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Secure Intelligent Fitness Based Search Method for Cable Fault Location in Smart Grids

Simi P. Valsan* and Arinjai Gupta

ABB, Bangalore - 560058, Karnataka, India;
simi.valsan@in.abb.com

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*Author for Correspondence

Abstract

Smart grid technology enables efficient, reliable, resilient and secure power flow using intelligent sensors, Advanced Metering Infrastructure (AMI), bidirectional communication networks, and automation. The work presented utilizes the smart grid framework - including edge computing, secure data analytics, and IoT enabled sensors - to propose a method for fast and accurate fault localization in underground cables. The approach employs a deterministic fitness-based intelligent search mechanism that addresses both operational efficiency and cybersecurity requirements critical to modern grid infrastructure. Fault location is usually carried out in the protection relay with single end measurements (current and voltages at one end) or in sophisticated methods using double end measurements (communicated to the relay from the other end relay). The accuracy obtained is usually from tens to hundreds of meters depending on the method used. Better accuracy than this usually means very high frequency sampling resulting in expensive infrastructure. The proposed method aims at using existing relay capabilities and secure communication to transmit fault records to centralized on-premises or cloud platforms, where an intelligent search-based algorithm performs precise fault location which is a critical requirement for underground cable networks. Unlike black-box AI/ML approaches that may introduce vulnerabilities, this deterministic method provides transparency and traceability while maintaining high accuracy, limiting costly and disruptive excavations for cable repairs.

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1. INTRODUCTION

Of late, there is a huge preference for underground cables for power transmission, especially in urban areas. Underground cables are suited for places where it is difficult to use overhead lines due to a variety of reasons. Unlike overhead lines, cables are less prone to environmental issues, are eco-friendly and provide good aesthetics. The continuous advances in cable performance have also helped in the widespread usage. Some of the major hurdles in using the underground cables are

- Difficulty in locating and repairing faults
- Insufficient accuracy of conventional fault location techniques
- Expensive sensors / detectors
- Expensive excavations at multiple places.

In the context of smart grid evolution, these challenges are compounded by cybersecurity threats targeting grid communication networks and control systems.

The motivation for the disclosed work is that in densely populated / urban areas which are predominantly opting for underground cables, when a fault occurs in the cable and the accuracy of estimated location is not good enough, then trial and error-based excavations need to be carried out on both sides of the estimated location to expose the faulted part causing lot of disruptions / discomfort to the population. Other option is to deploy expensive sensors and detectors along the path of the cable to pin point the location.

Because of the cost and time factors associated with these existing techniques, there is a need to estimate the faults more accurately to few meters especially for faults within the city center or urban areas. Also, in many of the estimation techniques deployed, fault resistance plays a major role in determining the accuracy of the location estimation. Fault resistance in case of cables can vary over a wider range. It should also be possible to estimate the fault location for all types of faults (phase to ground, phase to phase or three phase faults).

With the advent of advanced technologies and their adoption in measurement, communication and automation involving even Artificial Intelligence (AI) and Machine Learning (ML) techniques has paved

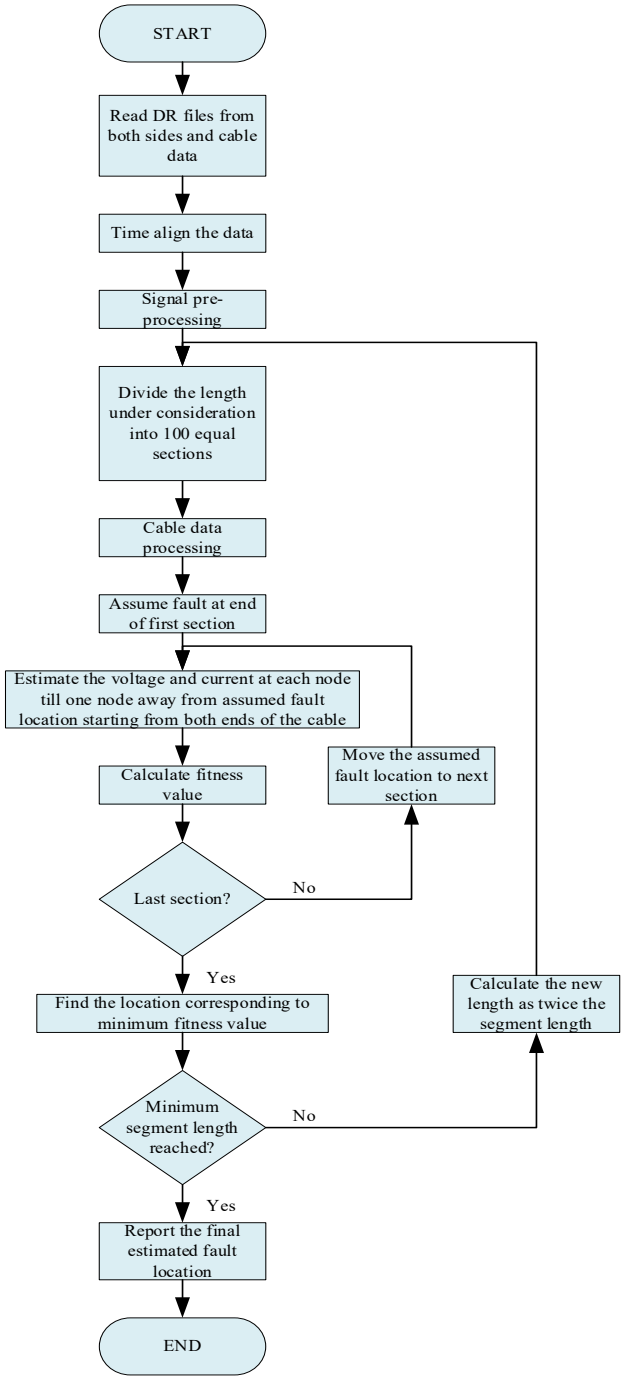


Figure 1. Flowchart for the proposed method.

way for application of sophisticated algorithms in an efficient and timely manner to resolve complex issues in power flow and monitoring making the modern grids truly smart. This paper attempts at providing a solution to the fault location power lines especially in underground cables, where high accuracy is preferred, utilizing the capabilities of digital technology like Synchronized Measurement Units (SMUs), secure data transfer protocols, edge analytics and intelligent algorithms to name a few.

In literature, the methods presented for fault location can be classified as (a) those using special type of sensors[1,2], (b) those employing high frequency, high voltage pulses or DC voltage injections[3-12], or (c) a combination of these[13]. A negative sequence voltage magnitude based fault location method for non-homogeneous lines is presented in[14] .

The method proposed here aims at locating cable faults with a higher accuracy by employing an intelligent search algorithm, so that costly sensors and multiple excavations can be avoided. Any existing relay used for cable protection can provide the current and voltage input data required for the location method which can be used along with standard cable parameters. When the relay detects a fault it generates a Disturbance Record (DR) which can be used as an input for fault location algorithm. The proposed scheme can work for both three phase and single phase systems. The scheme can be extended for multi-section and mixed type systems also.

2. FITNESS BASED FAULT LOCATION

2.1 Working Principle

The method proposed here aims at locating cable faults by employing an intelligent search algorithm. Once any fault is detected, the existing protection relays placed at the ends of the cable captures the current and voltage waveforms in a Disturbance Record (DR).

The algorithm uses current and voltage data from these DRs, along with the cable parameters to estimate the fault location based on fitness values for each assumed search location. The advantage of the method is that no special sensor or pulse/ DC injection is required (non-intrusive) other than the current and voltage transformers which are normally installed for the protection of the cable. The proposed scheme can work for all types of faults on an underground cable or an overhead transmission line with good immunity to fault resistance.

2.2 Operating Mechanism

The flowchart showing the various steps involved in the realization of the proposed method is shown in Figure 1.

2.3 Features and Benefits

The proposed method has a number of features and benefits as listed below:

- Intelligent fitness based search method
- Fast estimation of the fault location
- Accuracy versus time optimization is possible
- No additional sensors / signal injections are needed
- Can be easily deployed in centralized / cloud infrastructure
- Suitable for both single and three phase systems
- Suitable for multi-section and mixed type systems
- Better immunity to varying fault resistance.

3. PRACTICAL DEMONSTRATION

To explain the fault location method, a system as shown in Figure 2 is taken as an example. The system consists of a section of underground cable between buses M and N, protected using relays configured with an inter-tripping scheme. An inter-tripping scheme is a scheme where both relays independently watch out for faults and whichever relay detects the fault first communicates that information to the other side and thus ensures the circuit breakers at both ends are tripped. This will help in case the fault is feeble and towards one end and the relay at far end fails to detect it. As soon as the disturbance records are generated in both relays, they are sent to a centralized location / cloud through a secure gateway.

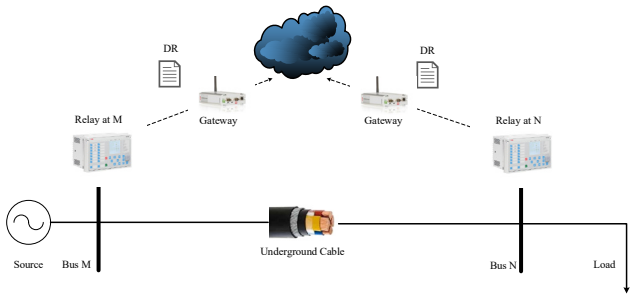


Figure 2. Example system.

3.1 Role of Relays

The voltage and current signals (through voltage and current transformers) at both ends are available as input to the respective relays. It is also possible to have separate relays to monitor voltage and current at each end. The relays keep monitoring the voltage and current signals till a fault is detected by protection. Once a fault is detected, the relays issue trip command to the circuit breakers to isolate the cable. A disturbance record (.cfg and .dat COMTRADE files) containing voltage and current signals immediately prior to the fault, during the fault and after tripping is created in each relay. Disturbance recorder can be set to record 50% pre-fault and 50% post-fault data with total duration of 0.5s or more. Figure 3 shows a typical disturbance record for a phase to phase fault(AB fault) taken from ABB REX640 relay and opened with Wavewin™ software with pre and post fault areas marked.

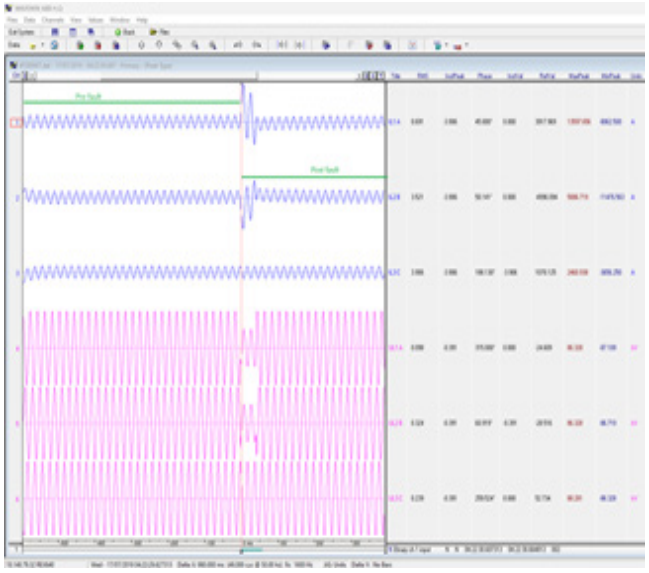


Figure 3. Typical disturbance record example with pre and post fault areas marked.

3.2 Data Synchronization

Time-stamped disturbance records are obtained from time synchronized relays at both ends of the cable which are normally used for cable protection. COMTRADE data from disturbance record having one voltage and current channel (1-phase systems) or three voltage channels and three current channels (3-phase systems) are read using custom scripts in Matlab™ as seen in Figure 4.

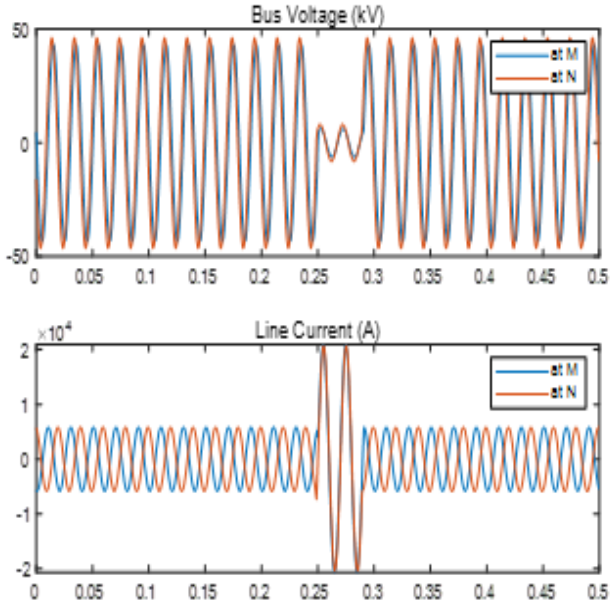


Figure 4. Voltage and current data read from disturbance record.

Since the instant at which the disturbance records are captured at both ends can be slightly different, data alignment needs to be done based on time stamp. Even after time aligning the data with respect to samples, due to differences in exact instants of sampling in different hardware, there can still be some synchronization errors as shown in Figure 5 (pictorial representation to demonstrate the concept).

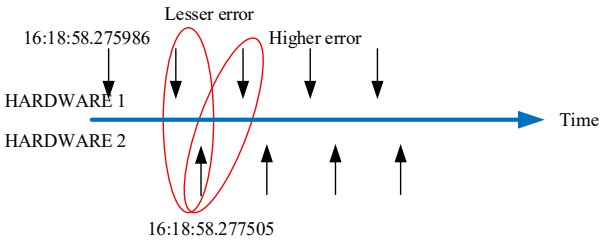


Figure 5. Synchronization error due to different hardware.

This error is corrected by linear interpolation. The DRs are first aligned based on samples choosing the nearest sample and then using linear interpolation, the sample value for the exact time instant is derived thus giving minimum possible error. The time aligned data is shown in Figure 6.

3.3 Signal Pre-processing

Discrete Fourier Transform (DFT) is applied to voltage and current signals from both ends to get magnitude and angle information as shown in Figure 7 and Figure 8. All plots are created with MatlabTM for clarity and better visualization.

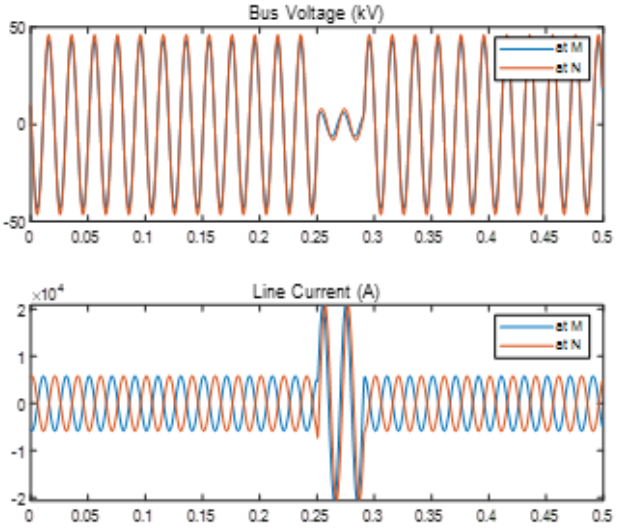


Figure 6. Time aligned data

3.4 Cable Data Processing

Cable data file consists of general cable parameters: positive sequence resistance (R1), positive sequence reactance (X1), positive sequence shunt susceptance

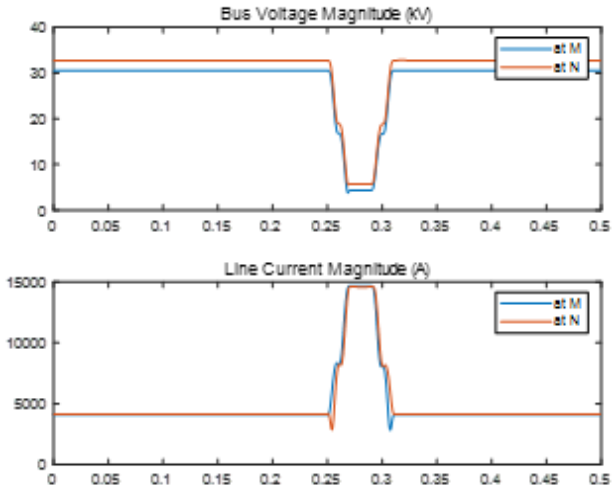


Figure 7. Voltage and current magnitudes.

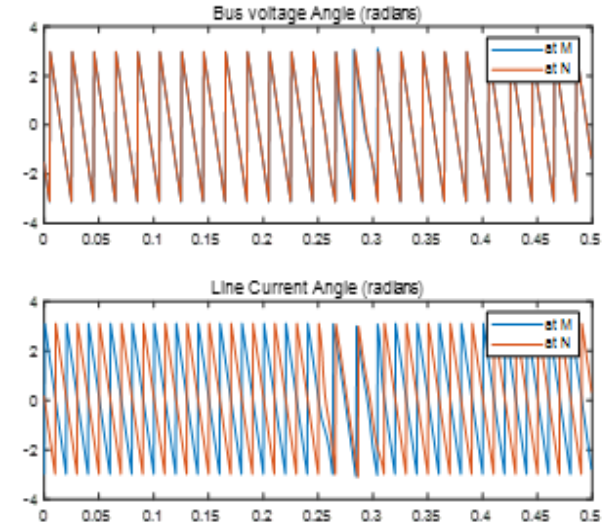


Figure 8. Voltage and current angles.

(Xc1), zero sequence resistance (R0), zero sequence reactance (X0) and zero sequence shunt susceptance (Xc0) per unit length and length of the cable for each section in case of multi-section cables.

For three phase systems, for each section of the cable, find the series impedance (Z_{series}) and shunt admittance (Y_{shunt}) matrices as:

$$Z_{series} = \begin{bmatrix} Rs + 1i * Xs & Rm + 1i * Xm & Rm + 1i * Xm \\ Rm + 1i * Xm & Rs + 1i * Xs & Rm + 1i * Xm \\ Rm + 1i * Xm & Rm + 1i * Xm & Rs + 1i * Xs \end{bmatrix} \quad (1)$$

where

$$Rm = \frac{(R0-R1)}{3},\ Rs = R1 + Rm,\ Xm = \frac{(X0-X1)}{3}$$

and $Xs = X1 + Xm$.

$$Y_{shunt} = \begin{bmatrix} 1i*Ycs & 1i*Ycm & 1i*Ycm \\ 1i*Ycm & 1i*Ycs & 1i*Ycm \\ 1i*Ycm & 1i*Ycm & 1i*Ycs \end{bmatrix} \quad (2)$$

where,

$$Ycm = \frac{1}{3}\left(\frac{1}{Xc0} - \frac{1}{Xc1}\right) \text{ and } Ycs = \frac{1}{Xc1} + Ycm \quad \text{and}$$

converting to modal quantities as

$$\left.\begin{aligned} Z0 &= T * Z_{series} * invT \\ Y0 &= T * Y_{shunt} * invT \end{aligned}\right\} \quad (3)$$

where,

$$T = \frac{2}{3}\begin{bmatrix} 0.5 & 0.5 & 0.5 \\ 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad \text{and}$$

$$invT = \begin{bmatrix} 1 & 1 & 0 \\ 1 & -0.5 & \frac{\sqrt{3}}{2} \\ 0 & -0.5 & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

In single phase system,

$$Z0 = Z_{series} \text{ and } Y0 = Y_{shunt}.$$

3.5 Search Process and Fitness Evaluation

Assuming there are s sections in the cable, each section of cable is divided into 100 equal segments as shown in Figure 9.

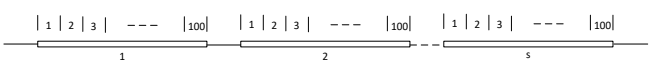


Figure 9. Sectionalizing the cable.

Length of each segment in each section *s* can then be found in meters as *lseg(s) = Ls/100*, where *Ls* is the length of the section s. The segment impedances and admittances are calculated as

$$\left.\begin{aligned} Z0_{seg(s)} &= Z0(s) * lseg(s) \\ Y0_seg(s) &= Y0(s) * lseg(s) \end{aligned}\right\} \quad (4)$$

The voltage and current values at both ends corresponding to fault instant are then extracted, i.e., the DFT values corresponding to one and half cycle after DR trigger point. One and half cycle offset is given for DFT delay and stabilization. The voltage and current phasors at M and N are shown in Figure 10.

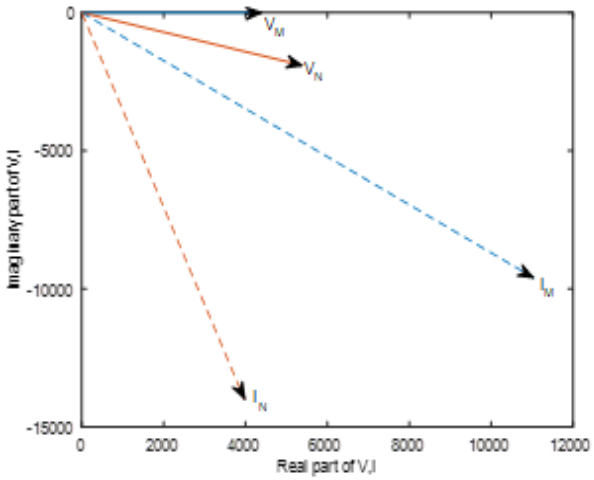


Figure 10. Phasors used for initializing the estimation.

Fitness based search mechanism is then applied as follows:

(a) Assume fault to be at segment *i* (*i* varies from 1 to 100*s*)

(b) Initialize the voltage and current values at end M and N as extracted and also initialize minimum fitness value to a very high value.

(c) Update voltage and current for each segment starting from the ends towards the assumed fault location based on voltage drop along the segments using line impedance matrices. Let the voltage values at the assumed fault location calculated from ends M

and N be V_M(s) and V_N(s) respectively. V_M(s) and V_N(s) gives the voltage at the nodes on either side of the segment *s*.

(d) Calculate fitness value for the assumed fault location as sum of square of absolute difference in voltages V_M(s) and V_N(s) and given below:

$$fitVal = \sum |V_M(s) - V_N(s)|^2 \quad (5)$$

(e) Update the minimum fitness value if the calculated value is less than the stored value and store the voltage and current values one segment away from the assumed faulted segment as starting values for further iterations. The fitness values obtained at end of first iteration is shown in Figure 11.

(f) Find the faulted segment as that corresponding to the minimum fitness value. This gives the approximate location of the fault. In the example considered, the minimum value corresponds to the segment 49.

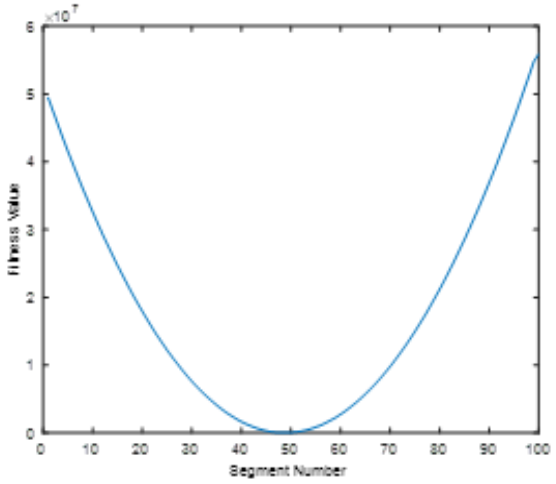


Figure 11. Fitness values obtained at end of first iteration.

The fault can be anywhere on segment 49, hence taking complete segments (48), rough estimation is 48*39 = 1872m where 39 is the segment length for first iteration (39 = 3900m/100). Since the segments are long, it is required to further iterate over segment 49 to get better accuracy. To handle end effect, the adjacent segment is also chosen for the next iteration. Hence, the segments 49 and 50 are chosen as the search area in next iteration. The location estimate after first iteration is hence fixed as 48*39 = 1872m to which the results of further iteration will get added to.

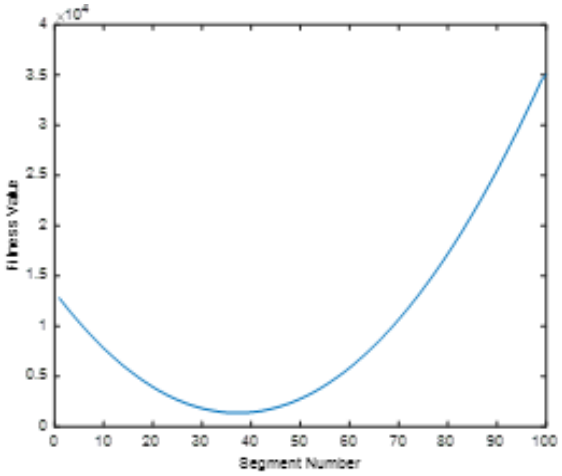


Figure 12. Fitness values obtained at the end of second iteration.

(g) If the segment length is more than the termination criteria, repeat the steps from *(c)* to *(e)* till the segment length is less than the set termination criteria. In this example, the segment length for first iteration is 39m. If the termination criteria is set as 1m, then the iteration must be repeated with segments 49 and 50. This is to accurately locate the fault within a new search area of 1872 to 1950m. The new segment length is 39*2/100 = 0.78m. The fitness value at the end of second iteration is shown in Figure 12. It can be seen that minimum value corresponds to segment 37. The actual location can be anywhere on 37 and hence the completed segments (36) is taken for location estimation, which means the additional length to be added to the starting point of this iteration is 36*0.78=28.08m, giving the fault location as 1872+28.08= 1900.1m.

Even though, it is an iteration based method, due to the optimal way in which segmentation is done, termination criteria is met within two or three iterations. More in-depth explanation is available in[15].

3.6 Selection of the Best Location

The accuracy can be improved if the estimate is obtained with multiple phasors equally distributed over a cycle as starting points for the estimation. In the example considered, four estimates were obtained with phasors from four quarter cycles and the final estimate is taken as an average of four estimates, which in this case comes to 1900.1m.

3.7 Fine Tuning to Required Accuracy

This is an optional step. The estimation of faults towards the ends of the line might have more error and that near the center will be more accurate. Hence, a weighting / correction factor can be applied based on the estimated fault location value to improve the overall accuracy.

3.8 Building in Security

The method proposed relies on the data in relay DRs. It is imperative that the DRs are accessible only with proper authentication. This is built into the system with secure file transfer in two stages – from relay to edge device and from edge devise to a centralized location – involving two stage password authentication. For example, to access DRs from ABB REX640 relay, one way is by logging into relay WebHMI with dedicated username and password. For this work, DR fetch was done programmatically from Python environment using 'webdriver' from 'selenium' library[16]. Secure File Transfer Protocol (SFTP) with password authentication was used to transfer DRs from edge device to centralized location. Further to detect tampering of final output, it is possible to run multiple instances of the fault location algorithms in parallel on different systems.

4. PROOF OF CONCEPT

A Proof of Concept (POC) setup was prepared to demonstrate the practical realization of the proposed method. Since it was not easy to get real field data for varying fault scenarios, a power system model as shown in Figure 13 was simulated in PSCAD™.

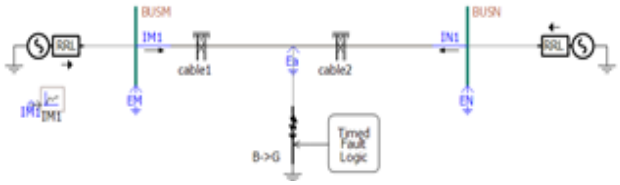


Figure 13. Model simulated in PSCAD.

A Python based automation script with a GUI was created to interactively apply different fault conditions as shown in Figure 14.

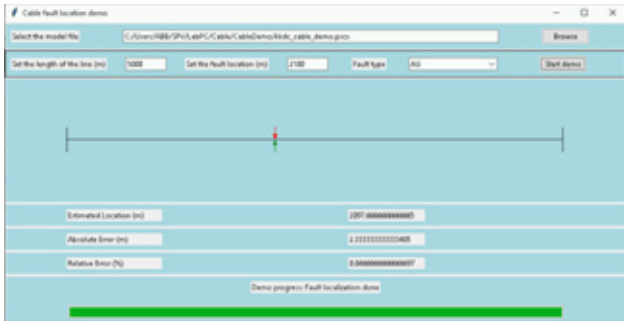


Figure 14. GUI of the POC setup.

Once a fault is simulated, the script automatically extracts the voltage and current information from both ends of the line and uses secondary injection kit, Omicron CMC to apply the same to two physical relays, using the Advanced TransPlayTM tool, to emulate actual field effect. The relays then detect the faults based on the protection functions configured and trigger a DR. The script retrieves the DRs from the relays to a centralized location. An observer script looks for new DRs and applies the fitness-based search mechanism to locate the fault and finally displays the same in the GUI.

The overall POC setup is as depicted in Figure 15 and consisted of three PCs to sectionalize the activities happening at different layers to make it as close to a practical deployment as possible.

One PC emulated the power system with PSCAD and had the Python script controlling the Omicron CMC device. The two relays then represented the actual relays at the buses M and N. An in-premises device

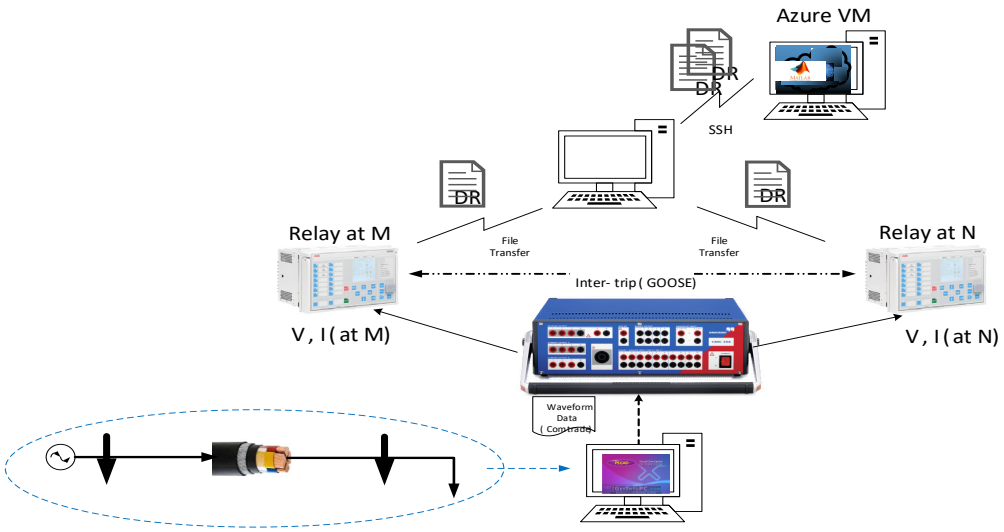


Figure 15. Proof of concept setup.

collected the DRs from the relays. Another centralized device (can be in-premises or cloud) had the observer running to look for fresh DRs and collected them to be passed on to the Matlab (or Python) script which executed the fitness-based fault location script.

5. RESULTS AND CONCLUSION

The method was tested on three phase systems for various fault locations, fault types and fault resistances. Disturbance records were taken from PSCAD

Table 1. Results for three phase system

Actual Location	Fault Type	Fault Resistance	Estimated Location	Absolute Error	Percentage Error
2100m	BG	0.1Ω	2100.5m	0.5m	0.0128%
2100m	AB	0.1Ω	2092.7m	7.3m	0.1872%
2100m	ABC	0.1Ω	2103.7m	3.7m	0.0949%
2100m	BG	0.5Ω	2099.8m	0.2m	0.0051%
2100m	AB	0.5Ω	2092.5m	7.5m	0.1923%
2100m	ABC	0.5Ω	2103.5m	3.5m	0.0897%
600m	BG	10Ω	601.57m	1.57m	0.0403%
2100m	BG	10Ω	2099.6m	0.4m	0.0103%
2100m	AB	10Ω	2098.6m	1.4m	0.0359%
2100m	ABC	10Ω	2097.2	2.8m	0.0718%
3300m	BG	10Ω	3300.6m	0.6m	0.0154%

simulations. Some relevant results are presented in Table 1. It can be observed that the errors for commonly occurring fault scenarios are quite small. Errors tend to be slightly higher for phase-to-phase faults, but still within 10m.

Method can be extended for multi-section lines with mixed underground cables and overhead lines as well as for multi-terminal lines.

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