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Enhancing Faults Monitoring in Secondary Electrical Distribution Network

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Abstract. Inefficient fault management in electrical Secondary Distribution Network (SDN) is one of the major challenges facing most power utility companies around the world including Tanzania. Currently, faults management processes from detection to clearance are done manually due to the lack of visibility in SDN resulting to long Mean Time To Repair (MTTR) and high operational costs. Advancements in Information and Communication Technology (ICT) and sensing technologies have made it possible to have cost effective electrical power network visibility solutions. This study proposes algorithms that enhance fault detection and monitoring in the Tanzania SDN based on distributed processing architecture. The proposed algorithms include sensing and data acquisition, fault detection, localization and visualization. The algorithms were deployed and tested on live network at University of Dar es Salaam (UDSM), Kijitonyama Campus.

Keywords: Fault Detection, Fault Clearance, Distributed Processing, Secondary Distribution Network, Remote Sensing Unit, Monitoring, Visibility, Algorithms, Distributed Architecture.

1 Introduction

Electrical power Secondary Distribution Network (SDN) provides last mile connectivity to the end customers [1]. Its primary task is to ensure a secure and efficient energy delivery to consumers [2]. For this to be possible, power from generation sites is transmitted to the primary substation through the transmission network and delivered to the secondary distribution network through Medium Voltage (MV)/Low Voltage (LV) transformers [3].

Most power utilities maintain the emergency desk to ensure supply continuity and customer safety hence guarantee the quality of service. In Tanzania, the electrical SDN is under Tanzania Electric Supply Company Limited (TANESCO). Defects and faults are reported by customers to the TANESCO's emergency desk and through visual inspection (line patrol) which are time consuming and inefficient [4]. The delays in fault clearance are mainly attributed by the lack of efficient and automated systems which continuously monitor the electrical SDN parameters so as to detect, report, classify and locate faults whenever they occur. Ineffective faults clearance mechanisms employed by the utility company have been the major cause of inefficient power supply in Tanzania resulting to increased complaints from customers and significant losses of revenue to both customers and utility.

There have been utility company initiatives to automate fault monitoring and detection in transmission and primary distribution parts of the electrical network using Supervisory Control and Data Acquisition (SCADA) and Distribution Management System (DMS), which are largely centralized [5, 6]. Due to the complexity and ubiquitous nature of the SDN, cost effective automations are still challenging. Few studies [7] have been conducted in LV distribution network in which controller at the transformer was used as a decision maker. However, advancements in ICT and sensing technologies have made it possible to have cost effective electrical power network visibility and faults handling throughout SDN [8, 9]. Therefore, this study proposes algorithms to enhance visibility and automatic faults monitoring in the Tanzania SDN based on distributed architecture.

The main contribution of this paper is the design and implementation of algorithms that extend monitoring capability of Tanzania's SDN. The proposed algorithms offer the ability to process data from the data sources as well as at the control center based on distributed processing. Tanzania utility company SDN was used as the case study, and was carried out at University of Dar es Salaam (UDSM), Kijitonyama campus. Moreover, Challenge Based Learning (CBL) [10,11] approach was adopted in this study to identify and refine the problem through involvement of stakeholders. The use of CBL approach enhanced the cooperation among industry and academia in the solution development. Furthermore, CBL allows people from different background, competences and disciplines to work together in accomplishing the objective of the study. In this way, products from academic addresses real problems of the society.

This paper is organized as follows: Section 2 discusses fault handling and management techniques. Section 3 describes the approach used for developing distributed algorithms for data acquisition, processing and visualization. Section 4 discusses the design of algorithms for fault handling. Section 5 describes system integration. Section 6 describes results and discussion. Finally, section 7 provides conclusion and future work.

2 Fault Handling and Management

2.1 Fault Detection, Classification and Localization

Electricity supply networks are subjected to various disturbances depending on the potential of production, atmospheric conditions, and industrial loads which affect them during the transmission and distribution of the energy produced. Disturbances in the electrical SDN may result into faults which are referred to as the discrepancy between the reference value and the measured value for any given network parameter [12].

Faults in overhead distribution system can be classified into two main types, i.e. series (open conductor) faults, and shunt (short circuit) faults. Series faults can be identified easily by observing the voltages on each phase. Short circuit faults can be identified easily by observing the current values on each phase. Short circuit faults are divided into two main types depending on the lines under short circuit, i.e. asymmetri-

cal faults, and symmetrical faults [13]. Having known the exact fault type after classification as discussed [14, 15] in the electrical SDN, it is equally important to determine the fault location. This will assist the maintenance crew to easily locate the fault areas rather than relying on information from reporters which are sometimes not accurate. The fault location techniques can be categorized into four main groups: automated outage mapping, impedance-based methods, expert systems, travelling waves and voltage sag measurements [16]. For efficient fault localization in distribution network, the process can be done in two stages. The first stage involves faulty branch identification and second stage is distance calculation to the faulty point. Fault branch identification normally starts, followed by distance calculation to eliminate the problem of multiple estimation during distance calculation [17, 18]. This study aims at detecting faults, classifying and finding the faulty branch using the expert system and then visualizing the fault location on the map.

Advancement of data acquisition, storage, processing, transmission and sensor technologies have enabled availability of low cost devices such as microprocessors, Field Programmable Logic Arrays (FPGA), Arduino, Raspberry Pi [19] and wireless sensors. This has facilitated the deployment of distributed algorithms to enhance automated fault detection and monitoring using distributed.

2.2 Applications System for Fault Monitoring

The past 20 years have seen the rapid deployment of various management techniques, Intelligent Electronic Devices (IEDs), sensors and tools for detection, classification and location of faults in power systems [20]. To leverage advancement of these technologies, ICT industry also had to catch up with the speed of these developments by allowing seamless adoption of information systems for visualizations and analytics into power systems through design of algorithms and software applications [9]. Among many features of software applications, Graphical User Interface (GUI) plays a significant role to allow users interaction with the system, if well designed. This has fundamentally changed the management and control of power systems at large by allowing improved range of display capabilities consistent with Human Computer Interaction principles [21]. In particular, SCADA systems have opened up to a wide range of user community by embracing the idea of distributed computing, which addresses issues of mobile SCADA Human Machine Interfacing [22, 23] and provision of Application Programming Interface (API) for other systems. For the case of Tanzania, limitation still exist particularly for SCADA system which is not exposed to external systems.

2.3 Related works

There has been a number of similar studies done on this area, such as authors in [24] who presented faults detection and location in LV grids based on RF mesh network. Their study demonstrated the distributed architecture with sensor nodes placed along the networks and uses the mesh network to relay the measurements to the Distribution Transformer Controllers (DTC) placed on each secondary substation. Fault detection and faults location algorithms were developed to run on the DTC which were used as the “decision maker”. Furthermore, a study done by [25] demonstrated

the use of SCADA and PLC to monitor and diagnose the distribution system. The proposed architecture in this study used on-line monitoring system which integrated a solid state device named Programmable Logic Controllers (PLC) and sensor packages which were mainly installed on distribution sub stations. The PLC and SCADA allows to detect the exact location of fault and without waiting SCADA to give an alarm to the operators for identifying and prevent it. Moreover, a study by [26] demonstrated a cost-effective fault management system in MV distribution systems and [27] considered the use of high-performance computing in theft detection of electricity by implementing parallelized algorithms for processing large data set with convincing results. However, most of the works done previously focused much on primary distribution network monitoring based on centralized approaches such as PLC and SCADA systems where the number of sensors and processors are relatively low, and programming were mainly done using low level languages with limited flexibilities and features. This study focuses on the SDN where the nature of the network is complex and sensors are installed ubiquitously along the network and hence enhanced algorithms are required to efficiently monitor the network. In addition, the study makes use of state of the art processors using high level programming languages allowing for easy deployment of complex and flexible algorithms.

3 Implementation Approach

3.1 Study Area

The study was conducted at University of Dar es salaam, College of Information and Communication Technologies, herein referred to as Kijitonyama campus. The campus has three main building blocks namely, administration block (Block A), teaching block (Block B) and engineering block (Block D). The campus has one installed secondary distribution transformer and one main distribution panel rated 800A, at the main power room, three subpanels installed at each building block. The rated values for block A, block B and block D are 200A, 400A and 150A respectively.

3.2 Challenge-Based Learning

This study adopted the use of the CBL approach where users who are the challenge owners (the utility company) were involved from the challenge identifications to the solution development. Out of Eight identified challenges [10], one challenge namely "*Inefficient faults clearance system in electrical secondary distribution*" was taken for consideration in this study. In achieving the objective, the solution was broken into three parts namely detection, communication and application. In each part, a number of researchers, depending on their expertise, were allocated specific tasks to handle and contribute to the solution development. A number of meetings among researchers, supervisors and stakeholders were held on weekly basis for brainstorming and presenting the progress.

3.3 Data Flow Architecture

The proposed system for automatic faults detection and monitoring consists of Remote Sensing Units (RSU), Distribution Control Units (DCU), hybrid communication network and control center as shown in Fig 2. The system deployed the concept of distributed processing by having a number of processing units at different substations in the SDN namely, DCU. Through hybrid communication networks, the DCUs collect data from different RSUs, process the data and send to control center. RSUs are equipped with current sensors and voltage sensors placed on different remote branches or nodes on electrical SDN. RSU sensors collect data from the network and send them to the DCU. DCUs are equipped with a number of sensors including voltage, current, temperature and transformer oil level. The DCU in each secondary substation processes different types of faults including short circuit faults, overcurrent faults, over/under voltage faults, earth faults, transformer oil level faults and temperature faults. The processed information is sent to the control center for further analytics, storage and visualization through the communication network.

4 Fault Monitoring and Processing Algorithms Design

4.1 Sensing and Data Acquisition

Sensors form a very significant part of the automatic systems for faults detection, monitoring and control in electrical SDN by capturing the real-time states of systems or processes. In this study, sensors at RSU capture voltage and current parameters and those at DCU capture voltage, current, transformer temperatures and oil levels. Sensors provide analogue output voltage whose variations correspond to the variations on the physical parameters under monitoring. The output values are then conditioned and converted to digital values for further preprocessing before being transmitted to the DCU for processing as summarized in Fig.2. The RSU has internal storage to temporarily store the recorded data when there is no communication. Current sensors and voltage sensors rated at 600A and 600V respectively were used at RSU while current sensors, voltage sensors, oil level sensor and temperature sensor rated at 1000A, 600V, 55cm probe and 80 °C respectively were used at DCU. All sensors were calibrated prior to installation; Table 1 shows calibration values for current sensor rated at 600A. These sensors were able to make the SDN visible and captured all types of faults under considerations in this study.

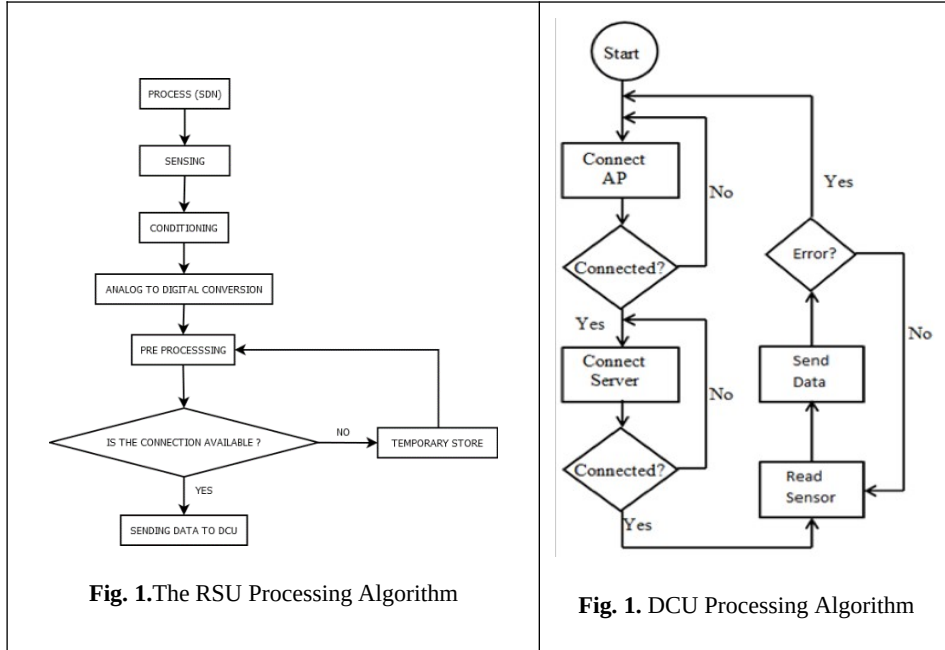


Table 1. Calibration values of 600A sensor

CHK600E KA5S2	Forward direction	Input current	0A	100A	200A	300A	400A	500A	600A
		Output	2.5V	2.5+0.33 3V	2.5+0.66 6V	2.5+1.0V	2.5+1.33 3V	2.5+1.66 6V	2.5+2.0V

4.2 RSU processing

RSUs consist of Data Acquisition (DAQ) module and Wi-Fi module. DAQ module is used for acquiring data from the sensors and the wireless (Wi-Fi) modules for enhancing communication between DCU and RSUs. The DCU Wi-Fi module sends data to the control center through wired network. The flow chart showing the basic program framework implemented at the RSU is shown in Fig.1.

RSU establishes connection with the server at DCU, if the connection is successful it starts to read the data from the sensor and send data to the server continuously. If the error occurs, the system starts over to the initial point as shown in Fig. 2.

4.3 DCU processing

The DCU consists of Mini-computer (Raspberry Pi), DAQ module (Arduino Mega 2560) and Wi-Fi module. Each DCU has its respective RSUs which are connected as clients. The Mini-computer performs many functionalities and services in parallel. The program starts a server by which RSUs will connect to the DCU. The *Scan New Client* thread keeps waiting and validates the clients requesting for services from the server. The *Data Handler* acquires data, process data and temporarily store data into the database. Data is acquired from the local sensors at the DCU and from the remote

RSUs. Data processing includes running fault detection algorithms, formatting the data for storage etc. The *send data thread* reads from database, send data to the control center and delete data from the database. The *Time Synchronization* thread is responsible for requesting the synchronization time from the control center and updates the DCU system clock.

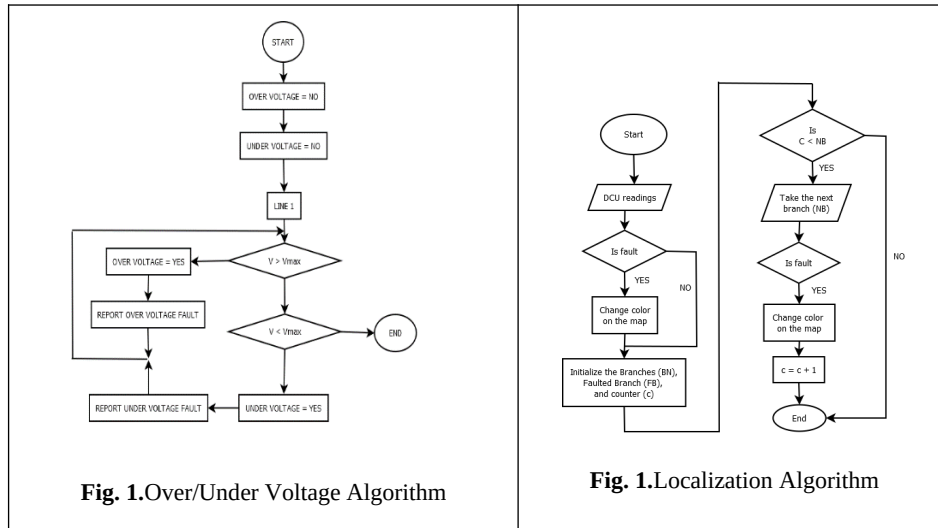


Table 2. Reference Threshold Values in Volts

Over/Under Voltage			
Condition	Voltage Range(V)	Operating Voltage(V)	Operations
Normal	230-220	252-242	Normal Operations
		208-198	Normal Operations
Under Voltage	Below 198	Below 198	Fault
Over Voltage	Above 252	Above 252	Fault

4.4 Fault detection, Classification and Localization

Fig. 3 gives details of algorithms for fault detection and classification. Detection of different types of faults was done by comparing the threshold values and the measured values as shown in Table 2. Thresholds values for current, voltage, temperature and oil level for each fault were identified with the help of stakeholders and other relevant technical documentations. After fault detection and classification, the fault localization algorithm was triggered as shown in Fig. 4. The aim of the fault localization was to identify and visualize the area under the fault on the map.

5 System Integration

5.1 Subsystems Integration

DCU, RSU and Control Center are considered as subsystems. The output of the RSU is the input of the DCU and the output of the DCU is the input of the Control Center. The wireless communication was used between RSU and DCU due to complexity and ubiquitous nature of the SDN while wired communication was used between DCU and Control Center for taking advantage of the existing infrastructure of the utility under the study.

5.2 Data Integration

The database architecture of the implemented system is comprised of two parts. The first part is the DCU database, which is designed to capture, aggregates and temporarily store real-time voltage and current measurements from RSUs, real-time voltage, current temperature, and oil level measured at the DCU. The second part of the database located at the control center (the main database) stores, copies and aggregates data from the DCUs through Message Queuing Agent (MQA) for permanent storage, analytics, visualization, and report generation.

5.3 External Systems Interfacing

The proposed system for automatic faults detection and monitoring was designed to collect data and store them to the system database. However, this developed system has to interact and communicate with other existing systems available at the utility company like customer call center and Geographic Information System (GIS) database, which hosts electrical network equipment information as well as customers' information. To enable this interoperability, a Representational State Transfer (REST) API to support information sharing was developed. However, due to the nature of the prototype only Hypertext Transfer Protocol (HTTP) based protocol was used such as HTTP GET and HTTP POST all database tables. The GET HTTP REQUEST returns a JavaScript Object Notation (JSON) file with the data from the database according to the given request when a correct API security key is supplied as shown in Fig. 5.

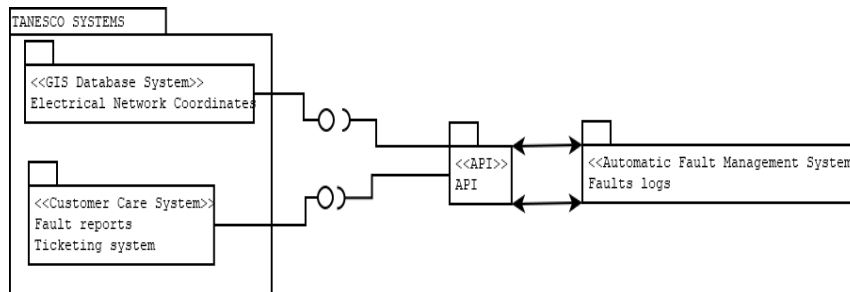


Fig.1. External Interfacing

6 Results and Discussion

6.1 CBL Contributions

The discussions and meetings with stakeholders were useful in identifying the challenge, breaking down and allocation the tasks to researchers, and development of the solution. The process revealed a number of fault types which are commonly affecting the SDN. These faults were over/under voltage, over current, low oil level and high temperature. Thresholds were also identified for these types of faults.

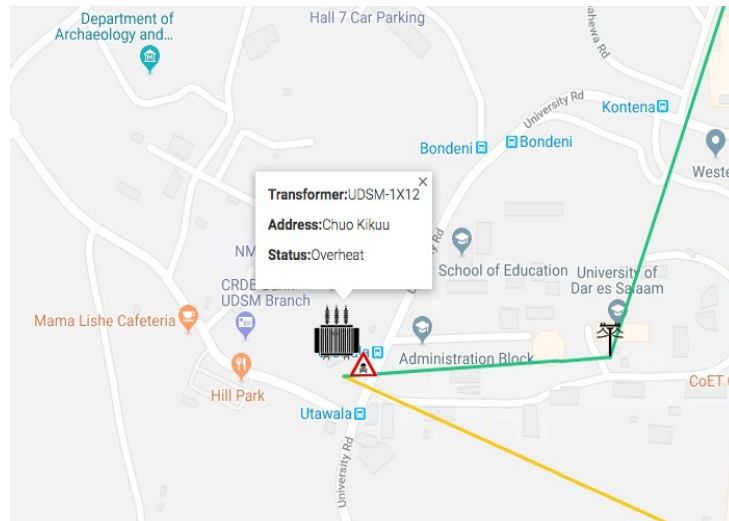


Fig.2. Fault detection and location

6.2 Detection and Localization

After implementing the algorithms represented by flowcharts in Section 4 the one line diagram for the distribution network at the demonstration site. Different fault types were identified, and faulty branch was differentiated from the normal branch by color codes as clearly stipulated in Fig. 6. Lines with faults were coded with red color, green color code for warning and black color for normal status. Upon clicking on the lines with color codes, further information can be obtained.

6.3 Visualization

Owing to the nature, size and complexity of electric grid networks, visualizations provide means to comprehend the structure, functions and other crucial issues of the grid. In this work, two modules of visualizations were implemented. (i) Data analysis and summarization module, which is for analyzing live and the archived data. It interprets and notifies fault situations through screens at the control center as shown in Fig. 7. (ii) Presentation module pictorially presents current and history information regarding fault status and functionality using conventional graphs and other relevant metrics.

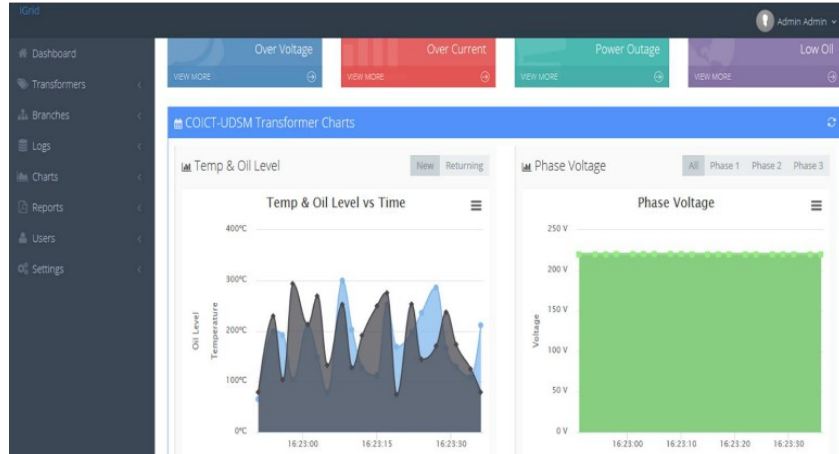


Fig.3. Visualization Modules

In this prototype visualization dashboard, the user, through menus, can graphically select the interested resources and metrics to view. One should be able to view status summary and fault information. Moreover, the prototype dashboard allows user to generate various reports, summary and other statistics of interest. The system can also monitor real time status of crucial equipment of the network like transformers, relays etc.

6.4 System Integration

The developed REST API was able to provide interface to and from other existing systems. The system will send requested data between systems when a correct API call accompanied with correct security key were supplied. On the other hand, the incorrect API calls will cause a system to send a respective error, where incorrect security key was supplied. The security key was used to prevent unauthorized access to application data from other systems or third-part applications like mobile applications.

7 Conclusion and Future Work

In this paper, distributed algorithms for enhancing fault detection and monitoring in the electrical secondary distribution network have been presented. By adopting distributed processing architecture, sensing and data acquisition, fault detection and localization, and data processing and visualization, algorithms were prototyped and deployed in live network. Challenge based learning was adopted throughout development phases. The proposed system was able to remotely acquire and process data, then forward to the control center through hybrid communication system for further processing, visualization and storage. Simulated faults could easily be identified and analyzed. This shows that, distributed fault management systems based on distributed algorithms can greatly enhance the monitoring of the SDN. Future work will focus on

improving the system by adding control, resiliency, security, actualization and other intelligence-enhancing features. The system will also add extra integration mechanisms with other external systems such as GIS, DMS, SCADA, etc.

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