LAUTECH Journal of Engineering and Technology 19 (1) 2025: 102-109
10.36108/laujet/5202.91.0190

Energy Theft and Fault Detection in Smart Energy Meter using Fuzzy Logic

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Article Info

Article history:

Received: Jan. 7, 2025
Revised: Jan. 30, 2025
Accepted: Feb. 10, 2025

Keywords:

Fuzzy Logic,
Intelligent systems,
Internet of Things,
Non-technical losses,
Smart meters,

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ABSTRACT

Energy theft and fault are significant global issues in the energy sector, which account for non-technical losses in power utilities. Specifically, in the Nigerian context, energy theft arises from meter tampering to reduce energy consumption readings, unauthorized or illegal connections, and meter swapping. The nexus of the Internet of Things and Fuzzy logic learning techniques applied in smart metering systems could mitigate this endemic problem. While there are efforts in the literature that address this problem, there is still a need for an optimal and smart metering system with increased intelligence and accuracy to address energy theft and fault detection problems in distribution networks. Hence, this work presents a solution to energy theft and fault detection in the distribution network by designing a smart-energy metering system that applies simple fuzzy logic rules to analyze data thereby detecting theft and fault in the system. The system compares the measurements from a pole-based smart meter and a consumer unit meter for the detection of faults and theft. The metering devices at the pole and consumer ends as well as the consumer mobile phones are all connected to a central cloud via the Internet for analysis, processing, and monitoring. The result shows that Fuzzy logic can be applied to incorporate a level of intelligence in smart metering systems which can be used to solve energy theft and fault detection problems. Performance evaluation was measured in terms of accuracy and precision calculations from the observations through repeated experiments. The accuracy and precision are 95% and 95%, respectively for energy theft as well as 91% and 95% for fault detection.

INTRODUCTION

Electricity in the modern world today is indispensable and has formed a very significant part of human life. Hence, the increase in demand has also brought about a rise in energy theft and fault occurrence. Energy theft can be described as an illegal use of electricity which is considered a significant global issue affecting the energy sector. According to a report from Distribution Companies (DisCos) in Nigeria, energy theft accounts for approximately 10 to 18 percent of their total monthly revenue losses (Nextier Power, 2023). Specifically, it leads to substantial financial losses for utilities and compromises the reliability of the grid. In Nigeria, research conducted estimated that energy theft costs the power sector approximately N21 billion annually (Osigwe *et al*., 2018). This can be attributed to the fact that in some regions, energy theft could require an increase in power generation due to abuse of power consumption because it is "free energy". This escalation in consumption can lead to transformer overload and can affect the system lifetime generally which can lead to faults later (Arango *et al*., 2016).

Faults are a disturbance in energy systems and can have significant consequences which lead to unreliable power systems. Fault impact can lead to interruptions and inconsistencies in power delivery, causing energy wastage leading to increased costs and environmental impact. Implementing early detection and diagnostic systems will prevent equipment damage, and accidents, and accordingly avoid costly repairs and potentially hazardous situations. A reliable power system is a system that performs satisfactorily under specific conditions during a given period. Therefore, protection devices are designed to monitor the system status and de-energize them by tripping the circuit breaker when there is a fault (Somefun, 2015). These devices are designed to be fast, reliable, and smart.

The European Smart Metering Alliance (ESMA) (Koponen *et al.,* 2008) describes a smart electricity meter as one that automatically processes, transmits, manages electricity data, enables two-way communication between meters, delivers timely and valuable energy consumption information and supports enhanced energy efficiency and the optimization of energy management systems (generation, transmission, distribution, and usage).

Fuzzy Logic is a mathematical theory introduced by Lotfi Zadeh in 1973 to break down vague inputs into precise output using linguistics rules. It transforms the "fuzzy" terminology into numerical values, performs reliable operations upon those values and then returns to natural language statements in a reliable manner (Onur *et al*., 2023). It is usually applied in decision-making where ordinary theories cannot give the output needed in a Fuzzy environment. FL is simply a method of enhancing computers to think more like humans to break down data to get a solution. Therefore, technological advancement has led to the discovery of methods to efficiently manage energy using Fuzzy Logic (FL) due to its simplicity in implementation in smart energy meters which has more advantages over traditional energy meters. Four derivative functions make up an FL. They are:

1. The membership function (MF)
2. Fuzzy sets
3. Fuzzy logical operators
4. Fuzzy rules

The rationale behind the application of FL to smart meters is to simplify the complexity that comes with modern energy grids. Implementing these enhancements leads to the design of an optimized meter. In this system, data acquired through current and voltage sensors will be transformed into actionable insight for decision-making and intelligence. Algebra, statistics and probability are the mathematical basis of these theories (Nuthakki *et al*, 2022). FL uses the values 0 and 1, false and true to break down a complex input to an output. To solve various problems with the aid of FL, learning on the part of the machine is required to understand the data (Yunior and Kusrini, 2018).

RELATED WORKS

Adhikari (2016) presented a study with a result that proves that uses fuzzy logic to detect the type of fault at high speed by using LabVIEW software which classifies transmission line fault by applying Programmable Automation and Control technology based National Instrument Compact Reconfigurable Input/Output (CRIO) devices.

Salik *et al*. (2016) presented a simple and effective smart meter technique to detect theft and function as a protective relay. Each smart meter monitors the load profile of the customer and sends a reading to the acquisition center wirelessly where the proposed algorithm is applied to detect theft or fault scenarios. The results showed that the system was able to differentiate between theft and fault signal and it was reliable and efficient.

Bhujbal *et al.* (2017) designed a fuzzy logic theft detection software model using MATLAB program to compare the total load supplied by distribution transformers and the total load used by the consumer and the difference is used to identify the power theft which is used to provide quality power.

Kunal *et al*. (2017) constructed a fuzzy logic-based smart detector working with a logic principle to detect a gas leak and prevent a fire outbreak. It also can avoid false alarms before there is an actual fire.

Palaniyappan (2019) developed a Neuro-Fuzzy logic-based meter to detect electrical power theft. This model allows the utility company to know the quantity of theft power, the exact location of the theft zone and controlling of theft in the location. It was concluded that the technique worked as it detected theft without any human interface.

Blazakis *et al*. (2020) studied the application of an intelligent algorithm using an adaptive Neuro Fuzzy Inference System (ANFIS) on a robust distribution system to detect energy theft. The result showed that if applied properly it could achieve very high success rates in various cases of fraudulent activities.

Cen *et al.* (2021) used FL to analyze energy consumption to determine energy demand by evaluating the consumption data by using a discrete wavelet transform (DWT), Principal Component Analysis (PCA) and Fuzzy C-Means (FCM) clustering algorithm to segment preserved features. This algorithm helped to decrease the computational complexity of the large dimensional data.

Mohammed (2024) used FL to address the complexity and uncertainty found in the usage of energy at home. The energy usage patterns and user behaviors in Saudi Arabia were observed, and the FL technique was used to analyze the data. This was a success, and it was discovered that FL has several benefits for Saudi Arabian residential construction.

Several research efforts have attempted to improve the accuracy and latency of the smart meters in the detection of theft and fault, however, there is still a need for improvement in terms of latency and accuracy. Hence, this paper builds on the works of Bhujbal *et al.* (2017), Cen *et al.* (2021) and Salik et al. (2016) by adopting the FL analysis techniques to detect theft and fault in a power distribution system.

METHODOLOGY

The proposed system comprises a Pole-based, and a Consumer-based metering unit linked up to a central server as shown in Figure 1. These two units consist of metering devices made up of voltage (ZMPT101B) and current sensors (ACS 712), microcontrollers, and WI-FI modules (ESP8622). Through communication links, data from the pole-based system is continuously compared with the consumer-based system. If there is any major difference between the measured data at both ends, it indicates a likelihood of energy theft or a fault. In this paper, a Fuzzy Logic rule was developed and applied to the smart meter. In the event of a fault or theft, a notification is sent to the consumer and the energy service provider, indicating the possibility of theft. Communication between the pole-based microcontroller, the consumer-based controller, and the cloud server is via an internet service provider. Furthermore, in the event of deliberate tampering with the pole-based and consumer controllers, the power (Vcc) of the microcontroller is periodically checked to ensure it has not been shut down due to a power outage. An alarm would be triggered in the event of a power failure in the controller. Finally, the administrator or consumer can track the system from a mobile phone using the Blynk app, allowing for real-time monitoring of the entire system.

Figure 2 Proposed Fuzzy Logic System Overview

The FL theorem relevant to these functions is the Fuzzy Decision Tree. It is used to predict a time series data value based on one or more input variables.

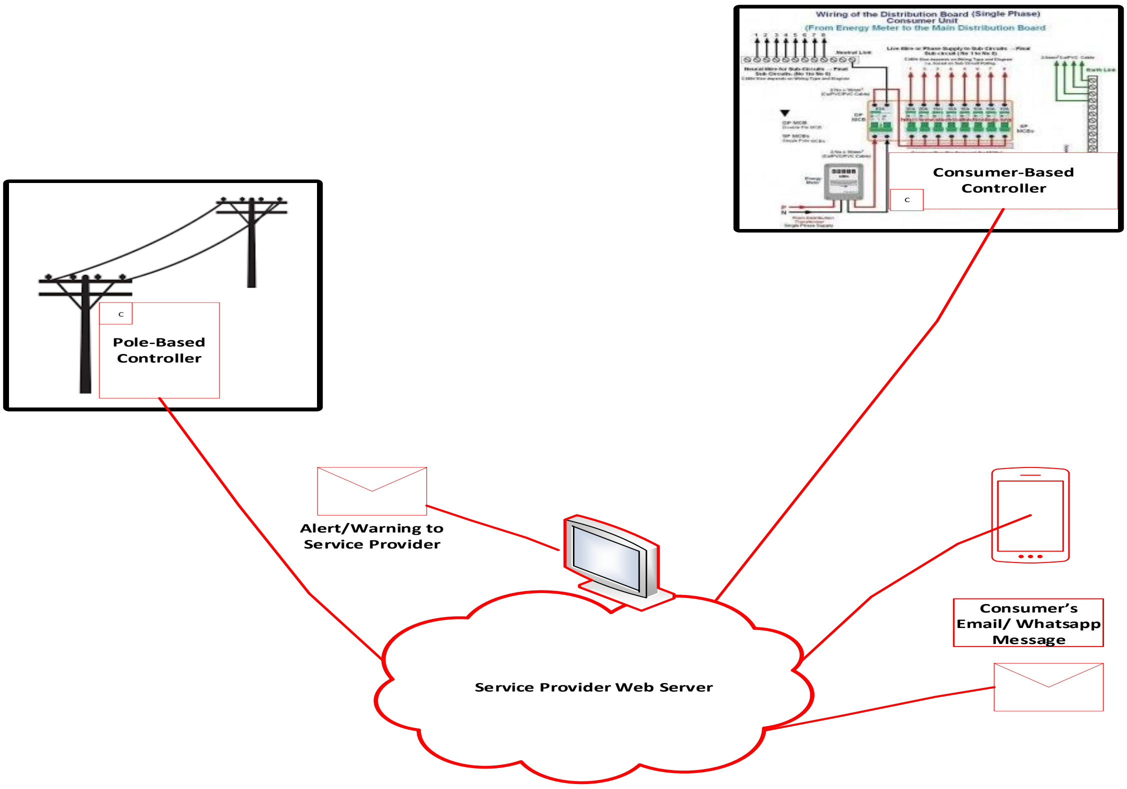

Figure 1 Proposed Framework for Energy Theft and Fault Detection using Fuzzy Logic

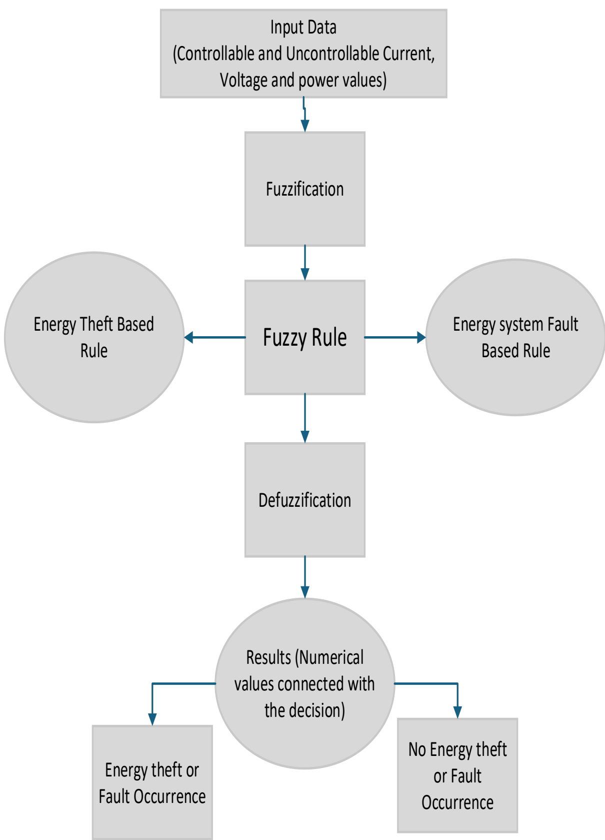

Figure 2 Proposed Fuzzy Logic System Overview

The goal of the model is to identify the relationship between the input variables and the output variable and use that relationship to make decisions about the output variable (Begenova and Avdeenko, 2018).

Figure 3 Implementation of the Proposed Model

Using Fuzzy Logic, the voltage and current data were analyzed as shown in Table 1 and Table 2:

Table 1 Fuzzy Logic for the Voltage

Voltage at the Pole unit (Vp)	Voltage at the consumer unit (Vc)	Outcome
0	0	Normal Condition
0	1	Not Possible
1	0	Fault (Short circuit)
1	1	Normal condition

Here,

0= Unavailable value of Voltage

1= Available Value of Voltage

Table 2 Fuzzy Logic for the Current

Current at the Pole unit (Cp)	Current at the consumer unit (Cc)	Outcome
0	0	Normal Condition
0	1	Not Possible
1	0	Fault (Short circuit)
1	1	Normal condition

Here,

0= Unavailable value of Current

1= Available Value of Current

The theft performance evaluation of the proposed model on the raw data is processed using this mathematical model:

$\Sigma Cp = \Sigma Cconsumed + Loss$ (it means No Theft)

$\Sigma Cp < \Sigma Cconsumed + Loss$ (it means Theft Occurred)

$\Sigma Cp > \Sigma Cconsumed + Loss$ (it means Theft Occurred)

Here,

Cp = Current measured by pole side energy meter

Cconsumed = Current measured by load side energy meter

Final Testing and Validation

The model was tested using the design objective requirements.

Testing the Input Sensor Readings

Using multimeter readings as a reference, the energy meter voltage and current reading sensors at no load are shown in Table 3 and Table 4:

Table 3 Voltage Sensor Accuracy Table

Actual Voltage Value	Measured Voltage Value	Observed Accuracy= (1 – (|A-M|/A)) (%)	Expected Accuracy at (220V)
223-224V	219-226 V	99.77%	98.4%

Table 4 Current Sensor Accuracy Table

Actual Current Value	Measured Current Value	Observed Accuracy= (1 – (|A-M|/A)) (%)	Expected Accuracy using (220V)
0.536	0.54A	99.2%	99.1%

Using the formula:

P=IV where P is Power, V is Voltage, and I is the current. The current value for a 60W incandescent bulb is 0.268A while for two bulbs it is 0.536A and the measured value for the prototype using the Arduino calibration value is shown in Table 5 and Table 6:

Table 5 Current Sensor Theft and Fault Detection

Description	Voltage before Load	Current before Load	Voltage after Load	Current after Load
Values	219-226V	0.04A	219V	0.54
Comment	No theft			

Table 6 Voltage Sensor Theft and Fault Detection

Description	Voltage after theft	Current after theft	Voltage after Open circuit	Current after Open circuit
Values	224	1.09	0	0
Comment	Theft Occurred		Fault occurred	

Taking 24 samples of measured data set with a mixture of theft and fault scenario programmed, the Performance Metrics are shown in Tables 7 and 8:

Table 7 Theft Detection Matrix Table

Confusion Matrix	Predicted Normal Theft	Predicted No Theft
Actual Theft	20 (TP)	2(FN)
Actual No Theft	1 (TN)	1 (FP)

Table 8 Fault Detection Matrix Table

Confusion Matrix	Predicted Normal Fault	Predicted No-Fault
Actual Fault	21 (TP)	1(FN)
Actual No-Fault	1 (TN)	1(FP)

Table 9 Performance Metrics Result

Performance metrics	Theft Detection Percentage (%)	Fault Detection Percentage (%)
Precision = TP/(TP+FP)	95	95
Recall = TP / (TP + FN)	95	95
F1-score= 2 * (Precision * Recall) / (Precision + Recall)	95	95
Accuracy= (TP+TN)/(TP+TN+FP+FN)	95	91
MCC= (TPTN - FPFN) / sqrt((TP+FP) (TP+FN) (TN+FP) (TN+FN))	73	71
Mean Absolute Error (%)	8.3	8.3
Reliability coefficient = TP+TN/ (No of Samples)	95	91

Therefore, the accuracy of the model was 95% for theft detection and 91% for fault detection, while the precision was 95% for both theft and fault detection.

CONCLUSION

This work successfully developed a model for energy theft and fault detection in a single-phase smart energy meter. The model was tested under several theft and fault operational requirements and the performance is with an accuracy of 95% with a little lagging due to Wi-Fi signal weakness and device calibration errors. The utility providers can only disconnect the power line remotely and reconnect the power line physically. Fuzzy logic was applied in this work to detect theft and fault.

The work can be improved in the future by adding the following capabilities such as detecting energy theft on the high-voltage transmission line before the consumer distribution board detects the electricity theft and by comparing other Machine Learning algorithmic applications with Fuzzy Logic applications.

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