

# Rogowski Coils for Design of Energy Meters for Nigeria Power Market

John Paul I. Iloh

**Abstract**—Proper metering of electricity consumption is the optimal way for effectively recovering revenues for power supplied to the consumers by the distribution companies (DISCOs). In Nigeria, the situation is quite problematic due to inadequate metering of the consumers. As a result, huge amount of revenues due to the DISCOs are left uncollected leaving the DISCOs to resort to estimated billing system. To solve this problem, this paper proposes a locally made digital energy meter built from locally available materials in Nigeria. Specifically, this work proposes to use an inexpensive rogowski coil wound from made-in-Nigeria wire on an improvised air core material as the current sensing element to be used in the meter. Two rogowski coil samples wound from SWG 36 and SWG 25 wires having resistances of 50ohm and 1.3 Ohms respectively were subjected to repeated experimental tests in order to study their characteristic behavior under varying load current scenarios. The results obtained were used to characterize the coils behaviors by using the basic fitting tool in MATLAB graphing window to generate the optimal equation representing the coils' behaviors. The equations so obtained are intended to be used to program the microcontroller for implementation of the Digital Energy Meter algorithm adopted in the proposed design. Results from the experiment showed that the coil with lower resistance exhibited better linear response while the coil with higher resistance was better optimized by quadratic and cubic polynomials. These findings serve as design guide for local fabrication of the rogowski coils to be used in the proposed digital energy meter being developed for the Nigerian power market.

**Index Terms**—Rogowski Coil, Current Sensing and Measurements, Digital Energy Meters, Local Content.

## I. INTRODUCTION

The power industry is one of the most critical sectors that impact greatly on the economic health of every country. In Nigeria, this sector is faced by a myriad of challenges which include inadequate power generation, poor transmission and distribution infrastructure, increasing power demand, poor returns on investment due to various constraints inherent in the system etc.

Having noted the existence of these problems, it becomes extremely necessary to harness the available power for effective distribution to the customers. Of course, power in its nature, is a special kind of commodity which must be used as soon as it is produced. Thus, to maintain an economically viable value chain in the power industry, an efficient means of revenue collection/recovery must be put in place. In order to achieve this, the usual practice is to

install energy meters at the consumers' location in order to measure the amount of electric energy in kilowatt-hour (kWh) consumed over a period of time. By means of the energy meter, the consumer is billed (or charged) for power consumed.

For an efficient and reliable system delivery, it is expected that all consumers on the power distribution network must be metered. However, the Nigerian situation is a far outcry from this reality. A very large number of power consumers are not metered. In some cases, many customers are still being metered using archaic analog meters. Such analog meters require the utility companies to regularly visit the customers' premises in order to read the meters and subsequently prepare the bills and return same to the customers. This is a very cumbersome procedure. Thus, the common trend now is the use of digital energy meters which are usually unattended by the utility personnel except for maintenance purposes.

Presently, the energy meters being used by the DISCOs for metering their customers are imported and dispensed to the customers at very exorbitant prices. Surprisingly too, most of the unmetered customers have expressed interest in having these meters installed in their premises but all to no avail. Thus, there appears to be a lack of capacity on the part of the DISCOs to adequately meter all their customers. Some of the major reasons for this lack of capacity include: (i) the non-availability of the required technology for production of these meters locally, (ii) the excruciating shortage of foreign exchange hindering businesses that require importation of finished products including the energy meters and (iii) the seeming lack of the political will on the part of the regulating authorities to compel the DISCOs to meter all their customers.

The focus of this research, therefore, is to develop and prototype a locally made alternative energy meter that can be mass produced within the country in order to achieve adequate metering of all customers on the Nigerian power distribution networks. The impact of this research will certainly rub off positively on the economy of this country as it will enhance the value chain of the Nigerian power industry through more reliable distribution networks, huge savings in foreign exchange and job creation.

### A. Statement of Problem

Inadequate metering of energy consumers in the Nigeria has remained a major challenge facing power distribution companies (DISCOs) in the country. It has been reported that about 54% of electricity consumers in Nigeria have no meters [1]. This results in loss of huge revenues by the DISCOs. It also encourages the much-despised estimated billing system used for unmetered customers. Of worthy note also is the fact that most of the meters used in Nigeria

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J. P. I Iloh, Department of Electrical/Electronic Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli Campus, Anambra State, Nigeria.

(e-mail: johnpauliloh@gmail.com, jp.iloh@coou.edu.ng).

are designed and manufactured abroad amounting to huge capital flight. Thus, there is need for locally made energy meters that can compete favorably with their foreign made counterparts in order to reduce these challenges to the barest minimum.

### B. Objectives of the Research

The objectives are:

- i. To develop an energy meter design that is affordable, efficient, reliable and has significant local content in its value chain.
- ii. To introduce the locally wound Rogowski coil as alternative current sensing element in place of the conventional current transformer.
- iii. To optimize the energy meter design using suitable application software environments.
- iv. To build, test and calibrate a prototype of the energy meter design.
- v. To carry out a performance evaluation study for the prototype in comparison to the foreign made counterparts.
- vi. To carry out a cost-benefit analysis to determine the viability of the energy meter for mass production and for possible deployment in the Nigerian power market.

## II. SUMMARY OF RELATED WORKS

Various attempts have been made by several researchers to design energy meters suitable for metering electric power consumption. Presently, the electromechanical induction type meters are being phased out especially in distribution networks. Thus, most recent research interests on distribution energy meters are focusing more on electronic and smart energy meters.

[2] designed and prototyped a single-phase energy meter proposed for domestic residences in Mexico. The prototype displays voltage, current, power and time measurements. The meter was built around the PIC16F874 microcontroller. The prototype has four major building blocks namely data acquisition (voltage and current sensors), signal conditioning, signal processing and visualization of results.

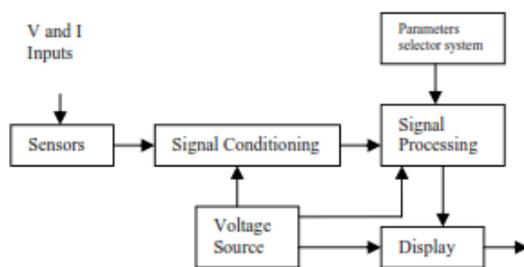


Fig. 1. Block diagram of domestic digital energy meter [2]

The block diagram of the energy meter is illustrated in Fig 1. The results presented in the work showed that the meter provided good level of accuracy as the meter was able to display measurements very close to the theoretically calculated results. However, the major drawback of this design is that it does not support prepaid systems and still requires utility personnel to visit the meter location in order

to read the meter and also return to deliver the bill. Also it has no remote facility to disconnect the customer in the event of non-payment of accumulated bills. With this type of energy meter, the utility company is still bound to lose considerable amount of revenue.

An attempt was made in [3] by proposing a prepaid energy meter with built-in mobile communication capability such that the meter behaves like a prepaid mobile phone. The meter contains a prepaid card analogous to the mobile Subscriber Identification Module (SIM) card of a mobile phone. The prepaid card enables bidirectional communication between the utility and the customer through the mobile communication infrastructure.

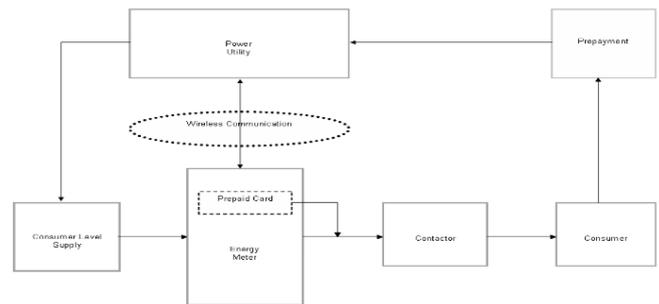


Fig. 2. Block diagram of prepaid meter using mobile communication [3]

The block diagram of the proposed prepaid meter is shown in Fig. 2. This meter has the capability of remotely switching off the load at the customer's premises whenever the energy units purchased from the utility is exhausted. Thus, there is total elimination of non-payment of bills for energy used by customers. The proposed design was modeled in MATLAB simulation environment. There was no physical hardware implementation and prototyping of the model.

In [4], a prepaid energy meter for efficient power management was designed and prototyped. In this design, a GSM modem was used as the communication module. The metering technology here is similar to that used in [3]. However, it has an additional feature of recording the consumer's maximum demand which enhances the utility's energy management system. The block diagram of the meter is shown in Fig 3.

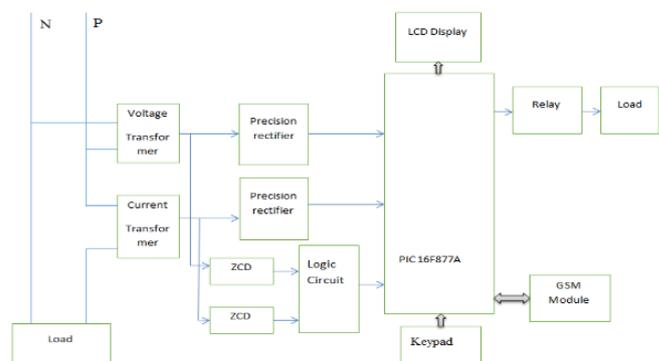


Fig. 3. Block diagram of prepaid energy meter for efficient power management [4]

[5] proposed a smart energy metering system based on GSM modem similar to the design presented in fig. 7. However, it introduces additional function of short message service (SMS) between the utility company and the

customer's energy meter. It also supports a more detailed database of the consumers under the utility's distribution network. The proposed design is expected to enable the consumers pay their bills via SMS recharge pin/code. The inherent challenge in this approach is that it will certainly be more expensive because of the relatively higher communication overhead. Again, the results shown in the work were snapshots obtained from a simulation environment using the Proteus software. Thus, no hardware prototype was produced to validate the proposed design.

III. ROGOWSKI COIL BASED CURRENT MEASUREMENT

In order to address the objective of this research which targets significant local content in the design and production of the proposed locally made energy meter, a locally wound rogowski coil (RC) was introduced in the design for current sensing. With the rogowski coil, current flowing through any conductor encircled by the coil can be accurately sensed and measured. The basic theory of operation of rogowski coils is presented in [6, 7, 8, and 9]. The theoretical fundamentals of rogowski coil design using a circular core are illustrated in Fig. 4 [6]. In using rogowski coil, the current  $i(t)$  flowing through a conductor, can be expressed as;

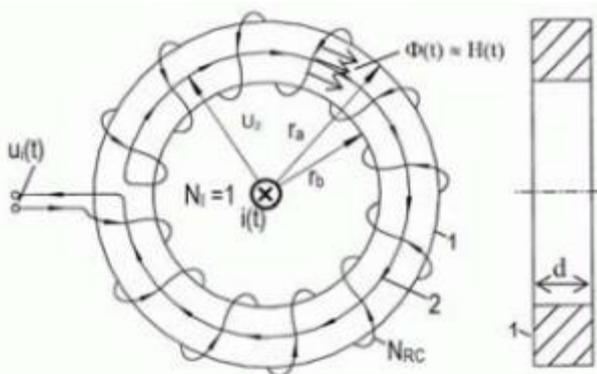
$$i(t) = \frac{1}{M} \int_0^T v_i(t) dt \tag{1}$$

Where,

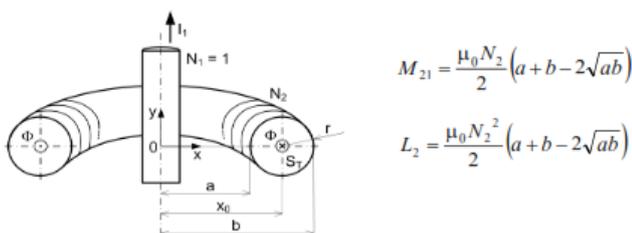
$M$  is the mutual inductance (in Henry) of the conductor carrying the current and the winding of the rogowski coil and  $v(t)$  is the voltage induced into the rogowski coil winding.

For the rogowski coil with circular core as shown in Fig. 4, the mutual inductance  $M$  is given by [6],

$$M = \frac{\mu_0 N_{RC}}{2} (a + b - 2\sqrt{ab}) \tag{2}$$



(a) Basic set up of rogowski coil for current sensing



(b) Rogowski coil arrangement using a circular core  
Fig. 4. Basic theory of rogowski coil [6]

Also, the self inductance of the rogowski coil is given by,

$$L_{RC} = \frac{\mu_0 N_{RC}^2}{2} (a + b - 2\sqrt{ab}) \tag{3}$$

Where,  $\mu_0$  is the permeability of free space,  $N_{RC}$  is the number of turns in the Rogowski Coil winding.

IV. METHODOLOGY

A. Study Area

This research specifically focuses on developing a single-phase digital energy meter prototype for use in the Nigerian power distribution networks with emphasis on achieving significant local content in its value chain when mass produced.

B. Materials

SWG 25 wire, SWG 36 wire, a coaxial cable with peeled off sheath, paper tape, a voltmeter, ammeter, an integrator circuit, a 2000W load board, a digital wattmeter.

C. Method

The following procedures adopted for the research were grouped in two phases.

The first phase of the research involves:

- i. Determination of the specifications
- ii. Fabrication of the current sensor from locally available materials
- iii. Experimental characterization of the current sensor
- iv. Implementation of a wattmeter meter circuit with the rogowski coil as the current sensor

The second phase involves:

- v. Development of the energy meter from the wattmeter circuit
- vi. Development of the control software for the energy meter
- vii. Integration of the communication interface into the energy meter design
- viii. Construction/assembly of the completed prototype of the energy meter
- ix. Testing and calibration of the prototype
- x. Performance evaluation of the prototype
- xi. Cost benefit analysis

For the purpose of this paper, only the preliminary results of the first phase of the research are reported. However, the second phase of the research is still ongoing and will be reported in subsequent publications when the research is completed.

1) Determination of the energy meter specifications:

The following specifications in Table I were drawn from the requirements set by the Nigerian Electricity Management Services Agency (NEMSA) [10]. Details of the requirements are presented in [11]. These specifications were carefully considered and the parameters relevant to our study were selected.

TABLE I: BASIC REQUIREMENTS FOR DISTRIBUTION METERS

S/N	Parameter	Specification
1	Voltage Rating	240V/415V
2	Operating Voltage	-40% to +10% Vref
3	Current Rating	5(60)A
4	Frequency	50Hz ± 2%
5	System	Single or Three Phase
6	Secondary Voltage Variations	(85 – 120)/(50 – 70) V
7	Internal Battery or an Equivalent Giving Total Stand-By Life of 10 Years (Minimum)	Lithium CR2025 – 1HF
8	Auxiliary Battery For Downloading Stored Data.	12 D.C. Supply
9	Accuracy Class	0.5s for 33KV, 0.2s for 132 and 330KV
10	Storage Temperature	Up to 700C
11	Life Span	10 Years
12	Relative Humidity. Non-Condensing	Up to 96% at 45o C
13	Burden	2VA/phase in voltage circuit and 1VA/phase in current circuit.

Source: <https://www.nemsa.gov.ng/site/distribution-requirements/> [10]

Based on the requirements, the following specifications were selected for the proposed energy meter design:

Voltage rating:	240 Vac
Operating voltage:	-30% to + 5% of $V_{ref}$ (i.e. 168V to 252V)
Current rating:	5(60) A
Frequency:	50Hz ± 2%
System:	Single phase
Accuracy class:	0.5s

### 2) Fabrication of the current sensor from locally available materials:

Two samples of rogowski coil current sensors were wound using SWG 36 and SWG 25 wires, coaxial cable used as the core (with sheath removed exposing the non-ferrous insulating material and the centre conductor intact) and paper tape. The sample with SWG 36 wire has heavy windings with resistance of  $50\Omega$  while the sample with SWG 25 has fewer windings but wound on a longer coaxial cable and folded into three loops with resistance of  $1.3\Omega$ .

### 3) Experimental characterization of the rogowski coil:

The two samples of rogowski coil were used to sense current flowing through conductor carrying the load current from the 2000W load board. The load board is made of 10 lamp holders connected in parallel with each having a separate ON/OFF switch for varying the load current. Various combinations of 40W, 60W, 100W and 200W bulbs were used to vary the load current. Results of the experiment were recorded and analyzed in order to characterize the coils in terms of equations representing the electrical behaviour of the coils.

### 4) Implementation of wattmeter circuit using the rogowski samples as current sensors:

From the results of the experiments in (iii) the equations derived for the coils were used to accurately predict the current flowing through the conductor encircled by the rogowski coils. In the next stage of the research, the coils will be first used with a wattmeter demonstration circuit to measure the instantaneous power consumed in the load. The block diagram of the proposed energy meter is shown in Fig. 5 illustrating the various modules that make up the design.

Thus, based on the concept presented in this block diagram, the hardware and software systems for the digital energy meter can conveniently be developed. The functions of the various blocks are briefly explained as follows.

### 5) Sensor signals:

This block represents the stage of the system which captures the current (I) and voltage (V) signals by means of the current transformer (CT) and voltage transformer (VT) respectively. The current and voltage signals acquired will be used in the next stages for computation of the instantaneous power consumed. Of worthy note, is the novel idea of using Rogowski coil as the current sensor [9]. The motive behind this idea is that the raw materials for producing Rogowski coils can be sourced locally in addition to the other attractive features of rogowski coil such as light weight, flexibility of use, non-intrusive nature, linearity over a wide range etc.

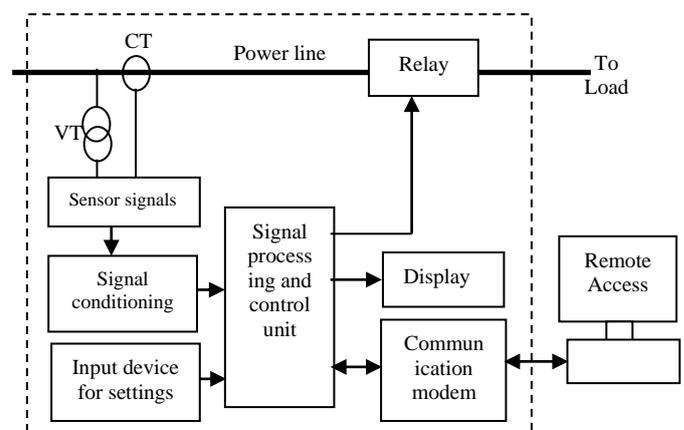


Fig. 5: Block diagram of the proposed energy meter

### 6) Signal Conditioning:

This block accounts for all the circuitry required for manipulating the current and voltage signals acquired in the previous block in order to make them suitable inputs to the signal processing stage. Typically, the signal conditioning block contains the precision rectifier circuits, the sampling circuit and the analog-to-digital conversion circuitry.

### 7) Input Device for settings:

This block represents the means by which the user can select preferred functions from a possible set of options. The input device can be in form of a keypad with a number of buttons for its operation.

### 8) Signal Processing and Control Unit:

This block houses the central processing unit (CPU) of the energy meter and at the same time carries out all control commands. It carries out all the necessary arithmetic and logic operations, takes decisions based on the results of the arithmetic operations and issues control commands to all the output devices such as the display, relay and communication modem. It receives the digital equivalents of the current and voltage signals from the signal conditioning block and uses them to calculate active power consumed at any instant by the load and continuously integrates the results over a period of time according to equation (1).

$$E = \frac{1}{1000} \int_0^t P dt = \frac{1}{1000} \int_{t_0}^t V_{rms} I_{rms} \cos \phi dt \quad (1)$$

Where,

- $E$  = energy consumed in kilowatt-hour (kWh)
- $P$  = power in watts
- $V_{rms}$  = root mean square voltage in volts
- $I_{rms}$  = root mean square current in amperes
- $\phi$  = power factor of the supply
- $t$  = time in seconds

The function of this block is usually implemented by means of a microcontroller which bears the control software (or program). One of the critical aspects of this research work is the development of this control program using application softwares such as Proteus.

9) Relay:

The relay's function is simply to effect the meter's control over the load. With the aid the relay, the customer's power supply can be turned on or off automatically whenever the conditions for the on or off states are satisfied respectively.

10) Display unit:

The display unit enables the visualization of the bill and total energy consumed. All other information meant for the customer are displayed on this unit. The liquid crystal display (LCD) is the most commonly used display device for modern metering systems.

11) Communication Modem:

This block represents the peripheral interface through which bidirectional communication can be established between the energy meter and the utility company. Through this modem, control commands can be issued remotely from the utility company for example, to either turn on or turn off the power supply to the load.

V. RESULTS AND DISCUSSION

The preliminary results of this research work are presented in Fig. 6 to 9. These results are limited to the experiments carried out with the two samples of rogowski coil. While Fig. 6, 7 and 8 are for the SWG 36 rogowski coil, Fig. 9 is for the SWG 25 rogowski coil.

*Observations:* It can be observed from the figures. (6, 7 and 8) that the SWG 36 rogowski coil exhibited a behavior that suggests a noticeable departure from the linearity principle for which rogowski coils are known. This observation is clearly illustrated by linear optimization (using the basic fitting tool in MATLAB graphing window) of the results (the red line) as shown in Fig. 6. However, it was also observed that the SWG 25 rogowski coil sample was found to exhibit better linearity property (as shown in Fig. 9) than the SWG 36 coil.

*Deductions:* The behavior of the SWG 36 coil was better characterized by quadratic and cubic polynomials as shown in Figs. 7 and 8 respectively while a linear characterization of the SWG 25 coil sufficiently represented the behavior of the coil as shown in Fig. 9. Thus, to deploy the SWG 36 coil for current measurement purposes, the cubic polynomial will be best suited for programming the control software while for the SWG 25 coil, the linear equation is just sufficient for programming the control software.

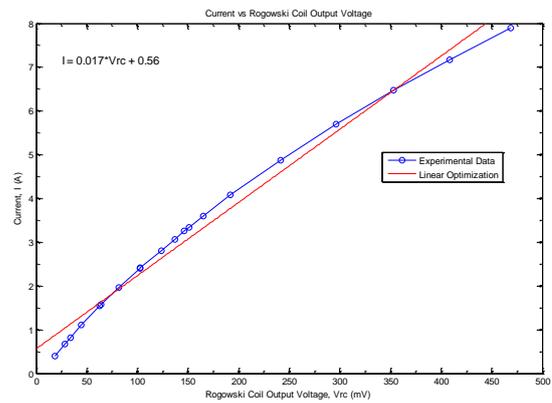


Fig. 6. Linear characterization of the SWG 36 rogowski coil

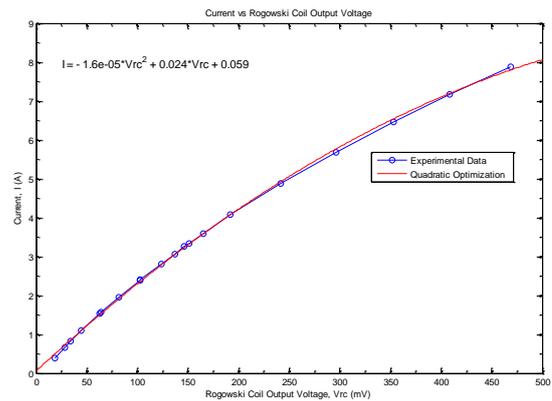


Fig. 7. Quadratic characterization of the SWG 36 rogowski coil

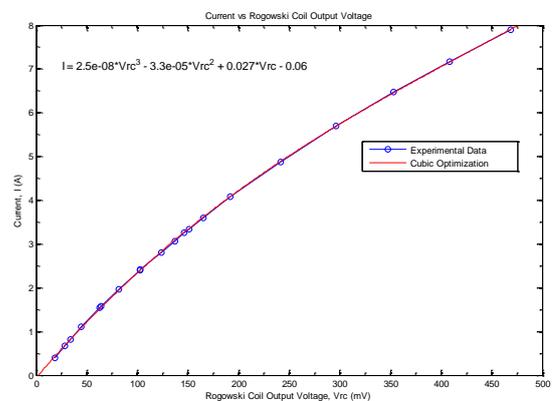


Fig. 8. Cubic characterization of the SWG 36 rogowski coil

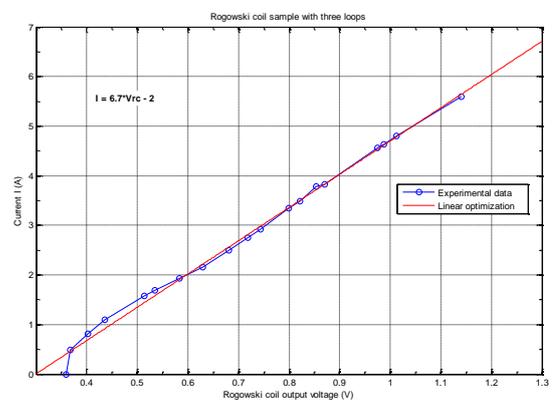


Fig. 9. Linear characterization of the SWG 25 rogowski coil sample

## VI. CONCLUSION

With the rogowski coil experiments carried out in this work, it was concluded that the SWG 25 rogowski coil sample with three loops provided a better linear response than the SWG 36 coil sample. However, in the case where the SWG 36 coil sample is to be used, the cubic characterization of the coil's behavior becomes the preferred option. It is important to note that the research for development of the locally made energy meter is still in progress. Further experimentation with the coils involving integrator and amplification circuitry for both coil samples will be carried out in the next stage of the research. Both coils will be deployed in the proposed energy meter design to determine which of the two provides better overall performance.

## ACKNOWLEDGMENT

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**John Paul I. Iloh** obtained his PhD in Electronics and Communication Engineering from the Chukwuemeka Odumegwu Ojukwu University, Anambra State, Nigeria in 2015. He equally holds a bachelor's degree (B.Eng) in Electrical/Electronic and Computer Engineering and a master's degree (M.Eng) in Electronics and Communication Engineering both of which he obtained from the Nnamdi Azikiwe University Awka, in 2002 and 2009 respectively.

He has several years of working experience both in the industry and the academia. Presently, he is a Senior Lecturer in the Department of Electrical and Electronic Engineering, Chukwuemeka Odumegwu University (Formerly, Anambra State University). His research interests cut across Instrumentation and Measurements, Automation Systems, Renewable Energy Systems, Solar/Battery Powered Systems, Energy Management Systems among others.

Dr. Iloh is a COREN (Council for Regulation of Engineering in Nigeria) registered engineer, a member of the Nigerian Society of Engineers (NSE) and also a member of the Nigerian Institution of Electrical and Electronic Engineers (NIEEE).