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Rogowski Coil Based Digital Energy Meter

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Abstract:*An improved system for current sensing and measurement using rogowski coil was designed and implemented. The rogowski-coil consists of a low cost, air cored and flexible induction sensor typically used for non-intrusive condition monitoring and thus can be used for current measurements in power systems monitoring, protection and control. Earlier energy meter designs mostly made use of current transformers which have inherent limitations such as magnetic saturations and non-linear response at high currents. In this work, an Optimized Modeling and Simulation approach was adopted to realize a rogowski coil based digital energy metering and billing system design. Proteus Isis 8.0 software was used to create a simulation model which was used as an experimental testbed for evaluating the response of a Rogowski coil. The testbed was used to verify the linearity characteristic of rogowski coils when used as a current sensor. Results obtained from the experimental testbed showed that it provided better linear response than the conventional current transformer. The frequency response and transient characteristics of Rogowski coil were also analyzed using MATLAB simulation software.Finally, the rogowski coil model was incorporated into a digital energy meter circuit built in Proteus environment and simulations were carried out. The simulation results showed that the calculated and measured energy were the same hence validating the design.*

Keywords: *Rogowski Coil sensor and Energy meter.*

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I. INTRODUCTION

Various devices can be used for current sensing applications. Such devices include low resistant current shunt, current transformer, hall-effect sensor, and rogowski coil. It has been demonstrated that a coil can be used to obtain the time rate of change in current (di/dt) flowing through a conductor. This is achieved by obtaining the magnetic field information around the power line based on the fact that there is a magnetic field around any conductor that carries current. Different options are available for the kind of coil used for this purpose. The choices include current transformer, shunt Resistor, and a more recent innovation-the Rogowski coil (Kojovic and Ljubomir, 1997). Rogowski coils are well suited for current sensing applications because of its two main characteristics;

i. It uses air core compared to iron core which is the more conventional choice for most other coils. This gives the user the ability to use this device in circuits with higher currents and frequency since saturation is not an issue because of the air core.
ii. It is flexible and open ended and can be used for non-intrusive applications. The current transformers are no longer the most attractive choice for use in current measuring and sensing because of the inherent problems of saturation and high CT burden.

Thus, there is need to explore these special advantages of the rogowski coil characteristics.

Due to these advantages, rogowski coils are now being used in various current measuring and sensing applications. Rogowski coils, also called air-cored coils evolved from simple solenoids. Early application of the rogowski coils was limited because the low output voltage was inadequate to drive the measuring equipment at that time. As the sensitivity of measurement devices improved, Rogowski coils became useful in a variety of specialized alternating current (AC) monitoring applications. Advances in solid state electronics and increased use of microprocessor technology provide avenues for applying Rogowski coil technology in an ever widening range of applications. More recently, Rogowski technology has been incorporated into commercially available sensor products in a variety of configurations, including the popular flexible type. These products offer several distinct advantages over other forms of current measurement, in most cases at lower cost.Rogowski coils are now incorporated in modern current measuringand sensing systems. Its feature of "air-cored" offers an advantage over iron-cored measuring devices (Ward et al, 1993). Due to its excellent linearity, high accuracy, wide dynamic range and no magnetic saturation, the coil can replace CTs and be used for metering and control purposes in the general electric current measurement field (Kojovic and Ljubomir, 1997; Luo et al, 2014). This paper specificallyfocuses on developing a digital energy meter design which uses rogowski coil as the current sensor.

II. RELATED WORKS

(Ward and Exton, 1993) showed that Rogowski coils have better performance in a vast majority applications; sudden short circuit test, lightning test and partial discharge monitoring, as compared to the other current measuring devices. (Ramboz, 1996) introduced a new construction of Rogowski coil, machine-able Rogowski Coil made of a rigid nonmagnetic coil and a single-layer winding. (Kojovic, 2002) and (Karrer and Hofer-Noser, 2000) proposed a new configuration of Rogowski coil based on printed circuit board (PCB) for use in transient current measurement. In that study, the amplitude of the coil's output signal is increased without decreasing its bandwidth, by increasing the number of PCB coils. (Kojovic, 2007 and Iloh, 2015) compared the performance characteristics of conventional CTs and Rogowski coils. Due to the fact that CTs have an output voltage that is directly proportional to the rate of change of measured current, situations would arise whereby relays will need to be specially designed to handle this type of signals (the relay specification needed for this very large signal is usually not readily available off the shelves). Iloh (2015) proposed that Rogowski coils could replace CTs for both measurement and protection applications in power systems.In this work, a series of formulations, methods and algorithms are adopted so as to effectively improve current sensing in a single phase energy meter using Rogowski coil.

III. CHARACTERISTICS OF ROGOWSKI BASED CURRENT SENSORS

The following characteristics are based on a survey of commercially available Rogowski based current measurement products (Kojovic, 2007). In most cases the use of a Rogowski based sensor system consists of a measurement head and integrator electronics, typically referred to as a current probe. Unless specifically indicated, the properties should be interpreted to include the effect of both the measurement head and integrator section. Attempt has been made to provide a comprehensive representation of the capability of commercially available Rogowski based current probes as a technology and to avoid comparing the specific product features of various manufacturers.

The specifications of these properties are illustrated in Table 1.

Table 1. Characteristics of Rogowski coil

S/N	Property	Specification
1	Linear Current Range	30 A – 100KA
2	Current Linearity	+0.2% to +0.5%
3	Temperature Sensitivity	+0.03% / °C to +0.08% / °C
4	Response Time	1ms
5	Bandwidth	1kHz to 1.5Mhz
6	Maximum Voltage	60V - 5KV
7	Maximum Current	100kA
8	Isolation	Galvanic isolation
9	DC Offset	< 1mV -50mV
10	Accuracy	±1% of reading to ±2%
11	External Power Requirements	3Vdc to 24Vdc or +15V
12	Output Type	0.01mV/Amp to 100mV/Amp with output range 200mV to 10V
13	System Cost	<$100 to <$1000

(Source: Kojovic, 2007)

IV. DESIGN APPROACH

This work followed an iterative approach in modeling the Energy metering system so as to monitor system performance effectively before achieving the prototype implementation. Model validity techniques such as simulation allows for comparison between input conditions and model output states with respect to the system output. The performance characteristics of the model intended for this study was developed using two simulation softwaresnamely MATLAB and Proteus Isis.

Figure 1 shows the block diagram for the proposed energy metering system using Optimized and Simulation Method (OM & SM).

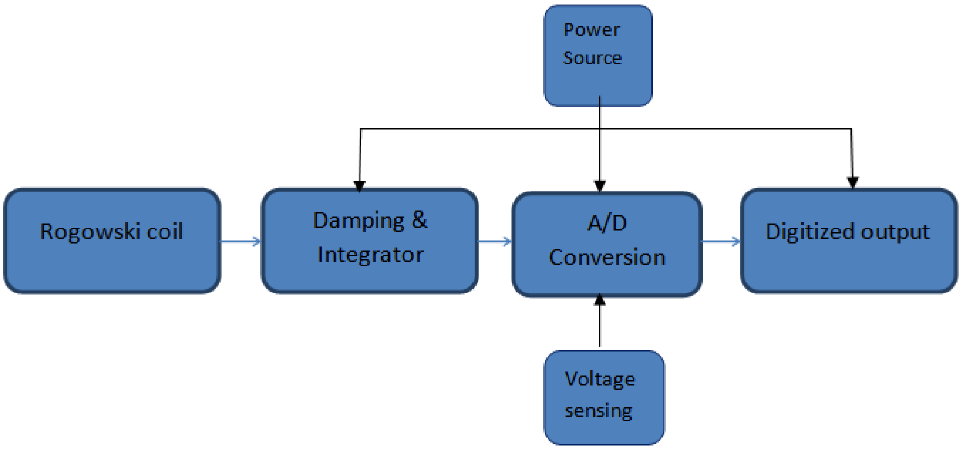

Fig. 1: Block diagram of Energymeter designwith Rogowski coil as current sensor

Proteus ISIS version 8.0 was used to develop a real time simulation scenarios using program description language which later was coded with Assembly language for embedded systems. All the logical components were characterized or modeled to describe the scenarios in real time.

Electrical Model of the Coil Head

When the coil is placed around the conductor carrying alternating or transient current $i_p(t)$to be measured, the voltage $V_{rc}(t)$induced within the coil is expressed as

$$V_{rc} = -M_c \frac{di_p(t)}{dt} \tag{1}$$

Where M_c ismutual inductance of the coilexpressed in Henryat a specific frequency

Mutual Inductance depends on the number of turns of the coil, cross sectional area of the core, and the diameter of the toroid (to determine the radial distance of the coil winding from the current carrying conductor placed at the centre of the coil).

For simplified analysis, the behaviour of the Rogowski coil with terminating impedanceZ_{out}can be represented by its equivalent circuit of the stacked parameters as shown in Figure 2,

Applying Kirchhoff's Voltage law in Fig.2, we have,

$$V_{rc} = V_{(R_1+Z)} + V_{L_1} + V_{C_1} \tag{2}$$

Putting (2) in its integro-differential form,

$$V_{rc} = (R_1 + Z_{out})i(t) + L_1 \frac{di(t)}{dt} + \frac{1}{C_1}\int i(t)dt \tag{3}$$

Differentiating (3),

$$\frac{dV_{rc}}{dt} = (R_1 + Z_{out})\frac{di(t)}{dt} + L_1 \frac{d^2i(t)}{dt^2} + \frac{1}{C_1} i(t)$$

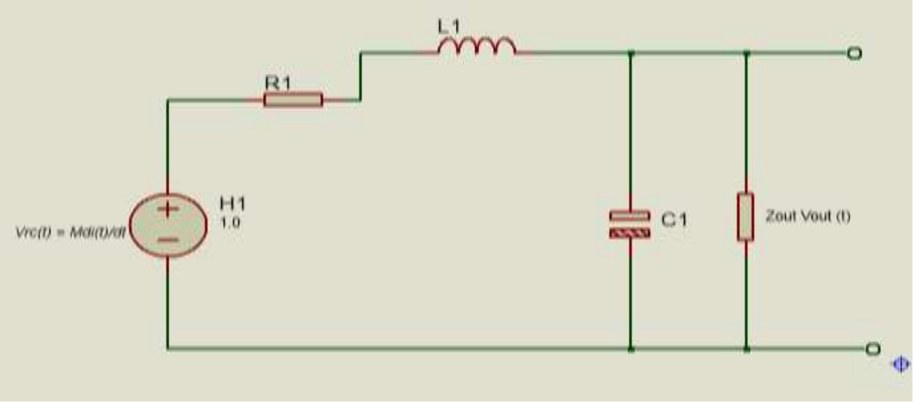

Fig. 2: The Rogowski coil equivalent circuit

WhereR_l, L_l, and $C_l$are the incident resistance, inductance, and capacitance of the coil, respectively. The high frequency behaviour of the coil, in particular its bandwidth and susceptibility to high frequency oscillations, is significantly influenced by the terminating impedance Z_{out}.

From equation (3), the transfer function of the Rogowski coil incident parameters modelcan be derived as:

$$H_1(s) = \frac{U_i(s)}{I(s)} = \frac{Ms}{[s^2 L_1 C_1 + s\,(L_1/Z_{out} + R_1 C_1) + (R_1/Z_{out} + 1)]} \quad (4)$$

Multiply through by Z_{out} we have

$$\frac{Vout}{Vrc} = \frac{Ms\,Z_{out}}{S^2 L_1 Z_{out}\,C \;\; + s(L_1 + R_1 Z_{out}\,C_1) + (R_1 + Z_{out})} \quad (5)$$

Usually the air-cored coil is used in combination with large load impedance, i.e., ωLl<<Zout. ωis the angular velocity (rad/s), where ω=2πf, and f is the frequency (Hz) of thepropagated signal. By assuming that the Rogowski coil has negligible resistance, theapproximate measured voltage at its output terminals becomes:

$$V_{out}(t) = V_{rc}(t) = -M_c \frac{di_p(t)}{dt} \quad (6)$$

So the output voltage at the terminals of the sensing coil is proportional to the time derivative of the current flowing in a conductor passing through the coil. An integrator is incorporated to the output of the coil, which integrates the output voltage $V_{out}(t)$according to equation (7) to convert it into the current flowing through the conductor;

$$i(t) = \frac{1}{M} \int V_{out}(t)dt \quad (7)$$

where M is the mutual inductance of the coil, and V_{out} is the coil's output voltage

V. SYSTEM IMPLEMENTATION AND RESULT ANALYSIS

The implementation of the design involvesfour stages namely

(a) Selection of rogowski coil parameters and winding of the rogowski coil
(b) Practical experimentation to evaluate the performance of the coil
(c) Creating a simulation model for the rogowski coil
(d) Simulation of the energy meter design using Proteus Software

The measured parameters for the rogowski coil wound for the energy meter application are shown in Table 2.

Table 2

Parameter	**Value**
Length of Coil	600mm
Diameter of coil core	3mm
Diameter of winding wire	0.42mm
Number of turns	100
Coil termination resistance	50 ohm

The rogowski coil thus wound was subjected to a practical experiment in which a current carrying conductor was encircled by the rogowski coil. During the experiment, while the current flowing through the conductor was varied, the voltage output of the rogowski coil was measured and recorded. The results of the experiment are presented in Table 3.

Table 3: Results from Rogowski coil experiment

S/N	**Current (A)**	**Rogowski Output,V_{rc} (mV)**
1	10.03	3.51
2	15.35	5.37
3	23.14	8.10
4	29.37	10.37
5	35.62	12.47
6	45.9	16.07

The graph of the results in table 3 is shown in figure 4. The graph clearly demonstrates the linear property of the rogowski coil. Thus its use in current sensing application over the desired current range for domestic energy metering will guaranty high level of accuracy. It should be noted that this graph enables the designer to determine the sensitivity (mV/A) of the coil which will be eventually used in programming the embedded system for the energy meter.

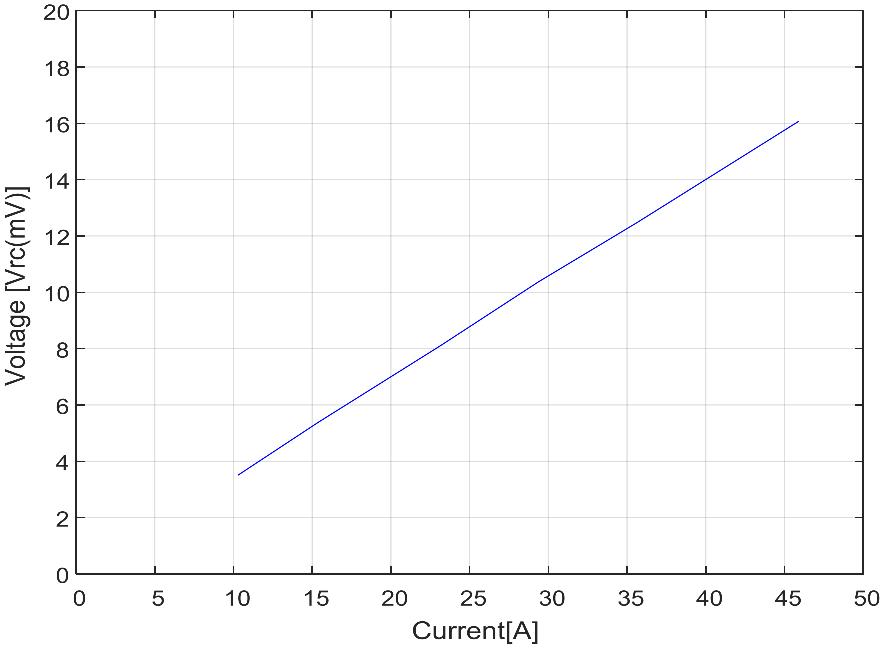

Fig. 3: Rogowski coil output voltage versus current flowing through the conductor

Having evaluated the performance of the rogowski coil sample used in the practical experiment, a simulation model representing the rogowski coil was built in Proteus. Figure 5 shows the coil connected to the integrator circuit.

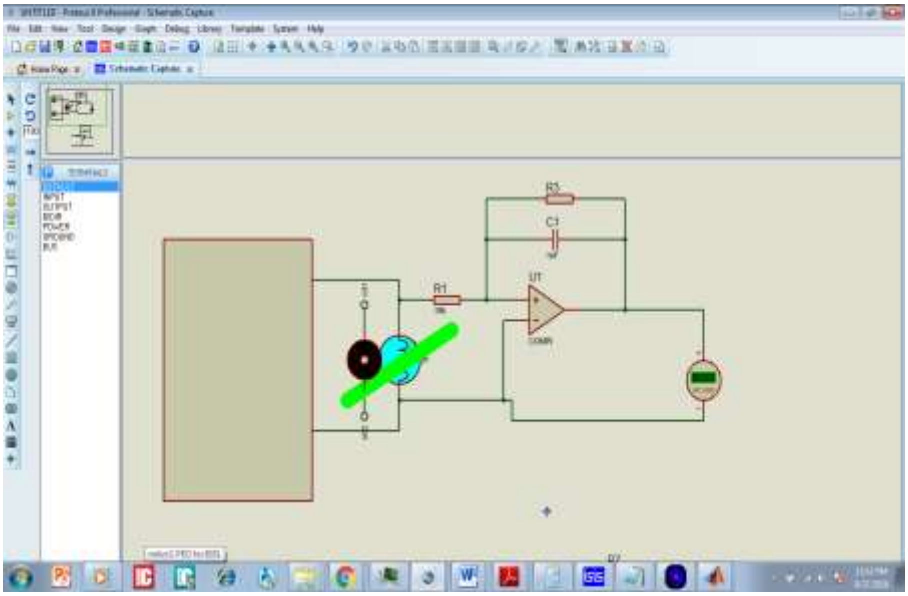

Fig. 4: Snapshot of the Rogowski coil sensor with the integrator circuit.

The frequency response of the rogowski coil with intrgrator circuit was studied in MATLAB 7.7.0. The results from the simulations showing the step response and bode plot for the frequency of the rogowski coil model are presented in figures 6 and 7 respectively.

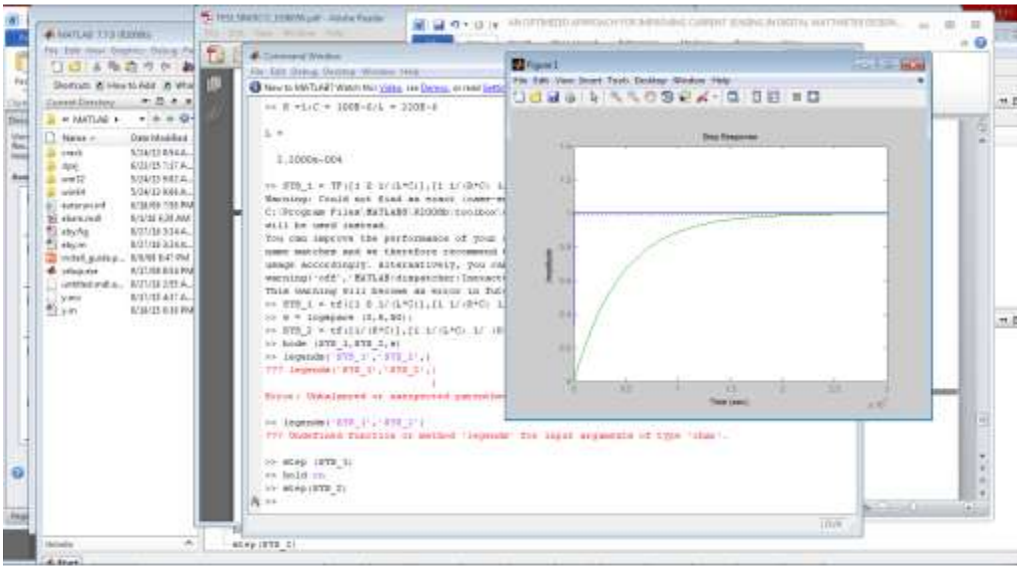

Fig. 5: Step response of the Rogowski coil showing time behaviour of the outputs when its inputs change from zero to one in a very short time

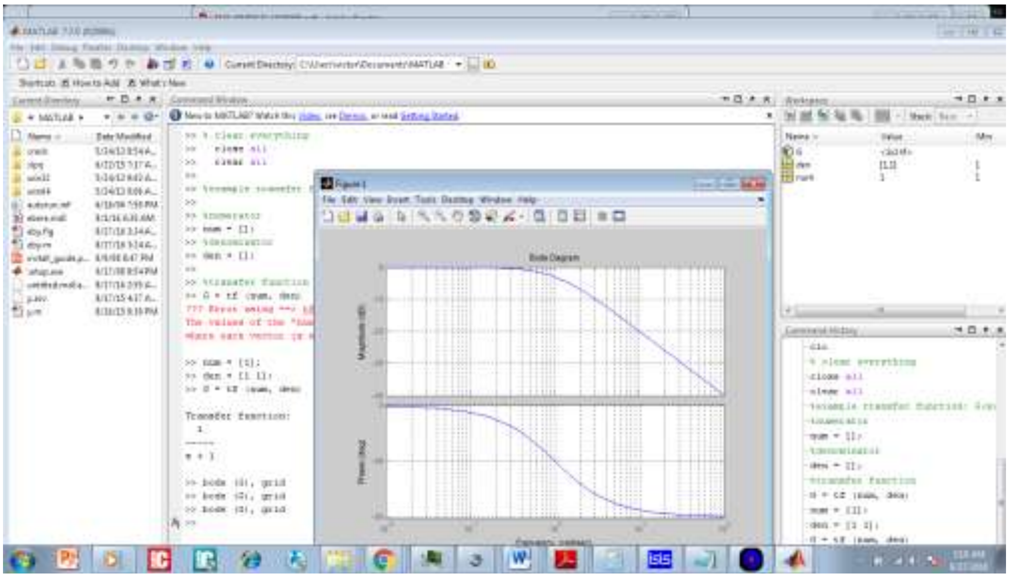

Fig. 6: Control code for bode plot of the frequency of the system.

The bode plot graph represents a Bode magnitude plot, expressing the magnitude of the frequency response, and a Bode phase plot, expressing the phase shift. Both quantities are ploted against horizontal axis proportional to logarithm of frequency.

Finally, the rogowski coil model was incorporated into the energy meter circuitry. The Proteus simulation model for the digital energy meter is shown in figure 9.

The results of simulations of the energy meter model are shown in Table 4. The results showed that the measured values were the same as the calculated values.

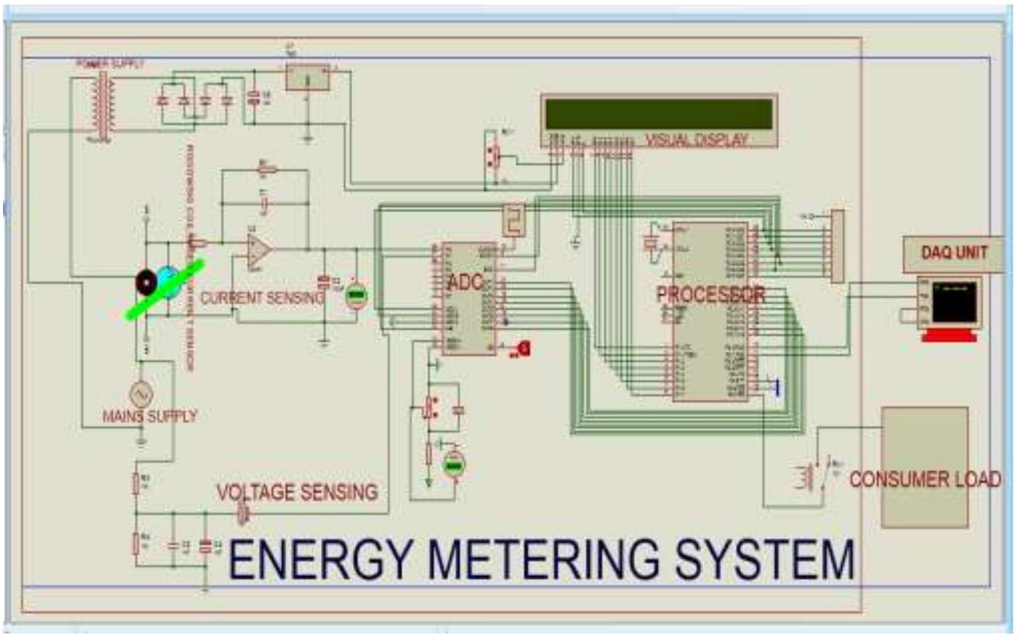

Fig. 7: Circuit diagram of the energy meter with rogowski coil as the current sensing element

Table 4 Results showing calculated energy and measured energy

nth simulation	Load (W)	Time (mins)	Time (h)	Energy (Calculated) (kWh)	Balance Displayed (Units)	Energy Measured (kWh)
1	0	0	0.000	0.00	200.00	0.00
2	100	5	0.083	0.01	199.99	0.01
3	200	10	0.167	0.03	199.96	0.03
4	300	15	0.250	0.08	199.88	0.08
5	400	20	0.333	0.13	199.75	0.13
6	500	25	0.417	0.21	199.54	0.21
7	600	30	0.500	0.30	199.24	0.30
8	700	35	0.583	0.41	198.83	0.41
9	800	40	0.667	0.53	198.30	0.53
10	900	45	0.750	0.68	197.63	0.68
11	1000	50	0.833	0.83	196.79	0.83
12	1100	55	0.917	1.01	195.78	1.01
13	1200	60	1.000	1.20	194.58	1.20

VI. CONCLUSION

In this paper, an improved mechanism for measuring and sensing current in adigital energy meter was presented. The system has an embedded real time Data Acquisition and storage capability. The application of Rogowski coil based current sensing in digital energy metering would allow for improved reliabilty of the system as it would not contend with issues like magnetic saturation or non-linearity at high currents like the conventional current transformers used in energy meter designs. A Proteus simulation model was used to implement the system while MATLAB was used to analyse the results.

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