A Prepaid Energy Meter Using GPRS/GSM Technology For Improved Metering And Billing

W.D.A.S. Rodrigo, H.K.I.S. Lakmal, N.S. Roshani, S.W.M.G.S. Samarakoon, and S.S. Samararatne

Abstract— **Most of the developing countries are moving in to smart meters equipped with prepayment facility to measure electricity in order to reduce the financial losses faced by utilities due to consumer reluctance to make bill payments on time. Prepaid smart meters enable consumers to effectively manage their electricity usage. But the main drawback of the currently available prepaid meters is their high cost which makes them infeasible for developing countries. This paper is based on a final year university project on designing and implementing a digital prepaid energy meter which is affordable for domestic consumers in a developing country like Sri Lanka. The prepaid energy meter described in this paper is a single phase230V/40A energy meter which consist of a metering devise designed according to the IEC1036 (1996-09) standard and a prepaid module that uses GSM/GPRS technology to communicate with the utility server.**

Keywords— **Credit card, Energy metering IC, Metering devise, Mobile service provider, Prepaid module.**

I. Introduction

Efficient usage of electricity has become an important concern worldwide. This has urged utilities throughout the world to shift from conventional electromechanical meters to smart meters which provide better security and control [1], [2].Smart meters equipped with prepayment facility has become a rapidly growing technology because it allows the utilities to manage their cash flow more efficiently [3].

Majority of the energy meters currently used in Sri Lanka are electromechanical energy meters which are gradually being replaced by digital and electronic energy meters [4]. Sri Lankan Power sector is currently focusing on introducing smart meters for domestic consumers as a method of implementing demand side management [4].The consequence with existing energy metering structure has led the Sri Lankan power sector to take this decision. Few issues related to existing Sri Lankan energy metering structure are listed below.

- A large number of inspectors have to be employed for meter reading and bill payment related tasks [4].
- Incorrect meter readings, billing errors and errors due to estimated bills [4].
- Reluctance of consumers for paying electricity bills on time.
- Uncontrollable demand growth [4].
- Electricity theft [4].
- Consumers have to spend time and energy standing in queues to make bill payments.

This paper present a proposed design of a 230V/40A single phase digital prepaid energy meter which consists of an energy metering devise and a prepaid module that is used for billing and recharging. The proposed energy meter communicates with the utility server through GPRS technology. Every user is provided a separate web account which can be used to recharge his/her account as well as monitor his/her energy usage. The prepaid module is equipped with a LCD display which the user can use to monitor the consumed energy as well as remaining energy. This is notified through a sms to recharge his account when the remaining energy drops below a threshold value. If the remaining energy goes below the disconnection threshold level, the energy meter will disconnect the power supply from the load. Once the meter is recharged above the reconnection threshold level the load gets reconnected to the supply. The utility server is updated every 15 min and the utility can monitor user information through the utility website that we have developed.

II. Existing Prepaid Metering technologies

- *SMART CARD based prepaid Energy Meters*

Smart card is a credit card sized plastic card embedded with an integrated circuit (IC) and usually it consists of a ROM, EEPROM and a CPU.A smart card provides both the memory capacity and the computational capability [5]. Access to data stored on the card is under the control of the smart card operating system. In this method consumer have to have the smart card recharged for the amount he choose and enter the card into the card reader of the energy meter [5]. Then the meter store the number of units recharged and start to measures the energy consumption. When purchased units are used up the meter disconnect the power supply until the next recharge [5].

- *RFID(Radio-Frequency Identification) based Prepaid Energy Meters*

Radio-frequency identification (RFID) is an automatic identification method, relying on storing and remotely retrieving data using devices called RFID tags or transponders [6]. The technology requires some extent of cooperation of an RFID reader and an RFID tag. An RFID tag is an object that can be applied to or incorporated into a product, animal, or person for the purpose of identification and tracking using radio waves. Some tags can be read from several meters away and beyond the line of sight of the reader [6].

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In this method RFID cards which are issued by the electricity suppliers to individual consumers are used. This RFID card is unique with a code in it and consumers are free to make flexible recharge [6]. When the consumer wants to use the system he needs to show the card to the reader, then the unique code inside the card is recognized by the reader, and starts deducing the amount of the RFID card as per the quantized unit charge. When the usage completes the consumer has to recharge the RFID card again.

- *Prepaid Energy Meters with GSM Technology*

In this method consumers are expected to reload their mobile account and send a SMS to the energy meter using GSM network. Then the meter holds the purchased energy units corresponding to the recharged value and let the consumer to use electricity until the purchased units are exhausted. If the available energy units are exhausted then the electricity supply is cut-off [7], [8]. After the next recharge occurs the microcontroller pulls the SMS sent by the mobile, decodes it, recognizes the Mobile no. and then makes the power supply connection again. After successful operation, controller sends back the acknowledgement to the consumer's mobile through SMS [7], [8].

III. Main Features Included in the Proposed Design

Following features are included in the proposed digital prepaid energy meter

- Automated service disconnection and remote meter reading facility.
- Includes a mobile app from which user can remotely monitor his electricity usage.
- A web account is allocated to each customer to make online payments and monitor his/her usage.
- Payments can be made through credit cards and mobile service providers.
- Customer receives a notification SMS when the remaining energy goes below the first notification level of 5 kWh.
- Consumer will be alerted by a beep alarm when the remaining energy goes below the second notification level of3 kWh.
- The connection gets disconnected when the remaining energy falls below the disconnection threshold of 1kWh and the user receives a sms verifying his supply is disconnected.
- The connection gets reconnected after the account is recharged above the reconnection threshold of 6 kWh and the user receives a sms verifying his supply is reconnected.

IV. Design Methodology

As the first step of the design process an online survey was conducted in order to decide the most convenient payment method for consumers. Hundred participants took part in the survey and 77.5% of them preferred making payments through credit cards and mobile service providers. The results of the online survey are shown in Fig. 1.Depending on the results of the survey, payments through credit cards and mobile service providers were selected as the most convenient method of payment for the proposed prepaid energy meter.

Implementation of the proposed prepaid energy meter is carried out in two stages.

A. First stage - Developing the prepaid module

B. Second stage - Developing the metering device

As shown in the *Fig. 2*utility power supply is fed to the energy meter and the prepaid module provides a control signal to the local contactor according to the remaining energy. Whenever the remaining energy goes below disconnection threshold it provides a disconnecting signal (0V) to the contactor so the power supply gets disconnected. When the consumer recharges his account above the reconnection threshold the prepaid module sends a reconnection signal (5V) to the contactor so the supply gets reconnected.

A. Prepaid Module

The prepaid module consists of a microcontroller, GSM module, a contactor (Solid state relay), a backup battery and an LCD display. The energy information is updated in the EEPROM on the microcontroller every 15 seconds to avoid any loss of information during a sudden power outage. The backup battery bank is used to power the prepaid module during a power failure in order to notify the utility about the electricity outage.

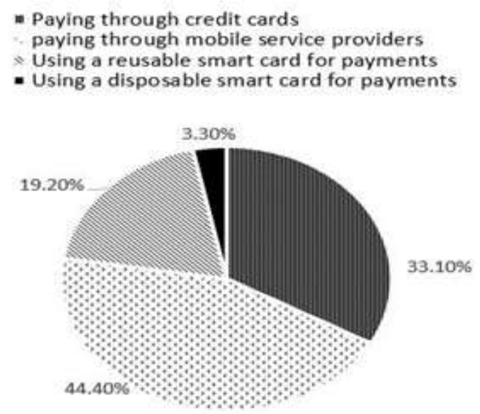

Fig. 1. The results of the online survey

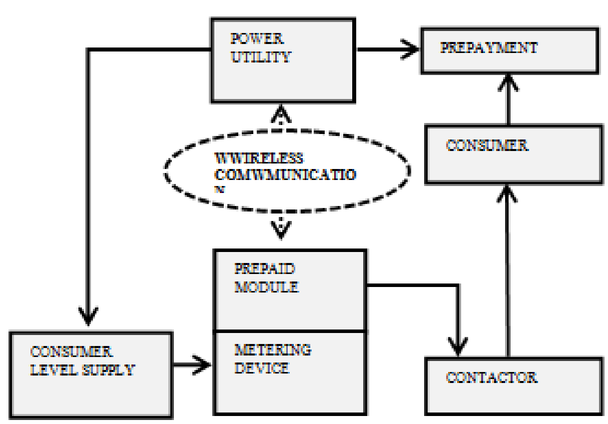

Fig. 2. Working scheme of the prepaid energy meter

1. Microcontroller

ATMEGA 2560 microcontroller is used in the prepaid module. The energy metering IC (AD7755AAN) supplies average real power information on the low frequency outputs F1 and F2 and thisF1 pulse output is interfaced with the Microcontroller as shown in Fig. 3. The power monitoring IC generates 100pulses/kWh while microcontroller detects and counts the pulses using a counter to calculate the consumed energy.

The consumed energy during a period of integration can be calculated as follows.

Average Frequency = Average Real Power = $\frac{Counter}{Time}$

Energy = Average Real Power × Time

= $\frac{Counter}{Time}$×Time=Counter

The microcontroller calculates the remaining energy by subtracting the consumed energy from the purchased energy. When the remaining energy reaches a notification level or a threshold level the microcontroller generates the required control signal

2. Communication with the utility and the GSM module

The sim 900A GPRS/GSM module is used as the communication devise of the prepaid module. In the proposed prepaid module the communication between prepaid meter and the utility server is done in 2 methods.

- Short Message Service
- GPRS Service

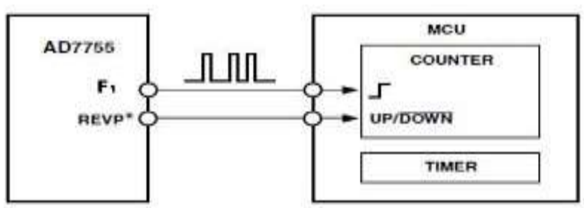

Fig. 3. Interfacing of the power metering IC with the microcontroller

3. Contactor

SSR-40DA Solid State Relay Module is used to disconnect the supply from the consumer whenever it gets a disconnection signal from the prepaid module. In this solid state relay,

- The input voltage is rated at 3-32V DC.
- The output voltage is rated at 24-380V AC.
- The maximum output current is 40A.

B. Metering Device

Metering device of this prepaid energy meter is designed according to the IEC1036 (1996-09)-Alternating Current Watt-Hour Meters for Active Energy (Classes 1 and 2) using AD7755AAN single phase unidirectional power metering IC. It generates an output frequency that is proportional to the average real power with a meter constant of 100 imp/kWh. The AD7755AAN also provides a high-frequency output (3200 imp/kWh) at the CF pin. This high-frequency output is available at a LED which is used to speed up the calibration process and meter functionality and accuracy verification in a production environment.

A shunt is used to provide the current-to-voltage conversion needed by the AD7755AAN and a simple divider network which attenuates the line voltage. The frequency outputs (F1 & F2) of the IC directly communicate with the microcontroller.

1. Operation of the AD7755AAN IC

As shown in the *Fig. 4.*voltage signals come through the voltage and current transducers are digitized using two analog-to-digital converters (ADCs).These ADCs are 16-bit second order sigma-delta with an oversampling rate of 900 kHz. In addition to that the programmable gain amplifier with user selectable gain of 1, 2, 8 or 16 in the current channel facilitates easy transducer interfacing. The instantaneous power signal is generated by directly multiplying the digitized current and voltage signals and the real power component (DC component) is extracted using a low pass filter. This operation is valid even when the voltage and current signals are non-sinusoidal and not in a phase. Then the IC generates two frequency outputs (low and high) using extracted real power component. The low frequency output is generated by accumulating real power component over a long accumulation time period and therefore the low frequency output is proportional to the average real power. But the high frequency output is generated accumulating real power information over a short time period and this frequency output is proportional to the instantaneous real power. This high frequency output (CF) is used for system calibration purpose.

Sometimes the voltage and current signals comes from transducers may have offsets and it contributes a DC component after the multiplication and it introduce a constant error to the real power calculation as shown by the calculation below.

$$\{V\cos(\omega t)+V_{OS}\} \times \{I\cos(\omega t)+I_{OS}\} = \frac{V\times I}{2} + V_{OS}\times I_{OS} + V_{OS}\times I\cos(\omega t) + I_{OS}\times V\cos(\omega t) + \frac{V\times I}{2}\cos(2\omega t)$$

Where,
V_{OS} -Offset of the voltage signal
I_{OS} -Offset of the current signal
V -Rms value of the voltage signal
I -rms value of the current signal

This problem is avoided by connecting a high pass filter (HPF) to the current channel. By removing the offset from at least one channel, the error DC component generated in multiplication can be eliminated.

2. Shunt selection

Load current is sensed by an analog voltage signal applied to V1P, V1N pins of the AD7755AAN IC. And this current-to-voltage conversion needed by the IC is done by using a shunt resistor as mentioned before. When selecting the size of the shunt resistor several factors have to be considered. First the power dissipation through the shunt resistor should be minimized (according to IEC1036 standard, maximum power dissipation of the meter should be less than 2W). In this design a 350 μΩ resistor was selected for the shunt and its maximum power dissipation is $(40\ A)^2 \times 350\ \mu\Omega = 560\ mW$ which is less than the maximum acceptable value. Secondly, the higher power dissipation and high temperatures may cause significant error at heavy loads. By making the shunt resistance value smaller this error can be made small. And also when the resistor value becomes small it creates a resistance to tamper by short circuiting the phase circuit because very low values of shunt resistance minimize the effects of shorting the shunt. Therefore the shunt resistance value should always be made as small as possible. But very small shunt may not be able to meet the IEC1036 accuracy requirements at light loads. Therefore there should be a good compromise for the size of the shunt resistor.

The 350 μΩ shunt resistor which is usein this design is manufactured from Manganin material, which is an alloy with a low temperature coefficient of resistance.

V. Power Supply Design

This design uses a simple capacitor divider network which consists of two capacitors (C17 and C18). Most of the line

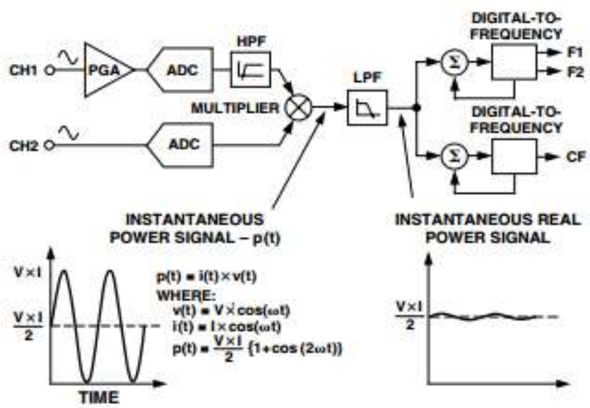

Fig. 4 Operation of the AD7755AAN IC

voltage is dropped across the C17, a 470 nF 250 V metalized polyester film capacitor. The size of C17 is decided according to the power consumption specification in IEC1036. The total power consumption of the circuit including power supply, is specified in section 4.4.1.1 of IEC1036 (1996-9) as 2 W and 10 VA under nominal conditions. The nominal VA rating of the supply in this design is 7 VA and the total power dissipation is approximately 0.5 W. Therefore the total power dissipation (power dissipated in the shunt at 40 A load and in the power supply) of the meter is 1.06 W. *Fig. 5*shows the basic power supply designs.

VI. Meter Calibration

The meter is calibrated using a simple divider network. The line voltage is attenuated using this divider network and the voltage which should be appear on the divider network can be calculated as below.

According to the AD7755AAN data sheet the equation that relates the low frequency output on F1 and F2 to the product of the rms signal levels at current channel (V1) and the voltage channel (V2) is given by the equation (1)

$$\text{Frequency} = \frac{8.06 \times V1 \times V2 \times Gain \times F1\text{–}4}{Vref \times Vref} \qquad (1)$$

Where,

V1- Differential rms Voltage signal on channel 1

V2- Differential rms Voltage signal on channel 1

Gain- 1,2,8or16 depending on the gain selection of the IC using logic input G0 and G1.

Vref- Reference voltage

F1-4- One of the four possible frequencies selected by using the logic input S0 and S1 of the IC

Design parameters:

Line voltage = 230 V (nominal)
I_{MAX} = 40 A
Base current (Ib)= 5 A
Counter = 100 imp/kWh
Meter constant = 3200 imp/kWh
Shunt size = 350 μΩ
F1–4 frequency=3.4 and Gain=16 (selected using the AD7755 data sheet)

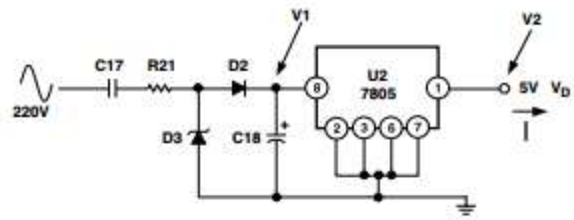

Fig. 5 Power supply design of the metering device

Then,

100 imp/hour = 100/3600 sec = 0.027777 Hz

Meter is calibrated at Ib (5A).Then the Power dissipation at Ib = 230 V × 5 A = 1.15 kW
Frequency on F1 and F2 at Ib = 1.15 × 0.027777 Hz = 0.03194355 Hz
Voltage across shunt (V1) at Ib = 5 A × 350 μΩ = 1.75 mV
Then

$$\text{Frequency} = \frac{8.06 \times V1 \times V2 \times Gain \times F1\text{–}4}{Vref \times Vref}$$

$$0.03194355\ \text{Hz} = \frac{8.06 \times 1.75mV \times V2 \times 16 \times 3.4Hz}{2.5V \times 2.5V}$$

V2 = 260.19 mV rms

Therefore, in order to calibrate the meter the line voltage needs to be attenuated down to 260.19 mV

VII. Protection Schemes

According to IEC1036 standard the meter should be designed in such a way that conducted or radiated electromagnetic disturbances as well as electrostatic discharge do not damage nor substantially influence the meter
The considered disturbances are

a. Electrostatic Discharge
b. Electromagnetic HF Fields
c. Fast Transience Burst

a. Electrostatic Discharge (ESD)

Some sensitive electronic components contain a certain amount of ESD protection on the chip. But they may not be possible to protect against severe discharge. Therefore the effects of ESD event should be eliminate before it comes in contact with sensitive electronic devices. Most of the times no additional components are necessary to protect devices and components which are already required in the circuit can perform this role. As examples,

1. The shunt is connected to the AD7755AAN through two low pass filters. These RC filters protect CMOS devices against ESD damage.
2. Two ferrite beads are placed in series with the connection to the shunt and it is effective at slowing the fast rise time of an ESD current pulse
3. The power supply circuit is directly connected to the terminals of the meter. Then the discharge will be dissipated by the ferrite, the line filter capacitor (C16), and the rectification diodes D2 and D3.
4. The voltage channel is protected by the large impedance of the attenuation network used for calibration.

b. Electromagnetic HF Fields

Due to resonance on the PCB there may be higher sensitivity to certain radio frequencies. These resonances could cause gain at certain frequencies which could cause problems for sensitive devices. Some of the techniques for protecting the system are

1. Minimize Circuit Bandwidth
2. Isolate Sensitive Parts of the System

1. Minimizing Circuit Bandwidth

In this design the required bandwidth is only 2kHz and the cable entry points are low pass filtered to reduce the amount of radio frequency radiation (out of the 2kHz bandwidth) entering the system. The antialias filters that are connected between shunt output and the AD7755 are used for this low pass filtering with help of ferrite beads. This combination of antialiasing filters and ferrite beads can double as very effective RF filters.

2. Isolation

One of the possible paths for RF is the I/O connections. Sensitive regions of the system are protected from RF radiation entering the system at the I/O connection using the technique called moting. Here the area surrounding the I/O connection does not have any ground or power planes and this limits the conduction paths for RF radiation. Power, ground, and signal connections must cross the moat achieved by using a ferrite bead Ferrite offers a large impedance to high frequencies.

In this design the moating technique is used to help isolate the signal ground surrounding the AD7755AAN from the external ground reference point (K4).

c. Fast Transience Burst

The electrical fast transience pulse can be particularly difficult to protect against because the disturbance is conducted into the system through external connections like power lines.

The protection techniques use for Electromagnetic HF Fields can also be applied equally well in the case of EFT. The electronics should be isolated as much as possible from the source of the disturbance through PCB layout and filtering signal and power connections. In addition to that a 10 nF capacitor (C16) is placed across the mains in order to provide a low impedance shunt for differential EFT pulses.

Since the PSU is consist of capacitors, a considerable current flow in the ground return back to the phase wire. This current has a frequency same as the signals being measured and could cause accuracy issues. Therefore in this design Power supply unit (PSU) is located in the digital portion of the PCB and it keep the return current away from the AD7755AAN and analog input signals.

VIII. Errors associated with the AD7755 IC

a. Phase error between channels

The High Pass Filter in current channel gives a phase lead response. Therefore a phase correction network is placed in the current channel in order to offset this phase response and equalize the phase response between channels. The phase correction network matches the phase to within ±0.1° over a range of 45 Hz to 65 Hz and ±0.2° over a range 40 Hz to 1 kHz.

b. ADC offset error

This refers to the dc offset associated with the analog inputs to the ADCs because Sometimes the voltage and current signals comes from transducers may have offsets. However because of the HPF the offset is removed from the current channel and the power calculation is not affected by this offset.

c. Gain error

The difference between the measured output frequency and the ideal output frequency of the AD7755AANis defined as the gain error. It is measured with a gain of 1 in channel V1 and the difference is expressed as a percentage of the ideal frequency.

IX. Conclusion

This paper presents a designing of a230V/40A single phase digital prepaid energy meter for domestic consumers with improved metering and billing facilities to eliminate major drawbacks of existing energy metering systems. Designing of the metering devise and the prepaid module are explained separately in this paper. The major advantage of the proposed system is its ability to upgrade the existing energy meters into prepaid energy meters with the attachment of prepaid modules which eliminates the need to entirely replace the energy meter. We hope that this proposed prepaid energy meter will be very useful for the power utilities in developing countries with large population who use traditional energy meters because upgrading the existing energy meters is more economical than replacing them fully with a prepaid energy meters.

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