ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

Design and Development of WCDMA-based Distribution Transformer Monitoring System

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Date of submission

Addis Ababa

This thesis has been submitted for examination with my approval as a university advisor.

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Advisor's Name *Signature*

Abstract

In electrical power systems, distribution transformer is an equipment which distributes power to the low-voltage users. For proper operation (i.e., under rated conditions) of the transformers, their operational conditions should be monitored and maintained. Overloading and overheating are two sources of transformers failure that cause power disruption for the customers and reduce the life time of the equipments on the power distribution system. Since it is very costly to repair or replace a single transformer, it also has its impact on the economy of the country. Hence, a system that properly monitors the power system and take corrective action should be in place.

This thesis presents the design and implementation of a Wideband Code Division Multiple Access (WCDMA) based distribution transformer monitoring system. This system monitors and records key parameters of a distribution transformer like load currents, load voltage, and transformer oil temperatures. These parameters provide useful information about the status of a transformer. The acquired parameters are processed and the data is sent to a central monitoring station through the WCDMA air interface. The data will then be further processed and analyzed each moment by the system operator. WCDMA has a very low latency which is best for real time systems. Besides that it provides a balance of trade-offs between cost, capacity, performance, and density.

The system is designed and implemented in a laboratory using Wi-Fi network and key parameters were recorded. The variations of the recorded values help us in identifying the possible failure that could occur, if the values are over the rated values. Monitoring of the transformer has been achieved in the laboratory through our system. Then, possibly corrective actions, like balancing the loads on each phase or even switching the transformer off, can be taken before the failures happen and we can identify the parts of the electric power distribution system which need stabilizing from the history we get. The latency of the WCDMA was also calculated. The maximum time of arrival of the data at the central station was found to be less than 100ms. Thus, this implemented system will help the utility to improve fault restoration time and optimally utilize distribution transformers for a longer period of time.

Key words: WCDMA, distribution transformer, monitoring

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Contents

Abstract i
Acknowledgment ii
List of Figures v
List of Tables vi
Abbreviations vii
1. Introduction 1
1.1. Overview of Power system 1
1.2. Ethiopian power system 2
1.3. Smart grid 6
1.4. Problem Statement 9
1.5. Research Objectives 9
1.5.1. General Objective 9
1.5.2. Specific Objectives 9
1.6. Research Methodology 10
1.7. Literature Survey 11
1.8. Contribution 13
1.9. Thesis Organization 13
2. Monitoring faults on distribution transformers 14
2.1. Key parameters to monitor 14
2.1.1. Current and voltage 14
2.1.2. Temperature 16
2.1.3. Transformer oil level 17
2.1.4. Harmonics 17
3. Communication technology and network options for distribution transformer monitoring system 20
3.1. Categories based on transmission media 20
3.1.1. Power line communication 20
3.1.2. Wired communication network 20
3.1.3. Wireless Network 21
3.2. Categories based on coverage area 21

3.2.1. Wide area networking technologies 21
3.2.2. Field area networks 22
3.3. Communication requirements 24
4. System architecture 26
4.1. Communication network design 26
4.1.1. Proposed communication network for DTMS in Addis Ababa 26
4.1.2. Benefits of WCDMA 27
4.1.3. Amount of network traffic generated 28
4.2. Prototype design 30
4.2.1. Microcontroller: Arduino YUN 32
4.2.2. LM335 Temperature sensor 34
4.2.3. Current Sensor: SCT-013-000 35
4.2.4. Voltage sensing circuit 36
5. Results and Discussion 38
5.1. Results of the proposed communication network 38
5.2. Results of the circuit evaluations 38
5.3. Discussion of the circuit evaluation 45
5.4. Limitations 45
6. Conclusions and future work 46
6.1. Conclusions 46
6.2. Future work 47
Appendix I: Arduino Code for Temperature Sensing 48
Appendix II: Arduino Code for Current and Voltage Measurement 50
Appendix III: Data Logging Code to Xively 51
Reference 55

List of Figures

Figure 1: Electric power system structure 2
Figure 2: Ethiopia's annual Gross Domestic Product (GDP) growth rate 3
Figure 3: The development witnessed in the electricity production and sales in Ethiopia 3
Figure 4: Smart Grid 7
Figure 5: Dragino 31
Figure 6: Concept of distribution automation system based on WCDMA communication system 31
Figure 7: Transmitting System Operation Flow Diagram 32
Figure 8: Receiver System Operation Flow Diagram 32
Figure 9: Arduino YUN 33
Figure 10: LM335 Temperature sensor 34
Figure 11: Schematic of a temperature sensing circuit 34
Figure 12: SCT-013-000 current transformer 35
Figure 13: current sensing circuit 36
Figure 14: Voltage measurement circuit 37
Figure 15: Temperature sensing circuit 39
Figure 16: Arduino monitor output of Temperature Reading 40
Figure 17: Temperature output at the remote Xively server 41
Figure 18: Current measuring circuit 41
Figure 19: Arduino monitor output for current reading 42
Figure 20: Current measurement Output at Xively server 43
Figure 21: Voltage measuring circuit 43
Figure 22: RMS voltage output on the Arduino serial monitor 44
Figure 23: RMS voltage output at the Xively Server 44

List of Tables

Table 1: The current power generation stations.. 4

Table 2: Transmission network distance by voltage level 4

Table 3: Number of substations 5

Table 4: Current distortion limits for general distribution systems (120V through 69000V)...... 18

Abbreviations

2G	Second Generation Mobile Networks
3G	Third Generation Mobile Networks
4G	Fourth Generation Mobile Networks
API	Application Programming Interface
BPL	Broadband over Power Line
CDMA	Code Division Multiple Access
CT	Current Transformer
DA	Distribution Automation
DMS	Distribution Management System
DS-CDMA	Direct Sequence CDMA
DTMS	Distribution Transformer Monitoring System
EDGE	Enhance Data rates for GSM Evolution
EPDS	Electric Power Distribution System
EV-DO	Evolution-Data Optimized
FDD	Frequency Division Duplex
GDP	Gross Domestic Product
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
HMI	Human Machine Interface
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
LAN	Local Area Network
NAN	Neighborhood Area Network

RF	Radio Frequency
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SIM	Subscriber Identity Module
SMS	Short Message Service
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
THD	Total Harmonic Distortion
UMTS	Universal Mobile Telecommunications System
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network

1. Introduction

Electric power systems are real-time energy delivery systems. Real time means that power is generated, transported, and supplied the moment it is needed. In power systems, distribution transformers are electrical equipments that distribute power to the low-voltage users directly. Their operational condition under rated condition, which guarantees their long life, is an important component of the entire distribution power system. Overloading and ineffective cooling are the major causes of distribution transformers failure resulting in unexpected loss of supply to a large number of customers ***[1].*** This eventually affects the systems reliability. Since it is very costly to repair or replace a single transformer, it also has its impact on the economy of the country. Therefore, a distribution transformer real-time monitoring system should be in place to detect most of the operating parameters, send to a monitoring centre in time.

The parameters can provide useful information about the health of transformers which will help the utility to optimally use their transformers and keep the asset in operation for a longer period. The sensed and collected data will first be sent through the WCDMA communication network. Then, the received data will be processed by the system operator to take corrective actions before failures occur. In addition, the history of the data measured will help the utility to plan ahead for cost saving and greater reliability of the distribution system.

1.1. Overview of Power system

Figure 1 shows the basic building blocks of an electric power system. The system starts with *generation*, by which electrical energy is produced in the power plant. High voltage power lines in the *transmission* portion of the electric power system efficiently transport electrical energy over long distances to the consumption locations. At the low voltage customer premises 11kv will be stepped down to 380V. At this voltage level of 380 V, generally 3-phase, 4-wire system is adopted for domestic connections. Residential buildings are supplied with single phase 220V, 50Hz.

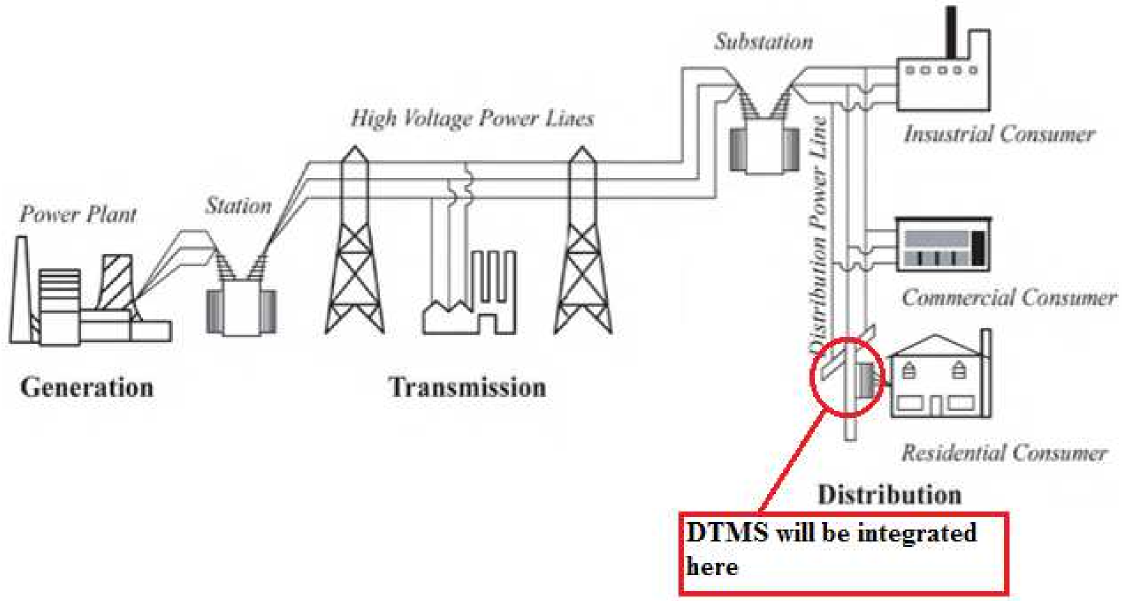

Figure 1: Electric power system structure *[2]*

1.2. Ethiopian power system

As shown in figure 2, the Ethiopian economy has been growing at double digit rate for the past decade. Growth in the industrial and commercial sectors has been even faster. This has caused rapid growth in electricity demand. It can be clearly seen in figure 3. In order to meet the growing demand, power supply has to expand as fast. Keeping the demand and economic growth in perspective, new power generation stations are being built with different kinds of sources and the old ones are being expanded. The current power generation stations are stated in table 1. With these developments of generation sites also comes the development of new electric power distribution networks. These electric power distribution networks consists of different power leveled wires and transformers ***[4][5].***

Figure 2: **Ethiopia's annual Gross Domestic Product (GDP) growth rate** *[5]*.

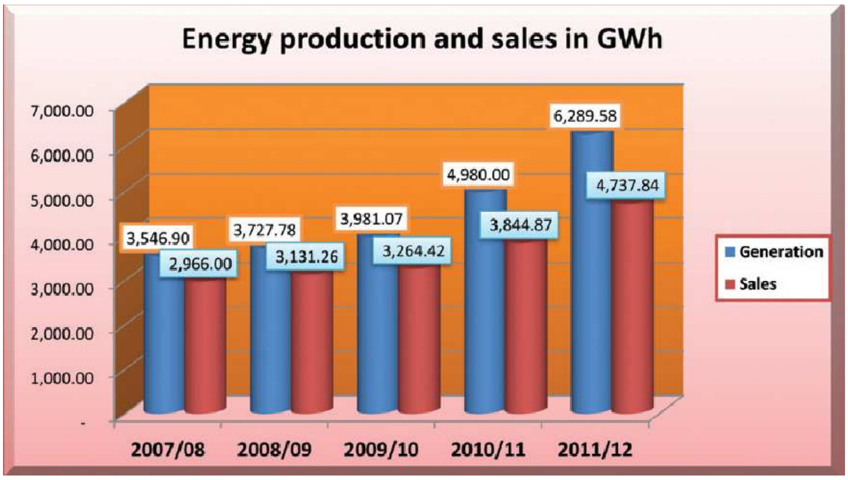

Figure 3: The development witnessed in the electricity production and sales in Ethiopia *[4]*.

S.No.	Stations	Capacity (MW)
1	Koka	42.00
2	Awash II	32.00
3	Awash III	32.00
4	Finchaa	134.00
4	Finchaa Amerit Neshe	97.00
5	Melka Wakena	153.00
6	Tis Abay I	11.40
7	Tis Abay II	73.00
8	Gilegel Gibe I	210.00
11	Dire Dawa	40.00
12	Awash 7 killo	35.00
13	Tekeze	300.00
14	Gilgel Gibe II	420.00
15	Beles	460.00

Table 1: **The current power generation stations**

In Ethiopia, the electric energy generated from the main hydro power plants is transported by high voltage transmission lines rated 45, 66, 132, 230, and 400 kV. The total length of the existing transmission lines is about 11,796.32 km as of 2012 G.C. The existing transmission lines status by voltage level is categorized as the following stated on table 2.

Electric power transmission network distance (km) by voltage level						
Year	**400kV**	**230kV**	**132kV**	**66kV**	**45kV**	**Total**
2007/08	-	2175.00	3983.25	2234.60	475.93	**8868.78**
2008/09	-	2175.00	3983.25	2234.60	475.93	**8868.78**
2009/10	211.38	2235.02	4170.69	2234.60	430.15	**9281.84**
2010/11	686.701	3550.90	4033.21	2234.60	475.93	**10981.34**
2011/12	686.701	4222.976	4658.471	1973.136	255.09	**11796.32**

Table 2: **Transmission network distance by voltage level**

Supply of the distribution network is provided by step down substations connected to the respective transmission voltages. Totally, there are 143 substations, of which 127 are supplying the distribution system the rest 16 are located by the power house areas (switch yards).The existing substations located in different areas of the country based on their voltage level are listed in table 3.

Number of substations by voltage level						
Year	**400kV**	**230kV**	**132kV**	**66kV**	**45kV**	**Total**
2007/08	-	12	55	30	23	**120**
2008/09	-	12	55	30	23	**120**
2009/10	2	12	55	30	23	**120**
2010/11	5	14	56	30	18	**123**
2011/12	5	17	57	30	18	**127**

Table 3: **Number of substations**

Power distribution in both Inter-connected system (ICS) and self contained system (SCS) is effected at a primary voltage of 33, 19, 15 and 11 kV, consisting entirely of 3-phases, 3-wire feeders, and is stepped down to a utilization voltage of 380/220 V (3-phase, 4-wire) using 3-phase transformers to customer's level. In Ethiopia in the year 2012, the distribution system consisted of 18,888 distribution transformers.

Keeping the above data in perspective, any kind of failure in the power system will affect the economy of the country as a whole. To better understand the effects caused due to failures let us look at the following data.

- Power outage level is reported to be 45 days per year in Ethiopia***.[3]***
- Power disruptions have serious economic impacts. One study estimates the lost output due to a one-day power cut to be between 10% and 15% of that day's GDP ***[7].*** But what may be even more detrimental is the fact that these frequent power cuts portray infrastructure services in Ethiopia to be unreliable discouraging both local and external investment.
- If we take the capital cities case, we have around 4500 distribution transformers; and one transformer costs around 350,000 birr/piece and a maintenance cost of 150,000 birr/piece,

which is high considering the economic status of our country. Therefore, wise management of these transformers is a necessity.

- ❖ One transformer provides connection to different small enterprises, especially in Addis Ababa. This implies that failure of one transformer will have a direct impact in the economy even if it may seem minor. This also has a direct influence on the large industries which get their input from those small enterprises.
- ❖ The failure of one transformer implies an outage of power for approximately 1000 people; which are totally unacceptable considering customer satisfaction.

Therefore, we need a means of monitoring the system on real-time to reduce the cost that the country should pay in order to keep the system working effectively. For this to happen we need to move to smart grids. One part of smarter grids is the ability of the utilities to monitor the main assets in the power system. Different causes of failures can be monitored and failures can be prevented using smart grid technologies. These technologies are cost effective, modern and smart ways which help in decreasing the power outages.

1.3. Smart grid

Smart grid is the application of digital processing and communications to the power grid, making data flow and information management central to the smart grid. A smart grid is an upgraded electricity network to which two-way digital communication between supplier and consumer, intelligent metering and monitoring systems have been added ***[12].*** The smart grid represents the full suite of current and proposed responses to the challenges of electricity supply.

Smart Grid is entitled to the next generation power systems. The smart control centers are expected to monitor and interact the electric devices remotely in real time; the smart transmission infrastructures are expected to employ new technologies to enhance the power quality; and the smart substations are expected to coordinate their local devices self-consciously. Enabled by the significant advancements in system automation and intelligence, the concept of Energy Internet has been proposed that envisions an exciting prospect of the future energy utilization paradigm throughout all the energy generation, storage, transmission, and distribution phases. As one of the enabling technologies, a fast, reliable and secure communication network plays a vital role in the power system management. The network is required to connect the magnitude of electric devices in distributed locations and exchange their status information and control instructions. The system-wide intelligence is feasible only if the information exchange among the various functional units is expedient, reliable and trustable.

Smart grids are expected to:

- ✓ Manage the power network more efficiently
- ✓ Create conditions for efficient use of electricity in transport through energy auditing
- ✓ Identify outages of transformers
- ✓ Provide event alarms
- ✓ Enhance energy efficiency
- ✓ Optimize management of the electricity grid
- ✓ Remotely diagnose and predict life time of assets
- ✓ Increase the reliability and sustainability of the power grid
- ✓ Boost technology development.
- ✓ To be flexible in network technology choice

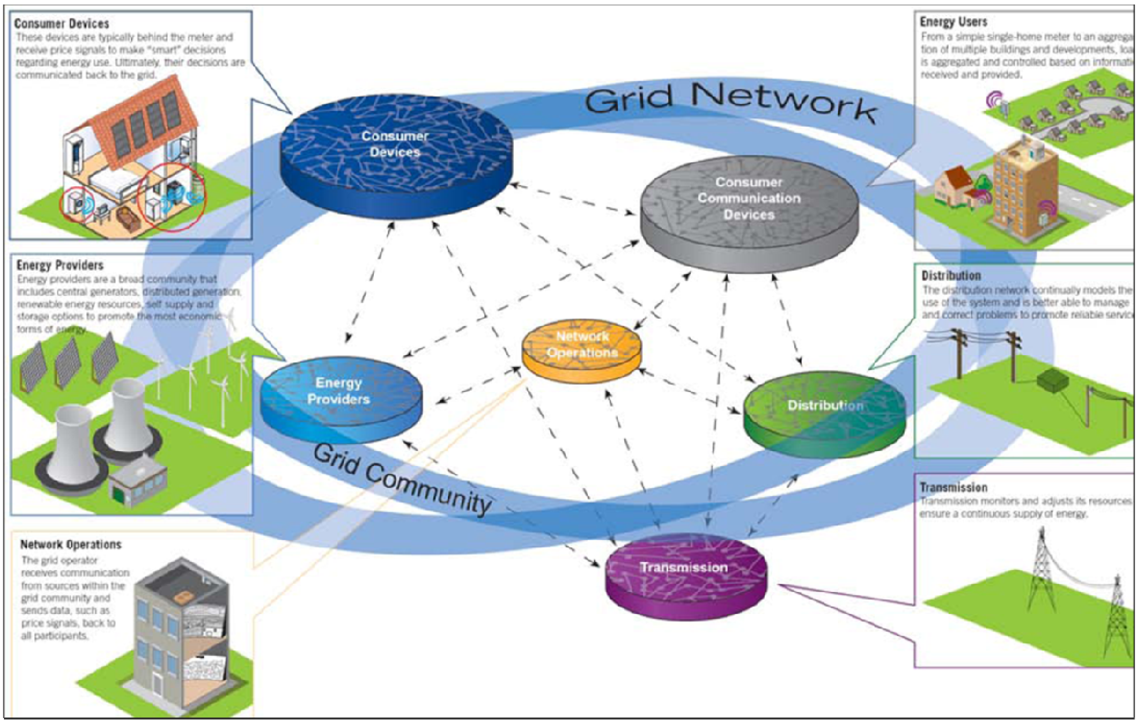

Figure 4: **Smart Grid** *[6]*

In the smart grid, many distributed renewable energy sources will be connected into the power transmission and distribution systems as integral components. The typical renewable energy sources include wind, solar, small hydro, tidal, geothermal, and waste. These sources generate extra electricity that supplements the electricity supply from large power plants and, when the electricity generated by distributed small energy sources exceeds the local needs, the surplus is sold back to the power grid.

Various capabilities result from the deeply integrated use of digital technology with power grids, and integration of the new grid information flows into utility processes and systems is one of the key issues in the design of smart grids. Communications systems play an important role in the electrical environment, such as the transmission of tele-control data from the power system to a remote control centre, voice and data communication between substations and the power generation plant, monitoring signals, alarms, remote surveillance, to mention a few ***[8].*** The communication requirements of electric utilities and other entities involved in the generation, transmission, and distribution of electricity are very important to dimension the required communications infrastructure and to support the applications of electric utilities and their consumers. One of the key technology areas of the smart grid is two-way communications, which allows for dynamic monitoring of electricity use as well as for the automated electricity use scheduling.

Generally, the smart grid is based on the concept that all components of the power grid are capable of communicating and supporting smart grid applications such as real-time energy consumption status, and remote controlling of appliances. To achieve this, the different subsystems that constitute the power grid have to be able to communicate with each other through a communications network. The adoption and use of standards-based networking technology brings a wide range of opportunities to the smart grid development. They enable electric utilities to integrate products from different vendors ensuring interoperability across intelligent electronic devices, networking technologies, and backhaul communication links endpoints. In addition, international, regional and national standards will enable the integration of equipment from multiple smart grid technology vendors.

1.4. Problem Statement

As it is stated above, electricity demand is growing in Ethiopia. Keeping the demand and economic growth in perspective, new power generation stations are being built in different areas and with different kinds of sources. With these developments of generation sites also comes the development of new distribution networks. But, with all this developments at hand we are not currently getting a satisfactory and continuous flow of electric power.

There are so many outages and frequent blackouts caused due to different factors. Examples of these causes include faults at power stations, damage to electric transmission lines, substations, power transformers or other parts of the distribution system, a short circuit, or the overloading of electricity mains.

When we specifically see the faults that occur in the distribution power transformers, it may be due to overheating, over loaded current or voltage. These failures of transformers have a wider impact not only on the power network but also on the country and its economy. The low voltage distribution transformers present in Ethiopia have no means of avoiding the faults before they happen or a faster way to repair the system. The only way used is field search by technicians after fault occurs. Therefore, the aim of this thesis is to develop a cost effective, modern and smart way to decrease the power outage which comes due to faults occurring on distribution power transformers and also increase the life time of the asset.

1.5. Research Objectives

1.5.1. General Objective

To develop a system that quickly diagnoses and resolves maintenance issues, improve fault restoration time, optimize asset utilization, predict remaining asset life, and achieve smart grid benefits previously out of reach is the general objective.

1.5.2. Specific Objectives

The specific objectives of the project are stated as follows:

- ✓ Monitor remote asset condition

- ✓ diagnose voltage and current problems
- ✓ monitor oil temperature
- ✓ Improve fault isolation time with line fault information
- ✓ set real time event alarming for temperature, overloaded current and voltage
- ✓ Improve revenue protection
- ✓ Utilization of an easy cost effective and state of the art wireless communication technology to transmit and receive real time data from the transformer

1.6. Research Methodology

In our research approach we used three methods – Identifying the problem clearly, literature review, and design and development - to investigate the research area and answer our research questions.

- **Identifying the problem:** In this research we 1st identified the existing problem in the power system of Ethiopia and gave more emphasis on those problems of the distribution power system. We then tried to address the issue of monitoring a distribution transformer and help in increasing the efficiency of the distribution system. Therefore, we identified the key parameters which are mainly affected when power system disturbances occur.
- **Literature review:** We identified the research gap and formulated a refined research goal. We knew more about the study area of the topic which we are going to research and learned from previous works done by other researchers in the area. In addition to this we gained better insight of our own research in relation to what has already been done.
- **Design and development:** In this thesis we designed a prototype for monitoring a transformer using WCDMA network. Since this study is not concerned solely about the creation of a prototype, we also made our work a factor that contributes to existing knowledge. The prototype is used to demonstrate the contribution of knowledge from the data gained in literature review and this part. In each step we used different software.
- **Analysis and interpretation** of the results and outcomes of the project was stated.

1.7. Literature Survey

There are different kinds of system developments, papers and thesis works done around this area. The Supervisory Control and Data Acquisition (SCADA) system has been developed since about 1998 and is implemented starting from generation up to substations level. But it is not used to monitor and control the status of distribution transformers due to its costly factor. Previous works on monitoring the distribution transformers status were mainly focused on GSM (Global System for Mobile communication) technologies and most stayed at the substation level.

In the journal of Energy and Power Engineering 7 (2013) 2181-2187, Samson et al. published a paper titled "Development and Implementation of GSM-Based Distribution Automation System with Graphic User Interface in Nigeria Electric Power Distribution Network." They developed a distribution automation system for Nigeria's electric power distribution network which mainly uses a GSM network for communication on the published paper. They stated that lack of up-to-date information on efficient operation and maintenance of electric power distribution systems (EPDS), Nigeria is addressed by designing and implementing an indigenous real-time monitoring and diagnosis system. Their system encompasses the development of software driven hardware positioned at the remotely located sub-stations at the low voltage level to keep track of the network in real-time. They achieved fault reporting time of 2 seconds. The developed system exhibits a high degree of accuracy and manifests no spurious reports during testing. They then concluded that the resultant system limited the effects of interruption and increases power availability by reducing the down time. The system strengthened engineering and management capabilities required to enhance reliability by providing information about the network health status. ***[9]***

In the thesis paper titled "Development of a novel fault management in distribution system using distribution automation system in conjunction with GSM communication" development and implementation of novel fault management at low voltage to enhance reliability of power for the consumers was focused on. The proposed fault management system is design based on GSM communication. Their system has been equipped with current sensor as field data interface devices, microcontroller as remote terminal unit, GSM as communication network, computer as master terminal unit and visual basic as human machine interface (HMI) software. A fault management strategy has also been designed to find out the fault location effectively without human intervention after a fault occurred. The laboratory results were compared with the simulation results to make the final conclusion on the functionality of the algorithm. This was published on International Journal of Smart Grid and Clean Energy, vol. 2, no. 3. ***[10]***

Choi et al. wrote a paper, "Communication system for DA using CDMA". They stated that a communication system plays an important role in distribution automation (DA) system, and various communication media have been applied to meet the utility's objective. They did develop a distribution automation technology using code division multiple access (CDMA) wireless communication network and showed its cost effectiveness and durability through the field test. Several system components for CDMA such as gateway, packet assembly disassembly and modem had been newly developed and their interfaces were standardized. Establishing a separate control channel for interworking function from central station, system reliability was significantly improved in the case of event processing. They finally have concluded that CDMA network would be applied to a small-scale DA system which could have a difficulty in constructing a communication network in an economic way, while fiber-optic cable would be applied to a large-scale DA system which needs high speed and reliability in a big city. ***[11]***

On another thesis paper published on the IOSR Journal of Electrical and Electronics Engineering titled "Microcontroller Based Substation Monitoring and Control System with GSM Modem", Amit Sachan designed a project to acquire the remote electrical parameters like Voltage, Current and Frequency and send these real time values over GSM network using GSM Modem/phone along with temperature at power station. Their project was also designed to protect the electrical circuitry by operating an Electromagnetic Relay. The Relay gets activated whenever the electrical parameters exceed the predefined values. The Relay can be used to operate a Circuit Breaker to switch off the main electrical supply. User can send commands in the form of SMS (Short Message Service) messages to read the remote electrical parameters. Their system also can automatically send the real time electrical parameters periodically (based on time settings) in the form of SMS. The system can be designed to send SMS alerts whenever the Circuit Breaker trips or whenever the Voltage or Current exceeds the predefined limits. ***[13]***

A survey of the related projects and papers shows that most of them use the existing GSM network to monitor transformers status at the substation level. In this thesis, we are proposing different network to monitor the health status of low voltage distribution transformers available in current Addis Ababa, which is a WCDMA based network which is due to the fact that GSM network is congested in present telecommunication network of Ethiopia.

1.8. Contribution

Presently in Ethiopia, we do not have any research done on the distribution power system nor any developed method or system of real-time monitoring and analysis of the health status of a distribution transformer. For this reason, we investigate ways to monitor these transformers and minimize the faults that occur on them, making the system more reliable. Also, from the researches we reviewed we saw that most of the systems and especially those deployed in few countries use GSM and other 2G (second generation) networks and make use of SMS. In our research we proposed a more advanced network which is WCDMA.

Furthermore, our research motivates the possibility to carry out an extensive research in the area of making the system much cheaper and utilizing the different advanced networking and communication technologies for monitoring the distribution system; and the role this could play on improving the reliability and efficiency of the distribution power system and making the grid smarter in the context of developing countries and their power source.

1.9. Thesis Organization

This thesis work consists of seven chapters. Chapter one gives the thesis work's introduction. Chapter two goes through distribution transformers and a brief summary of the key parameters and fault monitoring. Chapter three provides an in-depth explanation of the different communication and networking technologies that have a significant contribution in making the power system grid smart. Chapter four states the benefits we get from WCDMA networks. Chapter five provides the system architecture. Chapter six presents the results that we got from testing the system and discussions. Finally chapter seven concludes the thesis work and indicates future work.

2. Monitoring faults on distribution transformers

Distribution transformers have a long service life if they are operated under rated conditions. It is therefore, necessary to monitor the operating conditions and performance of these transformers in order to avoid or reduce disruption due to sudden and unexpected failure. The reliability of power distribution systems can be increased by using monitoring systems for transformers not only for high voltage power transformers but also for low voltage distribution transformers. Most power companies use the SCADA system for online monitoring of high voltage power transformers but extending the SCADA system for online monitoring of distribution transformers is quite expensive. Therefore, we need to develop a cost effective system that monitors the key parameters whose variations affect the distribution system.

Overloading (current or voltage) and ineffective cooling of transformers are the two major causes of failure in distribution transformers. Monitoring these key parameters is necessary for evaluating the performance of the distribution transformer and also helpful to avoid or reduce disruption due to sudden unexpected failure.

2.1. Key parameters to monitor

The parameters that need to be monitored include:

I) Current& voltage

II) Temperature

III) Oil level

IV) Harmonics

2.1.1. Current and voltage

In a transformer there are 3 main types of losses: copper loss, eddy current loss and hysteresis loss. These losses are dependent on input voltage, current and frequency. Therefore, in order to keep these losses at their lowest and keep them controlled we need to monitor them.

a. No Load Characteristics (hysteresis loss)

When there is no load connected to the transformer output, primary and secondary current (*Ip & Is*) are zero. However, there is still a small current drawn by the transformer from the supply. This current is required to magnetize the core in one direction, then the opposite, as the alternating current (AC) supply swings through a full mains cycle. This current is known as the *no load current (In)*.

The transformer core is subject to a loss mechanism known as hysteresis loss. This is the no load current or core loss (*Wcr*) ***[24].*** Under no load conditions both *Ip* and *Is* are zero thus change in secondary voltage (*ΔVs*) is zero while change in primary voltage (ΔVp) is only affected by *In* and is consequently small. For this reason the No Load Output Voltage is given by equation 2.1. Therefore, since this type of loss is part of the design of the transformer, monitoring the current value helps us to identify the change in output that occurs due to its design.

$$Vs = \frac{Vp * Ns}{Np} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (2.1),$$

Where *Np* is number of primary turns and *Ns* is number of secondary turns of the transformer

b. Coil Losses / Load Losses

When the transformer is on load, the secondary current (*Is*) flows in the load and the primary current (*Ip*) flows in the primary circuit of the transformer. Then, the coils of the transformer will dissipate power in a form associated with “Ohmic Heating”. The total coil losses will be given by $Wcl = (Ip^2 Rp) + (Is^2 Rs)$…………….. (2.2)

This loss applies at the room temperature. As the temperature of the transformer rises, both primary (*Rp*) and secondary resistances (*Rs*) will increase in value. The total transformer losses (*Wtotal*) are given by the sum of the core losses (*Wcr*) and the coil losses (*Wcl*).

$$Wtotal = Wcl + Wcr \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.3)$$

Therefore monitoring the current value will help us identify its effect on the rise of temperature.

c. Skin Depth Losses

When a current first starts to flow in a conducting wire, it initially flows in the outer surface of the conductor then gradually penetrates further into the bulk of the cross-sectional area. The lowest resistance the current sees occurs once the full cross-section of the conductor is being used to carry the current. If the rate at which the current starts and stops is faster than the time it takes to fully penetrate the conductor cross-section, then the effective resistance of the conductor is increased and the coil losses rise. Therefore the temperature will eventually rise and its heating effect will appear.

d. Eddy Current Losses

When conductor cross-sections become large then circulating currents start to be generated within the conductor itself. These currents are usually defined as a percentage of the load current and contribute to the self heating of coils by increasing the I^2R values. These currents reduce in magnitude as the temperature increases. Eddy currents are calculated by comparing the actual measured coil losses to the theoretical I^2R losses.

All these losses are dependent on current and voltage. They have an effect on increasing the resistances and eventually the temperature. Therefore, we need to keep the current and voltage changes in check to monitor and minimize their effect of over loading and overheating.

2.1.2. Temperature

The useful life of a transformer is determined partially by the ability of transformer to dissipate the internally generated heat to its surroundings ***[14].*** The ABB transformer standard C57.12.00 states that the ambient temperature shall average 30°C and the average winding temperature rise shall not exceed 65°C. This would mean the top oil will average 95°C in a 24 hour period and can reach 105°C at times. The comparison of actual and predicted operating temperatures can provide a sensitive diagnosis of the transformer condition and might indicate abnormal operation. The consequences of temperature rise may not be sudden, but gradual as long as it is within break down limit of the transformer. Among these consequences, insulation deterioration is so costly. The temperature rise (ΔT) of a transformer can be estimated by the following formula: $\Delta T = (Wtotal/A_T)^{0.833}$…………..(2.4)

Where *Wtotal* is the total transformer loss in mW and A_T is the surface area of the transformer.

In recent years, the use of non-linear loads has increased rapidly. Non-linear loads are for example battery chargers and other electronic devices which we use daily. Large, nonlinear loads have a significant impact on the temperature of a transformer as the current flowing through the system increases the heat. Under linear conditions, the current is only produced by the fundamental component, but under non-linear conditions, the current contains fundamental and harmonic components of higher order. As the harmonic components of the current become more significant, the *total harmonic distortion* (THD) increases. As a result the amount of current flowing through the transformer, under constant load, increases. This subsequently increases the temperature of the transformer.

2.1.3. Transformer oil level

The oil helps to cool the transformer. Because it also provides part of the electrical insulation between internal live parts, transformer oil must remain stable at high temperatures for an extended period. When temperature of transformer goes high, oil level in transformer tank decreases due to heating effect. If oil level decreases beyond required level, it affect cooling and insulation of the transformer. And this will indicate the life span of the transformer.

2.1.4. Harmonics

Power system harmonics is an area that is receiving a great deal of attention in recent days. This is primarily due to the fact that non-linear loads comprise of an ever-increasing portion of the total load. Examples of non-linear loads include common office equipment such as computers and printers, fluorescent lighting, battery chargers and also variable-speed drives. The increase in proportion of non-linear loads has prompted more stringent recommendations in Institute of Electrical and Electronics Engineers (IEEE) Std. 519 and stricter limits imposed by utilities. For example, table 1 shows the current distortion limits for general distribution systems described in Chapter 10 of IEEE 519-1992 ***[15].***

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc} / I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20 ❶	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 4: Current distortion limits for general distribution systems (120V through 69000V)

Where *Isc*= Maximum short-circuit current at point of common coupling (PCC)

TDD = Total demand distortion

L = Maximum demand load current at PCC and

PCC is the utility/customer connection point

The harmonic current limits change depending on the schort circuit current to maximum demand load current at PCC.

Incidence of harmonic related problems like harmonic related heating, malfunctioning of microprocessor based equipments etc. is low. But awareness of harmonic issues can help to increase power system reliability. High levels of power system harmonics can create voltage distortion and power quality problems **[15].** Reduction of harmonics is considered desirable.

One of the major effects of power system harmonics is to increase the current in the system. This effect can require special consideration in the design of an electric system to serve non-linear loads. In addition to the increased line current, different pieces of electrical equipment can suffer effects from harmonics on the power system. These effects of harmonics may be due to varying current or voltage.

a. Current harmonics

In a normal alternating current power system, the current varies sinusoidally at a specific frequency, usually 50 or 60Hz. When a linear electrical load is connected to the system, it draws a sinusoidal current at the same frequency as the voltage (though usually not in phase with the voltage). When a non-linear load is connected to the system, it draws a current that is quite complex. This depends on the type of load and its interaction with other components of the system. Regardless of how complex the current waveform becomes, it is possible to decompose it into a series of simple sinusoids, which start at the power system fundamental frequency and occur at integer multiples of the fundamental frequency. Under non-linear load conditions, the load current contains fundamental and harmonic components of higher order and can be expressed as:

$$I_l = I_{li} \sin \mathrm{w}_1 t + \sum_{h=3,5,7\ldots}^{\infty} I_{lh} \sin \mathrm{w}_\mathrm{h} t \ldots\ldots\ldots\ldots\ldots\ldots.. (2.3)$$

Where I_l is the load current

I_{li} is the fundamental load current

I_{lh} is the odd order h of current harmonic component

$w_1 = 2\pi f_1$

$w_h = h * f_1$

f_1 is the fundamental frequency

h=3, 5, 7, 9

b. Voltage harmonics

Voltage harmonics are mostly caused by current harmonics. A non-linear load will not directly cause voltage harmonics unless it is injecting power. However, the voltage provided by the voltage source will be distorted by current harmonics due to source impedance. If the source impedance of the voltage source is small, current harmonics will cause only a small voltage harmonics.

3. Communication technology and network options for distribution transformer monitoring system

Many network technologies can be used for communications in the distribution power system. But none of them suits all the needed qualifications for a distribution transformer monitoring application. There is always a best fit of a technology or a subset of technologies that may be chosen for this application, either operating in the same domain or having similar communication requirements ***[16].*** Communication technology is carefully chosen as well as a thorough analysis of the relevant enabling technologies is required to match the application requirements. The available network technologies may be categorized based on transmission media and area coverage.

3.1. Categories based on transmission media

3.1.1. Power line communication

The power lines are mainly used for electrical power transmissions, but they can also be utilized for data transmissions. The power line communication systems operate by sending modulated carrier signals on the power transmission wires. Data rates on power lines vary from a few hundred of bits per second to millions of bits per second, in a reverse proportional relationship to the power line distance ***[17]***. Typically data signals cannot propagate through transformers and hence the power line communication is limited within each line segment between transformers. Therefore this drawback makes it a less likely choice for distribution transformer monitoring.

3.1.2. Wired communication network

Dedicated wired cables can be used to construct data communication networks that are separate from the electrical power lines. These dedicated networks require extra investment on the cable deployment, but they can offer higher communication capacity and shorter communication delay. Therefore deploying wire line means of communication will not be favorable for developing a system of transformer monitoring. This is because it needs a cost effective means of communicating.

3.1.3. Wireless Network

Advancement in wireless networking technology has enabled us to connect devices in a wireless way, eliminating the installation of wire lines. Depending on the distance and area it covers, the wireless networks include satellite communications, Microwave radio, GSM, Wireless Local Area Network (WLAN), Wireless Fidelity (Wi-Fi), and others.

In general, wireless signals are significantly subject to transmission attenuation and environmental interference. By developing a means of filtering out the attenuation and interference effects, it is cost effective to deploy a wireless communication means to monitor transformers.

3.2. Categories based on coverage area

As the communication infrastructure connects an enormous number of transformers and manages the complicated device communications, it is constructed in a hierarchical architecture with interconnected individual sub-networks and each taking responsibility of separate geographical regions ***[18].*** The communication networks can be categorized based on coverage area into three main classes: wide area networks, field area networks, and home area networks.

3.2.1. Wide area networking technologies

Wide area networks (WAN) form the communication backbone to connect the highly distributed smaller area networks that serve the distribution power systems at different locations. When the control centers are located far from the distribution transformers, the real-time measurements taken at the devices are transported to the control centers through the wide area networks and, in the reverse direction, the wide area networks undertake the instruction communications from control centers to the devices ***[16].***

The WAN needs to be built up of high bandwidth fiber optics based telecommunication technologies, satellite or microwave technologies among many others.

3.2.1.1. Satellite

Satellite communication is a technology that has been used in electric utility networks to provide connectivity for SCADA and other applications such as data to remote substation sites that cannot be reached by other communications technologies. Deploying this means of communication is very costly. But, if the utility needs to centralize the nationwide power network of distribution transformers it can be used as a backbone network. Satellite networks can provide location and time synchronization based on a global positioning system (GPS).

3.2.1.2. Microwave

Microwave is a technology that is used in geographically difficult areas as an alternative transport technology for data applications. It can be used to create complete networks of distribution transformer monitoring systems found at distant rural and urban areas. And also, if there is no infrastructure available, the best solution is to install point-to-point microwave links.

3.2.2. Field area networks

Field area networks form the main communication facility for the electricity distribution systems ***[16].*** The electrical sensors on the distribution transformers form the main sources of information to be monitored by the Distribution Management System (DMS) at the control centers. The power system applications operating in the distribution domain utilize field area networks to share and exchange information. Field based applications are time sensitive in nature. Under field area networks the main network options are Local Area Network (LAN) and paging networks.

3.2.2.1. Paging networks

Paging networks are radio systems for delivering short messages from the transformer site to small, remote, mobile terminals. Paging systems use a variety of technologies like microwave and satellite as a backbone network. Like cellular systems virtually all of the paging networks use more than one transmitter to send a message over the entire paging service area to all base stations at a time. The main types of paging network are access Broadband over Power Lines (BPL), cellular, RF mesh and Worldwide Interoperability for Microwave Access (WiMAX).

a. Access BPL

Access BPL is a technology that carries broadband Internet traffic over medium voltage power lines. Access BPL systems carry high-speed data and voice signals over the medium voltage power lines from a point where there is a connection to a telecommunications network ***[21].*** This point of connection may be at a power substation or at an intermediate point between substations. This system can be used to provide electric utility companies with a means to more effectively manage their electric power distribution operations. Given that Access BPL can be made available in conjunction with the delivery of electric power.

b. Cellular (GSM/GPRS/CDMA)

GSM is the world's most popular technology for mobile telephone systems. GSM technology offers low-cost implementation of the SMS. Using the SMS function of a digital cellular network, it can be used to provide low-cost distribution transformer monitoring of its performance, when small amount of monitoring data is needed. Newer versions of the standard are General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE), for higher speed data transmission. **CDMA** is a cellular technology originally known as IS-95, where data and voice are separated from signals using codes and then transmitted using a wide frequency range. Because of this, there is more space left for data transfer for broadband access. **WCDMA** is an air interface standard found in 3G mobile telecommunications networks. It is sometimes used as a synonym for Universal Mobile Telecommunication Service (UMTS). It uses the Direct Sequence CDMA (DS-CDMA) channel access method and the Frequency division Duplexing (FDD) duplexing method to achieve higher speeds, reliability, security and to support more number of transformers compared to most time division multiple access (TDMA) and time division duplex (TDD) schemes used before.

c. RF MESH

RF Mesh is a technology that allows sensing devices to access the network by securely routing data via nearby devices. RF-based mesh networks have emerged as the leading Neighborhood Area Network (NAN) technology for smart metering applications ***[22].*** It can be expanded for use of distribution transformer monitoring. A mesh network forms a network topology by using mesh or star configurations. Any node not in direct communication range of its target destination will have its data relayed by another node in the mesh ***[23].*** New technologies based on RF mesh networking promise an ideal solution with high functionality and low cost.

d. WiMAX

WiMAX is a wireless technology that provides high-throughput broadband connections over long distances. It can be used as point-to-point or point-to-multipoint for providing mainly IP-based data-service of transformer monitoring. WiMAX can provide long distance communications beyond 16 km and in some instances beyond 48 km at data transfer rates of 75 Mbps. It can serve as the backbone of a transmission and distribution power system communication supporting Wi-Fi applications for monitoring.

3.3. Communication requirements

The communication infrastructure in distribution power system monitoring, which is part of the smart grid, undertakes important information exchange responsibilities. Unsatisfactory communication performance limits it from achieving its full energy efficiency and service quality. To protect the distribution transformers and ensure optimal operation, the communication infrastructure must meet the following requirements ***[19, 20].***

a. Data throughput and Network latency

Throughput is defined as the amount of data that must be transmitted, and at what rate, to meet a latency requirement. Network latency defines the maximum time in which a particular message should reach its destination through a communication network. The network architecture will determine if the message sent from one communicating entity to the other will reach its destination in one or more hops. This will directly affect the latency.

Similarly, the data rates supported by the communication medium also dictate how fast an entity can communicate an event observed or reply to a message received. Distribution transformer monitoring needs high throughput and low network latency.

b. Data delivery criticality

The protocol suite used for a distribution power system monitoring application must provide high level of data delivery criticality.

c. Reliability

In distribution transformer monitoring, it is extremely important for the communication backbone to be reliable for successful and timely message exchanges. The communication backbone reliability is affected by a number of possible failures. These failures include time-out failures, network failures, and resource failures. A time-out failure occurs if the time spent in detecting, assembling, delivering and taking action in response to a control message exceeds the timing requirements. A network failure occurs when there is a failure in one of the layers of the protocol suite used for communication. A resource failure implies failure of the end node which initiates communications or receives messages. Hence, there is a need to assess the reliability of the system in its design phase and find ways to improve it.

d. Security

In the future power systems, an electricity distribution network will spread over a considerably large area, e.g., tens or hundreds of thousand transformers in dimension. Hence physical and cyber security from intruders is of utmost importance. To provide security protection for the power systems, we need to identify various communication use cases and find appropriate security solutions for each use case.

e. Time synchronization

Distribution transformer monitoring system needs to be synchronized in time. The requirements for time synchronization of the system are critical. For example, any means of communication network has the strictest need of time synchronization as it provides a real-time measurement of electrical quantities (Temperature, voltage and current) from distribution transformers for analysis, measurement and control ***[19].***

4. System architecture

4.1. Communication network design

4.1.1. Proposed communication network for DTMS in Addis Ababa

Both wired and wireless communication technologies are possible deployment options for DTMS. Some of the relevant communication technologies are stated in the previous chapter. In certain situations wireless technologies have advantages over wired technologies, e.g., low cost, much faster to deploy and ease of connection. However, wireless networks suffer from high level of interference and signal attenuation.

On the other hand, wire line communication technologies are more reliable, less prone to interference, but very expensive to deploy especially if new infrastructure is required. Wireless technology is very attractive for DTMS deployment.

Especially, cellular network has several advantages for DTMS including increased capacity, reduced power use, large coverage area and reduced interference from other signals through spectrum reuse. The third and fourth (3G & 4G) generation technologies support higher data rates and faster service. And also cellular service is very attractive for use in the distribution network due to its widespread coverage.

Considering the data to be generated from the transformer site to be a maximum of 2kbit, we can compare the existing network based on their data rate and speed of delivery of the collected values to the monitoring center. GSM has a data rate between 9.6 and 14.4 kbps. WCDMA provides a data rate of up to 3Mbps for a fixed user. This shows us that, since we do not need that much of data rate, we can use GSM, WCDMA and all the other communication technologies in between their generations. But since we need a faster data speed, we should look at the time that the data will take to reach the server destination and get displayed. In the research paper published by Samson et al. *[9]*, they have achieved a fault reporting time of 2 seconds through GSM network. And considering our country Ethiopia, currently there are more than 28.5 million prepaid GSM mobile customers. Therefore adding a new network based on the same system will create more congestion than it has already been.

In addition, security issue is one consideration to choose a reliable network option for DTMS. WCDMA provides solutions to the weaknesses of GSM security. It consists of different security features. These are network access security, user domain security, and application domain security. Network Access Security provides the utility with secure access to WCDMA services and protect against attacks on the radio access link. User Domain Security provides secure access to monitoring unit at the transformer site. And **a**pplication Domain Security allows the secure exchange of messages and data between the monitoring unit and the controlling station. Visibility and configurability of security allows the operator at the controlling station to observe whether a security feature is currently in operation.

To deploy the DTMS system we need a communication network which is fast and reliable. Currently, ethio telecom has embarked on another massive telecom expansion project. Therefore, there will be enough unused free bandwidth available for future new services. 3G WCDMA network is one of the main networks being expanded. And taking some of the benefits listed above and in the section below, WCDMA network is proposed for the deployment of the monitoring system.

4.1.2. Benefits of WCDMA

To achieve the designed online monitoring system, we need an air interface which operates in a manner that is smart and fast. The available and expanding network relevant options in Ethiopia for DTMS are GSM and CDMA2000. The rationale of WCDMA over these networks is the followings:

- ✓ GSM is a 2G technology and WCDMA is a part of the newer 3G group of technologies. WCDMA offers much faster data speeds than GSM. Being newer and more advanced, WCDMA is now the technology that people want and it is slowly being deployed in a lot of areas that are already being occupied by GSM. Sooner or later, the WCDMA network would equal the coverage of GSM, making the GSM network redundant. With this said it is clear that the GSM network is slowly being phased out and replaced with the newer and better WCDMA.

- ✓ W-CDMA transmits on a pair of 5 MHz-wide radio channels, while CDMA2000 transmits on one or several pairs of 1.25 MHz radio channels. Though WCDMA does use a direct sequence CDMA transmission technique like CDMA2000, WCDMA is not simply a wideband version of CDMA2000. The WCDMA system differs in many aspects from CDMA2000. From an engineering point of view, WCDMA provides a different balance of trade-offs between cost, capacity, performance, and density.

4.1.3. Amount of network traffic generated

With the addition of a new system, the traffic demand increases. This demand and network utilization should be measured to estimate the future status of the network. Therefore, based on these estimates, the capacity of the network can be increased before any network congestion problem occurs due to the addition of another system. By measuring an estimate of the amount of network traffic generated, the operator can improve its services and prevent future congestion problems.

The traffic intensity offered by each monitoring unit is equal to the connection request rate multiplied by the holding time. That is, each user generates a traffic intensity of *Au* Erlangs given by

$$A_u = \lambda H \ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

Where *H* is the average duration of a connection and λ is the average number of connection requests per unit time for each unit. In a normal operation data is sent once in a day. The maximum holding time of the data network does not exceed two seconds. Therefore, each unit generates a traffic intensity of

$$A_u = \lambda H = (1/24*3600)*2 = 2.315*10^{-5} \text{ Erlangs}$$

Taking the 45 day/year average value of Ethiopia power system outage, we can approximate 3 hour maximum outage per day. This time of outage can happen twice or three times a day on average. Therefore, assuming fault occurrence to be four times a day, each user will generate $9.26*10^{-5}$ Erlangs.

For a system containing *U* units and an unspecified number of channels, the total offered traffic intensity *A*, is given as

$$A=UA_u \ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

With an approximate 4000 number of transformers in Addis Ababa, the offered traffic intensity will be of 0.0926 Erlangs in a normal operation and 0.3704 Erlangs in maximum faulty situation. This means that a radio channel is approximately occupied 22 minutes in an hour in faulty situations. This implies that higher load will occur on the network at the time the transformers data is collected. Therefore, by using less congested time of the day (may be after mid night) and different timing for each transformer, the data can be collected easily.

Furthermore, in a C channel trunked system, if the traffic is equally distributed among the channels, then the traffic intensity per channel, A_c, is given as follows.

$$A_c=UA_u/C \ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

When the offered traffic exceeds the maximum capacity of the system, the carried traffic becomes limited due to the limited capacity.

4.2. Prototype design

The system is comprised of both hardware and software components. An open source hardware and software interface is used to design the proposed system. The system performs three main functionalities.

1. Sense and collect data of the key parameters

   The data sensing unit consists of sensors, Arduino microprocessor and a Yun shield to monitor and transmit to the cloud server. This sensing unit is placed on the distribution transformer site. It monitors the transformers health condition like – temperature, voltage and current using the related sensors and sensing circuits. In normal operation the data is aggregated at the transformer site and sent once in a day. In faulty situations the data is generated automatically and sent.

2. Log the collected data to a cloud server

   Data sensed using the sensors is passed to the Arduino micro-processor. Arduino then receives the sensor data and logs it to Xively cloud server using the Xively API through the YUN shield. Data is logged to the server on certain interval of time that is set. The Arduino micro-processor that serves as a data logging unit is also responsible of executing sensor readings. This makes it serve as base station of the system. For our prototype we programmed data to be logged every second to simplify the process of evaluating the system at later times.

3. Make the logged data available for visual access.

   The sensor readings are continually uploaded to Xively cloud service and made available for access from any web browser using internet. We use Xively API service to feed our sensor data to channels we created on the cloud service. It is possible to view current sensor reading value both visually and numerically. The web application provides a graphical presentation of sensor readings over some period of time. It can range from current time up to three months of reading history.

Figure 5: **Dragino**

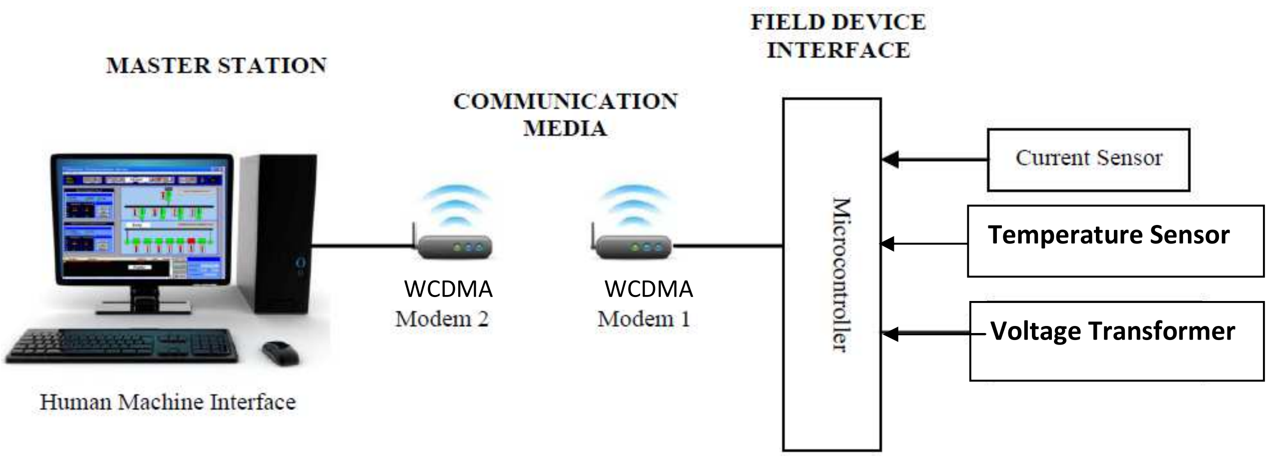

Figure 6: **Concept of distribution automation system based on WCDMA communication system**

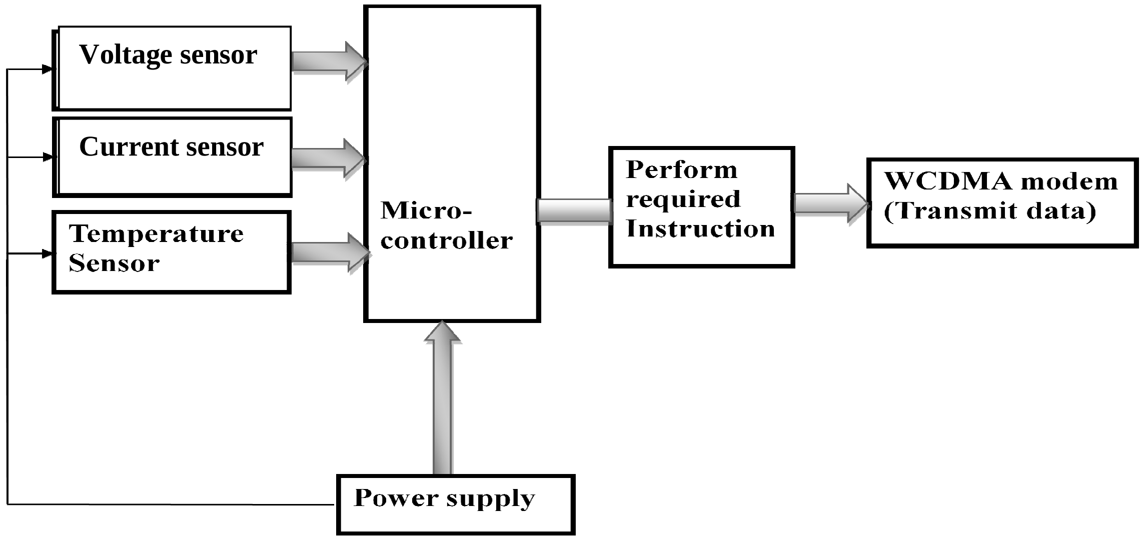

Figure 7: **Transmitting System Operation Flow Diagram**

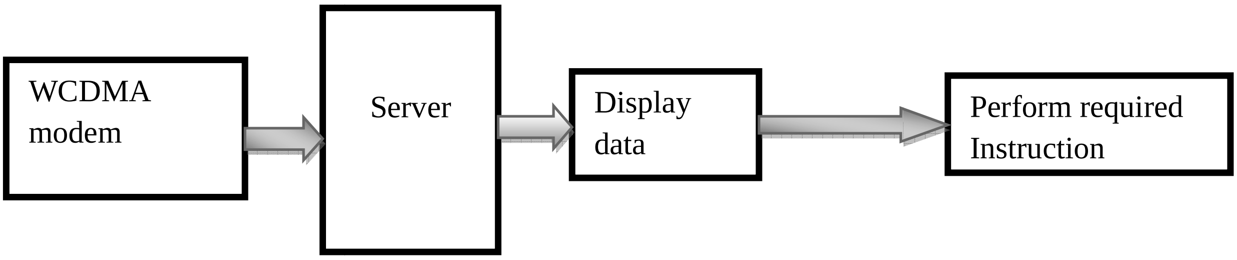

Figure 8: **Receiver System Operation Flow Diagram**

4.2.1. Microcontroller: Arduino YUN

Arduino is a tool for making computers that can sense and control more of the physical world than the desktop computer. It's an open-source physical computing platform based on a simple microcontroller board, and a development environment for writing software for the board. Arduino can be used to develop interactive objects, taking inputs from a variety of sensors, and controlling a variety of physical outputs. The ***Arduino Yún*** is a microcontroller board based on the ATmega32u4 and the Atheros AR9331.

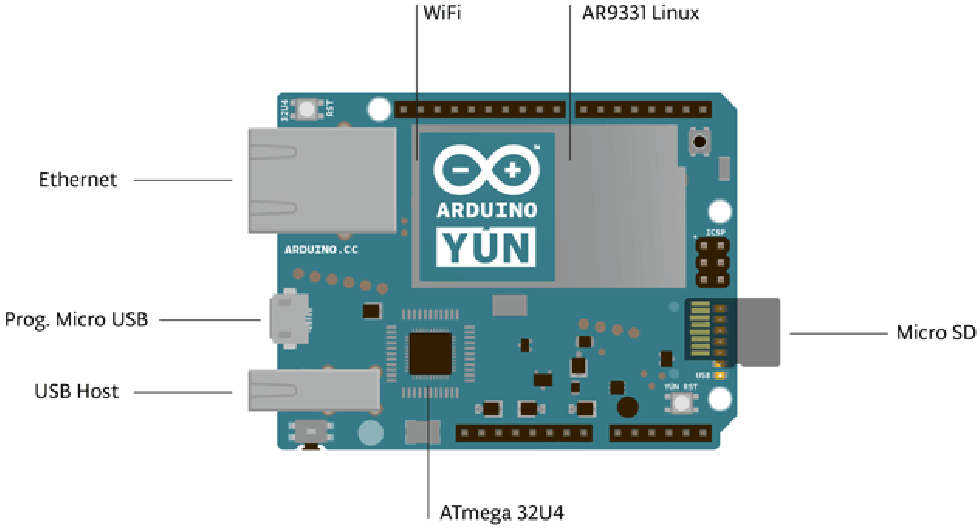

Figure 9: Arduino YUN

In summary the specifications are as follows

Microcontroller	ATmega32u4
Operating Voltage	5V
Input Voltage	5V
Digital I/O Pins	20
PWM Channels	7
Analog Input Channels	12
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (of which 4 KB used by bootloader)
SRAM	2.5 KB
EEPROM	1 KB
Clock Speed	16 MHz

4.2.2. LM335 Temperature sensor

The LM335 temperature sensor is an easy to use, cost-effective sensor with decent accuracy (around +/- 3 degrees C calibrated). It gives out the temperature in degrees Kelvin.

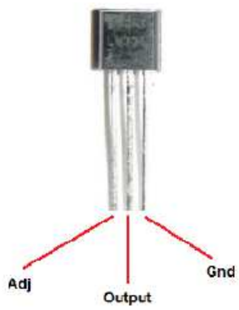

Figure 10: LM335 Temperature sensor

Pin 1 is the Adjustable Pin (Adj). This allows us to calibrate the temperature sensor if we want more precise temperature readout. It isn't required. Pin 2 is the output pin. We attach this pin to analog pin A0 of the Arduino board. We then take a 2KΩ resistor and connect that to the 5V terminal of the Arduino. Pin 3 is the ground pin and connects to the ground (GND) terminal of the Arduino.

Temperature Sensor Circuit Schematic

The temperature sensor circuit we will build is shown below:

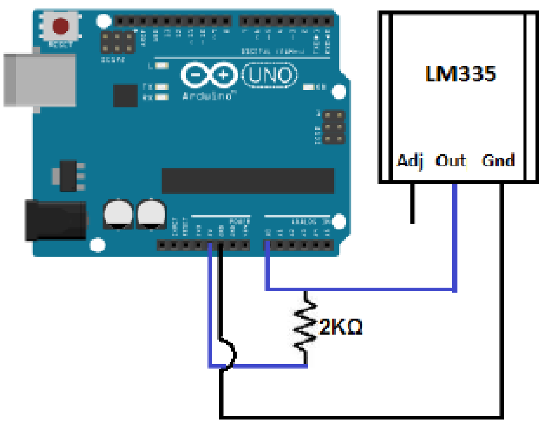

Figure 11: **Schematic of a temperature sensing circuit**

4.2.3. Current Sensor: SCT-013-000

Figure 12: **SCT-013-000 current transformer**

Current transformers (CTs) are sensors used to measure alternating current. The split core type is particularly suitable for monitoring use as it can be clipped straight on to either of the live or neutral wires coming out of a transformer without having to do any high voltage electrical work.

Specifications

- Input Current: 0~100A AC
- Output Mode: 0~50mA
- Non-linearity: ±3%
- Turn Ratio: 100A:0.05A
- Resistance Grade: Grade B
- Work Temperature: -25°C ~ + 70°C
- Dielectric Strength(between shell and output): 1000V AC/1min 5mA
- Leading Wire in Length: 1m
- Open Size: 13mm x 13mm
- Turns ratio: 2000:1

A current output CT needs to be used in conjunction with a burden resistor. A burden resistor completes (closes) the CT secondary circuit. The burden value is chosen such that it provides a voltage proportional to the secondary current.

CT Sensor Circuit Schematic

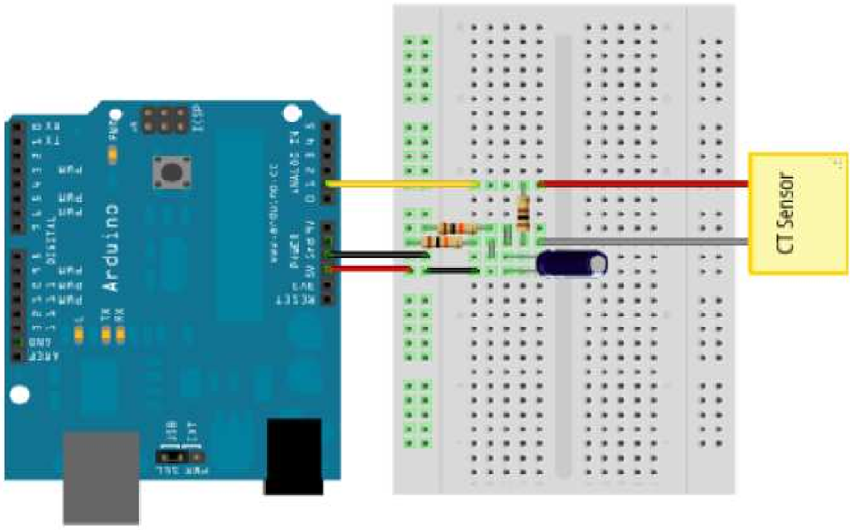

Figure 13: **current sensing circuit**

4.2.4. Voltage sensing circuit

This measurement can be made safely (requiring no high voltage work) by using an AC to AC transformer. The transformer provides isolation between the high and low AC voltage.

The output signal from the transformer is a near-sinusoidal waveform. For a 12V (RMS) transformer the positive signal peak should occur at +16.97V and the negative signal peak should occur at -16.97V. The voltage output of the transformer is proportional to the AC input voltage. The signal conditioning electronics needs to convert the output of the transformer to a waveform that has a positive peak that's less than 5V and a negative peak that is less than 0V and so we need to scale down the waveform and add an offset so that there is no negative component.

The waveform can be scaled down using a voltage divider connected across the transformer terminals and the offset (bias) can be added using a voltage source created by another voltage divider connected across the arduino's supply.

Below is the circuit diagram (left) and (right) the voltage waveforms:

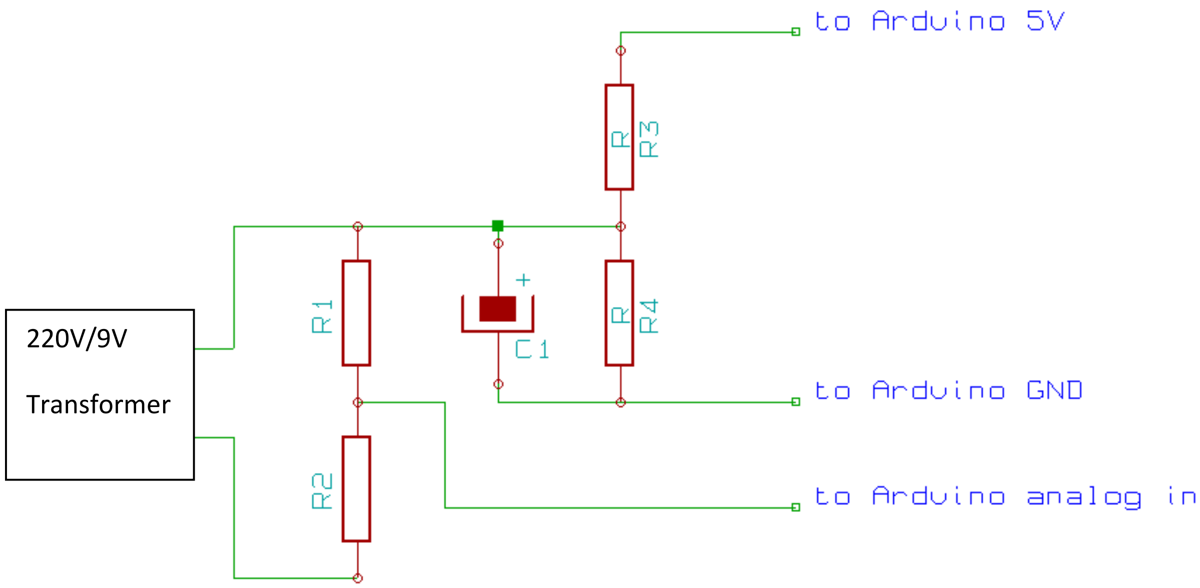

Figure 14: Voltage measurement circuit

Resistors R2 and R1 form the voltage divider that scales down the power adapter AC voltage and resistors R3 and R4 provide the voltage bias. Capacitor C1 provides a low impedance path to ground for the AC signal. For an AC-AC transformer with an AC 15.9V RMS output a resistor combination of 10k for R1 and 100k for R2 would give a suitable output:

$$\text{Peak-v-output} = R1/(R1 + R2)\ x\ \text{peak-voltage-input} = 10k/(10k + 100k)\ x\ 16.97V = 1.54 \ldots\ldots\ldots\ldots (4.3)$$

The voltage bias provided by R3 and R4 should be half of the Arduino supply voltage and so R3 and R4 need to be equal. Higher resistance lowers energy consumption. If the Arduino is running at 5V the resultant waveform of the circuit has a positive peak of $2.5V + 1.54V = 4.04V$ and negative peak of 0.96V satisfying the Arduino analog input voltage requirements and leaving plenty of room so that there is no risk of over or under voltage.

5. Results and Discussion

This chapter presents the results obtained from the proposed communication network and also the implemented prototype. We implemented the prototype in a laboratory level only. Even if our proposed communication network is WCDMA, we used a Wi-Fi network to implement it in the laboratory. To obtain the results we built the circuits and assembled them into one component. After assembling the parts and uploading the codes for the applications we were able to get results in the Xively website. Below, the results of each part are presented and discussed.

5.1. Results of the proposed communication network

In the laboratory we were able to upload the measured data to the online Xively cloud server in a gap of around 2 seconds by using Wi-Fi mesh network. This happened probably due to the fact that we are using a slow Wi-Fi connection, which may be a drawback, and a wired LAN network as a backbone network. But when we measure and quantify the proposed WCDMA network as a communication means, we will get a higher speed with lower latency.

The time that takes the whole system to report a fault on a transformer is dependent on the time it takes to process the data, log it to the modem and transmit it over the air interface. The microcontroller we are using has a maximum processing time of 2ms. The WCDMA network has a latency of 75ms for real time data. Therefore, considering the two and adding an error margin a data about any fault on the transformer can be transmitted to a controlling station in less than 100ms. Therefore, choosing a WCDMA network as a communication option is quite reasonable.

5.2. Results of the circuit evaluations

The designed Arduino-based system is capable of reading data on a one second interval of time and uploads it to Xively server. The sensed data is uploaded to a specific data stream using API (Application Programming Interface) key and feed ID of the data stream. The data is simply accessed at Xively.com. To access the data, the user should have the USERNAME and PASSWORD of the Xively account. The application does not allow a user access the system unless the user provides correct authentication information. This is important to keep the system secured and prevent an authorized access.

Average records of up to six months can be saved. However, it is important to note that we are using Xively just for demonstration but as a future work a specific database should be developed with its own server platform. This will be so helpful, since the utility needs long time data to work on identifying permanent issues (e.g. like increasing number of customers and their effects on the distribution system) to redesign and add assets to improve the capacity and performance of the distribution system.

The circuits we built are evaluated one at a time and we compiled them all together into one component. First, the sensing circuits were built. Each of these circuits was tested using a multi-meter and an oscilloscope. The temperature sensing circuit was our starting point. Secondly, we built the current measuring circuit. Finally, the voltage sensing network is built.

After building the circuit, we first saw the reading on the Arduino serial monitor. The readings were displayed each second. The temperature readings were displayed in Kelvin and Celsius scale. While, the voltage is displayed in volts and the current is displayed in Ampere. Then we uploaded the data to Xively server platform. At this point we were able to access the data both numerically and graphically. Each of the steps we took and the results we got are shown below.

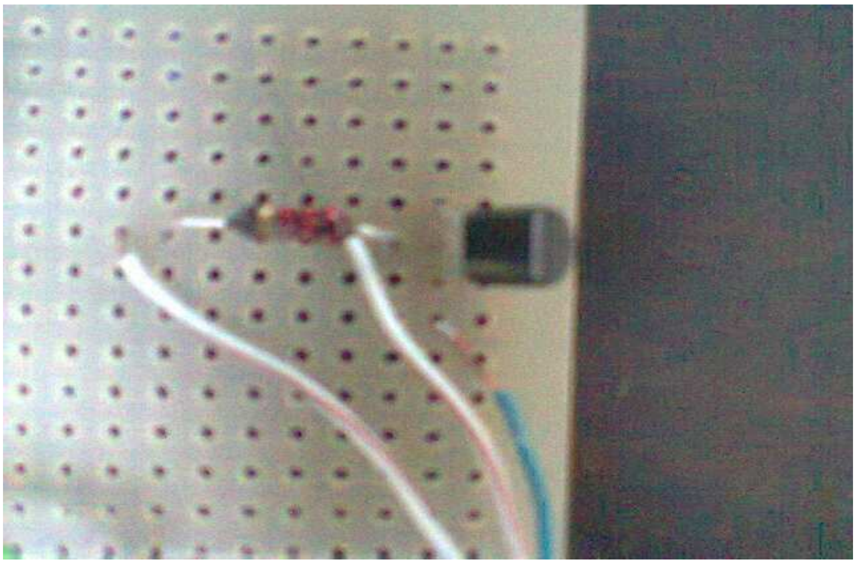

Figure 15: Temperature sensing circuit

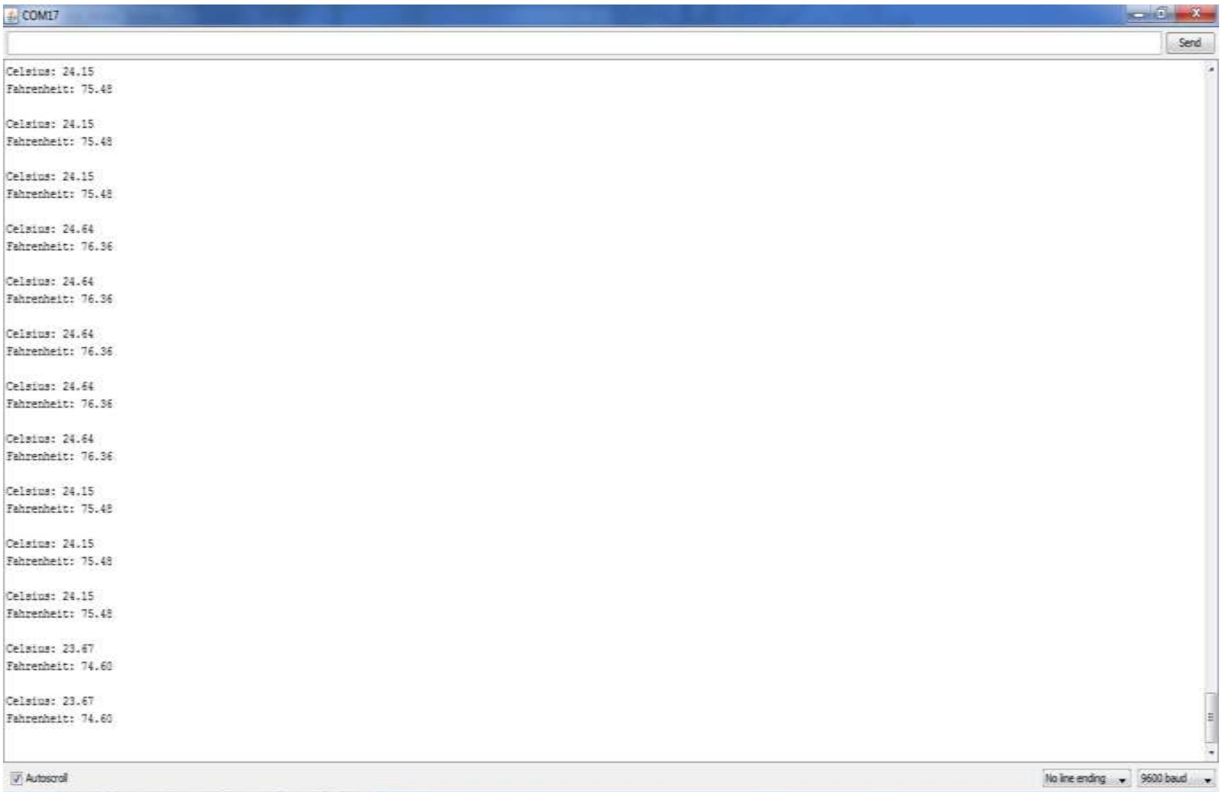

Figure 16: Arduino monitor output of Temperature Reading

In the transformer temperature changes occur due to different factors as stated in section 2.1. If the change in temperature is above rated value, it will affect the performance, its insulation and the life time of the asset. The above readings in figure 16 show us that by building a temperature monitoring unit we can get the real time data at each moment. And if the measured value is above the rated value, i.e. 95°c, the monitoring unit will transmit the reading and it will be displayed at the controlling station.

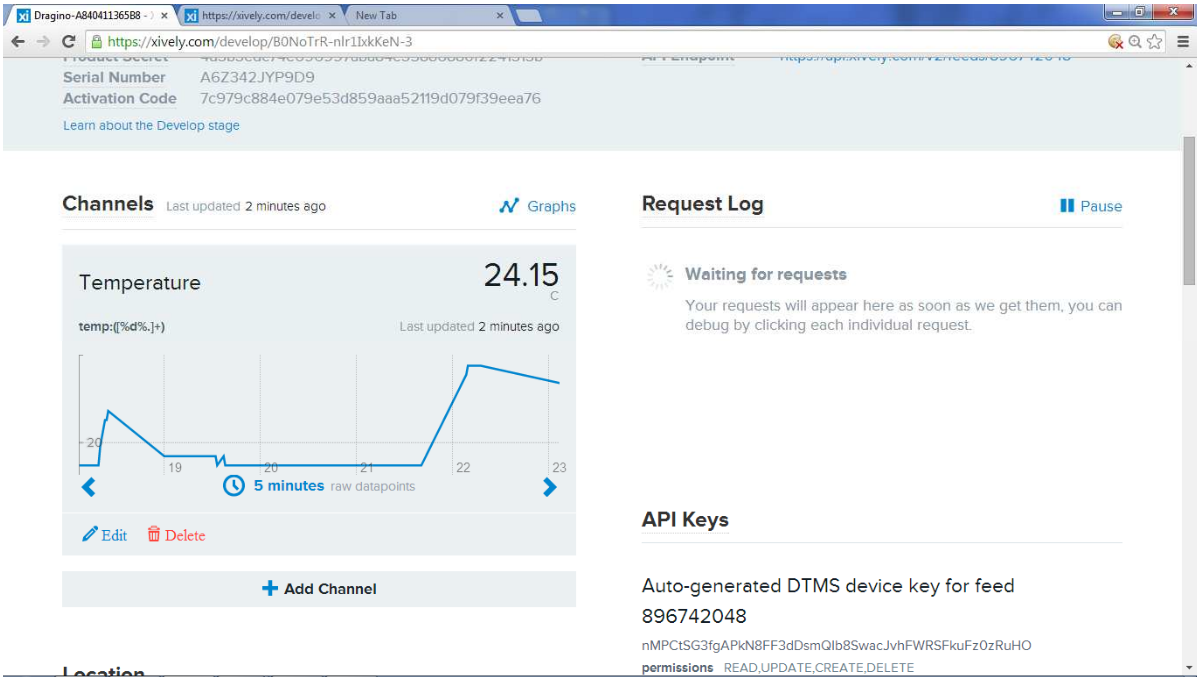

Figure 17: Temperature output at the remote Xively server

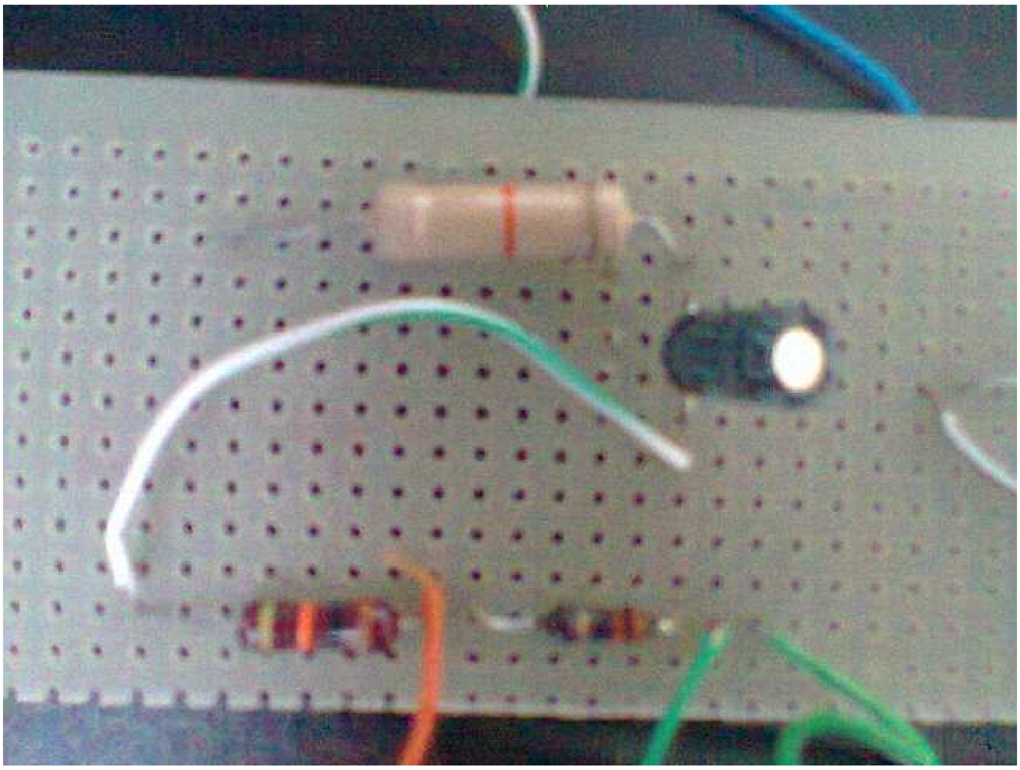

Figure 18: Current measuring circuit

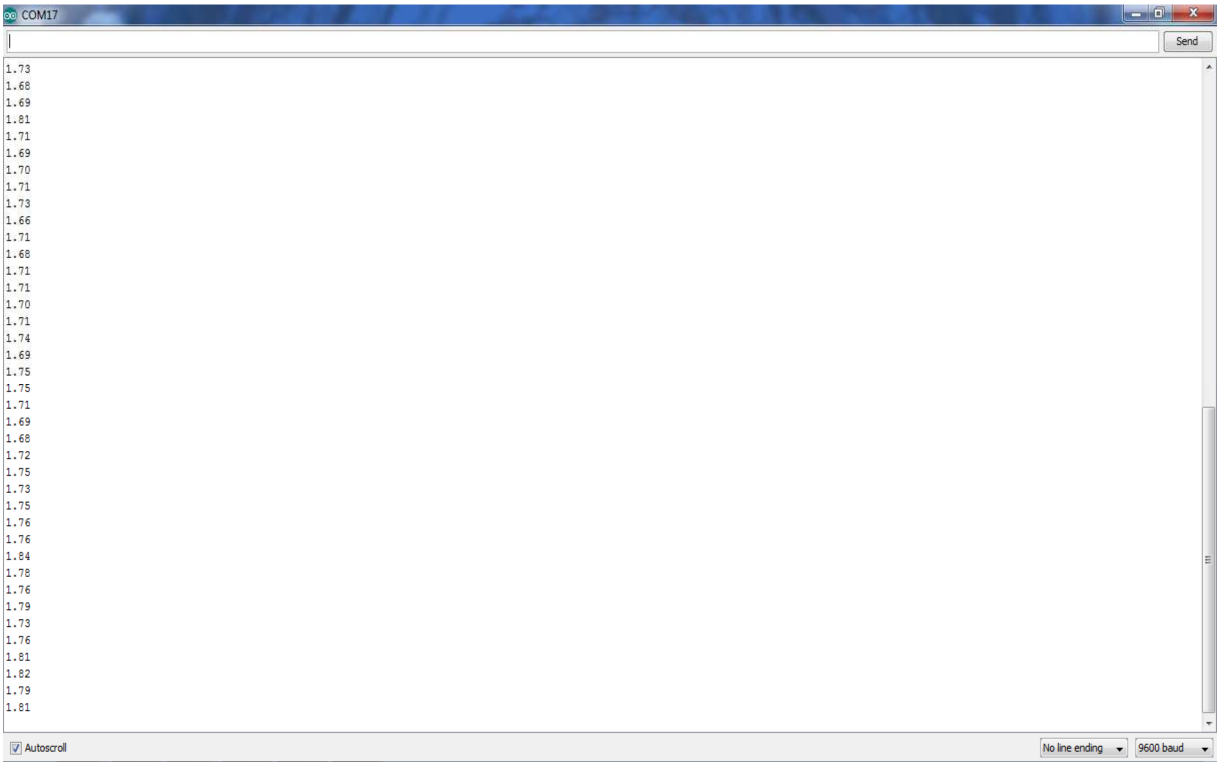

Figure 19: Arduino monitor output for current reading

By measuring the current we can minimize the losses that occur due to its increment. This is due to the fact that most of the transformer losses are directly related to the change in current. The readings in figure 19 shows us that by building a current monitoring unit we can view the changes in the current value and we can calculate the losses that occur due to it. When the values of current increases due to different factors like harmonics, it subsequently increases the temperature of the transformer. This eventually will increase the source impedance and lead to increase in losses. Therefore, by keeping the current in check, we can minimize the losses.

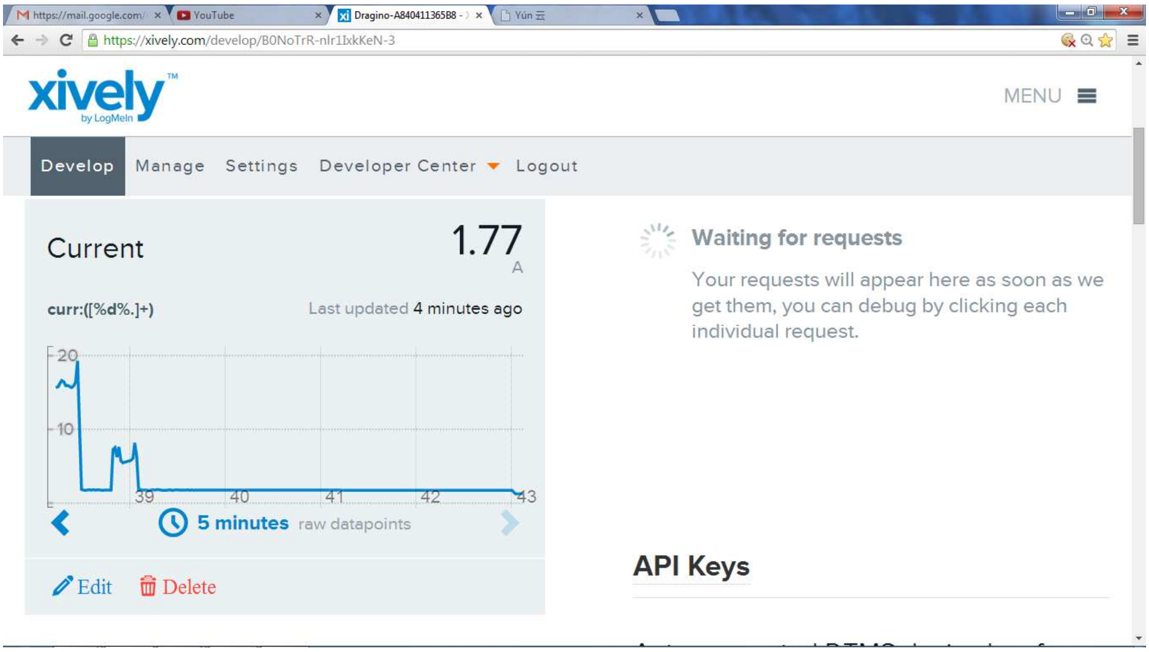

Figure 20: Current measurement Output at Xively server

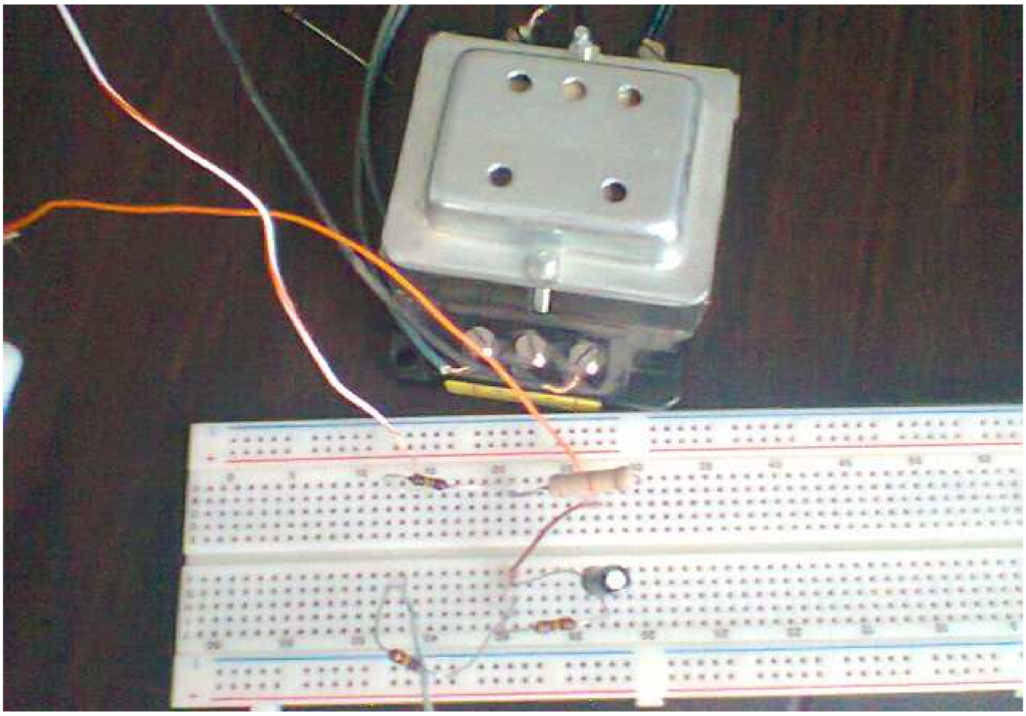

Figure 21: Voltage measuring circuit

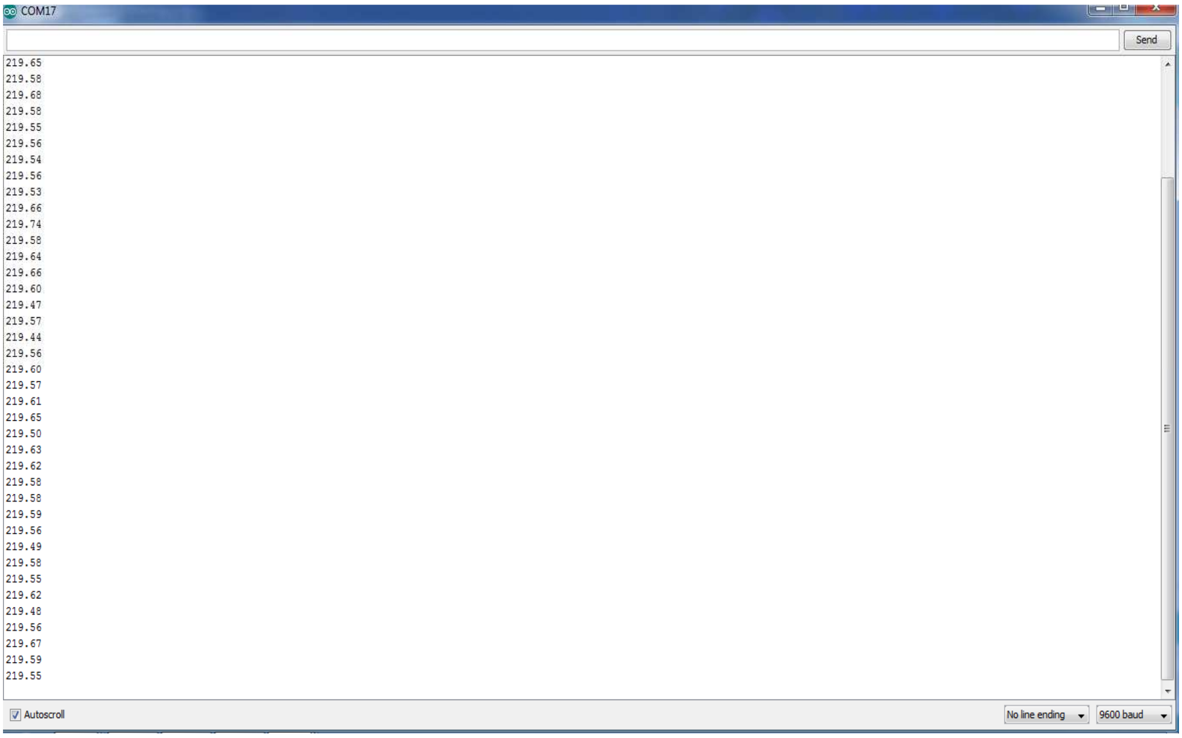

Figure 22: RMS voltage output on the Arduino serial monitor

As we can see from the displayed readings in figure 22, the voltage is almost constant every moment. The voltage from the source will be distorted by current harmonics due to source impedance. Therefore, it implies that keeping the current in check, we are also monitoring the voltage.

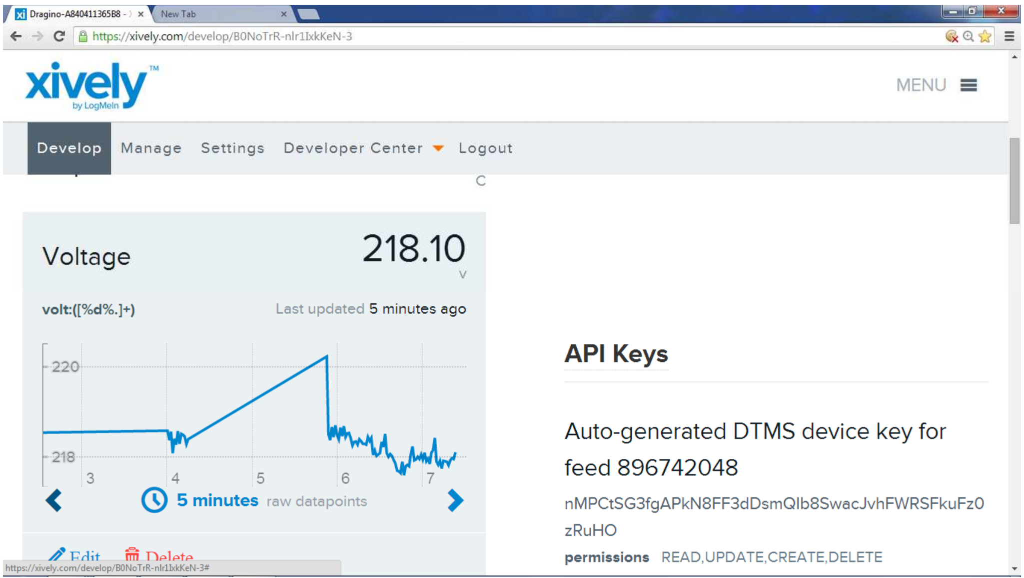

Figure 23: RMS voltage output at the Xively Server

5.3. Discussion of the circuit evaluation

From the above results we can see that real-time monitoring of key parameters can be implemented using wireless networking technologies. We used a Wi-Fi network to demonstrate our designed system in the laboratory. By changing the modem and few lines of our code we can implement the system by using WCDMA cellular network out in the field on the distribution transformers. But, to do so we need SIM cards and also an authorization from ethio telecom.

To view the output we used Xively website. This is a cloud server platform that is free and which stores data history of only six months. We have also encountered a problem of the online platform pausing after some readings. This problem we encountered can simply be resolved by developing our own secure and private database with its own server. We have not done this part since it is beyond the scope of the thesis. Taking these results as a prototype of the actual system, we can see that the data from sensors at the distribution transformer can be sent through a WCDMA modem and by developing a database and implementing a server we can view the sensor readings at a remote station and save reading history of a longer period of time.

By taking the results from the readings of the values the engineering unit can analyze it for further corrective measures to be taken. Any sign of abnormality at the distribution transformer will be analyzed and corrective measures will be taken in a short term and long term basis.

5.4. Limitations

By analyzing the limitations of the designed prototype, we are able to get insight for future work to improve the system and enhance the usability. However, more test and evaluation needs to be carried out on the hardware part of the prototype. The functionality of the designed hardware prototype is not tested and evaluated under actual conditions out in the field. This might lead to a failure if the system is implemented without testing the hardware components of the proposed system out in the field. Furthermore, the demonstration was done by utilizing a Wi-Fi network. Therefore, testing the system with a WCDMA network needs to be done.

6. Conclusions and future work

6.1. Conclusions

This paper has contributed towards implementation of the distribution transformer monitoring system. Presently, many power disruptions in the distribution system are due to faults on the distribution transformers. The utilities need their repairing teams along the distribution branches to find out the fault location. This process consumes plenty of valuable times. The monitoring system was designed to detect the problems on the sources of the faults (key parameters) and report it to the concerned bodies to take corrective actions before and after faults occur.

The system is implemented in a laboratory and key parameters were recorded. The recorded values help us in identifying the possible failure that could occur, if the values are over the rated values. The laboratory implementation was done using a Wi-Fi network. By taking the advantages of wireless networks and analyzing its use distribution transformer monitoring using WCDMA wireless communication network is forwarded as a better communication technology option for the system we have designed and developed to be implemented out on the field. As WCDMA network deployment is being expanded in Ethiopia, it will be much simpler to integrate it to the existing system.

The WCDMA based monitoring of distribution transformer is quite useful as compared to manual monitoring. And also, it is reliable as it is not possible to monitor always the oil temperature rise, load voltage, and load current manually. In a power distribution network, there are many distribution transformers. Associating each transformer with such system, we can easily figure out which transformer is undergoing fault. Then, corrective actions, like balancing the loads on each phase or even switching the transformer off, can be taken before the failures happen and we can identify the parts of the electric power distribution system which need stabilizing from the history we get. Thus, this implemented system will help the utility to optimally utilize distribution transformers for a longer period of time.

6.2. Future work

The research presented in this thesis needs to be tested and implemented out in the fields. In addition, it indicates some additional areas to exist for future research.

Firstly, by taking sinusoidal wave form of the measured data, harmonic analysis of the current and the voltage can also be done. Harmonics in power system results in increased heating in equipments and different kinds of problems on drives and motors. Reduction of harmonics is very much desirable. This will help to stabilize the waveforms and protect user devices from being temporarily or permanently out of use.

Secondly, a permanent database server specifically for this purpose should be designed with its own server module to store data for a longer time span of years. This database will be a useful source of information on the utility transformers. Analysis of these stored data helps the utility in monitoring the operational behavior of their distribution transformers. And also identify faults before any catastrophic failures thus resulting in significant cost saving as well as improving system reliability.

Finally, what we see as another potential of future work is developing the same system with a wireless mesh network. Especially, meshed Wi-Fi network can be deployed to meet the distribution power transformer monitoring requirements for robustness, manageability, and performance. Wi-Fi is cost effective, can be scaled to cover large geographies and many endpoints, and requires no new cabling. The new developments and advancements in the 802.11 based standards will lead to acceptance and deployment of the meshed networks.

Appendix I: Arduino Code for Temperature Sensing

```
/*
 * temperature_sensor.pde
  * Takes the sensor (LM335) input and converts it to Kelvin degrees, then celsius.
 * Subtract 2.5 celsius degrees that seem to be the sensor error perhaps due to the heat
 * generating by the current running through it.
*/
float temp_in_celsius = 0, temp_in_kelvin=0, temp_in_fahrenheit=0;
void setup ()
{
  Serial.begin(9600);
}
void loop()
{
  //Reads the input and converts it to Kelvin degrees
  temp_in_kelvin = analogRead(0) * 0.004882812 * 100;
  //Converts Kelvin to Celsius minus 2.5 degrees error
  temp_in_celsius = temp_in_kelvin - 2.5 - 273.15;
  temp_in_fahrenheit = ((temp_in_kelvin - 2.5) * 9 / 5) - 459.67;
  //Print the temperature in Celsius to the serial port
```

```
  Serial.print("Celsius: ");

  Serial.println(temp_in_celsius);

  //Print the temperature in Fahrenheit to the serial port

  Serial.print("Fahrenheit: ");

  Serial.println(temp_in_fahrenheit);

  Serial.println();

  delay(1000);

}
```

Appendix II: Arduino Code for Current and Voltage Measurement

```
#include "EmonLib.h" // Include Emon Library

EnergyMonitor emon1; // Create an instance

void setup()

{

Serial.begin(9600);

emon1.voltage(2, 234.26, 1.7); // Voltage: input pin, calibration, phase_shift

emon1.current(1, 111.1); // Current: input pin, calibration.

}

void loop()

{

emon1.calcVI(20,2000); // Calculate all. No.of wavelengths, time-out

emon1.serialprint(); // Print out all variables

}
```

Appendix III: Data Logging Code to Xively

```
/*
  Xively sensor client with Strings: - This sketch connects an analog sensor to Xively, using an Arduino Yún. http://arduino.cc/en/Tutorial/YunXivelyClient
 */
// include all Libraries needed:
#include <Process.h>
 #define APIKEY        "foo"                  // replace your pachube api key here
 #define FEEDID        0000                   // replace your feed ID
 #define USERAGENT     "my-project"           // user agent is the project name
// set up net client info:
const unsigned long postingInterval = 60000;  //delay between updates to xively.com
unsigned long lastRequest = 0;      // when you last made a request
String dataString = "";
void setup() {
  // start serial port:
  Bridge.begin();
  Serial.begin(9600);
  while (!Serial);   // wait for Network Serial to open
  Serial.println("Xively client");
```

```
  // Do a first update immediately
  updateData();
  sendData();
  lastRequest = millis();
}
void loop() {
  // get a timestamp so you can calculate reading and sending intervals:
  long now = millis();
  // if the sending interval has passed since your
  // last connection, then connect again and send data:
  if (now - lastRequest >= postingInterval) {
    updateData();
    sendData();
    lastRequest = now;
  }
}
void updateData() {
// PUT YOU CODE HERE
  // convert the readings to a String to send it: for example when reading temperature
```

```
//  dataString = "Temperature,";

// dataString += temp_in_celsius;

}

// this method makes a HTTP connection to the server:

void sendData() {

  // form the string for the API header parameter:

  String apiString = "X-ApiKey: ";

  apiString += APIKEY;

  // form the string for the URL parameter:

  String url = "https://api.xively.com/v2/feeds/";

  url += FEEDID;

  url += ".csv";

  // Send the HTTP PUT request

  // Is better to declare the Process here, so when the

  // sendData function finishes the resources are immediately

  // released. Declaring it global works too, BTW.

  Process xively;

  Serial.print("\n\nSending data... ");

  xively.begin("curl");

  xively.addParameter("-k");
```

```
xively.addParameter("--request");

xively.addParameter("PUT");

xively.addParameter("--data");

xively.addParameter(dataString);

xively.addParameter("--header");

xively.addParameter(apiString);

xively.addParameter(url);

xively.run();

Serial.println("done!");

// If there's incoming data from the net connection, send it out the Serial:

while (xively.available() > 0) {

  char c = xively.read();

  Serial.write(c);

}}
```

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