Research on the placement algorithm for Ubiquitous Internet of things terminals in distribution network

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Abstract. Placement of terminal is a crucial problem for Ubiquitous Internet of things in distribution network, which can ensure that the power system is fully observed. Based on Prim algorithm, an optimal placement method is utilized to solve the observability problem in power distribution network is proposed in this study. The method has fast calculation speed, precise and reliable results, good adaptability and low cost. At the end, the effectiveness of the established model and processing technique is verified by simulations on IEEE14-bus and 33-bus test system, which can be referred to by relevant researchers.

1. Introduction

The concept of “ubiquitous electric power Internet of things” was first put forward in the 2019 working conference by the State Grid. The ubiquitous electric power Internet of Things is a smart service system which is based on various links of the power system, fully using modern information technology and advanced communication technologies such as mobile internet and artificial intelligence to realize the interconnection of all things and human-computer interaction in all links of the power system. It has the characteristics of comprehensive state perception, efficient information processing, and convenient and flexible applications, including a four-layer structure: perception layer, network layer, platform layer, and application layer [1]. The basis for achieving these functions is its terminal which can monitor the data of the network in real-time.

Recently, there is few new article on the placement of the terminal in ubiquitous electric power Internet of things, so this work is especially important. With the aim of finding out the terminals placement which will achieve the best observable reliability, we need to consider not only the number of terminals but also the reliability of power system which can be noted that the line outage, the terminal failure and its communication channels need be interested. At the same time, in order to reduce the total cost, this method will give the most reasonable measurement redundancy for the system.

This paper begins with an introduction of this work and give basic theory in Section 2 and then presents the proposed algorithm in Section 3. Subsequently, the simulation results are shown in Section 4. Finally, the conclusions are drawn in Section 5.

2. Basic theory

This section will give the fundamental theory of about the proposed. It mainly shows the terminal based network observability, the modified adjacent matrix, the considering the zero injection bus, the object function for full observability of network and the contingency condition in detail.
2.1. The Observability of Distribution Network Based on Terminal

There are two main types of system observability algorithms: numerical analysis methods and network topology methods. Numerical analysis is determined by checking whether the information matrix is full rank. The core idea of the network topology methods are to check whether the configured measurement set can establish a full-rank support tree to cover all nodes in the entire network. Due to the large system, the former method has a huge calculation load. Moreover, accuracy is susceptible to cumulative errors. The latter methods are simpler; they are based on logic operations and require only information about the network connection. Anyway, the latter method has better practicability than the former method.

In this paper, we use the latter method to obtain the observability of power grids. Observability of the power system means that the voltage and phasor of each bus in the power system can be measured directly or indirectly. Based on the observability principle, this study determines the global observability of the system based on the following rules.

**Rule 1.** If node i is equipped with a measurement terminal, the voltage and its phasor of node i can be directly measured, that is, node i can be observed;

**Rule 2.** If a measuring terminal is installed at node i and the current and its phasor of the branch between the adjacent node j connected to it can be measured(a current analog channel is installed), the voltage and its phasor at node j can be calculated by Ohm's law, that is, node j can be observed;

**Rule 3:** If we know the voltage phase of both ends of a branch voltage phase, we can use the line impedance to calculate the current.

2.2. Modified adjacent matrix

A power grid can be described by a graph, which consists of a group of buses and a group of branches. In this model, the set of edges describes the transmission lines connecting between the buses of the power system. An adjacent matrix (A) matrix is used to describe the bus connectivity information of power system [2]. Here, we form a modified adjacency matrix($A_w$) for the purpose of optimizing the placement of IoT terminal in distribution network as follow:

\[
A_w = \begin{bmatrix}
A_{11} & A_{12} & A_{13} & \cdots & A_{1n} \\
A_{21} & A_{22} & A_{23} & \cdots & A_{2n} \\
A_{31} & A_{32} & A_{33} & \cdots & A_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_{n1} & A_{n2} & A_{n3} & \cdots & A_{nn}
\end{bmatrix}
\]

(1)

where $A_w$ is a square matrix of order n which expresses the importance and the connectivity of buses in network; n symbolizes the total number of buses in power grid; $A_{kk}$ is the importance of bus K (k=1,...,n) and $A_{kl}$ (K≠L) is the connectivity between bus K and bus L. $A_{kl}$ is a 0-1 variable. When $A_{kl}=0$, bus k and bus l are not connected, when $A_{kl}=1$, bus k and bus l are connected.

Important buses are those that play an important role in the characteristics and reliability of the power grid. The centrality measure technique is widely used to obtain the relative importance of nodes in the network. In this research, we improve the formula to calculate the importance of buses through an index called Observation Degree Index (ODI) [3,4]. The expression of ODI is as follows:

\[
ODI(i) = \frac{\sum_{st} P_{st}(i) / \sigma_{st}}{P_{\sum load}}
\]

(2)

where $ODI(i)$ is known as the importance of bus i in power grid. When the value of $ODI(i)$ is higher, it means that bus i is more important. $\sigma_{st}$ is the number of shortest paths from generation bus
“s” to load bus “t“, $P_{st}(i)$ is the total power pass through bus i in all shortest paths from bus s to other load buses and $P_{\sum_{load}}$ is a total of load power in the system.

2.3. Considering the zero injection bus
Zero injection bus (ZIB) means that the bus has neither a generator nor a load [5]. Considering zero-injection nodes can further reduce the number of IoT terminals. As shown in Figure 1, node i is a zero injection bus, and the other four buses are connected to it.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{ZIB_model.png}
\caption{The ZIB model}
\end{figure}

Let $f = AX$, $f$ is the node observable function matrix. The processing method for the ZIB is as follows:

$$f_i + f_1 + f_2 + f_3 + f_4 \geq 4$$

(3)

Where $f_i = x_1 + x_2 + x_3 + x_4$, when $f_i \geq 1$, the bus $i$ is observable, when $f_i = 0$, the bus $i$ is unobservable. When 4 nodes in Eq. (3) are observable, then the 5th node is observed according to the above rule 3.

2.4. Object function for full observability of network
The IoT terminal placement problem is to determine the minimum number and the most suitable locations of terminals to observe the full network. In other words, it needs to find one optimal solution for placing terminals with minimum cost. The objective function to minimize the total cost is defined as follow:

$$\min \sum_{k=1}^{g} w_k x_k$$

(4)

Subject to

$$f(x) = A_w x > 0$$

where $x_k$ is a variable of 0 or 1 indicating whether there is a terminal on the bus; $w_k$ is the cost of the terminal installed at that bus; $A_w$ is the adjacency matrix of power system; $f(x)$ is a vector function, whose entries are non-zero if the corresponding bus voltage is solvable using the given measurement.

2.5. Contingency modes
The distribution networks may encounter a variety of emergencies that may affect the observability of the system in operation process. The most important events that affect system observability are line and terminal failures. To ensure the full network observation, the most effective solution is to increase the bus observation redundancy. When some unimportant buses are considered twice, this constraint is used to remove them in the remaining bus sets [6,7].

3. Proposed method
In this method, the importance of buses and the connectivity of branches are firstly calculated and expressed to form the adjacent matrix. Then, the prim’s algorithm (PA) is applied to find the optimal
placement of measuring terminals in the power system [8]. Based on the matrix $A_v$, the PA always can find the minimum spanning tree, which is the basis of computing ODI of all buses in power grid. After that, we should optimize the number of terminals. The method optimizes both the number of IoT terminals and its channels. This means that the power system is observed by a minimum cost.

The proposed algorithm step are as follows:

**Step1.** Finding the branches’ connectivity and the importance of nodes.

**Step2.** Forming the adjacent matrix $A_w$.

**Step3.** Defining the redundancy requirement for the measurement system according to the specificity of the network.

**Step 4.** Finding the MST of power grid network by PA, the modified matrix $A_w$ will be expressed by matrix UG.

**Step 5.** Finding the optimal placement of terminals:
   Detail procedure for finding out optimal locations is as follows:
   (1) Finding out the buses having greater importance and put them in a set ($S_1$), these buses will be target buses.
   (2) Finding out the radial buses from matrix UG, and then the connected nodes will form a new set ($S_2$). Then the bus which is in the set $S_2$ but not in the set $S_1$ will be selected.
   (3) Summarize the total observable buses (TOB) after each of the above steps. TOB=7 means that the system will be completely observable and Step 6 will be executed. If TOB≠7, the remaining nodes in set $S_1$ will be chosen in order. Also, the set $S_1$ can be expanded.

**Step 6.** Satisfy the measurement redundancies:
   (1) Supplementing the measurement redundancy by increase the number of channels and even measuring device.
   (2) Get rid of the repeat channels to obtain the minimum total cost.

4. Simulations and Results
We simulate the IEEE14-bus and 33-bus systems to test the above solution using the software of MATLAB. The IEEE 14-node system has a based capacity of 100MVA, a based voltage of 23KV, and a total network load of $28.7 + 7.75MVA$. The original model had 16 branches, because the distribution network operation was operated in an open-loop model, the original 14, 15, and 16 three branches. The IEEE33 node system has 32 branches, the network’s first-end reference voltage is 12.66kV, the three-phase power standard value is 10MVA, and the total network load is $5084.26 + j2547.32kVA$ [9]. The diagrams are showed in Figure 2.

The two network structure diagrams are as follows:

![IEEE14-bus test system](a)

![IEEE33-bus test system](b)

**Figure 2.** Schematic diagram of distribution network
Through analysis and calculation, the MST can be obtained. Based on the parameters of IEEE system, Many valuable data s can be calculated. The Observation Degree Index of buses in IEEE14-bus and 33-bus test systems are showed in Figure 3.

![Observation Degree Index of buses](image)

(a) IEEE14-bus test system  (b) IEEE33-bus test system

**Figure 3. Observation Degree Index of buses**

In the IEEE14-bus system, the relatively important buses are bus 1, 3, 8, 2 and 4. The radial buses are 6, 7, 9, 10, 11, 12 and 14. Considering the buses connected to radial buses, bus 2, 5, 8, 3, 4 and 13 will be selected first. This placement meets the condition of TOB=14. Then considering the redundancy problem. In this method, each important bus with one redundancy will be analyzed.

In the IEEE33-bus system, the relatively important buses are bus 1, 2, 3, 4, 5, 6, 26, 27, 28, 7, 29, 8 and 9. The radial buses are 1, 18, 22, 25 and 33. Considering the buses connected to radial buses, bus 2, 17, 21, 24 and 32 will be selected first. Then the bus 3, 4, 5, 26, 27 and 28 will be put in the set. The measurement set will be expanded until TOB=33. In this method, each important bus with one redundancy will be analyzed and duplicate channels and extra equipment will be removed to meet the reasonable redundancy and reduce the cost.

The final result of this method for the two system is in Table 1.

**Table 1. Placement of terminals with this algorithm**

| system | Numble of terminals | Locations |  
|---------|---------------------|-----------|
| 14-bus  | 6                   | bus       |
|         |                     | 8 3 4 2 5 13  |
|         |                     | 2-1 2-6 3-1 3-8 3-11 4-12 4-13 |
|         |                     | 5-2 5-7 8-3 8-9 8-10 13-4 13-14 |
|         |                     | 2-1 2-3 2-19 17-16 17-18 21-20 21-22 |
|         |                     | 2 17 21 24 32 |
| 33-bus  | 16                  | channels  |
|         |                     | 24-23 24-25 32-31 32-33 3-2 3-4 |
|         |                     | 5-4 5-6 6-5 6-7 6-26 8-7 8-9 9-8 9-10 |
|         |                     | 29 9 11 12 14 |
|         |                     | 11-10 11-12 12-11 12-13 14-13 14-15 |
|         |                     | 27-26 27-28 28-27 28-29 29-28 29-30 |

From the above results, IEEE14-bus system need 6 terminals and 14 and IEEE33-bus need 16 terminals. Based on this configuration, we can obtain global observable and operation stability. The experimental results of this paper in the test system provide useful inspiration for the optimal configuration of the IoT terminals in the distribution network. The method in this paper can find a suitable solution in a large-scale network, and the search time is short. In short, the proposed method has great practicability for distribution network and provides the foundation for the development of ubiquitous electric Internet of things.
5. Conclusion
In this paper, a way to complete the full network observability of distribution network is expressed. The approach takes advantage of Prim algorithm to obtain minimum spanning tree of system to calculate the importance of buses in the system. This method helps to ensure stability of system operation and reduce the total cost of system observability. Also, a short time is used to search for the optimal solution. MATLAB programming is used to optimize the configuration model of the Internet of things terminals. From the simulation on the two bus systems in IEEE, the effectiveness of the given method is verified. The results of the example show that the improved model can meet the requirements of the power system well, and the disposal of the measurement terminal placement of the Internet of things makes the terminal configuration more economical and reasonable.

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