AN ELECTRONIC AMPERE-HOUR METER

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ABSTRACT

The electronic ampere-hour meter does not require any voltage supply and its operation is based on the magnetic coupling to electrical conductors feeding consumer's load. A capacitor inside the meter is charged at a rate proportional to the load current of the consumer and the number of discharges of the capacitor which occurs at a predetermined capacitor voltage is registered as the ampere-hour reading. Test results of a prototype meter for resistive, inductive and capacitive loads are compared with those from a conventional kWh meter. Results show that the Ah meter functions with reasonable accuracy and it is shown that it can be modified to work as a two-rate meter to implement a 'day-night tariff' without much increase in cost, with possible application in stand-alone hydro power type schemes. Other advantages of the meter are simple construction, less wear and maintenance and lower cost compared to the conventional kWh meter.

1. INTRODUCTION

The conventional unit for the measurement of electrical energy is the watt-hour, which is the energy expended in one hour when the power or rate of energy expenditure is one watt or one joule per second. A watt-hour meter is a motor mechanism in which a rotor element revolves at a speed proportional to the power flow and drives a registering device on which energy consumption is integrated. The conventional ac watt-hour meter measures energy by using the principle of the induction motor and the two main coils in the meter are fed with the voltage and the current at the consumer's terminals. The alternating fluxes in these two coils induce currents in an aluminum disk placed between them and the interaction of these currents and the fluxes creates the torque, which rotates the disk. The resulting speed of rotation of the disk is proportional to the power consumed by the load measured in watts or kilowatts, and the number of rotations of the disk is proportional to the energy consumed given in watt-hours or kilowatt-hours.

This electromechanical energy meter has been in existence for a long period of time, over which its performance has been improved and the cost has been reduced and there are no further possibilities of simplification or cost reduction. On the other hand, there are certain applications where a relatively simple and low cost meter is required for the measurement of electrical energy usage. Some examples are very low power consumers in urban and rural areas, who represent a sizable portion of the total number of electricity consumers in most developing countries, and users in rural stand alone hydro power and similar schemes. In such cases, measuring only the current as an indication of the power consumption may be sufficient, and therefore, the meter needs to read only the ampere-hours but not watt-hours. The total amount of energy sales revenue from very low power consumers is such a small percentage of the total energy sales of the utilities that any loss of income caused by not taking the voltage variations into account is much smaller than the savings from the cost of the meter.

The electronic ampere-hour meter, which uses completely different concepts from those generally used in electronic or conventional electromechanical energy meter designs and has been constructed at a cost of one-third to one-half the cost of the conventional energy meter has become the ideal solution to the above issue [1]. The meter does not require any type of voltage supply and its operation is based on the magnetic coupling to electrical conductors feeding the consumer's load. In Brazil, where the meter was developed by the utilities, national tariff rules were changed to include the Ah tariff, and it was found that the income to the utility remains essentially the same using the Ah meter or kWh meter. They also found the Ah meter to be robust with lifetime comparable to or greater than the kWh meter, while being a simple and low cost implementation.

This paper describes the principle of operation of the electronic ampere-hour meter and presents test results of a prototype meter constructed by authors, in comparison with those of a conventional kilowatt-hour meter.

2. PRINCIPLE OF OPERATION

Figure 1 shows the basic components of the meter. The current transformer (CT) primary in fact, is the phase conductor feeding the consumer loads.

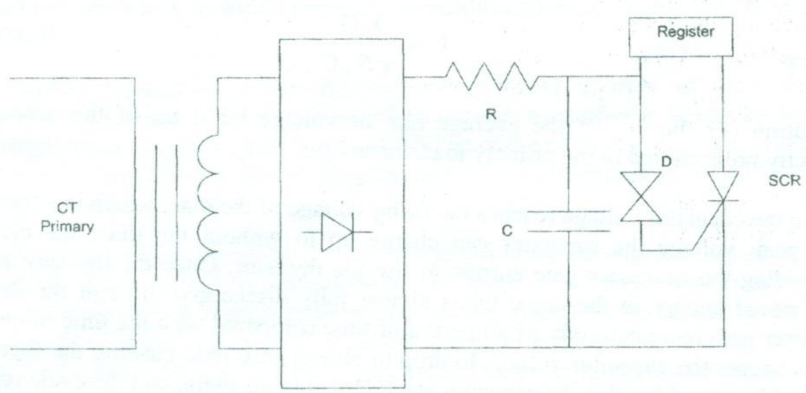

Figure 1. Basic components of the electronic ampere-hour meter

The diode full bridge rectifies the CT output and charges the capacitor C through the resistor R. The diac D and the SCR are normally in the OFF state. With the capacitor C initially uncharged, the corresponding diodes in the rectifier bridge starts conducting as the voltage across them starts to increase in the positive direction. Thus the direct current that flow in the CT secondary is

$$i_2 = \frac{|i_L|}{N_2} \quad (1)$$

where N_2 is the number of turns in the CT secondary and i_L is the load current in its primary.

Since this entire current flows through the capacitor with the diac and SCR in OFF state, the charging rate of the capacitor is

$$\frac{dV_c}{dt} = \frac{i_2}{C} = \frac{|i_L|}{N_2 C} \qquad (2)$$

The charging process takes place over several cycles of the load current, due to the fact that the time constant *RC* of the charging path is much larger than the period of the ac cycle. The average value of i_2 over this period is

$$i_{2,ave} = \frac{|i_L|_{ave}}{N_2} = \frac{2I_{Lp}}{\pi N_2} = \frac{2\sqrt{2}}{\pi N_2} I_L \qquad (3)$$

since $i_L = I_{Lp}\sin\omega t$, and I_L is the rms value of the load current in the CT primary which is assumed to be constant over the period of the capacitor voltage build up.

Therefore, the average charging rate of the capacitor C is

$$\left(\frac{dV_c}{dt}\right)_{ave} = \frac{i_{2,ave}}{C} = \frac{2\sqrt{2}}{\pi N_2 C} I_L = k\, I_L \qquad (4)$$

where

$$k = \frac{2\sqrt{2}}{\pi N_2 C} \qquad (5)$$

Equation (4) shows that the average rate of voltage build up of the capacitor is directly proportional to the primary load current I_L.

Once the capacitor voltage reaches the firing voltage of the diac, which is a fraction of the peak voltage the capacitor can charge up to without the diac, the diac fires providing the necessary gate current to fire the thyristor. Once the thyristor is fired, the stored energy in the capacitor is almost fully discharged through the thyristor-register path in a negligibly small period of time compared with the time of charging. This causes the capacitor voltage to drop to almost zero thus pushing the thyristor to the OFF state. After this the capacitor starts charging up again, and the cycle repeats.

Assuming a constant rate of charging for a given load current and zero discharge time, the capacitor voltage can be considered to be a triangular waveform as shown in Figure 2.

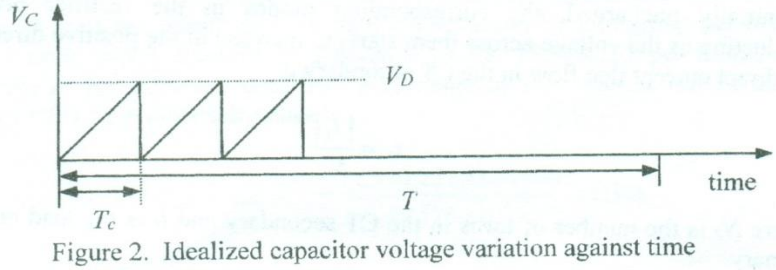

Figure 2. Idealized capacitor voltage variation against time

The number of discharges n during a time period T is

$$n = \frac{T}{T_C} = \frac{T}{V_D \Big/ \left(\frac{dV_c}{dt} \right)} = \frac{T}{V_D} \left(\frac{dV_c}{dt} \right) = \frac{k}{V_D} I_L T = k^{'} \left(I_L T \right) \qquad (6)$$

where V_D and T_C are the firing voltage of the diac and the time for the capacitor voltage to reach V_D, respectively. The load current I_L is assumed constant during the time period T.

The register records the number of discharges n of the capacitor, which according to equation (10) is proportional to the product $I_L T$ expressed in ampere-hours, and hence the name 'ampere-hour meter'.

3. PERFORMANCE OF Ah METER

A prototype electronic Ah meter along with the current transformer as shown in Figure 1 was constructed in order to check the performance of the meter and compare it with that of the conventional kWh meter. The current range for which the meter is designed is 0.09 A to 8 A, which represents a maximum power range of 20 W to 1840 W at 230 V.

A mechanical register of a conventional energy meter is used as the counting mechanism of the meter. The register is driven through a set of gear wheels by a small 1.5 V single stack stepper motor. Single discharge of the capacitor generates a current pulse through the stepper motor rotating the motor by one revolution, which turns the register by one small division.

The performance of the prototype Ah meter was tested for varying loading conditions for resistive, inductive and capacitive loads. The speed of the meter was measured by recording the number of discharge pulses per minute (ppm) of the capacitor, for load currents varying from 0.2 A to 7 A under three different power factors; 1.0, 0.8 lagging (inductive) and 0.8 leading (capacitive). A power factor meter was used to measure the power factors before each reading was taken. For comparison, a conventional kWh meter was also connected to the same circuit and its speed given in disk revolutions per minute (rpm) were recorded. Rated current of the kWh was 5 A, with 20 A maximum and the meter constant was 800 rev/kWh.

As can be seen from Figure A.1 in the Appendix, the speed of the Ah meter is directly proportional to the load current independent of the load power factor. The speed of the meter plotted against the load active power consumption shown in Figure A.2 shows that the meter speed is higher for inductive and capacitive loads for the same active power consumption, due to the higher current drawn by them, again proving its dependence on current, not on active power.

For comparison, the speed of the kWh meter is plotted against active power consumption in Figure A.3 for the same loading conditions as for the Ah meter. It can be seen that the speed of the kWh meter is directly proportional to the active power consumption independent of the power factor as expected. Figure A.4 shows the speed of the kWh meter plotted against load current which shows that for the same current, meter speed is higher for resistive loads than for capacitive or inductive loads because their active power consumption is less due to the non unity power factor.

Figure A.5 shows the percentage error of the Ah meter calibrated at 1 A, plotted against load current. Figure A.6 and A.7 show the percentage errors of the conventional kWh meter plotted against the active power and the load current respectively, for comparison.

4. APPLICATIONS OF Ah METER

4.1 As a low cost meter for utilities

The net direct cost of the prototype electronic ampere-hour meter was about Rs. 330.00 excluding the cost of labor, machinery, electricity and rent etc., and the breakdown is given in Table A.1 of Appendix. However, the final price of the meter in commercial production is yet to be estimated.

The cost of a conventional single-phase watt-hour meter presently varies between Rs. 900 (US $ 13) to Rs. 1600 (US $ 23). The Ceylon Electricity Board (CEB) collects a meter deposit of Rs. 650 or 300 for a single phase connections of 30 or 15 A respectively, from its consumers, in addition to the other fixed and variable charges to cover the cost of the connection. The CEB has also been providing a special 5 A connection in its rural electrification schemes in the past, collecting only Rs. 100 as the meter deposit in addition to other charges.

As can be seen from Table A.2, which is a summary of the consumption pattern of the domestic consumers of CEB for the month of August 1998, out of nearly 1.5 million domestic consumers of CEB, 63% or 933,500 households consume less than 60 units per month. About 475,000 households or 32% of domestic consumers use 30 units or less per month. The corresponding figures for LECO are, 37% or 60,000 households below 60 units and 13% or 32,500 households below 30 units. However, unlike CEB, LECO does not charge a separate meter deposit as such.

Table A.4 summarizes the number of consumer accounts and electricity sales distribution by tariff for CEB for 1998. It can be seen that 87.4% CEB consumers are domestic consumers. As can be seen from Table A.2, 32% of domestic consumers use less than 30 units per month and the total consumption by this group per month is 8,450,117 units which amounts to a revenue of Rs. 18,590,257 per month at the present rate of Rs. 2.20 per unit. The percentage of this amount out of the total revenue of CEB from electricity sales is

$$= \frac{18,590,257\, x\, 12\, x\, 100}{20,176\, x\, 10^{6}} = 1.1\%$$

This means that 32 % of the 87.4%, or 28% of the CEB consumers pay only 1.1 % of CEB revenue. In other words, nearly 28% of CEB energy meters are used to collect 1.1% of its total revenue.

It is very likely that the revenue to the two utilities at least from this group of consumers who consume below 30 units per month do not compensate for the investment on the conventional watt-hour meter. Therefore, a reasonably cheaper meter may be necessary for the low energy consumers to assure payback to the utilities, and the ampere-hour meter may be the choice if available at the right price. It is also important to take note of the fact that only one third of the Sri Lankan households have electricity at present and a large portion of the remaining households when electrified will be in this low consumption group. Therefore, the utilities may be able to make considerable savings by using low cost meters whenever possible.

4.2 As a day-night tariff meter

In order to encourage consumers to shift as much energy consumption as possible from peak hours to off-peak hours, utilities offer time-of-day tariff to their consumers. Under time-of-day tariff, consumers are charged at two different rates depending on the time of consumption of energy, a lower rate during off-peak hours and a higher rate during peak hours. The price of a two-rate meter at present is very high compared with the price of a single rate meter and is out of reach for consideration to be used at domestic consumer level.

One advantage of the electronic ampere-hour meter is that, it can easily be modified as shown in Figure 3 to run faster during the nighttime than during the daytime, so that for the same time independent tariff, consumers have to pay more for the ampere-hours consumed during the night than the same amount consumed during the day. In effect, this is a 'day-night' tariff system, which effectively charges consumers at a higher rate during the nighttime than that during the daytime.

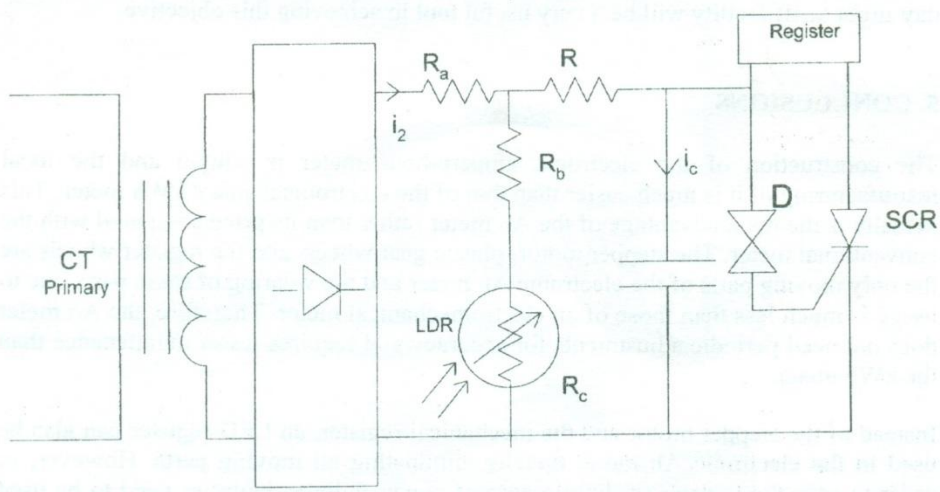

Figure 3. Modified ampere-hour meter for implementation of day-night tariff

The light dependent resistor (LDR) R_C has a very high resistance in the dark and a low resistance when exposed to light. The capacitor C is now charged according to the equation

$$\frac{dV_c}{dt} = \frac{i_c}{C} \tag{7}$$

replacing i_2 in equation (2) by i_c which is related to output current of the CT by the equation

$$i_c = \frac{(R_b + R_c)}{(R + R_b + R_c)} \; i_2 = f_r \; i_2 \tag{8}$$

where

$$f_r = \frac{(R_b + R_c)}{(R + R_b + R_c)} \tag{9}$$

is the *rate factor* of the meter, which changes the rate of charging of the capacitor depending on whether it is daytime or nighttime.

For example, for $R = R_b = 20$ kΩ, R_c (daytime) = 200 Ω and R_c (nighttime) = 1 MΩ, f_r is equal to 0.5 during the day and is equal to 0.98 during the night. This means that the charging rate of the capacitor is nearly doubled during the night compared with that during the day for the same load current through the ampere-hour meter. Thus, as can be seen from equation (6), the meter register runs at double the speed during the night than that during the day, and effectively makes the tariff during the nighttime twice as high compared with that during the daytime.

A two-rate meter having different tariffs for day and night as explained above may become very useful in stand-alone hydro power and similar power distribution schemes where it is not possible to control the energy input to the generators according to the time of the day. In such schemes, it is essential to encourage the consumers to use energy during the off-peak times and the ampere-hour meter with day-night tariff facility will be a very useful tool in achieving this objective.

5. CONCLUSIONS

The construction of the electronic ampere-hour meter is simple and the local manufacturing of it is much easier than that of the electromechanical kWh meter. This actually is the main advantage of the Ah meter rather than its price compared with the conventional meter. The stepper motor, plastic gear wheels and the register wheels are the only moving parts of the electronic Ah meter and the wearing of these parts due to usage is much less than those of an electromechanical meter. Therefore, the Ah meter does not need periodic adjustments for accuracy and requires lesser maintenance than the kWh meter.

Instead of the stepper motor and the mechanical register, an LED register can also be used in the electronic Ah meter thereby eliminating all moving parts. However, in order to save the register reading in case of power failures, batteries need to be used inside the meter.

The combined use of the Ah meter and the kWh meter can be used to estimate the average power factor of a consumer over a given period of time since,

$$average\ power\ factor = \frac{Wh}{VAh} = \frac{1000\,x\,(kWh\,meter\,reading)}{Voltage\,x\,(Ah\,meter\,reading)}$$

As can be seen from the test results, the lower the power factor of a load, the higher would be the speed of the Ah meter and therefore discourages poor power factor. This can be used as a low cost method of encouraging power factor improvement possibly in combination with the kWh meter.

The performance of the Ah meter under harmonic load conditions such as those from energy saving lamps and computers need to be studied since most consumers in the low consumption group use electricity mostly for lighting, and use energy saving lamps to reduce their electricity bills. The possibility of the presence of harmonic currents was not taken into consideration in the design of the prototype meter and therefore further improvements in the design is necessary before carrying out such tests.

ACKNOWLEDGEMENTS

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REFERENCES

1. Caldas R. P., Lippincott M., Alvarenga L. M., Junior J. E. R. M., da Costa R. S., Bandim C. J., Caixao S., Aguiar J. C., Junior A. V. P., Pimental J. C. G., Souza F. C., "Very Low Cost Meters for Low Power Consumers", IEE Power Engineering Journal, August 1996, pp 176-180.

2. CEB Tariff Unit Statistics – Domestic Consumption Pattern-August 1998.

3. LECO Total Company Sales Forecast –1998.

4. Statistical Digest 1998, Statistical Unit, CEB.

APPENDIX

(ppm = pulses per minute)

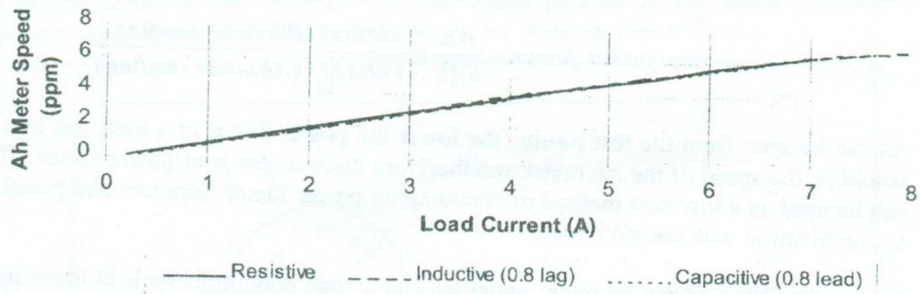

Figure A.1. Speed of the Ah meter Vs load current for three power factors

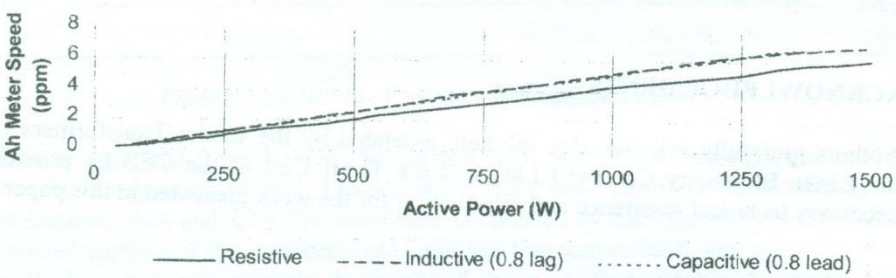

Figure A.2. Speed of the Ah meter Vs load active power consumption for different power factors

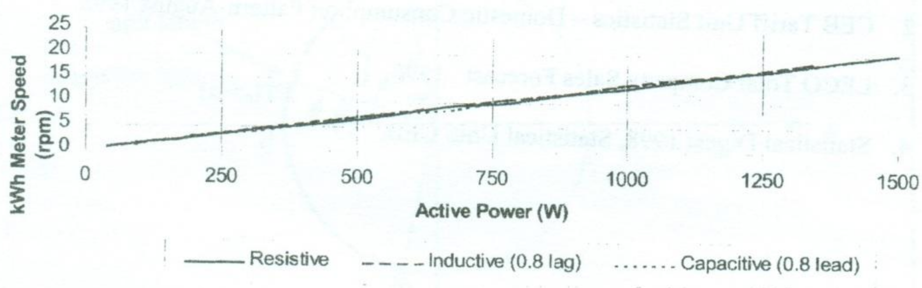

Figure A.3. Speed of conventional kWh meter Vs load active power consumption

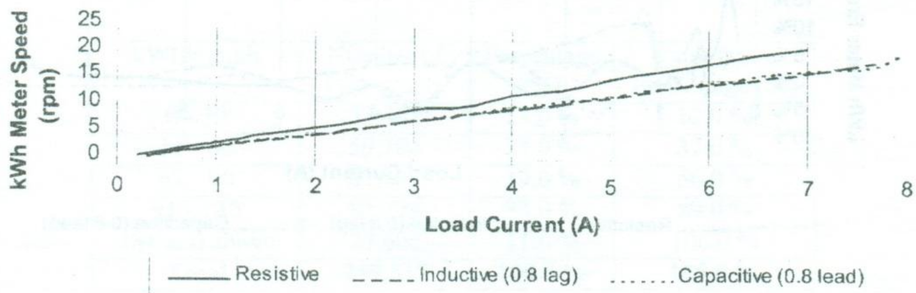

Figure A.4. Speed of conventional kWh meter Vs load current

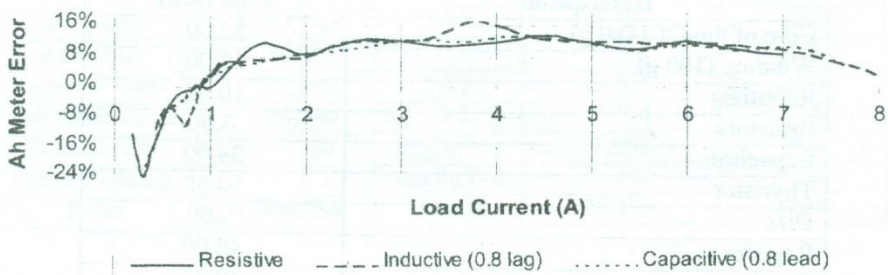

Figure A.5. Percentage error of the Ah meter Vs load current

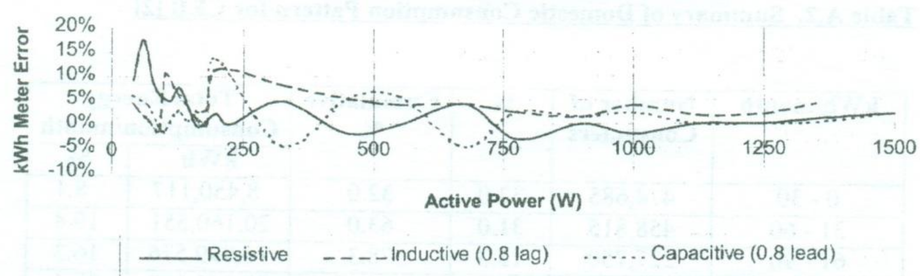

Figure A.6. Percentage error of the kWh meter Vs load active power consumption

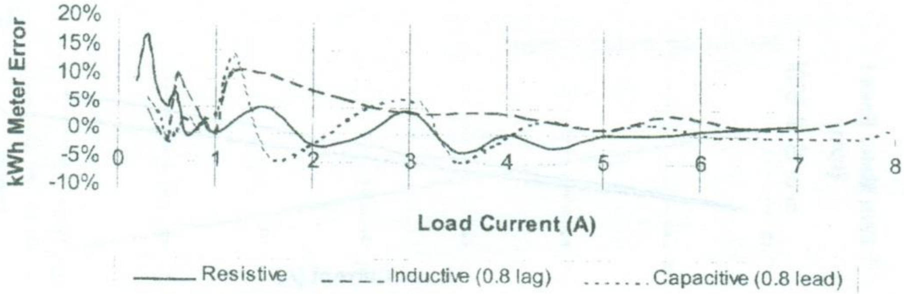

Figure A.7. Percentage error of the kWh meter Vs load current

Table A.1 Cost breakdown of the electronic Ah meter

Description	Cost (Rs.)
Core of the CT (480 g)	52.00
Winding (100 g)	65.00
Rectifiers	10.00
Resistors	3.50
Capacitors	34.00
Thyristor	50.00
Diac	9.00
Register	40.00
Stepper motor	40.00
Circuit board and solder	5.00
Plastic cover	20.00
Net direct cost excluding labor cost	**328.50**

Table A.2. Summary of Domestic Consumption Pattern for CEB [2]

kWh/month	Number of Consumers	%	Cumulative %	Total Energy Consumption/month	
				kWh	%
0 - 30	474,685	32.0	32.0	8,450,117	8.1
31 - 60	458,815	31.0	63.0	20,160,551	19.4
61 - 90	227,750	15.3	78.3	16,999,576	16.3
91 - 180	241,384	16.3	94.6	29,666,989	28.4
181 and above	79,602	5.4	100.0	27,347,079	27.8
Total	**1,482,236**	**100.0**	**100.0**	**104,218,226**	**100.0**

Table A.3. Summary of Domestic Consumption Pattern for LECO [3]

kWh/month	Number of Consumers	Percentage (%)	Cumulative Percentage (%)
0 - 30	32,462	13.0 %	13.0 %
31 - 60	59,794	24.0 %	37.0 %
61 - 90	47,382	19.0 %	56.0 %
91 - 180	82,273	33.0 %	89.0 %
181 and above	27,606	11.0 %	100.0 %
Total	**249,517**	**100.0 %**	**100.0 %**

Table A.4. Consumer Accounts and Electricity Sales by Tariff for CEB –1998 [4]

Tariff	Number of Consumers		Electricity Sales Revenue	
	Number	**%**	**Million Rs.**	**%**
Domestic	1,781,388	87.4	4,201	20.8
Religious	14,061	0.7	75	0.4
General Total	218,909	10.7	5,303	26.3
Industrial Total	24,040	1.2	8,394	41.6
Bulk Supply	59	negligible	1,982	9.8
Street Lighting	1	negligible	222	1.1
Total	**1,850,756**	**100.0**	**20,176**	**100.0**