# ANALYTICAL MODELLING OF SINGLE PHASE SMART METER WITH REAL-TIME TAMPERING ALERT

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***Abstract***

*The advent of wireless automation has led to drastic change in billing structure. This study presents a smart metering system without any human intervention which detects illegal electricity consumption by GSM/GPRS facilities in collaboration with a database installed at the central station. The system was implemented by modeling voltage and current transformers using Theveninn's Equivalence with relevant A.C parameters to process average utility consumption by the end user. Analog to Digital Converter and NAND gate converted the processed analog signal into digital form and eliminated jittering respectively, while microcontroller served as interface for the input and output modules so as to send and receive commands from GSM modules, Liquid Crystal Display (LCD) and Light Dependent Resistor (LDR). Finally, a mathematical model was developed for billing parameters while Assembly Language was used as firmware. The end result was launched into Proteus Electrical Card Tool for simulation, to ensure that virtual operation of the Single Phase Energy Meter was within the predefined requirements. The simulating results obtained showed that the prototype developed and tested, proved to be reliable, secure and cost effective. Significant time can be saved by implementing it.*

Key Words: Energy; GPRS; Modeling; Metering; Transformer.

## 1.0 Introduction

Ibadan Electricity Distribution Company (IBDEC), the custodian of electricity distribution in Southwest, Nigeria is currently facing the problem of revenue collection [1]. This is due to improper power management systems and the usage

of conventional energy metering system which resulted in huge financial losses.[2]. In view of this, Power Holding Company (PHCN) introduced a cash collection policy called Revenue Cycle Management (RCM) [3] that involved using private companies in the collection of unsettled bill owed by the customers. [4] This seems not to yield the expected results; hence PHCN introduced the digital pre-paid meter in 2006 which drastically reduced the movement of the personnel for revenue collection around the nooks and crannies of the country [4] also provided considerable detail regarding the average consumption of a locality. However, this prepaid metering system is not customer friendly because the consumer needs to be at PHCN's office to reload the meter cards. Moreover, it creates the opportunity of meter tampering, by-passing, and stoppage break down (damages or stopping due to technical fault) which the revenue office may get to know lately.
Today, GSM has become a viable and competitive form of data communication and can be switched off during the periods of inactivity; this greatly reduces its power consumption. This and other factors make it well suitable for residential and commercial metering. According to Zerfos et al, SMS delivery success rate was found to be 94.9% of the successfully delivered messages to reach the destination within 10seconds; about 5% of them required more than an hour and half while [5] around 1% to 5% of messages are lost entirely even during normal operating condition and others may not be delivered until long after their relevance has passed. With this delivery success rate of SMS, development of UMTS (Universal Mobile Telecommunications System) and several GSM cryptographic algorithms for security make GSM based kW Meter Reading very essential.

## 2.0 Literature Review and Theoretical Background

Recent trends in digital technology have resulted into monumental development. Embedded systems have become buzz around in the last twenty years, only that one needs to look around to see embedded systems everywhere, toys, cell phones, alarm clocks, personal data assistants (PDAs), automobile subsystems such as motor controller and cruise control, etc. These are now interfaced with transmission media modules to widen their scope and improve the application areas to greater extent. These trends have created new approach for data transmission in a power grid with a communication infrastructure which is termed smart grid. Smart grid extends over all the interconnected electric power systems from centralized bulk generation to distribution, from high voltage transmission system to low voltage distribution systems, from utility control centers to end-user home-area networks, from bulk power markets to demand response service providers. Various kinds of media have been used in a power system. Normally; the suitable media is selected by considering financial, operational, geographical and communicational limitations with new trends. In ICT application, more types of media are available; presently it can be categorized as dependent and independent media.

However, before interfacing energy consumed with transmission media modules, measured analog electrical signal has to be processed and converted into digital signal. An analog voltage signal described by the equation,[6]

$$E(t) = Em\sin(wt + \theta) \tag{1}$$

has an Effective Value ($E_{EFF}$) given by

$$E_{EFF} = \sqrt{\frac{I}{T}\int_{to}^{t_o+T} E^2\,(t)dt} \tag{2}$$

and Average Value ($E_{AV}$) of

$$E_{AV} = \frac{I}{T}\int_{to}^{t_o+\,T} E(t)dt \tag{3}$$

When digitalized by a typical Analog to Digital Converter (A/D), sampling and quantization process with period $T_s$ would have an equivalent value of

$$x(n) = X_m sin2\pi\, n\, T_S \tag{4}$$

with number of quantization (q) [6]

$$q = 2^N \tag{5}$$

and the smallest quantity of the measured value of quantization q is the smallest part of the $Fs$ value (Fs-Full scale) related by

$$q = \frac{Fs}{2^N}\,. \tag{6}$$

And has mean square value (RMS value) of the error represented as

$$\varepsilon_{rms} = \sqrt{\int_{-q/2}^{q/2}\epsilon^2\,p(\varepsilon)d\varepsilon} = {}^{q}\!/_{\sqrt{12}} \tag{7}$$

where N is number of resolution. However, any A/D converter is greatly influenced by two important parameters- the sampling frequency and the number of bit. In reference to these factors, a successive approximation A/D converter type has conversion time expressed as [7]

Conversion Time (CTV) = Number of bit (Resolution) (N) × clock Time ($T_{CLK}$). (8)

Several systems dealing with metering have been implemented, the paper by [8], proposed the design and implementation of Automatic Meter Reading System using GSM, ZIGBEE through GPRS, it structured the design into five subsystems starting from Energy measuring unit to utility control centre where there is a control server with needed programs and storage to read and collect power parameter from AMR-based embedded system (AES). But the workable circuit was not designed and application of ZIGBEE not specified.

Proposed work by [9] focused on saving of power consumption, titled "Domestic Prepaid Energy Distribution System" it had PIC microcontroller as central processing unit. The whole system was interfaced with PIC controller (PIC16F877A) and GSM serially while everything encoded in Micro C. It was only saved energy and not detected any illegal connection. [10] Presented a design and implementation of SMS-based Control for monitoring system. The paper had three modules involving sensing unit for monitoring the complex application, SMS for status reporting of power failure. And issues on billing system for electricity usage were not considered. [1] In their works, proposed a meter with voltage, current and power factor sensors, all the sensors were clipped by rectifier and squared through the zero crossing detectors. These signals are applied to a two-input AND gate to obtain the pulse equivalent of the phase angle difference and the data was transmitted using VART. Issues of metering event and by-passing were not addressed.

According to [11], they discouraged the use of pool of modems for parallel access to the meters because of scalability, security and cost. They suggested their own system architecture using GPRS. The meter was designed and constructed using the shelf components such as evaluation board (MCP3905A), a micro controller PIC16F84A and LCD (16*2). They used GM862-QUAD to integrate GSM/GPRS modules. [12] Proposed the usage of online Power Line Carrier for power telemetering by transmitting measured data through electrical power line between a transmitter and receiver located in the same electrical circuit which is directly linked to power line.

## 3.0 Modeling of Smart Metering Circuit

**Current transformer (CT),** [13] a metering CT requires good accuracy in an area close to the normal service current for metering devices to be protected from high current earlier saturation. For this design the following assumptions were suggested: Primary turn (NP) =2, Maximum Current Rating (standard) =100A/5A, Ns=40turns $E_S = 4.6kVolts = E_{rms}$.

Using equation (1) and equation (2) with identity $Cos^2 \propto = \frac{1}{2} + \frac{1}{2} cos2 \propto$

Thus, $E_m^2 Cos^2(wt + \theta_E = \frac{E_m^2}{2} + \frac{E_m^2}{2} Cos\ (2wt + 2\theta_m)$
(9)

Combining equations (2) and (8) by integration we have

$$E_{max} = \sqrt{2}E_{rms} = \sqrt{2} \times 4600 = 6505.38\ Volts$$

With equations (3) and (8), fourier series of the full wave rectified voltage supplying to the load is found to be $E_{dc} = 2E_{max}\left[\frac{1}{\pi} + \frac{1}{2}Sinwt - \frac{2}{3\pi}Cos2wt - \frac{2}{15\pi}Cos4wt \ldots\right]$

(10)

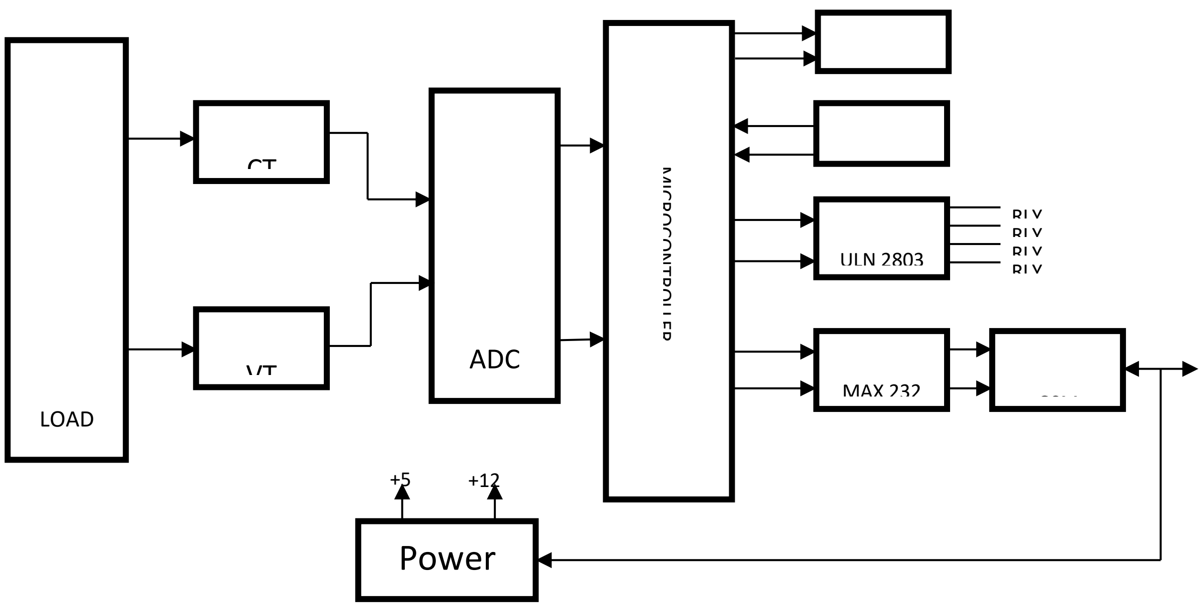


***Fig1: Block Diagram of Smart Metering Model***

While the first term , $\frac{2E_{max}}{\pi}$ $representing\ the\ dc\ component\ E_{dc}$

$$E_{dc} = \frac{2E_{max}}{\pi} = \frac{2 \times 6505.38}{\pi} = 4141.46\,Volts$$

Similarly, $I_{max} = \sqrt{2}\,I_{rms} = \sqrt{2} \times 5 = 7.07$

$$I_{dc} = \frac{2I_{max}}{\pi} = \frac{2 \times 7.07}{\pi} = 4.5$$

For rectification [14], $E_{\delta} = E_{rms} - E_{dc} = 4600 - 4141.46 = 458.54\ Volt$

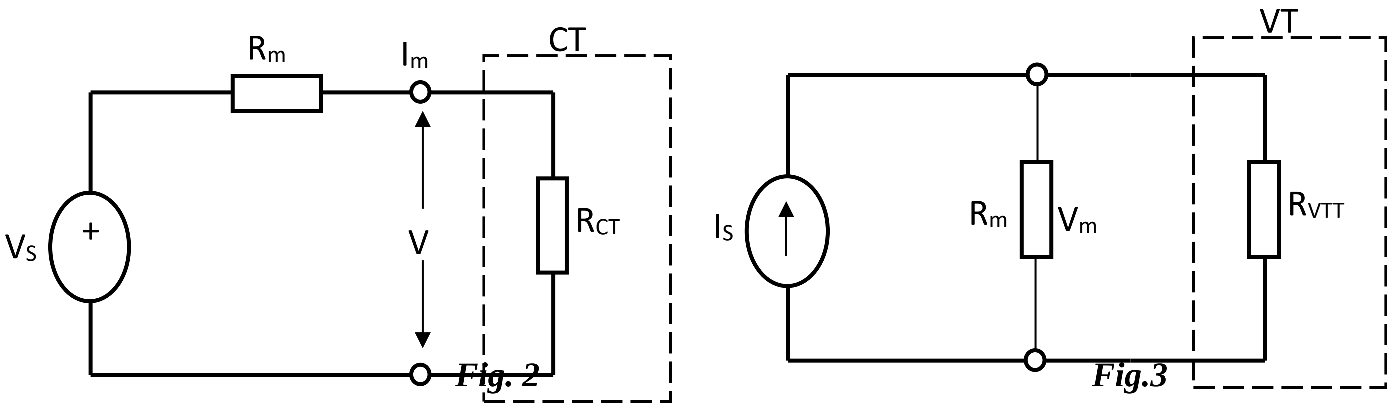


***Fig 2&3: Modeling of Current and Voltage Transformer for Smart Metering***

To safeguard the effect of surge, single phase Bridge Rectifier of 600V, 6A (GBU6S) was employed. As established by [15], current measurement always produces another interaction when an ammeter is inserted in a circuit branch; there would be ammeter (current) input resistance ($R_{CT}$). The current to be measured comes through resistance ($R_m$) which could be a Thevenin's equivalent resistance. The non-zero ammeter introduces a burden voltage V and the measured current would be:

$$Im = I_{dc} = \frac{V_{dc}}{(R_m + R_{CT})} \qquad (11)$$

Since actual current (Iact) is $I_{act} = \frac{V_{dc}}{R_m}$ (12)

It can be established that $I_{act} = \left(1 + {R_{CT}}/{R_m}\right) I_m$ (13)

In order to have a good current measurement instrument, $R_{CT} << Rm$ and $I_m \approx I_{act}$ . From ADC data sheet [30], the maximum power rating is 15mW and maximum voltage is 5V, giving the maximum current to be $\frac{15 \times 10^{-3}}{5} = 3mA$

Using equation (10) $3 \times 10^{-3} = \frac{4141.46}{(R_m + R_{CT})}$

Choosing $R_{CT} = 51\Omega$, $R_m = 1.38M\Omega - 51\Omega$ , $R_m \approx 1.4M$

*While* chosen value was *1.5M, 0.6W*

For bridge rectifier [16], $C = \frac{I_m}{4\pi f\ (E_m - E_{dc})}$ (14)

$$= \frac{3 \times 10^{-3}}{4\pi f(6505.38 - 4141.46)} = 2.02nF$$

Available value chosen *2.2nF*

**For Voltage Transformer,** as stated by [17], the nominal voltage of *VT* is *115V*, irrespective of what rated primary voltage may be,. Subject to this, the following parameters were suggested.

Voltage rating =*115V*, Primary rating =*50*, Primary Current ($I_P$) =*5 Amps*

Using transformation equation, $\frac{115}{230} = \frac{N_S}{50} = \frac{5}{I_S}$, $N_S = 25$ turns, $I_S = 10$

Similarly, $E_{max} = 162.63\ Volts$, $E_{dc} = 103.54 Volts$, $I_{max} = 14.14\ Amps$, $I_{dc} = 9\ Amps$ and $E_\delta = 11.6\ Volts$[14]. Single phase bridge rectifier of 50V, 35Amps was employed for surge protection.

For the *VT*, the interaction error in voltage measurements takes form of current loading [15]. $R_{VT}$ represents the total input resistance of the *VT* and the voltage to be measured appears across resistance $R_m$, which could be a Thevenin's equivalent resistance. The *VT* loads on the circuit by drawing the current *I* and the measured voltage $V_m$ is [15].

$$V_m = (R_m // R_{VT}) I_S \quad (15)$$

$$= \frac{R_m I_S}{\left(1 + {R_m}/{R_{VT}}\right)} \quad (16)$$

Since actual voltage without meter connected was $V_{act} = R_m I_s$, it could also be established as:

$$V_{act} = \left(1 + {R_m}/{R_{VT}}\right) V_m \quad (17)$$

A good voltage metering system should have large input resistance i.e. $R_{VT} >> R_m$

With ADC data sheet, the maximum voltage is 5.12V [18], if $R_{VT}$ = *1.5M* and $I_{dc}$ = *9 Amps*, by applying equation (16) $V_m = \frac{R_m \times 9}{\left(1+\frac{R_m}{1.5M}\right)}$, giving $R_m$ = *0.55*Ω

*1.2k*Ω resistor was eventually chosen to forestall any surge. While for the filtering capacitor, with equation 14: $C = \frac{3 \times 10^{-3}}{4\pi f(162.63-103.54)}$ = *810pF*

preferred value chosen was multilayer ceramic of *820pF*, *50V*.

To eliminate jittering, NAND gate, HIC132 was introduced, and proposed to operate at 90% of its operating voltage (5V) at frequency range 1MHZ to 10MHZ) [17]. For the proposed model, 1MHZ was chosen which is

i.e [19] $F = \frac{1}{k \times RC}$ (18)

where k is 0.9 for 4.5v. R =1.2kΩ. Then giving

$C = \frac{1}{0.9 \times 12000 \times 10^6} = 0.93nF$, eventually, 1nF was chosen

For the model, 8-bit up compatible A/D converter with 8 channels multiplexer (ADC0809) was suggested. [18] ADC0809 has revolution of bits, converted time of 100ns and single supply voltage of 5volt. Number of quantization is $q = 2^8 = 256$ and one quantization of q is

$\frac{5.12}{256} = 20mV$ (Equation 6)

Mean Square Value Error $\varepsilon_{rms} = \frac{20 \times 10^{-3}}{\sqrt{12}}$ = 5.6mV (equation 7)

Total expected error = 20mv +5.6mv = 25.6mv,

Clock time($T_{CLK}$) $of\ 12.5\mu s$ (equation 8)

Clock Frequency ($F_{CLC}$) $of\ 80kHZ.$ (Inverse of $T_{CLK}$)

Red LED was chosen as an indicator, it has nominal voltage and current of 2volts and 20mA,

$$R_{RED} = \frac{5-2}{0.02} = 150ohm.$$

AT89552 microcontroller was employed for interfacing the input and output modules (such as NPN Darlington Connected Transistor, LCD and RS 232). To obtain the standard band rate of 9600Hertz, the setting of TH 1 was [20]

$$BRL = 256 - \frac{2^{SMDD} \times F_{PER}}{6^{(1-SPD)} \times 32 \times Band - Rate} \quad (19)$$

For mode 1, band rate is 1/32 of oscillatory frequency $\left({F_{osc}}/{12}\right)$

Then, $$TH1 = 256 - \frac{2 \times 12 \times 10^6}{6^{(1-4)} \times 32 \times 9600 \times 12} = 253d$$

$$Th1 = 0FDh$$

To check the metering event, LDR was employed. For AT89S52, the voltage on any pin with respect to ground is – $\Delta - 0V$ to 7.0V. If R= 10kΩ, output $V_0$ is.

$$V_0 = V_{in} \times \left[\frac{R}{LDR+R}\right] \quad (20)$$

$$V_{out} = 5\left[\frac{10{,}000}{R_t + 10{,}000}\right]$$

## 3.1 Mathematical Model

**Voltage transformer,** rating is ${115}/{230}$ $i.e \propto_1 = {1}/{2}\,(transformation\ ratio)$ while step input of ADC $(5.12v) to\ V_o of\ transformer\ \ is \propto_2 = \frac{5.12}{115} = \frac{128}{2875}$

$$\propto_v = \propto_1 \propto_2 = \frac{128}{2875} \times \frac{1}{2} = \frac{64}{2875}$$

If' V' represents incoming measuring voltage, actual voltage of the consumer shall be

$$\frac{1}{\propto_v} \times V = 44.92V$$

**Current transformer:-:** Rating is $\frac{5}{100}$ $i.e\ \beta_1 = \frac{1}{20}$ and proportion of current of ADC to $I_o$ of transformer is $$\beta_2 = \frac{3 \times 10^{-3}}{5} = 6 \times 10^{-4}$$

$$\beta = \beta_1 \beta_2 = {1}/{20} \times 6 \times 10^{-4} = 3 \times 10^{-5}$$

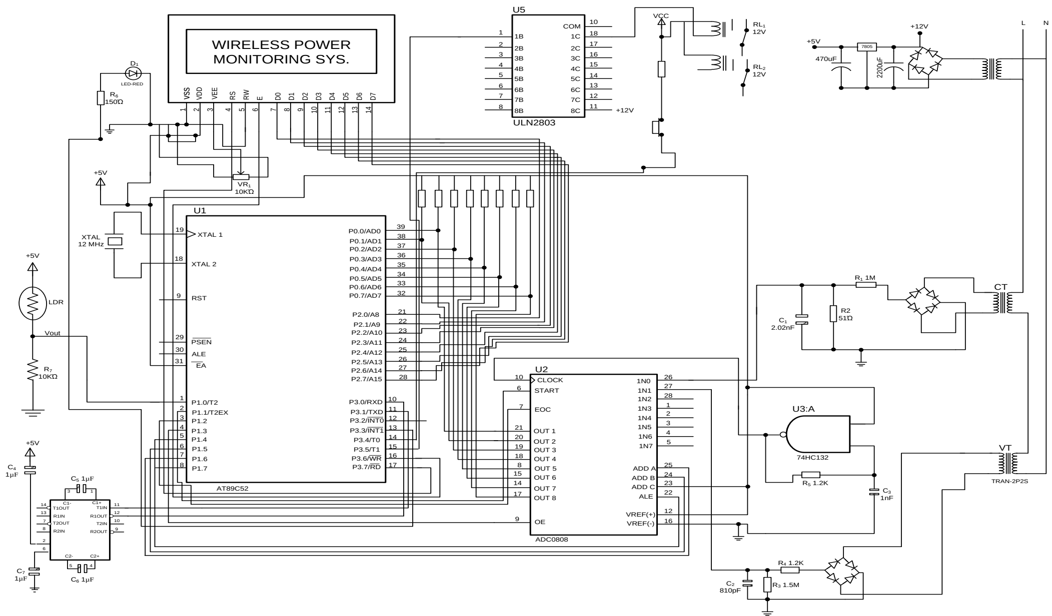


***Fig 4: Circuit Diagram of Digital Metering System***

If' I' represents incoming measuring current, the actual current will be

$$\beta_I = \frac{1}{\beta} \times I = 3.33 \times 10^5 I$$

Total bit available is $2^8 = 256$, giving step input voltage = $\frac{5.12}{256} = 20mV$

Total power consumed will be $20 \times 10^{-3} \times\propto_V \beta_I$

$$P_C = 299167.2VI\ Watts$$

Since most of loads used by residential customer are resistive (Like Light bulbs and heaters) except the motor which is inductive, the model assumed ideal power factor.

$$W = P_c \times p.f = 299167.2VI$$

Then estimated rate= $\frac{P_c \times p.f}{E_N}$, where $E_N = Energy\ charge\ per\ kwhr$

$$= \frac{299167.2VI}{1000 \times 3600} = 0.083VI$$

The simulation was carried out to ensure the model i.e. the system, operated correctly within the predefined requirement using Proteus Electrical Card Tool while Assembly Language was used to lunch hex file into AT89552 for virtual operation.

## Result Analysis and Discussion

The proposed SM started working by displaying the name and status of the system i.e. ‘system working’, then, sent SMS to electricity provider (fig 5). If not, it shows that meter is by-passed. The billing layer of the model was made of prepaid engine, when the system was simulated the current and voltage were generated to validate the units consumed in kw/hr, taking into account the loads on the smart meter. LCD displayed the reading of the consumed energy and GSM module sent the SMS at interval of 24hours (Fig 6). When the credit unit is exhausted, it will open and disconnect the load from the supply with SMS sent to the utility provider.

For the tamper proof, if a user deliberately tries to open the inner part of the meter, the dark resistance would be less than or equal to $R_i$ i.e. $R_F \le R_i$

Then, $R_t \ge R_i$ and $V_{out} \simeq V_{in}$

The relay will open, disconnect the load from the supply and send SMS to the utility center (fig 7).

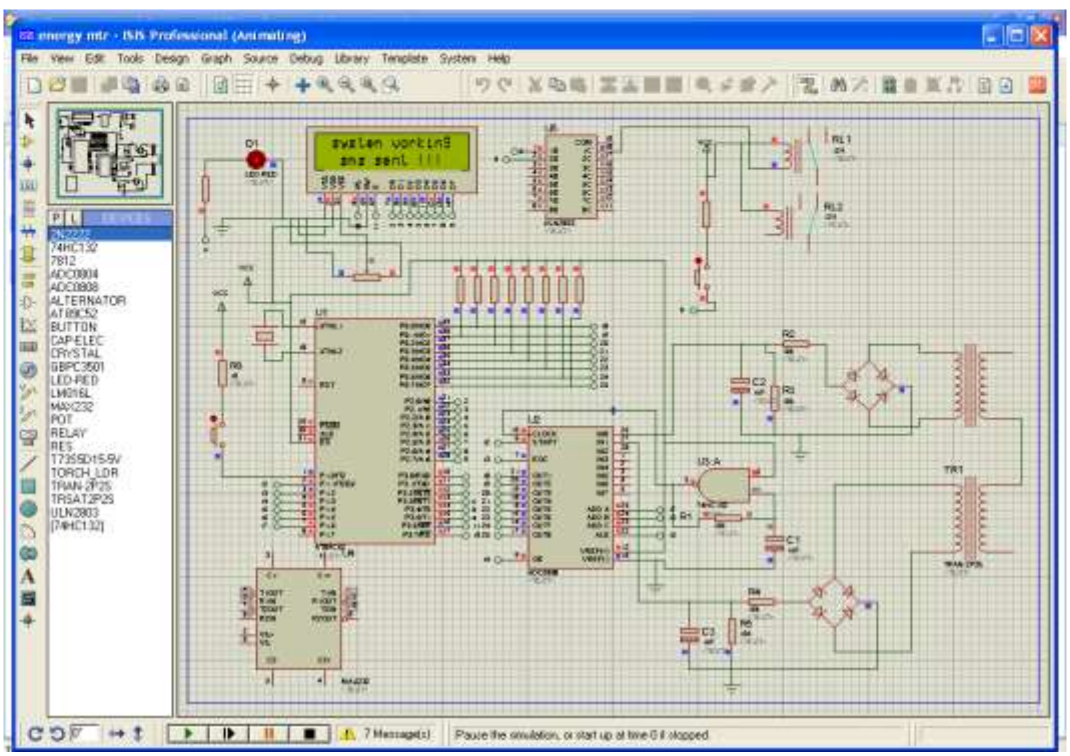


***Fig. 5: The Displaying of Smart Meter Status on LCD***

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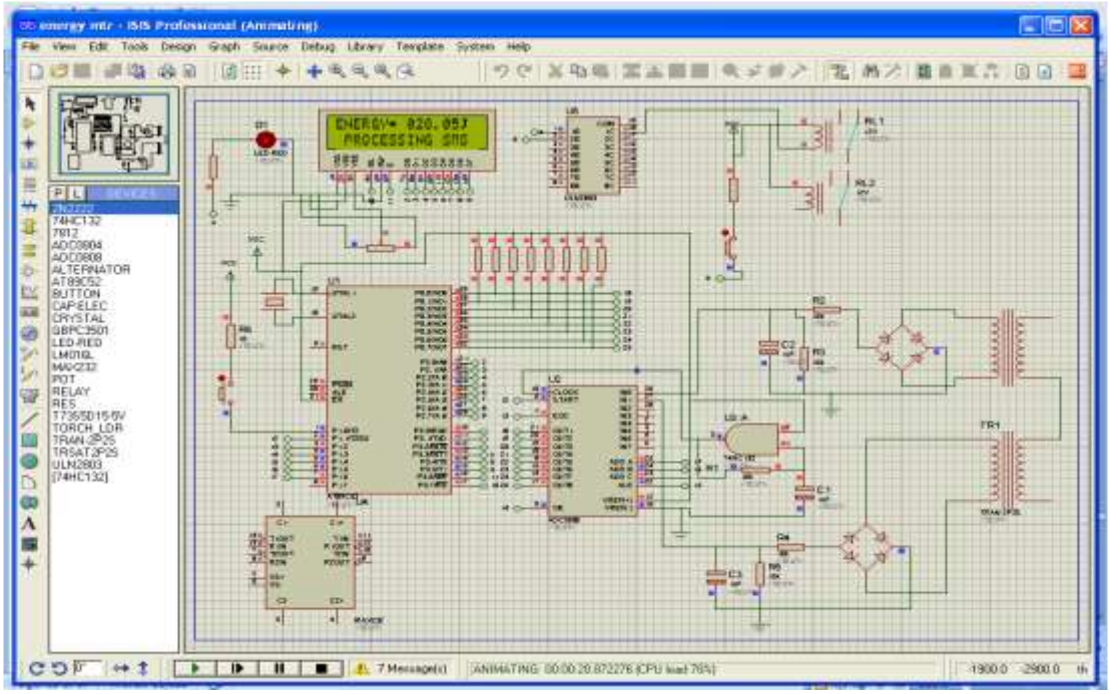


***Fig. 6: Displaying of Consumed Energy on LCD***

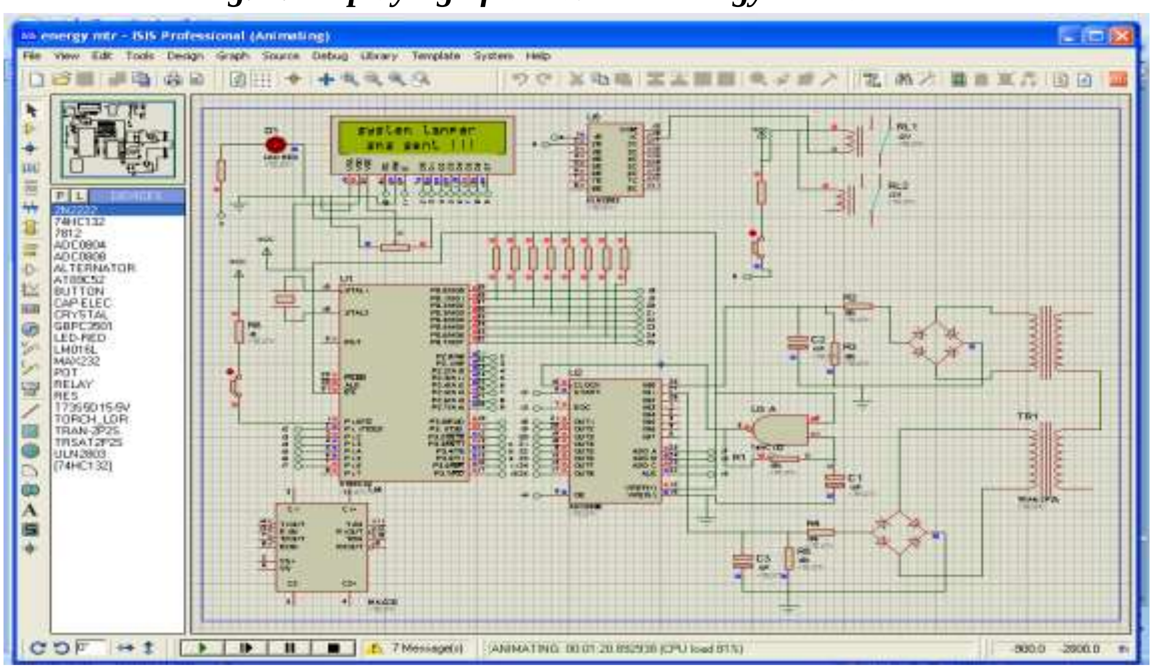


***Fig. 7: Result of the Meter Tampering***

## 5.0 Conclusion and Recommendations

Having modeled the design and virtual operation of Smart Meter using GPRS and GSM technologies, it was observed that the prototype developed and tested proved to be reliable, secure, cost effective, and significant time can be saved by implementing it. This work established a clear idea regarding the kind of architecture that needs to be developed in terms of hardware, software, database and network for wireless metering implementation. Also, if this model is practically implemented /adopted, consumers can be more accurately informed of their consumption mode; hence they will actively adjust their behaviour to reduce their energy cost, if necessary. Although, the model of the present system provides enough functionality to perform adequately, there is still room for enhancement to develop full Based Recharge System Architecture. The system can be further expanded as stated below.

1. A Smart module of such can be modeled for utility control centre server
2. Modeling of Power Telemetering System dedicated for based transformer in order to detect malicious end node connection
3. Development of Three-phase Smart meter for industrial application.

If these can be integrated, there would be a drastic reduction in the huge financial losses in electricity market.

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