

# Optimal Placement of $\mu$ PMUs in Distribution System Integrated with Distributed Energy Resources

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*Abstract:* - Performance of Power System Estimators have been improved with the development of Phasor Measurement Units (PMU). By considering the contribution of PMUs in transmission system, it is anticipated that in future it will be used in distribution networks. Arrival of micro-PMU ( $\mu$ PMU) make it attainable to use it for distribution system. Finding optimal location of  $\mu$ PMUs are the first step before implementing it in distribution system. Since PMUs are generally implemented in transmission system so mostly Algorithms related to OPP is not considered distribution networks radial topology. In this Article, Depth Search Algorithm and a proposed Hybrid Depth Search Algorithm are used to solve optimal placement problem. IEEE radial distribution feeder integrated with distributed energy sources are considered for examination of proposed placement methods and results indicate that proposed hybrid depth search algorithm overcomes the drawback of depth first search algorithm of not providing optimal solution.

*Key-Words:* - Phasor Measurement Unit (PMU), Depth First Search Algorithm (DFS), Binary Search Algorithm, System Observability Redundancy Index (SORI)

## 1 Introduction

Today's Distribution systems are gradually changes from passive mode to active mode due to integration of wind, solar, fuel cell and hybrid renewable energy resources [1]. The active distribution network is characterizes by two-way flows within distribution level, intentional and autonomous islanding [2]. Due to these characteristics and uncertainty in operation caused by the variability of renewable energy sources, situation awareness is required. Traditional monitoring technologies that used are not sufficient and creating challenging needs and opportunity for new technologies [3]. Noticeable consideration has been gained by the wide-area monitoring system (WAMS) area since the implementation of wide-area information, given by the PMUs [4]. PMU is global positioning system (GPS) based device which provides steep voltage, current and frequency signal with high sampling rate and time scale [5]. Although in transmission grids, PMU location methods and measurements has been used but directly it cannot be applicable to distribution grids [6]. Transmission grids are distinguished by the measurement availability which cannot be accomplished in distribution grids through deployment of PMUs at larger number of

nodes as this would be economically costly [7]. To counterbalance the limited availability of direct measurements, it relies on the pseudo-measurements obtained from prior knowledge [1]. Now PMUs are upgraded to micro-PMUs [8]. It offers to accumulate more measurement data with higher accuracy so that situational awareness can be improved and uncertainty in measurements reduced [9]. In Literature, plenty of research related to optimal PMU placement for system observability has been done since 1993 [10]. Algorithms used are broadly classified in to mathematical and heuristic algorithms [11]-[12]. Mathematical algorithms includes exhaustive search and integer programming. all possible placement sets that makes system observable is obtained by exhaustive search method and optimum solution is find out by evaluating this placement sets. However this method consumes large time when implemented to large power system as it checks all combinations exhaustively [13]. An integer programming proposed in [14] provided only one optimal solution whereas multiple solutions can be possible. In [15] PMU placed at the bus through which maximum buses are accessible until full observability is acquired. However optimal solution is not achieved by this method. All these work confined to

transmission system and not considered distribution networks radial topology. In This work, balanced Three Phase Radial Distribution networks with distributed energy resources are considered and Hybrid-Depth First Search Method is proposed which combines the attributes of Depth Search Method and Binary Search Method in order to overcome the drawback of Traditional Depth Search Method of not providing minimum number of  $\mu$ PMUs for complete system observability. Computation makes faster by removing radial buses from the list of potential locations where  $\mu$ PMU can be placed.

## 2 Formulation of Optimal Placement

The main focus of the optimal  $\mu$ PMUs placement problem is to determine the optimum solution that makes power system observable [16]. Observability is characterized by the measurement of complex current and voltages of network either directly or indirectly [17]. It is considered that the  $\mu$ PMUs have sufficient channels that makes direct observability of the installed buses and lines linked to that buses [18]. Optimal Placement is a challenging problem, formulated as [19]:

$$\text{Minimize } X \tag{1}$$

Where

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

$$n_t = 1 \forall t \in \text{pre}\mu\text{PMU} \tag{3}$$

$$n_k = 1 \forall t \in \text{BCRB} \tag{4}$$

Subject to

$$AZ \geq 1 \tag{5}$$

$n_i$  : Elements of vector Z which indicates the status of installation of PMUs on bus i.

$n_i = 1$  Point out that  $\mu$ PMU is installed while

$n_i = 0$  Show  $\mu$ PMU is not installed

$w_i$  :  $\mu$ PMU's installation cost at ith bus

$n_t$ , belong to the buses where  $\mu$ PMUs are preinstalled (pre $\mu$ PMU)

$n_k$ , buses connected to radial buses where  $\mu$ PMUs are assigned (BCRB)

B referred as a binary connectivity matrix which indicates the correlation of test system through distribution lines. Entries in it can be illustrated as:

$$B_{ij} = \begin{cases} 1 & \text{if } i = j \\ 1 & \text{if } i \text{ and } j \text{ are directly linked} \\ 0 & \text{if } i \text{ and } j \text{ are not linked} \end{cases} \tag{6}$$

BCRB is an array of buses connected to radial buses and it is defined as

$$\text{BCRB} = \begin{cases} j & \text{if RB is connected to } j \\ 0 & \text{if RB is not connected to } j \end{cases} \tag{7}$$

Where RB is a set of radial buses obtained by

$$\text{RB} = \min \left( \sum_{i=1}^n \text{degree}(i) \right) \tag{8}$$

## 3. Proposed Approach for Optimal Placement of $\mu$ PMUS

In Real Power System always there is some strategically significant buses such as bus connected to heavily loaded or economically important areas [13]. Such buses are considered as preferred buses and  $\mu$ PMUs are placed on it. Here in this paper, buses connected to distributed energy resources are considered as preferred buses. These buses are pre-assigned with  $\mu$ PMUs and remaining unobservable buses are made observable by placing additional required number of  $\mu$ PMUs. Proposed hybrid algorithm that is used for optimal placement comprises of following steps:

Step 1. Assign  $\mu$ PMUs to preferred locations  $N_1$ .

Step 2. Determine the degree of each bus. Buses having degree of one is considered as radial buses. Optimization algorithm automatically assigned  $\mu$ PMUs to the buses connected to radial buses as it improves the redundancy of system by one. Considered it be equal to  $N_2$ . Now check the observability of the system. If it is observable than go to step 7 otherwise go to step 3.

Step 3: In this step, Minimum number of  $\mu$ PMUs are placed on unobserved bus locations in such a way that whole system become observable. For this, Depth Search Algorithm is used in which  $\mu$ PMU placed on the bus having maximum connecting branches. This step will provide the solution

which makes system observable. Let it say total number of  $\mu$ PMUs equals to  $k$ .

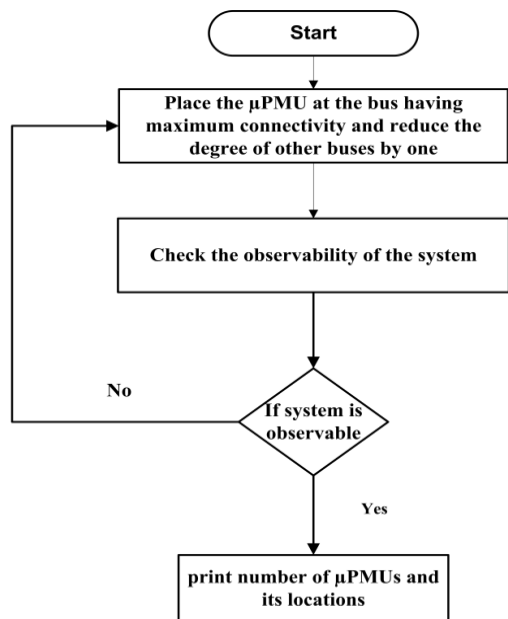


Fig. 1 Flowchart of Depth Search Algorithm

Step 4. Check whether the given number of  $\mu$ PMUs is optimal solution or not. For this reduce the number of  $\mu$ PMUs by one i.e.  $k=k-1$ .

Step 5. Distribute  $k - (N_1 + N_2)$   $\mu$ PMUs to the unobserved network buses by using Binary Search Algorithm [13] in which upper bound of minimum number of  $\mu$ PMUs is set as

$$L_{\mu PMUs}^{UB} = k - (N_1 + N_2) \quad (9)$$

Step 6. Check whether the system is observable or not. If it's observable than go to step 4 otherwise increment the  $\mu$ PMUs by one and go to step 7.

Step 7. Determine all possible locations and find optimal one by using SORI index.

Proposed method can be represented by flow chart in Fig. 2:

### 3. Results and Discussion

Proposed placement method and Depth Search Method is implemented on 33 test system, modified as 12.66 kV  $\mu$ G having 4 diesel –based distributed energy resources and 3 wind turbine units [20] and on 77 bus distribution network with the presence of seven PV generators and three Wind DGs. Buses installed with DGs, listed in Table 1 considered as preferred locations where installation of PMUs are

mandatory. Fig. 3 and Fig 4 shows the topology of 33 bus test system in which switches assumed be open during optimal placement of  $\mu$ PMUs and 77-bus distribution network respectively. Table 2 indicates the radial buses of the network and buses connected to radial buses. Optimizing algorithm removes these radial buses and assigned  $\mu$ PMUs to the buses connected to radial buses. Due to this step redundancy of the system will be increased at least by one.

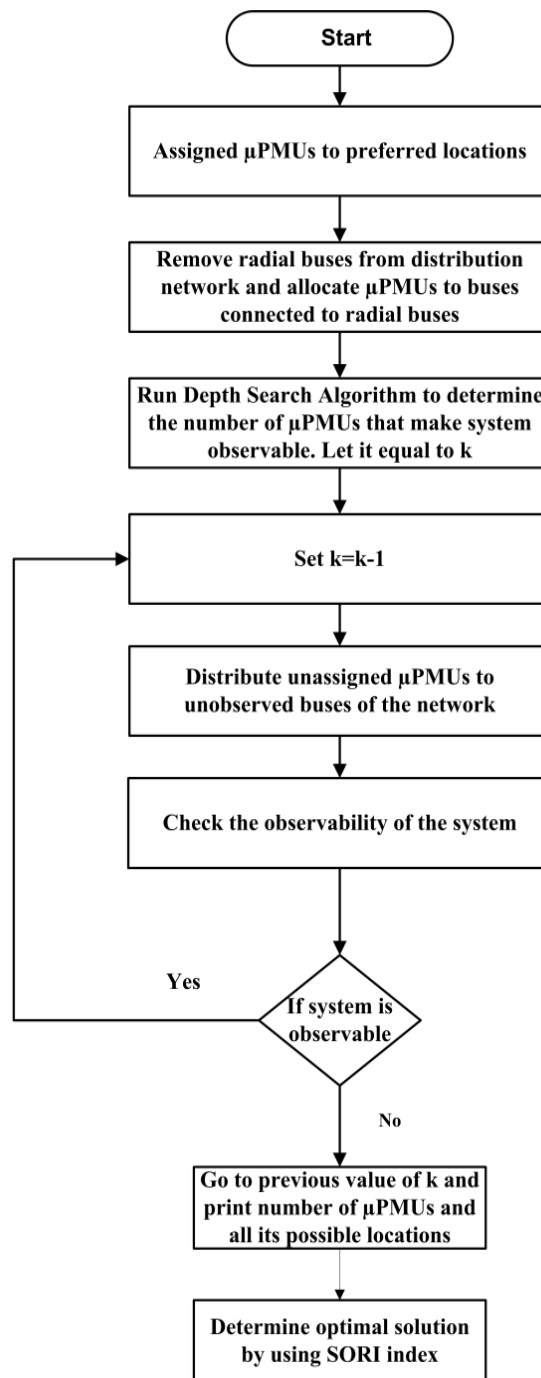


Fig. 2 Flowchart of proposed hybrid Algorithm

Table 1. Preferred Locations

Test System	Preferred Locations
33	8, 13, 14, 16, 25, 32
77	4, 7, 10, 18, 20, 31 32, 40, 42, 43, 64

Since distribution system has many radial buses, this step will dramatically reduce the computational burden.

Table 2. Radial buses and its adjoining buses

System	Radial Buses	Buses connected to radial buses
33	1 22 25 33 18	2 21 24 32 17
77	15 16 30 51 55 70 71 72 73 74 75 76	13 14 29 45 54 56 57 59 61 63 64 66

Implementation of proposed method on 33 bus test  $\mu$ G yields minimum 15 numbers of  $\mu$ PMUs that makes system observable. Total 36 placement sets are generated with fifteen number of  $\mu$ PMUs in each combination. However due to large number of solutions, SORI is calculated for each placement set and after comparison of SORI values of each set, there are two sets having maximum redundancy highlighted in red color in Table 2. Similarly in case of 77 bus distribution network, after executing the proposed method, eight sets having 28  $\mu$ PMUs in each set makes system observable. However optimal solutions, highlighted by red color in Table 2 are selected on the basis of observability redundancy index.

Table 3. Optimal locations for 33 bus test  $\mu$ G

System	Number of $\mu$ PMUs	Locations	SORI
33	15	2, 3, 6, 8, 10, 13, 14, 16, 17, 21, 24, 25, 28, 31, 32;	47
		2, 3, 6, 8, 11, 13, 14, 16, 17, 21, 24, 25, 28, 31, 32;	47
77	28	1, 4, 7, 10, 13, 14, 18, 20, 22, 29, 31, 32, 36, 38, 40, 42, 43, 45, 52, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;	103
		1, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43,	101

101	45, 46, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;	1, 4, 7, 10, 13, 14, 18, 20, 23, 29,31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;
	1, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 52, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;	2, 4, 7, 10, 13, 14, 18, 20, 22, 29, 31, 32, 36, 38, 40, 42, 43, 45, 52, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;
103	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;
	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;
109	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 46, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;
	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;	2, 4, 7, 10, 13, 14, 18, 20, 23, 29, 31, 32, 36, 38, 40, 42, 43, 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68 ;

Next Traditional Depth Search Method is implemented to find optimal placement for 33 bus test distribution system and 77 bus test distribution systems. Results are listed in Table 3.

Table 4: Optimal Locations using Depth Search Method

Test System	No of $\mu$ PMUs	Placement Set	SORI
33	16	2, 4, 6, 8, 10, 13, 14, 16, 17, 21, 24, 25, 27, 29, 30, 32;	47
77	30	2, 4, 7, 10, 13, 14, 18, 20, 22, 26, 27, 29, 31, 32, 34, 36, 40, 42, 43 45, 47, 54, 56, 57, 59, 61, 63, 64, 66, 68;	116

Table 5. Comparison among different Algorithms

Micro-Grid System	Depth Search Method		Proposed Method	
	No of $\mu$ PMUs	No of Placement sets	No of $\mu$ PMUs	No of Placement sets
33	16	1	15	2
77	30	1	28	2

The proposed algorithm is compared with depth search method in Table 5. By analysing the table it can be said that proposed method is more efficient

as it make system observable with reduced number of  $\mu$ PMUs and provides more than one placement sets.

#### 4 Conclusion

In this paper minimum number of  $\mu$ PMUs and all its possible locations are obtained by using proposed hybrid approach which utilizes the attributes of depth first search & binary search algorithm. Strategically important locations are pre-assigned with  $\mu$ PMUs and thereafter proposed approach determine the radial buses and allocated  $\mu$ PMUs to buses connected to it and modified upper bound of binary search algorithm in order to shorten the search space for optimal placement of  $\mu$ PMUs. Optimal solutions are determined by the comparison of System Observability Redundancy Index (SORI) of each placement set. The proposed method is implemented on modified IEEE 33 radial distribution feeder integrated with distributed energy resources and on 77 radial distribution test feeder. Results are compared with depth search algorithm and it can be said that proposed method overcomes the drawback of depth search algorithm of not providing minimum number of  $\mu$ PMUs. Future work will test the unbalance 3-phase distribution system considering various  $\mu$ PMUs contingencies.

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APPENDIX

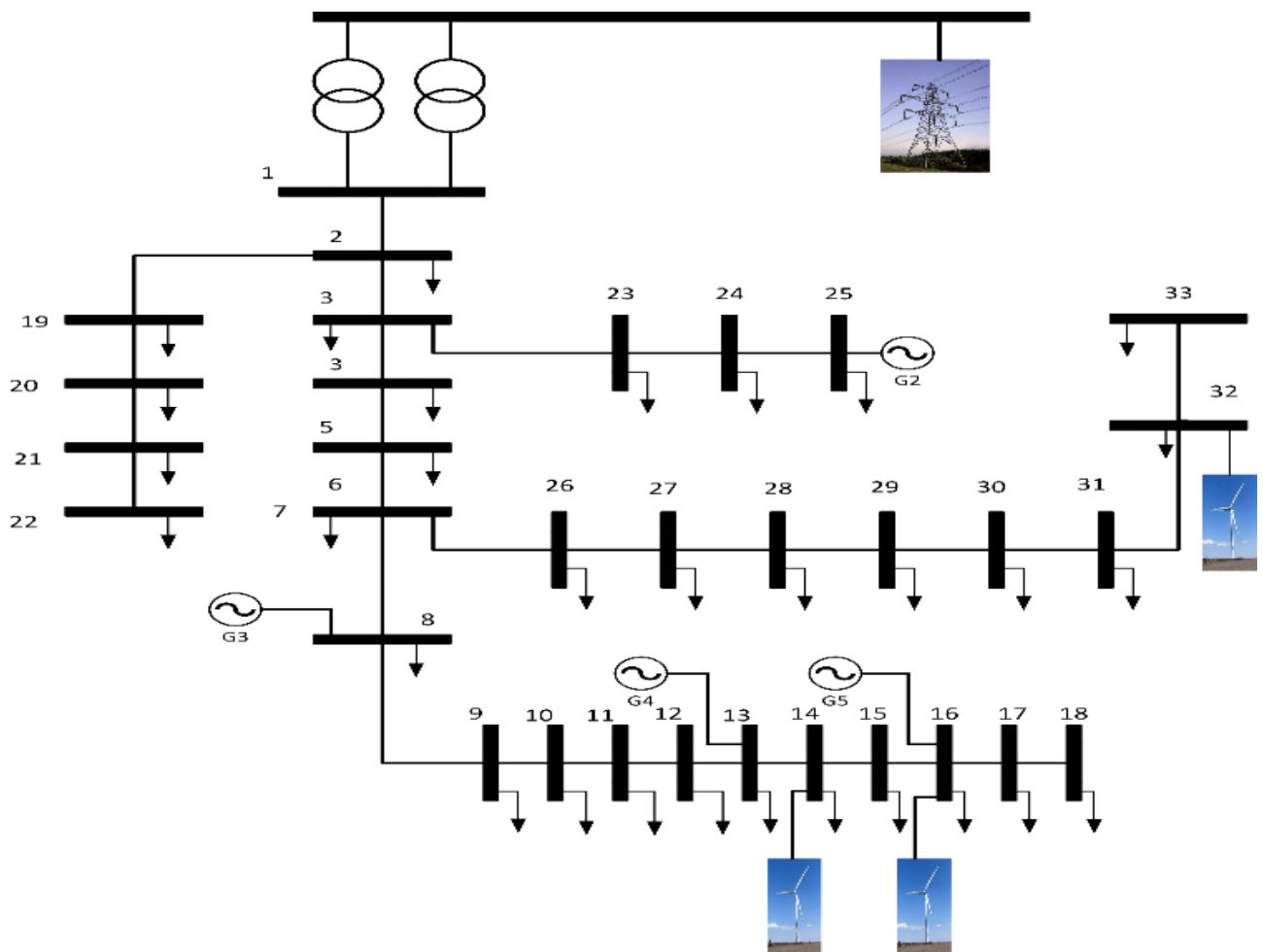


Fig. 3 33 distribution feeder integrated with distributed energy resources

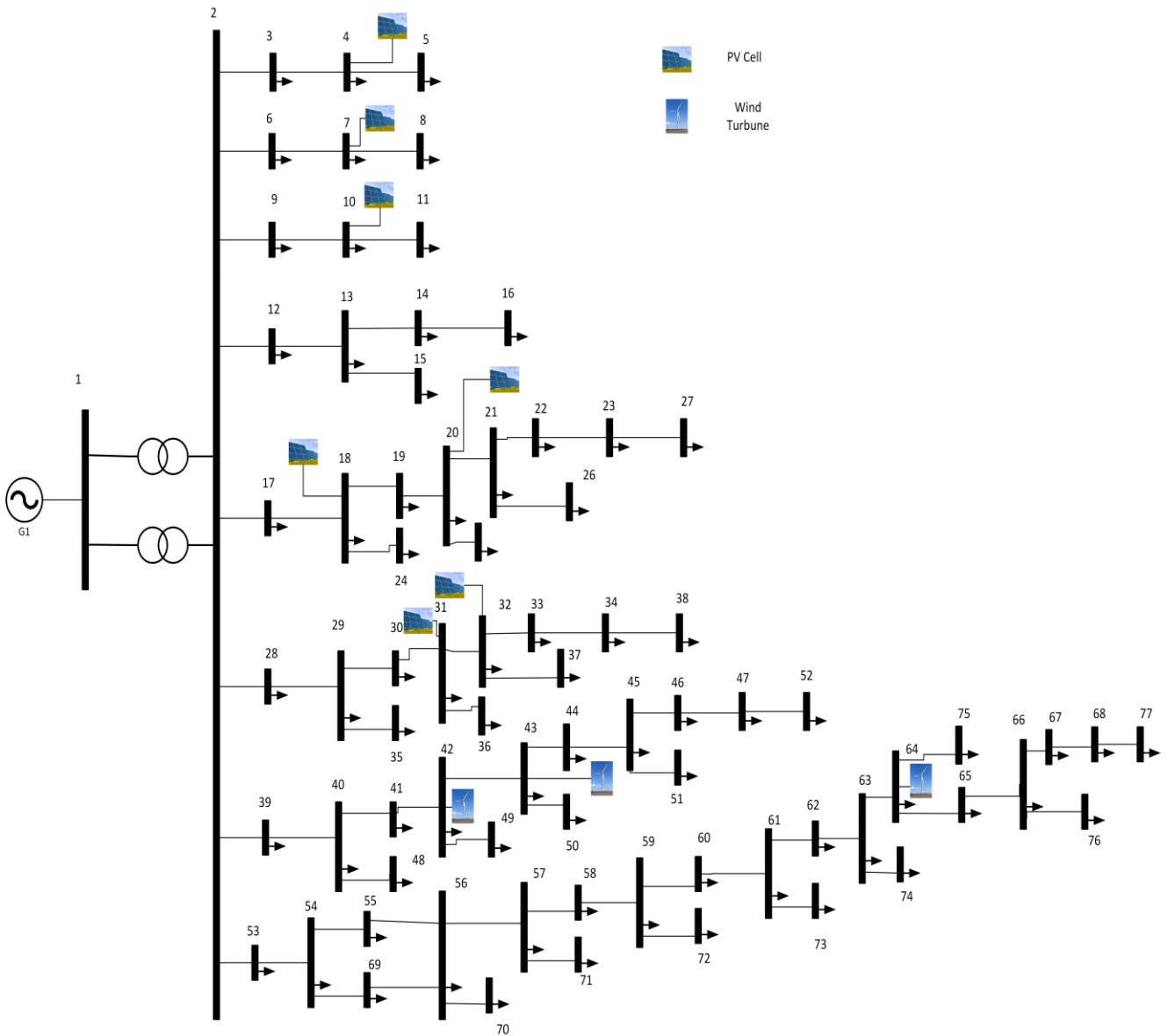


Fig 4. 77 bus Distribution System