Smart Computation and Interactive Communication for Infrastructure Monitoring and Control

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Article Info
Page Number: 393-408
Publication Issue:
Vol. 72 No. 1 (2023)

Article History
Article Received: 12 October 2022
Revised: 24 November 2022
Accepted: 18 December 2022

Abstract:
This study assessed the reliability of the critical infrastructure of the electrical distribution network; designed an intelligent network control and monitoring system capable of predicting fault conditions and restoring normalcy; developed the instrumentation circuits to achieve the designed network and evaluated the performance of the developed system. These were with a view to improving the availability of electric distribution system.

This research evaluated the rates of failure of critical infrastructure in conventional distribution networks through gathering and analysis of reliability data. The load on low to medium voltage feeders and distribution transformers were monitored to detect the conditions of the system after which faults were isolated thereby restoring normalcy. The impact of service restoration following fault conditions on distribution system availability without a complex Supervisory Control and Data Acquisition system on future power distribution systems was considered by comparing the system efficiency before and after monitoring. The automatic system which remotely monitors the state of the feeders and transformers continuously to determine the state of the network was designed. Abnormal conditions were automatically addressed through automatic sensors, isolators and switches which open or close depending on the status of individual feeder as detected by the sensing circuits. These circuits utilize sensors through remote operations for processing of data and actionable outputs in a virtual control room for automatic restoration, thereby reducing the system total downtime while improving the system availability.

Keywords- Abnormal conditions, faults, sensors, circuits, reliability, efficiency, switches, isolators

INTRODUCTION

The concept of the smart grid, as an advanced power system, is generally accepted to indicate the integration of communication, computing, control, and information technologies to enhance the reliability, flexibility, efficiency, and sustainability of the electricity grid (Qiao et al., 2010). Restrictions of energy resources, aging infrastructure, environmental concerns, and increasing expectations of customers are some of the drivers of the transition toward a smarter electrical grid (Basso and DeBlasio, 2009).

The transition of the contemporary grid to an advanced one will influence planning, operation, and maintenance of the power system. To achieve an advanced grid will require new infrastructure or monitoring of the old ones in such a way that the remote operations, functions and intelligent control strategies are enabled (Hamidi et al., 2010). The principle of intelligent grid in recent power systems is based on the idea of expressing functions further down the system structure. This simply means that in any smart network, monitoring and control can be done locally at a primary and even secondary distribution substation or even at the device level, allowing operators and computing resources in the control centre to be more effectively utilized. Figure 1.2 can be used to explain the concept of a smart grid which will integrate Information Technology, Communication tools, Control and intelligent monitoring devices into the system for improved system security and utilization of electricity supply at the consumers end. While a fully automated distribution grid might not be realizable in the immediate, the monitoring of the critical equipment in distribution substations has a major link in achieving this future plan.

The world faces major increased unavailability of power supply challenges particularly at the distribution portion of the power network. These challenges now and in the future will keep affecting the growth and reliability improvement of electrical power infrastructure negatively. Therefore as a consequence, the growth and development of any country which is dependent on the availability of electric supply is stagnated. Remote laboratories, industries, educational institutions, hospitals and even other small and medium enterprises depend on highly reliable power supply for the smooth running of their day to day activities. Therefore, the consequences of unreliable supply can result in life threatening situations and lack of socio-economic development. Needless to say, developing countries (like Nigeria) suffer these consequences more as electric utilities have a wide array of challenges to overcome whether they are in generation or distribution subsectors. Distribution companies however by virtue of their position on the power chain, face the most varied and complex technical and operational challenges. These challenges are mainly related to the size and complexity of the network and direct interaction with end-users (consumers of electricity).

The distribution company, as the direct interface with electricity consumers, is thereby burdened with the duty of recovering the revenue that drives the entire power chain. Electricity consumers can be roughly divided into three (3) categories-

(1) Residential consumers: Power intake is at low voltage only, Consumption is typically below 80A, and they are usually metered with digital meters which can be either prepaid or postpaid.

(2) Commercial consumers: Power intake is at low or medium voltage (individually served by a dedicated transformer). They are usually metered with Low Voltage (LV) or Medium Voltage Maximum Demand (MV MD) meters.

(3) Industrial consumers: Power intake is served at MV or in rare cases served at High voltage (HV).

To ensure improved availability of power supply and accurate revenue realization, an electricity utility must ensure that adequate protection is in place for distribution transformers and feeders with a reliable metering technology in place for each consumer type. Adequate monitoring and punitive measures must also be put in place to ensure security of supply and proper customer behaviour.

I. LITERATURE REVIEW

This project summarized a detailed review of techniques on in electric power distribution networks monitoring and control and their applications as well as their advantages. A lot of work has been done on monitoring and control at the transmission level, however control has not been widely implemented in distribution networks to date. This has mainly been due to a lack of investment in information and communications technology infrastructure at the distribution level. However, as these systems become much more divergent and complex due to increasing loads, generation resources, demand-responsive loads, electricity storage, and micro grids, there is the need for monitoring and control more than ever before for a more efficient network.

Power distribution system monitoring through instrumentation and control for electric power distribution systems is the main interest. System State estimation has been in use for monitoring and control of electricity transmission systems for several decades, yet it has not been widely implemented in distribution grids to date. However, with the recent drive towards low green energy, introduction of distributed generators, and the need for an intelligent power distribution network as well as the improvements in monitoring and communications infrastructure, power distribution system control through instrumentation has been receiving significant research interest. The monitoring and control of distribution networks presents a number of unique challenges due to the characteristics of distribution grids, and many of the well-established methods used in transmission systems cannot be applied directly. Since the initial development of the concept in the early 1970's (Schweppe and Rom, 1970), power system instrumentation has become a critical part of the operation and management of transmission systems worldwide. Until recently, the application of automation at the distribution level, i.e. Distribution System monitoring through instrumentation has not been of significant interest. This is largely because distribution networks have traditionally been designed and operated as passive systems, where power flows are unidirectional and relatively easy to predict and manage.

However, distribution networks are getting more cumbersome from distributed energy resources, such as small to medium sized Distributed Generation (DG), old and dilapidated infrastructures and equipment, demand-responsive loads, electric vehicles and devices with storage capability. This has led to a requirement for improved observability in distribution systems, and the need for Distribution System Operators (DSOs) to take a more active role in monitoring and controlling the operation of the networks. Since distribution networks have different characteristics to transmission networks (e.g. radial construction, high R/X ratios, phase imbalances, and a much lower quantity and quality of available measurement data), many of the methods and approaches developed for "conventional" transmission level instrumentation monitoring cannot be applied directly to distribution network. Hence, a number of sensors specifically designed for application at the distribution level has been proposed in some literatures in recent years.

Table 1 presents a list of smart technologies that are currently available in the market to improve MV network reliability (Holmlund, 2013), (U.S. D.O.E, 2012). Some of these technologies were already in use. The combination of these smart technologies is commonly referred to as Distribution Automation (DA); which is one of the major aspects in smart grid (Brown, 2012). System monitoring is used to improve system availability, monitor and detects errors in both distribution network measurements and network parameters, and to reduce measurement and communication unwanted signals. Detailed summaries of the main techniques and applications of conventional power systems monitoring were used in (Wu, 1990), (Monticceli, 1999), (Abur and Explito, 2004); (Filho et al., 1990). First, a structure processor verifies that the network parameters (e.g. line and switch statuses) provided to the sensors for state estimations are correct, ensuring that the network model is accurate and up to date (Liu et al.,1992); (Costa and Leao, 1993); (Liu and Lim, 1995);(Alsac et al., 1998). Next is the observability analysis which establishes that sufficient measurement data is measured by the sensors for further estimations. The observability can be quickly determined by examining the null space of the Jacobian matrix (Castilo et al., 2005).

II. DEVELOPMENT OF A SMART MONITORING AND FAULT DETECTION MODEL

The transformation of the contemporary medium voltage network to a smart one with automatic load monitoring and fault detection with service restoration system will offer several benefits. The transformed medium voltage networks will not only be measuring current and voltage level at various feeders but also other parameters such as instantaneous power and the amount of energy consumed over time, losses, future forecasting and field-base station interaction with high speed and accuracy. Data will be measured and stored at hourly intervals.

It comprised of arrangement of sensors that was not read manually but displayed at the base station for record and real-time information which can be used for future planning and immediate maintenance plans. In addition, the smart system design was done with a two-way communications such that feeders can either be interrupted or restored from the base station. Therefore, the designed smart system can be divided into five main blocks which are: Signal Acquisition (SAcq), Signal Training (STra), Signal Conversion (SCon), Signal Computation (SCom) and a two-way Communication. Figure 1a and 1b provide the general functional block diagram of the proposed smart monitoring and fault detection system.

Signal acquisition (SAcq)

Primarily a smart network obtains network parameters continuously at intervals with high accuracy for further computations and relaying (communication) to the base station. Since there are some fundamental powers parameters required,

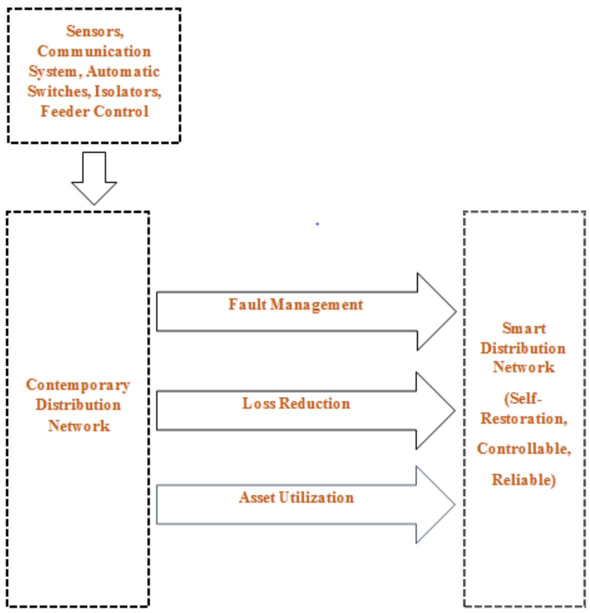

Figure 1a: Smart distribution network

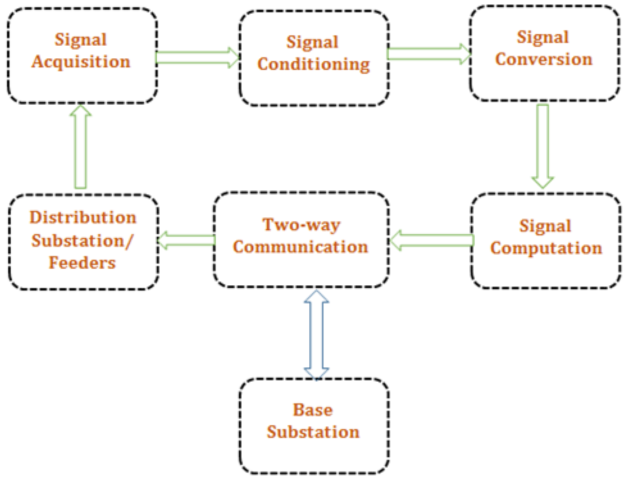

Figure 1b: Functional Block Diagram of the Smart Monitoring and Fault Detection System

the SAcq block was used to obtain these parameters through readings from automatic sensors. The fundamental parameters include: the magnitude of the voltage (|V|) of the network feeders and the magnitude of the current (|I|). Other parameters which are also needed such as the power, energy and losses were evaluated using these fundamental quantities (|V| and |I|).

$$|\mathrm{V}| = |\mathrm{V_i}| \leq (\mathrm{V_{rated}} + 5\%)\ \mathrm{kV} \quad (1)$$

$$|\mathrm{V}| = |\mathrm{V_i}| \geq (\mathrm{V_{rated}} - 5\%)\ \mathrm{kV} \quad (2)$$

$$|\mathrm{I}| = |\mathrm{I_i}| \leq (\mathrm{I_{rated}})\ \mathrm{A} \quad (3)$$

Else, the signal acquisition block sensed an abnormal condition different from the trained levels and error, interruptions and system failures were further investigated.

For a medium voltage network which is under normal operating condition, the voltage level must not be exceeded and the load current must be maintained within the operating capacity of its rated feeders. The criteria for the following equations therefore must be met at all times:

From the conditions above, suitable voltage and current sensors that can measure the voltage at the point of each feeder supply and the load current were selected. These sensors for measuring |V| and |I| were connected directly to the feeders. The typical arrangement of the SAcq block design and the instrumentation circuit is shown in Figure 2. In the Figure, the current transformer (CT) was used as the current sensor; the primary was connected

to the mains which is the secondary side of the transformer at a 33kV substation (AC Source). The secondary of the voltage transformer was stepped down and conditioned to a 5V level which is readable by the microcontroller. This was done by converting the output of the CT to a voltage by connecting a resistor across its secondary by connecting a resistor across its secondary.

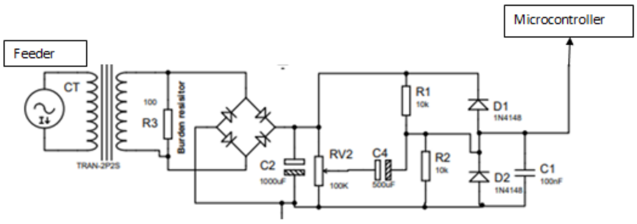

Figure 2: Signal sensing circuit for SAcq

Signal conditioning and processing

The signal conditioning and processing stage involves the preparation of the acquired signals from the SAcq block for the next block in the designed smart system which is the Signal Conversion block. This was achieved by setting the maximum and minimum values for the signals under investigation. This also included increasing or reducing the acquired signal magnitude and sometimes separating meaningful signals from several data signals through filtering. At the time or instance of physical implementation, the signal conditioning stage will be achieved as a completely separate group or combined with the Signal Conversion block as part of the combined circuit. From real life experience and under many circumstances, the acquired signal will require reduction or increase of its magnitude, so that it is acceptable to the signal conversion block. (That is, the minimum or maximum magnitude of the acquired signal must be initialized to a value that is within the readable or acceptable limits of the inputs for the signal conversion block).

Signal conversion

Acquired signals (current and voltage signals) from the sensors are first initialized as explained in the section 3.3.3 and then digitized to be processed further by the microcontroller's software. There are two acquired signals (current and voltage) to be converted or digitalized, therefore a multiplexer and an analogue to digital converter (ADC) was used so that individual signals can be sent in turn during conversion.

Signal Computation (SCom)

Computations were divided into mathematical operations on acquired signals, preparation of data for base station alerts, data storing, system predictions and auto switching activities and other needed relevant functions. Figure 3 shows the block diagram for the various needed blocks relevant to the SCom functions of the intelligent system under design. The mathematical operations evaluated are summarized in Table 2 and these are basically done for power, energy and losses parameters that are not fundamental quantities like the voltage and current magnitudes.

The mathematical operations were also used to evaluate with other customer related issues such as disconnection of erring customers (that is, electricity payment defaulters particularly for commercial, industrial or institutional consumers), and other interval or programmed functions like load shedding and bill generations. A computation bus with high speed was used for multiple tasks and functions involved.

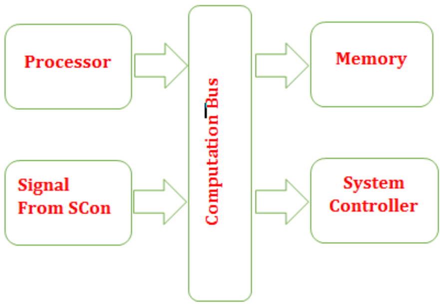

Figure 3: Signal computation block diagram

Signal computation block diagram

Communication medium

Intelligent monitoring system usually employs a wide range of network adapters for communication purposes. The designed system did not consider all wired options which include the Public Switched Telephone Network (PSTN), power line carrier, cable modems and Ethernet, and one of the wireless options will be considered. This is to minimize failure of the developed monitoring system. For prompt actions which will translate into switching actions to be taken, a fast and reliable communication medium must be used. Figure 4 shows the block diagram of the communication cycle. The communication cycle consists of the cloud hardware connection system (CHCS) with a two way interaction with the system hardware and the cloud. This simply means that the CHCS can send information to the internet where there is a dedicated site for the monitoring and switching actions of the feeders and in like manner the cloud can send instructions to the distribution transformer through the CHCS. The CHCS used was a Wi-Fi module which requires only a hotspot to function efficiently well.

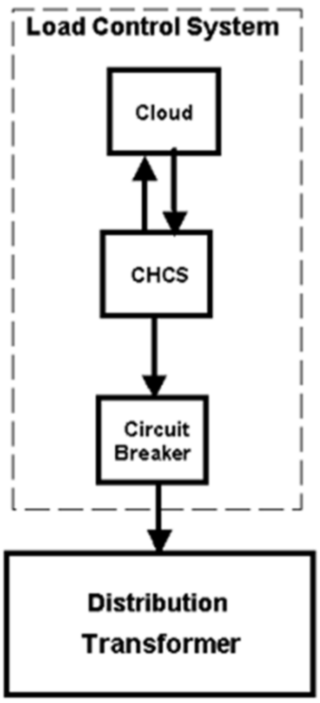

Figure 4: Communication system between substation and base station

Requirements for Smart Monitoring and Control

Monitoring was done by opening the isolators or switches or by sending a message concerning the status of the feeder depending on the diagnoses on individual feeders as detected by the sensing circuits. The sensing circuit utilized algorithms through two stages of flowcharts for monitoring and reporting power quality information and outages.

Functional description of feeder monitor

Each individual feeder which supplies energy to areas has specific energy allocated depending on the loads connected and distributed through the networks to the customers. Therefore the main services and requirements that are needed for a monitoring system must include

1. Monitoring magnitude voltage from transmission lines.
2. Monitoring magnitude of current at the consumers' end.
3. Calculating energy supplied by the line.
4. Investigating loss of voltage.
5. Providing previous data (this will help the technical operator in decision making).
6. Managing data for all process in the network from a base station or control room.

System design of feeder monitor

The design of a load or energy monitoring system that achieved the entire task involves hardware and software designs in the implementation the monitoring system. This enhanced the system design specifications while minimizing costs and ensuring long term system reliability improvements.

(a) Hardware design feeder monitor

The distributed system was interconnected by communication network, Figure 5 provides general layout of the designed distribution system monitoring and control system for MV networks. From Figure 5, the first two layers (field data and RTU subsystems) which monitored and controlled the whole system are interconnected to the Supervisory Centre through a communication system. For this purpose, controller in each layer must have modules dealing with both digital and analog signals as well as suitable interface with the control network.

The design of the monitoring and control system was based on three system layers per network. This was used to monitor load distribution across all

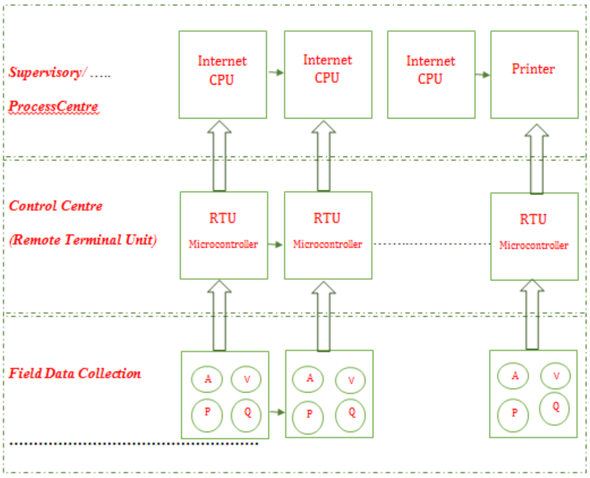

Figure 5: General layout design of monitoring and fault detection system in Medium Voltage Networks

network feeders, data collection through microcontrollers and transmission of actionable outputs to a base station through the communication link as shown in the overall block diagram of Figure 6. These microcontrollers are monitoring devices for the various signals generated from the current sensors on the field (that is through both the current and voltage transformer to read voltage and current signals respectively). On the other hand the microcontroller read all network parameters and thereafter transfers data to the base station through the internet module. The overall block diagram of the designed system have the load sensing unit, the temperature monitoring system, the cloud computing unit and the feeder controller.

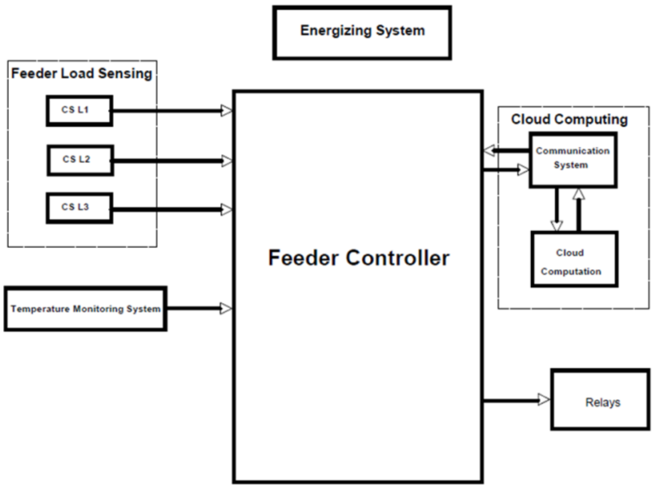

Figure 6: Overall block diagram for the monitoring and fault detection system

(b) Software design

Supervisory software for load monitoring, control and switching application is considered important to be integrated with the hardware design discussed above in order to achieve a good and secured system for reliability improvement. To design a system that will effectively monitor the energy supplied and distributed at each feeder in the region, a collection of sensors and microcontrollers will be arranged in a circuit. The solution involves designing monitoring software by using basic programming language such as MATLAB.

From some previous analysis of the system state assessment done as presented later, a certain percentage of the total energy distributed will definitely be lost due to incessant outages caused by faults and other unplanned occurrences. These occurrences will definitely affect some of the feeders that were scheduled to be in service at a particular instant. The need for the design of an automatic system of monitoring, that remotely monitors load on each feeder, detects faults and diagnose the kind of problem encountered as accurately as possible through automatic sensors, isolators and switches therefore arises. Figure 6 shows the functions of the overall block diagram for the designed smart medium voltage network.

For a medium voltage network which is under normal operating condition, the voltage level must not be exceeded beyond its limits and the load current must be maintained at the operating capacity of its rated feeders. The criteria for the equations (1), (2) and (3) therefore must be met at all times and this becomes the basis of developing the overall block diagram of the monitoring and fault detection system in Figure 6.

If these criteria were met, then the system is healthy, else, if the feeder load sensing block in Figure 6 senses an abnormal condition different from the initialized signal levels and error, interruptions and system failures will be further investigated. Knowing the facts above, suitable voltage and current sensors that can measure the voltage at the point of each feeder supply and the load current were selected. These sensors for measuring the magnitude of the |V| and current |I| were connected directly to the feeders.

The design also has temperature monitoring system which is the temperature condition measuring device. Since abrupt faults cause over heating of cable cores and even transformers bushings overheating, to determine the overall health condition of all substation infrastructure the temperature of equipment must be measured. This can be done via a touch and read temperature sensor, therefore a type K-thermos coupled probe was used. This thermos coupled probe measures temperature by performing cold-junction compensation. After performing the compensation, it digitalizes the measured signal and sends it to the microcontroller.

From the sensors on the feeders output, abnormal or fault currents are detected, then the control algorithm sends control signal via the cloud to the transformer to isolate a faulty feeder within 2 seconds of abnormality detection. The 2 seconds is the time lag needed for program execution. The control algorithm rechecks the system or feeder state after another five (5) seconds to ascertain the exact kind of fault on the feeder. If the magnitudes of the parameters measured are normal and within limits, the feeder is brought back into service and normalcy will be restored on the network even without customers noticing. However if the abnormality remains, then the feeder is marked faulty and a sustained interruption ensues. This starts in the order of data processing, logging on the dashboard and finally opening and closing of breakers depending on the health condition of the network. The next chapter explains the results and workings of the self-healing system. The use of a virtual control room was implemented through the internet of feeders and a site was dedicated to the feeders monitor in the cloud. Here, all the operating conditions data as sensed by the measurement unit and calculated by the computation buses were logged in the cloud and accessed from anywhere and from there, further computations such as availability assessment of the system states can be done.

The circuits for the switching system, Current and Voltage (AV) measurement and signal conditioning are shown in Figures 7 and 8 respectively. The switching circuit is a -12V 5V +12V power circuit. From Figure 7, the variable resistor RV2 sets the voltage level using voltage divider rule to take a portion of the input voltage that is safe for the microcontroller. C4 is a DC blocking capacitor. R1, R2 with D1, D2 are network called diode chopper which prevents the input voltage from going above or below acceptable level. In like manner, in Figure 8 there is an active filter designed around LM 741 and the actual zero crossing detector is LM 339 which is a comparator that compares the non-inverting input (+) with inverting (-). The inverting input is connected to the ground (0V) and whenever the signal is crossing zero volts, the output of the comparator changes.

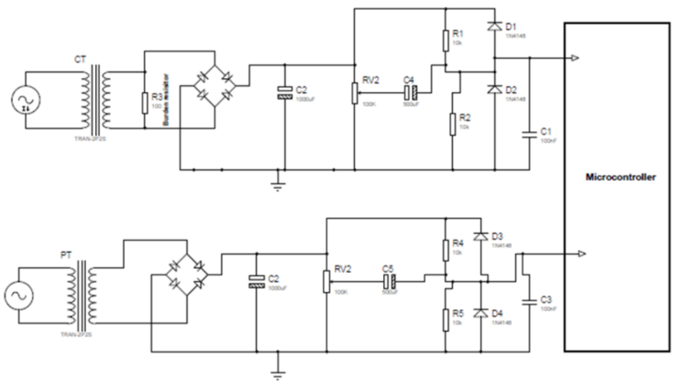

Figure 7: Current and Voltage measurement circuit

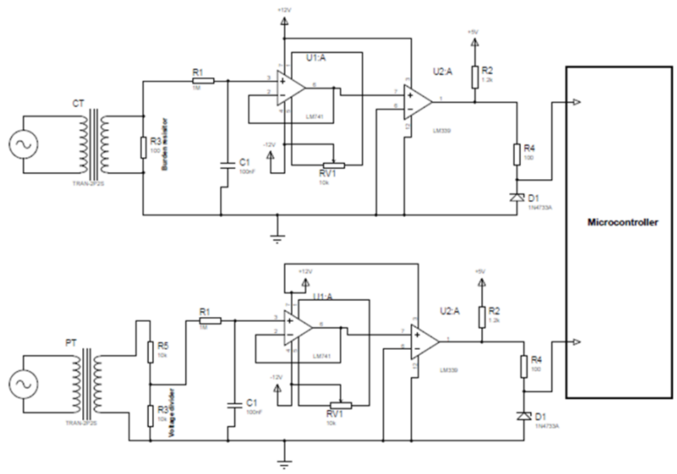

Figure 8: Signal conditioning circuit

Flow charts of monitoring stage

The process for monitoring, fault finding and decision making was illustrated in the flowchart of Figure 9 and SIMULINK was used for implementation. When the engineer or utility operator of the distribution system runs energy application, it should select the feeder numbers from overall system that are supposed to be in service and all data are read. The process of monitoring and fault detection has been grouped into three (3) as in the flowchart of Figure 9.

The system was designed to check for abnormality at each feeder node, that is, the system checks if there are deviations from preset ratings of the feeder. If there is an abnormality such as loss of voltage detected other than the scheduled outage due to load shedding, the system moves to the net phase (b) and performs further checks, otherwise the system goes back to start.

In this phase the system checks for the exact kind of abnormality and determines at what level it occurred and how severe the abnormality is. A tolerance value between the difference between unused energy and load isolated due to load shedding was preset and used to evaluate the optimal load control decision.

The final stage decides if there is an increase or decrease in system voltages or currents and furnishes the electric utility operator of the distribution network with results for further decision based on the diagnosis and further results.

The data collected by the sensors of the monitoring system were stored in the database using Logical Volume Manager (LVM) on an hourly basis.

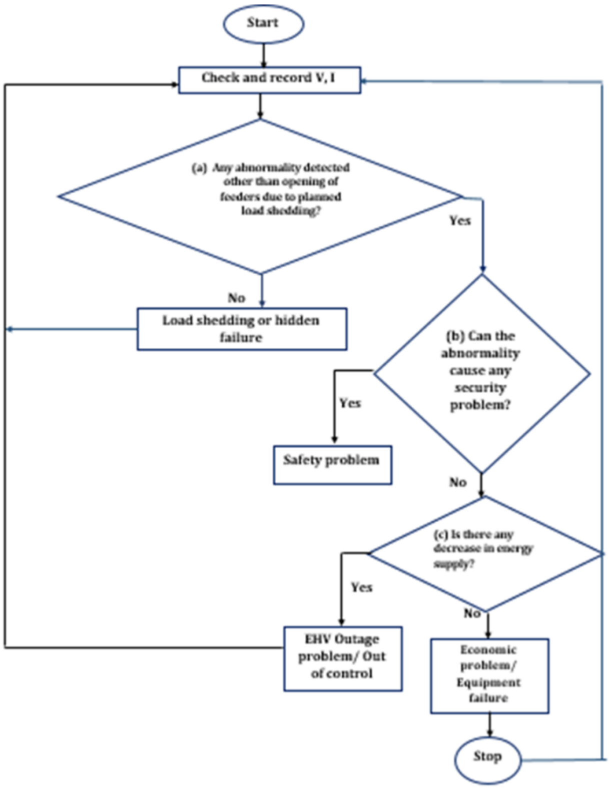

Figure 9: Flow chart for monitoring and fault detection stage

III. EXPERIMENTAL RESULTS

Monitoring and Fault Detection System Performance Evaluation

Results from methods involved in the evaluation of the performance of the smart system described in details in the previous section show considerable improvement in the system. This was done by studying some feeders as prototype in the distribution network under different line loadings using the same number of customers. The system states and availability indices with and without monitoring and automatic switching were calculated. The benefit to cost analysis of each model was carried out in order to strike a balance between smart controls that satisfies reliability and economic constraints. The chart in Figure 11 shows the milestones achieved before and after monitoring in the operation availability and outage duration for each feeder before and after monitoring.

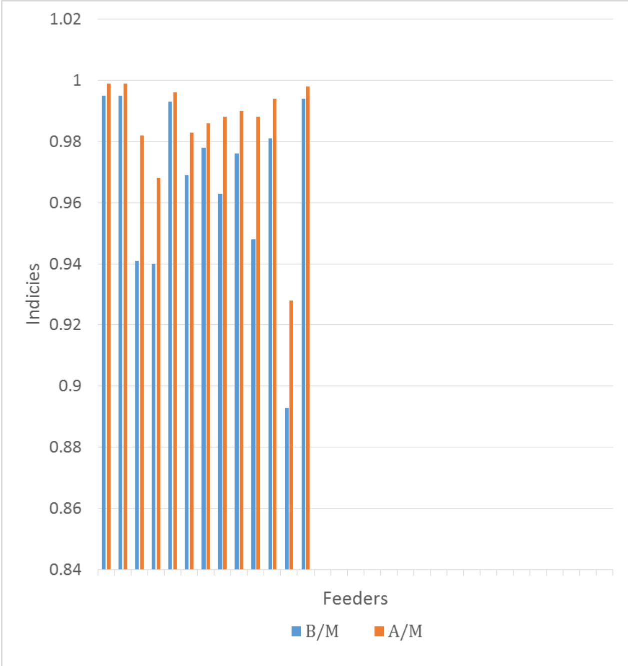

Figure 4.1: Operational availability of test bed feeders before and after monitoring

IV. CONCLUSION

This project developed a system for efficient health condition monitoring and interactive communication during fault occurrence in power systems based on accurate fault localization, and health condition relaying through system communication. Since voltage fluctuations and faults currents are currently the two most critical power quality interruptions and disturbances, fault monitoring was done by keeping strict vigil on both. In the end, there was considerable improvement in the operational availability of the test bed used after monitoring.

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Table 1: Summary of impact of smart monitoring methods

Method	Impact on number of faults	Impact on duration	Impact on number of customer interrupted
Smart fuse saver	Will reduce number of faults by improving fuse failure rates, as fuses operate for temporary faults	Will reduce the outage duration where fuse has blown due to transient fault. Will also provide visibility to SCADA for all fuse operations without intervention from the customer.	No impact on number of affected customers
Transformer	No impact on	Will reduce the	No impact on number

remote monitoring	number of faults	duration by a significant amount because it will provide visibility for all transformer interruption Without customer interventions.	of affected customers.
Smart fault indicators	No impact on number of faults	Will reduce the outage duration by a significant Amount	Will reduce the impact of number of customer affected, by quick identifying the faulted section. This will reduce the sectionalizing and fault finding time.
Automatic feeder switches	Will reduce the number of faults through self-healing	Will reduce the duration of the outage	No impact of number of customers affected through self-healing
Fault location, isolation and service restoration	No impact on the number of faults	Will reduce the duration with a significant amount	Will reduce the impact of number of customers affected through self-healing
AMI and smart meter for outage detection	No impact on number of faults	Will reduce the duration with a significant amount, by providing visibility all the way to the consumer.	No impact on number of affected customers.

Table 3.2: Determination of non-fundamental units

S/N	NON FUNDAMENTAL UNITS	COMPUTATION REQUIRED	DETAILS
1	Peak Voltage	Comparison	$\lvert V\rvert = \lvert V_i\rvert \leq (V_{rated} \pm 5\%)$ kV
2	Peak Current	Comparison	$\lvert I\rvert = \lvert I_i\rvert \leq (I_{rated})$ A
3	Real Power	Multiplication	$\lvert P\rvert = \lvert V_i\rvert\lvert I_i\rvert MW$
4	Energy Used	Multiplication	$TEL_O = (8760 - O_D) \text{ x } P_{Ave}$
5	Losses	Subtraction	$E_{loss} = 8760P_{ave} - TEL_O$
6	Percentage Losses	Multiplication and Division	$\frac{TEL1 - TEL2}{TEL1} \text{ x } 100\%$