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Optimal Placement of Phasor Measurement Unit Using Ant Colony Optimization

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ABSTRACT

Efficient and reliable Wide Area Monitoring System (WAMS) is crucial in preventing outages and cascading failures in the smart grid. Since Phasor measurement units (PMU)s are the critical part of the WAMS, the questions of the arrangement and number of PMUs to use and place in order to evaluate risk must be addressed. This paper presents the optimal placement of PMU, ensuring system observability. An Ant Colony Optimization (ACO) method for Optimal Placement of PMU (OPP) problems is suggested which is a probability-based searching method. The proposed method is applied to the OPP problem in IEEE 9–Bus, 14-Bus and 30-bus test systems to show its effectiveness. Results obtained using ACO has been compared to the results of PSO, SA, GA and other methods and it has been found that it is computationally robust and takes lesser time than other optimization algorithms.

Keywords: Phasor measurement units, Optimal placement, Ant colony optimization, observability.

1. INTRODUCTION

The extensive development of power networks has increased the requirements for robust, reliable and secure monitoring and control techniques. As an effort to lead healthy modern power systems, the utility industry across the world has tried to overcome the inherent insensibility of existing electricity system, which is resulted from non-time synchronized and unidirectional characteristics of traditional grid. With the need of robust modern electricity grid, the smart grid is expected to achieve the reliability and security in power grid system.

Phasor Measurement Units (PMUs) are an essential power system device that provides time synchronized information about dynamic performance of power network. The information derived from measurements are same-time sampled in voltage and current waveforms from Global Positioning System Satellites (GPS), which enable PMU data from different utilities to be time-synchronized and combined to create a comprehensive view of the broader electrical system. Phasor Measurement Units (PMUs) which provide time synchronized measurements of voltage and current phasors are the key elements of Wide Area MonitoringSystem (WAMS) [1]. This ability of a PMU to calculate synchronized phasors will improve the performance of state estimators. This feature makes PMUs one of the most important measurement devices in power system protection and control [2, 3]. However, due to high cost of PMUs or nonexistence of communication services in certain buses, it is impossible to place a PMU on every bus in the network, either as a stand-alone unit or relay-based function. Many algorithms utilizing PMU measurements for state estimation, voltage stability, fault location, network parameter estimation, among others, have been developed. The primary requirement of most of these is that they require the system under study to be completely observable through the PMU's installed. Because of the high cost estimated in the placement of the PMU in large number of buses, much work has been previously proposed to tackle the problem of minimizing the number of PMU devices subjected to various constraints.

Meta-heuristic methods involve intelligent search processes that can deal with discrete variables and non-continuous cost functions. Marin et al. [4] used a Genetic Algorithm based procedure to solve the OPPProblem. It was based on the process of genetic breeding, there was no implication on aspects of converging speed or execution time.Srivastava et.al [5] described the application of search based technique Particle swarm optimization (PSO) to solve network reconfiguration problem in distribution systems.Haijan et al. [6] used a modified Binary Particle Swarm Optimization (BPSO) for PMU placement. The algorithm evaluates the fitness of each particle in the search space with the objective to maximize the fitness of the entire population. Nuqui et al. [7] introduced concepts of incomplete observability and depth of observability. It made use of spanning trees of the power system graph to find the optimal locations of PMUs based on a desired depth of unobservability. Baldwin et al. [8] used a dual bisecting search algorithm and simulated annealing method based on topological observability to choose optimal minimum PMU and placement locations. This method suffered from excessive calculation burden if applied to a large power system.Deterministic techniques make extensive use of integer programming and numerical based methods.Abur et al. [9] used a numerical implementation of integer linear programming for network analysis and cost of PMU installation with mixed measurement sets, which included conventional power flow and injection measurements. Aminifar et al. [10] developed a basic ILP model for network observability.Then, power network contingencies such as measurement losses and line outages were added.Chakrabarti et al. [11] implemented an exhaustive binary searchto determine the minimum number of PMUs. The solution that provided the highest measurement redundancy was chosen.

In the proposed method, the Ant colony optimization (ACO) technique has been used to find the optimal PMU placement. ACO,a heuristic algorithm was first proposed by Marco Dorigo et al. [12, 13] for different combinational optimization problem. Later, Wang. B et al. [14] usesthis technique for PMU optimization problem.The contribution of this paper is that it shows the optimized tour of the artificial ants in the process and gives a graphical representation of the PMU placement through simulation.

II. OBSERVABILITY ANALYSIS

The ability to estimate the power system state for a given set of measurements is referred as observability analysis. For power system state estimation, it is essential to have geographical distribution of measurements throughout the network.

2.1 Observability Rules

There are certain set of rules which governed the observability of substations (busses in this case):

- If one end voltage phasor and the current phasor of a branch are known, then the voltage phasor at the other end of the branch can be calculated.
- If voltage phasors are known for both ends of a branch, then the current phasor of this branch can be directly obtained.
- If a zero-injection bus without PMU is there and the current phasors of the incident branches are all known but one, then the current phasor of the unknown branch can be calculated using KCL.

- If the voltage phasor of a zero-injection bus is unknown and the voltage phasors of all adjacent buses are known, then the voltage phasor of the zero-injection bus can be obtained through node voltage equations.
- If the voltage phasors of a set of adjacent zero injection buses are unknown, but the voltage phasors of all the adjacent buses to that set are known, then the voltage phasors of zeroinjection buses can be computed by node voltage equations. These were used to find how well a given PMU allocation would measure a system.

2.2 Power system Observability with PMU

Before the discussion of PMU placement methods, the basic PMU placement rules should be cited. A PMU installed on a certain bus is capablefor measuring the voltage magnitude and phase angle of the local bus and the branch current phasor of all branches emerging from this bus. The voltage magnitude and phase angle of the neighbouring bus can be computed using voltage drop equations. Thus the buses monitored by a PMU are directly observable, the adjoining buses connected to the PMU buses are indirectly observable and the other buses which are not linked with the PMU buses are unobservable. The following graph explains the bus observability in a system:

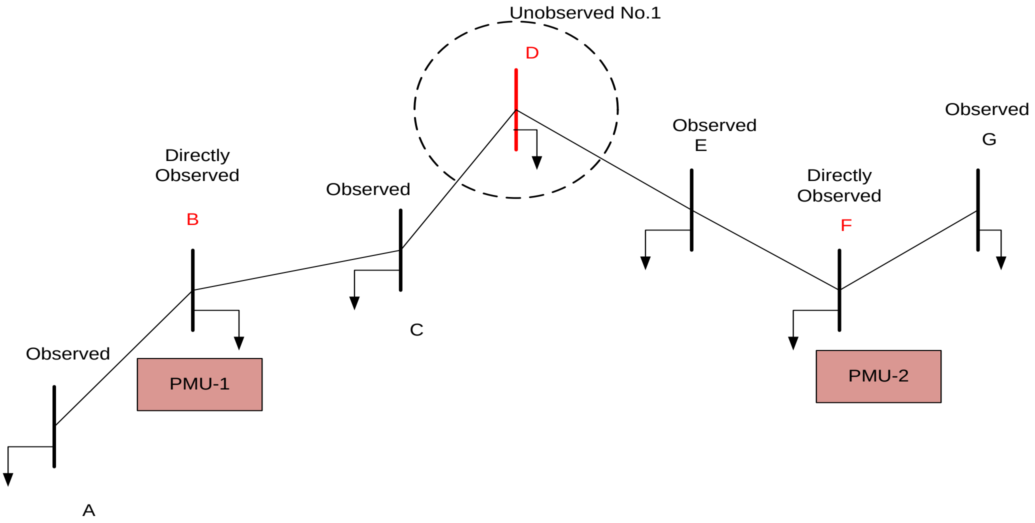

Fig.1 PMUobservability analysis

In Fig.1, the network has 7 buses from bus A to bus G. Assume two PMUs are located on bus B and bus F, so bus B and F are directly observable. Bus A, C, E and G are all connected to bus B and F so they are indirectly observable. Bus D is not associated with any PMU bus, so bus D is unobservable. So in this 7-bus system example, 6 buses are observable and 1 bus is not observable. Thus, this system is not a completely observed system. A completely observed system means all the buses in this system should be directly observed or indirectly observed with a proper PMU placement scheme.

III. ACO ALGORITHM

ACO, a novel population-based approach was proposed [12] to solve several discrete optimization problems. An ant is a simple computational agent in the ACO algorithm. It iteratively constructs a solution for the problem in hand. The intermediate solutions are a kind of solution states.

Based on the fact that ants are able to find the shortest path to their food using the communication of the pheromone they produced, this biological phenomenon is widely applied to searching and optimization problems. The search for PMU locations could also be simulated as the ants searching their food. The following four steps are proposed in order to utilize the Ant Colony Optimization method to find the optimal PMU placement.

STEP 1:

Randomly set a number of ants at different buses in a power system network and let these ants perform their movements. The buses that the ants stopped over represented the candidate PMU locations. In each movement performed by an ant, it should move three conjoint branches successively and the ant should not visit the same bus more than once during its completed tour. An ant stops its movement when it reaches a deadlock. The following Fig.2 simply illustrates a movement by an ant.

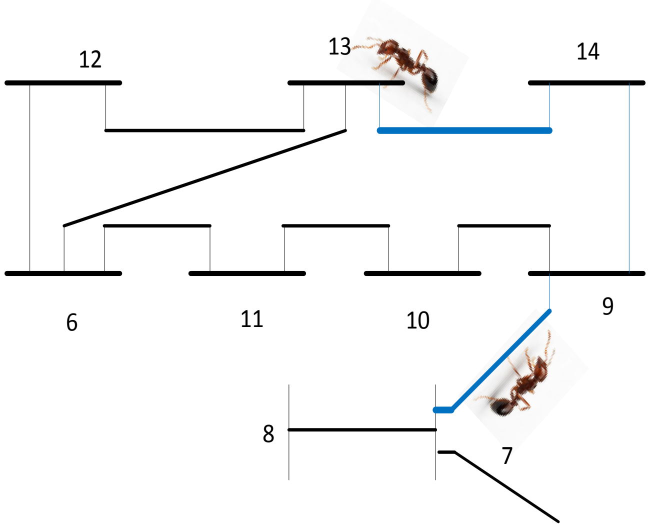

Fig.2ant's movement in a network

As can be observed in Fig.2, the ant moved from bus 7 to bus 13 through line 7-9, line 9-14 and line 14-13. The purpose that an ant should move three edges during a single movement is to minimize the required number of PMUs. Assuming in figure 2 that bus 7 and bus 13 are two candidate PMU locations, bus 9 and bus 14 can be indirectly observed by the couple of PMUs installed at bus 7 and 13 without any duplication. If ant only moves two branches in a movement, the ant will stop at bus 14 in the above figure and bus 14 will be a candidate PMU location instead of bus 13. In this condition, bus 9 will be twice-observed by both PMUs at bus 7 and 14. It is not wise to let two PMUs monitor the same bus in an optimal PMU placement, which explains the reason that an ant should move three edges in each movement. The following model shows the probability that how an ant chooses its path at a point of junction.

$$p_{ij}^{k} = \begin{cases} \frac{\tau_{ij}}{\sum_{l \in N_i^k} \tau_{il}} , if\ j \in N_i^k \\ 0, if\ j \exists N_i^k \end{cases} \quad (3.1)$$

Where τ_{ij} indicates the total amount of pheromone on branch *i -j; *N_i^kindicates the setof buses connected to bus *i*; p_{ij}^kshows the probability that the ant will continue its routeon line *i -j*. The amount of pheromone on each transmission line is accumulated basedon the ants assessments of their tours.

STEP 2:

Algorithm for finding the best tour for the artificial ants has been shown in the flowchart given in Fig.3.
After all ants finish their tours (each tour corresponds to a PMU placement), these tours (PMU placements) are evaluated by the number of observed buses by the action of these placements. The best tour which gives the maximum number of observed buses is selected. The branches composing the best tour are increased by a fixed amount of pheromones. Assume that initially each branch has the same amount of pheromone as one unit.

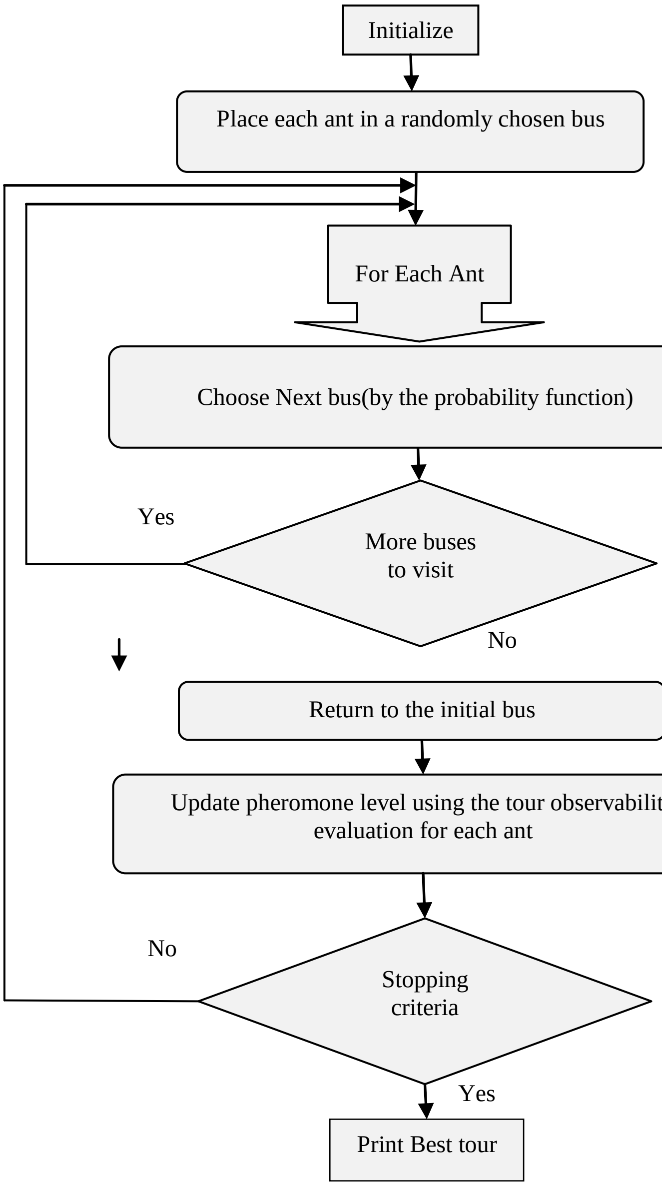

Fig.3 Flowchart for determining the best tour

STEP 3:

Repeat STEP ONE that the ants will perform their movements from their original buses. At this time, the distribution of the pheromones in the network has been changed due to the fact that pheromone amount on those branches composing the best were increased, thus the ants will perform different tours compared to the previous tours they made.

STEP 4:

Repeat STEP THREE and evaluate the tours. Finally it can be found that the pheromone amount on one tour will keep increasing compared to other tours. This tour is recommended to define the optimal PMU locations.

IV. SIMULATION RESULTS

The method will be applied to the standard test systems to demonstrate the application of our method. The simulation results will be shown for the same systems

As case studies, IEEE 9-bus and IEEE 14-bus system are chosen and solved by using the Ant Colony Optimization technique. Standard IEEE data sets are utilized in the problem

Case Study

For the purpose of representing the optimized tour path and the PMU placement graphically, the IEEE bus systems have been taken with the assumption of the bus coordinates from the graph system andthe coordinates taken from the graph are fed to the program, so that the optimized tour path and the buses with PMUs can be located.

Case 1: IEEE 9-Bus System

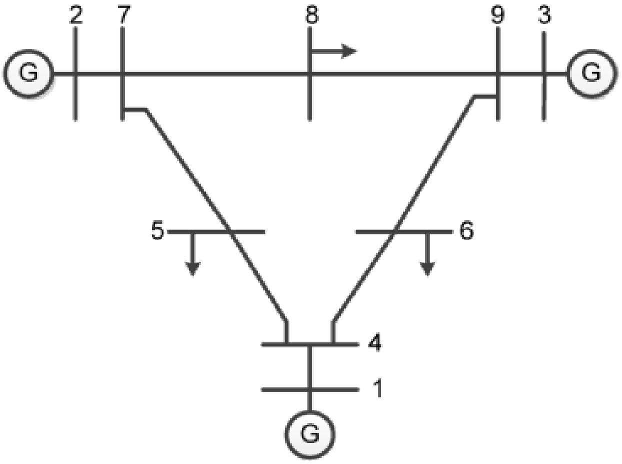

Fig.4 Standard IEEE 9-Bus System

When ACO algorithm applied on other optimization problems, it required the shortest path through the nodes, but here in PMU optimization , it doesn’t required to have shortest path, we have to ensure observability through checking every third node. Therefore we are not concerned about the length between the nodes here. And just through assuming the coordinates of the bus system and applied these coordinates as input to our simulation, we can have the graphical representation of the optimized tour as shown Fig.5in

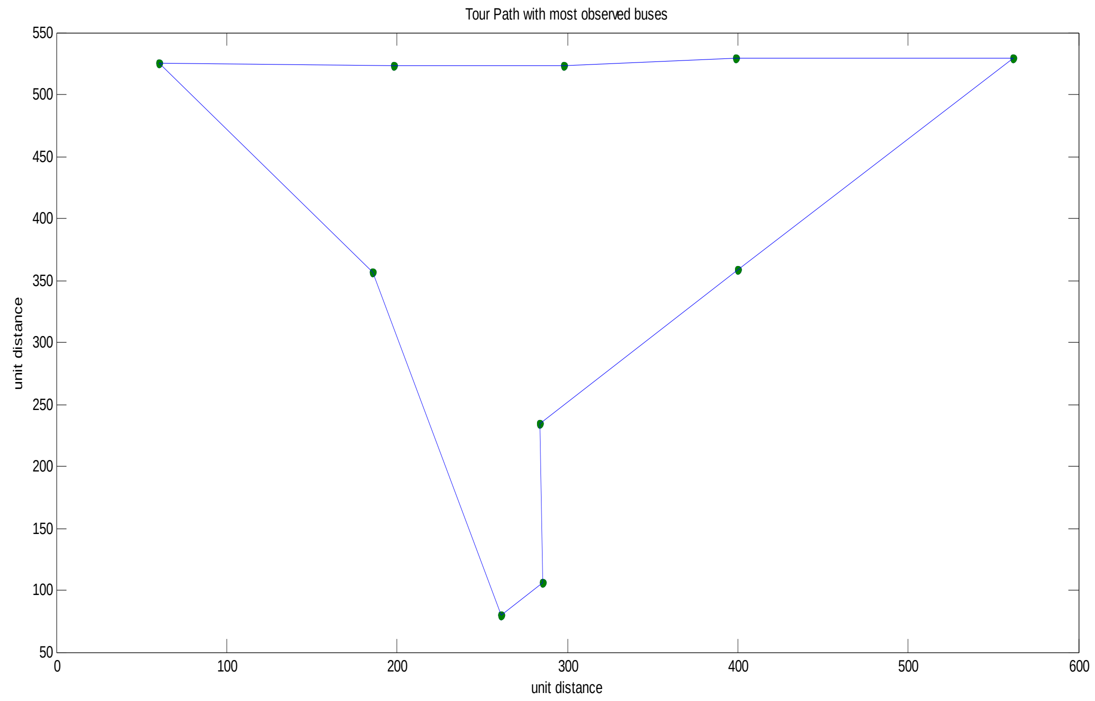

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Fig.5 Optimized Tour Path for IEEE 9-Bus System

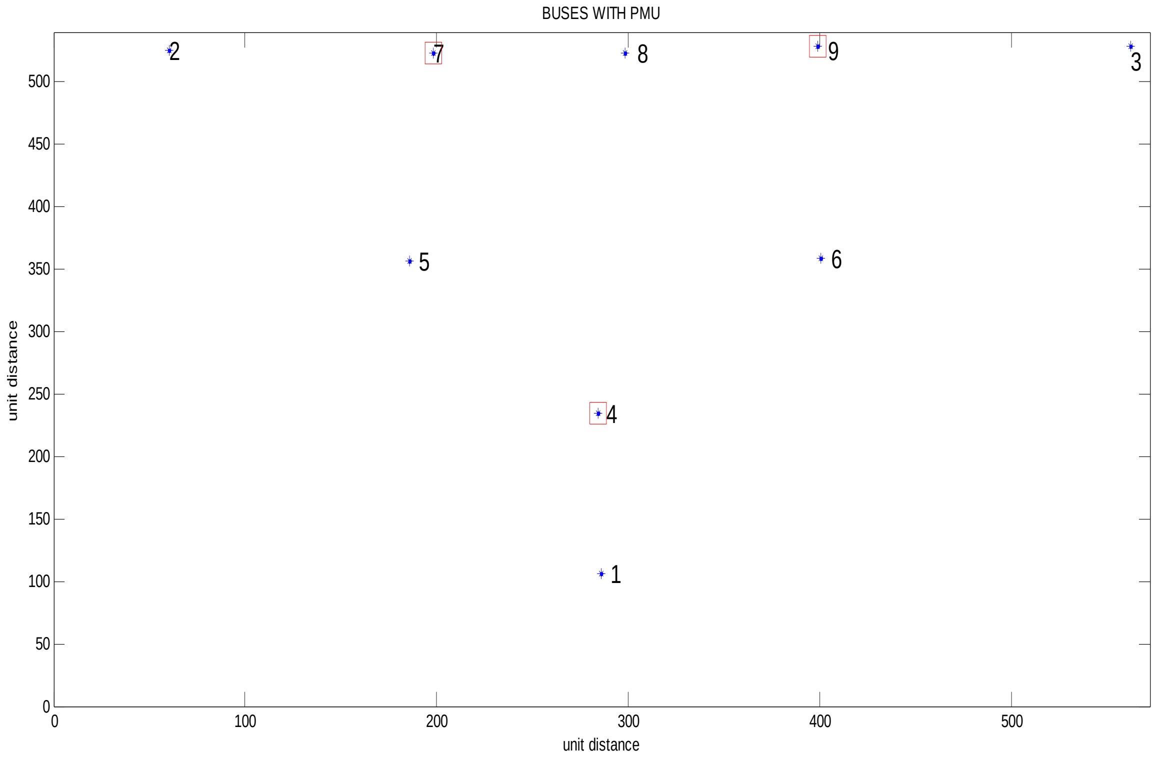

Fig.6 Optimized PMU locations for IEEE 9-Bus System

Simulation result has shown in the Fig.6, shows that the optimized locations of the PMUs in the IEEE 9-Bus system are bus-4, 7 and 9.

Case II: IEEE 14-Bus System

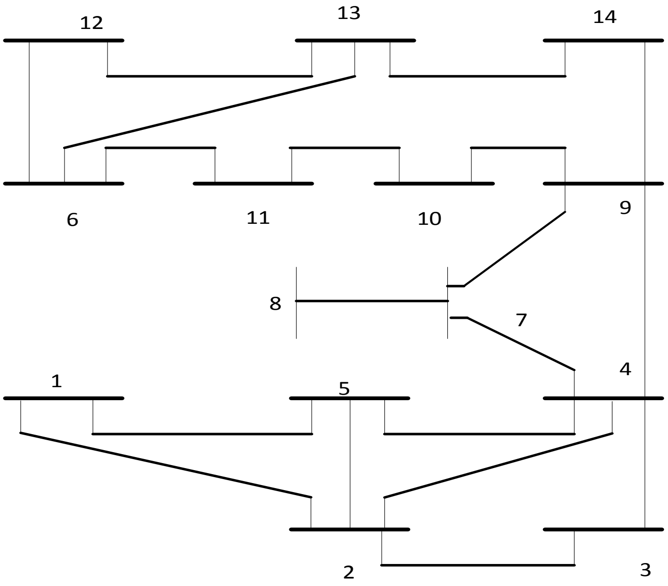

Fig.7 Standard IEEE 14-Bus system

Standard IEEE 14-bus system has been chosen as input to the simulation, and the results have been shown. Fig.8 shows the optimized path of the artificial ants or the path with most observable buses.

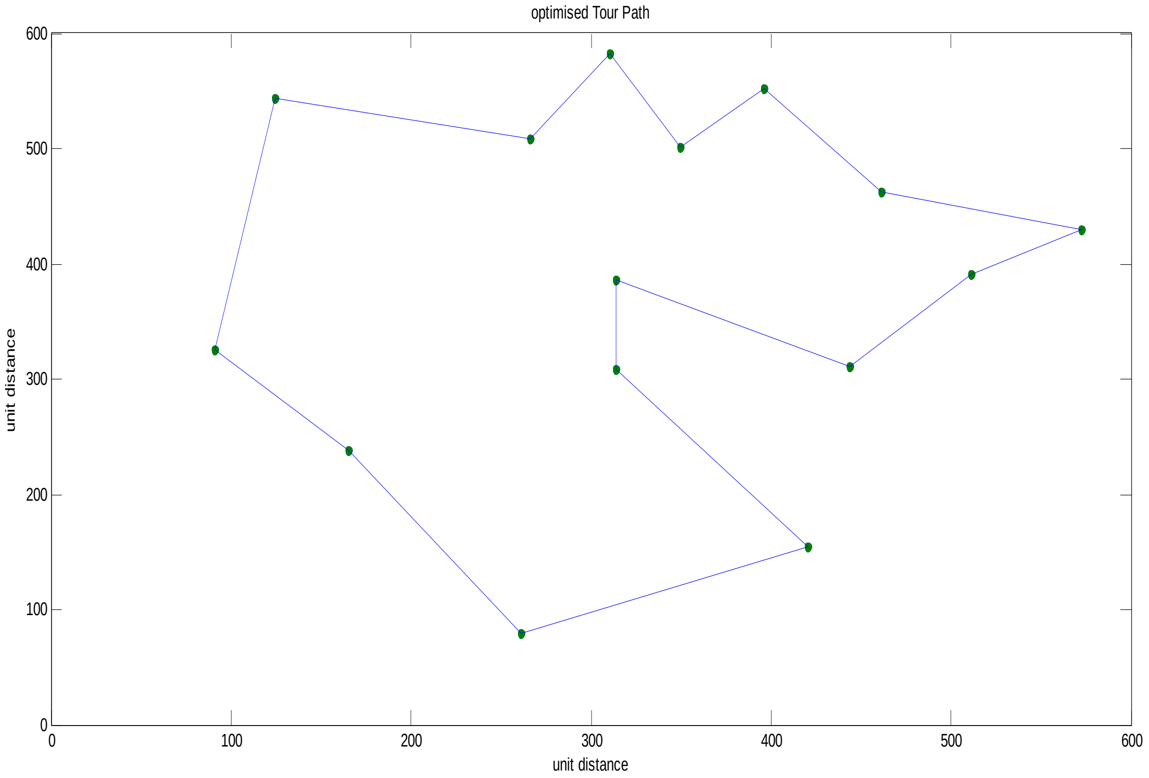

Fig.8 Optimized Tour Path for IEEE 14-Bus System

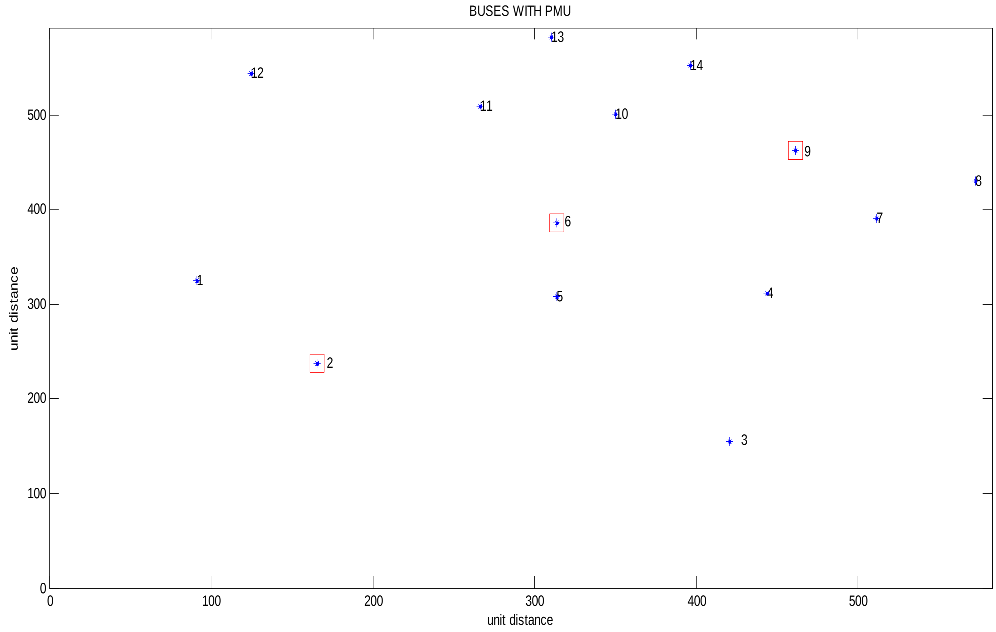

Fig.9 Optimized PMU locations for IEEE 14-Bus System

Simulation result has shown in the Fig.9, shows that the optimized locations of the PMUs in the IEEE 9-Bus system are bus-2, 6 and 9.

Table 1: Comparison in terms of minimizing the number of PMUs

Methods	9 Bus system	14 bus system
Proposed Method (ACO)	3	3
Genetic Algorithm[4]	3	4
Particle Swarm Optimization[5]	–	3
Simulated Annealing [8]	–	4
Integer Linear Programing [9]	–	4
Binary search algorithm [11]	3	3
Tabu Search [16]	3	3

Table 1 compares the optimized value of number of PMUs obtained by the different algorithms proposed before, and this can be seen that ACO optimization technique is providing us the best solution.

V. CONCLUSION

This paper objective is optimal PMU placement ensuring system observability. Efficient and reliable WAMS is crucial to preventing outages and cascading failures in the smart grid. Since PMUs are the critical parts of the WAMS, the questions of the arrangement and number of PMUs to use and place in order to evaluate risk must be addressed.

A modified ACO method forOPP problems is suggested. ACO has been compared toPSO, SA and GA and other methods. The proposed methods were appliedto the OPP problems in 9–Bus, 14-Bus and 30-bus IEEE standard powersystems to show its effectiveness. The proposedalgorithms were validated by simulation. The resultsobtained are indicative of the fact that the optimal placement of PMU increases the accuracy of theobtained estimates and efficiency of the bad datadetection algorithms. Howeverthe ACO's results are equal to the results of few more methods. Also this method also has a heavy computational burden.But the convergence speed in ACO is much better. The computation of this method is fast. Dueto the fact that the ACO method is a probability-based searching method, it is also enable to guarantee the optimal solution. The result from this method is always the best global solution.

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