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Original Research

Localization of Phasor Measurement Systems and Current Measurement Systems Using Dynamic Bacteria Foraging Algorithm

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Abstract

Phasor Measurement Units are power apparatuses which are able to measure voltage phasor and synchronized current in a power system. Today, Phasor Measurement Units (PMUs) are considered as modern distribution systems especially toward intelligent networks. PMUs should be installed appropriately in distribution networks. The issue of optimally utilizing PMU in such a way that be quietly observable and controllable has been analyzed in many references and articles. Based on high cost of PMU apparatuses, optimal placement and minimization of their numbers are especially important. Also, the present study presents a new method to determine optimal place and a few number of PMUs in a distribution network. In solving this problem, the typological method is utilized by using dynamic bacteria foraging algorithm. On the other hand, the problem is solved on a 34-bus standard network.

Keywords: phasor measurement units, network visibility, distribution network, optimization, dynamic bacteria foraging algorithm.

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1. Introduction

PMU systems are able to provide measurement of synchronized phasors of voltage and current from a distant place in an intelligent power network.

Biscaro, et al. [1], a new method to optimally place phasor measurement units was introduced for error setting in power distribution systems by using greedy random comparative innovation research methods and Monte Carlo simulation. The optimized placement method introduced at here is a general method which can be used instead of the apparatuses helping to record the range of voltage loss for each kind of algorithm to determine error place which uses voltage information in some limited nodes in feeder. Aneesh Rajeev, et al. [2], in first step, placement of phasor measurement units using binary algorithm is done and in the next step, placement of error and planning of identification are able to accurately identify error place immediately after its occurrence. The method introduced to identify error is used in both annular and radial feeders. Emad Jamil,et al.[3], a simple and useful PMU placement is presented for distribution networks, which significantly saves in calculation time. Hany A, et al. [4], the study the utilization of PMUs in a distribution system considering reconfiguration of the distribution system. In this article, using the Ant Optimization Algorithm to solve the loss power minimization problem, reconfiguration of the system was studied. Also, the greedy algorithm was used as an optimization devise to determine minimization of number of PMUs and their places.

Haghifam, et al. [5], a new method was presented to determine an optimal place and few numbers of PMUs in a distribution network which its principle is the estimation index of the best state. In DSE solution, a combination of Nedler-Mead's (NM) simple searching algorithm and Ant Colony Optimization (ACO) was used. This combination method, by decreasing the difference between the measured and calculated amounts of state variables, can estimate voltage phasor in each node and also ensure visibility of the distribution system under normal operational conditions.

Zakariazadeh A, et al. [6], are used PMUs and their sent information, load response was performed in the presence and influence of wind turbines. In this article, an immediate control method of voltage was presented which uses load decreasing as a part of demand response programs to maintain voltage of distribution feeders in a certain domain. As renewable production and unpredictable changes in load response and also outcomes of the distribution network identify voltage violation in some buses, the immediate voltage control recommended at here has been performed supposing the fact that there is voltage violation in some buses. It is assumed that in normal conditions, voltage control is done based on a voltage control program which is previously timed at the day before performing programs.

In the previous decades, in power system engineering, online monitoring of distribution network has been a controvertible discussion. In power systems, in order to help operators to manage these systems effectively, new control systems and relational links were devised. Distribution Automation (DA) systems provide the possibility of supervised control and data collection (SCADA) in the modern distribution system. Falvo MC, et al. [7]. The relational mechanism supports measurement (metrage) and control systems such as Remote Terminal Units (PMU) in accessory stations of distribution and or feeders, Cecati C, et al.[8]. Depending on presence of these DA systems, Distribution System Operator (DSO) can switch distribution tap changer to dynamically control voltage of buses in the acceptable scope. Additionally, by availability to DA properties, DSO can use demand response as an effective means to regulate voltage of distribution feeders in normal and emergency conditions. In fact, appropriate dispatching of Volt/VAr prepares the possibility of general loss decrease of power and also promotion of voltage profiles of the distribution feeders. Park JY, Park JK.[9]. Elkhatib ME, et al. [10], a new method are proposed to promote performance of voltage regulators in multiple feeders including DGs. This model is based on RTUs of each DG units and each of capacitor buses which correspondence with each other in a certain order. Data received from RTUs prepare the possibility of estimation of maximum and minimum voltage in the feeders and consequently the possibility of voltage control of feeders is prepared.

Cloud Computing provides on-demand service. Due to the benefits achieved with the use of cloud computing, in the recent year, many organization gone to use of cloud computing. According definition of cloud computing provided by the National Institute of Standards and Technology (NIST) "Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" [1].

2. Analysis of visibility based on PMU

Factors such as increasing development of consumption demand and expansion of the phenomenon of reconstruction cause increase of pressure on the transmitted lines and therefore power systems often work close to their instability border. In such conditions, using the current and its functions do not appear sufficient in order to ensure SCADA's of a stable and reliable performance of the system.

In general, visibility of the power system means calculation of variables of the network in order to estimate state of the system and if the required data is not present for state estimation, the network will not be visible. Network variables usually are considered as voltage phasor of buses.

2.1- Linear model of the system by PMU

In the numerical method, in order to obtain a mathematical definition for visibility, one should obtain a mathematical model for the intended power system or its measurements. Linear measurement model which is used in most of the state estimations is defined as following.

$$Z = HX + e \tag{1}$$

In this model, Z vector includes m measurement of voltage phasor and current of lines, X is n-dimensional state vector, H is Jacobin's stable Matrix of measurements and e was the vector of measurement error as m×1.

Analyzing vector Z as sub-vectors of voltage MV× 1 and current Mi× 1, (ZI, ZV) and analyzing of vector X to the measured sub-vectors NM×1 and unmeasured sub-vectors NC× 1 (VC, VM), Relation (1) becomes as following:

$$\begin{bmatrix} Z_V \\ Z_I \end{bmatrix} = \begin{bmatrix} I & 0 \\ Y_{IM} & Y_{IC} \end{bmatrix} \begin{bmatrix} V_M \\ V_C \end{bmatrix} + \begin{bmatrix} e_V \\ e_I \end{bmatrix} \tag{2}$$

Where I is Identity Matrix, YIM and YIC indicate series admittance and shunt of the network. By avoiding shunt elemetns, H matrix decreases as following:

$$H = \begin{bmatrix} 1 & 0 \\ M_{IB} Y_{BB} A_{MB}^{T} & M_{IB} Y_{BB} A_{CB}^{T} \end{bmatrix} \tag{3}$$

Where MIB is convergence matrix of measurement of cluster which includes phasor measurement of currents of clusters as MI×b, YBB is b×b diagonal matrix including admittance of clusters, AMN and ACB, respectively, are measured sub-matrix NM×b and sub-matrix of convergence of node and cluster as NC×b. in traditional methods, analysis of visibility is performed by considering the following formula:

$$Rank\,(H) = 2n - 1 \tag{4}$$

Based on (3), if Jacobin Matrix is of complete degree, the network is visible and state estimation is performed.

2.2. Topological Method of Visibility Analysis

Other method to consider visibility of the network is topological method. In this method, analyzing visibility is based on the following principles:

The buses which PMU is localized on them have known voltage phasor. Also, current of the lines which are connected to PMU is known, too.

If phasor of the voltage is one and current of the line which is connected to the intended bus is known, voltage of the bus of the other side is also calculable.

If the voltage of the buses of two heads of a line is clear, current of that line is calculable.

If current of all lines led to bus of zero injection except for one is clear, due to KCL Law, phasor of the unknown current is calculable.

Based on the mentioned principles of phasor of the bus voltage on which PMU is installed, also current of all clusters which enter into that bus is measured directly. In this article, a topological method is used for visibility analysis which will be explained in next section.

2.3. Formulation of Problem of PMU Placement

The PMU installed in a bus is able to calculate phasor of the object's phasor and also phasor of current of all clusters which are connected to that bus in PMU points. Therefore, by strategically installing a network, one can obtain the information required for visibility of the system. As mentioned earlier, two purposes of network visibility of estimation of state and decrease of number of PMU units are considered as substantial aims. For a n-bus system, the problem of optimal placement is expressed as the following formula:

$$\min \sum_{i}^{n} W_i X_i \tag{5}$$

Where x is a binary variable which is defined as following:

$$x_i = \begin{cases} 1 & \text{if a PMU is installed at bus i} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

W_i is the cost of PMU installed in bus I and f(x) is a function which shows condition of visibility of each bus of network. At the rest, we will indicate that if for each bus $f(x_i) \geq 1$, that bus will be observable. In the proposed plan, visibility conditions are considered in three cases:

1) in first case, it is supposed that except for PMU, another common measurer is not uses.

2) using PMU with an injective measurer (and or presence of bus of zero injection)

3) using PMU with injective measurer and current measurer.

To describe each case, an educational 7-bus network was used which is shown in Fig. 1.

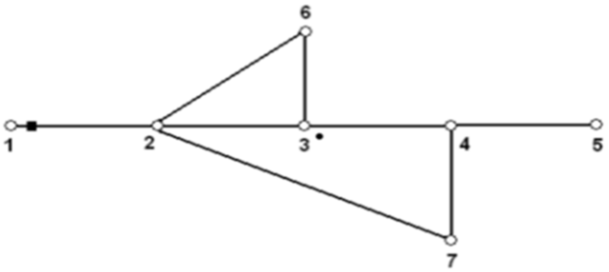

Figure 1. 7-bus sample system

First case: a system without a common measurer and a zero injection bus. Firstly, matrix of convergence of nodes is defined as following:

$$A = \begin{cases} 1 & \text{if } k = m \\ 1 & \text{if } k \text{ and } m \text{ are connected} \\ 0 & \text{if otherwise} \end{cases} \tag{7}$$

Matrix A is obtained directly by binarizing admittance matrix. Convergence Matrix A for a 7-bus network of Fig. 1 is as following:

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

Conditions required for visibility in this case is expressed as following:

$$f(x) = \begin{cases} f_1 = x_1 + x_2 & x \geq 1 \\ f_2 = x_1 + x_2 + x_3 + x_6 + x_7 & x \geq 1 \\ f_3 = x_2 + x_3 + x_4 + x_6 & x \geq 1 \\ f_4 = x_3 + x_4 + x_5 + x_7 & x \geq 1 \\ f_5 = x_4 + x_5 & x \geq 1 \\ f_6 = x_2 + x_3 + x_6 & x \geq 1 \\ f_7 = x_2 + x_4 + x_7 & x \geq 1 \end{cases} \tag{9}$$

In the above equations, operator + was used instead of reasonable operator OR and number 1 at the other side of the inequalities indicates that at each line at least one of the variables is non-zero. For example, the conditions related to Bus 1 and Bus 2 are as following:

$$f_1 = x_1 + x_2 \geq 1$$

$$f_2 = x_1 + x_2 + x_3 + x_4 + x_6 + x_7 \geq 1 \tag{10}$$

First condition $f_1 \geq 1$ means that for visibility of Bus 1, at least one PMU should be installed in buses 1 or 2 (or both buses) and so for visibility of Bus 2, at least one PMU should be installed in one of buses 1, 2, 3, 6, and 7.

Second case: a system with presence of an injective measurer (or bus of zero injection). An injective measurer may be expressed as a real measurer or as bus of zero injection which both cases behave in the same manner. Again, we consider the 7-bus Figure 1 so that in this case we assume that Bus 3 is the bus of zero injection. In this case, it is observed easily that if voltage phasor in Bus 3 is of four buses of 2, 3, 4, and 6, voltage phasor of the fourth bus is calculated by writing kcl in Node 3. Therefore, in topology of the network, one can combine the bus which includes an injective measurer and or the bus of zero injection with one of the adjacent buses. Fig. 2 is the same network while buses 3 and 6 are combined and the new bus $\mathbf{6'}$ is substituted with them. Convergence Matrix A in this case becomes as following:

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix} \qquad (11)$$

Therefore, equations of conditions in this case become as following:

$$f(x) = \begin{cases} f_1 = x_1 + x_2 & x \geq 1 \\ f_2 = x_1 + x_2 + x_{6'} + x_7 & x \geq 1 \\ f_4 = x_4 + x_5 + x_{6'} + x_7 & x \geq 1 \\ f_5 = x_4 + x_5 & x \geq 1 \\ f_6 = x_2 + x_4 + x_{6'} & x \geq 1 \\ f_7 = x_2 + x_4 + x_7 & x \geq 1 \end{cases} \qquad (12)$$

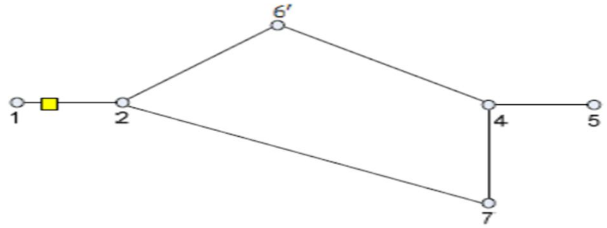

Figure 2. Sample system after combination with buses 3 and 6

Third case: a system considering an injective measurer along with a current measurer.

This case is also considered in the 7-bus network. In this case, the current measurer is installed between buses 1 and 2. Therefore, the conditions related to buses 1 and 2 vary as Relation (13). The noteworthy point at this case is that the current measurer installed on a cluster in fact determines the current of that cluster and if we have voltage of one head of this cluster, based on the mentioned rules, voltage of the other head is obtained. Therefore, we can combine the conditions related to buses 1 and 2 as following:

$$\begin{cases} f_1 = x_1 + x_2 & \geq 1 \\ f_2 = x_1 + x_2 + x_{6'} + x & \geq 1 \end{cases} \qquad (13)$$

$$f_{1new} = f_1 + f_2 = x_1 + x_2 + x_{6'} + x_7 \geq 1$$

The above equation means that if one of buses 1 and 2 is observable, the other bus also will be observable. Therefore, final conditions in this case change as following:

$$f(x) = \begin{cases} f_{1new} = x_1 + x_2 + x_{6'} + x_7 & x \geq 1 \\ f_4 = x_4 + x_5 + x_{6'} + x_7 & x \geq 1 \\ f_5 = x_4 + x_5 & x \geq 1 \\ f_6 = x_2 + x_4 + x_{6'} & x \geq 1 \\ f_7 = x_2 + x_4 + x_7 & x \geq 1 \end{cases} \qquad (14)$$

In the above equations, in addition to combination of buses 1 and 2, also Bus 3 because of being zero injection bus is combined with Bus 6 according to the explanations of second bus.

2.4. Placement of PMU using Bacteria Algorithm

The purpose of optimal placement of PMU in this research is to calculate the minimum required number of PMUs for quite visibility of the network and to maximize number of the measurement substitution elements in a system. Therefore, Fitness Function should be in such a way that the following cases are considered in it: 1) system visibility, 2) minimization of number of PMUs, 3) maximization of number of measurement substitution elements. Measurement substitution element is defined in [12]. In brief, one can say that if number of the times which a bus gets observable by PMU one unit is increased, number of measurement substitution elements for that bus increase one unit. Fitness Function which in this research is considered for bacteria algorithm is as following:

$$J(x) = w_1 \times \sum_{i}^{N_b} f_i + w_2 \times N_{pmu} + w_3 \times J_1 \tag{15}$$

$\sum_{i}^{N_b} f_i$ indicates number of the observable buses, N_{PMU} is number of PMUs and J_1 is the measurement substitution element. Weights w_1, w_2 and w_3 have been used to select a suitable range for each section of fitness function. Also, N_b is number of buses of the network.

J_1 and N_{PMU} are defined as following:

$$N_{pmu} = X^T X$$

$$J_1 = (M - AX)^T (M - AX) \tag{16}$$

Product of AX in formula (16) indicates number of the times which each bus of the network gets observable by substitution of PMU. Vector X which previously was defined shows PMU placement. Vector M is selected based on a desired level of measurement redundancy in the system. For example, if for all buses Level 2 is desired, all elements of Vector M should equal 3. Vector (M – AX) is the difference between desired number and real number of the times which each bus is observable. Therefore, decreasing this difference leads to increase of the measurement substitution element. As a result, the term J_1 is an index for measurement redundancy in PMU placement.

3. Bacteria Foraging Algorithm

The main idea of this algorithm is based on the fact that in nature, animates with poor foraging methods have more possibility to extinct than animates with successful foraging strategies. Then, generations of animates with poor foraging methods have extincted and or have evolved to a better state. In fact, one can consider bacteria searching method as an optimization approach in finding the areas which are full of nutritious. Every bacterium simultaneously not only tries to achieve the most energy in each time but also tries to avoid from toxic materials. Bacteria Foraging Optimization Algorithm has simulated four behaviors of real bacteria in order to solve this problem, which include movement, group performance, reproduction and deletion and dispersion. Every bacterium in this algorithm is a response to the problem which moves on surface of the function in order to find an optimal response for the problem. The trend of representation of bacteria foraging algorithm is indicated in Fig. 3.

4. Dynamic Bacteria Foraging Algorithm

Chemotoxic performer (movement) is the main core of bacteria foraging algorithm. If the movement step selected for this algorithm performer is very big, the bacterium will move toward the target area with high speed. But this high pace increases the possibility of passing from the optimal point and or being trapped in local optimal points. Also, selection of a small movement step also causes slower movement of bacteria and as a result, increase of time of determination of the optimal point. Therefore, at this section, the way to dynamically regulate movement steps and make dynamic case of bacteria foraging algorithm are presented at here. The way to dynamically regulate movement step is according to Relation 3-5.

$$C(i, j+1) = \left(\frac{C(i, j) - C(N_C)}{N_C + C(N_C)}\right) \tag{17}$$

In Relation (17), $C(N_C)$ indicates the first step. In other words, the only change produced in the algorithm in these conditions is substitution of amount of C(i) with the amount obtained from Relation 17 in each repetition.

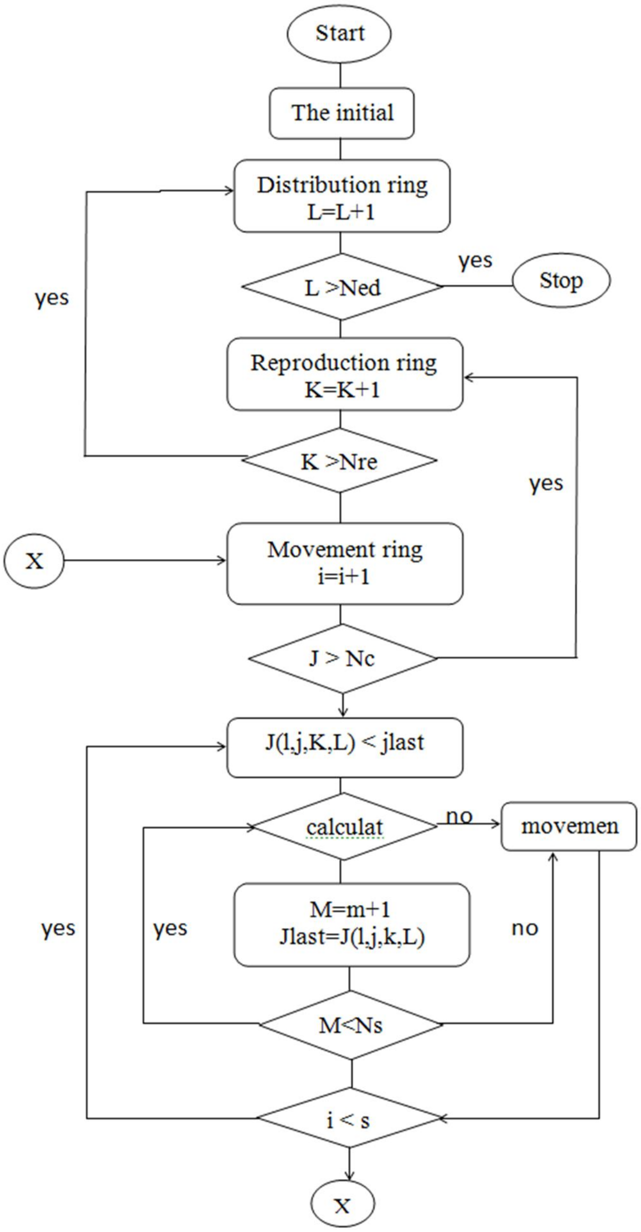

Figure 3. Flowchart of trend of dynamic bacteria algorithm implementation

5. Case study

The proposed method was applied in a real experimental system (a 20 kW radial distribution network which is indicated in Figure 4). Impedance of each lines is presented in Table 2 based on Ohm and peak amounts of charges in Table 1. Voltage of the network is 20 kw.

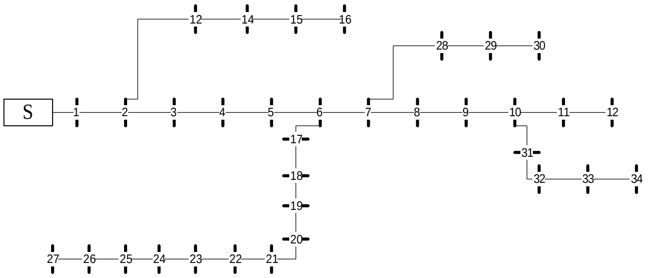

Figure 4. A Typical Distribution System for Testing

This Network Has 34 Buses Which The Information Related To This Network Is Presented At The Rest. Charges of This System Are In Three Commercial, Residential And Industrial Kinds (Commercial Charges Are Indicated With 1, Residential Charges With 2 And Industrial Charges With 3).

Table 1. Information of Charges the Real 34-Bus Network

No. of bus	P(KW)	Q(KW)	Kind of charge	Power factor
1	0	0	2	0.85
2	230	142.5	3	0.9
3	0	0	2	0.85
4	230	142.5	1	0.8
5	230	142.5	2	0.85
6	0	0	2	0.85
7	0	0	2	0.85
8	230	142.5	2	0.85
9	230	142.5	2	0.85
10	0	0	1	0.8
11	230	142.5	2	0.85
12	137	84	2	0.85
13	72	45	2	0.85
14	72	45	2	0.85
15	72	45	3	0.9
16	13.5	7.5	3	0.9
17	230	142.5	1	0.8
18	230	142.5	2	0.85
19	230	142.5	2	0.85
20	230	142.5	2	0.85
21	230	142.5	2	0.85
22	230	142.5	2	0.85
23	230	142.5	2	0.85
24	230	142.5	1	0.8
25	230	142.5	2	0.85
26	230	142.5	2	0.85
27	137	85	2	0.85
28	75	48	2	0.85
29	75	48	2	0.85
30	75	48	2	0.85

31	57	34.5	1	0.8
32	57	34.5	2	0.85
33	57	34.5	2	0.85
34	57	34.5	2	0.85

Table 2 – Information of the Studied Network Lines

Numbe of lines	First bus	Fin l bus	R(Ω)	X(Ω)
1	1	2	0.117	0.048
2	2	3	0.10725	0.044
3	3	4	0.16445	0.04565
4	3	13	0.1572	0.027
5	4	5	0.1495	0.0415
6	5	6	0.1495	0.0415
7	6	7	0.3144	0.054
8	6	17	0.1794	0.0498
9	7	8	0.2096	0.036
10	7	28	0.1572	0.027
11	8	9	0.3144	0.054
12	9	10	0.2096	0.036
13	10	11	0.131	0.0225
14	10	31	0.1572	0.027
15	11	12	0.1048	0.018
16	13	14	0.0524	0.036
17	14	15	0.16445	0.018
18	15	16	0.2079	0.009
19	17	18	0.189	0.04565
20	18	19	0.189	0.0473
21	19	20	0.189	0.043
22	20	21	0.189	0.117
23	21	22	0.262	0.117
24	22	23	0.262	0.117
25	23	24	0.3144	0.117
26	24	25	0.2096	0.117
27	25	26	0.131	0.117
28	26	27	0.1048	0.018
29	28	29	0.1572	0.027
30	29	30	0.1572	0.027
31	31	32	0.2096	0.036
32	32	33	0.1572	0.027
33	33	34	0.1048	0.018

In Figure (5), a 24-hour profile is presented for the intended charge which indicates rate of changes of each kind of charges during 24 hours.

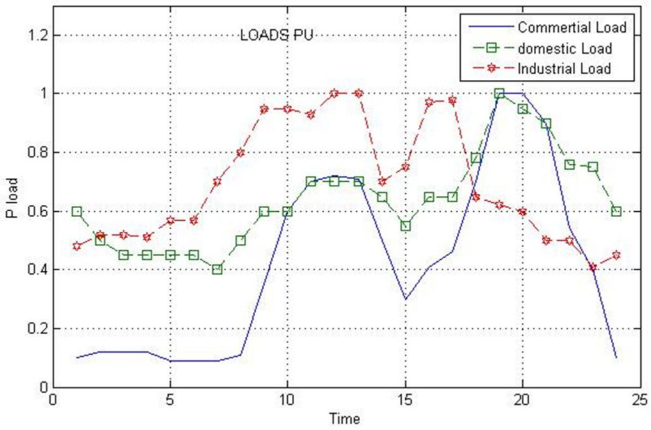

Figure 5. 24-Hour Profile for the Intended Charge

5.1. PMU Placement in Sample Distribution Network by the Topological Method

In this section, according to the conditions presented in the field of visibility of PMUs at the previous chapter and also based on the objective function presented at the previous section, the best possible places are determined for placing PMUs with the most possible amount for visibility of the system. In this section, two experiments are performed which in first experiment PMU placement is done without considering current measurement units and in second case, this is done by considering current measurement units. Results are presented and compared in Table 3.

Table 3. Results obtained from PMU placement using DBFA algorithm

	Without current measurer	With current measurer
Number of PMU units	14	9
Installation place of PMU units	2,5,7,9,12,15,16,18,21,24,26,29,31,33	6,7,10,11,14,17,21,25,28
Number of current measurer units	0	2
Installation place of current measurer units	-	2,31
Visibility amount	41	41
Objective function amount	16.439	11.439

As it is observed in the results, in case 2, considering the current measurement units which located in places 2 and 31 decrease number of the used PMUs. Of course, in both cases, the whole system is observable in which the issue was designed with the purpose of quite visibility. Also, in a simple comparison in Table 4 it is observed that for second case DAPSO gives better results than BPSO algorithm and also has higher convergence pace than this algorithm which is indicated in Figure 6.

Table 4. Results obtained for PMU placement using bacteria algorithm and DAPSO and PSO for experiment

	Bacteria algorithm	DAPSO algorithm	GA algorithm
Number of PMU units	9	10	11
Installation place of PMU units	6,7,10,11,14,17,21,25,28	4,6,9,12,15,17,21,24,30,32	5,7,12,15,18,20,21,24,27,30,32
Number of current measurer units	2	2	2
Installation place of current measurer units	2,31	3,26	1,12
Amount of visibility	41	45	41
Amount of objective function	11.439	12.22	13.439

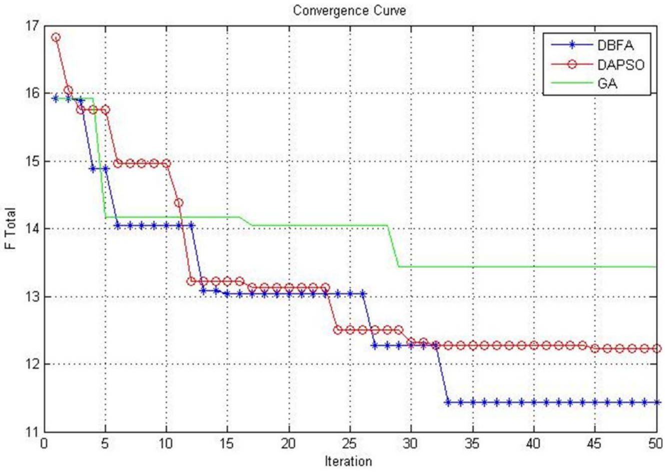

Figure 6. Convergence path of the system for different optimization algorithms

As it was observed in this study, the best result relates to dynamic bacteria algorithm which is convergent in repetition of 33 systems.

6. Conclusions

The issue of PMU placement in practical conditions includes more than quite visibility and cost minimization. Requirements of an especial application such as PMU failure, relational errors, additions and uncertainty of measurement, number of measurement channels, environmental conditions and presence of the other respective apparatuses should be considered. For visibility of the system, phasor measurement units or PMU and current measurer systems were used progressively and it was observed that dynamic bacteria algorithm is one of the best methods for PMU placement and its complete visibility in the system and network.

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