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Research Article

An Enhanced Framework for Data Acquisition and Processing for a Power Distribution System

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Abstract

The optimization and synchronization of substation operations, including data acquisition and processing, are widely acknowledged as crucial, particularly given the rapid pace of technological advancement. An optimized data collecting and processing scheme is developed in this research as an effort to enhance substation operations. This work, proffers a solution that comprises data generation using a substation model, improved data collecting from modeled apparatus and finally application of data processing and consistency checking algorithms. The process of data collecting and processing is automated and repeated in equidistant time intervals. Results of processing and related reports are concisely displayed for those monitoring the substation operations in remote locations and even on remote devices in real time without redundancy.

Keywords	*Electrical Transmission; Electrical Distribution; Supervisory Control and Data Acquisition (SCADA), Remote Terminal Unit (RTU)*
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Introduction

An electric power system comprises interconnected electrical components responsible for generating electrical power from various sources such as coal, water, gas, wind, nuclear energy, and oil. Once electricity is generated, it needs to be transmitted over long distances from power plants to substations and eventually to consumers. In its most general configuration, Electric Power Systems (EPS) encompass three primary components: generation, transmission, and distribution (Glover and Sarma, 2002; Strielkowski *et al*., 2021). In electricity transmission, high and medium voltage electricity is conveyed through a network of transmission lines from generation facilities to power distribution facilities located near populated areas. 400 kV, 275 kV, and 132 kV are typical voltage levels used in high-voltage transmission systems (Lazaropoulos and Cottis, 2009; Nor *et al*., 2021).

The distribution subsystem (DS) is responsible for stepping down the high-voltage power received from the transmission system and delivering it to end-users through a network of cables. The DS plays a crucial role in the electric power system by bringing electricity from the transmission network to end-users, such as homes, businesses, and industrial facilities. These voltage levels – 240 V, 11 KV and 33 KV - are commonly employed for distributing electricity from the distribution substations to consumers' premises (McDonald et al., 2012; Jendernalik *et al.,* 2022). Substations are vital components in electric power systems, serving as critical nodes for voltage transformation, switching, protection, and control. Substations typically incorporate components dedicated to switching, protection, control, and voltage transformation, as specified in the IEC 61850 standard from 2003. They serve as indispensable elements within any power network. In the language of electrical circuits, substations are likened to nodes, where numerous branches converge. Their primary function is to enable the interconnection of transmission lines and cater to various auxiliary needs. Electric power substations typically serve as crucial intermediaries' units, which link the power generation system to the extensive user networks (Kabeyi *et al*., 2023).

Advancements in complexity and technology have led to more sophisticated methods of electric energy shedding, enabling better control and utilization of energy resources. Transitioning from a predominantly manual electric load shedding control system to a computer-based system offers significant ease and efficiency. With computer-based systems, load shedding can be executed swiftly and accurately (Holmukhe et al., 2022). Sharwa (2013) details the integration of a Supervisory Control and Data Acquisition (SCADA) system alongside a robust fibre optic communication infrastructure for the automatic real-time detection of system conditions. Ribeiro *et al.* (2007) delineates SCADA within electric power management as a complex system comprising one or more computers equipped with suitable application software, linked via a communication system to numerous remote terminal units (RTUs), commonly known as intelligent electronic devices (IEDs). Roshan *et al.* (2012) elucidates that high-scale SCADA systems with enhanced capabilities are not only employed for wide-area system operation but also encompass functions such as distribution management system (DMS), Energy Management System (EMS), diverse network applications, and metering management systems

Though several works have been done on the application of SCADA, there are some grey areas in power consumption optimization. The aim of this research is to formulate a framework which includes methods, algorithms and procedures for the development of data acquisition, data transfer and processing that would operate in a synchronized manner so as to optimize operations of a distribution system. The specific objectives of this research are:

(a) To effectively characterize the operation of a distribution system via data acquisition and processing.
(b) To adopt a series of mathematical formulation and algorithms for improved data acquisition operations of the proposed system.
(c) To develop a novel simulation model that effectively brings to life the improved system leveraging on a series of methods, procedures and mathematical expressions.

Volume 5, Number 1 | 2024 | 27-38 | *DOI: https://doi.org/10.5281/zenodo.11049188*

Materials and Methods

System Design

The two most important features of this design are: collecting data from all the devices installed in the substation and the other one is processing the collected data/creating desired output.

Data Collection

The model of electrical sources generating power flow through the substation entails an ideal generator with equivalent impedance connected to the neighbouring substation network. It operates with specified parameters including received voltage magnitude, phase angle, and a frequency of 50Hz.

Switching Element

Circuit breakers and disconnect switches installed in substation are both model with the switching element block. For this research, they are controllable switches. Contact status (digital measurement) of all switching elements is captured through the appropriate control blocks. This measurement is done using intelligent electronic devices (IED). This information is later used in substation topology determination. The status can only have two different values: '1' for closed and '0' for opened position.

Analogue Measurements

There are two types of analogue measurements: Current and voltage. These are Continuous time domain signals obtained from current transformer (CT) and voltage transformer (VT) blocks are fed to the Fourier analyser to produce the magnitude and phase angle (Math Work Inc, 2002). These two parameters completely determine phasors of measured electrical quantities.

Distribution measurement is determined based on two rules:

(a) Each circuit breaker has two current measurement (one on each sides).

(b) Each transmission line has one current measurement, one voltage measurement and calculated active and reactive power measurement

Triggering Process

The triggering is an important step in the process of providing captured measurements. Its purpose is to control data exchange rate between components and to call processing subroutine that manages utilization of measurement from model.

Processing and Consistency Checking

This is the core of the processing routing. After the snap-shot data is pre-processed, it is further handled by various processing routines. The routines make the core of the system (these routines are implemented in the control program me of the simulation). Several different processing and consistency check algorithms are implemented in the processing routine in this research work.

Double Current Measurement

Some branches have two measurements of currents (branches with circuit breakers). One redundant measurement of current can also be obtained from a digital relay or Intelligent Electronic Device (IED) that is monitoring the branch (Anderson, 1999). The algorithm calculates one value for the branch current based on both measurements and performs consistency check at the same time, check for existence of redundant measurement of current in the branch; if not, the measurement is branched current and skip the rest of the logic. If redundant current exist, consistency check is performed such that difference between measured phasorvalue should be less than certain percentage of the absolute value of a larger measurement.

Volume 5, Number 1 | 2024 | 27-38 | DOI: https://doi.org/10.5281/zenodo.11049188

The current in the branch is determined as an average value of two current measurements.
The variable MPDMD (Maximum Permit able Double Measurement Discrepancy) determines the percent. For this research, 0.0001 is the assumed default value. The flow chart of algorithm is shown in Figure 1.

Kirchoff's Current Law Consistency Check

This type of check can be performed for all nodes where three or more branches meet and the measurements of current exist in all branches. Check for external node; if present first Kirchoff's current law is not performed. Reason is that branch split into two part (connecting two substations). If internal node is present; Determine the incident branches. Check to determine all branches are equipped with the units measuring currents; if not, skip (since Kirchoff's current law cannot be performed). If present, first Kirchoff's law condition is checked.
Ideally, the sum of currents should be zero. But the routine allows the existence of certain error whose value is initiated in the research as 0.0001 default. Algorithm flow chart is shown in Figure 2.

Branch Status Determination

Determination of a branch status is accomplished considering all the switching elements in particular branches. The configuration of switch elements is either (1) disconnects the switch or disconnects the circuit breaker and (2) disconnects the switches in the branch. . If the branch has only one switching element, it is a disconnect switch. Hence, status is determined based on the status of the switch. Branches with three switching elements, status is determined to be "1" closed only if all switching element in the branch are "1". But if any one switching element is "O" opened, the branch status will be determined as "O". Only branch status is determined. No check done. Algorithm flow chart is shown in Figure 3.

Branch Current Value Status

The following algorithm is developed to perform consistency check between branch current value and branch status. It is the most complex algorithm applied that determines correct switching element status based on additional information about branch current. Current as a zero flow if current value is less than NCV (Null Current Value). Assumed default value of NCV is 0.0002. The non-zero value status of the branch is "1" otherwise "O". In case enough voltage difference exists to create the current but branch flow is still zero, status is determined to be "O". If already be "O", it is not changed. When the branch status is "1" but no current flow through the branch, the algorithm states the status number and "No flow through closed switch in branch." Figure 4 shows the algorithm flow chart.

Time Series Changes

This algorithm performs consistency check of changes from the previous state. Analogue set of measurements and topology data are examined and their values compared between the current and the previous snapshot. It determines the Maximal Permitted Analogue Measurement Changes (MPADC).

Algorithm examines the change in topology and the change in analogue measurement values. If no change in analogue or topology values, no action is performed. Consistency fulfilled. A change in topology (status) with no changes in analogue measurement; hence, tagged "no bad data". A change in analogue measurement with no change in topology, is considered a very serious case. As shown in Figure 5.
In Figure 1, check is perform on current measurement after which control is passed for current law check in Fig2 and the various values are stored. The branch status algorithm is then giving the next priority and the value obtain are stored in Fig 3. The algorithm in Fig.4, compares the values of each branch current and status. Whatever changes gotten after all checks are done are then compare with predetermined values, processed and send to various terminals or store.

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Volume 5, Number 1 | 2024 | 27-38 | DOI: https://doi.org/10.5281/zenodo.11049188

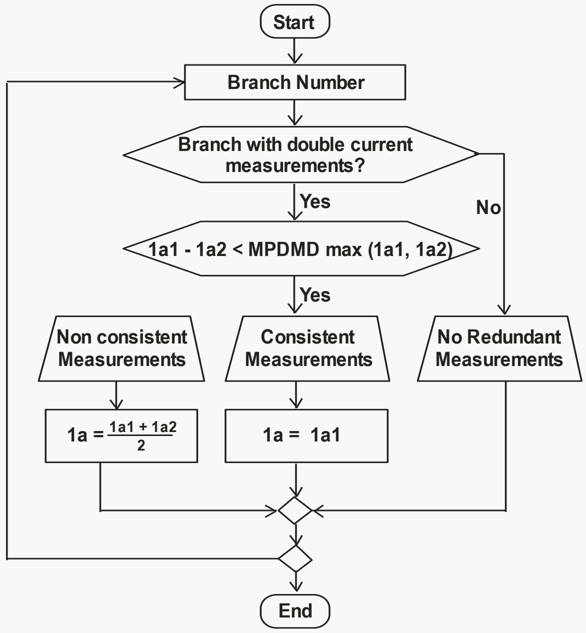

Fig. 1: Flowchart of the algorithm for branch currents consistency check

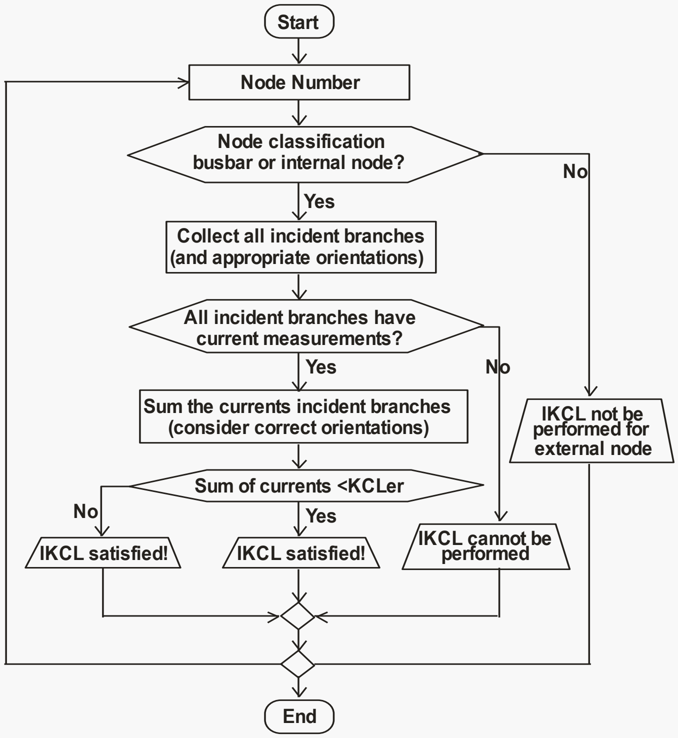

Fig. 2: Algorithm for Kirchhoff's current aw check

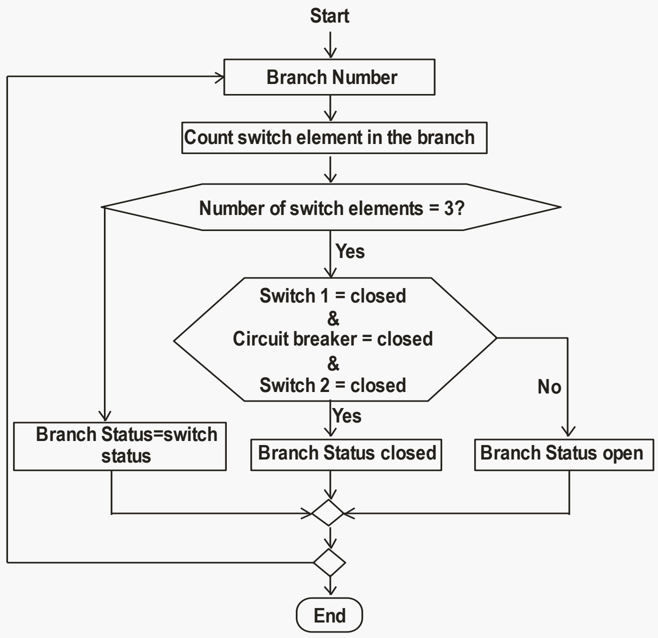

Fig. 3: Flowchart of the algorithm for branch status determination

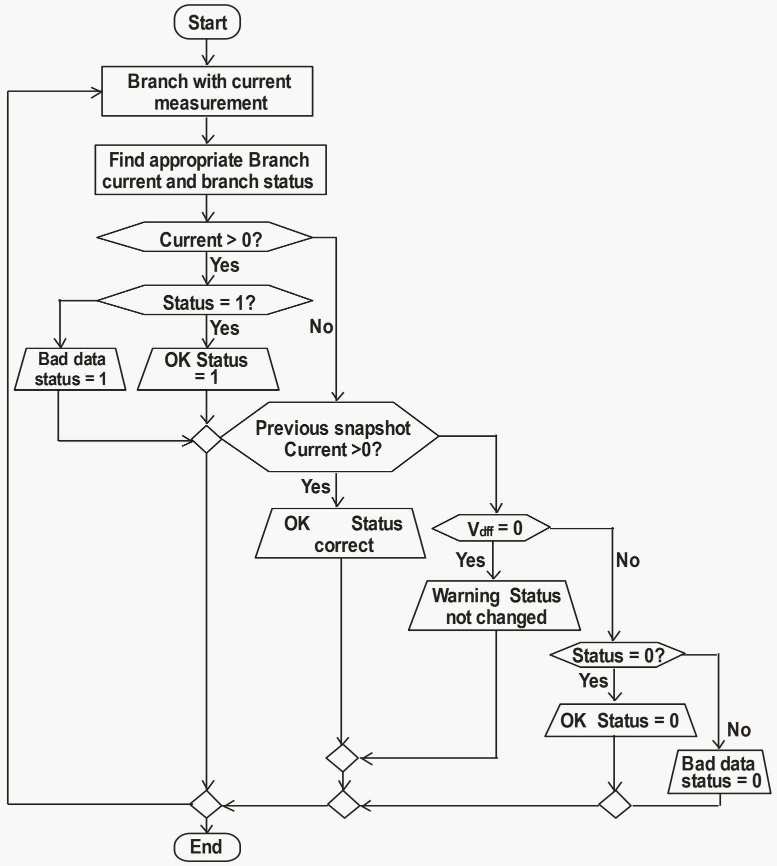

Fig. 4: Flowchart of the algorithm for consistency check of branch current and status

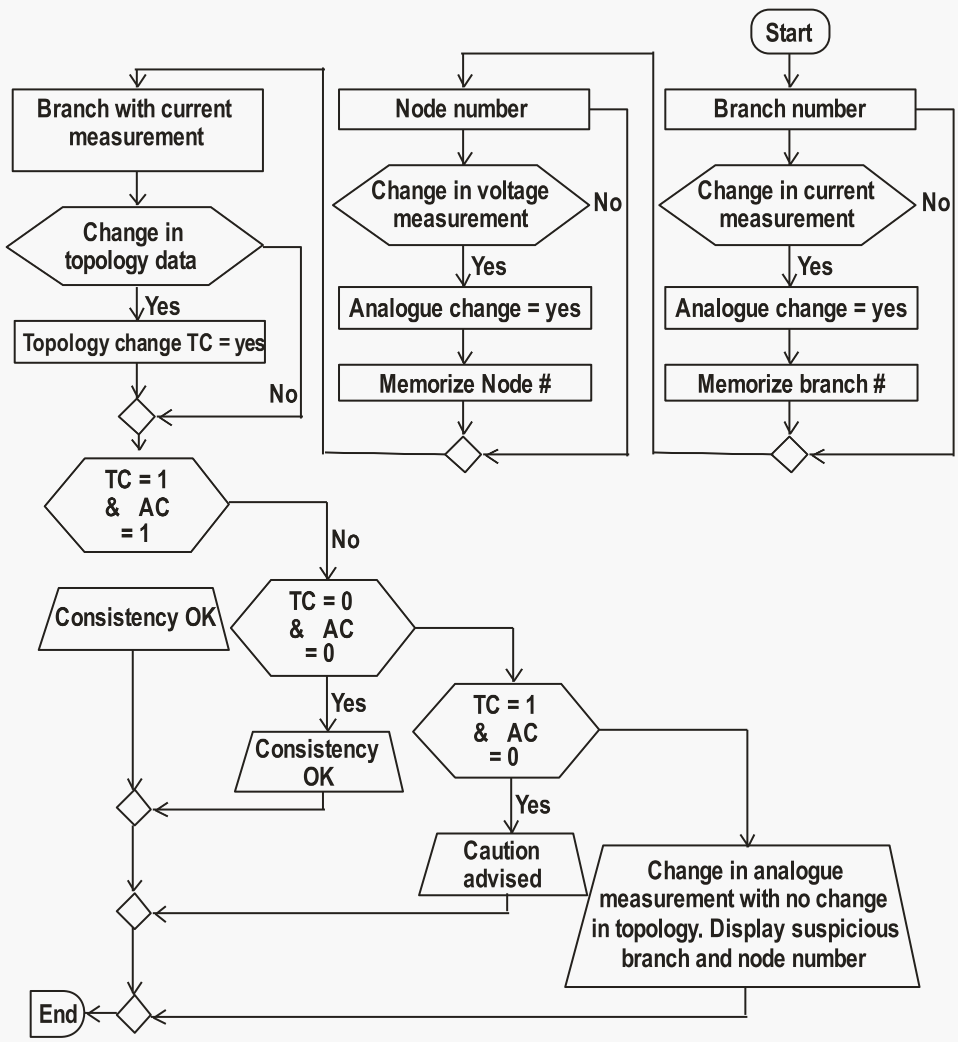

Figure 5: Algorithm that performs change of topology

Mathematical Characterization of Data Acquisition System

During normal operation of the system, data samples are processed continually from the measurement taken of instantaneous voltages and currents. Using sequential samples, the algorithm can extract information about the measured values such as amplitude and phase angle faulted or other system conditions can be determined by comparing the measured values to predetermined settings (assumed default settings). Samples obtained from the sinusoidal signal can be described as mathematical equation. The assumption made is that the voltage and current maintains sinusoidal form under varying conditions: amplitude and phase of the signal can be obtained using a limited number of samples.

Samples obtained from sinusoidal signals can be described as:

$$v(t) = V_1 \sin(\acute{\omega}_0 t) \qquad 1$$

Then the first derivative of the signal is

$$V^1(t) = \acute{\omega}_0 V_1 \cos(\acute{\omega}_0 t) \qquad 2$$

Where:

$V^1(t) = \frac{d}{dt}[v(t)]$

$V^1(t) = \acute{\omega}_0 V_1 \cos(\acute{\omega}_0 t)$ 3

From Eqs.1 and 2.

$[v(t)]^2 = V_1^2[\sin(\acute{\omega}_0 t)]^2$ 4

$[v(t)]^2 = V_1^2[\sin(\acute{\omega}_0 t)]^2$

$[\frac{v'(t)}{\acute{\omega}_0}]^2 = V_1^2[\sin(\acute{\omega}_0 t)]^2$ 5

The peak value of the sinusoidal signal can be expressed as:

$V_1 = \left([v(t)]^2 + \left[\frac{v'(t)}{\acute{\omega}^0}\right]^2\right)0.5$ 6

$v'[K] = \frac{\Delta v}{\Delta t} = \frac{v[k+1]-v[k]}{\Delta t}$ 7

$V[K] = \left(v[k]^2 + \left[\frac{v(k+1]-v[k]}{\acute{\omega}^0 \Delta t}\right]^2\right)0.5$ 8

$\emptyset[K] = tan^{-1}\left(\frac{v[k]\acute{\omega}^0\Delta t}{v[k+1]-v[k]}\right)$ 9

The above operations performed on instantaneous voltage are equally performed instantaneous current

$I[k] = \left\{\frac{\{i[k]^2+i[k+1]\}- i[k]^2)}{(\Delta t)\hat{}2}\right\}0.5$ 10

$\emptyset[k] = \tan^{-1}\left\{\frac{i[k]\acute{\omega}_0\Delta t}{i[k+1]-i[k]}\right\}$ 11

Leveraging the first and second derivatives it can reduce errors due to the decaying DC components (Russel, 1978). Using the second notations as for the previous mathematical simultaneous in Eqn. 7, the second derivatives of the sinusoidal signals.

$Vk = \frac{v[k+1]- 2v[k]+ v[k+1]}{(\Delta t)\hat{}2}$ 12

Thus the amplitude and the phase angle of the sampled signal can be obtained as

$V[k] = \frac{1}{\acute{\omega}^0}\left(v'[k]^2 + \left\{\frac{v"[k]^2}{\acute{\omega}^0}\right\}^2\right)0.5$ 13

$\emptyset[k] = \tan^{-1}\left\{\frac{v"[k]}{\acute{\omega}^0 v'[k]}\right\}$

14

$I[k] = \left(\frac{1}{\acute{\omega}^0}[I(k)]^2 + \left[\frac{I"[k]}{\acute{\omega}^0}\right]^2\right)0.5$

15

$\emptyset[k] = \tan^{-1}\left\{\frac{i''[k]}{\acute{\omega}^0 I''[k]}\right\}$

16

The mathematical formulations from eqns. 3.8 – 3.11 and eqns. 3.14 -3.17 are extremely sensitive to deviations.

$v(t) = K_n e^{-t/}\pi + K_1 \sin([?]_1 t + [?]_3) + K_3 \sin([?]_3 t + [?]_3)$ 17

Where τis the time constant describing the decaying exponential. Using the first three elements of the Taylor series expansion of the DC component, the previous equation can be written as

$$v(t) = K_n - K_0 t/\tau + K_0 \frac{t^2}{2\tau^2} + K_1 \sin([?]_1 t + [?]_3) + K_3 \sin([?]_3 t + [?]_3) \quad 18$$

$$\sin([?]t + [?]) = \sin([?]t) \cos([?]t) + \cos([?]t) \sin([?]) \quad 19$$

Eqn.19 can be written as:

$$v(t) = K_0 - K_0 t/\tau + K_0 \frac{t^2}{2\tau^2} + K_1 \sin([?]_1 t + \cos[?]_1) + K_1 \cos([?]_1 t + \sin[?]_1) + K_3 \sin([?]_3 t + \cos[?]_3) \quad 20$$

The above equation is value for any t. with the following notations

$aK_1 = 1$

$aK_2 = \sin([?]_1 t_k$

$aK_3 = \cos([?]_1 t_k$

$aK_4 = \sin([?]_3 t_k$

$aK_5 = \cos([?]_3 t_k$

$aK_6 = t_k$

$aK_7 = t^2 k$ 21

And

$x_1 = k_0$

$x_2 = k_1 \cos([?]_1)$

$x_3 = k_1 \sin([?]_1)$

$x_4 = k_3 \cos([?]_3)$

$x_5 = k_3 \sin([?]_3)$

$x_6 = \frac{-k0}{2\tau^2}$

$x_7 = \frac{-k0}{\tau}$ 22

Can be written to consecutive value t_1, t_2 …………………………………… t_m as

$S_1 = \sum_{n=1}^{7} a\, 1nxn$

$S_2 = \sum_{n=1}^{7} a\, 2nxn$

.

$S_m = \sum_{n=1}^{7} a\ mnxn$ 23

The values of x_j can be obtained using the pseudo-inverse of matrix A = [a_{ij}],

Where i = 1, 2, …… m and j = 1, 2, ……7. The matrix format of eqn. 23 is

$S = AX$ 24

Where X = [X_j], with j = 1, 2, ……..7. It can be subsequently written that:

$A^T S = A^T AX$ 25

$(A^T A) - 1AS^T S = (A^T A)^{-1} A^T AX 27$

As a result:

$X = (A^T A)^{-1} A^T S$

Using the values of X, the DC component, the amplitude and phase angle of the fundamental and the third harmonic can be obtained.

Results and Discussion

The propose system architecture of this research work is shown in Fig. 6.

The following steps represent how it works.

Integration of Measurement Devices

Measurement devices such transducers and instrument transformer for measuring analog quantities such as branch current and voltage are integrated IED (Intelligent Electronics device) for measuring status of devices like circuit breakers are integrated to remove redundancy and error in measurement. Accuracy is of utmost importance

Processing of Data Obtained

Data obtained are processed using the mathematical characterization of eqn. 1-17 to get the phase, current and voltage values which are consistently compared to predetermine data's stored. These values (phase, current and voltage) extremely sensitive to deviation which determine whether there is fault in a branch or not.

SCADA (Supervision Control and Data Acquisition System)

This is the installed brain of the substation proposed system for acquisition and processing of the large volume of data in the system with a Remote Terminal Unit for feeding information collected to handheld devices of selected end users.

Decision making by the SCADA

Decisions are made by the SCADA after collecting, checking and processing of data. These decisions are used by the control unit in opening or closing circuit breakers or displaying values as the case maybe. According to the related literature, this work adopts SCADA system as the central artificial intelligent system with propose integration of digital IED sensors, analogue CT and VT. The aim is to combine the advantages of both the digital and analogue sensors in measurement, taking their mean value and comparing to a predetermine value stored in the SCADA for a much improve data processing by the SCADA in other to completely eliminate error in distribution system if all other conditions are constant.

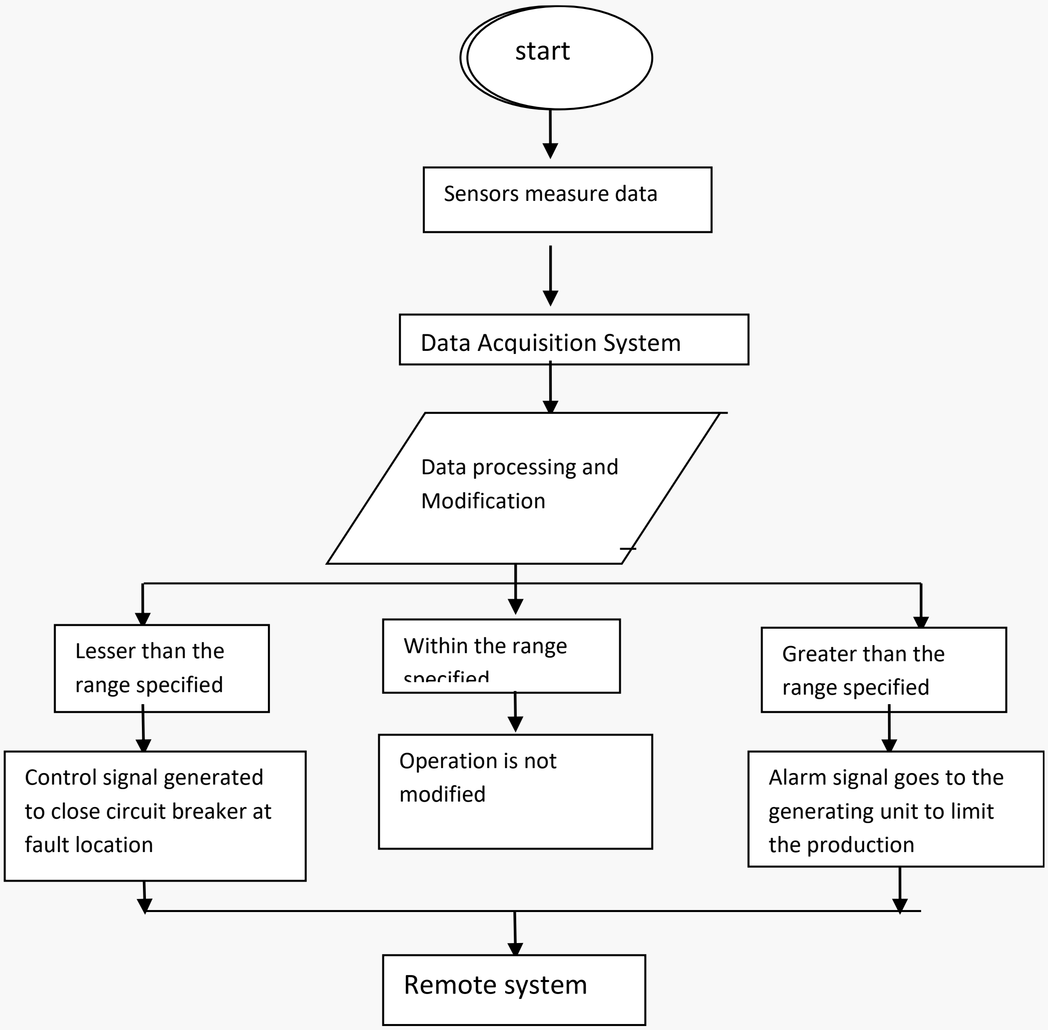

Figure 6: Flow diagram of data flow model

Conclusion

This research has demonstrated that power distribution substations can be optimally automated through systematic collection, processing (of both analog and digital data), and transmission of control signals to activate devices such as breakers. The result is to create a better power quality distribution by effectively monitoring and controlling information within the substation to reduce downtime, mistakes, faults and errors created by personnel. Hence, improving energy saving with the option of sending information to remote devices. While the research has optimized the substation, there are areas for further exploration, such as developing algorithms capable of identifying fault types, pinpointing the exact location of occurrence, and assessing the current condition of devices and facilities within the substation (determining whether they are functioning properly or exhibiting weaknesses) along with identifying specific areas of weakness.

Volume 5, Number 1 | 2024 | 27-38 | *DOI:* https://doi.org/10.5281/zenodo.11049188

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