An Optimized Approach for Improving Current Sensing In Digital Wattmeters Using Rogowski Coils

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Abstract: *A Rogowski-coil is a low cost, air cored and flexible induction sensor for non-intrusive condition monitoring and thus can be used for a variety of operations. Most digital wattmeter designs make use of current transformers and shunt resistors which have a lot of limitations like magnetic saturations, nonlinear reading at high currents and isolation issues. This research work systematically embodies a framework forthe improvement of digital wattmeter designs by integrating Rogowski coils with improved filtering circuits. This research goes ahead of analyse the linearity of the response of Rogowski coils when used as current sensors in metering devices and this linearity is effectively seen in the MATLAB graphs generated Also Rogowski-coil and its effect in metering design is evaluated through theoretical analysis, experiments and simulation while equally presenting an overview of Rogowski coil current sensing technology highlighting its basic principle of operation and its application in the rapidly evolving power system automation. The frequency characteristics and transient characteristics of Rogowski transducer and Rogowski-coil are deeply analysed. A real time simulation model that effectively characterizes the system is equally developed and as experimental testbed of evaluating the response of a Rogowski coil is equally carried out in this research. Finally, some measures are proposed for the performance improvement of Rogowski-coil to meet the requirements of metering applications.*

Keywords*: Integrator, wattmeter, Rogowski coil*

I.   INTRODUCTION

There are a series of devices that can be used for current sensing in a wattmeter. It is possible to use a coil to obtain the time rate of change in current measurements (di/dt) by obtaining magnetic field information around the power line. This is based on the fact that there is a magnetic field around any line 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). There are different factors that differentiate these choices. This research makes use of a Rogowski coil in wattmeter because of its two main characteristics; Rogowski coil uses air core versus iron that 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 frequencies, since saturation is not an issue because of the air core. The second characteristic of a Rogowski coil is that it is flexible and open-ended.

In conventional electrical wattmeter, current transformers (CTs) have over the years been used for current measurements and sensing because of their ability to produce high power output. However, with the rapid growth in technology and the emergence of microprocessor based designs, the need for high power output is no longer necessary thus leading to the adoption of other current measuring devices. One of such measuring devices which have significant advantages over the CTs for use in wattmeter is the Rogowski coil transducers (Kojovic and Ljubomir, 1997). More recently Rogowski technology has been incorporated into commercially available sensor products in a variety of configurations, including the popular flexible type. Rogowski coils can now be incorporated in modern current measuring/ sensing systems and in equally used in this research. Its feature of "air-cored" offers an advantage over iron-cored measuring devices (Ward et al, 1993). Thanks to the benefits of Rogowski coils, such as excellent linearity, high accuracy, wide dynamic range and no magnetic saturation, they can replace CTs and be used for metering and control purpose in the general electric current measurement field (Kojovic and Ljubomir, 1997) & (Luo et al, 2014). The advantages of Rogowski coil sensor over the traditional current transducers will make more attractive for use in modern digital wattmeter.

This work is geared towards improving the overall operation of digital wattmeter designs by optimizing the sensing ability of the Rogowski coil and at the same time, improving the filtering ability of the integrator

circuit that is connected to the output of the Rogowski coil. The Rogowski coil and the integrator as effectively coupled into as the digital wattmeter and form the sensing input of the digital wattmeter.

II. LITERATURE REVIEW

In July 1988, Don Kirk designed an analogue-based talking wattmeter which he called the orator for the impaired people. The design included a single chip microcomputer and an analogue-to-digital converter. The orator was designed to be used in conjunction with an analogue wattmeter. A voltage sample derived from the wattmeter drives the orator. One of two modes of operation, voice or tone, is selected by the toggle switch at the left of the control unit. In the voice mode, synthesized speech announces the power output in watts measured by the wattmeter. The Orator range steps from 0-190 watts. When the talk button is pushed, the orator will voice the power level in digits followed by the word watts. If the power level is above 190W, the orator says out of range. This design all had a shunt resistor incorporated and as such had issues like current from the mains not completely isolated from wattmeter (Kirk, 1988).

There are wattmeter designs that can measure sinusoidal and non-sinusoidal waves with frequency between the range of 50 Hz and 60 Hz. In the work done by (Svensson, 1995), he described an instrument that utilizes digital sampling techniques which has been built and evaluated at the Swedish National Testing and Research Institute (SP). The Digital Sampling Watt Meter (DSWM) is based on standard laboratory equipment: digital multimeters, voltage dividers, shunt resistors and a PC. The DSWM is versatile and can be used for calibrations of many quantities. The most basic ones are the (total) active power and the amplitude and phase angle of individual harmonics of non-sinusoidal voltages and currents. The DSWM was first verified for sinusoidal signals. At 120 V and 5 A and power factor one, the DSWM has an estimated uncertainty (2σ) of 60 ppm at 50 Hz and 600 ppm at 20 kHz. The wattmeter has also participated in three international comparisons with satisfactory results. The most important additional feature, the input distortion, has been verified to be less than 800 ppm for all harmonics and lower than 100 ppm for most harmonics. The limitation in this research work arises from saturation as a result of use of current transformer for current sensing.

(Scherrer, 2002) designed a Digital Radio Frequency (RF) Wattmeter with LC Display for 1 kHz to 1 GHz This RF wattmeter uses an AD8307 to measure the power level. The AD8307 front end circuit is both frequency-compensated and optimized for return loss to give optimum input SWR over a wide frequency range. A pre-programmed microcontroller type PIC16F876 with built-in 10-bit analogue to digital converters is used to convert the analogue voltage output from the AD8307 into digital values. Next, a set of lookup tables are used to convert the dBm values into RF voltage and RF power (watts). The readout of all values including a bar-graph appears on a large 20×2 LCD display with back light. There is also a DC voltmeter with minimum and maximum peak storage. This research work still made use of Hall Effect sensors for current sensing and had problems of in accurate results whenever it is used to measure current consumption for motors or solenoids

(Freescale Semiconductor, 2002) in its work titled "LH60 Single Phase Power Meter Reference Design" described a reference design on the construction and features of a static single phase power meter with direct measurement. Static means that the power meter does not contain any mechanical parts. Static meters are microcontroller based. Current flowing to the load is sensed on a shunt resistor, this is called direct measurement. Voltage and current are measured using a high precision AD converter. Power is then calculated from the measured values. Finally, the power is summed in time to get the total active energy (Wh). This work had issues with current isolation from the mains.

III. DESIGN

In the context of reengineering digital wattmeter designs for optimized current measurement vis-à-vis meeting its specific requirements, a series of research methodologies can be considered which are: real-time system development methodology, gate level oriented methodology, discrete-event modelling and simulation methodology.

3.1.1 Optimized Modelling and Simulation Methodology (OM & SM)

Modelling is defined as the process of producing a model which is a representation of the construction and working of some system of interest (Valigura et al, 2004). A model is similar to but simpler than the system it represents. The major objective of a model is to enable an expert predict the effect of changes to the system. In this case, the model should be a close approximation to the real system and incorporate most of its salient features as well as not being unnecessarily complex such that it is impossible to understand and experiment with it. A good model is a meticulous trade-off between objectivity and simplicity. In all cases, this work followed an iterative approach in modelling the smart automation 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. Generally, the performance characteristics of a model intended for a simulation study can be developed with a series of simulation software such as MATLAB and Proteus Isis which would be used for event modelling in context of this work.
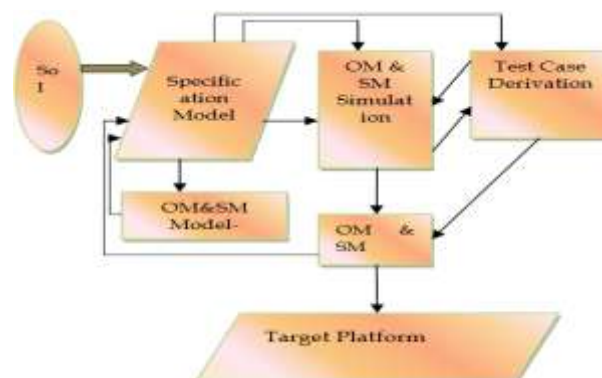
A simulation of a system model is literally the envisioned operation of a model of such a system. In a technical sense, simulation is a technique used to evaluate the performance of a system (existing or proposed) under different configurations of interest over long periods of real time. Basically, the model can be reconfigured and experimented with through simulation in order to achieve its best performance objectives, but usually, this is impossible, too expensive or impractical to do directly in the system it represents owing to obvious factors. Besides, if the operation of the model can be clearly studied, hence, the properties concerning the behaviour of the actual system or its subsystem can be inferred. Based on the above stated advantages of modelling and simulation alongside with real-time system development and prototype methodology, this research then adopted this approach in of making comparisons of frequency response and unit step response between Rogowski coils and conventional current transformers used in many digital wattmeter designs. Also a unified simulation model for the characterization of the operations of the optimized current sensing unit of the wattmeter would also be achieved. The Optimized Modelling and Simulation Methodology (OM & SM) offers the following advantages;

- Reliability: logical and timing correctness rely on OM & SM system theoretical roots and sound mathematical characterizations.
- Model reuse: OM & SM has well-defined concepts for coupling of components and hierarchical modular model composition.
- Hybrid modelling and knowledge reuse: it has been proven that OM & SM is generally a flexible approach to developing a system that will stand the test of time.
- Process flexibility: These integrated modelling capabilities allows for flexibility, abstraction and easy integration of the analytical processes of the system leading to better performance.

3.2 OM & SM Development Cycle.

Figure 3.1 shows the architecture of the process used for the proposed system using OM & SM. The steps that are involved in the OM & SM development cycle as shown in the figure 1.

As the design process evolves, both software and hardware models can be refined, progressively setting checkpoints in real prototypes. The OM & SM allows for execution of dynamic models and to schedule static and dynamic tasks. Here, those parts that are still unverified in the formal and simulated environments are tested, increasing the confidence of the implementer. Any modifications require going back to the same model specifications, which ensure that consistency is guaranteed throughout the system development.

Figure 1: A conceptual framework for OM & SM Development Cycle.

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.

3.2 Tools/Applications used in design
➢ Program Description Language (PDL)
➢ Proteus 7.8 Isis
➢ MATLAB

3.3 Components of Rogowski Coil Sensor
A current measuring sensor consists of a complete measuring operation from initial detection to final indication of the measured quantity as described in Figure 2. Considering Rogowski coil sensor, the initial

detection is done by a current sensing coil which acts as an interface between primary and measured current. Intermediate signal processing consists of signal conditioning based on the operational features of the coil, its physical and electrical characteristics, and the purpose (requirement) of measurements and diagnostics.
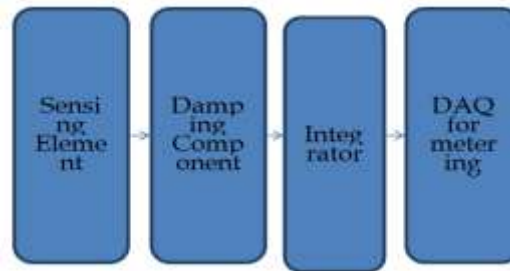

Figure2: Essential elements of a Rogowski coil current measuring sensor.

This is accomplished by damping component and integrator. Final indication is recorded with the help of a suitable Data Acquisition System (DAQS) for the metering purpose. Figure 2 represents the sequential construction and operation ofRogowski coil measuring sensor.

3.3.1 Coil Head/Sensing Element
The Rogowski coil's main sensing part is composed of toroidal wound coil with n number of turns, on an air-core (dielectric) former of constant cross-sectional area. The air-core is split in one location to allow assembly of the coil head unit. As shown in Figure 3, the wire is wound such that the winding start from the first end, progresses towards the other end and returning through the centre of the coil back to the first end, so that both terminals are at the same end of the coil. The number of turns (n), outer diameter of coil (d_0), inner diameter (d_i) and core diameter (d_{rc}) are some of the major physical parameters of Rogowski coils are selected based on the application requirements of the coil. Space for installation, bandwidth, and sensitivity of the coil are the main concerns required to initiate the design. For this research makes the following assumptions; n =30 turns, (d_0) = 0.16m, (d) =0.14m and (d_{rc}) = 0.02m.
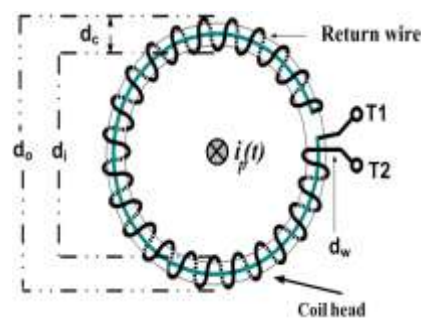

Figure 3: Physical model of the Rogowski coil.

3.3.2 Damping Component
Every piece of wire has resistance and inductance while every two wires present some capacitance during an electrical application (Knight, 2010). Response of the Rogowski coil to primary current signal can be well explained by developing electrical model of this electromagnetic device. Lumped parameter model is used in this work where Rc, Lcand Cc are structure-based inherent self-resistance, self-inductance and self-capacitance of the Rogowski coil. During current measuring operation, the sensed signal passes through RLC circuit of the coil which introduces oscillations in the output voltage and current. The rate of these oscillations is determined by the resonant frequency of the coil. Such oscillations can be damped by properly terminating the response of the coil with a suitable resistance which is normally connected across the output terminal of the coil.

3.3.3 Integrator
The output voltage of Rogowski coil which is induced by the variable current passing through the primary conductor is proportional to the derivative of primary current. The main operating principle is thus described with Faradays' law. The reliability of the measurement depends on how accurately the primary signal is captured. In order to recreate the original waveform of the measured signal, first step was to remove sensor's oscillations using damping component (described above). An integration operation is needed to process differential output to provide output waveform (measurement result) to match the measured primary current waveform. Rogowski coil is an air-core induction sensor and relatively low number of turns is required to

guarantee the high-frequency operation. Therefore the current transfer ratio (output current to input current) is very low; even minor resistive losses can significantly reduce the amplitude of the measured signal in the sensors' output.

3.3.4 Data Acquisition System

The output of Rogowski coil sensor is an analogue signal. For more detailed analysis and recording of the measured current transients patterns, the signal is passed on to a DAS system and digitized. This incorporates an Analogue-to-Digital Converter (ADC) with very high sampling rate, in order to capture the extremely short-time transient currents. The Nyquist criterion states that the sampling frequency of a system needs to be at least twice of the frequency needed to be captured. The ADC would need to have at least 8-bit resolution. The current transients have specific waveforms and recognition/detection of such waveforms can be then used for triggering the further storage and processing operations. The data bandwidth is reduced for easy data storage (and further analysis if need be). Suitable equipment for establishing the DAQS would be for example Digital Storage Oscilloscopes (DSO) in the laboratory measurements or on-chip data logger systems can be used for the purpose of analysis.

3.4 Stage-Wise Design and Implementation of Rogowski Coil Sensor for digital Wattmeter

This section gives the mathematical breakdown of what happen at the various stages in measuring current for this research.

3.4.1 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, $i_2(t)$ is the induced current, Ci is the capacitance, Zoutis the output impedance,$u_0(t)$ is the voltage fed to the DAQS. The voltage $V_{rc}(t)$ induced within the coil is expressed as

$$V_{rc}(t) = -M_c \frac{di_p(t)}{dt} \qquad (3.1)$$

$$i_2(t) = Ci\, du_0(t)/dt + u_0(t)/Z_{out} \qquad (3.2)$$

$$V_{rc}(t) = Li\, di_2(t) + (Ri + Z_{out})i_2(t) - ZoutCi\, du_0(t)/dt \qquad (3.3)$$

Where Mc is mutual inductance or sensitivity of the coil, expressed in V /A at 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 the physical parameters of the Rogowski coil head to be used in this research it is assumed that our n =30 turns, (d_0) = 0.16m, (di) =0.14m and (d_{rc}) = 0.02m. For the value of electrical parameters of the Rogowski coil, the following modelling assumptions are made; self-resistance of coil Rc = 0.7Ω, inductance of coil system Lc = 1.2μH, capacitance of coil Cc =15pF and the measuring resistance Rm = 1MΩ. For simplified analysis, the behaviour of the Rogowski coil with terminating impedance Zoutcan be represented by its equivalent circuit of the stacked parameters as shown in Figure 4
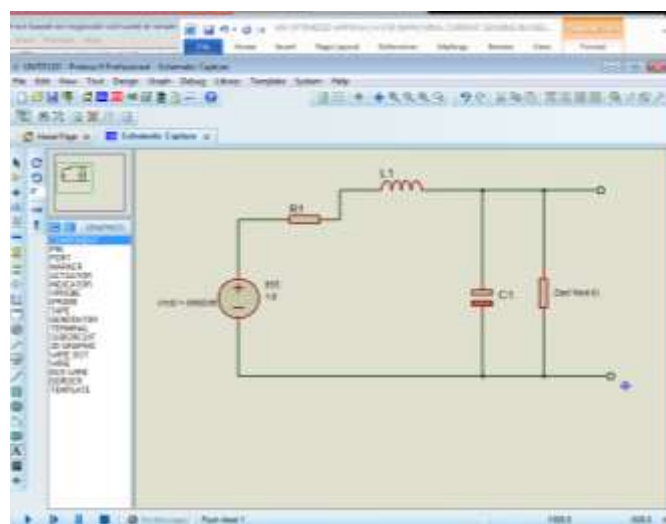

Figure 4: The Rogowski coil equivalent circuit (stacked parameters model)

Where R_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 Zout.

Based on Eqns.3.1 -3.3, the transfer function of the Rogowski coil incident parameters model

$$\text{Hi(s)} = \frac{U1(s)}{I_{in}} = \frac{Ms}{sC_lL_lC_l \ldots} \qquad (3.4)$$

Multiply through by Z_{out} we have

$$\frac{Vout}{U_{in}} = \frac{Ms\,Zout}{s2L_l\,Zout\,C_l \ldots} \qquad (3.5)$$

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 terminals becomes:

$$V_{out}(t) = V_{rc}(t) = -M_c\frac{dip(t)}{dt} \qquad (3.6)$$

So the output voltage at the terminals of the winding wounded around the sensing coil is proportional to the time derivative of the current flowing in a conductor passing through the coil. An integrator is incorporated with the coil, which integrates the output voltage v_{out}(t) according to the following equation to convert it into the current following through the conductor

$$i(t) = \frac{1}{M} \int Vout\,(t)dt \qquad (3.7)$$

The components of a flexible Rogowski coil are the sensing coil and integrator which is been used in this research work. However, the Rogowski coil without integrator has been used to capture directly the current signals produced.
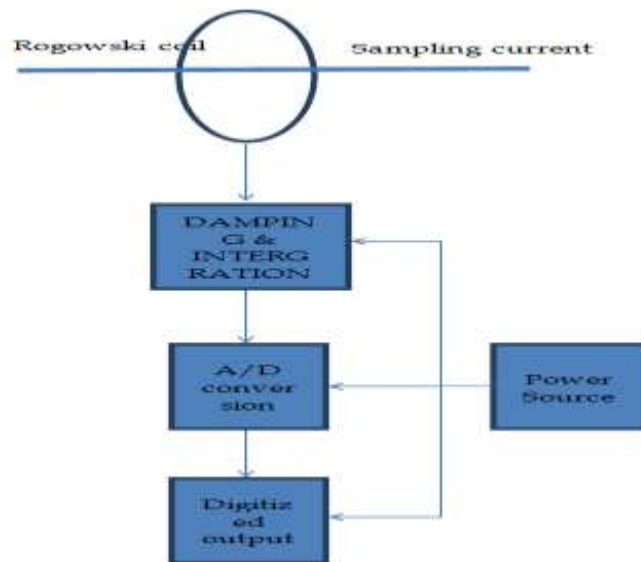

Figure 5: Schematic diagram of the Wattmeter based on Rogowski coil Sensing

3.5Mathematical Characterization of the Proposed Data Acquisition for Digital Wattmeter

During normal operation of the wattmeter, there is continuously processing of data samples taken from the measurement of instantaneous currents for the unit under observation or measurement. By adopting sequential samples, the algorithm can extract information about the measured currents' amplitude and phase angle.

If the assumption is made that the current maintains sinusoidal form under varying conditions; amplitude and phase of the signal can be obtained using a limited number of samples.

Samples obtained from the sinusoidal signal can be described as

$$i(t) = I_1 sin(\omega_0 t) \qquad (3.8)$$

Then the first derivative of the signal is

$$i'(t) = \omega_0 I_1 \cos(\omega_0 t) \qquad\qquad (3.9)$$

Where:

$$i'(t) = \frac{d}{dt}[i(t)]$$

From Eqns. 3.8 and 3.9, we have

$$[i(t)]^2 = I_1^2[\sin(\omega_0 t)]^2 \qquad\qquad (3.10)$$

$$[i'(t)]^2 = (\boldsymbol{\omega}_0)^2 I_1^2 [\cos(\omega_0 t)]^2 \qquad\qquad (3.11)$$

$$[\tfrac{i'(t)}{\omega_0}]^2 = I_1^2 [\cos(\omega_0 t)]^2 \qquad\qquad (3.12)$$

The peak value of the sinusoidal current acquired can be expressed as:

$$I_1 = ([i(t)]^2 + [\tfrac{i'(t)}{\omega_0}]^2)^{0.5} \qquad\qquad (3.13)$$

The above equations are valid for any instant. The derivative of the signal can be obtained if, between two consecutive samples, the signal is considered linear. This research work makes a modelling assumption that the derivative will be the slope of the linear segment of the signal and can be represented as

$$i'[k] = \frac{\Delta i}{\Delta t} = \frac{i[k+1]-i[k]}{\Delta t} \qquad\qquad (3.14)$$

Where Δt is the time interval between instances when two current samples were taken.

The amplitude and the phase angle of the signal can therefore be calculated after each new sample using the following two equations:

$$I[k] = (i[k]^2 + [\tfrac{i[k+1]-i[k]}{\omega_0 \Delta t}]^2)^{0.5} \qquad\qquad (3.15)$$

$$\Phi[k] = \tan^{-1}(\tfrac{v[k]\omega_0 \Delta t}{\ldots}) \qquad\qquad (3.16)$$

By leveraging first and second derivatives, it can reduce errors due to the decaying DC component (Russel, 1978) in this context; the current been measured.
Using the same notations as for the previous mathematical formulations in Eqn. 3.14, the second derivatives of the sinusoidal signals

$$I''[k] = \frac{i[k+1]-2i[k]+i[k+1]}{\Delta t \Delta t} \qquad\qquad (3.17)$$

Thus, the amplitude and the phase angle of the sampled signal can be obtained as:

$$I[k] = \tfrac{1}{\omega_0}(i'[k]^2 + [\tfrac{i[k]}{\omega_0}]^2)^{0.5} \qquad\qquad (3.18)$$

$$\Phi[k] = -\tan^{-1}([\tfrac{i[k]}{\omega_0 i'[k]}]) \qquad\qquad (3.19)$$

This summary describes mathematically the process of DAQ unit of the wattmeter unit. DAQ is used to describe the physical connection of devices whose currents are measured and the flow of data within the wattmeter.

3.6 Data Acquisition Section
This research would entail the implementation of the system design and development in a simulation platform and the following steps would be implemented.

A. Interfacing of Current sensors based Rogowski with Data Acquisition System
Many interfacing applications require the acquisition or generation of signals from the interfaced system; hence a DAQ (for short) is used in the process. Mostly, the substation data are real world signals that are analogue. Most of the instrumentation systems can handle only the digital or discrete data. So the analogue signals are converted into digital signals.

B. Data transfer to the Computer
Typically, DAQ boards are installed in a PC with a high speed data bus like the PCI bus. A DAQ communicates with PC via RS232/485, USB protocol or IEEE 1394. Data transfers can occur between microprocessor and memory at about 20MHz to 40MHz.

C. Selecting a DAQ device
   The physical properties that need to be measured now and in the future are determined. The transducers are selected accordingly. The signal conditioning unit required is determined. The allowable A/D conversion error is set. The sample rate required to accurately capture the physical properties is calculated. A DAQ device is then selected that would meet the requirements.

3.7 Voltage Acquisition Section of Digital Wattmeter
If V_{hfrms} is the RMS voltage of the half wave AC sine wave in volts and the circuit has its own impedance, then;

$$V_{hfrms} = \frac{Vpeak - vz}{\char`\^} \qquad (3.20)$$

$$= \frac{(Vrms) - vz}{\char`\^} \qquad (3.21)$$

Where $Vpeak$ is the peak voltage and $Vrms$ is the rms value of the voltage.
The voltage sensing section measures the incoming voltage on the AC circuit. The circuit is necessary to alert the wattmeter of voltage change due to power fluctuations. When the voltage is lower, appliances will need to draw more current to get the same amount of power. If the wattmeter does not know that the voltage has changed, it will think that the appliance actually demands more power, which is not the case. The voltage sensing circuit is a voltage divider circuit that references the AC signal about to enter the ADC of the microcontroller. That means that it feeds a reduced 5V to the ADC. The electrolytic capacitors in the network decouple the signal to the ADC thereby allowing only AC properties into the microprocessor. The mains voltage (across the load) is divided by a factor 220 and the shifted to a DC level of 2.5V. This voltage is then fed into one of the channels of the ADC. The level shifting enables the measurement of both positive and negative voltages.

3.7.1 Sampling
   Both analogue inputs of voltage and current are sampled. In this research work, 100 samples are taken at the rate of one sample at 400µS. this means a total of 40mS, which translates into two full 50Hz cycles. Two full AC cycles is the minimum suitable for this type of voltage sampling at 50Hz frequency. It is also important to determine the tolerable range of voltage that the device can adjust to work with. This research operates from 190 -240V. This 50V is then converted to a microcontroller safe value of 0V -5V. Assuming proportionality, using this scheme, the microcontroller would read a value of about 2.29V when the original AC input was about 220V and the microprocessor would register this as 469 in a 10bit operation.

<center>**IV. CALCULATING VOLTAGE AND CURRENT RMS VALUES**</center>
For both;
The RMS value or the effective value is the square root of the mean of all the samples squared. This means;
- The square of all scaled samples are calculated
- Their average values (mean) are calculated from those squared samples
- The square root is taken from the average.

In formular:

$$X_{rms} = \left[\frac{1}{-} (x_1^2 + x_2^2 \ldots \ldots + x_n^2) \right]^{0.5} \qquad (3.22)$$

Where $x_1, x_2 \ldots x_n$ are the scaled sample values, n is the number of samples and Xrms is the RMS values calculated from the samples. In this case X could either be current or voltage.
The apparent power (volt amperes) is the product of rms voltage and rms current and it can be written as;

$$S \text{ (in VA)} = V_{rms} \times I_{rms} \qquad (3.23)$$

The real power in watts is the average (mean) of all the products of V and A scaled samples and can be expressed as:

$$P \text{ (in watt)} = \frac{1}{-}(V_1I_1 + V_2I_2 \ldots\ldots V_nI_n) \qquad (3.24)$$

Where $V_1, V_2\ldots\ldots V_n$ are the scaled voltage samples and $I_1, I_2\ldots\ldots I_n$ are the scaled current samples with n as the number of samples collected.
The power factor is gotten by dividing the real power in watts by the apparent power in VA

$$\Phi = P \text{ (in watt)}/ S \text{ (in VA)} \qquad (3.25)$$

4.1 Simulation Based Implementation of System in Proteus Isis

Proteus 8.0 Isis was used to characterize proposed system. Proteus 8.0 provides the platform through which the system was characterized. Typical applications of Proteus 8.0 Isis include standard-based electronic and logical component feature characterization. The Proteus 8.0 Isis environment is organized into; probe/simulation environment, component editor, sub circuit editor with a comprehensive collection of simulation tools that was used to characterize the proposed system. The Proteus 8.0Isis environment provides several modules for the simulation comprising a vast enterprise of digital and analogue tools which with friendly graphical user interface can be manipulated to achieve desired results. Key features of Proteus 8.0 Isis include;

- Graphic specifications
- Detailed simulation log
- Flexibility (enabling one to manipulate custom designs and values to achieve desired target).
- An interactive animation process (allowing variable's manipulation)
- Hierarchical modes and options

With the aim of establishing the correctness of the design each component was simulated and tested. All program codes were implemented using C programming language which is characterized by on the embedded microcontrollers.
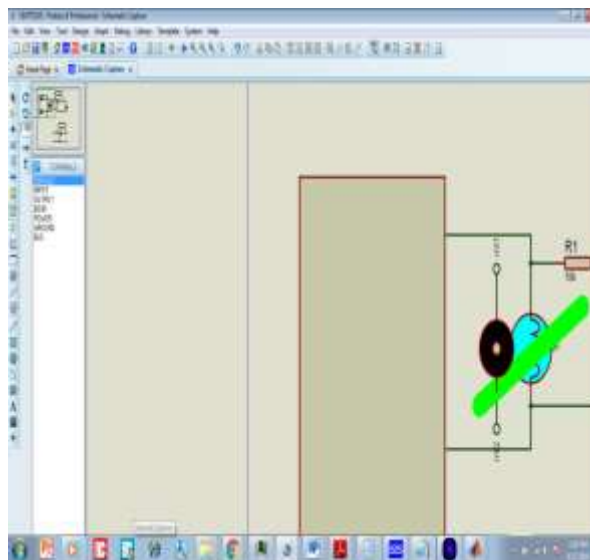

Figure 7 Snapshot capture of the input section of the digital wattmeter with a Rogowski coil current sensor Proteus 8.0.
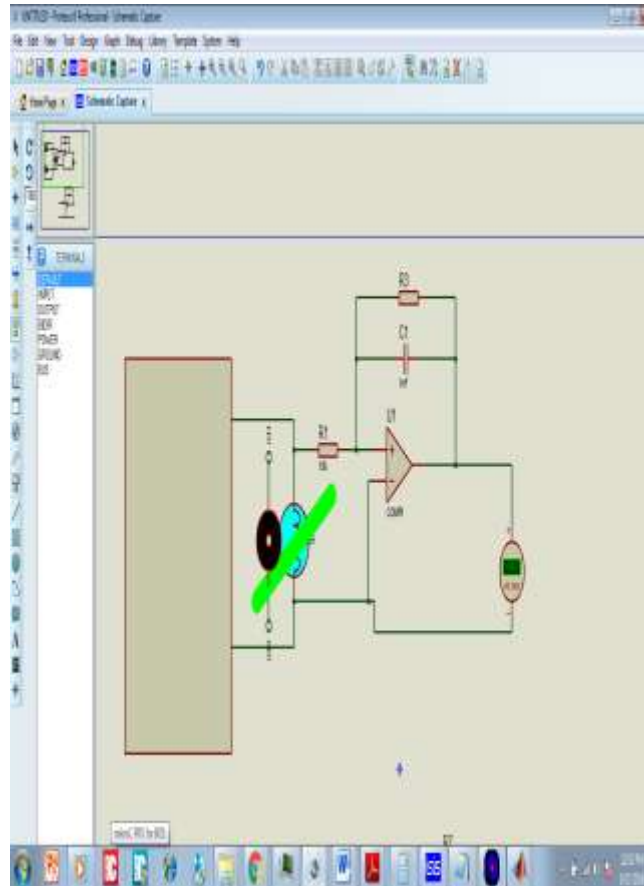
Figure 8Snapshot capture of the input section of the digital wattmeter with a Rogowski coil current sensor and integrator circuit Proteus 8.0.
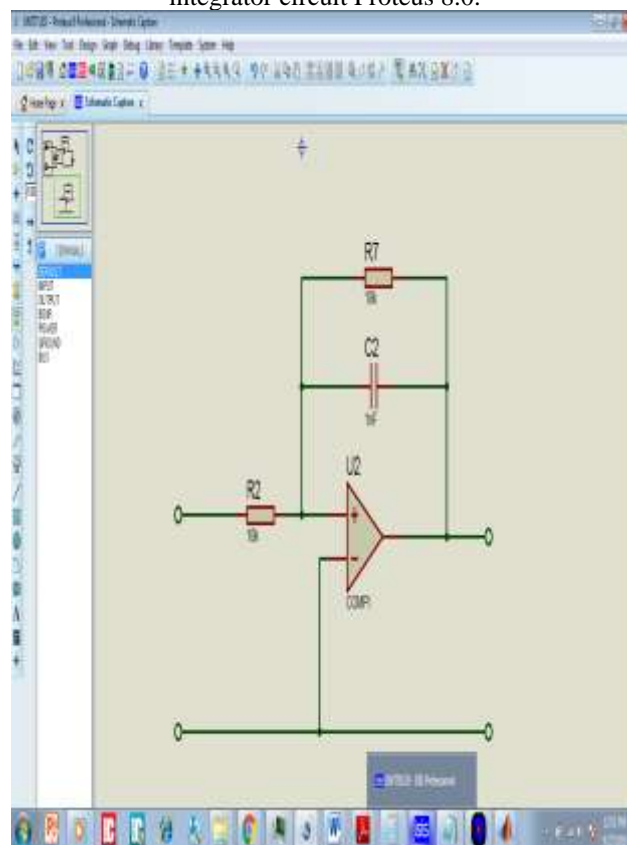

Figure 9 Snapshot capture of the input section of the digital wattmeter showing the integrator circuit Proteus 8.0.
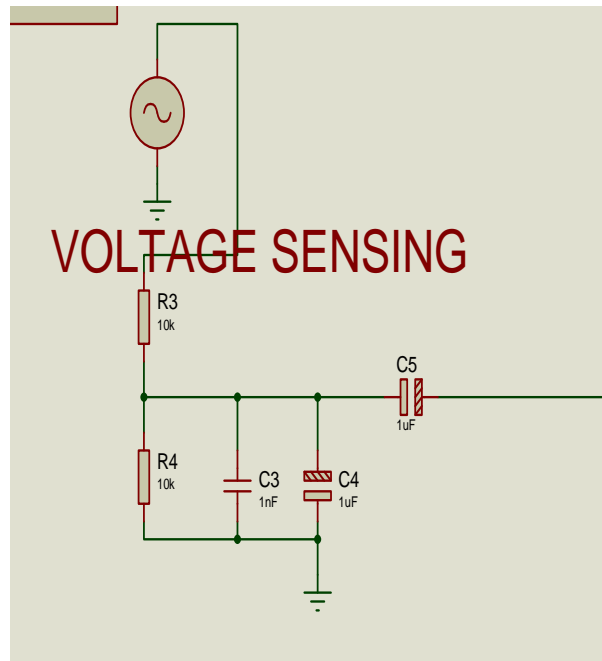
Figure 10 Snapshot capture of the input section of the digital wattmeter with the voltage sensing section in Proteus 8.0.
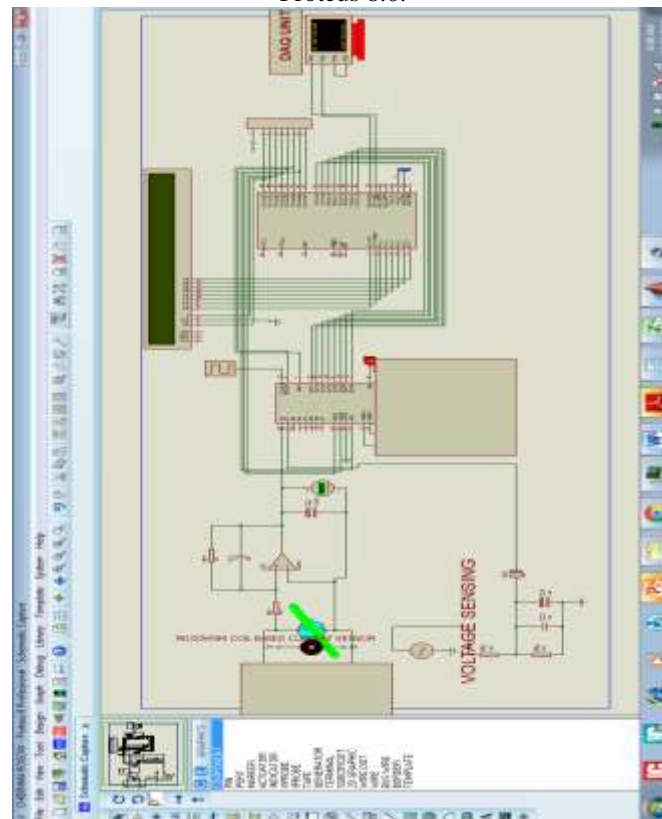

Figure 11 Snapshot capture of the system when it has not yet been initialized Proteus 8.0.
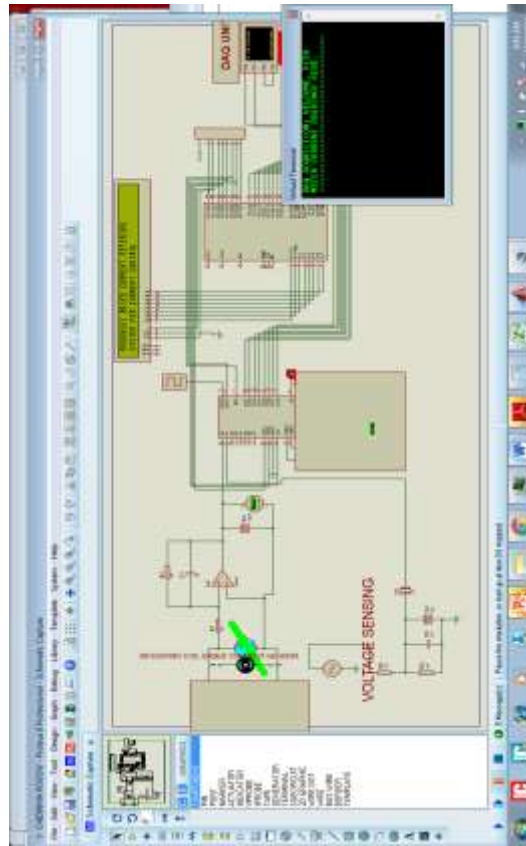
Figure 12 Snapshot capture of the system when it has just been initialized Proteus Isis 8.0.

4.2 Experimental Test-bed Setup for Current Sensing

Figure 13 Snapshot of Rogowski Current Sensor as it is wound

Figure 14 Snapshot of Rogowski Current Sensor with an induced magnetic field and connected to an operational amplifier LM385 that is configured as an integrator

Figure 15 Snapshot of an experimental test-bed set up for a current transformer

4.3 Experimental Results

The coil is wound as a continuous helix of round wire. According to the coil principle, it only measures the current of the conductor passing through the coil's window and rejects the flux generated by conductors outside the coil's window. However, the incremental pitch advancement of the coil's helical winding sums over its circumferential length to create an undesirable one-turn loop normal to the axis of the coil. Any magnetic flux normal to this loop induces an error voltage into the coil's output. Sources of flux in this direction can originate from the bus-bar geometry, nearby return conductors, other current carrying conductors, leakage flux from transformers, or warped fields due to the presence of ferromagnetic materials. To compensate for this undesirable one-turn loop, another one turn loop is place inside of the helical winding in the opposite direction to that of the pitch advancement. It is connected electrically in series with the coil output. In theory, a compensation voltage is induced equal and opposite to that induced in the pitch advancement loop. This, under certain flux condition, cancels the errors caused by the one turn pitch loop when both are exposed to the unwanted flux. When it is placed around the current carrying conductor, the coil generates a voltage, e0, at its terminals proportional to the coil's mutual inductance, M, and rate of change of current, di(t)/dt. In normal operation of coil, each individual coil-turn is electrically connected in series with the next turn so to complete the entire coil. Each individual coil turn forms a voltage generator that contributes to the overall coil output by the sum of the voltages all of the turns. To obtain a measure of current, the coil's output voltage must be integrated, and scaled by the reciprocal of the values of mutual inductance. The integration is done with an electronics integrator configured from an operational amplifier.

An experimental testbed for the Rogowski coils wound from improvised materials namely, coaxial cables and laminated copper wires is implemented.

Table 4.1 Design Parameters:

Name	parameter
Length of Coil	600 mm
Diameter of coil core	2.85 mm
Diameter of winding wire	0.42 mm
Number of turns	1320
Coil termination resistance	50 ohm

Table 4.2 Experimental results from Rogowski coil during voltage and current sensing

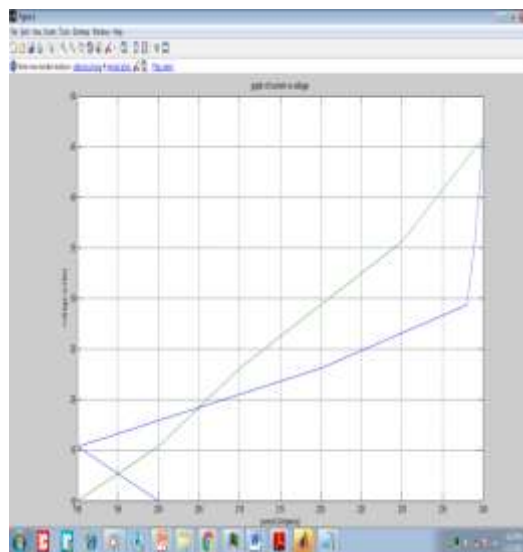| S/N	Current (A)	Voltage (v)	Rogowski integration (mV)	1/M (*10^6 H^{-1})
1	10.03	190	1.419	70.68
2	15.35	200	2.225	60.07
3	23.14	210	3.482	66.65
4	29.37	220	4.573	64.22
5	35.62	230	5.5	64.76
6	45.9	240	7.13	64.37

Figure 4.16 MATLAB of Voltage vs current from Rogowski coil (green colour) and CT (blue colour)

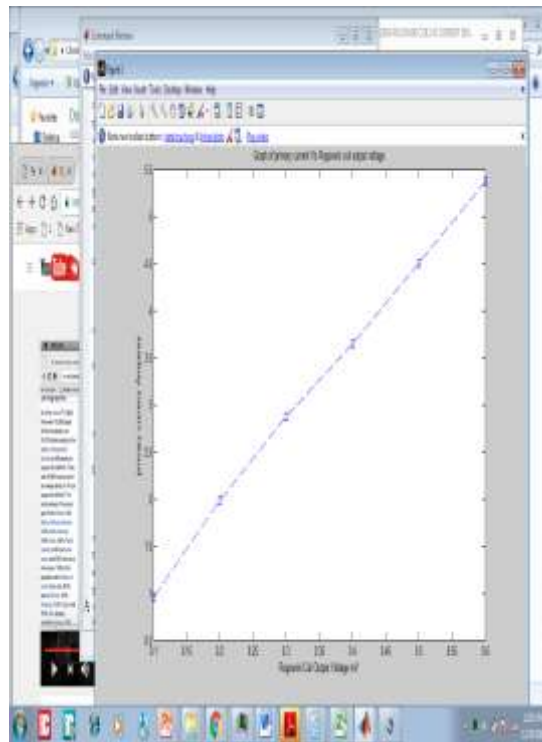| Primary Current (Amps)	Coil output (mV)
0.95	0.1
1.98	0.2
2.87	0.3
3.65	0.4
4.51	0.5
5.37	0.6

Figure 17 MATLAB graph of Rogowski coil voltage output vs primary current

V. CONCLUSION

We have developed and simulated the proposed system that acquires real time data in the distribution sub section of an elect power system parameters in real time and takes into cognizance the dynamic behaviours of these parameters. The developed a system that has embedded in it a real time DAQ and supervisory control from a remote location for intensive monitoring and processing of data from various components of the distribution section of a power system.

The simulation based implementation of data acquisition and processing taking into cognizance data consistency checking algorithms in substation automation will greatly help the control and protection engineers to reduce the faults and error conditions that frequently happen in substation. The reliability of the system is greatly enhanced. The system also proved to be very economical. The initial and maintenance cost of the entire system is reduced and thus there is a major advantage of decrement in cost of power supply system. Also the system can be characterized to be adopted for any scale of a distribution substation. The above automation system, which is functionally based on the Proteus Isis concept and SIMULINK and can be used in procedures for developing software tools and techniques to solve the problems of data verification and error handling in the distribution section of a power system. It will help the control and protection engineers to have a clear picture of the operation of the substations even if it is located in a remote location.

This research was bake to fully integrate an optimized data processing and consistency checking algorithms into the substation model.

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