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Fault Location Identification for Ring and Radial Power Distribution Network with Optimally Placed PMU's

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Abstract - Synchrophasor measurements from phasor measurement units (PMUs) will help network operators in many tasks including optimization of power flow, controlling power systems, contingency analysis, detection of fault etc. To achieve these, there is no requirement of PMUs to be placed in all the nodes of power network. In this paper, binary based search algorithm is used for optimal placement of PMUs and evaluated in different IEEE standard networks. After optimal placement of PMUs, next phase is the identification of fault location. The suggested scheme for fault location identification technique consists of three parallel paths which will be running concurrently. From the outputs of these parallel steps, the possible fault point can be found. The proposed scheme has been evaluated using PSS®E & MATLAB to provide 98 % precise results in the selected line span.

Keywords Phasor Measurement Units, Synchrophasors, Distribution Network, Fault location, Optimal Placement, PSS®E, Distributed Generation

1. Introduction

PMUs are phasor measurement units that have the capability of measuring voltage phasors and current phasors. Synchronized signals received from the global positioning system (GPS) are used in PMU for time stamping and provide the phasors of voltage (V) and currents (I) measured at a given node (substation). Synchronized PMU is a monitoring device, which was introduced in USA in mid-1980s [1, 2].

Thorough monitoring of the system operating conditions is highly required for the secure operation of power system. Conventionally, this is carried out with the help state estimator which is in the control room and has remote access to various substations in the monitored system [3, 4]. By collecting analog measurements such as voltage, current, frequency and circuit breaker status from remotely monitored substations, the state estimation can be carried out [5, 6]. Subsequently, feeding them as inputs into state estimation function can cater an image for all metered and un-metered electrical quantities the system. Further, it detects and filters out all errors in the measurement set. [7]

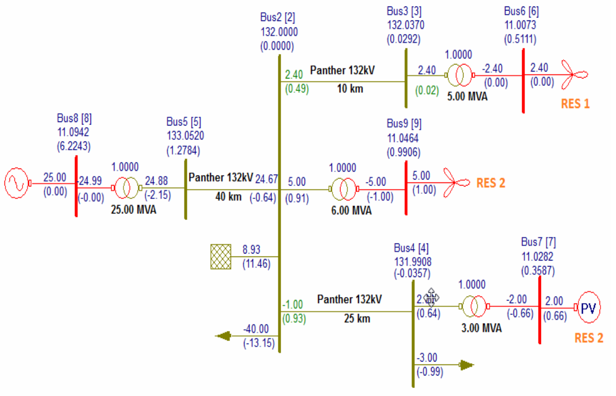


Fig. 1. Single line diagram of an eight bus distribution feeder

Most of the monitoring systems until recently did not cover phasor measurements because of the technical problems related to measurement synchronization at several locations. With the advancement in global positioning system (GPS) technology, these complications shall be mitigated and lead to the invention of phasor measurement units (PMU) [8, 9].

For the eight-bus network shown in Fig. 1, placing PMUs on every bus will directly make the system completely observable [10, 11]. In a network, a bus can be considered as observable if PMU is directly connected to it or a PMU connected to any of its adjacent buses. Also, it is neither necessary nor cost-effective to place PMU in all the buses in a network. Because of above reasons, a problem entitled Optimal PMU Placement (OPP) problem is developed [12]. In this paper, one of the goals is the optimal placement of PMU for complete network observability. For optimal placement, binary based search algorithm is used.

Due to the latest advancements in synchrophasor technologies many utilities across the globe are placing PMU in their network for applications such as state estimation, fault identification etc. The main aim of this work is to find the fault in distribution networks with the help of optimally placed PMUs [2].

Optimal PMU placement for fault observability is investigated in [12] and [13]. Authors in [14] and [15] have carried out a review of fault location identification methods for distribution power system. Authors in [16] have developed an accurate synchrophasor based fault location method for emerging distribution systems. Though the available approaches take advantage of various algorithms to impose observability constraints, the important issue of optimal placement and fault location together is considered in very few literatures. In [17], μPMU options for placing minimum number of PMUs in a power system to locate fault in the power system are covered. However, in this paper the fault identification in different types of distribution feeders are not covered. The proposed work considers optimal placement and fault identification in ring and radial power distribution feeders which identify fault locations in distribution networks with 98% accuracy.

2. Observability

Observability can be defined as a state in which measured parameters and its dispersal are enough to solve and understand the existing condition of power system. The different terminologies used for observability are detailed in the following section [13].

- With the support of a PMU, if voltage magnitude and angle for a bus can be measured then a bus is directly observable.
- A bus is observable with the support of other PMUs called as calculated bus.
- An unobservable bus is a bus which has one or more unobtainable parameters from any of the PMUs.
- A system is said to be completely observable when all the buses in that system is directly seen or calculated.
- In a completely observable system, all the buses are directly observed or calculated.
- If some buses are not observed, then that system is incomplete observable system.
- The minimal placement set that supplies full observability is called optimal set.

PMU deployment at all substations can provide the voltage magnitudes and angles in real time which will make power system observable. However, it is not mandatory because of the vital property of PMU. For a bus, if the current and voltage phasors are known, then it is possible to calculate the phasors for all the interconnected bus [14]. According to ohm’s law, for bus A voltage phasor is known, then the bus B voltage will be bus A voltage minus the voltage drop in the transmission line [15]. So, if a particular bus is observable with one PMU, then all the bus interconnected to this bus is also observable as shown in Fig. 2. This is the first rule for observability.

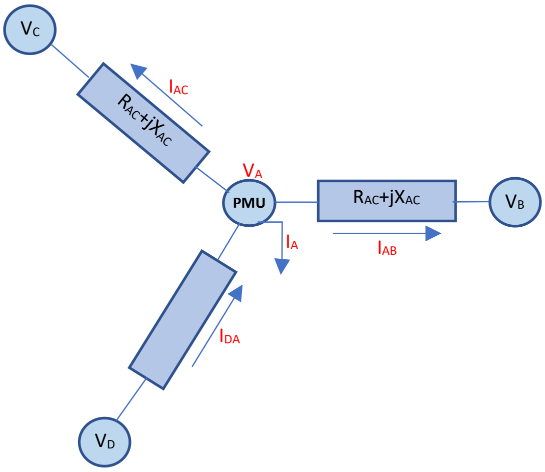


Fig. 2. Four bus system (V_A, I_A, I_{AB}, I_{AC} & I_{AD} are known).

$$V_B = V_A - I_{AB} + \left(R_{AB} - jX_{AB}\right) \tag{1}$$

$$V_C = V_A - I_{AC} + \left(R_{AC} - jX_{AC}\right) \tag{2}$$

$$V_D = V_A - I_{DA} + \left(R_{AD} - jX_{AD}\right) \tag{3}$$

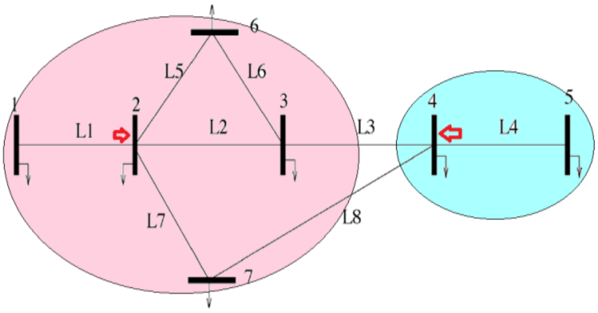


Fig. 3. Optimal PMU placement for seven bus system.

If the above rule is applied, the number of PMUs required for complete observability of a particular system can be reduced substantially. For a seven-bus system detailed in Fig. 3, keeping PMUs at second bus and fourth bus will make the system observable [17]. Seven bus system can be made completely observable with the help of two PMUs.

3. Binary Based Optimal Placement Algorithm

The algorithm is comprehensive that it inspects all probable groupings of positions before finalizing the number of PMUs [5]. The construction of problem is shown in Fig. 4 exclusively considering PMU.

Step-1: Binary Connection Matrix (A_{km}) Development

Binary connectivity matrix A_{km}, will be formed initially to arrange the constraint set. The entries in this set are defined below,

$$A_{km} = \left\{ \begin{matrix} 1, \mathit{if}\ k = m\ or\ k\ and\ m\ are\ connected \\ 0, otherwise \end{matrix} \right\} \quad (4)$$

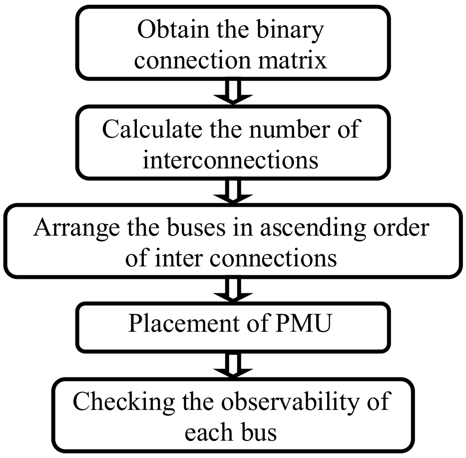


Fig. 4. Binary based algorithm-flow chart.

Step-2: Interconnections Calculation

Number of interconnections are calculated from interconnection matrix by adding the number '1' present in each column. The order of the new matrix will be N X 1.

Step-3: Arrange the buses in ascending order based on inter connections

This will be an N X 2 matrix with buses arranged in descending order of interconnects. The first column will be the bus number and the second column will be the number of interconnects for each bus laid out in descending order.

Step-4: PMU Placement and observability monitoring

For the ith bus, the condition for observability for a particular bus is given by

$$\sum_{j=1}^{N} A_{ij} x_j \geq 1 \quad (5)$$

where A_{ij} = interconnection matrix

$$x_i = \left\{ \begin{matrix} 1, \mathit{if}\ PMU\ is\ installed\ at\ bus\ i \\ 0, otherwise \end{matrix} \right\} \quad (6)$$

It is also an N x 1 matrix and may indicate that a system can be observed if all elements of that matrix are equal to or higher than one. The algorithm is tested for IEEE 7, 14 & 30 standard bus systems. The results are presented in Table 1.

Table 1. Results of optimal placement.

Number of Buses	Number of PMUs	PMU Locations
7	2	2,4
14	4	2,9,6,7
30	10	2, 4, 6, 9, 10, 12, 15, 18, 25, 27

The proposed PMU optimization algorithm is applicable for all types of ring and radial power transmission network with distributed generation.

4. Fault Location for Power Distribution Systems

Electrical power distribution networks will be either ring or radial in nature [16, 17, 18]. The proposed fault location method is applicable for both radial and ring systems. There are three steps in the proposed algorithm which are running in parallel. As an initial step, from the phasor data collected from the PMU, fault distance is calculated. The second step consists of identification of the bus on the main network which is linked to the fault location. This identification is as per the phasor data collected from the PMUs placed at two ends of distribution feeder [19, 20, 21]. The final step is the fault distance calculation in the sub feeder. For this step also, the phasor data collected from the PMUs placed at two ends of distribution feeder is used. The depiction of the proposed workflow is shown in Fig. 5. The main advantage that can be achieved when compared to the typical directional relay is that this scheme uses the synchrophasor from PMU which gives accurate results.

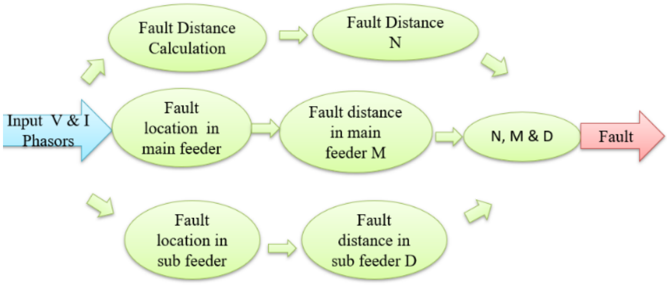


Fig. 5. Workflow representation.

For the illustration of radial network, an 11-bus feeder system shown in Fig. 6 is used. The radial feeder consists of a single nodal line (main breach), three sub-branches, seven demand points which are feeding from bus-1 as shown in Fig. 6. For this network, PMUs are connected at bus-1 and bus-5 which provides phasor measurements.

A ring network scenario for proposed fault location identification method is illustrated with the 14-bus feeder network. The ring feeder consists of a single nodal line, three subbranches, five demand points which are feeding from bus one and bus 5 as shown in Fig. 7. For this network, PMUs are connected at bus-1 and bus-5 which supplies phasor measurements. The distribution line data, demand data and the topology of the network are known.

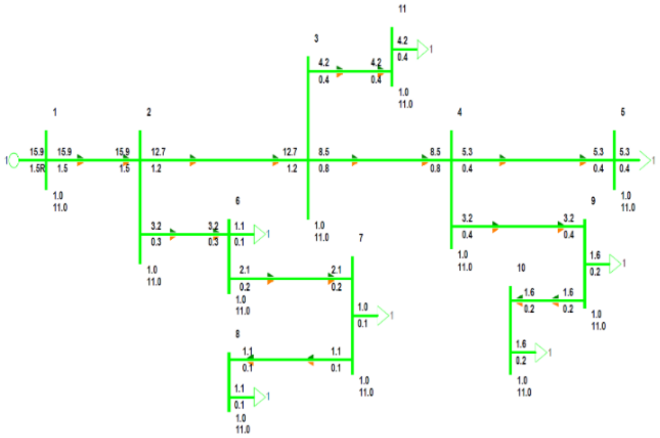


Fig. 6. Load flow results - radial feeder.

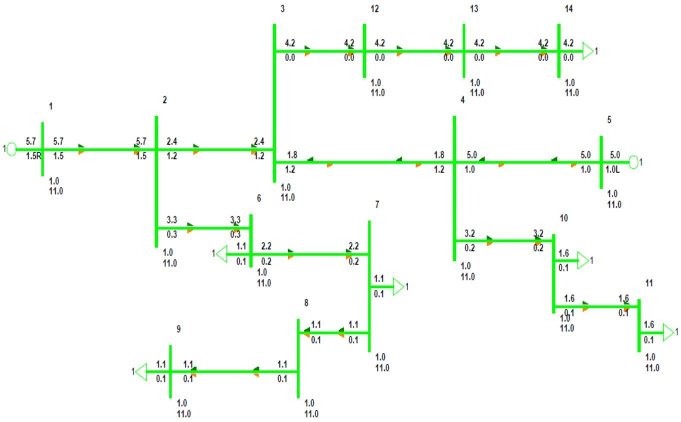


Fig. 7. Load flow results - ring system.

Step 1-Calculation of Fault Distance

The steady state fault condition in a network is described through iterative solutions in the proposed fault distance estimation method. To demonstrate the procedure, a single line to ground (SLG) fault at phase A is created, as detailed in Fig. 8. For the faulted line segment, the voltages and currents at the sending-end are known with the help of PMU located at that bus [22, 23, 24, 25].

$$V_a = D*(Z_{aa}*I_a)+(I_f*R_f) \tag{7}$$

where, D = fault distance (Variable N for Step 1 and M for Step 2)

I_f = fault current

R_f = fault resistance

For solving the above equation, an iterative method is used and the fault distance (D) is calculated [13].

1. The process starts by the calculation of initial fault current I_f

$$I_f = I_a - I_a^{'} \tag{8}$$

where, $I_{a'}$ - pre-fault current on the faulty phase.

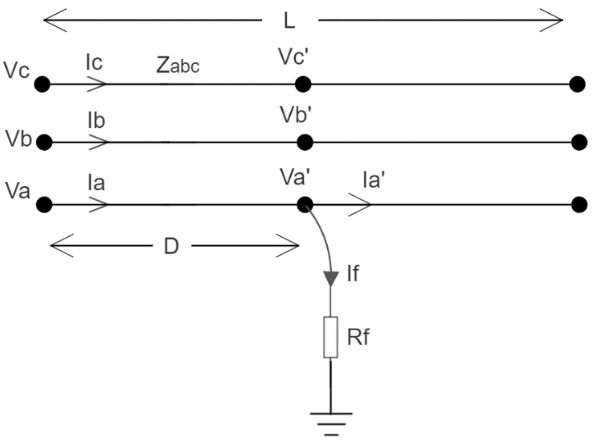


Fig. 8. Fault on phase A.

2. Upon calculation of I_f, the separation of real and imaginary parts of the equation (8) will give the fault resistance and fault current.
3. Voltage at the fault location can be calculated after the fault distance is found.

'N' is the calculated fault distance in kilometers. Steady state load flow studies and short circuit analysis are conducted for the calculation of pre-fault and post-fault conditions of the network.

Step 2 – Fault Bus Identification in Main Network

For the network in Fig. 9, consider a fault at a point which is a distance *m* [pu] from bus 'G'. For the same faulted point, the distance from bus H, can be given as (1–*m*) [pu]. The faulted location voltage can be denoted as V_F. The voltages for bus G and bus H can be written as in equation (9) & equation (10):

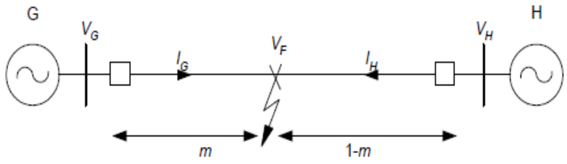


Fig. 9. A fault at the ring feeder.

$$V_G = m*Z*I_G + V_F \tag{9}$$

$$V_H = (1-m)*Z*I_H + V_F \tag{10}$$

To eliminate unknowns, voltage V_F is subtracted from the above two equations which results in equation (11):

$$V_G - V_H = m*Z*I_G + (m-1)ZI_H \tag{11}$$

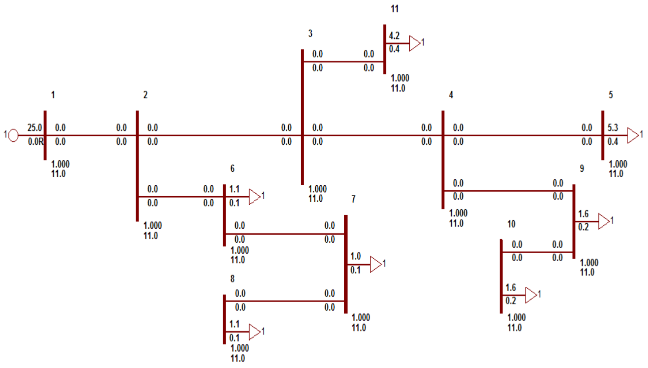
Z = Feeder impedance (per km)
V_G = Generator 'G' terminal voltage
I_G = Generator 'G' current injection
V_H = Generator 'H' terminal voltage
I_H = Current Generator 'H' injection

For equation (11), 'm' is the only unknown parameter and that can be solved [26, 27]. This 'm' will be per unit distance and the actual distance 'M' can be calculated based on the actual distance of the feeder. This distance 'M' in kilometers will be the fault distance for PMU-1 which is located at bus G [28, 29, 30].

Step 3-Sub-feeder Fault Distance Calculation

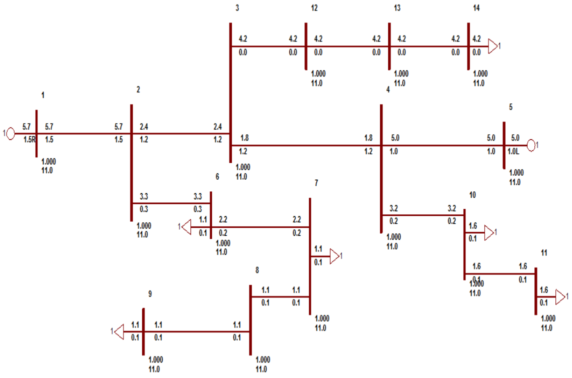
To compute the fault distance in the sub feeder, the procedure similar to step 1 is followed. The change is that, in fault distance calculation, the distance from the bus in the main feeder to the fault location will be calculated. This calculated parameter 'D' will be in kms [20]. Fig. 10 shows the short circuit analysis (fault at bus 8) for a radial feeder.

With the calculated M, N & D values, the algorithm can decide that fault occurred in the primary feeder or the sub feeder. The algorithm will check for the condition M=N and if this is true, then the fault location will be on the main bus. For this case, the fault distance will be M kilometers. If the condition is false, then fault location is on sub feeder. For this case, the distance of the fault will be (M+D) kilometers. Fig. 12 shows the detailed flow chart of the algorithm. Fig. 11 below shows the short circuit analysis (fault at bus-12) for a 14-bus ring feeder respectively.



```
                                     THREE PHASE FAULT
X---------- BUS ----------X           /I+/      AN(I+)
     8  [           11.000] AMP       5407.9    -75.59
```

Fig. 10. Radial system fault at bus 8.



```
                                    THREE PHASE FAULT
X---------- BUS ----------X          /I+/      AN(I+)
   12  [           11.000] PU       2.0069    -86.91
```

Fig. 11. Results of three phase fault at bus 12.

For various fault locations in radial and ring systems, the algorithm is evaluated. These test cases consist of various fault locations in the main feeder and sub feeder.

Table 2. Test results for radial system

Faulted Bus Number	Fault Dista-nce* (N)	Distance in main network* (M)	Sub feeder distance * (D)	Check	Fault Bus (Distance*)
Bus 8	8 km	2 km	4 km	N≠M	**Bus 8 (6)**
Bus 9	11 km	2 km	6 km	N≠M	**Bus 9 (8)**
Bus 11	14 km	6 km	2 km	N≠M	**Bus 11 (8)**
Bus 2	2 km	2 km	0.07 km	N=M	**Bus 2 (2)**

Distance in km

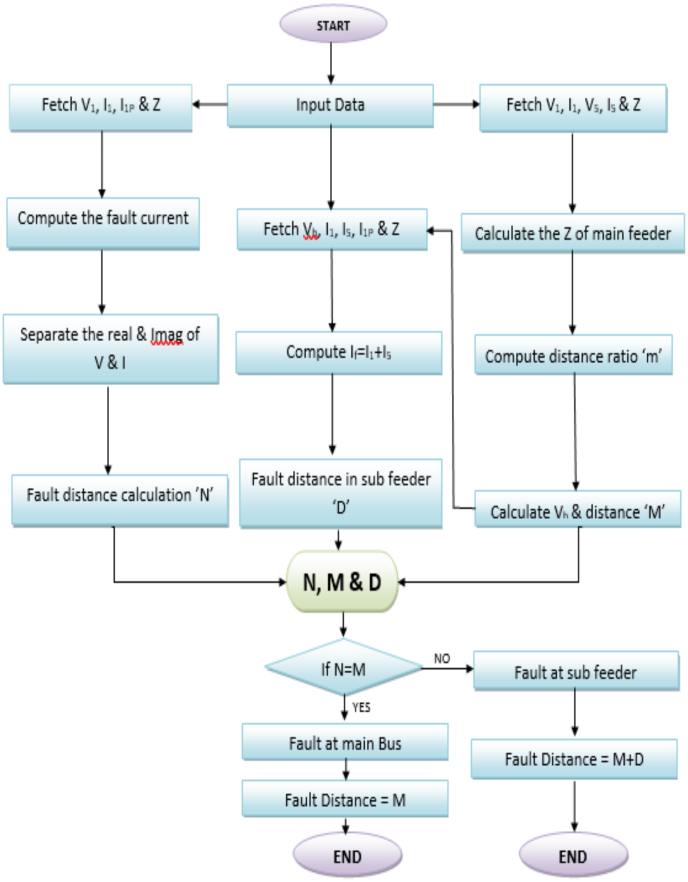


Fig. 12. Detailed flow chart.

The corresponding results for radial and ring feeders are tabulated in Table 2 & Table 3.

Table 3. Test results for ring system

Faulted Bus Number	Fault Distance* (N)	Distance in main network* (M)	Sub feeder distance * (D)	Check	Fault Bus (Distance*)
8	6 km	2 km	4 km	N ≠ M	**Bus 8 (6)**
12	17 km	2 km	6 km	N ≠ M	**Bus 12(8)**
11	9 km	6 km	2 km	N ≠ M	**Bus 11 (8)**
3	4 km	4 km	0.21 km	N = M	**Bus 3(4)**

Distance in km

The proposed fault detection algorithm can identify fault locations in ring and radial distribution feeders. If a distributed generator is connecting to a node which is having a distributed generator or embedded generator [31], then the proposed scheme can identify the fault location accurately.

5. Case Studies

Ring Feeder 1–Kelambakkam Feeder

Kelambakkam ring feeder is fed via 110 kV Mambakkam substation at one side and 33 kV Kelambakkam substation at the other end. This feeder is owned and maintained by Tamil Nadu State Electricity Board (TNEB). The load flow for this feeder is in Fig. 13.

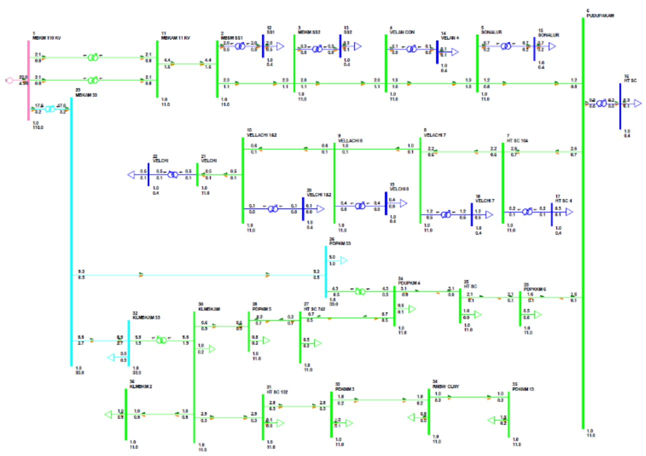
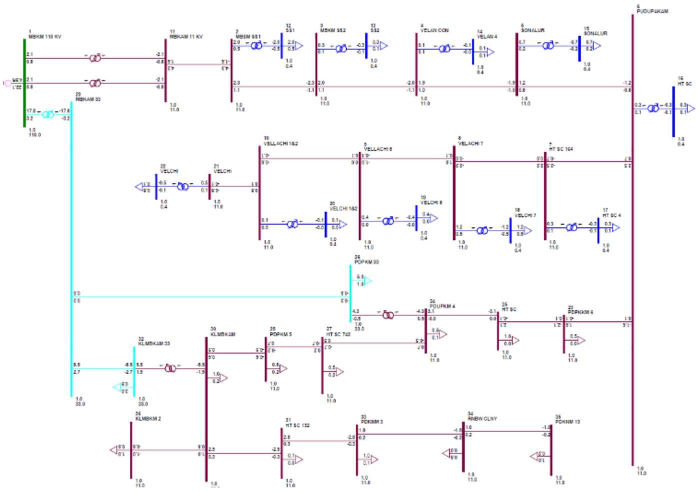


Fig. 13. Load flow in Kelambakkam ring feeder.

The ring feeder in Fig. 13 has been chosen to validate the algorithm. This feeder consists of thirty-six buses which feeds 14 transformers with an overall connected demand of 22 MVA. At five different locations in this network, symmetrical faults were generated to assess the proposed scheme. In one such case, fault at bus 24 is shown in Fig. 14.



```
                                     THREE PHASE FAULT
X---------- BUS ----------X           /I+/      AN(I+)
  24 [PDUPKM 4    11.000] AMP         5617.7    -78.11
```

Fig. 14. Fault at Bus Kelambakkam ring feeder.

Radial Feeder 1 – VIT Chennai Campus Feeder

Mambakkam is the 110 kV distribution substation which is feeding power to VIT Chennai Campus feeder with a connected demand of 16.2 MVA as displayed in Fig. 15. This radial feeder is chosen to validate the algorithm. This feeder consists of 22 buses which feeds 11 transformers with an overall connected demand of 5.6 MVA. In this feeder, there are two transformers which are for dedicated customers. One such dedicated consumer is VIT Chennai Campus.

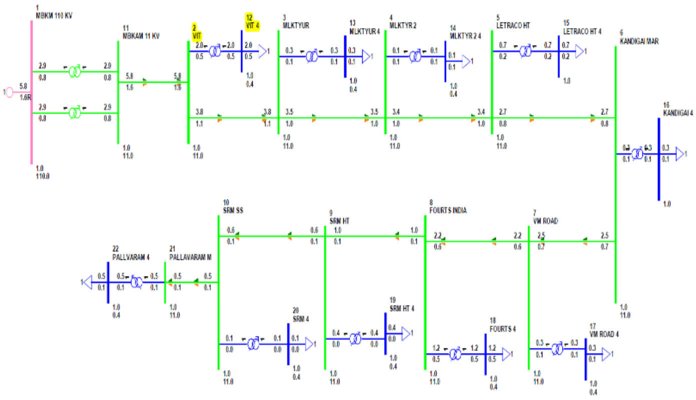
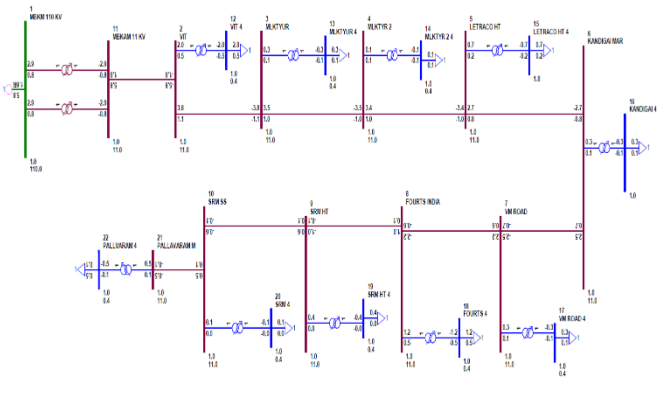


Fig. 15. Load flow in VIT Chennai Campus radial feeder.

At three different locations in this network, symmetrical faults were generated to assess the proposed scheme. One fault location on the above is created at VIT feeder as shown in Fig. 16.

Ring Feeder 2 –IISc Bangalore

Indian Institute of Science, Bengaluru (Bangalore) is fed from a dedicated 66/11 kV substation as detailed in Fig. 17. This ring feeder is chosen to validate the algorithm. This ring feeder consists of 11 buses that supply 8 distribution transformers with a total connected demand of 10 MVA.



```
                                     THREE  PHASE  FAULT
X---------- BUS ----------X             /I+/     AN(I+)
    2 [VIT          11.000] AMP        5338.6    -86.69
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Fig. 16. Fault on VIT Chennai Campus radial feeder.

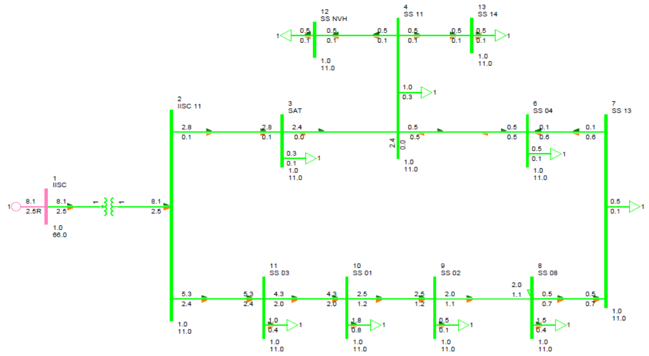
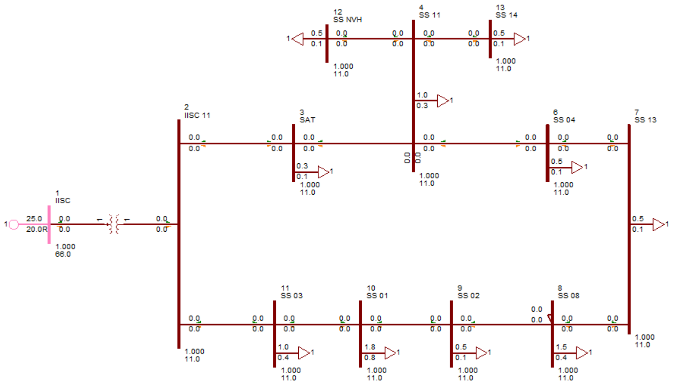


Fig. 17. Load flow in IISc Bangalore ring feeder.

At three separate locations in this network, symmetrical faults were generated to assess the proposed scheme. Fault at Bus 9 for this network is detailed in Fig. 18.



```
                                     THREE  PHASE  FAULT
X---------- BUS ----------X             /I+/     AN(I+)
    9 [SS 02        11.000] AMP        6431.3    -78.20
```

Fig. 18. IISc Bangalore ring feeder fault.

6. Conclusions

Synchrophasor based solutions are being proven and verified in various applications in power system. One such application is proposed and validated in this paper. Binary based algorithm is developed for the optimal placement of PMUs and is tested for various bus system networks. Also, PMU deployment solution is not unique in nature. The established optimization scheme may produce various sets of optimal solutions depending upon the starting point. Each solution delivers similar optimum number of PMUs at various locations.

The proposed scheme is capable of identification of fault location upon its occurrence with the help of synchrophasor measurements from various locations. The proposed scheme is tested for various power distribution networks (ring & radial) with different fault cases. It is noted that processing time is 0.26 seconds for the proposed scheme with the system configuration - Core™ i5 processer and 4 GB RAM. The experimental results show that the proposed fault location identification scheme give outcomes at 98 % precision of the line span.

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