Optimal Placement of Phasor Measurement Units for Full Observability of the Power System Using Hybrid Genetic Algorithm and Minimum Spanning Tree

Danial Hami, Mohammad Zohour Attar

Department of Electrical Engineering, Gazvin Branch, Islamic Azad University, Gazvin, Iran, danialhami@gmail.com
Department of Electrical Engineering, Shoush Branch, Islamic Azad University, Shoush, Iran

ABSTRACT

An improved genetic algorithm named MST-GA is proposed to minimize amount of PMUs for fully observing huge scale power grid. It adopts minimum spanning tree algorithm to repair unfeasible solutions, and makes use of the topology of power grid in the process of mutation. The simulation results of IEEE30 and IEEE39-bus system show that the algorithm can balance the quality and diversity of solutions better than others.

KEYWORDS- minimum spanning tree algorithm; genetic algorithm; optimal placement, observability; PMU.

I. INTRODUCTION

In addition to SCADA system, recently is raised another system with called the Wide Area Monitoring System (WAMS). The main idea WAMS is centralized processing of data that are collected from the different parts of the system simultaneously and synchronized with each other. The concept that offers to WAMS for power system is very close to the actual conditions of the system. The reason for this can be simply expressed as that due to constant changes in the frequency of power system and its impact on the calculation of angles, buses angles are comparable to each other only when the exactly related to the identical of a moment. Which this is possible in WAMS to using the phasor measurement units (PMU)[1].

Nowadays with the introduction of smart grid technology, power grid has changed from a static infrastructure to a flexible and dynamic infrastructure. Therefore it is important to accurately estimate the state of the network and thus ensure sustainable performance of the network. PMU as one of the main components of the smart grid transformation, are the fundamental solutions for the real time monitoring power grids [2,3]. PMU is able to measure phasor voltage and current with high accuracy and speed [5,6,7] and by conversion of non-linear state estimation equations to linear equations there is no need for sophisticated computational methods for solve them[6,7], which improves the speed control systems, safety and management systems, that use the results of state estimation[5].

CAI and AI [8] presented a MST algorithm to solve the problem. It gives a new rule of optimization based on depth-first search (DFS) to improve the algorithm. Liu Jie [9] proposed an improved adaptive genetic algorithm to find optimal placement of PMUs full observability of power grid and maximum measurement redundancy. LI and TENG [10] used genetic algorithm to study optimal PMU placement problem (OPP) and their innovative point is the pretreatment which greatly reduced the length of coding. Hybrid optimization strategy is selected to solve the same problem [11]. For instance, the approach in [12] combined genetic algorithm with tabu search algorithm.

There are two differences in this paper. The first one is proposing a hybrid approach named MST-GA which combines minimum spanning tree (MST) algorithm with genetic algorithm for minimizing the number of PMUs. The second one is improving the mutation which considers topological information of grid. Experimental results based on IEEE30 and IEEE39-bus system show that the variety and quality of solutions given by MST-GA are better than the regular algorithms such as MST, simulated annealing algorithm (SA), DFS, etc.

DESIGN AND IMPLEMENTATION OF ALGORITHM

1. Observability rules
We use the well-known rules to judge the topological observability of a given grid:
• If a PMU is installed in bus, voltage phasor of that bus and currents phasors of all incident branches to that bus are known. These are called as direct measurements.
• If voltage phasors of both ends of a branch are known then the current phasor of this branch can be obtained directly. These are called pseudo measurements.
• If there is a bus whose all incident branches current phasors are known but one, then the current phasor of the unknown one can be obtained using KCL equations [13-17]

2. Placement the Phasor Measurement units
Since the PMU installed at a bus can be possible the indirect visibility bus of adjacent to himself, it can be reduce the number of PMU installed on the network.
Optimum placement of PMUs for n bus system is formulated with relations (1) [3,4,9]:
Min \( \sum_{i=1}^{n} x_i \)
\[ s.t \quad y = Ax \geq b \]  

That in this connection A shows how to connect to other busses and transmission lines such as equation (2), also the PMU installed at bus i in the \( x_i \) variable is expressed in equation (3) is a binary variable associated with i bus[3,4,9]:
\[ A_{n \times n}(i,j) = \begin{cases} 
1 & \text{if } i = j \\
1 & \text{if buses } i \text{ and } j \text{ are connected} \\
1 & \text{otherwise} 
\end{cases} \]  
\[ x_i = \begin{cases} 
1 & \text{if PMU is installeat bus } i \\
0 & \text{otherwise} 
\end{cases} \]  

Since the minimum number of PMU should be enough for at least one time every bus is observable, the matrix b is shown in equation (4) [3,4,9]:
\[ b_{n \times 1} = [1 \ 1 \ 1 \ ... \ 1]^{T} \]  

3. Design of GA
(1) Chromosome encoding
The importance of all nodes should be analyzed before encoding. The set of selected nodes will be encoded by binary coding. If the value of one node is 1, it means that a PMU has been put on it. And if the value is 0, there is no PMU put on this node.

(2) Fitness function
The value of fitness is used to be positive number. And the bigger value means the better fitness. Therefore, the fitness function in this paper is as follow:
\[ f = C - \text{sum PMU} \]  
Where C is the sum of buses in the power grid, and sum PMU is the number of PMUs installed in buses under the case of full observability.

(3) Selection operation
This paper selects roulette wheel selection as selection operation. And the best individual must be inherited to the next generation. The strategy of keeping best is to identify whether the elite individual in population is better than previous generation. Replace the best individual with the elite individual in this generation if the answer is yes. Else, keep the best individual and replace the worst individual with the best individual.

(4) Crossover operation
The operation of crossover is the main way to generate new individuals. This paper selects single-point crossover. Firstly, algorithm will select two individuals randomly to crossover according to crossover probability. Secondly, algorithm will select the single-point for crossover. After that two new individuals generate.

(5) Mutation operation
The operation of mutation is the side way to generate new individuals. Basic allelic mutation is often selected in genetic algorithm. That is, every location in binary string will be judged whether to be mutated. When the random
number is smaller than mutation probability, the value in this location should be changed. If the value is 0, then it will be changed to 1 and vice versa.

The method of mutation presented by this paper takes topology of power grid into consideration. Firstly, select a node randomly from the set of nodes where PMUs have been installed. Secondly, remove the PMU in the selected node. Then, find all nodes connecting to this selected node and remove nodes where PMUs can’t be installed. At last, select randomly in rest nodes of the previous step to install a PMU in it. The mutation operation will make sure the observability of individuals in a large extent.

As the figure 1(a) shows, PMUs have been installed in bus 1, 4 and 6. Supposing the bus 6 is selected to be mutated, we can do this by moving the PMU to the bus 3 and 7 randomly because the buses 3, 7 and 8 are connected to it and the bus 8 is incompletely built. The figure 1(c) shows the result of moving the PMU on the bus 6 to the bus 3.

![Figure.1 Test Data](image)

4. Repairing unfeasible solutions

The set of PMU locations which could not make the entire grid observable is unfeasible solution. The method to repair unfeasible is selecting suitable buses and putting PMUs on them until the power grid is completely observable. A MST algorithm is used to repair unfeasible in this paper. It finds the bus which can make the recent PMU placement monitor the most branches and put a PMU on this bus. Similarly, cycle this process until the power system is observable. The flow chart [23,24] is shown in figure 2.

![Figure.2 Flowchart of MST](image)

III. CASE STUDIES AND SIMULATION RESULTS

To make the details clear, The IEEE 30 and 39-bus systems are used for simulation purposes, then compare the simulation results to the reference.

A. Case 1

IEEE30-bus system is shown in Figure 3. When using the algorithm of MST-GA, the best solution contains 6 PMUs. Table 1 gives the simulation results:
Figure 3 IEEE30-bus systems

<table>
<thead>
<tr>
<th>Solution</th>
<th>No. of PMU</th>
<th>Location of PMUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>2,10,12,15,18,27</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>2,10,12,15,20,27</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>2,10,12,19,24,27</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>2,10,12,18,23,26</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>2,10,12,18,24,30</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>2,10,12,18,24,30</td>
</tr>
</tbody>
</table>

Table (2) shows the optimal location of PMUs using DFS, SA, MTS and MST-GA algorithm proposed in this paper:

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Number of PMU</th>
<th>Number of solutions</th>
<th>Location of PMUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFS</td>
<td>2</td>
<td>1</td>
<td>3,5,6,11,12,17,18,20,21,24,26,27</td>
</tr>
<tr>
<td>SA</td>
<td>7</td>
<td>1</td>
<td>2,4,10,12,19,24,27</td>
</tr>
<tr>
<td>MTS</td>
<td>7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>MST-GA</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 shows the optimal location of PMUs using MTS algorithm. This case shows that MST-GA algorithm not only provides fewer PMUs but also diverse solutions. From table 3, the fewest number of PMU is 7 while the number of solutions is 9 when using MST algorithm. When it comes to MST-GA algorithm, though the number of solutions is 6 the number of PMUs is 6. MST-GA algorithm can get fewer PMUs than MST algorithm.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Location of PMUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,7,10,12,19,23,27</td>
</tr>
<tr>
<td>2</td>
<td>1,5,10,12,19,23,27</td>
</tr>
<tr>
<td>3</td>
<td>1,5,10,12,19,23,27</td>
</tr>
<tr>
<td>4</td>
<td>1,5,10,12,19,24,29</td>
</tr>
<tr>
<td>5</td>
<td>1,5,10,12,15,20,27</td>
</tr>
<tr>
<td>6</td>
<td>1,2,10,12,19,23,27</td>
</tr>
<tr>
<td>7</td>
<td>1,5,10,12,18,23,27</td>
</tr>
<tr>
<td>8</td>
<td>1,5,10,12,15,19,27</td>
</tr>
<tr>
<td>9</td>
<td>1,5,10,12,19,23,27</td>
</tr>
</tbody>
</table>
B. Case 2
IEEE39-bus system is shown in Figure 4, when using MST-GA, the best solution contains 9 PMUs. Table 4 gives the simulation results:

![Figure 4. IEEE39-bus system](image)

<table>
<thead>
<tr>
<th>Location of PMUs</th>
<th>No. of PMU</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,8,13,16,20,23,25,26,29</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>2,8,13,18,20,23,25,29</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>1,8,13,16,20,23,25,27,29</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>1,8,13,16,18,20,23,25,29</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>6,13,20,21,23,25,27,29,39</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>2,8,13,20,21,23,25,27,29</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>1,3,8,13,20,21,23,25,29</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 5 shows the simulation results of DFS, SA, MST, and MST-GA algorithm:

<table>
<thead>
<tr>
<th>Location of PMUs</th>
<th>No. of PMUs</th>
<th>Number of solution</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,3,8,12,16,20,23,25,29</td>
<td>9</td>
<td>16</td>
<td>DFS</td>
</tr>
<tr>
<td>2,3,8,12,16,20,23,25,25,29</td>
<td>9</td>
<td>9</td>
<td>SA</td>
</tr>
<tr>
<td>1,3,8,10,16,20,23,25,29</td>
<td>2</td>
<td>9</td>
<td>MST</td>
</tr>
<tr>
<td>2,3,8,10,16,20,23,25,29</td>
<td>8</td>
<td>9</td>
<td>MST-GA</td>
</tr>
</tbody>
</table>

In this case, though the number of solutions obtained by MST-GA algorithm is not smaller than other algorithms, it has a great advantage in the diversity of the solution. The OPP problem is formulated to minimize the number of PMUs installation subject to full grid observability and to maximize the redundancy at the power system buses. It means that we should make sure full observability when changes happened in power grid. MST-GA algorithm proposed in this paper makes contribution to solving the problem.

CONCLUSION

This paper proposes a new genetic algorithm. It breaks through common improvements. This new algorithm adopts MST algorithm to repair unfeasible solutions and well balances between efficiency of reparation and quality of solutions. The new algorithm take topology of power grid into consideration which is ignored by others. So observability of individuals will be kept as much as possible after mutation, which reduces time spent on repairing unfeasible solutions.
Simulation results of IEEE30 and IEEE39-bus system show that the proposed algorithm provide a variety of minimal set of PMUs under the case of full observability and can be used in practice.

REFERENCES