ASSESSMENT OF ENERGY LOSSES IN SINGLE PHASE ENERGY METERING IN SRI LANKA

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Degree of Master of Science

Department of Electrical Engineering

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Sri Lanka

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree
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ABSTRACT

Sri Lanka has achieved almost 100% electrification at the end of the year 2017. The total number of consumer accounts adds up to 6.76 million and out of that about 6 million are single phase consumers in the tariff categories, domestic, religious, small general purpose and small industrial etc. (2017). Since all the energy served to these consumers is measured by electromechanical energy meters, the significance of the energy loss incurred in these single phase energy meters to the overall energy loss of the system is important.

In this research, losses in single phase energy meters are identified and analyzed using mathematical models. Two types of single phase energy meters are taken into consideration (one is the presently used electromechanical meter and the other is the electronic meter), and separately assessed for losses and compared as the method of discovering minimization of losses in energy meters. The losses are quantified by modelling load profiles of consumer categories and extrapolating to the consumer population.

The research concluded that the annual additional energy that can be accounted for, from single phase energy metering in Sri Lanka is 36.5 GWh. The total annual energy that could be saved by using single phase electronic energy meters is 19.4 GWh.

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T. M. N. P. Jayawardana
April 2019

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List of Abbreviations

Abbreviation	Description
CEB	Ceylon Electricity Board
LECO	Lanka Electricity Company
IEC	International Electrotechnical Commission
DD2	Distribution Division 2
R&D	Research and Development
rms	Root Mean Square
V	Voltage
I	Current

CHAPTER 1

1. INTRODUCTION

Energy is one of the most important physical quantity in science and engineering streams. In the modern world electricity has become a basic human need that is used in almost every human activity. In electrical engineering, energy is the elementary measurement that quantifies the amount of work that an electrical system is capable of doing. Electrical energy can be mathematically defined as the integral of absolute power over a given time interval.

$$E(\Delta t) = \int_{(t_0)}^{(\Delta t + t_0)} p dt$$

Electrical power across two terminals of an electrical network is given by the product of voltage across the two terminals and the current flowing through the section itself.

The energy demand of the world is growing very rapidly with the population growth and technology advancements. With limited energy resources available, ways of efficiency improvement and energy conservation in all fields has become an important research area.

When producing electricity or transporting it through the transmission-distribution network, losses do occur at every stage. It is well known that highest levels of losses are in the distribution sector. Electricity metering is done at many points in this chain, and the greatest number of metering points are in the distribution phase, where most of our final consumers are. Improving efficiency and conserving energy in measuring equipment of electrical quantities are also important. Energy measuring devices are used to measure delivered electrical energy and they play a major role because they are widely used at households and industries to measure delivered energy.

1.1 Energy Distribution in Sri Lanka

Electricity distribution in Sri Lanka is done by five distribution licensees, four of which are Ceylon Electricity Board (CEB) and LECO. Energy delivered is measured by energy meters installed at different types of consumers. Consumers are categorized according to their capacity and tariff type. Therefore, different types of energy meters are used to measure the energy delivered to those consumer categories. Number of consumers are growing rapidly every year and a considerable amount of energy will be used by the energy meters installed at their connection point.

Table 1-1 Energy meter types for consumer category

Consumer Capacity (kVA)	No. of Phases	Current (A)	Energy Meter Type
Up to 7 kVA	1	30	2 Wire direct connected (1 phase meter)
Between 7 kVA & 21 kVA	3	30	3×2 Wire direct connected or 1×4 wire direct connected (3 phase meter)
Between 21 kVA & 42 kVA	3	60	3×2 Wire direct connected or 1×4 wire direct connected (3 phase meter)
Above 42 kVA	3	60 <	CT Connected 4 wire or 3 wire

According to the Statistical Digest 2017 published by CEB, number of consumers and energy distribution breakdown for the year 2017 are given in Table 1-2.

Table 1-2 Number of Consumer Accounts by Tariff

Tariff		No. of consumer accounts CEB	No. of consumer accounts LECO	Percentage of total
Domestic		5,425,060	467,939	87.243%
Religious		37,999	2,604	0.601%
General purpose	GP 1 – Small	662,436	86,167	11.083%
	GP 2 – Medium	4,497	1,193	0.084%
	GP 3 – Large	129	3	0.002%
Hotel	H 1 – Small	183	0	0.003%
	H 2 – Medium	39	62	0.001%
	H 3 – Large	15	3	0.000%
Industrial	IP 1 – Small	55,540	2,807	0.864%
	IP 2 – Medium	4,885	589	0.081%
	IP 3 – Large	269	13	0.004%
Government	GV 1 – Small	1,446	387	0.027%
	GV 2 - Medium	359	42	0.006%
	GV 3 – Large	2	0	0.000%
Total		6,754,668		

Source: Statistical Digest -2017, CEB

Table 1-2 shows that the number of accounts is dominated by the domestic consumers and small category of all others and from that majority of them are up to 7 kVA capacity.

Table 1-3 Electricity Sales by Tariff

Tariff		Sales (GWh) by CEB	Sales (GWh) by LECO	Percentage of total
Domestic		4,385	620	37.5%
Religious		78	11	0.7%
General purpose	GP 1 - Small	1593	308	14.2%
	GP 2 - Medium	843	196	7.8%
	GP 3 - Large	343	4	2.6%
Hotel	H 1 - Small	3	0	0.0%
	H 2 - Medium	169	53	1.7%
	H 3 - Large	100	7	0.8%
Industrial	IP 1 - Small	315	28	2.5%
	IP 2 - Medium	1987	213	16.5%
	IP 3 - Large	1741	39	13.3%
Government	GV 1 - Small	4	2	0.0%
	GV 2 - Medium	163	18	1.4%
	GV 3 - Large	4	0	0.0%
Street Lighting		108	22	1.0%
Total		13,357		100.0%

Source: Statistical Digest -2017, CEB

Table 1-3 shows that the highest energy share has been consumed by domestic consumers.

1.2 Research Motivation

In the energy conservation context, loss reduction in every component and securing every kilowatthour of energy is vital to narrow down the overall energy loss in a utility network. A known fact is that a majority of the losses occur in the distribution network and the energy measuring devices are installed at the consumer end. The data of Table 1-2 and Table 1-3 can be analyzed as follows,

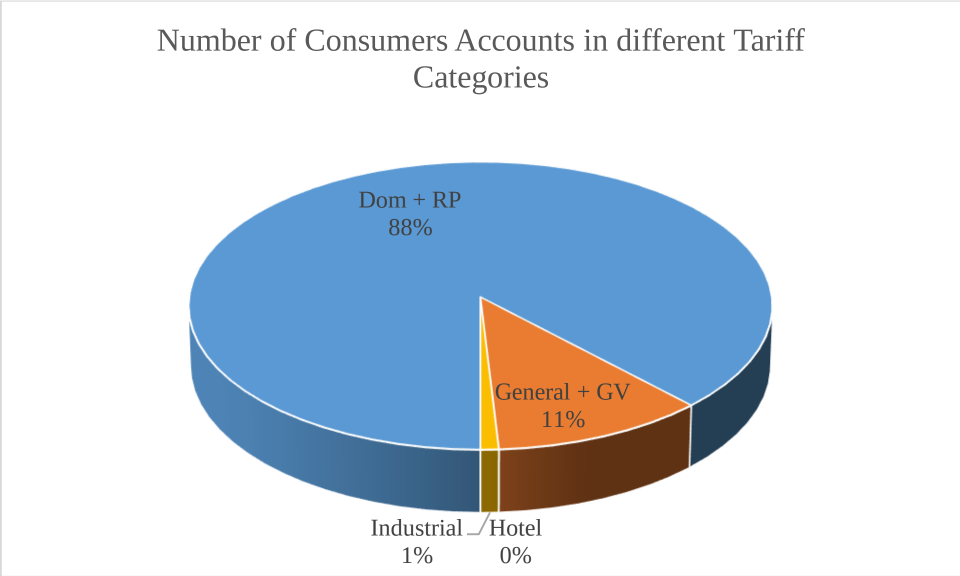

Figure 1-1 Number of Consumer Accounts for the year 2017

Energy consumption can be summarized as follows,

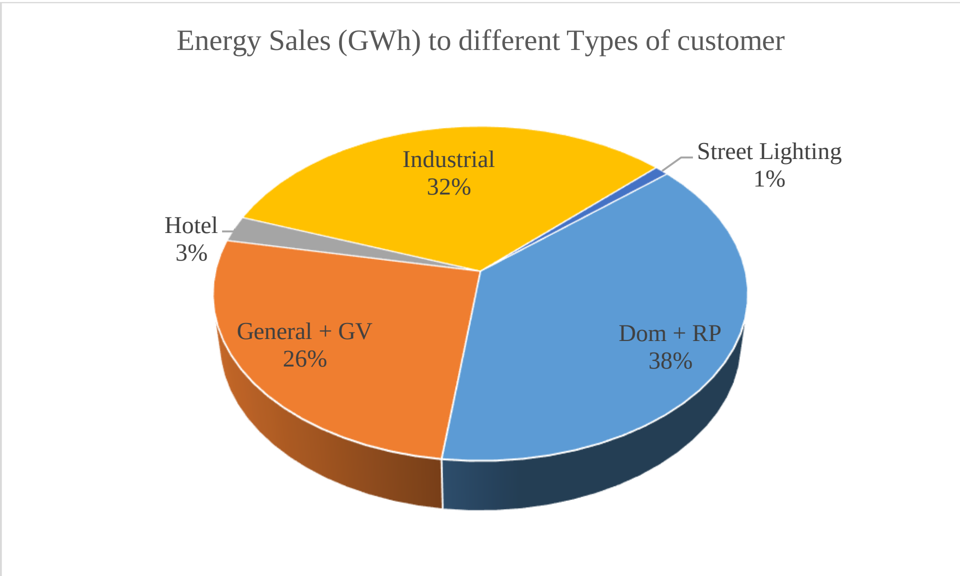

Figure 1-2 Comparison of energy sales to different types of customer

From above comparisons, it is clear that largest share of electricity is consumed by the domestic sector. Most of them are domestic and small capacity consumers other tariff categories up to 7 kVA and measured with single phase energy meters

Table 1-4 Energy Consumption of Domestic and Small Capacity Consumers for the year 2017

Tariff	Energy (GWh)
Dom + Religious	5,094
General + Government	1,907
Hotel	3
Industrial	343
Total	7,347
Total	13,357
% of Total sales	55%

Source: Statistical Digest -2017, CEB

To achieve the loss targets given by Public Utilities Commission of Sri Lanka it is important to explore all opportunities, even minute measures, to reduce the overall loss by reduction of losses incurred by single phase energy meters installed in Sri Lanka which is done by this research.

Distribution loss targets given for the years 2018 to 2020 for each distribution divisions by the Public Utilities Commission of Sri Lanka given in Table 1-5.

Table 1-5 Distribution Loss Targets for 2018 - 2020

Distribution Division	Year	Loss Target (as a % of Purchase by each DD)		
		Technical	Non-Technical	Total
DD1	2018	5.54%	1.21%	6.75%
	2019	5.51%	0.66%	6.18%
	2020	5.48%	0.12%	5.60%
DD2	2018	6.12%	1.45%	7.58%
	2019	5.99%	0.75%	6.74%
	2020	5.85%	0.10%	5.94%
DD3	2018	6.65%	0.65%	7.30%
	2019	6.39%	0.38%	6.78%
	2020	6.43%	0.11%	6.54%
DD4	2018	6.72%	0.95%	7.67%
	2019	6.63%	0.54%	7.17%
	2020	6.68%	0.12%	6.80%

Source: Revision of Network Loss Targets Final Report

1.3 Objective

Objectives of this research is to assess the energy losses associated with single phase energy meters in LV consumers in Sri Lanka and to evaluate loss reduction method which lead to,

- Assessment of the significance of losses in single phase energy metering to overall distribution loss.
- Accurate billing through minimization of technical errors.

1.4 Methodology

In the process of achieving the objectives of this study, as the first step, losses associated with single phase energy meters were identified. Next, two types of meters (presently installed type of meter and a commonly used low loss meter) was selected and relevant data, such as accuracy error test and meter consumption test was obtained. Further, the load profile of typical consumer categories and statistical data of the same consumer categories was obtained. Then mathematical models were developed for accuracy error and meter consumption error for the two types of energy meters and were mapped into sample load profiles of different consumer categories. Using the weighted average method, the model was applied to the entire population of single phase energy meters installed in Sri Lanka and results were compared for two types of meters. From that a comprehensive loss assessment will be done.

1.5 Outline of the Thesis

Chapter 2 identifies the type of losses involved in single phase energy meters and their effect on the power system, and describes the technology used in different types of single phase energy meters and their construction. This study will evaluate and compare the accuracy, calibration point and power consumption etc., of the meters described.

Further it explains the methodology that is used to model the types of losses incurred in energy meters.

Chapter 3 describes the experiments conducted and presents the results and analyses conducted to develop the models to assess the losses in single phase energy meters.

Chapter 4 presents analyses of assessed losses of each type of meter considered in this research and the calculation of total losses in single phase energy metering in Sri Lanka power system. Quantification of the reduction of losses by comparing the existing and proposed single phase energy meters, is also presented in chapter 4, followed by financial benefits of replacing electromechanical energy meters with electronic energy meters.

Chapter 5 concludes the study, explaining recommendations.

CHAPTER 2

2. LITRETURE REVIEW

2.1 Types of losses in Energy Meters

Energy meter is a measuring device, like every other measuring device, it also has different kinds of errors in measuring. Measuring devices are not ideal instruments that can record the absolute quantity to be measured. Any measuring device has its measuring range it could measure with some allowed accuracy level. When using any kind of measuring device, its accuracy, working range and the calibration point (the measuring point with zero error) is important to know. If errors exist in measuring devices, losses will add up to the quantity that is being measured, especially in energy measuring.

In energy meters there are two types of losses identified [1].

- Non-technical loss
- Technical loss

2.1.1 Non-Technical Loss

Non-technical loss or commercial loss is mainly due to accuracy error. When measuring energy, if the measured amount by the meter deviates from the absolute amount, it will add an error to the billing process. Energy is consumed but the reading deviates from the actual value. Power consumption in a load will vary time to time, and since the voltage is kept constant, the varying factor will be the load current. Therefore, the working range of the energy meter must be carefully selected. The calibration point should be selected such that the average current of the load is as close as possible to the calibration point.

2.1.2 Technical Loss

Energy meters run on electrical power to sense the energy flowing through it. The energy consumed by the meter does not count to the end user, therefore it is a technical loss to the utility. When technical losses of all the meters add up, it is a considerable amount of energy loss that need to be minimized.

Energy consumption loss mainly depends on the technology used in the energy meters. Older meters that operate on induction theory have magnetic coils that consume larger amounts of energy, and modern meters that operate on sensors and digital theory consume energy for the operation of their circuitry.

2.2 Loss Assessment Methodology

Energy should be measured at the point of end-user to ensure continuity of the business. It involves losses in measuring instruments. In this study, the approach is to assess losses in two types of energy meters (Electromechanical and electronic) and compare the results, thus leading toward minimizing losses [4],[5].

To assess the losses in single phase energy meters widely used in Sri Lanka, first the relevant data required to be collected. Then from the data, a model was required to be developed to assess the losses involved.

2.2.1 Data Collection

To assess non-technical and technical losses, collecting the relevant data is important. The data fields collected in this study are as follows.

- Meter accuracy test data:

  Samples of accuracy test data for single phase electromechanical meters and electronic meters were taken from "ANTE LECO" meter factory. These are all standard IEC tests done keeping the applied nominal voltage constant and for two power factors (PF=1 and PF=0.5 lagging), varying load current [9], [10].

- Meter consumption test data:

  A sample of electromechanical and electronic meters were tested at DD2 meter laboratory at Kiribathgoda, the keeping applied nominal voltage constant and for two power factors (PF=1 and PF=0.5 lagging), varying load current in the same criteria as in meter accuracy test.

- Load profile data:

  Load profiles of single phase consumers at Dunagaha area was taken from CEB R&D branch for the month of June 2018. The data was taken covering the following consumption categories, and 5 consumers from each category were taken (total sample 25 consumers)

  Category 1 – Below 60 kWh

  Category 2 – From 60 kWh to 90 kWh

  Category 3 – From 90 kWh to 120 kWh

  Category 4 – From 120 kWh to 180 kWh

  Category 5 – Above 180 kWh

- Statistical data of single phase consumers:

  Statistical data of single phase consumers for the above consumer categories was taken from CEB "Corporate Strategy" branch, for the month of June 2018.

2.2.2 Development of Loss Models

There are two separate models developed to assess non-technical loss and technical loss.

2.2.2.1 Development of a Model for Non-Technical Losses

Steps in developing the non-technical loss model were as follows,

- Model curves for accuracy error for two power factors (PF=1 and PF=0.5 lagging) were obtained from averaging the percentage error values of the samples taken from the ANTE LECO meter factory [9].
- Accuracy error values for varying power factor were interpolated using the model error curves for two power factors and tabulated.

- The three variables, current ratio-I/Ib (Ib-basic current), %error and power factor were plotted in a three dimensional space.
- The surface fit was analyzed and divided into regions to simplify the analysis.
- The plot was fitted with a best fit surface and the surface equations for different regions were obtained.
- The process was done for both types of energy meters considered in this study.
- The actual current in the load profiles taken for varying power factors was tabulated and arranged in ascending order of current ratio and the %error was mapped into the load profile data time intervals using the appropriate surface equation.
- Energy loss was calculated using the actual error obtained and the total energy error was summed up for the whole month and the percentage error for the particular consumer was calculated.
- The average percentage energy error for each customer category was calculated running the above model for both types of energy meters and for each sample load profile taken into consideration.
- From the statistical data for the period, using the weighted average method, the total energy that was not accounted or the energy error occurred in the metering process was calculated for the total population of single phase meters operational in Sri Lanka.

2.2.2.2 Development of a Technical Loss Model

Steps of developing the technical loss model was as follows,

- Model curves for power consumption for two power factors (PF=1 and PF=0.5 lagging) were obtained from averaging the power consumption values of the samples tested at DD2 meter laboratory for ANTE LECO meters (both electromechanical and electronic).
- Power consumption values for varying power factor were interpolated using the model power consumption curves for two power factors and tabulated.
- As in the accuracy error model, the three variables, current ratio (I/Ib), power consumption and power factor were plotted in a three dimensional space.

- The plot was fitted with a best fit surface and the surface equation was obtained.
- The process was repeated for both types of energy meters considered in this study.
- The actual current in the load profiles taken for varying power factors was tabulated and arranged in ascending order of current ratio and the power consumption was mapped into the load profile data time intervals using the surface equation obtained.
- Energy loss is calculated using the actual energy consumption obtained and the total energy consumption was summed up for the whole month and the percentage energy consumption from the total energy delivered to the particular consumer was calculated.
- The average percentage energy consumption for each customer category was calculated from the above model for both types of energy meters considered and for each sample load profile taken into consideration.
- From the statistical data taken for the period, using the weighted average method, the total energy consumption in the metering activity was calculated for the total population of single phase meters operational in the country.

The total non-technical and technical losses associated with single phase energy metering in Sri Lanka was calculated and the improvement achievable using electronic energy meters was quantified.

2.3 Technology Assessment of Energy Meters

Electric energy measuring is generally based on active energy. In the past, the most traditional and widely used energy meter was the induction meter, also known as the electromechanical meter. With the technological advancement, static energy meters without rotating parts are now widely used, which have higher accuracies and more stability came to use.

In this study two types of meters, namely the traditional electromechanical meter which is still used in Sri Lanka for single-phase connections and the widely used modern static energy meter were taken for comparison.

2.3.1 Induction Energy Meter (Electromechanical energy meter)

The induction energy meter is built to operate on the induction theory. It consists of three electrical circuits, magnetically coupled, two of them permanently fixed while the third rotates around the main rotating axis [2], [3].

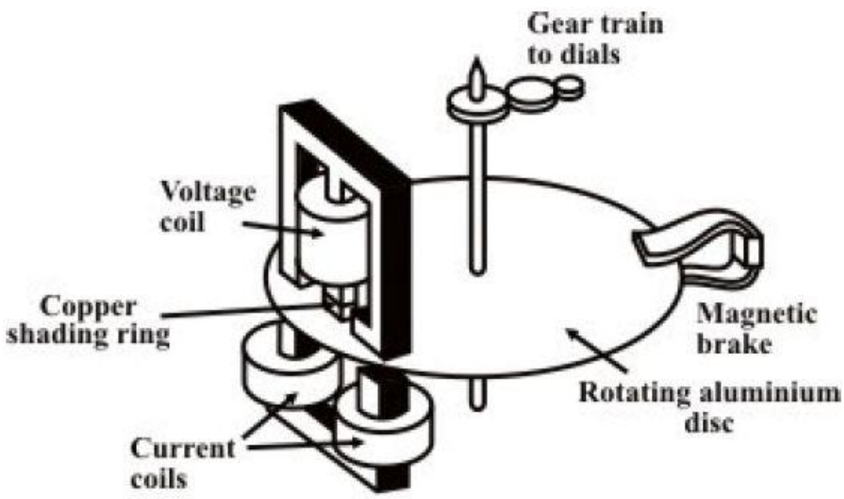

Figure 2-2 Typical Construction of an Induction Energy Meter

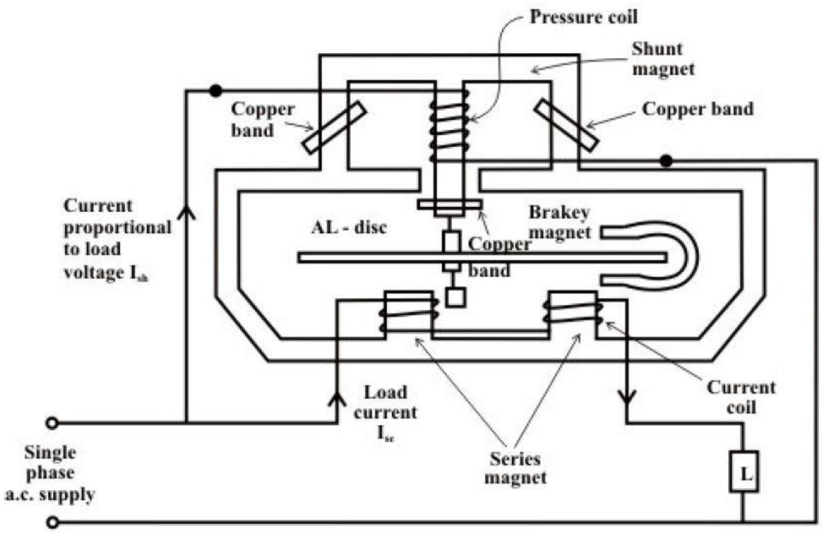

Figure 2-3 Typical Connection Circuit of an Induction Energy Meter

A coil with a large number of turns of thin wire is wound on the central member of the shunt magnet which has a comparatively higher resistance. This coil is known as a "pressure or voltage coil" and is connected to the mains. This voltage coil has many turns and is designed to be as highly inductive as possible, making the coil voltage produce a high ratio of inductance to resistance. This causes the current and flux to be behind the supply voltage by almost 90°. Adjustable copper shading rings are provided in the center arm of the shunt magnet to cause the phase angle shift between the magnetic field produced by the shunt magnet and the supply voltage is approximately 90°. Copper shading bands are also called a power factor compensator or compensation loop. The series electromagnet is energized by a coil, known as a "current coil", which is with comparatively negligible resistance connected in series with the customer load, so that it carries the load current. The flux produced by this magnet is proportional and in phase with the load current. The time varying (sinusoidal) fluxes produced by the shunt and series magnets induce eddy currents on the aluminum disk. The interaction between these two magnetic fields and the eddy currents creates a drive torque on the disk. The disc is mounted on the rotating shaft that connects to the gear train of the counter. Torque is given by, [2], [3]

$$Cm = KVI\sin(\propto)$$

Where,

Cm	= Mechanical torque
K	= System constant
V	= rms value of the applied voltage
I	= rms value of the applied current
α	= Phase angle between the fluxes generated by V and I

The torque produced causes the disc to rotate, thus the number counter connected to the rotating shaft turns. The angular speed is proportional to the power flow through the current coil.

When selecting an energy meter to a particular load, the specification of the meter is important to accurately read energy delivered. General technical specification of an electromechanical meter is given Table 2-1 [9].

Table 2-1 Technical Data of a 1 phase, 2 wire, 10(40)A, 50 Hz Energy Meter

TECHNICAL DATA

DD949, 1P2W, 240V, 10(40)A, 50Hz

Item	Unit	Data
Accuracy		2
Applicable Standard		IEC62052-11
Connection		BS
Reference Voltage	(V)	240
Basic current Ib (Rated max. current Imax)	(A)	10(40)
Reference Frequency	(Hz)	50
Meter constant	(rev/kWh)	480
Register gear ratio		480
Register		00000.0
Basic speed of disk	(rpm)	19.2
Rotation speed at rated maximum load	(rpm)	76.8
Disk weight	(g)	24
Basic torque	(g.cm)	4.5
Torque at rated maximum load	(g.cm)	18
Voltage circuit consumption	(W)	≤1
Current circuit consumption at basic current	(VA)	≤2.5
Mean temperature coefficient i) from 0.1Ib to Imax at unity PF ii) from 0.2Ib to Imax at 0.5 lagging	 %/℃ %/℃	 ≤0.1 ≤0.15
Creeping		80~110%Un
Starting current		0.5%₀Ib
Limit of errors i) 0.05Ib at unit PF ii) from 0.1Ib to Imax at unity PF iii) 0.1Ib at 0.5 lagging iv) from 0.2Ib to Imax	 (%) (%) (%) (%)	 ±2.5 ±2.0 ±2.5 ±2.0
Direct current Insulation withstand 500V	(MΩ)	>50
Power frequency withstand voltage for 1min	(kv)	4
Impulse withstand voltage (peak value)	(kv)	8
Weight	(kg)	1.4

Apart from the general specifications the climatic conditions that the meter is operated on, is also important as the meters are running under different conditions and the error of the meter will change accordingly.

Before placing the meters into operation, it is necessary to have a good idea about the load condition that it is subjected to, because the calibration point will be the key factor that enables the energy meter to record accurately. Energy meter manufacturers usually provide the accuracy error curve, detailed specification of which includes the working range and calibration data with the meters to select the meter for a particular load. For example, if the average current of a particular load is around 10A, it is suitable to use a 10(40)A (basic current 10A and maximum current is 40A). A typical accuracy curve of an electromechanical energy meter is shown below.

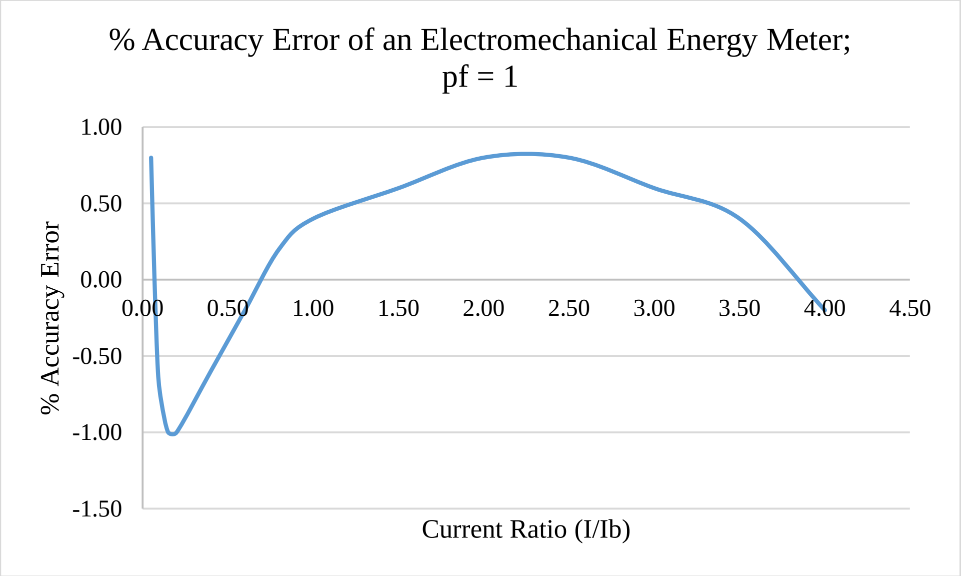

Figure 2-1 Typical % Accuracy Error Curve of an Electromechanical Energy Meter

Source: Extracted from [9]

The power consumption of measuring devices has been ignored because they are small compared with other electrical equipment. Energy meters are similar to other electrical equipment; consumes energy to operate. In a power system, energy meters are installed and their energy consumption has been largely ignored because they consume only small amounts of energy. However, when considering all the meters installed in a system, it is a significant number, and it will add into in overall system energy loss.

Power consumption in an electromechanical energy meter occurs in its voltage or pressure coil, and the current coil. Owing to the high inductance in the voltage coil, it consumes more power than the current coil. Power consumption of the current coil is almost zero and it can be neglected, with the dominant part of power consumption occurring in the voltage coil. Average power consumption of a 10(40), 230V, 50Hz, 1 phase 2 wire energy meter is around 1W, the IEC standard is below 2W [1].

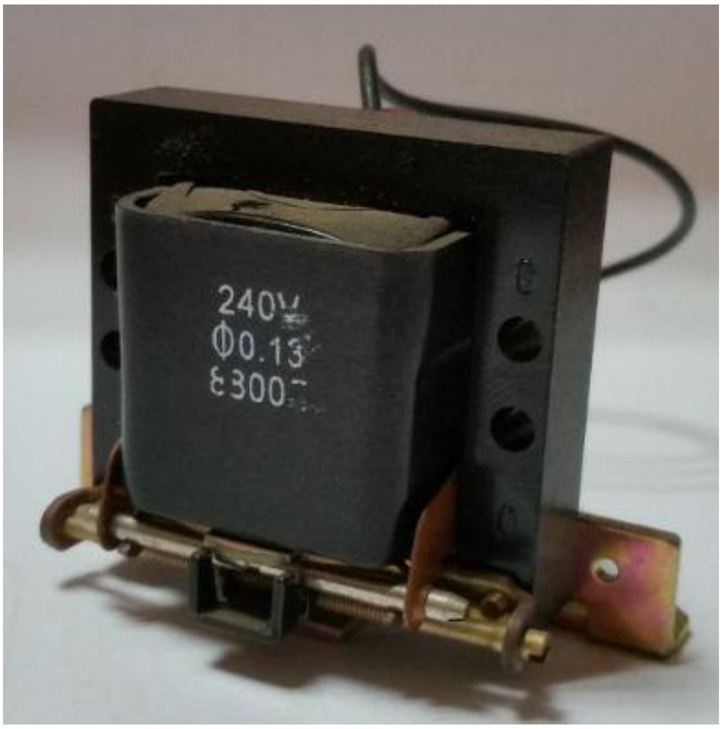

Figure 2-2 Voltage Coil of 10(40)A, 230V 1-phase 2W

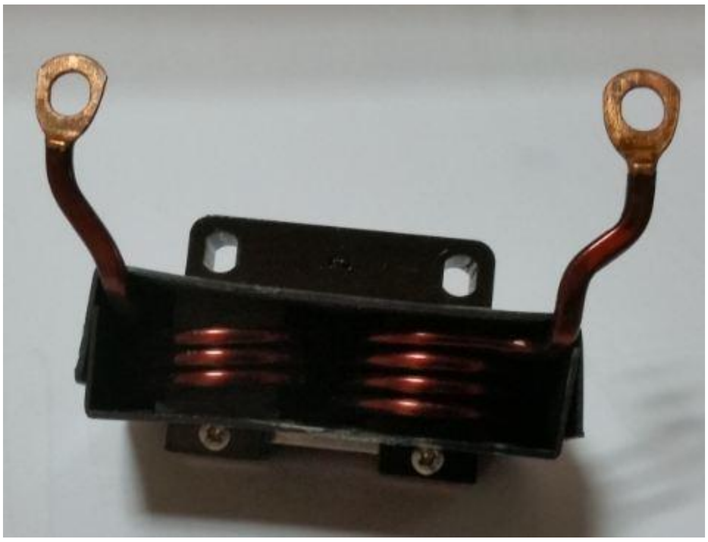

Figure 2-3 Current Coil of 10(40)A, 230V 1-phase 2W

2.3.2 Static Energy Meter

Modern meters are all static energy meters which comprises electronic components of different technologies. As the word describes, there are no moving parts in static energy meters. In the early electronic era when electronic multipliers were developed, voltage and current were multiplied directly. Electronic multipliers used analog components (operational amplifiers, resisters, capacitors, etc.) while digital electronic came into the picture and they used digital components and programmable logic devices. Voltage and current signals were processed to determine a signal proportional to the real power flow of the line. Then it is integrated over time to calculate the energy. Since electronic components have a large frequency range from DC to high frequencies, the equipment can be applied to DC, AC and distorted signals with varying frequencies (special circuitry is used to do the accurate sampling in order to convert it for the correct digital signal for processing).

There are various types of static energy meters developed over the years. The equipment can be categorized according to their functional differences [2], [5].

2.3.2.1 Electronic Energy Meter

The main feature of this electronic instrument is that it uses voltage inputs for both voltage and current channels. Because the electronic circuitry only accepts voltage signals, it has negligible current drawn from the system under measurement. Owing to the high input impedance, the amplitude of the input signal is limited to the range of 5V to 15V. Since it uses small signals, signal conditioning systems are used to create accurate current to voltage transformation and proper voltage reduction.

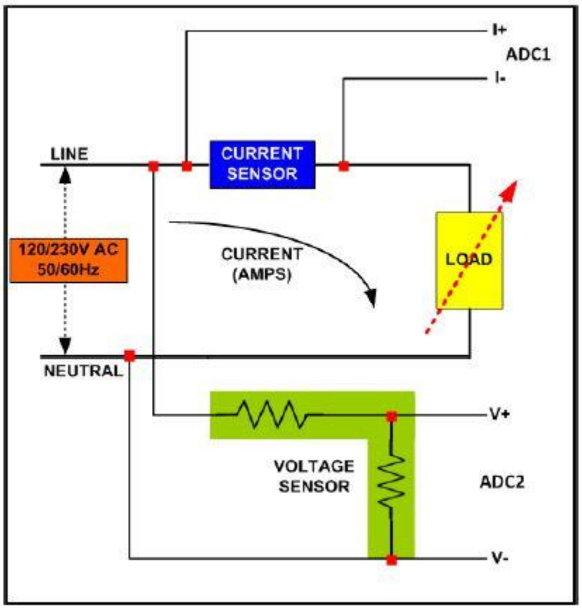

Figure 2-4 Typical Line Connection of Sensing Components in Electronic Energy Meter

Source: Extracted from [8]

The basic block of conditioning system comprises voltage divider for voltage input and a shunt for current input. The voltage and current sensors are then connected through two amplifiers for boost up the small signals before processing. There are two types of display options available in electronic energy meters, mechanical display option and electronic display option [2].

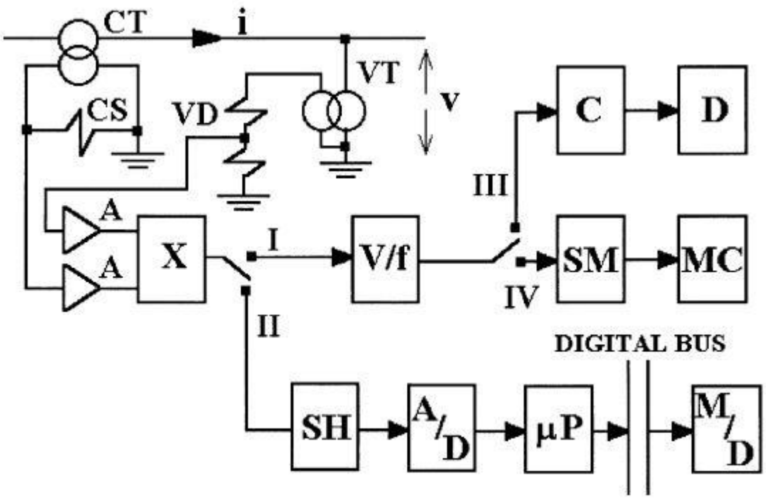

Figure 2-5 Block Diagram of an Electronic Energy Meter

Source: Extracted from [2]

In Figure 2-5,

Mechanical display option is shown from I to IV

Electronic display option is shown from I to III

Electronic display option and digital processing of the power signal is shown by II

CT: Current transformer

VT: Voltage transformer

VD: Voltage divider

CS: Current shunt

A: Analog signal processing block

X: Multiplier

V/f: Voltage to frequency converter

SM: Stepper motor

MC: Mechanical counter

C: Electronic counter

D: Display

SH: Sample and hold

A/D: Analog to digital converter

µP: Microprocessor (CPU)

M/D: Memory and display

Electronic energy meters can be divided into two types depending on their technology and the processing techniques.

2.3.2.1.1 Electronic-Analog Energy Meters with Digital Output

In this type, current and voltage sensed by the meter (both voltage signals) are multiplied by an analog multiplier and the output signal (voltage) which is proportional to the instantaneous power flowing through the line corresponds to the input signals. This output is sent through a filtering unit to calculate the energy. To calculate the energy flow, the output signal is integrated over the observation time. This can be done in two different ways.

1st procedure: the power signal is fed into a voltage frequency converter to convert it into a frequency pulse sequence for which the counting process performs the integration of power over the observed time interval, i.e., the measurement of energy. The final output can be shown by a digital display or the pulse output can be fed into a DC stepper motor which connects to a mechanical counter (same setup as in the electromechanical energy meter) which records energy permanently. The angular position of the rotor advances by each frequency pulse by a fixed angular increment. The rotor position indicating the total number of complete rotations performed by the system which is proportional to the energy under measurement [2].

A circuit diagram of a similar low cost electronic meter developed by "Analog Devices" which uses ADE7757 chip is shown below [6].

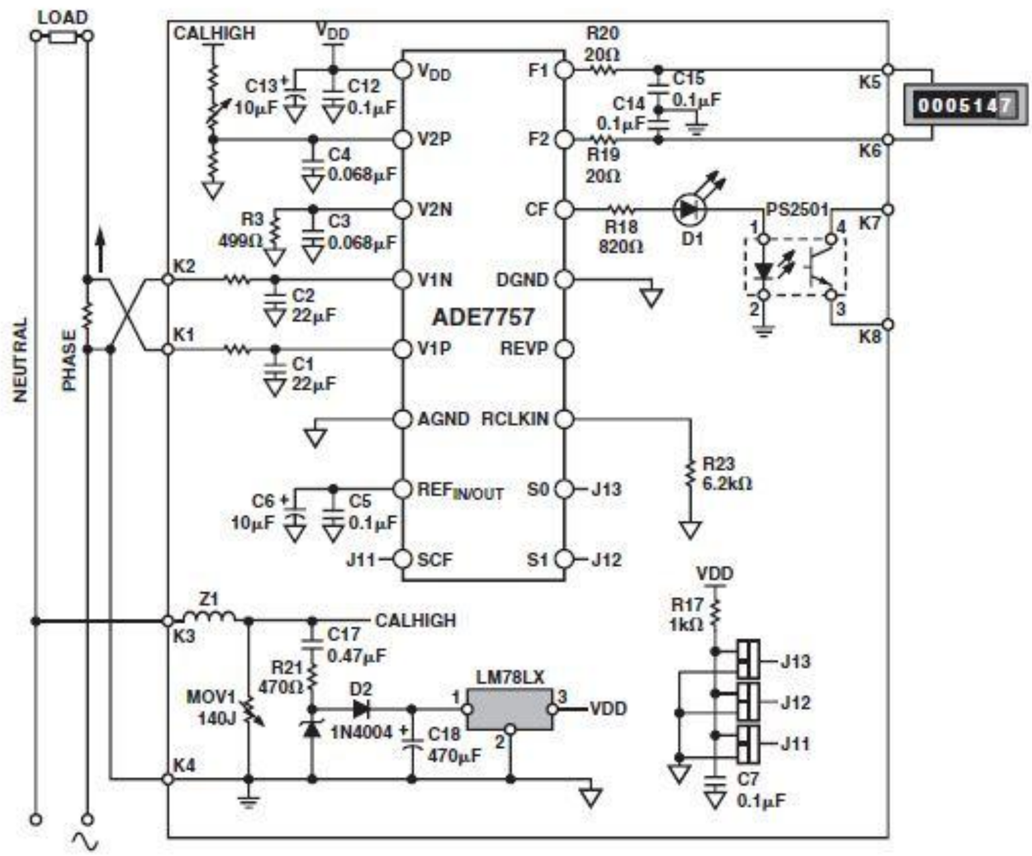

Figure 2-6 Schematic of a Single Phase Watt-Hour Meter based on ADE7757

Source: Extracted from [6]

2nd procedure: this process is based on analog to digital converter (ADC). The signal output of the analog multiplier is connected to the ADC, thus producing a uniform sampling over the signal period. The sampling process is driven by an internal clock. According to the sampling theory, the sum of samples is proportional to the integral of the power signal, i.e., to the energy during the observed time period. The calculation is done by a dedicated CPU and the results sent to the digital memory to store and display. The data is available on a data bus which can be accessed serially or parallelly and sampling is done by a sample and hold circuit [2].

2.3.2.1.2 Electronic - All Digital Energy Meter

All digital energy meter is the most advanced energy measuring solution which samples the input voltage and current signals (both voltage signals) before any other processing. The data bus holds the sampled input signals in digital form enabling access to perform digital signal processing to do complex calculations and analysis. Both input signals are driven by a synchronized sample signals provided by a CPU to improve accuracy.

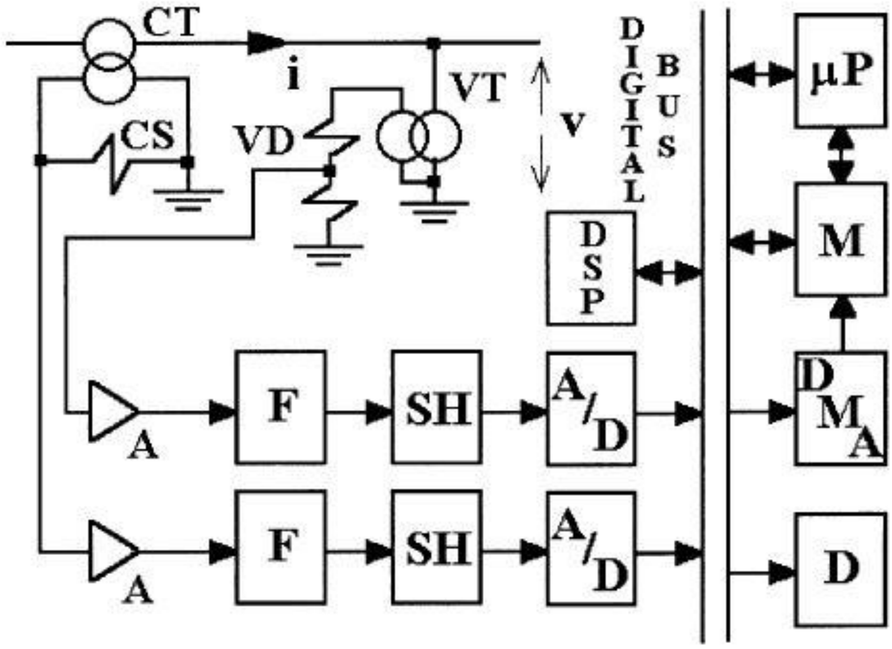

Figure 2-7 Block Diagram of an All Digital Energy Meter

Source: Extracted from [2]

In Figure 2-7,

CT: Current transformer

VT: Voltage transformer

CS: Current shunt

VD: Voltage divider

A: Analog signal processing block

F: Analog electronic filter

SH: Sample and hold

A/D: Analog to digital converter

μP: Microprocessor (CPU)

M: Memory

DSP: Digital signal processor

DMA: Direct memory access circuit

D: Display

Filters, programmable gain amplifiers and sample and hold circuits generally consist of ADCs to meet the sampling theorem requirements. The system is equipped with DSPs capable of providing hardware resource to implement real time evaluation of complex parameters of the signal and energy measurements. Advance performance meters are equipped with dedicated hardware and software performing instrument testing and other advance features. Data management is done in two possible ways. One is to send the sampled data directly to the signal processing system for calculation, or accessing memory through DMA procedures to compute energy. The results are available in the system data bus to be sent to other system resources or to be displayed [2].

An example for an all-digital single phase energy meter based on MSP430 processor series by Texas Instruments is shown below. The device is constructed in two parts, metering part which has MSP430AFE processor runs as slave and the application part has the MSP430F6638 processor runs as the host processor [7].

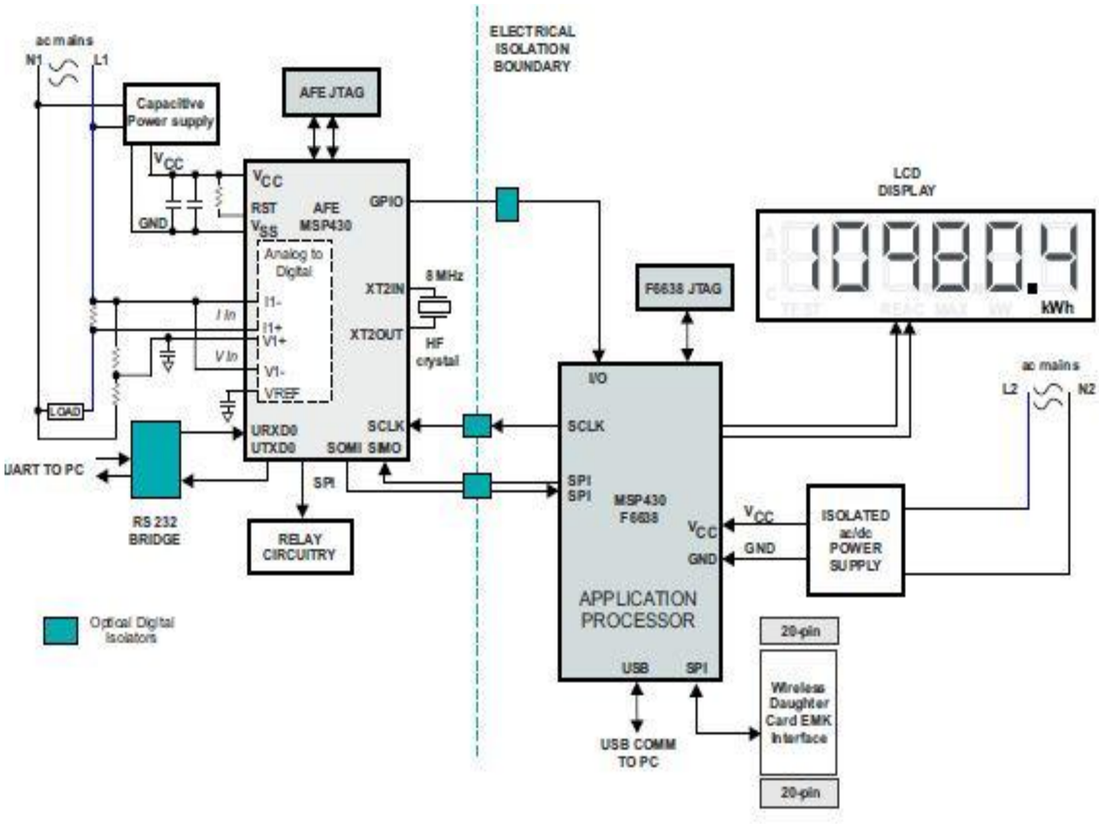

Figure 2-8 Block Diagram of an Energy Meter by Texas Instruments

Source: Extracted from [7]

For this study, a commonly used low cost electronic meter which operates on similar technology is considered. As of today, new installations in CEB and LECO are done by these meters. The meter manufacturer is “ANTE LECO” Meter group Ltd. The meter uses a Manganin resister (an alloy which consists of 84% copper, 12% manganese and 4% nickel) to sense current passing through the line to the load and the voltage drop across the resister acts like the current shunt. In this way, power consumption is very low for current sensing when compared with the CT measuring technique. Typically from this type of meters, high accuracy can be achieved ranging from 1% to 0.2%. The average power consumption of 5(30)A, 230V, 50Hz 1 phase, 2 wire, meter is around 0.5W.

2.3.3 Performance Comparison of Different Technologies

Depending on technology, the performance of the energy meters will be different.

Table 2-2 Performance Comparison of Different Types of Energy Meters

Energy Meter Type	Field of Performance	Description
Electromechanical	Accuracy	±2% to ±1%
	Power consumption	0.8W to 2W
	Features	Energy measurement only
	Construction	Robust construction
	Operational Complexity	Operates under fundamental induction theory, involves a lot of mechanical parts.
	Bearing capability for surges	Because of robust construction and no electronic parts, good bearing capability to surges.
Electronic-Analog Energy Meters with Digital Output	Accuracy	±0.5% to ±0.2%
	Power consumption	0.4W to 0.8W
	Features	• Since data is stored in memory historical reading recall facility available. • Remote communication available • Register programming available
	Construction	Does not involve mechanical parts, all electronic component such as filters, multipliers, amplifiers memory, ADCs and communication modules included in construction.
	Operational Complexity	Complex operation because of multiple features.
	Bearing capability for surges	Surge bearing capacity is low.
Electronic-All Digital Energy Meter	Accuracy	±0.5% to ±0.2%
	Power consumption	0.4W to 0.5W
	Features	In addition to all other features real time data processing facility and two way energy registering (Import, Export) available.
	Construction	Involves digital electronics with several processors.
	Operational Complexity	Very complex operation
	Bearing capability for surges	Surge bearing capacity is low.

3. MATHEMATICAL MODELLING

There are four types of data that need to be prepared for modelling,

- Accuracy error test data
- Power consumption test data
- Load profile data
- Single phase consumer statistical data

3.1 Formulation of Mathematical Model for Accuracy Error

For the study following single phase energy meters are taken,

Electromechanical meter:

Make: ANTE LECO

Type: DD949 1-Phase 2-Wire

Voltage: 240V

Current: 10(40)A i.e.,Ib=10A

Frequency: 50Hz

Accuracy Class: 2 i.e., ±2%

Meter Constant: 480 rev/kWh

Number of samples: 12

Electronic meter:

Make: ANTE LECO

Type: DDSF949 1-Phase 2-Wire

Voltage: 230V

Current: 5(40)A i.e.,Ib=5A

Frequency: 50Hz

Accuracy Class: 1 i.e., ±1%

Meter Constant: 1600 imp/kWh

Number of samples: 10

The two types of meters were tested for accuracy error for different current ratios (I/Ib) and for two power factors PF=1 and PF=0.5 lagging.
The test results taken from LECO meter factory is given in Appendix I.

3.1.1 Accuracy Error Model for Electromechanical Energy Meter

From the accuracy error test results for the electromechanical energy meters, reading were averaged and taken as the values of model meter errors.

Table 3-1 %Accuracy Error of Electromechanical Model Meter

Current Ratio (I/Ib)	% Accuracy Error	
	PF=0.5L	PF=1
0.05	0.67	0.08
0.07	0.97	-0.58
0.09	0.03	-0.93
0.11	-0.48	-1.13
0.15	-1.05	-1.37
0.20	-1.35	-1.35
0.40	-1.37	-0.97
0.60	-1.05	-0.53
0.80	-0.77	-0.18
1.00	-0.48	0.03
1.50	0.02	0.40
2.00	0.18	0.45
2.50	0.25	0.45
3.00	0.23	0.38
3.50	0.05	0.07
4.00	-0.42	-0.44

As the basic current Ib is 10A, the test values for the range 0.5A to 40A is in Table 3-1 for each power factor. The accuracy error is negative when the meter is reading less than the actual value, and the accuracy error is positive when the meter is reading more than actual value and when it is zero the meter is reading exactly the same value as actual value.
It is essential to plot the accuracy error curves in order to formulate the model to assess the total energy error.

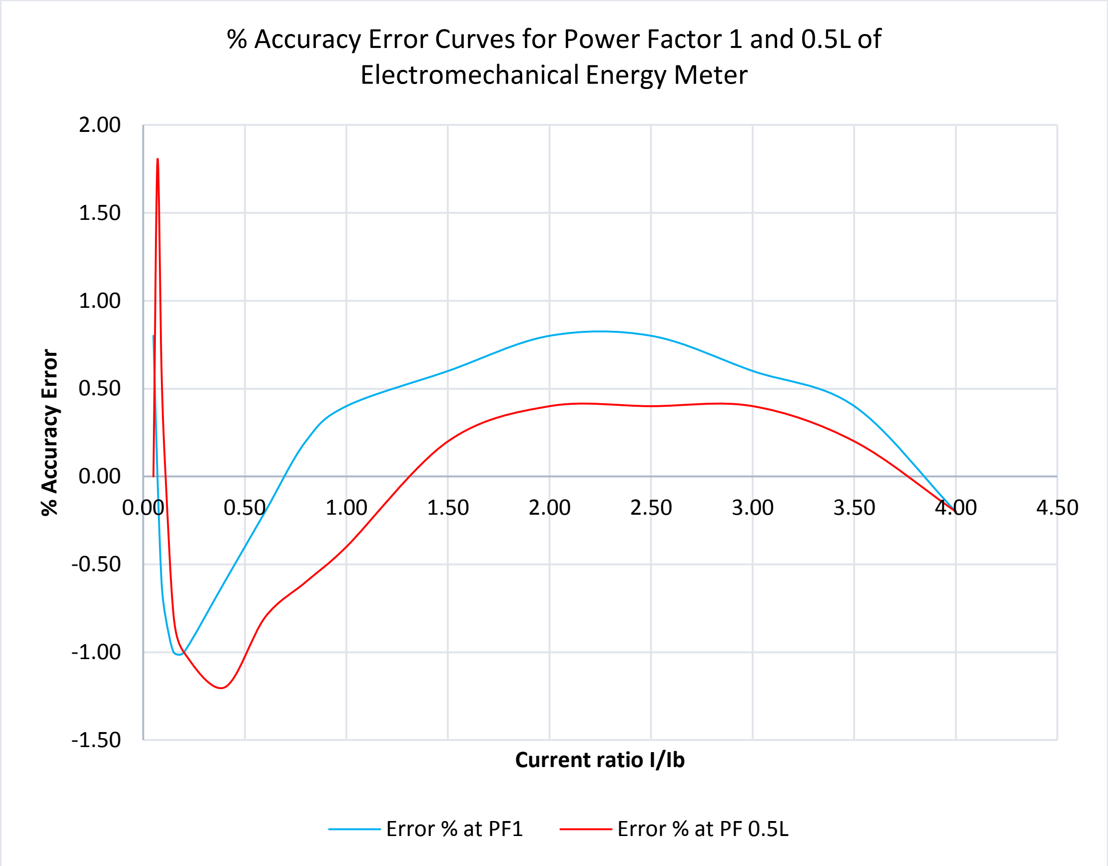

Figure 3-1 Accuracy Error Curves of Model Electromechanical Energy Meter

The error varies with the load current and power factor. The load current and power factor changes with the types of loads switching ON and OFF. Therefore, the algebraic total error for a considered time period for a particular consumer is the factor that counts to the final energy error.

3.1.1.1 Three Dimensional Accuracy Model for Electromechanical Meter

As the power factor varies with the load, current flowing through the meter also varies. Therefore it is required to find the percentage accuracy errors for the corresponding current ratios and the corresponding power factor. Using the values of power factors 0.5L and 1, the error values corresponding to intermediate power factors were interpolated and tabulated in Table 3-2.

Table 3-2 Accuracy Error of Electromechanical Meter for Different Power Factor

% Accuracy Error		Power Factor					
		0.5	0.6	0.7	0.8	0.9	1
<---- Current Ratio (I/Ib)	0.05	0.67	0.55	0.43	0.32	0.20	0.08
	0.07	0.97	0.66	0.35	0.04	-0.27	-0.58
	0.09	0.03	-0.16	-0.35	-0.55	-0.74	-0.93
	0.11	-0.48	-0.61	-0.74	-0.87	-1.00	-1.13
	0.15	-1.05	-1.11	-1.18	-1.24	-1.30	-1.37
	0.20	-1.35	-1.35	-1.35	-1.35	-1.35	-1.35
	0.40	-1.37	-1.29	-1.21	-1.13	-1.05	-0.97
	0.60	-1.05	-0.95	-0.84	-0.74	-0.64	-0.53
	0.80	-0.77	-0.65	-0.53	-0.42	-0.30	-0.18
	1.00	-0.48	-0.38	-0.28	-0.17	-0.07	0.03
	1.50	0.02	0.09	0.17	0.25	0.32	0.40
	2.00	0.18	0.24	0.29	0.34	0.40	0.45
	2.50	0.25	0.29	0.33	0.37	0.41	0.45
	3.00	0.23	0.26	0.29	0.32	0.35	0.38
	3.50	0.05	0.05	0.06	0.06	0.06	0.07
	4.00	-0.42	-0.42	-0.43	-0.43	-0.44	-0.44

The percentage accuracy error depends upon the power factor and current ratio (I/Ib), hence the plot of the percentage accuracy error will be in a three dimensional space. The 3D plot should be drawn in order to find a matching equation. The technique to find the energy error is to map the equation found in the 3D surface to the load profile where the actual current is.

For this purpose, a special software tool called "Table Curve 3D" was used to plot a surface in a 3D space.

Software details:

Name: Table Curve 3D

Version: 4.0.01

Copy right: SYSTAT Software inc., 1993-2002

The 3D plot for the data in table 3-2 is as follows,

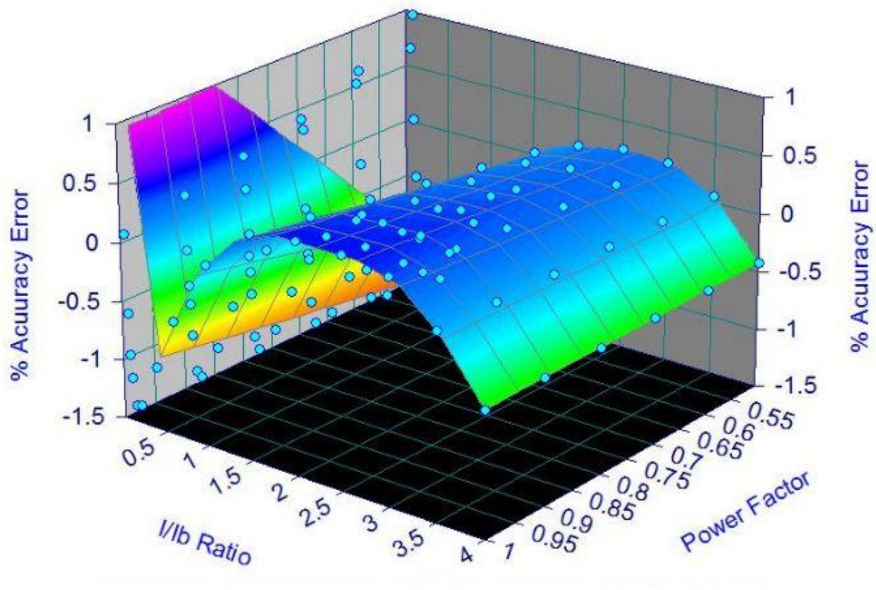

Figure 3-2 Accuracy Error for Electromechanical Meter

By observing this surface it is clear that the % accuracy error decreases rapidly from (I/Ib)=0.05 to (I/Ib)=0.15, and from there onward, it is a curvy smooth surface. Similar features can be seen in the 2D plot (Figure 3-1) as well. Therefore, the surface plot was analyzed dividing it into two parts. One from (I/Ib)=0.05 to (I/Ib)=0.15 and the other from (I/Ib)=0.15 to (I/Ib)=4.

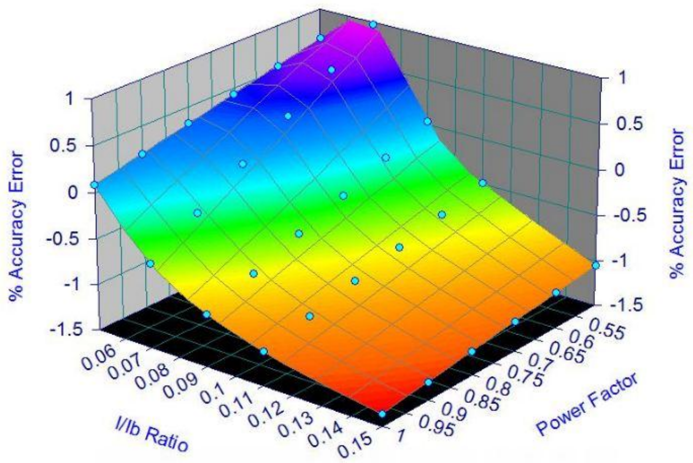

Figure 3-3 Accuracy Error for Electromechanical Meter: lower loads

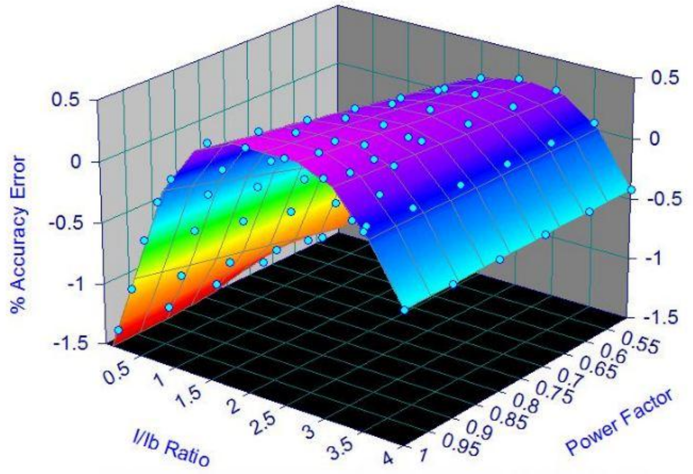

Figure 3-4 Accuracy Error for Electromechanical Meter: higher loads

For the two segments, two separate 3D plots were taken from Table 3D Curve software for accuracy error. From the software, a best fit surface equation was obtained for the two surfaces. The surface equations were chosen such that the goodness of fit is over 95% and it would be possible to map into the load profile in Microsoft “Excel” format. All equations are third order equation.

Approximation for the first part of the surface,

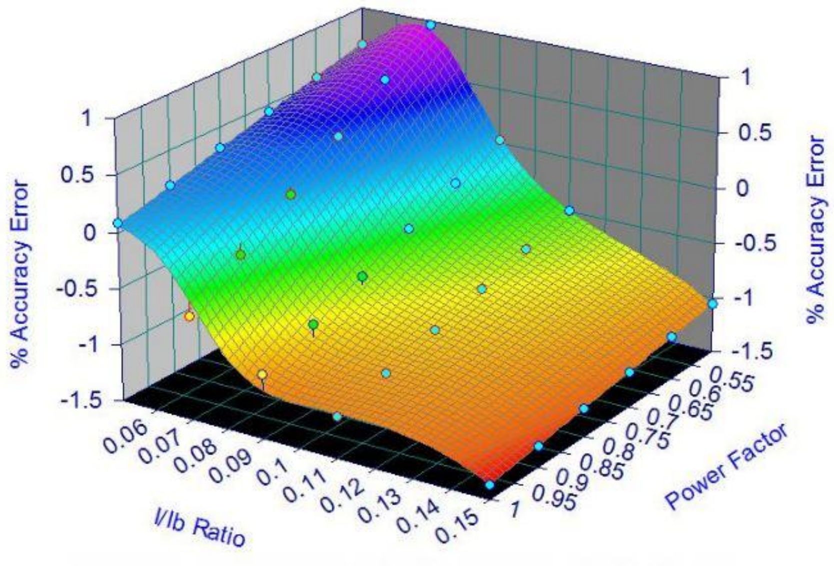

Figure 3-5 Approximated Accuracy Error Surface of Electromechanical Meter : lower loads

Equation for the approximated % cccuracy error surface for current ratio (I/Ib) 0.05 to 0.15 and power factor 0.05L to 1 of electromechanical meter is,

$$z = \frac{(a + bx + cx^2 + dy + ey^2 + fy^3)}{(1 + gx + hy + iy^2 + jy^3)}$$

With r^2 = 99.41%

The Statistical report generated by the “Table 3D Curve” software for the above surface fit is given in Appendix II.

Table 3-3 Coefficients for Approximated Accuracy Error Surface for Electromechanical Meter

Coefficient	Value
a	0.22475198
b	-0.17180691
c	-0.002274477
d	-0.29791589
e	-7.5096798
f	-62.756571
g	0.001398244
h	-29.407302
i	286.01438
j	-815.9437

Approximation for the second part of the surface,

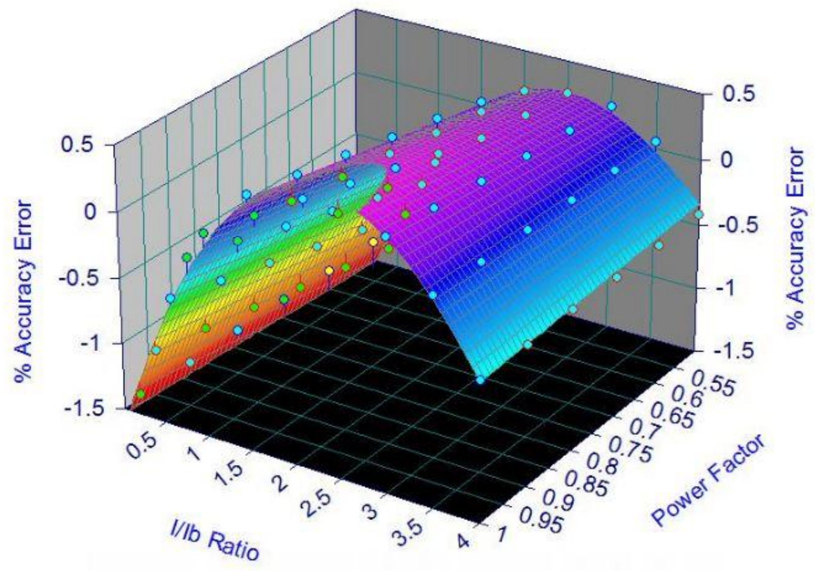

Figure 3-6 Approximated Accuracy Error Surface for Electromechanical Energy : higher loads

Equation of the approximated % accuracy error surface for current ratio (I/Ib) 0.15 to 4.00 and power factor 0.05L to 1 of electromechanical energy meter is,

$$z = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y$$

With $r^2 = 98.56\%$

Statistical report generated by the "Table 3D Curve" software for the above surface fit is given in Appendix III.

Table 3-4 Coefficients for Approximated Accuracy Error Surface for of Electromechanical Meter: higher loads

Coefficient	Value
a	-2.2257517
b	0.58229466
c	1.7383968
d	-1.06726E-13
e	-0.40323078
f	0.35096898
g	5.38143E-14
h	0.023507219
i	-0.13921982
j	-4.14674E-15

3.1.1.2 Equation Mapping to Load Profile

Load profiles for five consumer categories were taken. In the load profiles, following data fields were taken.

- Date and Time
- Active Power (kW)
- Active Energy (kWh)
- Apparent Power (kVA)
- Power Factor
- Actual Current (A)
- Actual Current Ratio (I/Ib)
- % Accuracy Error
- Active Energy Error (kWh)

Coefficients of the surface equations were separately entered besides the load profile. The load profile was rearranged such that the actual current ratio (I/Ib) is in ascending order. Then the load profile was divided into two parts for the I/Ib ratio 0.05 to 0.15 and 0.15 to 4.00. The actual current ratio and power factor was mapped to the relevant surface equation to find the %accuracy error which leads to the calculation of energy error corresponding to the considered time interval.

All the energy errors of all the time intervals were summed up at the end and the total energy error for the month was calculated. Hence the % energy error for the perticular consumer was calculated.

3.1.2 Accuracy Energy Model for the Electronic Energy Meter

From the accuracy error test results for the electronic energy meters, values were averaged and taken as the values of model meter values.

The same procedure was followed for the development of the mathematical model for the accuracy error of the electronic energy meter.

Table 3-5 Accuracy Error of Electronic Meter

Current Ratio (I/Ib)	% Accuracy Error	
	PF=1	PF=0.5L
8.00	-0.05	-0.10
3.50	-0.03	-0.09
3.00	-0.03	-0.08
2.50	-0.03	-0.08
2.00	-0.03	-0.09
1.50	-0.03	-0.08
1.00	-0.03	-0.08
0.80	-0.02	-0.08
0.60	-0.03	-0.08
0.40	-0.03	-0.09
0.20	-0.04	-0.13
0.15	-0.05	-0.13
0.11	-0.06	-0.15
0.09	-0.08	-0.17
0.07	-0.09	-0.21
0.05	-0.14	-0.26

As the basic current (Ib) is 5A, the test values for 0.25A to 40A is tabulated above for the two power factors. As in the electromechanical meter, the accuracy error is negative when the meter is reading less than the actual value and the accuracy error is positive when the meter is reading more than actual value and when it is zero, the meter is reading exactly the same value as the actual value.

Accuracy error curves for the two power factors can be plotted as below.

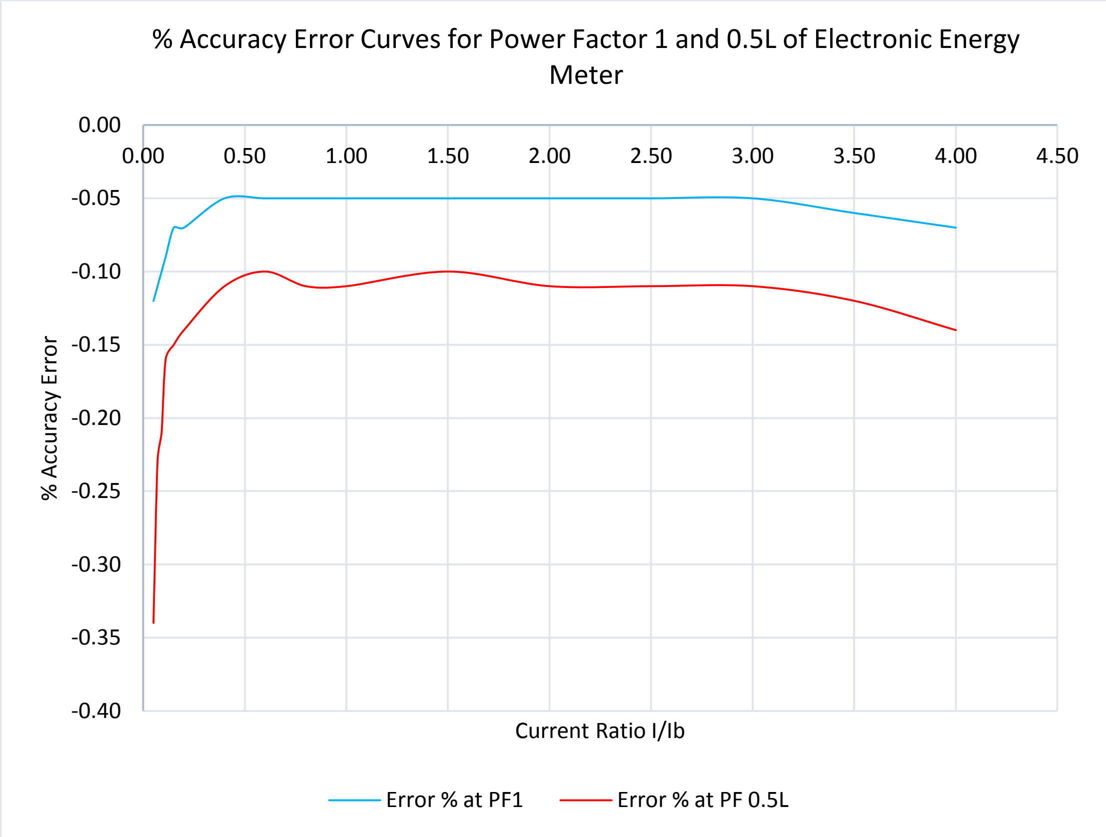

Figure 3-7 Accuracy Error Curves of Model Electronic Meter

3.1.2.1 Three Dimensional Accuracy Model for Electronic Meter

For the % accuracy error for power factors between 0.5L and 1 was interpolated and the data for the three dimensional plot was developed.

Table 3-6 Accuracy Error of Electronic Meter for Different Power Factor

% Accuracy Error		Power Factor					
		0.5	0.6	0.7	0.8	0.9	1
<---- Current Ratio (I/Ib)	0.05	-0.26	-0.24	-0.21	-0.19	-0.16	-0.14
	0.07	-0.21	-0.19	-0.16	-0.14	-0.11	-0.09
	0.09	-0.17	-0.15	-0.13	-0.12	-0.10	-0.08
	0.11	-0.15	-0.13	-0.11	-0.10	-0.08	-0.06
	0.15	-0.13	-0.11	-0.10	-0.08	-0.07	-0.05
	0.20	-0.13	-0.11	-0.09	-0.08	-0.06	-0.04
	0.40	-0.09	-0.08	-0.07	-0.05	-0.04	-0.03
	0.60	-0.08	-0.07	-0.06	-0.05	-0.04	-0.03
	0.80	-0.08	-0.07	-0.06	-0.04	-0.03	-0.02
	1.00	-0.08	-0.07	-0.06	-0.05	-0.04	-0.03
	1.50	-0.08	-0.07	-0.06	-0.05	-0.04	-0.03
	2.00	-0.09	-0.08	-0.07	-0.05	-0.04	-0.03
	2.50	-0.08	-0.07	-0.06	-0.05	-0.04	-0.03
	3.00	-0.08	-0.07	-0.06	-0.05	-0.04	-0.03
	3.50	-0.09	-0.08	-0.07	-0.05	-0.04	-0.03
	8.00	-0.10	-0.09	-0.08	-0.07	-0.06	-0.05

The 3D plot for the data in Table 3-6 is as follows,

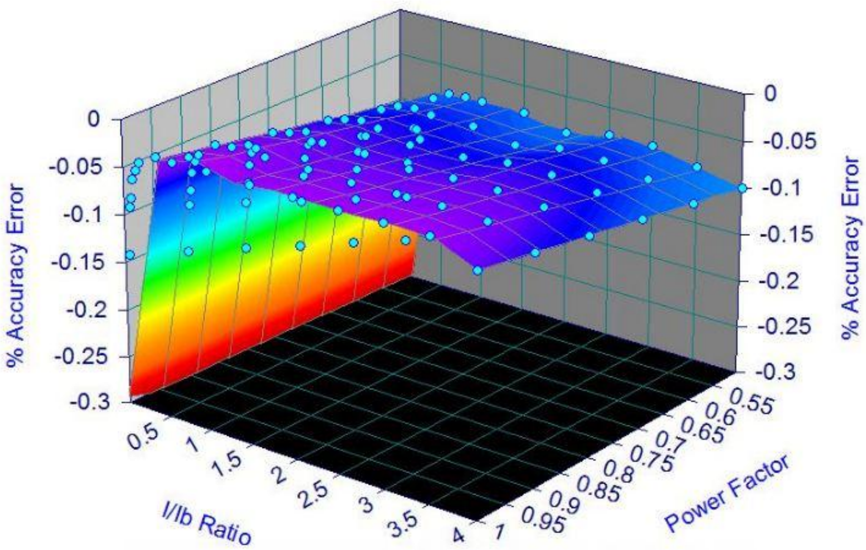

Figure 3-8 Accuracy Error for Electromechanical Meter

By observing this surface it is clear that the % accuracy error is changing very rapidly from (I/Ib)=0.05 to (I/Ib)=0.15, and from there onward, it is a smooth surface. This feature can also be seen in the 2D plot (Figure 3-8) as well. Therefore, the surface plot was analyzed by dividing it into two parts: one from (I/Ib)=0.05 to (I/Ib)=0.15 and the other from (I/Ib)=0.15 to (I/Ib)=8.

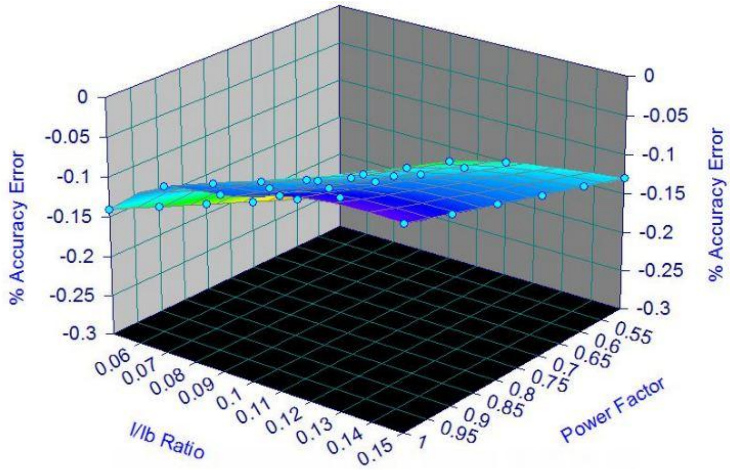

Figure 3-9 Actual Accuracy Error Surface for Electronic Meter: lower loads

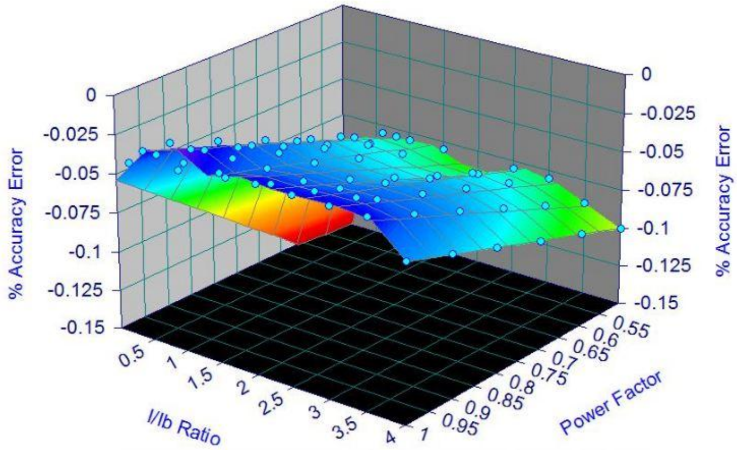

Figure 3-10 Accuracy Error for Electronic Energy Meter: higher loads

For the two parts, two separate 3D plots were taken from Table 3D Curve software for percentage accuracy error. From the software, a best fit surface equation was obtained for the two surfaces. The surface equations were chosen such that the goodness of fit is over 95% and it would be possible to map into the load profile in Microsoft "Excel" format. All equations are third order equation.

Approximation for the first part of the surface,

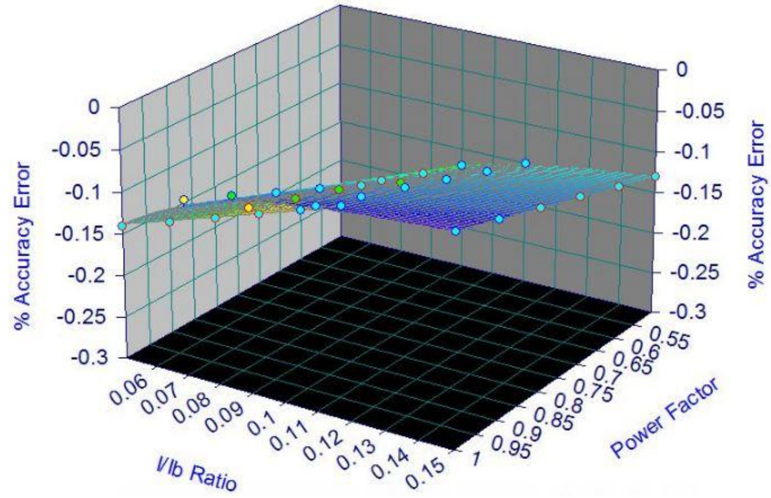

Figure 3-11 Approximated Accuracy Error Surface for Electronic Meter: lower loads

Equation for the approximated % accuracy error surface for current ratio (I/Ib) 0.05 to 0.15 and power factor 0.05L to 1 of the electronic energy meter was derived to be,

$$z = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y$$

With r^2 = 99.75%

Statistical report generated by the "Table 3D Curve" software for the above surface fit is given in Appendix IV.

Table 3-7 Coefficients for Approximated Accuracy Error Surface Electronic Meter: lower loads

Coefficient	Value
a	-0.69405119
b	0.344068483
c	8.510432876
d	1.02E-14
e	-52.5779274
f	-2.26656848
g	-4.65E-15
h	115.9591195
i	6.885125184
j	5.76E-15

Approximation for the second part of the surface,

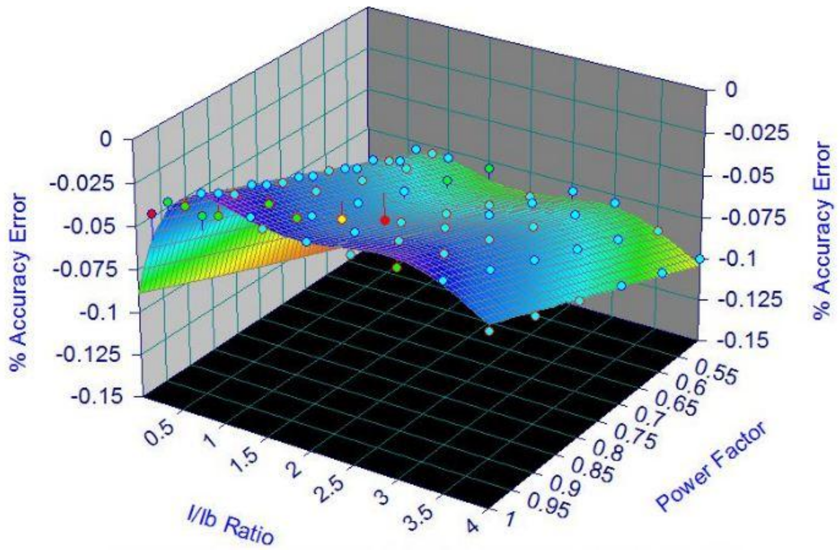

Figure 3-12 Approximated Accuracy Error Surface for Electronic Meter: higher loads

Equation for the approximated % accuracy error surface for current ratio (I/Ib) 0.15 to 4.00 and power factor 0.05L to 1 of electronic energy meter was derived to be,

$$z = a + bx + cy + dy^2 + ey^3 + fy^4 + gy^5$$

With r^2 = 96.24%

Statistical report generated by the "Table 3D Curve" software for the above surface fit is given in Appendix V.

Table 3-8 Coefficients for Approximated Accuracy Error Surface for Electronic Energy Meter: higher loads

Coefficient	Value
a	-0.20365901
b	0.114545455
c	0.217176285
d	-0.24949522
e	0.123813059
f	-0.02745823
g	0.002218211

3.1.2.2 Equation Mapping to the Load Profile

For the same load profile used to assess the performance of the electromechanical energy meter, coefficients of the surface equations were separately entered besides the load profile. The load profile was rearranged such that the actual current ratio (I/Ib) is in ascending order. Then the load profile was divided into two parts for the I/Ib ratio 0.05 to 0.15 and 0.15 to 4.00. The actual current ratio and power factor was mapped to the relevant surface equation to find the %accuracy error, which leads to the calculation of energy error corresponding to the considered time interval.

All the energy errors of all the time intervals were added at the end and the total energy error for the month was calculated. Hence the % energy error for the perticular consumer was calculated.

3.2 Formulation of Mathematical Model for Energy Consumption Error

To develop the mathematical model for the power consumption of energy meters, the power consumption should be measured. The power consumption measurement of the two types of meter were done at CEB, DD2 meter laboratory at Kiribathgoda.

Power consumption of the two meter types were tested by varying the load current for two power factors. The same current ratios of the accuracy error test were chosen so that the equation obtained for the power consumption model can be mapped into the same load profile used in the accuracy model.

3.2.1 Testing of Power Consumption of Energy Meters

Test Equipment details:

Meter test bench: METERTEST SPOO

Power Analyzer: YOKOGAWA WT310

The meter test bench was used for current and voltage injection purpose and the power analyzer was used to measure the power consumption of the energy meter. The schematic of the wiring for the test is shown below.

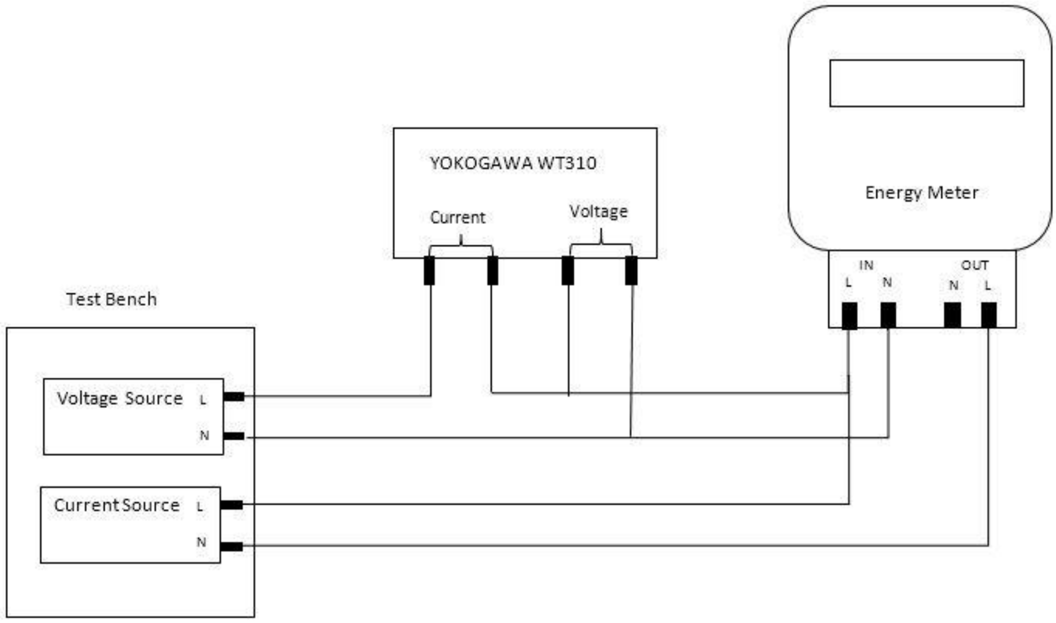

Figure 3-13 Wiring Schematic for the power consumption Test

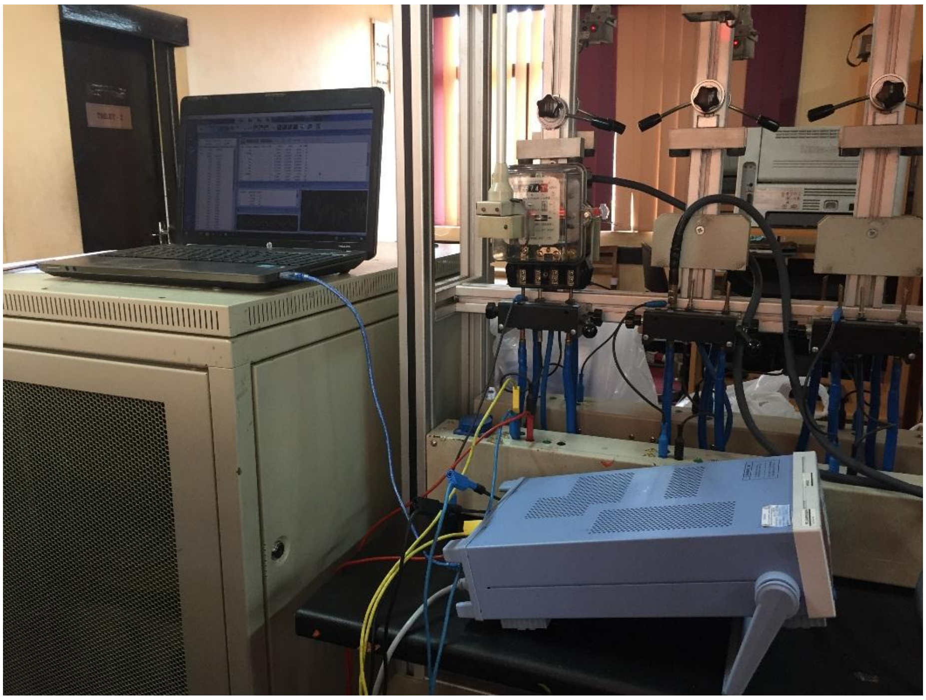

Figure 3-14 Image 1 of testing Power Consumption of Electromechanical Meter

Figure 3-15 Image 2 of testing Power Consumption of Electromechanical Meter

The resistance of the voltage and current coil of electromechanical meter was tested with an Ohm meter with 0.0001 Ω resolution.

Resistance of voltage coil – 982 Ω

Resistance of current coil – 000 Ω (Less than the resolution of Ohm meter)

Since the resistance of the current coil is very small in the electromechanical meter and the i^2r loss is the real power loss, the power consumption of the current coil was neglected [2]. Therefore, the power consumption of the voltage coil of the electromechanical energy meter was measured. For the electronic meter, the power supply for the electronic circuitry is taken from the voltage supply, and the power consumption of the electronic meter was also measured from the voltage supply to the meter.

Power consumption of five energy meters of the two types of energy meters were tested by varying applied current for two power factors (PF=1 and PF=0.5L).

3.2.2 Power Consumption Model for Electromechanical Meter

From the power consumption test results for the electromechanical energy meters, values were averaged and taken as the values of model meter values given Table 3-9.

Table 3-9 Power Consumption of Electromechanical Model Meter

Current Ratio (I/Ib)	Meter Consumption (W)	
	Power Consumption PF=1	Power Consumption PF=0.5L
0.05	0.889	0.887
0.07	0.883	0.886
0.09	0.888	0.882
0.11	0.882	0.878
0.15	0.879	0.884
0.20	0.888	0.878
0.40	0.879	0.878
0.60	0.875	0.877
0.80	0.882	0.880
1.00	0.869	0.882
1.50	0.873	0.880
2.00	0.872	0.878
2.50	0.866	0.873
3.00	0.850	0.874
3.50	0.852	0.876
4.00	0.840	0.882

As the basic current (Ib) is 10A, the test values for 0.5A to 40A are given in Table 3-9 for the two power factors. It is essential to plot the power consumption curves in order to formulate the model to assess the total energy consumed by the meter.

Note that the measured power consumption by the ANTE LECO meter factory for electromechanical energy meter at no load condition is around 0.73 W.

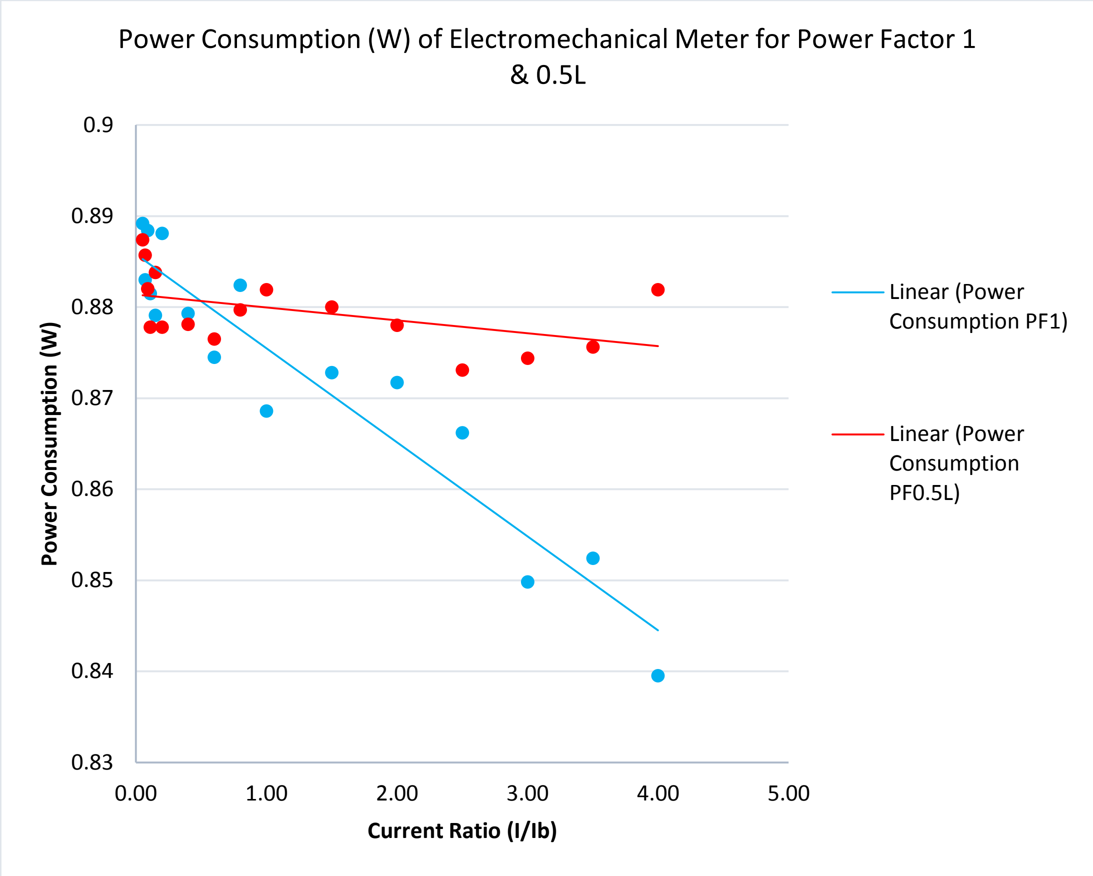

Figure 3-16 Power Consumption of Model for Electromechanical Energy Meter

By observing the above graph, it can be noticed that the points are scattered showing no definite pattern. However, it can be seen that there is a reducing trend, and a trend line was plotted. Although the goodness of fit is poor this fit is selected as no better fit is available.

When connected to a load, the power consumption varies with the load current and power factor, both load current and power factor changes with the type of loads switched on and off.

3.2.2.1 Three Dimensional Power Consumption Model for Electromechanical Meter

Since the power factor varies with the load, current flowing through the meter varies, too. Therefore it is required to find the power consumption for the corresponding current ratios and the corresponding power factor. Using the values of power factors

0.5L and 1.0, the power consumption corresponding to intermediate power factors were interpolated and tabulated in Table 3-10.

Table 3-10 Power Consumption of Electromechanical Meter for Different Power Factor

% Accuracy Error		Power Factor					
		0.5	0.6	0.7	0.8	0.9	1
<---- Current Ratio (I/Ib)	0.05	0.887	0.887	0.888	0.888	0.889	0.889
	0.07	0.886	0.885	0.885	0.884	0.884	0.883
	0.09	0.882	0.883	0.884	0.886	0.887	0.888
	0.11	0.878	0.879	0.880	0.880	0.881	0.882
	0.15	0.884	0.883	0.882	0.881	0.880	0.879
	0.20	0.878	0.880	0.882	0.884	0.886	0.888
	0.40	0.878	0.878	0.878	0.879	0.879	0.879
	0.60	0.877	0.877	0.876	0.876	0.875	0.875
	0.80	0.880	0.880	0.881	0.881	0.882	0.882
	1.00	0.882	0.879	0.877	0.874	0.872	0.869
	1.50	0.880	0.879	0.877	0.876	0.874	0.873
	2.00	0.878	0.877	0.876	0.874	0.873	0.872
	2.50	0.873	0.872	0.870	0.869	0.867	0.866
	3.00	0.874	0.869	0.864	0.860	0.855	0.850
	3.50	0.876	0.871	0.866	0.862	0.857	0.852
	4.00	0.882	0.874	0.865	0.857	0.848	0.840

The power consumption depends on the power factor and current ratio (I/Ib). Hence the plot of power consumption will be in a three dimensional space. The 3D plot should be drawn in order to find a matching equation. The technique is the same technique followed in the accuracy error model, to find the energy loss due to power consumption. The equation developed in the 3D surface was mapped to the load profile for different levels of load current..

For this purpose too, “Table Curve 3D” software was used to plot a surface in a 3D space.

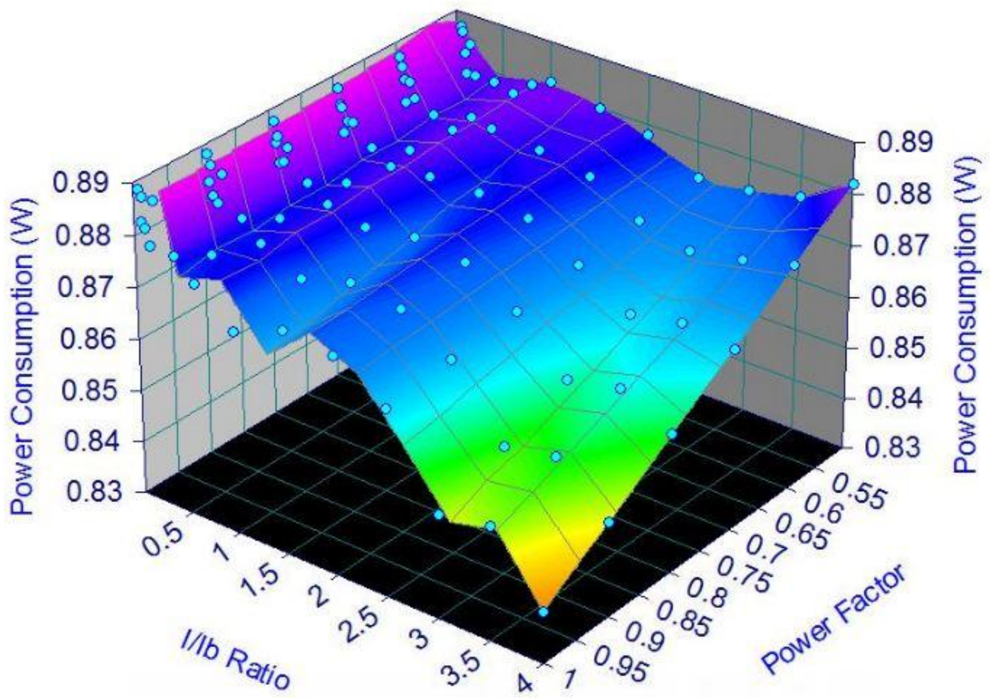

Figure 3-17 Actual Power Consumption Plot for Electromechanical Meter

By observing the actual surface, it can be seen that it is a very rough surface, and therefore, fitting a suitable surface for these values is very difficult. However, for the modelling to be done, a surface equation is required and it was done considering higher power factor values. Therefore, the goodness of fit of the surface is poor.

By observing the 3D plot, the surface can be fitted with a surface as a whole and an equation can be developed for that.

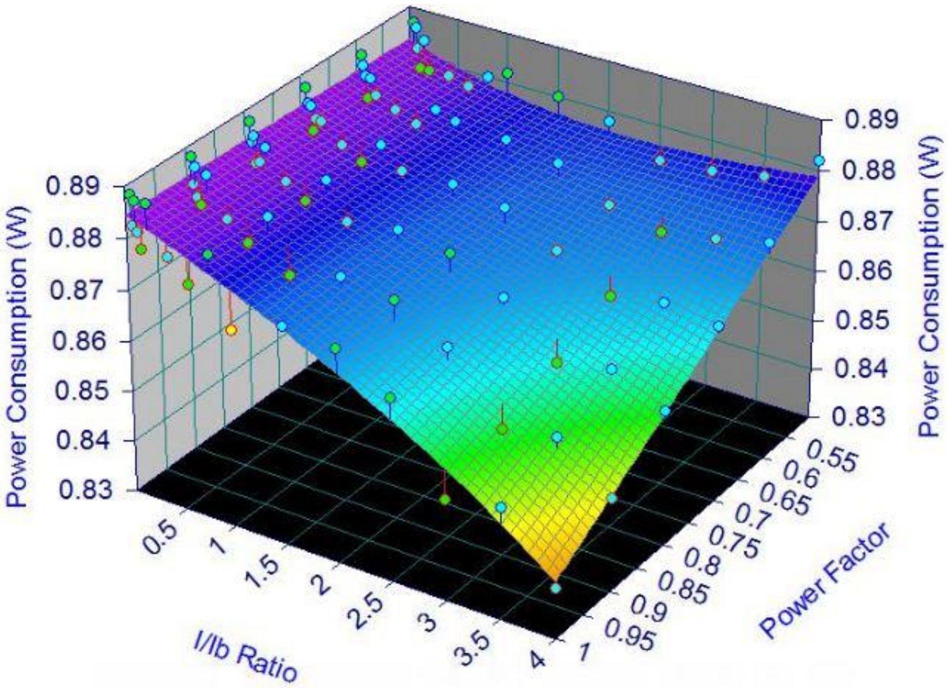

Figure 3-18 Approximated Power Consumption Plot for Electromechanical Meter

Equation of the approximated power consumption surface plot is,

$$z = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y$$

With r^2 = 89.44%

Statistical report generated by the "Table 3D Curve" software for the above surface fit is given in Appendix VI.

Table 3-11 Coefficient table for Approximated Power Consumption Surface for Electromechanical Meter

Coefficient	Value
a	0.882033748
b	0.002683168
c	-0.0071271
d	7.28021E-14
e	0.004626126
f	-0.00079374
g	-3.2257E-14
h	-0.00017071
i	-0.0046746
j	-7.6185E-17

3.2.2.2 Equation Mapping to the Load Profile

For the same load profile used in accuracy error model, coefficients of the surface equations were separately entered beside the load profile. The load profile was rearranged such that the actual current ratio (I/Ib) is in the ascending order. The actual current ratio and power factor was mapped to the relevant surface equation to find the power consumption of the time interval considered, which leads to the calculation of energy loss due to power consumption of the meter.

All the energy portions of all the time intervals were added at the end and the total energy used by the meter for that perticular month was calculated, and thereby, the % energy consumption for the perticular consumer was calculated.

3.2.3 Power Consumption Model for the Electronic Meter

From the power consumption test results for the electronic energy meters, values were averaged and taken as the values of model meter values.

Table 3-12 Power Consumption of Electronic Meter

Current Ratio (I/Ib)	Meter Consumption (W)	
	Power Consumption PF=1	Power Consumption PF=0.5L
0.05	0.423	0.432
0.07	0.425	0.424
0.09	0.423	0.419
0.11	0.423	0.419
0.15	0.426	0.447
0.20	0.424	0.420
0.40	0.428	0.421
0.60	0.429	0.418
0.80	0.425	0.423
1.00	0.425	0.420
1.50	0.427	0.417
2.00	0.429	0.422
2.50	0.430	0.425
3.00	0.425	0.428
3.50	0.433	0.418
4.00	0.428	0.435

As the basic current Ib is 5A, the test values for 0.25A to 20A are tabulated above for the two power factors. It is essential to plot the power consumption curves in order to formulate the model to assess the total energy consumed by the meter.

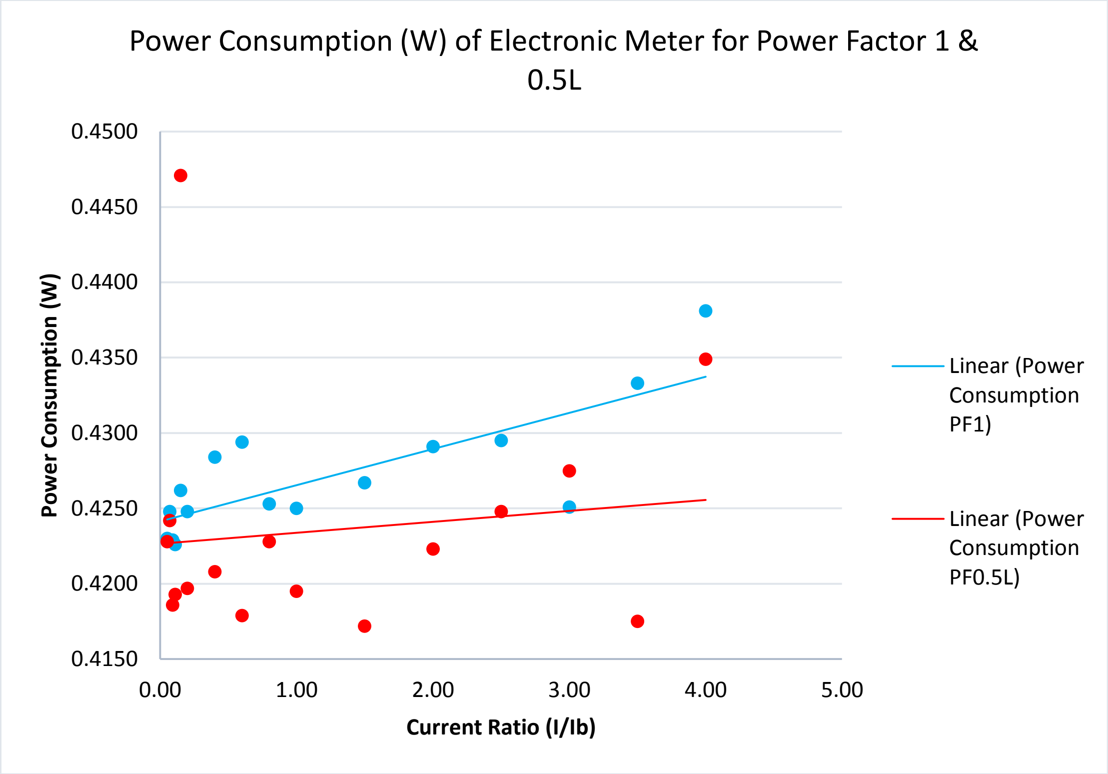

Figure 3-19 Power Consumption of Electronic Energy Meter

As in the electromechanical meter, the values are scattered all over, but it can be noted that there is a rising trend. Therefore a trend line was fitted. The goodness of fit will be very poor.

The same procedure was followed for the electronic meter to obtain the power consumption 3D Surface to reflect the power factor variation in loads.

3.2.3.1 Three Dimensional Power Consumption Model for Electronic Meter

Three dimensional data table of power consumption for the varying current ratio and power factor was interpolated as before.

Table 3-13 Power Consumption of Electronic Model Meter for Different Power Factor

% Accuracy Error		Power Factor					
		0.5	0.6	0.7	0.8	0.9	1
<---- Current Ratio (I/Ib)	0.05	0.432	0.430	0.428	0.427	0.425	0.423
	0.07	0.424	0.424	0.424	0.425	0.425	0.425
	0.09	0.419	0.420	0.421	0.421	0.422	0.423
	0.11	0.419	0.420	0.421	0.421	0.422	0.423
	0.15	0.447	0.443	0.439	0.434	0.430	0.426
	0.20	0.420	0.421	0.422	0.422	0.423	0.424
	0.40	0.421	0.422	0.424	0.425	0.427	0.428
	0.60	0.418	0.420	0.422	0.425	0.427	0.429
	0.80	0.423	0.423	0.424	0.424	0.425	0.425
	1.00	0.420	0.421	0.422	0.423	0.424	0.425
	1.50	0.417	0.419	0.421	0.423	0.425	0.427
	2.00	0.422	0.423	0.425	0.426	0.428	0.429
	2.50	0.425	0.426	0.427	0.428	0.429	0.430
	3.00	0.428	0.427	0.427	0.426	0.426	0.425
	3.50	0.418	0.421	0.424	0.427	0.430	0.433
	4.00	0.435	0.434	0.432	0.431	0.429	0.428

The 3D plot for the actual power consumption is as before,

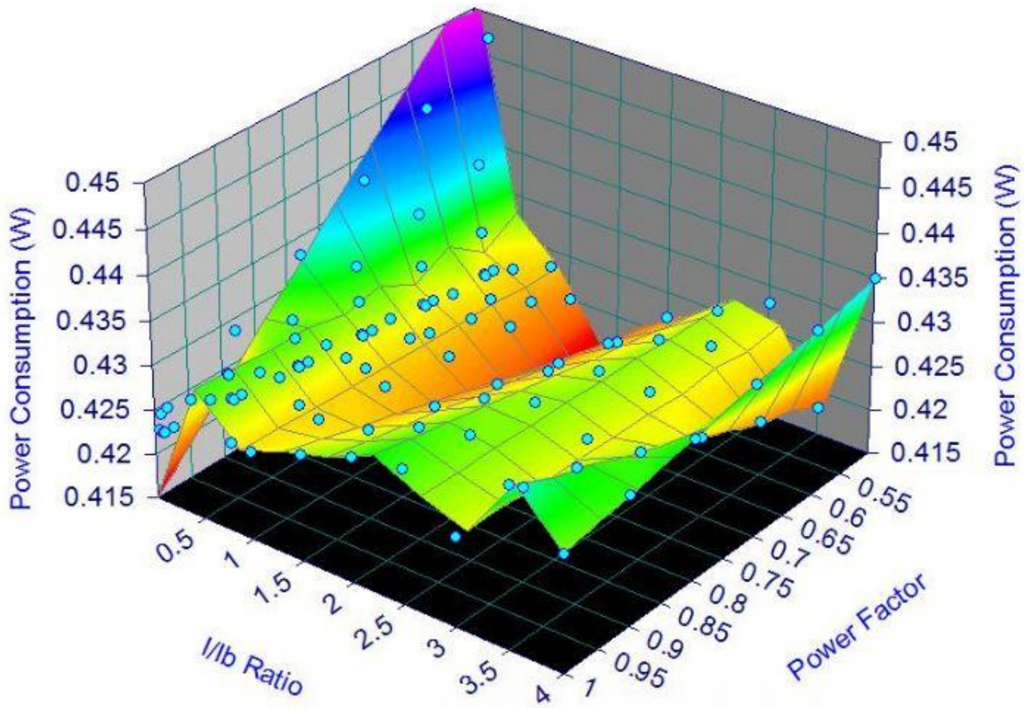

Figure 3-20 Actual Power Consumption Plot for Electronic Energy Meter

As seen in the actual surface, it is a very rough surface. Therefore fitting a suitable surface to these values will beis very difficult. However, for the modelling to be done, a surface equation is needed and it was done considering higher power factor values. Therefore, the goodness of fit of the surface is very poor.

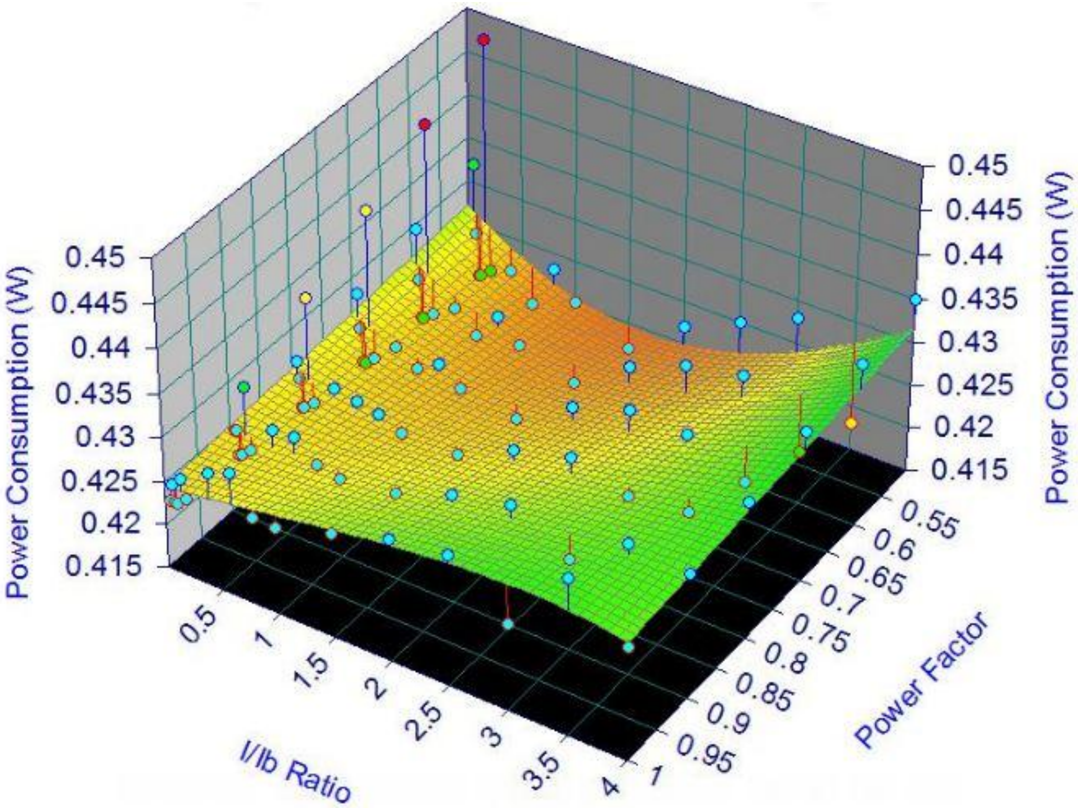

Figure 3-21 Approximated Power Consumption Plot for Electronic Energy Meter

Equation of the approximated power consumption surface plot is,

$$z = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y$$

With $r^2 = 21.50\%$

Please refer Appendix VII for the statistical report generated by the “Table 3D Curve” software for the above surface fit.

Table 3-14 Coefficient table for Approximated Power Consumption Surface for Electronic Energy Meter

Coefficient	Value
a	0.429628747
b	-0.00523397
c	-0.02077751
d	3.379590E-14
e	0.006197278
f	2.23684E-02
g	-1.5103E-14
h	-0.00017453
i	-0.00563371
j	9.09985E-17

3.2.3.2 Equation Mapping to the Load Profile

Equation mapping was done in the same procedure as in the electromechanical meter to calculate the % power consumption for a month of a perticular consumer.

4. MODELLING RESULTS

Total loss in single phase energy meters includes, loss due to accuracy error and loss due to power consumption of meters. Both types of losses were modelled in actual load profiles taken for following consumer categories.

Category 1 – Below 60kWh

Category 2 – From 60kWh to 90kWh

Category 3 – From 90kWh to 120kWh

Category 4 – From 120kWh to 180kWh

Category 5 – Above 180kWh

Models for accuracy error and power consumption of meters were implemented in five load profiles in one consumer category. Hence for accuracy error, 25 consumer load profiles were considered and for power consumption, the same 25 consumer load profiles were considered for one meter type. Therefore, 25 consumer load profiles were considered for two types of losses incurred in two types of energy meter (i.e., accuracy model was run for 50 times for two types of meter and power consumption model was run for 50 times for two types meters). For the two loss types, the percentage loss for each consumer category was obtained, averaged and summarized.

Energy sales statistics for the month of June 2018 was taken for the four distribution divisions (Distribution Regions) for the above consumer categories as given in Appendix VIII. from the average value of percentage loss, using weighted average method the loss for each distribution division was found. From that, the total loss incurred from single phase energy meters was calculated for the whole island.

4.1 Loss due to Energy Meter Accuracy Error

Percentage energy loss due to accuracy errors for all consumer categories are summarized in Table 4-1.

Table 4-1 Average of Percentage Energy Loss due to Accuracy Error

Meter Type	% Energy Loss due to Accuracy Error				
	Less than 60[1]	Between 60 & 90	Between 90 & 120	Between 120 & 180	Greater Than 180
Electromechanical 1	0.41%	0.64%	1.01%	1.14%	0.01%
Electromechanical 2	0.61%	0.77%	0.68%	0.92%	0.83%
Electromechanical 3	0.40%	0.71%	0.64%	1.18%	1.50%
Electromechanical 4	0.20%	0.45%	0.77%	0.75%	1.50%
Electromechanical 5	0.68%	0.48%	0.76%	1.10%	1.13%
Average	**0.46%**	**0.61%**	**0.77%**	**1.02%**	**0.99%**
Electronic 1	0.08%	0.06%	0.06%	0.05%	0.04%
Electronic 2	0.10%	0.06%	0.09%	0.06%	0.06%
Electronic 3	0.12%	0.08%	0.07%	0.05%	0.06%
Electronic 4	0.10%	0.07%	0.07%	0.05%	0.07%
Electronic 5	0.09%	0.08%	0.04%	0.05%	0.05%
Average	**0.10%**	**0.07%**	**0.07%**	**0.05%**	**0.06%**

[1]household consumption blocks, in kWh per month

Table 4-2 Summary of Percentage Energy Loss due to Accuracy Error

Household Consumption Category	% Energy Loss due to Accuracy Error	
	Electromechanical	Electronic
Less than 60	0.46%	0.10%
Between 60 & 90	0.61%	0.07%
Between 90 & 120	0.77%	0.07%
Between 120 & 180	1.02%	0.05%
Greater Than 180	0.99%	0.06%

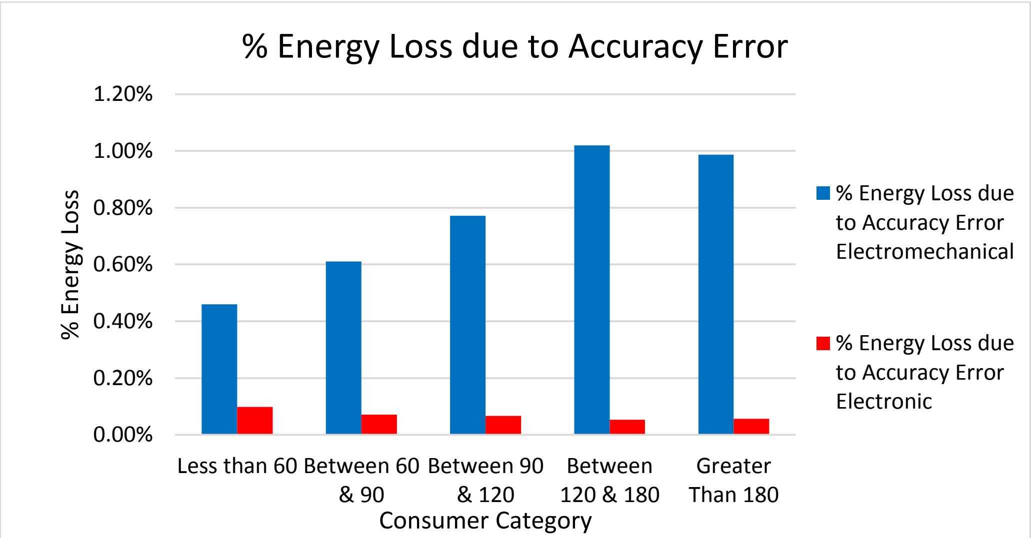

Figure 4-1 Percentage Energy Loss due to Accuracy Error in Consumer Categories

Using the weighted average method, the loss due to accuracy error was calculated for the four distribution divisions.

A sample calculation is shown below.

Distribution Division	Customer Class	Consumption Blocks	No of Customers	Total annual sales (kWh)	Energy Loss (kWh) due to Accuracy Error At Actual Power Factor	
					Electromechanical	Electronic
DD1	D1	ZRO	299,533	322	1.48	0.32
	D1	LT030	216,230	4,345,891	19,991.10	4,258.97
	D1	LT060	363,239	19,059,254	87,672.57	18,678.07
	D1	LT090	332,501	27,433,704	167,345.59	19,203.59
	D1	LT120	162,102	18,309,379	141,439.95	11,901.10
	D1	LT180	115,406	17,785,667	181,058.09	9,604.26
	D1	MT180	58,056	19,668,974	194,722.84	10,817.94
	GP1	ZRO	55,604	135	0.62	0.13
	H1	ZRO	10	0	0.00	0.00
	I1	ZRO	8,828	3	0.01	0.00
	R1	ZRO	2,359	4	0.02	0.00
	R1	LT030	2,262	42,855	197.13	42.00
	R1	LT090	2,919	194,905	1,505.64	136.43
	R1	LT120	973	115,312	890.79	74.95
	R1	LT180	1,485	244,712	2,491.17	132.14
	R1	MT180	3,162	1,781,181	17,633.69	979.65

Consumption Category	Meter Type	
	Electromechanical	Electronic
Less than 60	0.46%	0.10%
Between 60 & 90	0.61%	0.07%
Between 90 & 120	0.77%	0.07%
Between 120 & 180	1.02%	0.05%
Greater Than 180	0.99%	0.06%

Figure 4-2 Sample Calculation of Energy Loss due to Accuracy Error

Summary of the energy loss due to accuracy error for all distribution divisions are given in Table 4-3.

Table 4-3 Monthly Energy Loss due to Accuracy Error

Distribution Division	Total Energy Sold (kWh)	Total Energy Loss (kWh) due to Accuracy Error			Percentage Energy saving for Actual PF
		Electromechanical	Electronic	Difference	
DD1	108,982,298	814,951	75,830	739,121	0.68%
DD2	136,450,530	983,649	96,773	886,876	0.65%
DD3	76,479,054	541,553	55,276	486,277	0.64%
DD4	70,290,926	516,899	49,203	467,697	0.67%
Total	392,202,808	2,857,052	277,082	2,579,971	0.66%
Average Power (kW)		3,968	385	3,583	

Note: for June 2018

In the above results, losses are negative values because the energy meter are reading values lower than the actual energy delivered. In the difference column it shows the energy that can be additionally read if all electromechanical energy meters were replaced by electronic meters. The average power loss was taken to find the annual loss due to accuracy error and to find the additional energy that can be accounted when all the energy meters are replaced by electronic meters.

The calculation for annual energy that can be accounted for by the utility is as follows: Using the statistical data taken from the 2017 statistical digest, and considering only the single phase meters serving household customers,

Average loss to CEB due to meter errors (electromechanical meters compared with electronic meters)	= 3583 kW
Annual energy loss to CEB	= 3583 × 8760
	= 31,387,080 kWh
	= **31.387 GWh**
Total energy delivered from single phase meters in CEB	= 5993 GWh
Additional annual % energy loss to the utility	= (31.387/5993) × 100%
	= **0.53%**

Using the same percentage value of annual % energy loss to CEB, annual energy loss (energy not accounted) to LECO due to accuracy error was calculated.

LECO sales with single phase metering for the year 2017 = 969 GWh

Annual energy loss to LECO = 969 × 0.53% = **5.1357 GWh**

Total possible additional energy that could be accounted in Sri Lanka (CEB + LECO) = 36.5227 GWh

4.2 Loss due to Energy Meter Power Consumption

Percentage energy loss due to energy meter power consumption for all consumer consumption categories are summarized in Table 4-4 and 4-5.

Table 4-4 Average of Percentage Energy Loss due to Meter Power Consumption

Meter Type	% Energy Loss due to Power Consumption				
	Less than 60	Between 60 & 90	Between 90 & 120	Between 120 & 180	Greater Than 180
Electromechanical 1	0.82%	0.59%	0.67%	0.34%	0.07%
Electromechanical 2	1.22%	0.65%	0.54%	0.41%	0.31%
Electromechanical 3	1.50%	0.81%	0.61%	0.37%	0.27%
Electromechanical 4	1.18%	0.72%	0.60%	0.41%	0.22%
Electromechanical 5	1.36%	0.77%	0.58%	0.42%	0.17%
Average	**1.22%**	**0.71%**	**0.60%**	**0.39%**	**0.21%**
Electronic 1	0.40%	0.28%	0.32%	0.16%	0.03%
Electronic 2	0.59%	0.31%	0.26%	0.20%	0.15%
Electronic 3	0.72%	0.39%	0.29%	0.18%	0.13%
Electronic 4	0.57%	0.35%	0.29%	0.20%	0.11%
Electronic 5	0.66%	0.37%	0.28%	0.20%	0.08%
Average	**0.59%**	**0.34%**	**0.29%**	**0.19%**	**0.12%**

Table 4-5 Summary of Percentage Energy Loss due to Meter Power Consumption

Consumption Category	% Energy Loss due to Power Consumption	
	Electromechanical	Electronic
Less than 60	1.22%	0.59%
Between 60 & 90	0.71%	0.34%
Between 90 & 120	0.60%	0.29%
Between 120 & 180	0.39%	0.19%
Greater Than 180	0.21%	0.12%

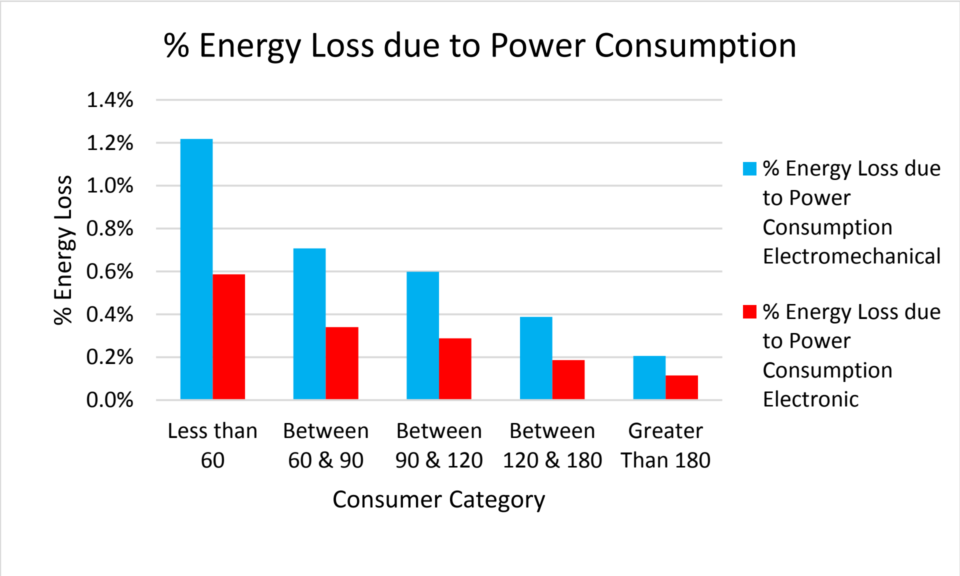

Figure 4-3 Percentage Energy Loss due to Meter Power Consumption of each Consumer Consumption Blocks

Using the weighted average method, the loss due to meter power consumption was calculated for the four distribution divisions.

The sample calculation is shown below.

Distribution Division	Customer Class	Consumption Blocks	No of Customers	No of Units (kWh)	Energy Loss (kWh) due to Meter Power Consumption – At Actual Power Factor	
					Electromechanical	Electronic
DD1	D1	ZRO	299,533	322	3.92	1.89
	D1	LT030	216,230	4,345,891	52,919.47	25,474.55
	D1	LT060	363,239	19,059,254	232,082.60	111,720.70
	D1	LT090	332,501	27,433,704	193,973.18	93,244.00
	D1	LT120	162,102	18,309,379	109,835.62	52,793.50
	D1	LT180	115,406	17,785,667	69,101.16	33,219.60
	D1	MT180	58,056	19,668,974	40,451.25	22,648.86
	GP1	ZRO	55,604	135	1.64	0.79
	H1	ZRO	10	0	0.00	0.00
	I1	ZRO	8,828	3	0.04	0.02
	R1	ZRO	2,359	4	0.05	0.02
	R1	LT030	2,262	42,855	521.84	251.21
	R1	LT090	2,919	194,905	1,378.10	662.46
	R1	LT120	973	115,312	691.74	332.49
	R1	LT180	1,485	244,712	950.76	457.07
	R1	MT180	3,162	1,781,181	3,663.18	2,051.03

Consumption Category	Meter Type	
	Electromechanical	Electronic
Less than 60	1.22%	0.59%
Between 60 & 90	0.71%	0.34%
Between 90 & 120	0.60%	0.29%
Between 120 & 180	0.39%	0.19%
Greater Than 180	0.21%	0.12%

Figure 4-4 Sample Calculation of Energy Loss due to Meter Power Consumption

Summary of the energy loss due to meter power consumption for all distribution divisions are given in Table 4-6.

Table 4-6 Total Energy Loss due to Meter Power Consumption of Single Phase Energy Meters in CEB for the Month of June 2018

Distribution Division	Total Energy (kWh)	Total Energy Loss (kWh) due to Power Consumption			Percentage Energy saving for Actual PF
		Electromechanical	Electronic	Difference	
DD1	108,982,298	705,574.57	342,858.20	362,716	0.33%
DD2	136,450,530	944,005.48	456,394	487,611	0.36%
DD3	76,479,054	546,288.96	264,260.68	282,028	0.37%
DD4	70,290,926	467,620.52	226,626.86	240,994	0.34%
Total	392,202,808	2,663,489.52	1,290,140.20	1,373,349	0.35%
Average Power		3,699	1,792	1,907	

In the Table 4-6 the difference column shows the energy that can be saved by using electronic energy meters instead of electromechanical meters for each distribution division.

The calculation for annual energy that can be saved by the utility is as follows using the statistical data taken from the 2017 statistical digest.

According to the 2017 statistics,

Possible average power saving	= 1907 kW
Possible annual energy saving	= 1907 × 8760
	= 16,705,320 kWh
	= **16.75 GWh**
Total energy delivered from single phase meters in CEB	= 5993 GWh

Total annual % energy that can be saved by using electronic meters

= (16.75/5993) × 100%

= **0.28%**

Using the same percentage value of annual % energy loss to CEB, annual energy loss to LECO due to energy meter power consumption was found.

LECO sales done for single phase metering for the year 2017	= 969 GWh
Annual energy loss to LECO	= 969 × 0.28%
	= **2.7132 GWh**

Total possible energy saving in Sri Lanka (CEB + LECO) = 19.46 GWh

4.3 Financial Benefit

Note that financial benefit of minimizing the nontechnical and technical losses are calculated only for CEB.

The annual financial benefit by using electronic energy meters in place of electromechanical energy meters is calculated below.

i. For the Nontechnical Loss:

According the 2017 statistics,

The average selling price is taken as 16.26 Rs/kWh

Additional revenue that could gain through accurate billing:

Additional annual energy	= 31,387,080 kWh
Average selling rate of electricity	= 16.26 Rs/kWh
Additional revenue benefit	= 31,387,080 × 16.26
	= 51,035,392.80 Rs
	= **510.354 MRs.**

ii. For the Technical Loss:

According the 2017 statistics,

The average cost of electricity (energy cost excluding capacity cost) is taken as 14.00 Rs/kWh.

Possible annual energy saving	= 16,705,320 kWh
Average cost of electricity	= 14.00 Rs/kWh
Additional energy cost benefit	= 16,705,320 × 14.00
	= 233,874,480 Rs
	= **233.874 MRs.**

The total annual financial benefit for CEB from minimizing nontechnical and technical losses = 744.228 MRs.

4.4 Discussion

The minimization of losses associated in single phase energy meters were assessed by considering two types of energy meters. One is the existing electromechanical energy meter and the other is the electronic energy meter, which is used by utilities in developed countries.

4.4.1 Consumer Load Analysis:

When considering energy measurement, the main variable component that affects is the load current. Therefore, when selecting measuring equipment, the working range of the meter is very important because, the equipment must be suitable to work in the region where it is calibrated to. For an example in 5(40)A electronic energy meter, the basic current is 5A for which the meter is calibrated to. That means it is more suitable to use where average current flowing through the meter is around 5A.

In the Sri Lankan context, single phase consumers have a very low average current. A summary of average load current statistics extracted from load profiles taken from Dunagaha area for this study is shown below.

Table 4-7 Average Load Current Statistics for Consumer Categories

No.	Consumer Category	Load Current (A)	
01	Less than 60 kWh	Mean	0.326
		Maximum	**4.214**
		Minimum	0.016
		Std. Deviation	0.517
02	Between 60 kWh & 90 kWh	Mean	0.584
		Maximum	**4.217**
		Minimum	0.009
		Stan. Deviation	0.541
03	Between 90 kWh & 120 kWh	Mean	0.762
		Maximum	**3.935**
		Minimum	0.120
		Stan. Deviation	0.513
04	Between 120 kWh & 180 kWh	Mean	1.109
		Maximum	**5.278**
		Minimum	0.122
		Stan. Deviation	0.757
05	Greater than 180 kWh	Mean	2.114
		Maximum	**8.417**
		Minimum	0.504
		Stan. Deviation	1.567

Form the above table it can be noted that the maximum load current does not exceed the 10A for any consumer taken for the study (Note that Dunagaha area represents a semi urbanized area in the country). The mean current of larger consumer categories

02 and 03 is around 1A, which means the average current that goes through most of the single phase energy meters used in Sri Lanka is around 1A. So, the question arises that, whether the correct energy meters are being used to measure domestic or small consumers.

4.4.2 Results Analysis:

The methodology used in this study was meant to model the losses involved in single phase energy meters as accurately as possible.

Loss due to accuracy error (nontechnical loss):

The gap between losses due to accuracy error in electromechanical energy meter and the electronic energy meter is large. There are two possible reasons for this,

- The electromechanical meter has been calibrated to a basic current of 10A and the electronic meter has been calibrated to a basic current of 5A. When studying the load statistics, it is clear that the most suitable meter out of these two meters is the electronic energy meter because its calibration point is close to the average current flowing through the meter than the electromechanical meter.
- When comparing the sensitivity of the two energy meters, it is clear that the electronic meter which uses latest technology has a higher sensitivity than the electromechanical meter.

Loss due to meter power consumption (technical loss):

The loss due to meter power consumption in electromechanical energy meter is somewhat lower than expected. The power consumption of the electronic meter is around 0.4W whereas it is around 0.8W in the electromechanical meter which is still within the IEC standards. The possible reason for this is most of the power is used in electromechanical energy meter is to produce rotational torque for the disc. However more recent designs use materials with lower weight and low-friction forces giving better performance.

CHAPTER 5

5. CONCLUSIONS

This study reveals some important facts about losses associated with single phase energy meters. It shows clear evidence regarding superiority of electronic energy meters for single phase applications.

Non-technical loss:

- One of the main reasons for non-technical loss is improper selection of calibration point of energy meters. The study clearly shows that the best suited calibration point of basic current is 5A, for single phase energy meters in Sri Lanka.
- The study quantifies that the annual additional energy that can be accounted from single phase energy metering in Sri Lanka is 36.5 GWh.

Technical Loss:

- The study assessed the total annual energy saving that could be achieved by using single phase electronic energy meters is 19.5 GWh.

Financial Benefit:

- The annual financial benefit that CEB can gain by using single phase electronic energy meters is 744.2 million LKR.

5.1 Recommendations

Energy metering in a power system is done at different voltage levels and in different capacities. In this study, losses were assessed only in single phase energy metering in the distribution network in Sri Lanka. However, to develop the total picture, it is necessary to study all other measuring systems of electrical energy. Other measuring systems include low voltage three phase energy measuring systems and high voltage measuring systems which involve losses in measuring transformers and meters.

5.2 Study Limitation and Suggestions for Future work

The methodology used in assessing accuracy and power consumption was based on three dimensional modelling. The intended quantity (accuracy error and power consumption) depends on two variables; current ratio and power factor. The data received from standard tests carried out is for two power factors only. Therefore, values in between is found using interpolation of existing figures assuming the variation to be linear.

It is recommend to carry out the tests in order to obtain the exact values of intended quantities by varying the current ratio and power factor both at the same time.

6. REFERENCES

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Appendix I:

Test Report for Accuracy Error of Electromechanical Energy Meters

For Power Factor = 1.0, te table shows the error in %

Current	Meter 1	Meter 2	Meter 3	Meter 4	Meter 5	Meter 6	Meter 7	Meter 8	Meter 9	Meter 10	Meter 11	Meter 12	Model Meter
Imax	-0.1	-0.4	-0.2	-0.8	-0.4	-0.4	-0.4	-0.4	-0.4	-0.6	-0.2	-1	-0.44
3.5Ib	-0.4	0.2	0.4	0	0.2	0	0.2	0.2	0.2	0	0.2	-0.4	0.07
3Ib	0.2	0.4	0.6	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.4	0	0.38
2.5Ib	0.4	0.6	0.8	0.4	0.6	0.4	0.4	0.6	0.4	0.4	0.4	0	0.45
2Ib	0.4	0.6	0.8	0.4	0.6	0.4	0.4	0.8	0.4	0.4	0.2	0	0.45
1.5Ib	0.4	0.6	0.6	0.4	0.6	0.2	0.4	0.6	0.4	0.4	0.2	0	0.40
Ib	0.2	0.2	0.4	0	0.2	-0.2	0	0.2	-0.2	0.2	-0.2	-0.4	0.03
0.8Ib	0	0	0.2	-0.2	0	-0.4	-0.2	0	-0.4	0	-0.6	-0.6	-0.18
0.6Ib	-0.4	-0.2	-0.2	-0.6	-0.4	-0.8	-0.6	-0.4	-0.8	-0.4	-0.8	-0.8	-0.53
0.4Ib	-0.8	-0.6	-0.6	-1.2	-1	-1.2	-1	-0.6	-1.4	-0.8	-1.2	-1.2	-0.97
0.2Ib	-1.2	-0.8	-1	-1.4	-1.4	-1.6	-1.6	-1	-1.8	-1.2	-1.6	-1.6	-1.35
0.15Ib	-1.2	-0.8	-1	-1.4	-1.4	-1.6	-1.6	-1	-2	-1.2	-1.6	-1.6	-1.37
0.11Ib	-1	-0.6	-0.8	-1.2	-1.2	-1.4	-1.4	-1	-1.6	-1	-1.2	-1.2	-1.13
0.09Ib	-0.8	-0.4	-0.6	-1	-1	-1.2	-1.2	-0.8	-1.4	-0.8	-1	-1	-0.93
0.07Ib	-0.6	0	0	-0.6	-0.4	-1	-1	-0.6	-1	-0.4	-0.8	-0.6	-0.58
0.05Ib	-0.2	0.8	0.8	0	0.4	-0.2	-0.6	0	-0.4	0.4	0	0	0.08

For Power Factor 0.5 Lagging

Current	Meter 1	Meter 2	Meter 3	Meter 4	Meter 5	Meter 6	Meter 7	Meter 8	Meter 9	Meter 10	Meter 11	Meter 12	Model Meter
Imax	-0.8	-0.6	-0.2	-0.4	-0.4	-0.4	-0.2	-0.6	0	-1	0.4	-0.8	-0.42
3.5Ib	-0.2	0	0.2	0	0.2	0	0.2	0	0.2	-0.4	0.8	-0.4	0.05
3Ib	0.2	0.2	0.4	0.2	0.4	0.2	0.2	0.2	0.4	-0.2	0.8	-0.2	0.23
2.5Ib	0.4	0.2	0.4	0.4	0.4	0.2	0.2	0.2	0.2	-0.2	0.8	-0.2	0.25
2Ib	0.4	0.2	0.4	0.4	0.4	0	0	0.2	0	-0.2	0.6	-0.2	0.18
1.5Ib	0.4	0	0.2	0.2	0.4	-0.2	-0.2	0	-0.2	-0.4	0.4	-0.4	0.02
Ib	0	-0.4	-0.4	-0.4	-0.2	-0.8	-0.8	-0.4	-0.8	-0.6	-0.2	-0.8	-0.48
0.8Ib	-0.4	-0.6	-0.6	-0.8	-0.4	-1	-1	-0.6	-1.2	-1	-0.6	-1	-0.77
0.6Ib	-0.6	-1	-0.8	-1	-0.8	-1.4	-1.4	-0.8	-1.6	-1.2	-0.8	-1.2	-1.05
0.4Ib	-1	-1.2	-1.2	-1.4	-1.2	-1.6	-1.6	-1	-2	-1.4	-1.2	-1.6	-1.37
0.2Ib	-1.2	-1	-1	-1.4	-1.2	-1.6	-1.8	-1	-2	-1.4	-1.2	-1.4	-1.35
0.15Ib	-0.8	-0.6	-0.8	-1.2	-0.8	-1.4	-1.6	-0.8	-1.8	-1	-0.8	-1	-1.05
0.11Ib	-0.6	0	0	-0.6	-0.2	-0.8	-1.2	-0.2	-1.2	-0.4	-0.2	-0.4	-0.48
0.09Ib	-0.2	0.6	0.6	0	0.4	-0.4	-0.8	0	-0.6	0.2	0.4	0.2	0.03
0.07Ib	0.6	1.6	1.8	0.8	1.4	0.4	-0.2	1	0.6	1.2	1.4	1	0.97
0.05Ib	1.8	1.4	0	0.2	-1	1.8	1	0.2	1.4	0.4	0.6	0.2	0.67

Appendix II:

Statistical Report: % Accuracy Error of Electromechanical Meter 3D Surface Fit Model for Current Ratio 0.05 to 0.15.

ank 30 Eqn 1067 z=(a+bx+cx^2+dy+ey^2+fy^3)/(1+gx+hy+iy^2+jy^3)

r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.9941119219	0.9910129334	0.0632018368	375.18823158

Parm	Value	Std Error	t-value	95.00% Confidence Limits		P>|t|
a	0.224751975	0.90351004	0.248754264	-1.65993694	2.109440893	0.80609
b	-0.17180691	1.547040821	-0.11105519	-3.39887751	3.055263699	0.91268
c	-0.00227448	1.00250212	-0.0022688	-2.09345726	2.088908302	0.99821
d	-0.29791589	37.74964121	-0.00789189	-79.0422876	78.44645582	0.99378
e	-7.50967975	369.8169123	-0.02030648	-778.934241	763.9148815	0.98400
f	-62.7565709	1289.07343	-0.04868347	-2751.71663	2626.203486	0.96165
g	0.001398244	0.546758342	0.002557335	-1.13911967	1.141916159	0.99798
h	-29.4073016	9.17053546	-3.20671587	-48.5367034	-10.2778998	0.00443
i	286.0143819	139.6083158	2.048691586	-5.20346182	577.2322257	0.05384
j	-815.294365	800.6946876	-1.01823376	-2485.51422	854.9254854	0.32073

X at Fn Zmin	Y at Fn Zmin	Fn Zmin
1	0.15	-1.367798946

X at Fn Zmax	Y at Fn Zmax	Fn Zmax
0.5	0.0663166479	0.9519631315

Procedure

GaussElim

r^2 Coef Det	DF Adj r^2	Fit Std Err
0.9941119219	0.9910129334	0.0632018368

Source	Sum of Squares	DF	Mean Square	F Statistic	P>F
Regr	13.488111	9	1.498679	375.188	0.00000
Error	0.079889443	20	0.0039944722		

Total 13.568 29

Description: % Accuracy Error for I/Ib 0.05 to 0.15 of Electromagnetic Energy Meter

X Variable: Power Factor

Xmin: 0.5 Xmax: 1 Xrange: 0.5

Xmean: 0.75 Xstd: 0.1737020834

Y Variable: I/Ib Ratio

Ymin: 0.05 Ymax: 0.15 Yrange: 0.1

Ymean: 0.094 Ystd: 0.0349975369

Z Variable: % Accuracy Error

Zmin: -1.366666667 Zmax: 0.9666666667 Zrange: 2.3333333333

Zmean: -0.38 Zstd: 0.6840044364

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Appendix III:

Statistical Report- % Accuracy Error of Electromechanical Meter 3D Surface Fit Model for Current Ratio 0.15 to 4.

Rank 11 Eqn 310 z=a+bx+cy+dx^2+ey^2+fxy+gx^3+hy^3+ixy^2+jx^2y

r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.9856016484	0.9829837663	0.0771713759	425.9260134

Parm	Value	Std Error	t-value	95.00% Confidence Limits		P>|t|
a	-2.22575173	1.169991894	-1.90236509	-4.56952713	0.118023672	0.06227
b	0.582294657	4.835933465	0.120409981	-9.10524417	10.26983349	0.90459
c	1.738396818	0.230578243	7.539292496	1.276493093	2.200300544	0.00000
d	-1.0673e-13	6.53685325	-1.6327e-14	-13.0948906	13.0948906	1.00000
e	-0.40323078	0.058280814	-6.91875689	-0.51998128	-0.28648028	0.00000
f	0.350968984	0.491785772	0.713662339	-0.6341963	1.336134269	0.47840
g	5.38143e-14	2.890496168	1.86177e-14	-5.79035962	5.790359621	1.00000
h	0.023507219	0.007478278	3.143400047	0.008526428	0.03848801	0.00267
i	-0.13921982	0.045008888	-3.09316288	-0.22938346	-0.04905618	0.00309
j	-4.1467e-15	0.302942537	-1.3688e-14	-0.60686683	0.606866826	1.00000

X at Fn Zmin	Y at Fn Zmin	Fn Zmin
0.5	0.2	-1.57055371

X at Fn Zmax	Y at Fn Zmax	Fn Zmax
1	2.2569798509	0.5792403993

Procedure

GaussElim

r^2 Coef Det	DF Adj r^2	Fit Std Err
0.9856016484	0.9829837663	0.0771713759

Source	Sum of Squares	DF	Mean Square	F Statistic	P>F

Regr	22.82912	9	2.5365688	425.926	0.00000
Error	0.33350359	56	0.0059554213		
Total	23.162623	65			

Description: % Accuracy Error of Electromagnetic Energy Meter for 0.15 to 4 I/Ib

X Variable: Power Factor

Xmin: 0.5 Xmax: 1 Xrange: 0.5

Xmean: 0.75 Xstd: 0.1720912102

Y Variable: I/Ib Ratio

Ymin: 0.2 Ymax: 4 Yrange: 3.8

Ymean: 1.7727272727 Ystd: 1.266678935

Z Variable: % Accuracy Error

Zmin: -1.366666667 Zmax: 0.45 Zrange: 1.8166666667

Zmean: -0.290530303 Zstd: 0.5969489491

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Appendix IV:

Statistical Report- % Accuracy Error of Electronic Meter 3D Surface Fit Model for Current Ratio 0.05 to 0.15.

Rank 30 Eqn 310 z=a+bx+cy+dx^2+ey^2+fxy+gx^3+hy^3+ixy^2+jx^2y

r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.9975562201	0.9962700202	0.0031421125	907.11590212

Parm	Value	Std Error	t-value	95.00% Confidence Limits		P>|t|
a	-0.69405119	0.081609475	-8.50454178	-0.86428558	-0.52381681	0.00000
b	0.344068483	0.304286909	1.130737055	-0.29066289	0.978799852	0.27154
c	8.510432876	0.92317356	9.218670516	6.584726575	10.43613918	0.00000
d	1.01956e-14	0.398421426	2.55901e-14	-0.83109253	0.831092531	1.00000
e	-52.5779274	7.978554249	-6.58990662	-69.2209	-35.9349549	0.00000
f	-2.26656848	1.185395352	-1.91207809	-4.73925986	0.206122892	0.07030
g	-4.6512e-15	0.174561804	-2.6645e-14	-0.36412954	0.364129542	1.00000
h	115.9591195	25.56452913	4.535938015	62.63244619	169.2857928	0.00020
i	6.885125184	3.099514607	2.22135594	0.41965101	13.35059936	0.03803
j	5.75592e-15	0.668363137	8.61196e-15	-1.39418107	1.394181073	1.00000

X at Fn Zmin	Y at Fn Zmin	Fn Zmin
0.5	0.05	-0.261503043

X at Fn Zmax	Y at Fn Zmax	Fn Zmax
1	0.15	-0.050129074

Procedure

GaussElim

r^2 Coef Det	DF Adj r^2	Fit Std Err
0.9975562201	0.9962700202	0.0031421125

Source	Sum of Squares	DF	Mean Square	F Statistic	P>F
Regr	0.080602543	9	0.0089558381	907.116	0.00000
Error	0.00019745742	20	9.8728708e-06		

Total 0.0808 29

Description: % Accuracy Error of Electronic Energy Meter for I/Ib 0.05 to 0.15

X Variable: Power Factor

Xmin: 0.5 Xmax: 1 Xrange: 0.5

Xmean: 0.75 Xstd: 0.1737020834

Y Variable: I/Ib Ratio

Ymin: 0.05 Ymax: 0.15 Yrange: 0.1

Ymean: 0.094 Ystd: 0.0349975369

Z Variable: % Accuracy Error

Zmin: -0.26 Zmax: -0.05 Zrange: 0.21

Zmean: -0.134 Zstd: 0.0527845327

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Appendix V:

Statistical Report- % Accuracy Error of Electronic Meter 3D Surface Fit Model for Current Ratio 0.15 to 4.

Rank 31 Eqn 5 z=a+bx+cy+dy^2+ey^3+fy^4+gy^5

r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.9623611801	0.957818564	0.0045664141	251.42175837

Parm	Value	Std Error	t-value	95.00% Confidence Limits		P>|t|
a	-0.20365901	0.005141119	-39.6137561	-0.21394637	-0.19337166	0.00000
b	0.114545455	0.003291243	34.80310003	0.107959693	0.121131216	0.00000
c	0.217176285	0.021189527	10.24922751	0.174776139	0.25957643	0.00000
d	-0.24949522	0.031472063	-7.92751409	-0.31247067	-0.18651977	0.00000
e	0.123813059	0.019311348	6.411414485	0.08517114	0.162454978	0.00000
f	-0.02745823	0.005153068	-5.32852123	-0.0377695	-0.01714697	0.00000
g	0.002218211	0.000495622	4.475608593	0.001226473	0.003209949	0.00004

X at Fn Zmin	Y at Fn Zmin	Fn Zmin
0.5	0.2	-0.111983558
X at Fn Zmax	Y at Fn Zmax	Fn Zmax
1	0.8466721052	-0.022086018

Procedure

GaussElim

r^2 Coef Det	DF Adj r^2	Fit Std Err
0.9623611801	0.957818564	0.0045664141

Source	Sum of Squares	DF	Mean Square	F Statistic	P>F
Regr	0.031456087	6	0.0052426812	251.422	0.00000
Error	0.0012302762	59	2.0852138e-05		
Total	0.032686364	65			

Description: % Accuracy Error of Electronic Energy Meter for Power Factor and I/Ib Ratio

X Variable: Power Factor

Xmin: 0.5 Xmax: 1 Xrange: 0.5

Xmean: 0.75 Xstd: 0.1720912102

Y Variable: I/Ib Ratio

Ymin: 0.2 Ymax: 4 Yrange: 3.8

Ymean: 1.7727272727 Ystd: 1.266678935

Z Variable: % Accuracy Error

Zmin: -0.13 Zmax: -0.02 Zrange: 0.11

Zmean: -0.060454545 Zstd: 0.0224246992

Date Time File Source

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Appendix VI:

Statistical Report- Power Consumption of Electromechanical Meter 3D Surface Fit Model.

Rank 20 Eqn 310 z=a+bx+cy+dx^2+ey^2+fxy+gx^3+hy^3+ixy^2+jx^2y

r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.894441827	0.8820232184	0.003244856	80.968515524

Parm	Value	Std Error	t-value	95.00% Confidence Limits		P>|t|
a	0.882033748	0.040003559	22.04888182	0.802509304	0.961558191	0.00000
b	0.002683168	0.167291838	0.016038848	-0.329882	0.335248336	0.98724
c	-0.0071271	0.007230441	-0.98570709	-0.02150074	0.007246544	0.32704
d	7.28021e-14	0.227486511	3.20028e-13	-0.45222822	0.452228217	1.00000
e	0.004626126	0.001826202	2.533195656	0.000995757	0.008256495	0.01312
f	-0.00079374	0.016311074	-0.0486624	-0.03321908	0.031631606	0.96130
g	-3.2257e-14	0.100773868	-3.2009e-13	-0.20033182	0.20033182	1.00000
h	-0.00017071	0.000245057	-0.69660479	-0.00065786	0.000316449	0.48793
i	-0.0046746	0.001502843	-3.11050529	-0.00766216	-0.00168705	0.00253
j	-7.6185e-17	0.010206162	-7.4646e-15	-0.02028918	0.020289178	1.00000

X at Fn Zmin	Y at Fn Zmin	Fn Zmin
1	4	0.8413326818

X at Fn Zmax	Y at Fn Zmax	Fn Zmax
1	0.05	0.8843207318

Procedure

GaussElim

r^2 Coef Det	DF Adj r^2	Fit Std Err
0.894441827	0.8820232184	0.003244856

Source Sum of Squares DF Mean Square F Statistic P>F

Regr	0.0076727232	9	0.0008525248	80.9685	0.00000
Error	0.00090550176	86	1.052909e-05		
Total	0.008578225	95			

Description: Power Consumption (W) for {Power Factor and I/Ib Ratio of Electromagnetic Meter

X Variable: Power Factor

Xmin: 0.5 Xmax: 1 Xrange: 0.5

Xmean: 0.75 Xstd: 0.1716790151

Y Variable: I/Ib Ratio

Ymin: 0.05 Ymax: 4 Yrange: 3.95

Ymean: 1.248125 Ystd: 1.3076707396

Z Variable: Power Consumption (W)

Zmin: 0.84 Zmax: 0.889 Zrange: 0.049

Zmean: 0.8763125 Zstd: 0.0095024789

Date	Time	File Source
Nov 22, 2018	8:57:14 PM	g:\research\energy meter losses\meter power consumption data\surface model for power for actual pf for em.xls

Appendix VII:

Statistical Report- Power Consumption of Electronic Meter 3D Surface Fit Model.

ank 32 Eqn 310 z=a+bx+cy+dx^2+ey^2+fxy+gx^3+hy^3+ixy^2+jx^2y

r^2 Coef Det	DF Adj r^2	Fit Std Err	F-value
0.215008594	0.1226566639	0.004627564	2.6172599463

Parm	Value	Std Error	t-value	95.00% Confidence Limits		P>|t|
a	0.429628747	0.057049999	7.530740593	0.316217101	0.543040392	0.00000
b	-0.00523397	0.238578754	-0.02193814	-0.47951284	0.469044891	0.98255
c	-0.02077751	0.010311498	-2.01498487	-0.04127609	-0.00027893	0.04703
d	3.37959e-14	0.324423767	1.04172e-13	-0.6449331	0.644933103	1.00000
e	0.006197278	0.002604388	2.379552205	0.001019925	0.011374631	0.01955
f	0.022368395	0.023261599	0.961601764	-0.02387413	0.068610923	0.33895
g	-1.5103e-14	0.143715941	-1.0509e-13	-0.28569783	0.285697834	1.00000
h	-0.00017453	0.000349481	-0.4993873	-0.00086927	0.000520219	0.61878
i	-0.00563371	0.00214324	-2.62859331	-0.00989432	-0.00137309	0.01015
j	9.09985e-17	0.014555243	6.25194e-15	-0.02893487	0.028934866	1.00000

X at Fn Zmin	Y at Fn Zmin	Fn Zmin
0.5	1.6229267464	0.4196001513

X at Fn Zmax	Y at Fn Zmax	Fn Zmax
0.5	0.05	0.4265405229

Procedure

GaussElim

r^2 Coef Det	DF Adj r^2	Fit Std Err
0.215008594	0.1226566639	0.004627564

Source	Sum of Squares	DF	Mean Square	F Statistic	P>F
Regr	0.00050442226	9	5.6046917e-05	2.61726	0.01009
Error	0.001841634	86	2.1414349e-05		
Total	0.0023460563	95			

Description: Power Consumprion of Electronic Meter for Power Factor and I/Ib Ratio

X Variable: Power Factor

Xmin: 0.5 Xmax: 1 Xrange: 0.5

Xmean: 0.75 Xstd: 0.1716790151

Y Variable: I/Ib Ratio

Ymin: 0.05 Ymax: 4 Yrange: 3.95

Ymean: 1.248125 Ystd: 1.3076707396

Z Variable: Power Consumption (W)

Zmin: 0.417 Zmax: 0.447 Zrange: 0.03

Zmean: 0.42534375 Zstd: 0.0049694395

Date	Time	File Source
Nov 26, 2018	8:38:41 PM	g:\research\energy meter losses\meter power consumption data\surface model for power for actual pf for electronic.xls

Appendix VIII:

Energy Delivered Statistics for the month of June 2018 of four Distribution Divisions.

Region	Customer Class	Tariff Interval	No of Customers	No of Units (kWh)
R1	D1	ZRO	299,533	322
	D1	LT030	216,230	4,345,891
	D1	LT060	363,239	19,059,254
	D1	LT090	332,501	27,433,704
	D1	LT120	162,102	18,309,379
	D1	LT180	115,406	17,785,667
	D1	MT180	58,056	19,668,974
	GP1	ZRO	55,604	135
	H1	ZRO	10	0
	I1	ZRO	8,828	3
	R1	ZRO	2,359	4
	R1	LT030	2,262	42,855
	R1	LT090	2,919	194,905
	R1	LT120	973	115,312
	R1	LT180	1,485	244,712
	R1	MT180	3,162	1,781,181
R2	D1	ZRO	106,891	418
	D1	LT030	282,666	5,025,906
	D1	LT060	524,739	25,776,105
	D1	LT090	507,067	39,785,105
	D1	LT120	250,092	26,943,990
	D1	LT180	161,718	23,815,562
	D1	MT180	50,102	12,891,931
	GP1	ZRO	37,166	87
	H1	ZRO	5	0
	I1	ZRO	1,882	0
	R1	ZRO	747	0
	R1	LT030	2,647	41,322
	R1	LT090	3,112	189,930
	R1	LT120	1,200	131,172
	R1	LT180	1,808	278,792
	R1	MT180	3,584	1,570,210
R3	D1	ZRO	75,828	127
	D1	LT030	202,447	3,662,491
	D1	LT060	342,010	16,653,107

	D1	LT090	273,924	21,407,302
	D1	LT120	125,130	13,519,659
	D1	LT180	79,019	11,764,244
	D1	MT180	30,186	8,542,207
	GP1	ZRO	19,586	53
	H1	ZRO	2	0
	I1	ZRO	926	1
	R1	ZRO	570	1
	R1	LT030	1,675	25,131
	R1	LT090	1,721	104,556
	R1	LT120	551	60,957
	R1	LT180	836	128,216
	R1	MT180	1,500	611,002
R4	D1	ZRO	48,019	25
	D1	LT030	135,848	2,384,846
	D1	LT060	251,257	12,410,029
	D1	LT090	248,685	19,594,261
	D1	LT120	123,688	13,358,952
	D1	LT180	79,205	11,726,975
	D1	MT180	33,821	9,795,080
	GP1	ZRO	16,090	17
	H1	ZRO	0	0
	I1	ZRO	688	0
	R1	ZRO	209	0
	R1	LT030	1,116	17,423
	R1	LT090	1,284	77,409
	R1	LT120	459	50,285
	R1	LT180	755	116,928
	R1	MT180	1,612	758,696