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Optimal Placement of Synchronized Voltage Traveling Wave Sensors in a Radial Distribution Network

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ABSTRACT A transmission line fault generates transient high frequency travelling waves (TWs) that propagate through the entire network. The fault location can be determined by recording the instants at which the incident waves arrive at various points in the network. In single end-based methods, the incident wave arrival time and its subsequent reflections from the fault point are used to identify the fault location. In heavily branched distribution networks, the magnitude of the traveling wave declines rapidly as it passes through multiple junctions that cause reflection and refraction to the signal. Therefore, detecting the first incident wave from a high impedance fault is a significant challenge in the electrical distribution networks, in particular, subsequent reflections from a temporarily fault may not be possible. Therefore, to identify a high impedance or temporary faults in a distribution network with many branches, loads, switching devices and distributed transformers, multiple observers are required to observe the entire network. A fully observable and locatable network requires at least one observer per branch or spur which is not a cost effective solution. This paper proposes a reasonable number of relatively low-cost voltage TW observers with GPS time-synchronization and radio communication to detect and timestamp the TW arrival at several points in the network. In this regard, a method to optimally place a given number of TW detectors to maximize the network observability and locatability is presented. Results show the robustness of the proposed method to detect high impedance and intermittent faults within distribution networks with a minimum number of observers.

INDEX TERMS Fault location, traveling wave, medium voltage distribution networks, high impedance faults.

I. INTRODUCTION

Identification of high impedance and temporary faults location in radial distribution networks has been a subject of interest for electric utilities and researchers. In rural radial networks, fault locating poses a significant challenge due to the length and accessibility of these networks. Some of the challenges include conductor size changes, multiple feeder taps and laterals, inaccurate system data and dynamic configurations, insufficient energy for establishing clean arcs, evolving fault characteristics and magnitudes and effect of fault impedance and pre-fault power flow [1]. Impedance based methods for fault location in distribution networks require additional means to distinguish whether the fault is on the lateral or the feeder [2]. It also requires voltage and current data for each branch that may not be accessible for rural distribution networks. Moreover, these methods are unable to locate momentary and high impedance faults. Fault occurring in power lines generates transient high frequency traveling waves (TWs) that propagate through the entire network. Fault location can be identified by recording the instants at which the incident TW arrives at various points of the network [3]. The TW arrival time along with the propagation speed which is close to the speed of light are used to identify the fault

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location within the line. This method has high precision, high reliability and is unaffected by the pre-fault state of feeders and fault impedance [4]–[8]. Rural distribution networks are not profitable, and many systems need major capital investments that cannot be justified on economic grounds alone. The Victorian bushfires royal commission (VBRC) reported that the electricity aged assets prone to failures were the main cause of five bushfires on 7 February 2009 [9]. Western power, west Australia Network Corporation, currently faces a \$2 billion backlog of maintenance work for its aging population of 600,000 wooden poles. Several of the VBRC recommendations specifically related to the improvement of network asset maintenance procedures. Technology that could locate intermittent and high impedance (HIF) faults would reduce the risk of catastrophic failures and wildfires. Widespread and cost-efficient deployment of synchronized measurements on feeders, would allow the development of distributed TW observers that can time-stamp the arrival times of travelling waves with reasonable accuracy and identify fault location precisely. Borghetti *et al.* proposed and tested a single-ended method for distribution networks using a simple test feeder with only one tee junction [10]. However, in densely branched distribution networks, the TWs attenuate rapidly. Therefore, it is difficult to detect the initial arrival time at the observer point and the subsequent reflections. In [11], a fault location method using distributed synchronized TW detectors to fully observe a radial distribution network is presented. The method is applicable to intermittent and high impedance faults. The distributed observers increase the chance of detecting weak TWs initiated by HIFs. In [11], the proposed method only utilises the initial TW arrival time and does not rely on the subsequent reflection to locate the intermittent faults. Moreover, the proposed method employs voltage TWs instead of current TWs to locate HIFs. The authors developed a voltage traveling wave detector prototype which is reported in [12]. Because only initial TW arrival times is utilized, a fully observable and locatable radial network requires at least one sensor per branch or spur. From an economic point of view, this is an unlikely solution. A reasonable number of relatively low-cost voltage TW observers with GPS time synchronization and radio communication can be optimally deployed to detect and time stamp the traveling wave arrivals at several points of the distribution networks. In continuation of previously published articles by authors in [11] and [12], the main contribution of this paper is to extend the practical feasibility of the TW-based fault locating technique for distribution networks. In this regard, a cost-effective method to optimally place a given number of traveling wave detectors within a distribution network is developed. The method is aimed to maximize the area of the network in which fault location can be precisely identified with a minimum number of TW observers.

The reminder of this paper is organized as follows: Section II, presents a brief review for the fault location technique proposed in [11]. Section III describes the proposed TW detectors optimum placement method. In section IV, the practical feasibility of the proposed method is demonstrated through multiple scenarios on the studied system. Key conclusions are drawn in Section V.

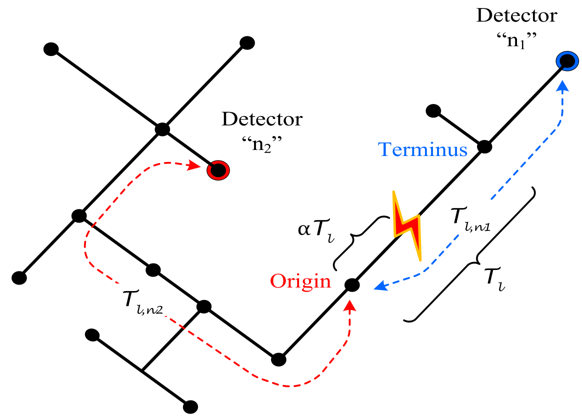


FIGURE 1. Fault location in distribution grids using travelling wave observers.

II. REVIEW OF FAULT-LOCATION ALGORITHM

When N-detectors, which are independently measuring the time of arrival (ToA) of a voltage TW launched by an electrical fault within a power line, are implemented in a radial distribution network, a set of ToAs ($\{T_n : 1 \leq n \leq N\}$) can be used to locate the fault. A set of traveling times ($\{T_l ; 1 \leq l \leq L\}$) can be computed for a given network with L distribution lines. $\{T_l\}$ is a set of theoretical TW's propagation times from the line's origin to its terminus as shown in Fig. 1. Considering Fig. 1, the traveling time to detector n from a fault occurring on line l is equal to:

$$T_{l,n} + S_{n,l}\alpha^{(l)}T_l \tag{1}$$

where αT_l is a propagation delay from the fault location to the origin of line "l"; α defines the fault location from the line origin as a fraction of the line length and $0 \leq \alpha \leq 1$. $S_{n,l}$ is -1, if the closer path to detector n includes the line "l" terminus otherwise $S_{n,l}$ is $+1$. Then the arrival time difference between detectors n_1 and n_2, $\Delta T^{(f)}_{n_2,n_1}$ can be expressed as follows (assuming $T_{l,n_1} < T_{l,n_2}$):

$$\Delta T^{(f)}_{n_2,n_1} = \left(T_{l,n_2} - T_{l,n_1}\right) + \left(S_{n_2,l} - S_{n_1,l}\right)\alpha T_l \tag{2}$$

By exchanging the theoretical time differences ($\Delta T^{(l)}_{n_2,n_1}$) with the measured time differences ($\Delta T^{m}_{n_2,n_1}$), a fault location equation can be derived as below.

$$\Delta T^{(l)}_{n_n,n_i} + S^{(l)}_{n_n,n_i}\alpha^{(l)}T_l - \Delta T^{m}_{n_n,n_j} = 0 \tag{3}$$

where

$$\Delta T^{(l)}_{n_n,n_i} = \begin{pmatrix} T_{l,n_1} - T_{l,n_i} \\ T_{l,n_2} - T_{l,n_i} \\ \vdots \\ T_{l,n_N} - T_{l,n_i} \end{pmatrix} \tag{4}$$

$$T_{l,n_i} = \min(T_{l,n_1}, T_{l,n_2}, \ldots, T_{l,n_N}) \tag{5}$$

$$\mathbf{S}^{(l)}_{n_n,n_i} = \begin{pmatrix} S_{l,n_1} - S_{l,n_i} \\ S_{l,n_2} - S_{l,n_i} \\ \vdots \\ S_{l,n_N} - S_{l,n_i} \end{pmatrix} \tag{6}$$

$$\boldsymbol{\Delta T}^{m}_{n_n,n_j} = \begin{pmatrix} T^m_{n_1} - T^m_{n_j} \\ T^m_{n_1} - T^m_{n_j} \\ \vdots \\ T^m_{n_1} - T^m_{n_j} \end{pmatrix} \tag{7}$$

$$T^m_{n_j} = \min(T^m_{n_1}, T^m_{n_2}, \ldots, T^m_{n_N}) \tag{8}$$

Equation (3) is an over determined set of equations for $N > 2$. Most of the quantities in (3) can be determined and stored prior to the fault occurrence. Only $\Delta T^m_{n_n,n_j}$ is to be evaluated after the fault occurrence and the ToAs must be measured. To address the issue of measurements and propagation velocity estimation accuracy, (3) can be redefined as a constrained optimization problem as follows:

$$min_{\{l,\alpha\}} \left\| \boldsymbol{\Delta T}^{(l)}_{n_n,n_i} + \mathbf{S}^{(l)}_{n_n,n_i} \alpha^{(l)} T_l - \boldsymbol{\Delta T}^{m}_{n_n,n_j} \right\| \tag{9}$$

By choosing $\|*\|$ as the standard vector norm (Euclidean), the cost function becomes:

$$F^{(l)}_c = \left\| \boldsymbol{\Delta T}^{(l)}_{n_n,n_i} + \mathbf{S}^{(l)}_{n_n,n_i} \alpha^{(l)} T_l - \boldsymbol{\Delta T}^{m}_{n_n,n_j} \right\|_2^2 \tag{10}$$

$$\delta^{(l)} = \alpha^{(l)} T_l \tag{11}$$

By applying the first-order optimality condition, the below closed-form expression can be obtained for $\delta^{(l)}$:

$$\frac{\partial F^{(l)}_c}{\partial \delta^{(l)}} = 2\mathbf{S}^{(l)}_{n_n,n_i}{}^T (\boldsymbol{\Delta T}^{(l)}_{n_n,n_j} + \mathbf{S}^{(l)}_{n_n,n_j} \delta^{(l)} - \boldsymbol{\Delta T}^{m}_{n_n,n_j}) = 0 \tag{12}$$

Equation (12) can be rewritten for $\delta^{(l)}$ **as:**

$$\delta^{(l)} = \frac{1}{K} \mathbf{S}^{(l)T}_{n_n,n_j} (\boldsymbol{\Delta T}^{m}_{n_n,n_i} - \boldsymbol{\Delta T}^{(l)}_{n_n,n_j}) \tag{13}$$

$$K = \sum_{n=1}^{n=N} (s^{(l)}_{n_n,n_j})^2 \tag{14}$$

where N denotes the number of observers. The optimisation problem can be solved by performing an exhaustive search for the full range of possible l and α values [6]–[8]. Although there is a limited number of lines, reaching a level of accuracy for α can be challenging and is depending on individual lines' lengths. Therefore, a more effective two-step approach is proposed as follows:

Step-1: Determine the optimum values of α for $l \in \{1, 2, \ldots, L\}$.

Step-2: Search over l values to determine the minimum value of the corresponding cost function for $l \in \{1, 2, \ldots, L \,|\, 0 \leq \alpha \leq 1\}$. More details about this technique can be found in [11].

III. PROPOSED OPTIMAL DEPLOYMENT METHOD

This section presents the proposed optimum deployment method through fault observability and locatability analyses as elaborated below.

A. FAULT OBSERVABILITY ANALYSIS

On a transmission system, TWs propagate freely towards the ends of the line over many kilometers. In contrast, the distribution network comprises many laterals and load taps along a relatively short distribution line that represent many points for TW partial reflection [13]. Hence, the energy of fault-induced TW deteriorates rapidly when passing through multiple laterals and bifurcation points. Where there are multiple bifurcations between the fault and the TW observer, energy of the TW may be insufficient to be detected by the observer. This issue is more challenging for HIF in which the energy of the generated TW is much lower than that due to low impedance faults. Therefore, the total reflection coefficient between each line and TW detectors must be considered when placing the distributed TW observers.

A branch or a line is regarded as an "observable" by the observer if the fault in the line can be detected by considering the refraction coefficient between line ends and the TW detectors. Otherwise, the branch or line segment is said to be "unobservable". The minimum refraction coefficient can be determined based on the TW detector sensitivity. For known locations of the TW synchronized detector, the analysis of determining "observable" and "unobservable" branches of a radial distribution network referred to as a fault observability analysis in this article. A matrix $\boldsymbol{B}_{\boldsymbol{L}\times\boldsymbol{N}}$ can be built for a given network of L lines and N buses as below.

$$\boldsymbol{B} = \begin{bmatrix} b_{1,1} & \cdots & b_{1,N} \\ \vdots & \ddots & \vdots \\ b_{L,1} & \cdots & b_{L,N} \end{bmatrix} \tag{15}$$

The total refraction coefficient for a wave to travel from line "l" to bus n can be determined by multiplying the refraction coefficients of all the junctions between line "l" start or terminus and bus "n". It is worth noting that the refraction coefficients are also dependent on the direction which the incident wave travels. Then a vector $M_{L\times N}$ is defined as:

$$\boldsymbol{M}^{\boldsymbol{l}}_{N\times 1} = \begin{bmatrix} m_{l,1} \\ \vdots \\ m_{l,n} \\ \vdots \\ m_{l,N} \end{bmatrix} \tag{16}$$

where

$$\boldsymbol{M}^{\boldsymbol{l}}_{N\times 1} = \begin{cases} 1, & if\ b_{l,n} > \beta\ for\ 1 \leq n \leq N \\ 0, & else\ 1 \leq n \leq N \end{cases} \tag{17}$$

where β is a threshold value that depends on the detector required sensitivity to detect the TW. The non-zero value of $m_{l,n}$ indicates that if the observer is installed at node "n", it can observe faults within line "l".

If a binary variable, z_n, represents the existence of an observer at bus-n and "$\circ$" is chosen to represent the

Hadamard product, the following observability vector can be calculated for line "l":

$$Z^l = M \odot Z = \begin{bmatrix} m_{l,1} \\ \vdots \\ m_{l,n} \\ \vdots \\ m_{l,N} \end{bmatrix} \circ \begin{bmatrix} z_1 \\ \vdots \\ z_n \\ \vdots \\ z_N \end{bmatrix} = \begin{bmatrix} z_1^l \\ \vdots \\ z_n^l \\ \vdots \\ z_N^l \end{bmatrix} \tag{18}$$

Non-zero value of z_n^l indicates that an observer exists at node "n", which can detect faults within line "l".

B. FAULT LOCATABILITY ANALYSIS

A branch or a line is regarded as a locatable if the fault in the branch can be uniquely located using the available set of measurements otherwise, the branch or line segment is said to be unlocatable. The locatability is independent of the observability as the fault within a line could be observable but not locatable. Considering the multi-terminal line shown in Fig. 2, the arrival time difference between observers A and C, Δt_{AC}, for a fault between points B and D is

$$\Delta t_{AC} = (t_{BA} + t_{XB}) - (t_{BC} + t_{XB}) = t_{BA} - t_{BC} \tag{19}$$

where t_{BA} is the incident wave traveling time from node B to node A, t_{XB} is the incident wave traveling time from the fault location at point X to node B and t_{BC} is the incident wave traveling time from node B to node C.

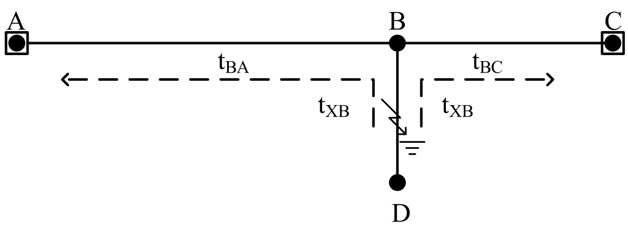


FIGURE 2. Three-terminal system with TW observers installed at nodes A and C.

It can be seen that Δt_{AC} is not a function of the fault location between nodes B and D. Then the value of K in (13) is equal to zero for the line connecting node B to node D. This condition exists if all the observers are installed at the start or terminus side of the line, then the fault location cannot be uniquely identified on a particular line although this line may be observable.

A matrix S, of $L \times N$ dimension is then built for the given network as below.

$$S = \begin{bmatrix} s_1^1 & \cdots & s_N^1 \\ \vdots & \ddots & \vdots \\ s_1^L & \cdots & s_N^L \end{bmatrix} \tag{20}$$

where s_n^l is equal to -1 if the closer path to detector n includes line l terminus while s_n^l is equal to $+1$ if it does not include line l terminus.

$$W(S, Z)^l = \begin{bmatrix} s_1^l & \cdots & s_n^l & \cdots & s_N^l \end{bmatrix} \begin{bmatrix} z_1 \\ \vdots \\ z_n \\ \vdots \\ z_N \end{bmatrix} \tag{21}$$

From (20), the line l is considered observable if the absolute value of $W(S, Z)^l$ is smaller than the total number of observers, P. When $W(S_{1\times N}^l, Z)^l$ equals $-P$, it means, the shortest path to all observers includes line l terminus. If $W(S_{1\times N}^l, Z)^l$ equals $+P$, the shortest path to none of the observers include the line l terminus. Under these conditions, the value of K is equal to zero and therefore $\alpha^{(l)}$ cannot be determined. Then a vector Q^z is defined as:

$$Q^z = \begin{bmatrix} q_1^Z \\ \vdots \\ q_l^Z \\ \vdots \\ q_L^Z \end{bmatrix} = \begin{bmatrix} R(W(S,Z)^1) \\ \vdots \\ R(W(S,Z)^l) \\ \vdots \\ R(W(S,Z)^L) \end{bmatrix} \tag{22}$$

where

$$R(W\,(z)^l) = \begin{cases} 1, & if \ \left|W(S,Z)^l\right| < P \\ 0, & if \ \left|W(S,Z)^l\right| = P \end{cases} \tag{23}$$

For the given vector Z, and matrix S, the zero values in the column vector Q^z imply that the respective branch or line is unobservable; whereas the 1 values indicate that the respective branch or line is observable. Although the fault location may not be observable, the faulted line or branch can be identified.

C. TRAVELING WAVE DETECTOR PLACEMENT MODEL

A traveling wave detector placement (TWDP) is a binary optimization problem. The most popular heuristic optimization techniques that can handle binary problems are binary particle swarm optimization (BPSO) [14], [15] and genetic algorithm (GA) [16]. BPSO and GA are computational optimization methods that are searching an optimum solution by iteratively trying to improve a candidate solution. The BPSO offers a significant potential to identify a near-optimal solution for highly dimensional, nonconvex, and non-continuous optimization problems. All particles in the BPSO method and their histories contribute to the search, unlike in genetic algorithm where poor solutions are eliminated. By remembering all particle's historical contributions, all undiscovered good neighborhoods in the vicinity of these particles can be explored and a good solution may be within close vicinity of a poor particle [17]. Hence, the proposed TWDP model is solved by the BPSO algorithm.

In PSO, a randomly generated swarm population consist of individuals particles. Each particle represents a potential solution for the optimization model. A D-dimensional space is searched through by each particle for an optimal solution. At each iteration, particles update its position based on its own experience as follows [14]:

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{24}$$

$$V_i^{t+1} = \omega V_i^t + c_1 r_1 \left(P_{besti}^t - X_i^t\right) + c_2 r_2 (G_{best}^t - X_i^t) \tag{25}$$

where ω is the inertia weight; c_1, c_2 are the acceleration constants; r_1, r_2 are two random numbers uniformly distributed in the range [0, 1]; P_{besti}^t is the best position searched by particle i at the t^{th} iteration step and G_{best}^t is the best position ever searched by the entire swarms at t^{th} iteration step.

In BPSO, a position of i^{th} agent can be expressed by the N-dimensional binary solution space where the velocity is still a real number [15]. At the $t+1$ iteration step, the position of the i^{th} particle can be expressed by an N-bit binary string:

$$\left\{X_i^{t+1}\right\} = \{x_{i,1}^{t+1}, \ldots, x_{i,N}^{t+1}\} \tag{26}$$

In the process, V_i is related to the possibility that $x_{i,1}^{t+1}$ takes a value of 1 or 0. It is implemented by a sigmoid function (SF) of which its value depends on the particle velocity V_i^t.

$$SF\left(V_i^t\right) = \frac{1}{1+\exp(-V_i^t)} \tag{27}$$

The position, X_i^{t+1}, is updated by using the following equation:

$$X_i^{t+1} = \begin{cases} 1, & if\ r_3 < SF\left(V_i^t\right) \\ 0, & otherwise \end{cases} \tag{28}$$

where r_3, a random number between 0 and 1, is generated at each iteration step [18]. Transpose particles position X for the traveling wave placement problem is equal to the vector $\mathbf{Z}$.

D. OPTIMIZATION OBJECTIVE FUNCTION

The objective is to place a limited number of TW observers within the distribution network in a way that minimises the number of unobservable or unlocatable lines. In this regard, the following objective function (OF) is proposed:

$$OF(\mathbf{S},\mathbf{Z},\mathbf{M},\mathbf{L}_{L\times 1}) = \sum_{i=1}^{L} q_l^{Z^i} L_i \tag{29}$$

where L_i is the length of line i, the output of the OF is equal to the total line length which is observable and locatable.

E. CONSTRAINT HANDLING

The placement of the TW observers is a constrained optimisation problem. The optimisation algorithm tries to maximise the number of lines which are observable and locatable. If the number of observers is not constrained, the solution would not be economical to implement.

There are several ways to handle a constrained BPSO problem. The most common constraint handling technique is a penalty function method. In this method, a penalty term is included in the fitness function for any violation of the constraints [16]. The penalty function, $PF(\mathbf{Z})$, is defined as:

$$PF\left(\mathbf{Z}\right) = \begin{cases} 0 & P(\mathbf{Z}) = p \\ (P(\mathbf{Z}) - p)^2 & P\left(\mathbf{Z}\right) \neq p \end{cases} \tag{30}$$

where p is a desired number of observers and $P(\mathbf{Z})$ is calculated from:

$$P\left(\mathbf{Z}\right) = [1 \cdots 1] \begin{bmatrix} z_1 \\ \vdots \\ z_N \end{bmatrix} \tag{31}$$

$P\left(\mathbf{Z}\right)$ is a function which returns the number of observers presents in the vector $\mathbf{Z}$. $PF\left(\mathbf{Z}\right)$ is equal to zero, when the number of observers in the vector $\mathbf{Z}$ is equal to the desired number of observers p.

F. OPTIMISATION MODEL

Based on the objective and the penalty function, the optimization observer placement model for maximizing the length of observable and locatable lines with a given number of available observers (assumed in this study to be from 3 to 12) is as follows:

$$\min CF = \left(1 - \frac{OF(\mathbf{S},\mathbf{Z},\mathbf{M},\mathbf{L}_{L\times 1})}{L_t}\right) + w \times PF\left(\mathbf{Z}\right) \tag{32}$$

where L_t and w are the total length of the feeder, including all branches and the weight of the penalty function, respectively.

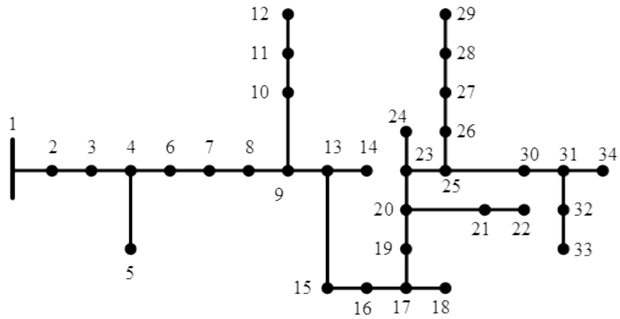


FIGURE 3. Modified single-line diagram of the IEEE 34-bus distribution network.

IV. SIMULATION RESULTS AND ANALYSIS

To verify the feasibility, effectiveness, and robustness of the proposed method, the modified IEEE 34-bus radial distribution network as shown in Fig. 3 is employed in this analysis. The total length of the lines within this network is 93.913 km. All lines are considered to have the same characteristic impedance. For a relatively low number of observers, the best solution can be found by an exhaustive search over all feasible solutions. The number of feasible solutions is equal to the binomial coefficient (combinatorial number).

$$C_P = \binom{N}{P} \tag{33}$$

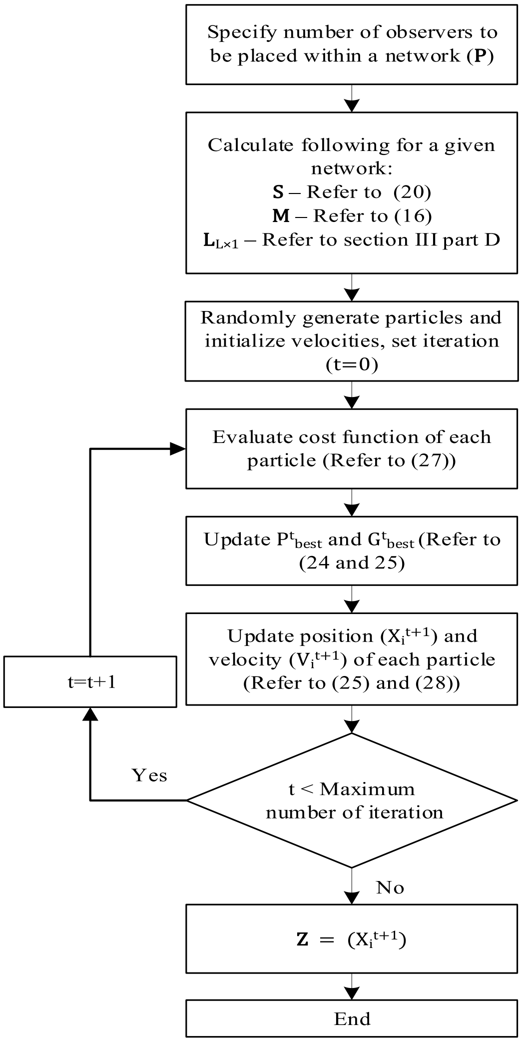


FIGURE 4. Flowchart of the proposed BPSO method for placement of traveling wave observers.

where P is the number of observers and N is the number of busses. As an example, assuming a maximum of 7 observers are to be deployed into the 34-bus network, the number of feasible solutions would be:

$$C_7 = \binom{34}{7} = 5,379,616 \tag{34}$$

An exhaustive search for the viable solutions using the proposed optimisation method is used for $P = 3$ to $P = 7$. Results are compared to determine the best optimisation penalty function weight w and performance of the proposed optimization method. Based on this comparison, the value of w is set to 0.5 to ensure the number of observers is constrained as required. The exhaustive search for a higher number of observers ($P > 7$) is not practical where the optimization approach is necessary. Fig. 4 is a flowchart that summaries all the steps of the proposed BPSO method for optimum placement of traveling wave observers in a distribution network. The parameters used in the BPSO are summarized in Table 1 for three values of β: 0.5, 0.3 and 0.01. The particle size is set to 1000 to increase diversity. It is assumed that all lines are of equal characteristic impedance. Therefore, the refraction of all the T-junctions is equal to 0.66. Fig. 5 shows the optimum placement of the TW observers for $\beta = 0.5$, $P = 7$ to $P = 12$ along with the total length of lines (OF) that are observable and locatable.

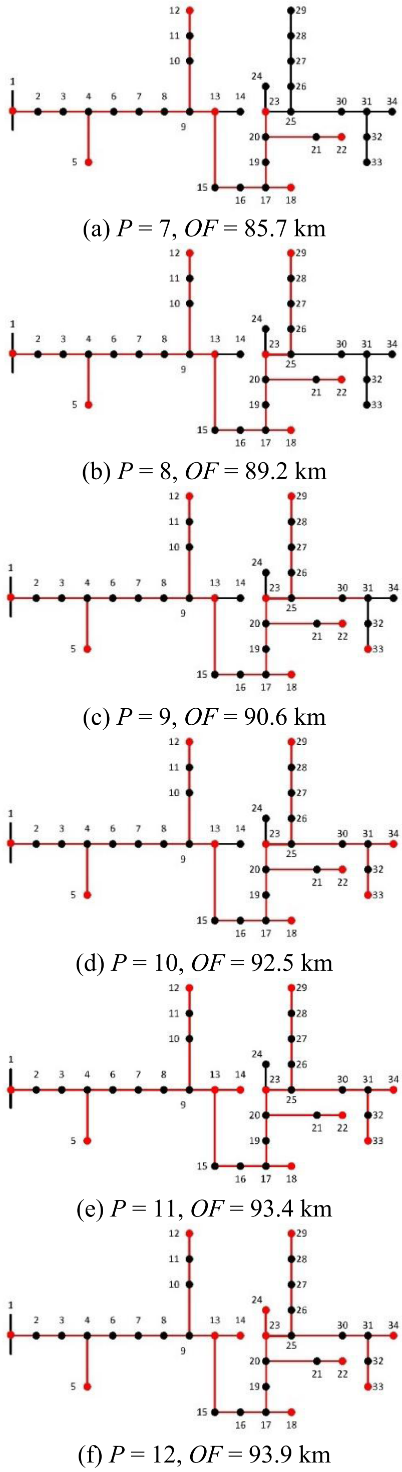
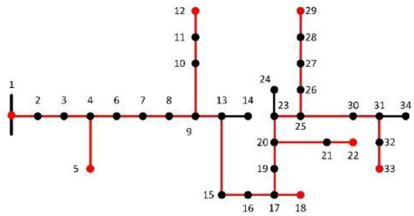
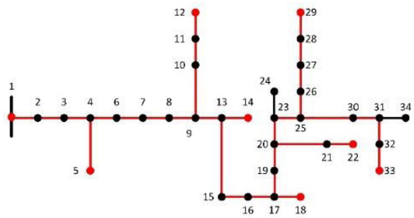


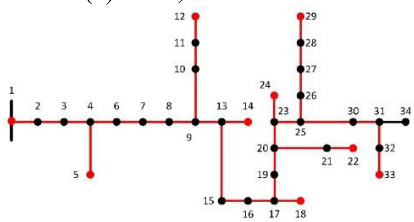
FIGURE 5. The optimum placement of traveling wave observers for $\beta = 0.5$. The red lines are observable and locatable. The traveling wave observers placed at the buses are shown in red.



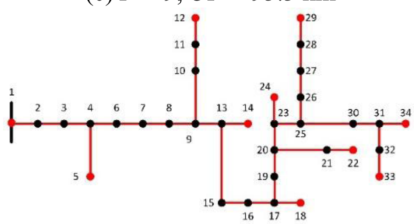
(a) $P = 7$, $OF = 92.2$ km



(b) $P = 8$, $OF = 93.1$ km



(c) $P = 9$, $OF = 93.3$ km



(d) $P = 10$, $OF = 93.9$ km

FIGURE 6. The optimum placement of traveling wave observers for $\beta = 0.3$. The red lines are observable and locatable. The traveling wave observers placed at the buses are shown in red.

TABLE 1. Summarize parameters of BPSO optimization.

Particle size		1000
Number of iteration		700
Threshold (β)	Scenario 1	0.50
	Scenario 2	0.30
	Scenario 3	0.01
Penalty function weight (w)		0.50

More than one optimum solution may be available. For example, where nine observers are installed ($P = 9$) within the distribution network, a single observer can be placed in any of the buses 31, 32 or 33 without changing the OF. As shown in Fig. 5(f), the network is fully observable and locatable for $P = 12$. Results for $\beta = 0.3$ and $P = 7$ to $P = 10$ are shown in Fig. 6. It can be seen that with the same number of observers, the OF increases as the value of β decreases for the low number of observers. For $\beta = 0.3$, total network coverage is achieved with 10 observers ($P = 10$) whereas 12 observers are required for total network coverage in case of $\beta = 0.5$ as shown in Figure 5(f). Fig. 7 shows the per unit cost of a fault location system versus the number of observers for different threshold values. As shown in Fig. 7, the cost per unit length of observable and locatable lines increases with the increase of the number of observers. However, the required number of observers for fully observable and locatable networks does not decrease when β is decreased below 0.3. The required minimum number of observers for a fully observable and locatable network is determined by the number of branches within the network. By decreasing β to 0.01, the OF is improved for $P = 3$ to $P = 5$. However, for a higher number of observers, results show no improvement from $\beta = 0.3$ case. When $\beta = 0.01$, a fault's original TW can be detected by all observers in the tested network.

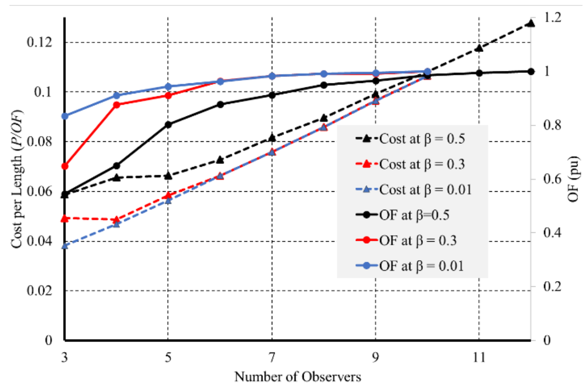


FIGURE 7. Cost per length of observable and locatable lines.

It is worth noting that the proposed method is applicable for various large interconnected network topologies. These networks can be the partitioned as per [19] to facilitate easy implementation of the proposed method. Also, according to [20], the harmonic distortion in distribution networks is dominated by the 5th, 7th, 11th, and 13th components, with harmonic pairs visible in the spectrum well beyond 1,000 Hz. High-frequency network voltage background noise proved to be complex and it is varied over time. Typically, the high-frequency voltage noise is about 0.3-0.8 Volts. The largest components of this noise are due to disturbances or signals from AM radio stations. The voltage traveling wave created by 10A fault in overhead line with 300 Ω characteristic impedance is equal to 3000V. Thus with the use of appropriate signal processing technique such as the technique presented in [21] within the TW observers, a high frequency generated faults can be distinguished from the noise.

V. CONCLUSION

This paper presents a new strategy to place a given number of traveling wave observers in a radial distribution network to maximize the observable and locatable lines in the network. The proposed method can be used for a cost-effective design of voltage TW based fault location schemes in radial distribution networks to detect high impedance and intermittent faults which enhance the network reliability and decrease the risk of fire in rural areas. Results show that the cost per length of fault location system is a function of TW observer sensitivity (β), the number of observers and number of laterals. The proposed method can be implemented for various network topologies.

Further research may consider redundancy and effect of loss of the GPS synchronization on the proposed optimal placement scheme.

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