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Hybrid Approach-Based Placement of Micro-Phasor Measurement Units in Active Distribution Networks

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Abstract: The placement of monitoring devices like micro-Phasor Measurement Unit (µPMU), which works 24 hours, at all nodes in the distribution system, is contributing to temperature rise. This temperature rise can be reduced by placing the µPMUs at selected nodes. Therefore, this paper depicted a hybrid approach for µPMUs optimal placement in the distribution system. Optimal placement recognises the placement set containing the least number of µPMUs with optimum redundancy with which the phasors of voltage, as well as the current, can be calculated at each bus of the system. Constraints such as communication link unavailability, zero injection buses, and network reconfiguration are considered in the optimal µPMU placement formulation. The proposed approach overcomes the downside of Integer Linear Programming (ILP) which provides a single optimal location set. The proposed approach automatically assigned µPMUs to buses connected to radial buses, established by the degree of each bus, and reduces the computational concern. Provided algorithm efficiency is checked out with IEEE 40 bus feeder and IEEE 85 bus feeder system under Matlab/Simulink environment.

Key words: Binary search method, integer linear programming, micro-phasor measurement unit.

Introduction

The assimilation of renewable energy resources at a rapid rate makes the present-day power grid a complex system (Gill et al., 2022; Singh et al., 2022). Due to its complex nature, operators need a tool that provides fast and reliable information for monitoring the system states accurately. Concerning this issue, Prof. A. G. Phadke proposed the concept of the Phasor Measurement Unit in the mid-’80s (Phadke et al., 1993). PMU data update rate is about 10-60 samples/second and able to measure the dynamics of the system (Martin et al., 2014). These are widely deployed across the network and synchronised through a standard time signal, and made available to various applications such as visualisation, oscillation, etc. (Lee et al., 2017; Ree La et al., 2010). The complexity of the distribution system and its dynamic behaviour also require PMU-type supervision. However, the measurement accessibility in transmission networks differentiates it from a distribution network in which it cannot be achieved via the release of PMUs at a vast number of buses, as this would certainly be expensive (Liu et al., 2012). For the restricted direct measurement attainability, it depends on the pseudo-measurements obtained from anticipation (Liu et al., 2014). Currently, PMUs are updated to µPMUs (Pinte et al., 2015). It offers to collect a lot more measurement details with greater precision to see to it that situational acknowledgment can be enhanced as well. In comparison to typical measurements, accuracy is obtained at a more considerable expense, so it’s not affordable to place µPMUs whatsoever nodes. Hence

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optimal placement is required. However, techniques used for PMU's placement in the transmission system cannot be used directly. ADNs are distinct from transmission networks in numerous peculiar methods such as (Mohamed et al., 2019; Santos et al., 2016):

1. Configuration-wise, ADNs are different from transmission systems. ADNs are mostly radial or weakly loop type in nature, while transmission systems have meshed type formation.
2. Compared with the transmission system, ADNs topology continually changes as a result of the high infiltration of renewable resource sources, etc. These network reconfigurations can make the system unobservable.

Therefore, the optimal placement of μPMUs in ADNs is a more challenging task as compared to the transmission system. Recently, there have been some papers (Teimourzadeh et al., 2019; Wu et al., 2018) that discussed the observability of the ADNs. Smart Meters and the micro-PMUs optimal strategy are proposed in the study by Teimourzadeh et al. (2019). The given problem is split into two sub-problems by using the Bender decomposition technique, which is further solved with the help of a mixed-integer linear programming approach. Results indicate that it requires a large number of devices for complete observability, and different location sets are proposed for different network configurations. In Wu et al. (2018), topology changes are considered while minimising the load loss; however, it does not provide complete observability of the system. An ILP framework is proposed by Wang et al. (2019), which solves the optimisation problem in the distribution system by considering topology reconfiguration, ZIBs, and conventional measurements.

Similarly, in a study by Chauhan et al. (2019), ILP is used to find out the configuration of PMUs, which minimise the cost. Up to now, limited work has been done towards optimisation of micro-PMUs in ADNs. Hence, in this paper, a hybrid algorithm that combines the desired features of ILP and binary search method is proposed for optimal placement of μPMUs, which reduces the temperature rise. Communication links unavailability, ZIB & network topology changes are considered to examine the performance of the proposed method. The main contributions of these papers are:

1. To reduce the temperature rise caused by the Micro-PMUs through optimal placement of Micro-PMUs.
2. To study the effect of communication link unavailability and the existence of zero injection bus on the system's observability.
3. Determine the number of μPMUs and their locations, which makes the system observable in case of any network topology change.

The paper comprises the following sections: Section: **Optimal Placement of μPMUs and its Formulation** presents the general optimal placement formulation of μPMUs and its various constraints; Section: **Proposed Method** explains the hybrid approach implemented for Optimisation; followed by **Results and Discussion** section and finally, the last section: **Conclusion**.

Optimal Placement of μPMUs and its Formulation

Mathematically μPMUs can be stated as (Gou et al., 2008; Singh et al., 2017).

$$\text{Minimise P} \tag{1}$$

where

$$P = \sum_{i=1}^{m} w_i n_i + n_t + n_r \tag{2}$$

$$n_t = 1 \forall t \in BCRB \tag{3}$$

Subject to

$$A.\ Z \geq 1 \tag{4}$$

n_r : Buses connected to distributed generation

n_i : Aspects of vector Z, which shows the status of μPMUs set up on the bus

n_r = 1 indicate that μPMU is placed

n_i = 0 μPMU is not placed

w_i : μPMU's setup expenses at ith bus

n_t, buses linked to radial buses (BCRB) where μPMUs are mounted.

B described as a binary connectivity matrix, which shows the relationship of the test system via distribution lines. Entries in it are done as:

$$B_{jk} = \begin{bmatrix} 1 : j = k \\ 1 : j \,\&\, k \text{ are link} \\ 0 : j \,\&\, k \text{ are not link} \end{bmatrix} \tag{5}$$

BCRB is an array of neighbouring buses of radial buses, which is characterised as

$$BCRB = \begin{bmatrix} j \text{ if } RB \text{ is connected to } j \\ 0 \text{ if } RB \text{ is not connected to } j \end{bmatrix} \tag{6}$$

Where RB is a set of radial buses obtained by

$$RB = \min\left(\sum_{i=1}^{n} \text{degree}(i)\right) \tag{7}$$

Optimal Placement Considering Zero Injection Buses

The incorporation is done by modifying the binary connectivity vector through (5) such that

$$B_{ij} = \begin{cases} 1: \ \mu PMU \text{ is placed at node} \\ 1: \ \text{Two nodes connected by zero injection bus} \\ 0: \ \mu PMU \text{ is not placed} \end{cases} \tag{8}$$

Optimal Placement Considering Communication Links Unavailability

Communication infrastructure is not possible to be available at all placement sites. It may be the communication installation cost is higher than that of the µPMUs. The approach to solving optimal placement must be efficient in recognising the constraints posed by the limited communication infrastructure (Theodorakatos et al., 2015). For this, the Binary connectivity matrix is modified by multiplying it with a communication link vector. Mathematically it can be written as

$$C_i = \begin{cases} 1 \text{ if communication link is available} \\ 0 \text{ if communcation link is not available} \end{cases} \tag{9}$$

where C_i is communication link vector

Multiplied (9) to (5) such that:

$$D_t = C_i \times B_{ij} \tag{10}$$

D_i is the modified binary connectivity matrix

Optimal placement of µPMU Under Network Reconfiguration

Reconfiguration of the distribution system is done by changing the states of sectionalised switches & tie switches. Switches are open and closed so that load transfer among the feeders. Optimal placement of µPMUs under network reconfiguration is a challenging task as it should provide complete system observability under various topologies of tie switches and sectionalized switches. Here it is done by adding the constraint that each non-µPMU bus is observed by two µPMU in the proposed hybrid approach. It can be written as

$$\{R_1 + R_2 + \ldots R_k\} \geq 2 \tag{11}$$

R_k: Redundancy of k^{th} non-PMU buses

Observability Index

BOI and SORI are used to evaluate the quality of the optimal placement solution when multiple solutions have the same number of µPMUs (Dua et al., 2008). BOI states how many times a particular bus is observed by µPMUs, and the sum of BOI is SORI. It can be denoted as:

$$SORI = \sum_{i=1}^{n} BOI_i \tag{12}$$

where n indicates the number of system buses.

A higher value of SORI illustrates that the reliability of a based monitoring system is higher.

SORI is written as [9]:

$$\min\left\{\max SORI\left(K_p,\ S\left(K_p\right)\right)\right\} \tag{13}$$

Subject to $O_b(K_p, S(K_p)) = 1$

K_p indicates the minimum number of µPMUs

$SORI$ (K_P, $S(K_p)$) is the System Observability Redundancy index & O_b is observability function

Proposed Method

The proposed method can be comprised of the following three steps:

Candidate Location Identification

Buses integrated with distributed generation (DG) are assumed as essential buses on which µPMUs are directly mounted. After that, µPMUs are placed at BCRB buses despite radial buses, as it enhances the redundancy level. So for this, the proposed approach determines the direct connectivity of each bus with other buses, defined as the degree of the bus. The radial bus degree is considered to be equal to one. The optimization approach automatically assigned µPMUs to buses connected to radial buses. It removes radial buses and BCRB from potential locations where extra µPMUs need to be installed. Considering the number of radial buses in the distribution system, the search space will reduce drastically.

Minimum number of µPMUs

By considering the number of µPMUs assigned to step 1. Determine the minimum number of PMUs by using ILP that guarantees to provide an optimal solution.

Locations of µPMUs

After finding out the minimum number of µPMUs, all possible location sets, which make the network entirely noticeable, are determined by using the Binary Search Method. It is done by placing the lower bound equal to the number of µPMUs obtained in step 2. To get the optimal solutions in existing available placement sets, BOI and SORI are calculated for each possible solution. Placement steps having maximum redundancy are considered an optimal solution. All these three steps of the proposed hybrid approach solve the optimal placement problem of µPMU. The pseudocode of the proposed algorithm under different constraints is given in Figures 1-3.

```
Set i = Z(:,1)
Set j=Z(:,2)
Z → Network data
A=determined by equation 5
A → Binary Connectivity Matrix
Set B=degree of G
Set C = 0 or 1
Communication link (C) available = 1
Communication link (C) not available = 0
D=A*C
D→ Modified binary connectivity matrix
G → Graph of the bus system
Set loop for elements of B
If B==1
Set RB = B
end of if statement
end of loop
BCRB=neighbors of RB
RB →Radial Buses
BCRB→Bus connected to radial buses
x1=intlinprog(f,intcon,D,b,Aeq,beq,lb ,ub)
m=elements of x1>0
Y= total number of elements in m
m→location of µPMUs determined by ILP
Y→total number of µPMUs determined by ILP
Remove RB & BCRB from potential location c
Set a1 =Y- BCRB
N→ total number of buses in the system
z = combntns(c ,i)
z→Determine all combinations of i
x2 = concentation (z, BCRB)
x2→added combinations of i with m
Q=zeros(40,40)
Q→ set an matrix of 40×40 elements
E = allcomb (x2, Q, N)
E→Place µPMUs in 40 elements matrix
Set loop i =1 to length of E
if redundancy of E >=1
Determine µPMU & its location
Determine SORI index for each set

end of if statement
end of loop
```

Figure 1: Pseudocode for the proposed method under communication link unavailability.

Results and Discussions

The proposed hybrid approach is implemented on IEEE standard test feeders. Figures 4 and 6 show

```
Set flag =0
Set i = Z(:,1)
Set j=Z(:,2)
Z → Network data
A=determined by equation 8
A →Modified Binary Connectivity Matrix
Set B=degree of G
G → Graph of the bus system
Set loop for elements of B
If B==1
Set RB = B
end of if statement
end of loop
BCRB=neighbors of RB
RB →Radial Buses
BCRB→Bus connected to radial buses
x1=intlinprog(f,intcon,A,b,Aeq,beq,lb ,ub)
m=elements of x1>0
Y= total number of elements in m
m→location of µPMUs determined by ILP
Y→total number of µPMUs determined by ILP
Remove RB & BCRB from potential location c
Set a1 =Y- BCRB
N→ total number of buses in the system
z = combntns(c ,i)
z→Determine all combinations of i
x2 = concentation (z, BCRB)
x2→added combinations of i with m
Q=zeros(40,40)
Q→ set an matrix of 40×40 elements
E = allcomb (x2, Q, N)
E→Place µPMUs in 40 elements matrix
Set loop i =1 to length of E
if redundancy of E >=1
Determine µPMU & its location
Determine SORI index for each set

end of if statement
end of loop
```

Figure 2: Pseudocode for the proposed method under zero injection measurement.

```
Set flag =0
Set i = Z(:,1)
Set j=Z(:,2)
Z → Network data
A=determined by equation 6
A →Binary Connectivity Matrix
Set B=degree of G
G → Graph of the bus system
Set loop for elements of B
If B==1
Set RB = B
end of if statement
end of loop
BCRB=neighbors of RB
RB →Radial Buses
BCRB→Bus connected to radial buses
x1=intlinprog(f,intcon,A,b,Aeq,beq,lb ,ub)
m=elements of x1>0
y= total number of elements in m
m→location of µPMUs determined by ILP
y→total number of µPMUs determined by ILP
if redundancy of m>=2
Determine all possible µPMU locations
Determine SORI of each set
else
Remove RB & BCRB from potential location c
Set a1 = N-y
N→ total number of buses in the system
Set a loop from i =1 to a1
z = combntns(c ,i)
z→Determine all combinations of i
x2 = concentation (z, m)
x2→added combinations of i with m
Q=zeros(40,40)
Q→ set an matrix of 40×40 elements
E = allcomb (x2, Q, N)
E→Place µPMUs in 40 elements matrix
Set loop i =1 to length of E
if redundancy of E >=2
Determine µPMU & its location
Determine SORI index for each set
Set flag=1
end of if statement
end of inner loop
If flag =1
Than terminate the loop
end of outer loop
end of if statement
```

Figure 3: Pseudocode for the proposed method under network reconfiguration.

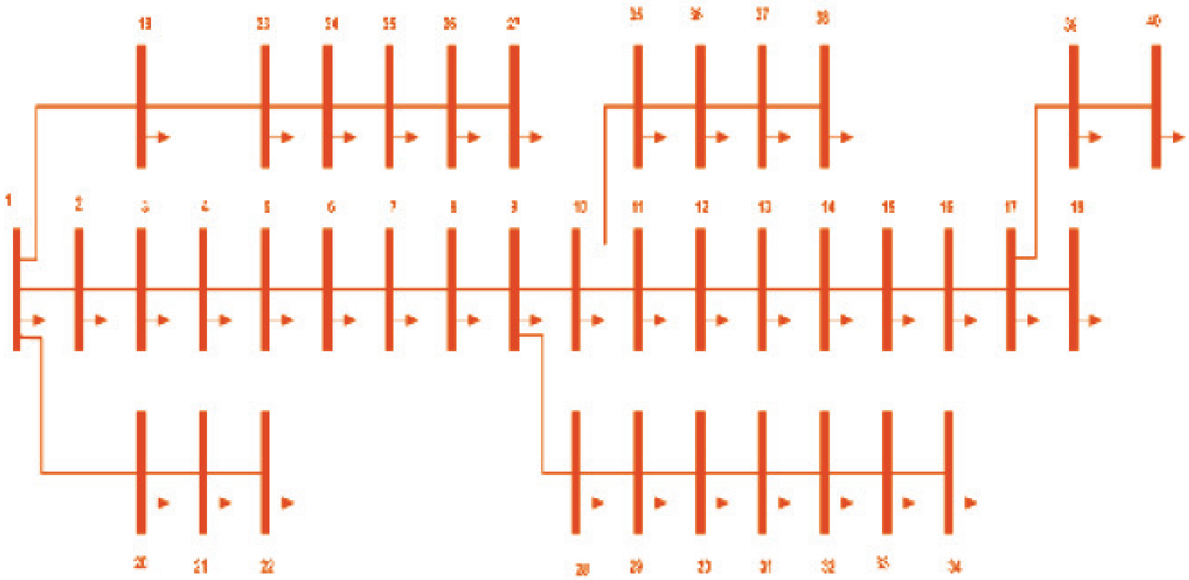

Figure 4: IEEE 40 Test Feeder System with topology changes.

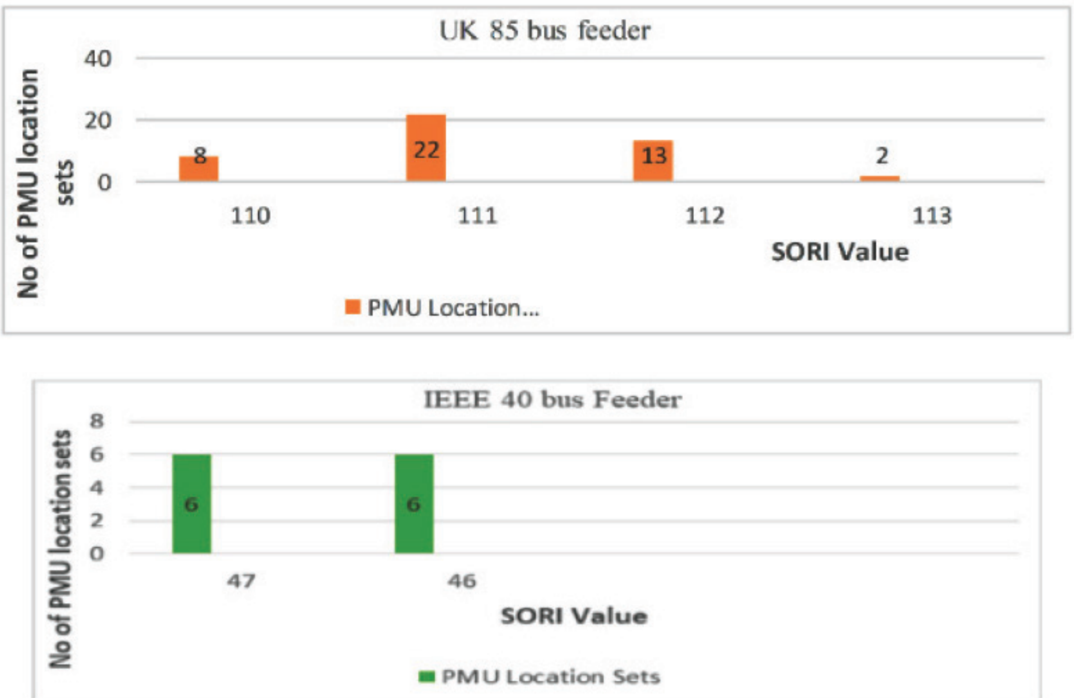

Figure 5: µPMUs location sets at different SORI value for (a) UK 85 bus feeder (b) IEEE 40 bus Feeder.

Table 1: Radial buses and BCRB µPMU buses

System	*Radial buses*	*DG bus*	*BCRB*
40	1 18 19 22 27 34 38 40	23	2 17 21 26 33 37 39
85	1 16 17 22 23 24 59 62 66 77 72 79 75 71 76 85 15 82 78 37 38 39 42 43 47 36 55 54 56 51 84	58 61 65	2 3 21 19 7 58 61 65 67 74 70 13 14 81 10 26 27 29 41 46 35 52 53 49 50 83

Table 2: µPMU and its possible locations

System	*µPMUs Required*	*All possible locations*	*SORI*
40	14	2 6 9 10 ***11*** 14 17 21 23 26 30 33 37 39 :	47
		2 6 9 10 ***12*** 14 17 21 23 26 30 33 37 39 :	47
		2 6 9 10 12 ***15*** 17 21 23 26 30 33 37 39 :	47
		2 6 9 10 ***13*** 14 17 21 23 26 30 33 37 39 :	47
		2 6 9 10 13 ***15*** 17 21 23 26 30 33 37 39 :	47
		2 6 9 10 13 ***16*** 17 21 23 26 30 33 37 39 :	47
85	30	2 3 5 7 10 13 14 19 21 26 27 29 32 34 35 41 46 49 50 52 53 58 ***60*** 61 65 67 70 74 81 83 **:**	113
		2 3 5 7 10 13 14 19 21 26 27 29 32 34 35 41 46 49 50 52 53 58 61 ***64*** 65 67 70 74 81 83:	113

the topology of the IEEE 40 and IEEE 85 test feeder systems, respectively. According to step 1 of the proposed approach, radial buses and allocated µPMU buses are shown in Table 1. Implementation of Step 2 and Step 3 determines all possible location sets with the least required number of µPMUs. It is observed that for 40 bus test feeder systems, 12 possible location sets with 14 µPMUs in each make the system observable. Possible solution sets are further ranked up by calculating the SORI of each, as shown in Figure 5. After a comparison of SORI, 6 placements sets having maximum redundancy are considered for the optimal placement, indicated in Table 2. Similarly, 85 test feeder systems require a minimum of 30 µPMUs, which can be distributed in 46 placement sets. Out of 46 sets, 2 sets achieving maximum redundancy are favourable for µPMU placement.

µPMU Placement Considering Communication Link Unavailability

In this case, buses of IEEE test feeders are considered without communication links. It is observed that in

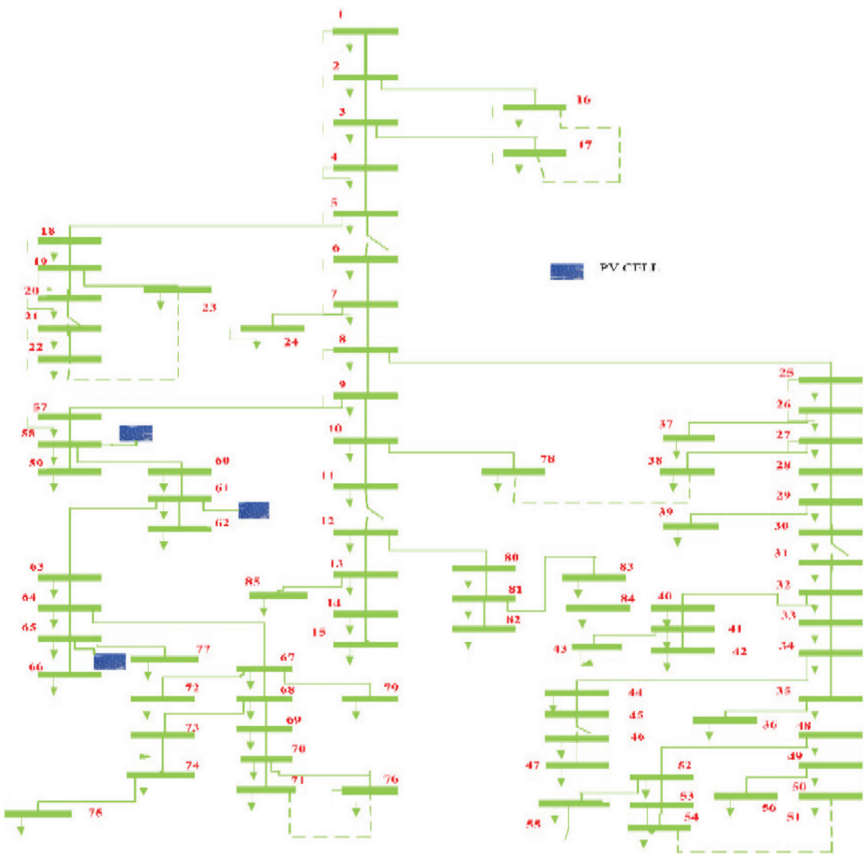

Figure 6: IEEE 85 Test Feeder System with topology changes.

Table 3: µPMUS considering without communication link

Feeder Test System	*Buses without a communication link*	*Number of µPMUs required*	*All Possible Sets*	*SORI*
40	6,8,13,24, 30,37	15	2 4 7 11 14 17 21 23 26 28 31 33 ***35*** 38 39 :	48
			2 4 7 11 14 17 21 23 26 28 31 33 ***36*** 38 39 :	48
			2 4 7 ***12*** 14 17 21 23 26 28 31 33 35 38 39 :	48
			2 4 7 12 ***15*** 17 21 23 26 28 31 33 35 38 39:	48
85	5,19,32,44,63,81	31	2 3 7 10 12 13 14 18 21 23 26 27 29 31 34 35 41 46 49 50 52 53 58 ***60*** 61 65 67 70 74 82 83 :	111
			2 3 7 10 12 13 14 18 21 23 26 27 29 31 34 35 41 46 49 50 52 53 58 61 ***64*** 65 67 70 74 82 83 **:**	111

the case of the IEEE 40 bus feeder system, there are 8 number of placement sets with 15 µPMUs in each set, which makes the system observable, and it is further confined by calculating the SORI value of each. Out of 8 placement sets, 4 have a higher SORI value, as shown in Figure 7. These location sets are indicated in Table 3 and considered as the optimal solution.

µPMU Placement Considering Zero Injection Measurement

The effect of the inclusion of zero injection buses on the total number of micro-PMU requirements is depicted in Table 4. In the 40 test feeder system, bus 10 is considered as ZIB, and its adjacent buses are observable to each other. The Binary Connectivity Matrix is modified according to it, and hence the minimum number of µPMUs requirement is reduced by one. Similarly, in the case of 85 test feeders, the optimal number of µPMU also decreased.

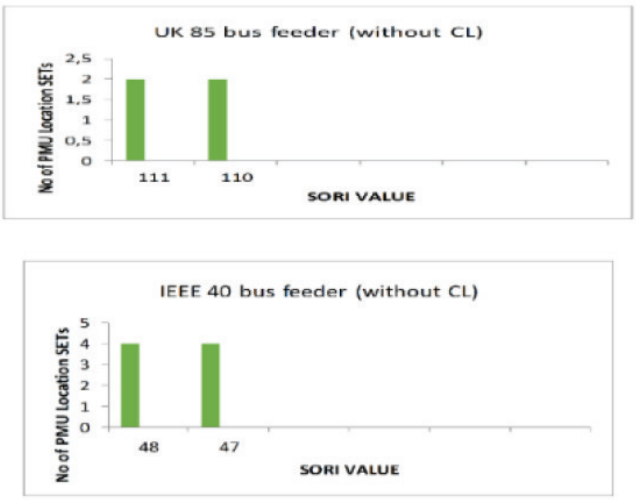

Figure 7: µPMUs location sets at different SORI value for (a) IEEE 40 bus Feeder (b) UK 85 bus feeder without communication link.

µPMU Placement Under Changes in Network Topology

To analyse the effect of network topology changes. The following scenarios are considered:

Scenario 1: In this case, it is assumed that in 40 test feeder systems sectionalised **switches (3-4, 7-8, 13-14, 16-17, 20-21, 31, 32)** are open while tie lines are close as depicted in Figure 4. Similarly, in the case of 85 test feeder systems, sectionalised switches **(5-6, 11-12, 20-21, 30-31, 45-46)** are open, and tie lines are closed. Because each non-PMU is observed by two PMU buses, so non-PMU bus is still observable if it loses its connectivity with one of the PMU buses due to topology changes. By adding this constraint in the proposed placement algorithm, it can be found out that there are 23 µPMUs that make 40 feeder system completely observable and all its possible location are

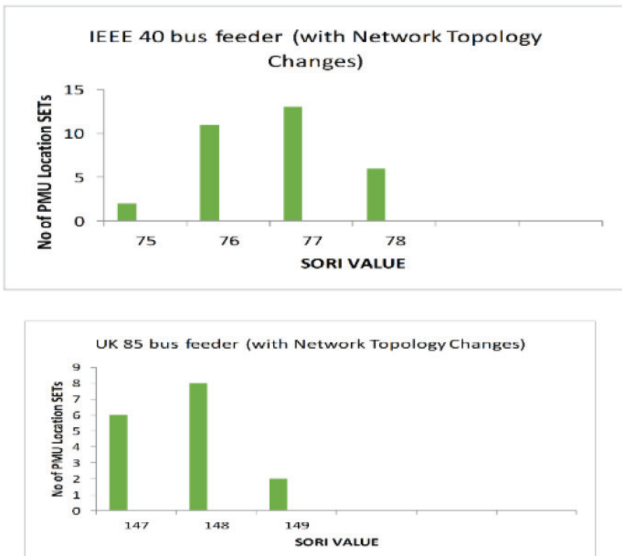

Figure 8: µPMUs location sets at different SORI value for (a) IEEE 40 bus Feeder (b) UK 85 bus feeder with network reconfiguration.

Table 4: µPMUs with zero injection measurement

Feeder test system	*Zero injection buses*	*Minimum number of µPMUs*	*Possible Locations*	*SORI*
40	10	13	**2 6 9 11 14 17 21 23 26 30 33 37 39 :**	**47**
			2 6 9 12 14 17 21 23 26 30 33 37 39 :	45
			2 6 9 12 15 17 21 23 26 30 33 37 39 :	45
			2 6 9 13 14 17 21 23 26 30 33 37 39 :	45
			2 6 9 13 15 17 21 23 26 30 33 37 39 :	45
			2 6 9 13 16 17 21 23 26 30 33 37 39 :	45
85	18, 45	28	**2 3 7 10 13 14 19 21 26 27 29 32 35 41 46 49 50 52 53 58 *60* 61 65 67 70 74 81 83 :**	**107**
			2 3 7 10 13 14 19 21 26 27 29 32 35 41 46 49 50 52 53 58 61 63 65 67 70 74 81 83 :	106
			2 3 7 10 13 14 19 21 26 27 29 32 35 41 46 49 50 52 53 58 61 *64* 65 67 70 74 81 83 :	**107**

Table 5: µPMUs with network topology changes

Test System	*Scenarios*	*µPMUs*	*Possible Locations*	*SORI*
40	1 & 2 & 3	23	1 2 4 6 7 9 10 12 14 15 17 19 21 23 25 26 29 30 32 33 36 37 39	78
			1 2 4 6 8 9 10 12 13 15 17 19 21 23 24 26 28 30 31 33 36 37 39	78
			1 2 4 6 8 9 10 12 13 15 17 19 21 23 24 26 28 30 32 33 36 37 39	78
			1 2 4 6 8 9 10 12 13 15 17 19 21 23 25 26 29 30 32 33 36 37 39	78
			1 2 4 6 8 9 10 12 14 15 17 19 21 23 24 26 28 30 31 33 36 37 39	78
			1 2 4 6 8 9 10 12 14 15 17 19 21 23 24 26 28 30 32 33 36 37 39	78
85		37	2 3 4 5 7 8 9 10 12 13 14 19 21 26 27 29 31 32 33 35 41 44 46 49 50 52 53 58 61 63 65 67 68 70 74 81 83	149
			2 3 4 5 7 9 10 12 13 14 19 21 25 26 27 29 31 32 33 35 41 44 46 49 50 52 53 58 61 63 65 67 68 70 74 81 83	149

indicated in Table 5. The number of µPMUs that makes 85 test feeder system observable under this scenario is equal to 37, and its possible location sets are 16, as given in Table 5.

Scenario 2: Here, sectionalised switches remain in the open state as in scenario 1, and tie lines change their status from close to open. Initially, in the 40 test feeder system, the tie line connecting from bus 27 to bus 38 is closed, bus 27 is observed by bus 26 while bus 38 is followed by bus 37. When the tie line is open observability of the bus remains the same.

Scenario 3: In this case, both sectionalized switches and tie lines are closed, and It's finding that 23µPMUs in the 40 bus feeder system and 37 µPMUs in the 85 bus feeder system make the system observable. All possible locations of µPMU are indicated in Figure 8.

Conclusion

An efficient and optimum hybrid method is introduced for optimal placement of µPMUs in the distribution system which indirectly improves the global warming. The proposed approach solve the optimal location problem with the minimum number of µPMUs, required for full observability of system. Contingencies such as communication link unavailability, zero injection buses, and changes in network topology are considered, and performance is tested successfully on IEEE 40 test feeder system and IEEE 85 test feeder system. Best optimal location sets, determined through the ranking of SORI values, have higher redundancy concerning solution provided by integer linear programming. This paper form a base as optimal placement is the first step for deploying µPMU in the distribution system for various applications. Future work would consider the multi-configuration distribution network under the contingencies of µPMU channel limitation.

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