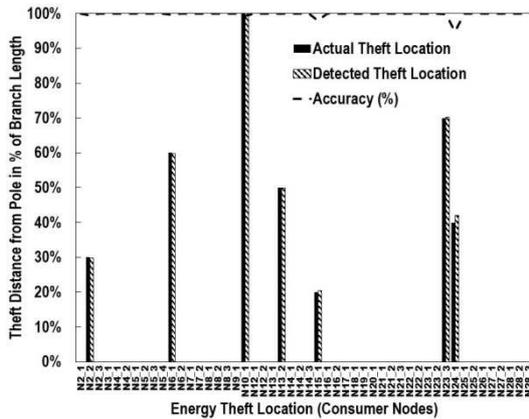


Figure 12. Detection of theft at consumer nodes.

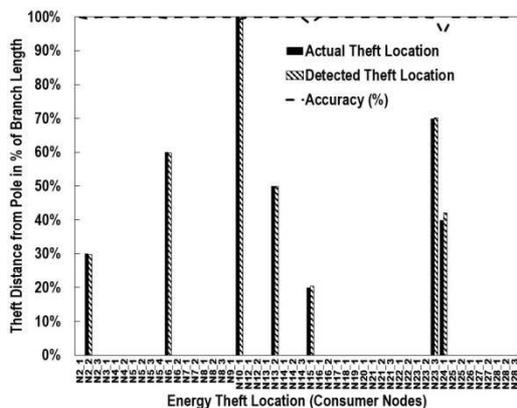


Figure 13. Detection of theft at pole nodes.

5. Conclusion

Electric energy theft is a global problem, combating it should be a critical task especially for a developing country like Nigeria that generates less than 30% of the national demand [35] and yet more than 50% of the paltry sum is lost. In this paper, we have described a technique for energy theft detection using data obtained from smart meters to compute the consumer branch impedances and then detecting inconsistencies in pole node voltages to locate theft points. Application of the technique to a case study distribution network of Ekong Uko Street in Eket, Nigeria showed accuracy of theft location above 94% with the minimum detectable theft power at a node being in the range of 10 W to 260 W. Adoption of this technique in a distribution automation system will result in gains for the power utility.

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