Designing a Remote Monitoring System for Improving the Reliability of Distribution Feeders in Sri Lanka

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Abstract— *In urban areas feeder pillars are used to sub distribute Low Voltage (LV) underground distribution feeders emerging from distribution transformers or ring main units. Each feeder pillar consists of several three phase sub feeders and each phase is protected by a fuse. Currently, there is no proper mechanism to monitor the LV distribution network and usage of an industrial monitoring solution would be costly. Therefore, it is problematic for the utility to be aware of a localized power failure or any other undesirable condition in the LV network useless a consumer complains. This reduces the reliability performance of the utility due to increased amount of downtime. A low cost monitoring unit has been proposed in this research which has the capability of monitoring electrical power related parameters such as voltage, current, active power, power factor and the condition of the fuses of a feeder pillar in order to make the utility be aware of the present situation of the LV distribution network. The monitoring unit mainly comprises of ADE7758 three-phase energy metering IC, Arduino Mega, fuse condition detection circuits, and a GPRS gateway to transmit measured parameter values periodically to a central server using TCP. A TCP server was developed to collect data asynchronously from multiple monitoring devices, validate received data and store in a database. To view the data graphically, a HTTP server was developed to display collected feeder pillar data, estimate transformer loads on the Medium Voltage (MV) side, indicate faults in feeder pillars and transformers and to calculate standard reliability parameters. Any faults identified can then be attended to immediately to improve the reliability metrics of urban distribution systems in Sri Lanka.*

Keywords— Reliability parameters, Remote Monitoring, GPRS, TCP server

I. INTRODUCTION

In Sri Lanka, electrical power generated from power plants is transmitted through the national grid which consists of two operating voltages: 220 kV and 132 kV. Then, power is distributed among the consumers through the widespread Medium Voltage (MV) and Low Voltage (LV) distribution network. The 220 kV network carries power from hydro power stations to main load centres while the 132 kV network interconnects the Grid substations (GSS) around the country, which steps down 132 kV to 33 kV feeders. In urban areas, Primary substations (PSS) step down 33 kV to 11 kV feeders which are distributed either as overhead lines or underground cables. In urban areas, such as Colombo, 11 kV feeders are arranged in a ring architecture unlike in suburbs or rural areas where feeders are radially distributed.

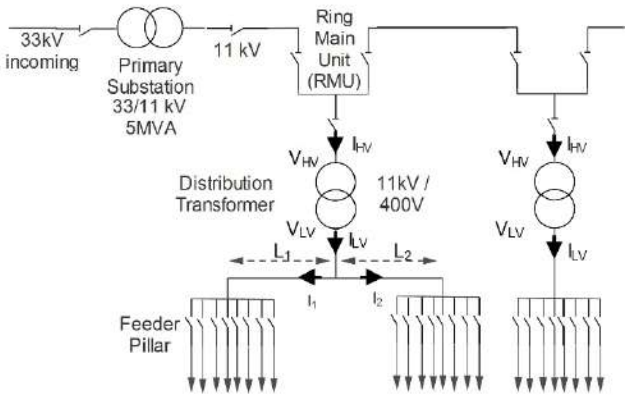


Figure 1. MV and LV distribution Architecture

In an underground distribution system, Ring Main Units (RMU) are placed along MV feeders to isolate the ring and as well as to distribute power to LV side. A RMU has 2 circuit breakers on either side and a transformer that steps down 11 kV to 400 V. These 400 V lines are then sent to feeder pillars which further distribute power using underground cables to the end consumer. Each LV feeder could serve several domestic consumers depending on their level of requirement.

A typical feeder pillar contains at most, seven outgoing three phase feeder lines. Each phase of feeder pillar is protected by a 160 A ceramic fuse. Currently, the distribution system of Sri Lanka has several problems related to the maintenance and meeting reliability standards. One such problem is not being able to identify faults such as a fuse being blown out in a transformer or a feeder pillar, immediately unless a consumer complains. Even if the customer complaints, utility cannot exactly determine whether the problem is with the fuse or a problem in the consumer installation without a site visit. Therefore, this increases downtime unnecessarily. Moreover, there are other power quality related issues such as over voltages, under voltages, voltage and current imbalances that are not monitored unless it is essentially required.

Another such issue is finding the MV loads for the usage calculation, but measuring MV loads directly is not economically feasible, as it requires costly current transformers.

Utilities constantly monitor certain reliability parameters in order to preserve the standard of the distribution system. Certain standard reliability metrics as given in IEEE distribution reliability standards are calculated periodically by utilities (IEEE Power and Energy Society, 2012). These parameters are used as the baseline for determining reliability of service provided to the consumer and currently these are calculated periodically and manually by obtaining past data from either a PSS or a GSS. This approach is time consuming and the level to which the reliability can be calculated is limited up to the level of PSS. Moreover, due to the massive amount of data that needs to be browsed through, this calculation becomes complex and requires special software.

This research aims at developing a cost-effective monitoring system for an upcoming underground LV feeder system in Sri Lanka to address the above-mentioned issues on MV and as well as LV side. The proposed solution consists of developing two components: An electronic remote monitoring device that can be installed on feeder pillars to monitor LV power parameters and transmit that data to a remote server through GPRS (General Packet Radio Service) and an open source server and database solution for collection, storing and processing data obtained from feeder pillars periodically. The objective of this solution is to improve the reliability through periodic remote monitoring which could be customized according to the needs of Sri Lankan utilities.

II. Methodology

Development process of the project initiated with the development of the monitoring unit. Once the initial circuits and Printed Circuit Boards (PCB) were tested, communication and server environments were developed.

A. Monitoring Unit

ADE7758 poly phase energy metering Integrated Circuit (IC) was used for the measurement of voltage, current and active power of the feeder pillar since it is a widely used IC for smart metering (Weranga, et al., 2014) .This IC can be connected to a Microcontroller Unit (MCU) through a Serial Peripheral Interface (SPI) bus for the calculation of real world voltage, current and active power parameters. MCU used for the developed prototype was Arduino Mega 2560, which based on an ATmega 2560 microcontroller. Figure 2 shows a block diagram of the monitoring unit used.

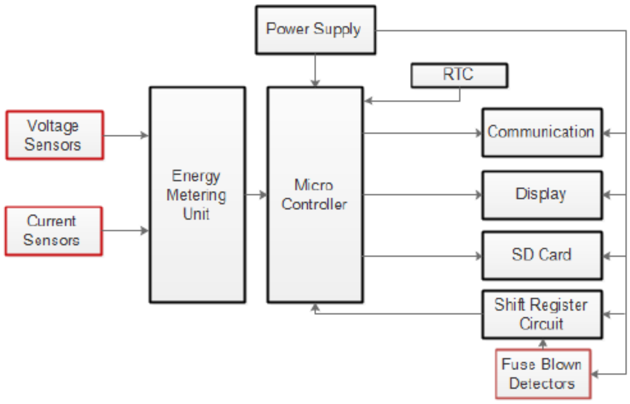


Figure 2. Block Diagram of the monitoring Unit

ADE7758 has the capability to measure the phase voltage 230 V AC that is connected to the IC via a voltage divider circuit, which limits the supply voltage to ±500 mV. It is also able to measure current by converting the current signal too to a voltage signal of ±500 mV through a burden resistor. To measure current, SCT 019 current sensor was used, which gives an output of 0-33 mA for a current of 0–200 A.

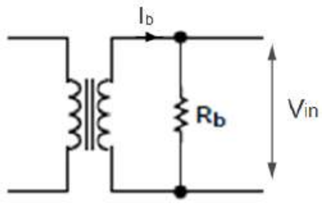


Figure 3. Equivalent circuit for current measurement

$$R_b = \frac{Vin}{Ib}$$

By performing the calculations using the equivalent circuit, a burden of 10.7 Ω was selected.

ADE 7758 IC provides its accuracy only for a selected range. For current measurement, IC gave an accuracy level of 0.5% (Guimaraes, et al., 2015). However, for voltage measured from the voltage divider circuit, the IC gave a tolerance of a 2%. Therefore, a Kalman filter was used to get an estimated reading when measuring voltages using the present reading and the previously estimated value.

A circuit was designed to determine the fuse conditions of feeders in the feeder pillar, which outputs 5 V if 230 V AC is detected after the fuse location and outputs 0 V if no voltage is detected. Since each feeder pillar consists of 21 such fuses, 21 detection circuits were required. Moreover, since it would render the PCB on which the MCU is mounted much larger in area and complex to connect 21 inputs, it was decided to use 3 daisy chained 8-bit shift register circuits. Three 74HC165N 8-bit parallelto-serial shift registers were used to reduce the 21 inputs to just 4 inputs. A standard GPRS gateway used by Sri Lankan utilities: TMAS T50 which has a RS232 serial data input was used for developing the prototype.

MCU was connected to the GPRS gateway using a TTL (Transistor Transistor Logic) to RS232 converter designed using MAX3232 level conversion IC because, the Arduino serial supports only TTL (0 V to +5 V), while the GPRS modem supports RS232 (-13 V to +13 V) voltage levels.

DS1307 Real Time Clock (RTC) was used to synchronize the MCU to the real-world time. The RTC provides the second during which the MCU needs to transmit data to the server. A Thin Film Transistor (TFT) display is placed in the monitoring unit to display the parameters in the feeder pillar such as voltage, current, power factor, active power and fuse status. A SD card module is connected with the MCU to permanently store the parameters measured by the metering IC within the monitoring unit itself as a backup.

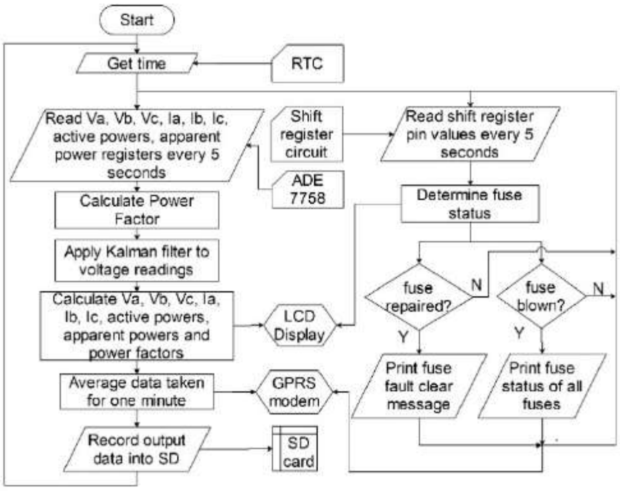


Figure 4. Algorithm developed for the parameter monitoring device

Every 5 seconds, parameters are measured from the ADE7758 IC and is averaged over a minute. Parameters measured are: three phase voltages (V_a, V_b, V_c), three line currents (I_a, I_b, I_c) and active power. Using these three parameters, line voltages (V_{ab}, V_{bc}, V_{ca}) and the average power factor (pf) is calculated. This process is illustrated in Figure 4. Every minute, the averaged parameters are transmitted as a single text string to the server using the GPRS gateway as shown in Figure 5.

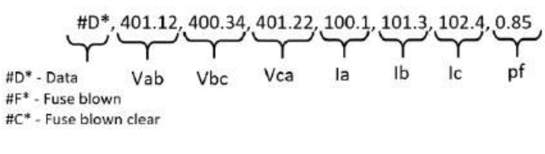


Figure 5. Structure of the text string generated every minute which is transmitted from the monitoring unit

Meanwhile, the monitoring unit is able to monitor the condition of each and every fuse by checking the bit pattern output of shift register circuit every 5 seconds. Fuse status is output as a "1" or "0", where "1" indicates fuse is operational and "0" indicates fuse is blown.

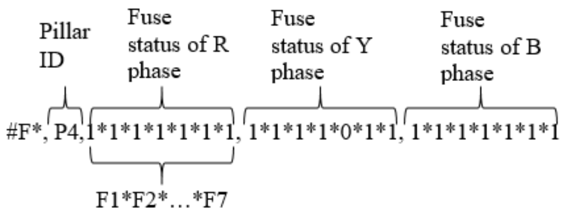


Figure 6. Message Format for a fuse blown indication

When a fuse is blown, the fuse detection circuit detects this due to absence of voltage and outputs a "0", which is detected by the MCU and at the moment of detection, it sends a message as shown in Figure 6 to the TCP server.

Main power requirements for the monitoring unit was a 12 V and a 5 V power supply. A power supply was designed to fulfil these requirements which would draw power from one of the incoming 230 V lines and a 7 Ah 12 V battery was used as a backup. 5V supply was necessary for the operation of ADE 7758, shift register IC where 12V supply was needed in MCU, GPRS and in making a reference voltage for the fuse blown circuits.

B. Communication and Server

Processed data from the monitoring unit is then transmitted to a server in a remote location using GPRS through TCP (Transmission Control Protocol) which ensures data packet delivery. Even though the standard monitoring period for smart metering and bulk metering is 15 minutes in Sri Lanka, since it is required to monitor sudden changes and indicate faults quickly, the monitoring time period was selected as 1 minute. A time period less than that was not required, since instantaneous changes in the distribution system is generally ignored and knowing any within a minute of occurrence is more realistic. Data is transmitted by the GPRS gateway as one data string per minute and the timing for this process is determined by reading time from RTC.

Two servers were developed for this system: TCP and HTTP (Hyper Text Transfer Protocol) server. TCP server is used to listen to all the communications from each and every monitoring unit connected to a feeder pillar and store data in a database once a data transmission is received. HTTP server is used to serve the stored data in a HTML based format to the user.

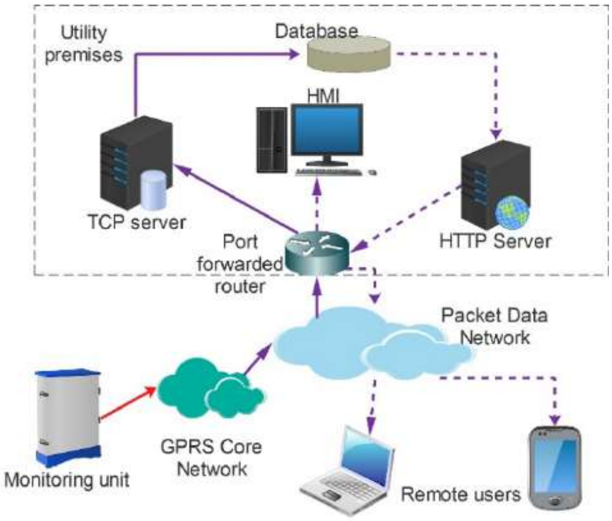


Figure 7. Architecture of the server and communication mechanisms

1)TCP Server: TCP server was programmed using Node.js due to reduced complexity of programming the server and its ability to asynchronously communicate with many clients at the same time. For the prototype system testing, the TCP server was hosted in a computer connected to a router, which had a static IP address. The server programme was programmed to listen on a specific port, which is not a commonly used port, by other programmes. In the router, port forwarding settings were set to direct all TCP traffic to the local IP address of the computer hosting the TCP server.

The database used for this system was MongoDB, to which, Node.js has native support. MongoDB is a document-oriented database and for each monitoring device, a document is created each hour and the TCP server stores data relevant to each device in the relevant document in the relevant minute (Ramesh D, 2016).

2) HTTP Server: The HTTP server was developed to represent and view the stored data in HTML format. This too was programmed using Node.js, AngularJS and Express.js which too are open source web technologies. The HTTP server was hosted on a different computer, which too was in the same network as the TCP server. The HTTP server serves several web pages to the users who are able to access the system using any device that has internet capabilities provided the user has necessary authorization. This HTTP server provides a platform independent, device independent and location independent service to the user and requires no further licensing. The whole server software provides several services.

C. Calculations performed by the server program

1) Estimation of transformer loads and voltages: Each transformer consists of at least one feeder pillar. Therefore, if the loads, voltages and the distance of the feeder of each of the feeder pillars from the transformer is known it is possible to estimate the load and voltage at the transformer. The TCP server has a separate routine, which checks for the load, voltage of the feeder pillar along with the cable distance and impedance per unit length of the cable, which connects each feeder pillar with the relevant transformer. Then, the routine calculates LV and MV load at each transformer along with the voltages by using the below relationships.

$$V_{TLV} = \frac{\sum_{i=1}^{i=n} V_i + \sqrt{3}\, L_i * R}{n} \tag{1}$$

Where;

V_{TLV} : Transformer Low Voltage side line voltage
V_i : Line voltage at the i^{th} feeder pillar
L_i : Length of the LV line connecting the transformer and the i^{th} feeder pillar in km
R : Line impedance of the LV line in Ω/km
n : Number of feeder pillars served by the transformer

The MV side voltage(V_{THV}) is approximated using the turns ratio of the transformer which is 11 kV / 400 V.

$$V_{THV} = \frac{11000}{400} V_{TLV} \tag{2}$$

Similarly, MV side loads can be approximated by accumulating the LV side current loads.

$$I_{TLV} = I_1 + I_2 + \cdots I_n \tag{3}$$

$$I_{THV} = \frac{400}{11000}\, I_{TLV} \tag{4}$$

Where;

I_{THV} : Transformer High Voltage side current
I_{TLV} : Transformer Low Voltage side current

2) Reliability Analysis of the MV feeders: IEEE distribution reliability standards provide definitions for several reliability analysing metrics and out of those, four major metrics were selected to be analysed by this research.

SAIDI (System Average Interruption Duration Index): This is a measure of total duration of interruption for the average customer.

$$SAIDI = \frac{Total\ consumer\ interruption\ durations}{Total\ consumers\ served}$$

$$SAIDI = \frac{\sum_{i=0}^{i=m} N_i T_i}{\sum_{i=0}^{i=m} N_i} \tag{5}$$

SAIFI (System Average Interruption Frequency Index): This shows how often the average customer experiences a sustained interruption.

$$SAIFI = \frac{Total\ consumer\ interruptions}{Total\ consumers\ served}$$

$$SAIFI = \frac{\sum_{i=0}^{i=m} N_i I_i}{\sum_{i=0}^{i=m} N_i} \tag{6}$$

CAIDI (Customer Average Interruption Duration Index): This indicates the average duration of interruptions per customer that had an interruption

$$CAIDI = \frac{Total\ consumer\ interruption\ durations}{Total\ consumer\ interruptions}$$

$$CAIDI = \frac{\sum_{i=0}^{i=m} N_i T_i}{\sum_{i=0}^{i=m} N_i I_i} = \frac{SAIDI}{SAIFI} \qquad (7)$$

ASAI (Average System Availability Index): This is the percentage of time a customer has received power during the reporting period.

$$ASAI = \frac{Total\ consumer\ minutes\ served}{Total\ consumer\ minutes\ in\ demand}$$

$$ASAI = \frac{\left(T_D \times \sum_{i=0}^{i=m} N_i\right) - \sum_{i=0}^{i=m} N_i T_i}{T_D \times \sum_{i=0}^{i=m} N_i} \qquad (8)$$

where;

- N_i : Number of consumers served by i^{th} transformer
- I_i : Number of failures sustained on i^{th} transformer during selected time period
- m : Total number of transformers on the selected feeder
- T_i : Time in minutes which the i^{th} transformer lost power during selected time period
- T_D : Total selected time period in minutes

III. Experimental design

A. Monitoring unit

The proposed monitoring unit was prototyped using the hardware components mentioned and the ADE7758 IC was calibrated to measure voltages up to 240V and currents up to 200 A.

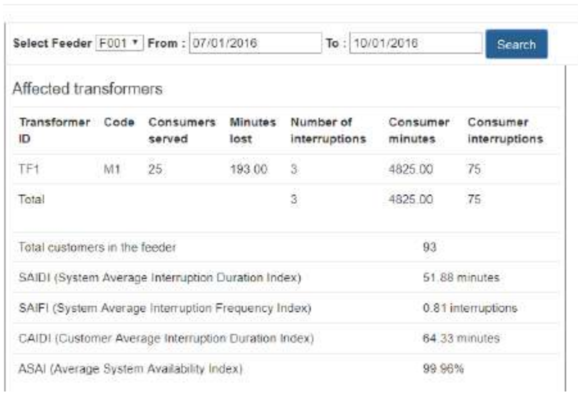
Figure 8. The developed prototype-monitoring unit and the TFT display

B. HTTP Server user interfaces

1) *Geographical view:* This is the main interface, which displays any selected MV feeder along with all the transformers and feeder pillars as markers on Google Maps API. It can be used to view the estimated LV and MV loads on transformers and to view the measured parameters and fuse conditions of each monitored feeder pillar. This view automatically refreshes its data and updates data on the map itself. Additionally, if the TCP sever detects any fault in a feeder pillar or a transformer, that fault too is immediately indicated on the map while triggering an alarm.

Figure 9. User interface of the main geographical view

2) Reliability parameter calculation: This interface provides the user the ability to calculate reliability parameters such as SAIDI, SAIFI, CAIDI and ASAI for a selected MV feeder. The user has to select a MV feeder, start date and an end date for which the parameters must be calculated. Then, the Node.js server program fetches all the power loss faults associated with each and every transformer that have lasted more than five minutes over the selected period along with the amount of consumers affected and the number of minutes each fault affects a set of consumers. Using these data, the programme calculates all the four reliability parameters using the equations.



Select Feeder F001 From : 07/01/2016 To : 10/01/2016 Search

Affected transformers

Transformer ID	Code	Consumers served	Minutes lost	Number of interruptions	Consumer minutes	Consumer interruptions
TF1	M1	25	193.00	3	4825.00	75
Total				3	4825.00	75

Total customers in the feeder	93
SAIDI (System Average Interruption Duration Index)	51.88 minutes
SAIFI (System Average Interruption Frequency Index)	0.81 interruptions
CAIDI (Customer Average Interruption Duration Index)	64.33 minutes
ASAI (Average System Availability Index)	99.96%

Figure 10. Reliability parameter calculation interface

IV. Discussion

The monitoring unit was calibrated against a standard panel meter: Siemens PAC 3100, which has an error of 0.01%. The proposed measuring unit was found to provide an error of only 0.5% for voltages greater than 40 V, currents and active powers. Due to the noise and interference between the components in the support circuit of ADE 7758 IC and due to the voltage divider input the voltage reading was less accurate. Therefore, a

Kalman filter was used to make the measured voltage value be closer to the actual value. The Kalman filter predicts the next value of the measurement using the previous predicted value and the measured value (Soliman, et al., 1997).

The monitoring unit and the server system can be even used for an overhead LV distribution system too, if the monitoring device is implemented at the transformer instead of the feeder pillar. Then, it is possible to directly monitor the transformers of the MV feeder and the only change required for the monitoring device is finding a current sensor such as a current transducer which can measure currents of higher magnitudes and some slight changes to the server programme.

This monitoring device is more sensitive for faults that persist more than a minute and an instantaneous fault might not be measured or even if it is measured, as 12 data points are taken within a minute and averaged, the effect of that measurement would be negated by the averaging function. Any fault that persists more than one minute, would be accurately indicated along with the location and the region which is affected by the fault. Therefore, the fault can be attended to immediately, which would drastically reduce the fault clearing time.

By the time this prototype was developed, underground infrastructure had not been completed and the monitoring unit was not field tested. Therefore, the monitoring unit physical design must be done in order to withstand severe weather conditions and harsh environments.

The TCP server used to collect data and the HTTP server used to view data is web based, which means there is always a higher risk of being subjected to cyber-attacks, for which there should be much stronger threat detection and prevention mechanisms along with proper access control mechanisms. The risk could be much higher for this type of a system because it uses open source technologies, which everyone has access to learn and use for malicious activities.

The TCP and HTTP server performances need to be tested when handling a large number of monitoring devices and when handling a larger number of viewing devices in order to get a proper understanding of the hardware and software optimizations that need to be done.

V. Conclusion

Through this project we were able to develop a three phase monitoring unit which can measure voltage, current and active power of a LV distribution feeder pillar with an error of 0.5%. It also can monitor the fuse condition of the feeder pillar indicating if the fuse is blown or not. We were able to develop a server and a database to collect data from monitoring devices and to store in a database. Unlike a usual SCADA system which requires expensive software and hardware, due to the usage of open source languages, there is no licencing cost for the server system and it provides platform independent performance which means that existing hardware can be used for accessing the system. Moreover, usage of open source software for server and as well as hardware embedded system programming, allows for customization of the system according to the needs of the utility thus enabling pathways for future expansion.

Acknowledgement

We wish to convey our gratitude to Dr. Narendra De Silva, Head of Engineering of Lanka Electricity Company Private Limited (LECO) for his valuable advice and guidance for making this research a successful. We also would like to thank Prof. J.R Lucas, Senior Lecturer in KDU for his valuable insights provided. Moreover, our sincere gratitude goes to Eng. Dasun Ranasinghe, who was assisted us in obtaining equipment and information from LECO.

References

Analog Devices, 2011. *Polyphase Multifunction Energy Metering IC with Serial Port ADE7758,* s.l.: Analog Devices.

Guimaraes, A., Fretias, T., Griner, H. & de Almeida, T., 2015. Smart energy monitoring system with ADE7758 IC. *2015 5th International Youth Conference on Energy (IYCE).*

IEEE Power and Energy Society, 2012. *IEEE Guide for Electric Power Distribution Reliability Indices,* New York: IEEE.

Ramesh D, S. A. S. S., 2016. *Data Modelling for Discrete Time Series Data Using Cassandra and MongoDB.* Dhanbad,India, IEEE.

Soliman, S., Abdel-Rahman, M. & EL-Hawary, M., 1997. Linear Kalman filtering algorithm applied to measurements of power system voltage magnitude and frequency: A constant-frequency model. *Canadian Journal of Electrical and Computer Engineering,* 22(4), pp. 145-153.

Weranga, K., Kumarawadu, S. & D, C., 2014. *Smart Metering Design and Applications.* s.l.:s.n.