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A Survey of Fault Location Techniques for Distribution Networks

دراسة تقنيات تحديد موقع الخطأ في شبكات التوزيع

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KEYWORDS:
Fault location, Distribution networks, Fault passage indicators, Artificial intelligence, Impedance methods, Injection methods, PMUs, Smart meters.

الملخص:- **إرتباط المجتمعات الحديثة بالكهرباء وتطبيقاتها أصبح يتطلب توفير مستوى أعلى من إستمرارية هذه الطاقة. التوسع في الشبكات الكهربية وأنظمة الطاقة جعلها أكثرعرضة للأعطال الكهربائية المختلفة. نتيجة لتلك الأعطال يجب فصل العناصرالمعيبة وعزلها في أسرع وقت ممكن للحد من الأضرار الناتجة وإزالة حالة الطوارئ من النظام بأكمله. جودة الطاقة في الشبكات الكهربية تحث المسؤولين عنها بسرعة اكتشاف وتحديد مكان الخطأ واسترداد النظام وبالتالي تقليل وقت انقطاع التيار الكهربائي والتكاليف المرتبطه بذلك. كل هذه الظروف أبرزت أهميه تحديد مكان الخطأ والتقنيات المستخدمة للكشف السريع عن المنطقة التي بها خلل. في هذا البحث يقوم الباحثون بتقديم عدة مقارنات تقوم بتصنيف واستقصاء عدد كبير من طرق تحديد موقع الخطأ في شبكات التوزيع .**

***Abstract*— Since recent societies become more hooked into electricity, a higher level of power supply continuity is required from power systems. The expansion of those systems makes them liable to electrical faults and several failures are raised due to totally different causes. As a result of these failures, the faulty element ought to be disconnected and isolated as soon as possible to reduce the damage and remove the emergency state from the whole system. Power quality considerations impose the grid to spot the faulted area as rapidly as doable, which forces utility operators in speeding up fault detection and system recovery and subsequently decreasing blackout time and pertinent costs. All these conditions have raised incredible significances about investigating methods and techniques used for fast detecting of faulted area, thus this matter needs to be pulled in broad consideration among researchers in power systems. In this paper, a comparative environment classifies and surveys a wide number of fault location procedures for distribution networks. The paper can be considered as a guide for operating engineers and researchers to settle on the foremost viable plausibility backed their existing framework and necessities.**

I. Introduction

Electrical networks comprise generation, transmission, and distribution systems. Distribution networks are the last stage of transmitting electricity to individual customers. The fast development in human-life needs in the previous few decades has increased both the electricity requirements and the number of electric users, consequently, the distribution networks have to increase distribution lines and feeders to provide consumers with their electricity requirements. The extension of distribution networks has increased the possibility of faults and the need for new methods and techniques to detect and locate the faults as fast as possible.

For many years, utilities and electric energy researchers have surveyed the electricity outages reasons over power networks. The main reasons for energy outages in electric power systems are the electrical faults, particularly those faults that occurred in distribution networks (about 80%). These faults are raised due to several reasons including equipment failure, lightning, storms, adverse weather, rain, insulation breakdown, trees,

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birds, etc. [1]. Fast and accurate locating of the fault along distribution networks enhances system reliability and continuity of supply, quick reclamation of the power supply and subsequently decreasing service outage time. Based on the critical issues of fault locating, different techniques have been proposed to help operation engineers to locate faulted point as quick as possible.

Generally, most of the methodologies that identify the fault location are applicable for transmission lines, unlike distribution networks. The detection of faults in distribution networks is a complex task due to various parallel branches, numerous taps along the feeders, multiple conductors, and complex structure, in addition to less amount of monitoring apparatus, poor communication, and data transfer infrastructure [2].

This paper presents a comparative analysis between most of the commonly used techniques that are applied to spot the faulty point in distribution systems. The comparison includes the progress and improvements of these techniques due to new technologies of monitoring and communication. The leftover portion of the paper is formed as follows. Section II illustrates classification of fault location methods. Section III describes the non-electrical techniques. Section IV shows the electrical-data based methods to locate the fault. Finally, the conclusion of this paper is introduced in section VII.

II. Fault Location Methods

Fault detection techniques can be divided into two main groups: *(i) the non-electrical data-based techniques*, and *(ii) electrical data-based techniques*. The classifications of each group are illustrated in Fig. 1.

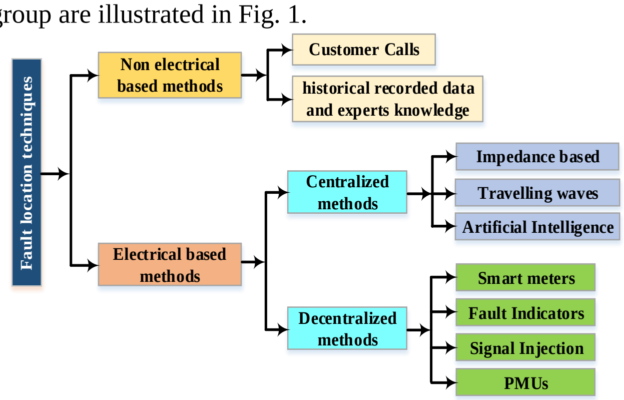

Fig.1. Classifications of fault detection methods

The first primitive methods to detect fault points were the non-electrical based methods due to lack of required technology and infrastructure. These methods are based on the available information from customers, experts, stored history, etc. The large time required to determine the faulty point in addition to the poor accuracy of fault location are considered the main defects of these methods.

Motivated by recent technology and the new era of communication mediums to transfer collected data to control centers, electrical-based techniques were developed. The main advantages of these techniques lie in improving time factor and accuracy to spot the fault points compared to the non-electrical based methods [3, 4]. The main advantages and disadvantages of the two groups are summarized in Table I.

III. Non-Electrical Date Based Techniques

In this section, the main non-electrical data-based methods used to detect fault location are presented. These methods are based on either customer calls reporting power supply interruptions or historical data collected from previous failures and experts' knowledge.

Customer calls (trouble calls) are the most traditional methodology to detect faulted areas. When there is trouble (such as faults) in a system, a certain portion of the network might be de-energized. In the areas affected by the power outage, the customers tend to call the utility company to let them know about the power- failure. In other words, when the service is not available, consumers quickly complain loud and long to whoever will listen. By knowing the customer's address, the utility company can narrow down the faulted area. Technicians drive around the neighborhood searching for a pop-out fuse or broken line to locate the fault [4-9]. User calls based method accompany some disadvantages: (i) for night-time occurring faults, there might be a little number of client calls which makes the interrupted area reporting whichever challenging alternately impossible, (ii) fake calls need an aid to be realized as true ones otherwise they will cause false determination and time-wasting, furthermore (iii) this entirety process requires unacceptable time.

Historical recorded data and ***experts' knowledge*** methods for fault location were discussed in Refs. [10, 11]. The authors in [10], utilized rough set theory as a data-mining tool to arise appropriate rules and patterns for faulty equipment diagnosis and fault location in distribution system. Data mining is a branch of computational intelligence that introduces new techniques and mechanisms for processing extensive data [12]. The rough set theory is one of the data mining hypotheses that can be utilized to model the occasional associations between the faulty equipment and the proofs about perceptions throughout feeder outages and the encompassing situations [4].

In [11], the authors applied a probabilistic graphical model (Bayesian network) to incorporate expert knowledge and historical data for fault location in the power delivery system and examined the method on a distribution feeder in Taiwan. The developed Bayesian network uses localized representation for propagating evidence to locate fault at the points of interest. It depends on information elicitation, the viability of the knowledge base, and computation of probabilities.

A comparison between the advantages and disadvantages of non-electrical date-based methods are listed in Table II.

IV. Electrical Date Based Techniques

Electrical data-based methods used to pinpoint the faulty points are partitioned into two basic groups; (*i) Centralized methods* and (*ii) Decentralized methods.*

Regarding centralized methods, the metering instruments are executed at the main station and the measured values are then used to specify the fault location. Whereas in the decentralized methods the measurements on different feeders and buses are transmitted to the control center with appropriate communication links to detect the faulted points. Table III presents a comparison between centralized and decentralized methods. A detailed discussion of these methods is given in the following subsections.

TABLE I
COMPARISON BETWEEN NON-ELECTRICAL AND ELECTRICAL BASED METHODS.

Method	Advantages	Disadvantages
Non-electrical data based	- Simple - Low cost - Practical	- Time-consuming - Low accuracy and sensitivity - Large amount of recorded data and customer help based - Identify faulted area not point
Electrical data based	- Short execution time - High accuracy - Identify faulted point	- High implementation cost - Complicated - High sampling rate measuring units - Strong communication infrastructure to transfer data

TABLE II
CHARACTERISTICS OF NON-ELECTRICAL BASED METHODS.

Method	Advantages	Disadvantages
Trouble calls method	- Simple - Low cost - Practical	- Little calls during the night - False calls - Customers based - Time-consuming - Low accuracy
Historical recorded data methods	- Low cost - Based on previous data without customer help	- Large amount of recorded data - Complicated - Time-consuming

IV.1. Centralized methods for fault detection

In centralized methods, fault detection techniques use the measurements that carried out at the primary substation only. Impedance based strategies, travelling wave techniques, and artificial intelligence methods are the main centralized methods.

1. Impedance based methods

In these methods, voltage and current values are measured at one or two ends of protected lines. The apparent impedance is calculated based on these measured quantities. The distance of the fault from the measuring point to the fault location can be estimated from the calculated apparent impedance. As this impedance is proportional to the total length of the protected line, the distance to the faulted point is computed from the measured impedance with the help of line impedance per unit length. In this method, the accuracy of the fault location depends on the accuracy of the calculated impedance [3].

The impedance-based techniques can be grouped into two leading groups, (i) one end-based techniques and (ii) two end-based techniques.

Methodologies given in [13-16], employed principles of one end impedance-based techniques while Refs. [17, 18] discussed the two-end impedance-based techniques. In [19] and [20], the impedance-based philosophy is applied for radial as well as looped networks in the presence of distributed generators.

A. One end-based techniques

One-end impedance-based procedures evaluate the impedance to faulted point through the voltage and current values obtained from meters held at a single point (major substation) [17]. Fig. 2. shows a model used to illustrate the one-end philosophy.

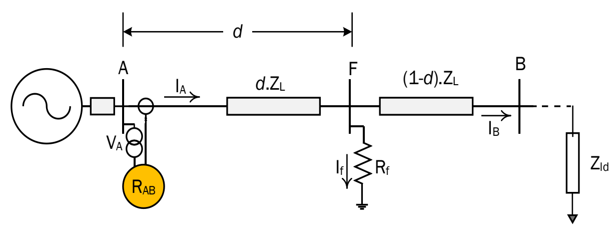

Fig. 2. A model for one-end based methods.

With the help of measured voltage and current at the main substation, the fault distance d is obtained as illustrated in (1).

$$V_A = d\, Z_L\, I_A + R_f\, I_f \quad (1)$$

where V_A is the measured voltage at bus A, Z_L is the line impedance, d is fault distance from measuring point A to fault point F, I_A is the current flow from point A to point F, R_f is the fault resistance, and I_f is the fault current.

In spite of the simplicity of the required measurement framework, some drawbacks are recorded. The foremost common disadvantage is the numerous fault locations issue. This is typically noticed when the distance d corresponds to diverse network points where each one is located in a different section. A conventional arrangement for this issue is to combine these methods with extra instrumentation, or complementary signals like voltage droop, currents variations, etc. In addition to multiple estimations problem, fault resistance (R_f) has a great influence on the measured distance, which definitely increments the location error when it is not small [17].

TABLE III
COMPARISON BETWEEN CENTRALIZED AND DECENTRALIZED METHODS.

Method	Advantages	Disadvantages
Centralized methods	- Low cost - Cost-effective - No need for modern communication technology	- Time-consuming due to laterals - Possibility of misidentifying the location due to many branches
Decentralized methods	- Short execution time - Simple implementation - Accurate and sensitive - Accurately identifying faulty points - Not affected by laterals and branches	- High implementation cost - Require a large number of meters and measuring devices - Need a powerful communication infrastructure

B. Two end-based techniques

Within the two-end or multi-end measurement-based procedures, voltage and current values from two or multi spots are required as shown in Fig.3.

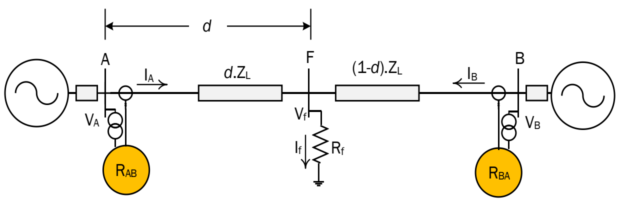

Fig. 3. A model for multi-end based method.

These methods utilize the fault voltage (V_f) as a common value between two circuits as in (2) and it is conceivable to streamline this to deduce (3).

$$V_A = d\, Z_L I_A + V_f\,; \quad V_B = (1-d) Z_L I_B + V_f \qquad (2)$$

$$V_A - d\, Z_L I_A = V_B - (1-d) Z_L I_B \qquad (3)$$

where V_A is the measured voltage at bus A, V_B is the measured voltage at bus B, Z_L is the line impedance, d is fault distance from measuring point A to fault point F, I_A is the current flow from point A to point F, I_B is the current flows from point B to point F, R_f is the fault resistance, and I_f is the fault current.

As seen in (3), the value of R_f is not critical as in one-end methods. Multi ends measurements make the impedance methods compatible with bidirectional flows which in turn avoids the different position estimation. Unlike one end-based impedance fault location algorithms, two end based techniques are more accurate, but they require synchronization between the measurements from different terminals of the line [13].

Generally, faulted phases must be identified first to detect suitable values of voltage and current to obtain the correct distance in impedance-based techniques. Table IV shows the required input quantities for all fault types [21] where m is a compensating factor equals to $\frac{Z_0 - Z_1}{Z_1}$; Z_1 and Z_0 are the positive and zero sequence impedances of the protected line respectively.

2. Travelling wave techniques

Fault occurrence leads to a discontinuity point (faulted point) on the faulted line at which line impedance changes. Due to these discontinuities, refraction and reflection of any wave along this line will take place at the faulty point [22]. Application of this phenomenon results in two main travelling waves-based approaches used to analyze fault location issues. The first one depends on injecting electrical pulse into the faulted line then recording the consecutive reflected signals. Detecting the incident and reflected waves from the faulted point enables the operators to identify the fault location quickly [23, 24]. The other technique is the recording of signals at different points on an energized system within the first few milliseconds after fault detection [25, 26].

The Operation principles of this strategy are outlined in Fig. 4. If the propagation velocity of the travelling wave within the line is known and nearly equals to the velocity of light, hence the distance to fault d is calculated as follows:

$$d = v \times \frac{\Delta t}{2} \qquad (4)$$

where v is the speed of the traveling wave within the line, and Δt is the time difference within the first arrival of wave and its reflection [3, 27].

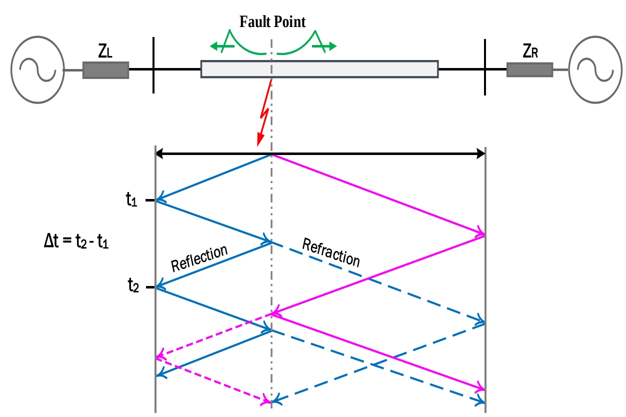

Fig. 4. Travelling wave basic operation.

TABLE IV
REQUIRED INPUT QUANTITIES FOR IMPEDANCE-BASED TECHNIQUES FOR DIFFERENT FAULT TYPES.

Fault type		**Input voltage**	**Input current**
Phase to ground faults	A/G fault	V_A	$I_A + m.I_0$
	B/G fault	V_B	$I_B + m.I_0$
	C/G fault	V_C	$I_C + m.I_0$
Phase to phase faults/ phase to phase to ground faults	A/B or A/B/G fault	V_{AB}=V_A-A_B	I_{AB} = I_A-I_B
	B/C or B/C/G fault	V_{BC}=V_B-V_C	I_{BC} = I_B-I_C
	- A/C or A/C/G fault	V_{AC}=V_A-V_C	I_{AC} = I_A-I_C
Three-phase faults	A/B/C fault	V_{AB} or V_{BC} or V_{AC}	Corresponding values of I_{AB} or I_{BC} or I_{AC} to input voltage

3. Artificial intelligence (Learning) based methods

Artificial intelligence (AI) is defined as a sub-field of computer science that explores how the thought and activity of human creatures can be mimicked by machines. Implementation of AI techniques such as Artificial Neural Network (ANN), Fuzzy Logic (FL), Experts' System (ES) and Genetic Algorithm (GA) for identifying faulty points makes the time factor is substantially reduced in addition to minimizing human mistakes [28]. AI methods require a data set for each type of fault where about 20% of that data to instruct the algorithm and the remaining data is used to classify the faults [2, 29]. Refs. [30, 31] surveyed different algorithms to locate fault based on ANN and FL respectively.

In spite of AI-based methods precision and small execution time, the most downside of these-based techniques is the necessity of various real or simulated fault cases for modeled AI system training. In addition, like other fault location strategies, these methods are based on the substation measurements, assess fault distance rather than the fault location or related bus, and thus they may detect different locations for the same fault distance [4].

Table V, gives an outline of the advantages and drawbacks of the discussed centralized methods.

IV.2. Decentralized methods

In this category, the measurements at different points of the system are collected together with a suitable communication system. These measurements are then utilized to execute the fault location algorithms. The decentralized methods include; smart meters, fault passage indicators, signal injection and Phasor Measurement Units (PMUs) based methods. The fundamentals of these methods are illustrated in Fig. 5.

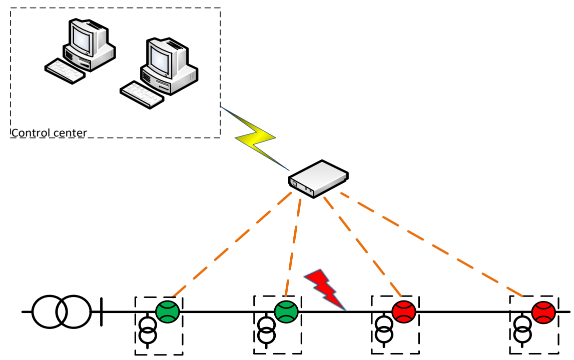

Fig. 5. Principle of decentralized fault location methods.

1. Utilization of smart meters

Smart meters are electronic estimation devices that utilize the utilities to get data for charging purposes, observing, controlling and operating electric systems remotely [32, 33]. Ref. [34], proposed a strategy that depended on the reality that "when a fault happens on a feeder, voltage droops proliferate showing distinctive characteristics for each feeder node". With the assistance of smart meter measurements, and by knowing the voltage sag characteristics, it is conceivable to detect the defective node or the faulty zone of the feeder.

TABLE V
COMPARISON BETWEEN CENTRALIZED BASED METHODS.

Method	***Advantages***	***Disadvantages***
Impedance based	- Simple implementation - Cost-effective	- Time consuming due to laterals - Fault type identification - Multiple location estimation - Dependent on line parameters
Travelling wave	- High accurate - Independent of network data	- Un required reflections due to laterals - Complex implementation - More expensive - High sampling rate of fault recorders.
Artificial intelligence	- Short execution time	- May report multiple locations - A large amount of data for training - Continuous training to include network changes

Authors in [35], utilized smart meters to limit down the search area for finding the faults. In this case, whenever a fault occurs on a system, the upstream protective device opens the circuit. This protective device may be a fuse, recloser, or substation relay. At that point, all downstream customers will be de-energized, the communication among the feeder, consumer meters, and the control center permits monitoring de-energized meters and, thus, detecting the de-energized part of the network.

Figure 6. illustrates an example of a method proposed in [35]. In this system, whenever a fault happens at F1, then CB1 trips causing all meters (SM1 to SM4) to report an outage in search zone 1. On the other hand, whenever s fault occurs at point F2, then if the fuse 1 blows, only SM4 reports an outage so that the search zone will be reduced to zone 2.

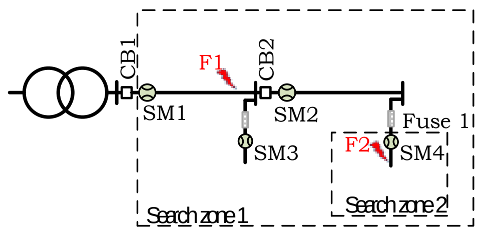

Fig. 6. Distribution feeder outage mapping.

Ref. [36] applied the Support Vector Machines (SVM) and smart meters for fault localization in distribution systems. The authors in [37], combined the voltage monitoring capability of smart meters with impedance-based fault location methods to provide an efficient fault location approach for improving service restoration. In [38], a method that utilized the faulted negative sequence voltage was used to locate the faulted sections by applying the relationship between fault distance and the clustered measurement groups.

Referring to the aforementioned methods, there are some drawbacks, perhaps the most prominent lies in the using of voltage magnitudes under the assumption of equal phase shift between the three phases A, B, and C, (i.e. 120º between each phase). In a real distribution system, these phases are frequently unbalanced [39]. In addition, in order to identify the affected zone accurately, several smart meters are required. Keeping in mind that failure of any meter will result in a wrong detection of the faulty section.

2. Fault passage indicators

Fault Passage Indicators (FPIs) are known innovation applied particularly to find short faults. Dependable FPIs prepared with communication to upper-level data frameworks, empower e.g. SCADA to imagine the way of the fault current to the operator within the control center [40]. The fault indicators enable the distribution network operators to quickly identify the faulty section of the network and restore power supplies to customers on healthy sections in the shortest time possible [3]. Ref. [41] shows different generations of FPIs describing the evolution of them during the time, their performances and their limits and the reasons that lead to this evolution. The FPI module consists mainly of reed switches and alert LEDs. The attractive force actuated by the fault current flows through the line segment magnetizing the reed switch closing a few contacts and flashing power Led for a fault sign.

The fault exists between the final activated fault indicator and the first indicator which is still dormant. The path of the fault current from the feeding point to the faulted area is stamped by the triggered indicators. Figure 7 illustrates the concept of faulted line-section location by outwardly assessing the FIPs' statuses. The control center can collect fault data by the communication network and display the data in a graphical user interface [42-45].

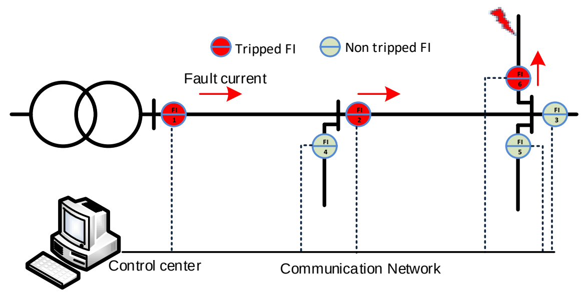

Fig. 7. Faulted line-section location by visual inspection based on FIs.

Another FPI based method was explained in ref. [46] which utilized the changes in symmetrical component currents after fault occurrence. It depended on measuring the change in negative sequence and zero-sequence currents at the same point. The strategy asserts that beneath fault point, the negative sequence current is or maybe noteworthy with little variations from the feeding substation up to the fault location while it is irrelevant after the fault point. Based on this strategy, the measuring point was within the fault path in case that the change in zero sequence and negative sequence currents exceeded their limits at the same time.

3. Signal injection-based methods

In these methods, a diagnostic signal is injected into power lines after fault occurrence. The trace of this signal is collected from detectors cover the power system with the help of communication mediums [47]. Different methods to inject the diagnostic signals were discussed in [48] including injection via fault phase voltage transformer, arc suppression coil or neutral point of Y-connected capacitor. The principle of operation of such based methods is illustrated in Fig. 8. When a fault happens, detectors identify the diagnostic current within the comparing line. Then the measurement collected from all detectors are sent to the control centers by means of the communication systems and consequently, the fault line can be detected by comparing the results. The line corresponding to the detector with the greatest output must be the faulted one.

Concisely, injection-based strategies need injection devices at the main substations which will cause more complications and confrontations. In addition to injection devices, signal detectors are required to identify the injected signals. Additionally, these methods are not appropriate for unearthed-neutral systems.

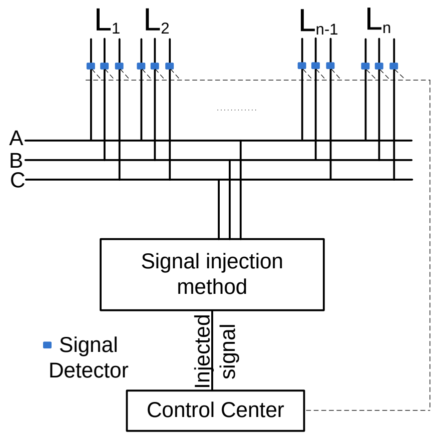

Fig.8. Principle of faulted line detection using signal injection-based methods

4. PMUs based techniques

PMUs are devices that give synchronized estimations of real-time phasors (voltages and currents). Synchronization is accomplished by a same-time sampling of measures signal waveforms utilizing timing signals from the Global Positioning System Satellite (GPS) which helps in capturing the wide area snap shot of the power system. The presentation of PMUs in power systems essentially moves forward the conceivable outcomes for observing and analyzing power system dynamics. Synchronized measurements make it possible to straight forwardly measure phase angles between corresponding phasors in several areas within the power system [49]. PMUs able to provide the following measurements (synchronously):

- Positive sequence voltages and currents.
- Phase angle of voltages and currents.
- Local frequency.
- Local rate of change of frequency.
- Active, Reactive and complex power.
- Power factor.

Figure 9 outlines the fundamental blocks of PMU [50].

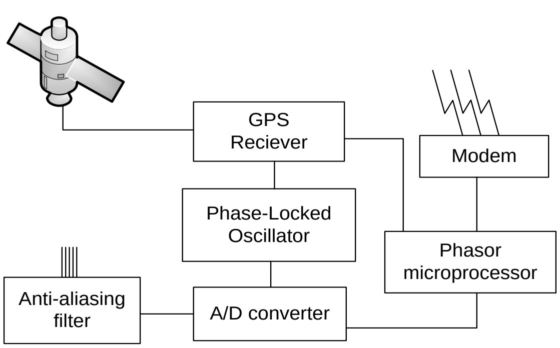

Fig. 9. Basic block diagram of PMU operation.

The Voltages and currents in their analog form are derived from the potential and current transformers (PT and CT) secondary which are then fed to Anti-Aliasing filter as shown in Figure 9. Anti-aliasing filters are low-pass filters with a cut-off frequency which is equal to half the sampling frequency used to avoid phenomena of aliasing in which high frequency components of input signal appear to be a part of fundamental frequency component. They could be passive, consisting of resistors and capacitors exclusively; or active, utilizing operational amplifiers. To convert analog signals obtained from input interface, Analog to Digital Converter (ADC) is applied. ADC digitizes the analog signal at sampling instants defined by the sampling time signals from Phase Locked Oscillator (PLO) which divides the one pulse per second signal from GPS into required number of pulses per second for sampling. The sampling instant could be identified, as the pulse number within one second interval is identified by the GPS time tag. Lastly, the digitized samples are fed to Phasor microprocessor which is programmed to calculate the positive sequence components from the digitized sampled data by using a recursive algorithm which is usually Discrete Fourier Transform (DFT) as described in. These calculated phasors are transmitted to the remote location through a proper communication channel using modems.

Recently, PMUs are already installed in several utilities around the world for various applications such as post-mortem analysis, adaptive protection, system protection schemes, and state estimation [50]. Recent literatures have discussed the use of phasor measurement units to develop fault detection strategies as one of protection applications.

In this section, some of the methods that use PMUs to identify the fault location are discussed.

In [39], the authors proposed a strategy for fault location in distribution systems utilizing compressive sensing. Voltages were measured by PMUs along the feeders during fault and pre-fault. The voltage droop vector and impedance matrix were combined to get a current vector with a nonzero component corresponding to the faulted bus. The proposed method had the ability to recover signals from few measurements, as the current vector was obtained, then faulted point could be identified. Authors in [51], proposed a method uses the measured voltage and current from PMU at one terminal. The technique is based on dividing distribution system into line segments, by iterating every line segment (section), a fault distance is obtained. This distance represents the proportional distance between the endpoints of the line segment. If the determined distance is less than 1.0, a fault can be indicated for the corresponding line segment such, else the next line segment of the model can be analyzed.

Ref. [52], presented a modification to the method applied in [51]. The technique utilized the source impedance to eliminate the error caused by fault resistance, load, and inhomogeneity of the circuit. The proposed method improved the precision of detecting fault location.

The work in [53], proposed a fault location strategy to detect the fault in ring or radial networks. The scheme comprised three autonomous steps that running together to get the precise location of the fault from the main substation. Firstly, the fault distance was calculated with the help of the data available from PMU at one end of the main feeder. Secondly, the bus-related to fault location within the primary network was detected based on the information accessible from PMUs located at both the ends of that main feeder. Hence, the fault distance in the sub feeder was detected.

In [54, 55], fault location procedure based on state estimation

(SE) was presented. SE may be an effective tool at whatever measurement points are rare in a system. This mathematical method depends on finding relate degree correct regression of each doable state inside the system (i.e. voltages and currents over a network). The authors in [54] used the measurements obtained from optimally located PMUs whereas in [55] the measuring points were selected randomly. The technique in [54, 55] put a value to fault current equal to grid injected current to any bus. With the assistance of the system impedance matrix, bus voltages were obtained. Comparing obtained voltages to the known ones, an error indication was obtained. The correct assumption matched with the case of the smallest error. Authors in [56] applied the same technique used in [54, 55] but with inserting PMUs at each bus. The methodology was less accurate at the quarter of a line compared to the middle of the line. It was deeply influenced by noise and fault resistance.

Authors in [57] proposed a procedure based on estimating the voltage fluctuations for all buses due to fault events within the distribution system from accessible measurements and system impedance matrix. This estimation was carried after assuming that fault was located on a different bus at a time. In this way, for each bus, there were different calculated voltage variations. A record represented the error within the calculated voltage variations for each bus. The bus with the littlest deviation was recognized as the closest to the faulted point.

Table VI, summarizes the main characteristics of different techniques that utilize PMUs technology. Whereas, Table VII illustrates the advantages and drawbacks of surveyed decentralized methods (smart meters based, FPIs based and Signal injection-based). Table VIII, summarize main features of reviewed fault location techniques.

TABLE VI
CHARACTERISTICS OF THE PRESENTED PMU BASED METHODS.

Method	Advantages	Disadvantages
Ref. [39]	- Simple implementation - Accurate - No need for fault classification step - Handle different scenarios easily - Short time	- PMUs distributed randomly - PMUs number is not optimized
Ref. [51]	- Acceptable accuracy - Require only two PMUs	- Time-consuming due to iterating each line segment - Need fault classification step
Ref. [52]	- More accurate than [51] - Require only two PMUs	- Time-consuming due to iterating each line segment - Need fault classification step
Ref. [53]	- Optimal placement for PMUs - Low implementation cost - Short time - Handle distributed generators existence	- Need fault classification step before applying the algorithm
Ref. [54]	- Use real-time data - Optimal placement of PMUs	- Low accuracy - Time-consuming
Ref. [55]	- Use real-time data	- PMUs distributed randomly
Ref. [56]	- Handle distributed generators existence - Use real-time data	- Influenced by noise and fault resistance - Less accurate at the quarter of a line - Complicated implementation - Large number of PMUs
Ref. [57]	- Simple - Accurate - Not affected by fault type or resistance - No-fault classification required	- Time-consuming

TABLE VII
CHARACTERISTICS OF THE PRESENTED DECENTRALIZED BASED METHODS.

Method	Advantages	Disadvantages
Smart meters-based	- Simple implementation - Accurate	- Require a lot of smart meters - Requirement of an effective communication network - Failure of any meter cause location error - High cost
FPIs based	- Simple implementation - High sensitivity - Accurate	- Require a lot of FPIs - High cost - Requirement of an effective communication network - Failure of any FPI threats location identification - Fault path is followed hardly in large power systems
Signal injection	- Simple implementation - System data depend less - Accurate	- High implementation cost - Require signal injection and receiver devices which are costly - Defect of any signal detector or communication links cause misidentification of faulty point

TABLE VIII
COMPARISON OF THE REVIEWED FAULT LOCATION METHODS.

Method		Type	Requirements	Accuracy	Ease of implementation	Cost	Execution time
Trouble calls method		Non-electrical data based	- Customer calls	- Low accuracy	- Simple	- Low cost	- Time-consuming
Historical data methods			- Historical data - Network topology - Experts knowledge - Fault evidences	- Low accuracy	- Complicated due to needed data	- Low cost	- Time-consuming
Impedance based		Electrical data based [Centralized methods]	- Substation voltage and current - Network topology - Line and load data	- Based on fault type identification and network topology	- Simple implementation	- Cost effective	- Time consuming due to laterals and fault classification
Travelling wave			- Measurements with very high sampling rate - Network topology	- Accurate results for single transmission and distribution lines	- Complex implementation	- Costly detection devices	- Time-consuming due to laterals
Artificial intelligence			- Substation voltage and current - Measurements with very high sampling rate - Line and load data	- Accurate based on performed training	- Simple but need Continuous training to include network changes	- Low cost	- Short execution time
Smart meters-based		Electrical data based [Decentralized methods]	- Smart meters along the feeder	- Accurate	- Simple implementation	- High cost due to meters	- Time-consuming
FPIs based			- FPIs along the feeder - At least current sensors	- Accurate	- Simple implementation	- High cost due to FPIs	- Time-consuming
Signal injection			- Injection device at the primary substation - Current sensors	- Accurate	- Simple implementation	- High cost due to required devices	- Time-consuming
PMU based methods	Ref. [39]		- Voltage phasors at some buses - Line and load data	- Accurate	- Simple implementation	- High cost due to required PMUs	- Small required time
	Ref. [51]		- Voltage and current phasor measurements at substations - Line and load data	- Acceptable accuracy	- Simple implementation	- Low cost as it depends on two PMUs only	- Time-consuming due to iterating each line segment
	Ref. [52]		- Voltage and current phasors measurements at substations - Line and load data	- More accurate than [51]	- Simple implementation	- Low cost as it depends on two PMUs only	- Time-consuming due to iterating each line segment -
	Ref. [53]		- Voltage and current measurements at substations - Line and load data	- Accurate	- Simple implementation	- High cost due to PMUs although they optimally located	- Low time consuming
	Ref. [54]		- Voltage and current measurements at buses - Line and load data	- Low accuracy	- Complex implementation	- High cost due to PMUs	- Time consuming
	Ref. [55]		- Voltage and current measurements at substations - Line and load data	- Low accuracy	- Complex implementation	- High cost due to PMUs	- Time consuming
	Ref. [56]		- Voltage measurements - Injected current phasors	- Less accurate at the quarter of a line	- Complex implementation	- High cost due to PMUs	- Time consuming
	Ref. [57]		- Voltage and current phasors measurements at substations - Line and load data	- Accurate	- Simple implementation	- High cost due to PMUs	- Time-consuming

V. CONCLUSION

Fault location has been of respectable interest to electrical power engineers. In distribution systems, the fast location of the faulted area leads to minimizing of disturbance caused to the influenced clients. This may well be turning into additional essential as there is associate accentuation set on quality and reliability of supply. Thus, the faulted area must be taken into consideration as an essential function to be integrated into advanced substation control system. This paper investigated the fault and outage location strategies as one of the foremost reasonable and efficient ways to upgrade distribution systems flexibility within confront of threats. Different algorithms were conferred so as to actuate a much superior estimation of fault distance counting on the extracted data from accessible resources. The suitable choice of a strategy may be a troublesome and broadly time-consuming task due to the expansive variety of methods. The paper presented a sensible comparison between large number of strategies in order to support power engineers and researchers, to settle on the correct methodology supported their needs and therefore the accessible information and measurements. The comparison went far away from primitive techniques that depending upon client calls and recorded information as a history of occurred faults, into highly accurate and quick strategies in locating faulted points looking on helps raised from new revolution data measurements and digital communication.

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