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A PMU Placement Optimal Method in Power Systems using Modified ACO Algorithm and GPS Timing

***Abstract**. In this paper, optimal placement of Phasor Measurement Unit (PMU) using Global Positioning System (GPS) is discussed. Ant Colony Optimization (ACO) is used for this problem. Pheromone evaporation coefficient and the probability of moving from state x to state y by ant are introduced into the ACO. The modified algorithm exceeds the ACO in obtaining global optimal solution and convergence speed, when applied to optimizing the PMU placement problem. The fitness function includes observablity, redundancy and number of PMU. Eigenvector Method (EM) is used to calculate the weights of fitness function. The suggested optimization method is applied in 14-bus IEEE system and the simulation results show that the proposed method can find the optimal solution in an efficient manner.*

***Streszczenie.** W artykule analizowano optymalne usytuowanie jednostki PMU (phasor measurement unit) przy wykorzystaniu system GPS. Do rozwiązania problemu wykorzystano algorytm mrówkowy. (**Optymalna metoda usytuowania jednostki PMU w systemie zasilania przy wykorzystaniu algorytmu ACO i systemu GPS**)*

Keywords: Phasor Measurement Unit, Placement Optimization, Ant Colony Optimization, Analytical Hierarchy Process.
Słowa kluczowe: jednostka PMU (phasor measurement unit), GPS.

Introduction

The Global Positioning System (GPS), which is a satellite based system, is the main synchronizing source that is used to provide a time reference on the communication networks, and its widespread availability makes it possible to obtain, at each point of the tested system, a clock signal that is synchronized with the one generated in other remote places. Currently, GPS is the only satellite system with sufficient availability and accuracy for most distributed monitoring and control applications in distribution systems. Synchronizing signals could also be broadcast from a terrestrial location, and, with respect to this, radio broadcasts are probably the least expensive [1].

The time reference signal, to which the standard refers for the evaluation of the synchronized phasors, is the Coordinated Universal Time (UTC). To this purpose, GPS receivers specify that the synchronization signal shall have a basic repetition rate of one Pulse Per Second (1 PPS). The synchronizing source shall have sufficient availability, reliability, and accuracy to meet power system requirements [2].

Monitoring the operating state of the system and assessing its stability in real time has been recognized as a task of paramount importance and a tool to prevent blackouts. Phasor Measurement Units (PMUs) is used to predict system stability [3].

Recently, PMUs equipped with GPS is applied in power systems monitoring and state estimation. PMUs can directly measure the voltage amplitudes and phase angles of key buses in power systems with high accuracy. Since GPS provides negligible synchronization error, the interests are concentrated on where and how many PMUs should be implemented in a power system with the smallest cost and with the largest degree of observability [4].

Because of the strong correlation between PMUs and the GPS, PMUs began to spread widely after the great improvement in the satellite techniques and communications [5].

The PMU Placement Optimization (PPO) is to minimize the number of PMUs and maximize the redundancy by optimizing the PMU's locations, while keeping all the nodes voltage phasors observable. A specially tailored non-dominated sorting Genetic Algorithm (GA) for a PMU placement problem is proposed in [6] as a methodology to find these Pareto-optimal solutions.

Taking the full network observability of power system operation states and the least number of PMUs as an objective function, an improved optimal PMU placement algorithm was proposed in [7]. In this algorithm, GA was effectively combined with the Particle Swarm Optimization (PSO) algorithm to ensure that the optimal solution could be obtained [7].

In this paper, Ant Colony Optimization (ACO) algorithm for a PMU placement problem is proposed to find optimal solutions.

Power System Observables with PMUS

Power system observability might be defined by graph theory [8]. An N -bus power system is represented as a no oriented graph $G=(V,E)$, where V is a set of graph vertices containing all system nodes, and E is a set of graph edges containing all system branches. The PMUs could measure the voltages and all the branch current phasors at the nodes where they are placed. The phasors of the nodes without PMUs, may be prepared via pseudo-measurement. The pseudo-measurement includes three parameters [9]:

1) If a branch has known voltage at both ends, the current of that branch can be calculated using Ohm's laws.

2) If a node voltage and one branch current are known, the voltage of another end of the branch can be calculated using Ohm's laws.

3) If a node where all but one branch current are known, the last unknown current can be inferred by using Kirchhoff's law.

Totally observability is devided by numerical and topological states. In this paper observability is calculated by topological state. In topological state observability function (fi) for any node of network calculates using incidence matrix [10]. For example for the network that is shown in Fig. 1 incidence matrix is:

$$A=\begin{bmatrix} 1\,1\,0\,0\,0 \\ 1\,0\,1\,0\,1 \\ 0\,1\,1\,1\,0 \\ 0\,0\,1\,1\,0 \\ 0\,1\,0\,0\,1 \end{bmatrix} \tag{1}$$

and observability function is:

(2)
$$F=\begin{cases} f1 = x1 + x2 \\ f2 = x1 + x3 + x5 \\ f3 = x2 + x3 + x4 \\ f4 = x3 + x4 \\ f5 = x2 + x5 \end{cases}$$

Where '+' is OR (logic operator) and xi is defined:

(3)
$$xi=\begin{cases} 1 \ ; \ If\ a\ PMU\ is\ installed\ at\ node\ i \\ 0 \ ; \ Otherwise \end{cases}$$

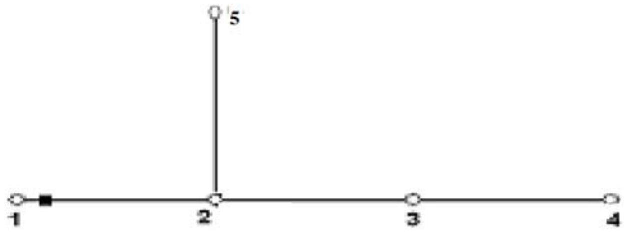

Fig. 1. Example for 5-bus system

Problem Formulation

In this section, at the first, we determine fitness function. Then, we talk a bout ACO algorithm and values of its parameter in this problem.

Fitness Function

Fitness function for placement in this paper is defined:

(4)
$$J(X)=W_1 * \sum_{i=1}^{Nb} fi + W_2 * N_{PMU} + W_3 * J_1$$

Where $\sum_{i=1}^{Nb} fi$ shows the observability value of the power system and N_{PMU} is the number of PMU in power system network. If we assume favorite level of redundancy is 2, J_1 is deference between favorite and real. To calculate the weights of fitness function, we consider the importance of each factor in comparison to the other factors. Table 1 is used to calculate the scales of pair-wise comparisons.

Once a hierarchy framework is constructed, users are requested to make a pairwise comparison matrix at each hierarchy and compare each other by using a scale pairwise comparison [12].

Table 1. Scale for pair-wise comparisons [11]

Relative intensity	Defnition
1	Equal value
3	Slightly more value
5	Essential or strong value
7	Very strong value
9	Extreme value
2,4,6,8	Intermediate values between two adjacent judgments

The below 3*3 matrix is calculated according to Table 1:

(5)
$$\begin{bmatrix} 1 & \frac{1}{3} & 5 \\ 3 & 1 & 9 \\ \frac{1}{5} & \frac{1}{9} & 1 \end{bmatrix}$$

W_i can be calculated as follows:

(6)
$$W_i = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_j^n a_{ij}}$$

where a_{ij} is an item of this matrix and n is number of fitness function factors. This function is called Eigenvector Method (EM), which is a part of the Analytical Hierarchy Process (AHP) algorithm [11].

ACO Algorithm

ACO metaheuristic, a novel population-based approach was proposed in [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. At each repeat of the algorithm, each ant goes from a state x to state y, corresponding to a more complete intermediate solution. Therefore, each ant k computes a set $A_k(x)$ of feasible expansions to its current state at each repeat, and moves to one of these in probability. For ant k, the probability p_{xy}^k of moving from state x to state y depends on the combination of two values. The attractiveness η_{xy} of the move, as computed by some heuristic indicating a priori desirability of that move and the trail level τ_{xy} of the move, indicating how proficient it has been in the past to make that particular move. The trail level shows a posteriori indication of the desirability of that move. Trails are updated usually when all ants have completed their solutions, increasing or decreasing the level of trails corresponding to moves that were a part of "good" or "bad" solutions, respectively. In general, the $k th$ ant moves from state x to state y with probability:

(7)
$$p_{xy}^k = \frac{(\tau_{xy}^{\alpha})(\eta_{xy}^{\beta})}{\sum(\tau_{xy}^{\alpha})(\eta_{xy}^{\beta})}$$

Where τ_{xy} is the amount of pheromone deposited for transition from state x to y. $\alpha \geq 0$ is a parameter to control the effect of τ_{xy}, η_{xy} is the desirability of state transition xy (a priori knowledge, typically $\frac{1}{d_{xy}}$, where d is the distance) and $\beta \geq 0$ is a parameter to control the influence of η_{xy}. When all the ants have completed a solution, the trails are updated by:

$$\tau_{xy}^{k} = (1-\rho)\tau_{xy}^{k} + \Delta\tau_{xy}^{k} \quad (8)$$

where τ_{xy}^{k} is the amount of pheromone deposited for a state transition xy, ρ is the pheromone evaporation coefficient and $\Delta\tau_{xy}^{k}$ is the amount of pheromone deposited, typically given by:

$$\Delta\tau_{xy}^{k} = \begin{cases} \dfrac{Q}{L_k} & ;\ \textit{If ant } k \textit{ uses curve } xy \textit{ in its tour} \\ 0 & ;\ \textit{Otherwise} \end{cases} \quad (9)$$

where L_k is the cost of the $k\,th$ ant's tour (typically length) and Q is a constant [13]. In this problem, we assume $\beta = 0$, $\alpha = 1$ in equation (8) and $Q = 1$ in equation (9).

Case Study

The placement of the PMU is done in a 14-bus IEEE system, using ACO, that its topology is shows in Fig. 2. We assume that the observability is complete. Therefore only the answers are select which make all nodes voltage phasors observable.

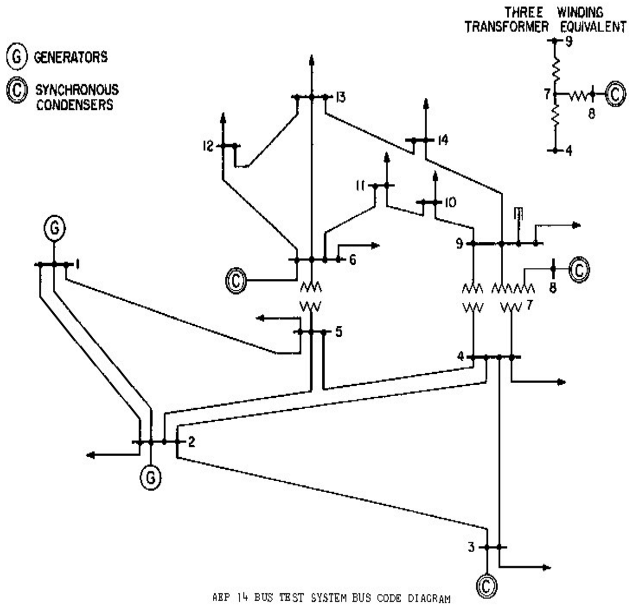

Fig. 2. Schematic of 14-bus IEEE system [14]

Simulation Results

Six ants travel on the nods of network; the tour is finished when the network has been observable. When the tour is completed by six ants, pheromone matrix changes, and new ants begin traveling with new values of pheromone. This process continues to find the optimum result. Fig. 3 shows the best of fitness function values in any repeat. Pheromone evaporation coefficient in any repeat is calculated by:

$$\rho_{min} = \rho_{min} + (\rho_{max} - \rho_{min})e^{-k(\frac{t}{T})b} \quad (10)$$

where ρ_{min} and ρ_{max} determine range pheromone evaporation coefficient, t is current repeat and T is maximum repeat. k and b determine the attenuator's descending speed. In this problem, we assume $k = 5$ and $b = 10$ in equation (10).

In this simulink, five PMUs placed in the buses 2, 6, 7, 9 and 12. Fig. 4 shows the placement of PMU in 14-bus IEEE system.

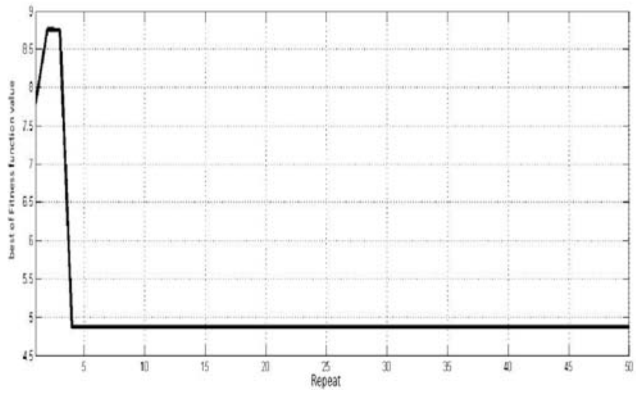

Fig. 3. Best of fitness function

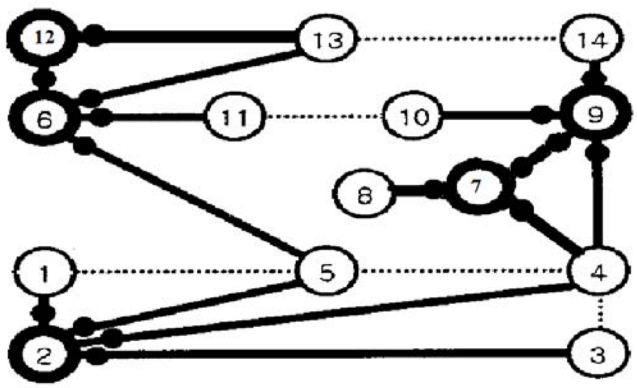

Fig. 4. Placement PMU in 14-bus IEEE system

Reference [5] did simulation with zero bus injection, but in this paper, simulation did not with zero bus injection. Therefore, number of PMUs is bigger than the result which proposed in [5], but redundancy is better in this paper. Table 2 shows this comparison.

Table 2. Comparison of the obtained results based on GA, PSO and ACO

Algorithm	J_1 (Redundancy)
GA	12
PSO	12
ACO	7

Conclusion

In this paper a modified ACO method for PPO problems was suggested. ACO was considered to speed up the convergence. The proposed method was applied to the PPO problems in 14-bus IEEE standard power systems to show its effectiveness. Simulation results show that the proposed algorithm finds the solution in smaller search spaces than previous works. The future works should include the consideration of zero injection bus and changes in the topology of the power systems.

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