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An ACO Based Algorithm for Distribution Networks Including Dispersed Generations

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Abstract**—**With Power system movement toward restructuring along with factors such as life environment pollution, problems of transmission expansion and with advancement in construction technology of small generation units, it is expected that small units like wind turbines, fuel cells, photovoltaic, … that most of the time connect to the distribution networks play a very essential role in electric power industry. With increase in developing usage of small generation units, management of distribution networks should be reviewed. The target of this paper is to present a new method for optimal management of active and reactive power in distribution networks with regard to costs pertaining to various types of dispersed generations, capacitors and cost of electric energy achieved from network.

In other words, in this method it's endeavored to select optimal sources of active and reactive power generation and controlling equipments such as dispersed generations, capacitors, under load tap-changer transformers and substations in a way that firstly costs in relation to them are minimized and secondly technical and physical constraints are regarded. Because the optimal management of distribution networks is an optimization problem with continuous and discrete variables, the new evolutionary method based on Ant Colony Algorithm has been applied. The simulation results of the method tested on two cases containing 23 and 34 buses exist and will be shown at later sections.

Keywords**—**Distributed Generation, Optimal Operation Management of distribution networks, Ant Colony Optimization (ACO).

I. Introduction

DURING some last decades due to a great increase in operation efficiency and encouragement of financiers, electric power industry has encountered basic changes in the light of management and ownership, in a way that for making a proper competitive conditions, various parts such as generation, transmission and distribution have been independent from each other.

These changes along with factors like environment pollution, transmission line establishment and technology advancement in economical construction of small-scale generation units in comparison with large ones have resulted in an increase in the usage of small-scale ones under the topic named dispersed generations that mostly connect to distribution networks without needing transmission lines.

Researches made by researching centers such as EPRI have anticipated that until the year 2010, about 25 percent of electric power is generated by dispersed generations. Therefore with developing usage process of these generations, field of management and operation should be studied more carefully. Generally, optimal operation management of power systems is applied to optimal usage of active and reactive power generation equipments entirely and controlling devices. The reason for is that firstly costs are minimized and secondly technical and physical constraints are regarded.

In the past, distribution networks only consisted of reactive power generation sources. Because of this, most of explorations done in this part of power systems had to do with optimal operation of reactive power[1-9]. But these days due to existence of dispersed generations, the effects of various types of these generations in the light of active and reactive power generation should be considered.

This paper presents a method for optimal operation from distribution networks with regard to cost effect of active and reactive power generation consisting of dispersed generation substations and capacitors in order that firstly cost of active and reactive power generation and network losses are minimized, secondly technical constraints are regarded too.

In other words, the object is to determine active and reactive power generated by dispersed generations, main substation (distribution offices), capacitors and also tap-changer transformers in a manner to minimize objective function and regard the physical and technical constraints.

In overall view, because optimal operation of distribution networks is an optimization problem including continuous and discrete variables, evolutionary methods due to independence on primary conditions, being differentiable and continuous can be considered more and more.

One of evolutionary methods that have been considered recently is implementation of finding shortest path process done by ants. For the first time, Dorigo and his collaborators proposed the usage of Ant Colony Method for solving complicated optimization problems such as TSP (Traveling Salesman Problem) and QAP (Quadratic Assignment problem). Until now the Ant Colony Algorithm has been applied for solving some optimization problems such as TSP, ATSP, QAP, JSP, SMTTP, programming of Hydro electric power generation, economic dispatch, unit commitment, voltage and power control in distribution networks with regard to the effects of dispersed generations and pricing reactive power in restructured networks [10-18].

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With help of new method based on Ant Colony Algorithm that is presented in this paper, several optimization problems consisting of continuous and discrete variables such as operation management of distribution networks can be solved. Then optimal operation management of distribution networks with regard to the effects of dispersed generations along with costs of electric power generation for various types of dispersed generations are presented and after that, Ant Colony Algorithm mechanism and its application to solve optimization problems along with flowchart and solving method are observed. Finally simulation results achieved through the use of this Algorithm tested on two networks containing 23 and 34 buses are shown.

II. Optimal Operation Management of Distribution Networks with Regard to Dispersed Generation

From a mathematical standpoint the optimal operation management of distribution network with regard to distributed generation is an optimization problem with inequality constraints. The objective function is the summation of active and reactive cost of DGs, reactive cost of capacitors and active power cost of substation as follows:

$$f(x) = C_{Sub}(P_{Sub}) + \sum_{i=1}^{N_g} C(P_{gi}) + \sum_{i=1}^{N_g} C(Q_{gi}) + \sum_{i=1}^{N_c} C(Q_{ci}) + \sum_{i=1}^{N_b} Ploss_i * MCP \quad (1)$$

where:
C_{Sub} is substation active cost.
$C(P_g)$ and $C(Q_g)$ are active and reactive cost of DGs.
$C(Q_c)$ is reactive cost of capacitors.
Ploss is branch loss.
N_c is number of capacitors.
N_g is number of DGs.
N_b is number of branches.
MCP is market-clearing price.

Constraints are defined as follows:

- Active and reactive power constraints of DGs:

$$P_{g\min i} < P_{gi} < P_{g\max i}$$
$$Q_{g\min i} < Q_{gi} < Q_{g\max i} \quad (2)$$

- Transmission line limits:

$$|P_{Lij}| < P_{L\max ij} \quad (3)$$

- Reactive power of capacitors:

$$0 < Q_{ci} < Q_{c\max i} \quad (4)$$

- Tap of Transformers:

$$Tap_{\min i} < Tap_i < Tap_{\max i} \quad (5)$$

- Load flow equations.

III. Evaluation Cost of Distributed Generation

Generally, costs of distributed generation to customers include the installed cost of the equipment, fuel costs, nonfuel operation and maintenance (O&M) expenses, and certain costs that the customers' utility imposes.
Table (I) shows comparison of different cost of some distributed generations.

TABLE I
COMPARISON OF SELECTED ELECTRICITY GENERATION TECHNOLOGIES[20]

	Capacity (kW)	Capital Costa ($/kW)	Fuel Cost ($/kWh	O&M Cost ($/kWh)	Service Life (Years)
Micro turbine Power Only	100	1485	.075	.015	12.5
Micro turbine-CHP	100	1765	.035	.015	12.5
Gas ICE-Power Only	100	1030	.067	.018	12.5
Gas ICE-CHP	100	1491	.027	.018	12.5
Fuel Cell-CHP	200	3674	.029	.01	12.5
Solar Photovoltaic	100	6675	0	.005	20
Small Wind Turbine	10	3866	0	.005	20
Large Wind Turbine	1000	1500	0	.005	20
Combustion Turbine-Power Only	100000	715	.067	.006	20
Combustion Turbine-CHP	100000	921	.032	.006	20
Combined-Cycle System	1000000	690	.032	.006	20

Cost of DGs (per kWh/$), based on above table, can be defined as follows:

$$C(P) = a + b * P \quad (6)$$

In mentioned equation a & b coefficients can be evaluated as follows:

$$a = \frac{CapitalCost(\$/kW) * Capacity(kW) * Gr}{LifeTime(Year) * 365 * 24 * LF} \quad (7)$$

$$b = FuelCost(\$/kWh) + O\&MCost(\$/kWh)$$

where Gr and LF are yearly rate of benefit and DG loading factor.

The cost of reactive power produced by generators is called opportunity cost which due to capability diagram of generator shown in fig (1), reduces the active power production capacity.

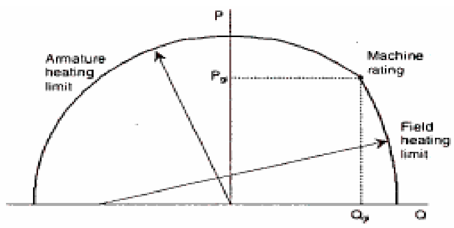

Fig. 1. Loading capability diagram

Opportunity cost depends on demand and supply in market, so it is hard to determine its exact value. In simplest form opportunity cost can be considered as follows:

$$C_{gqi}(Q_{Gi}) = \left[C_{gpi}(S_{Gi,\max}) - C_{gpi}\left(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2}\right)\right]K \quad (8)$$

Where:

$S_{Gi,\max}$: Maximum apparent power in i^{th} bus

Q_{Gi} : Reactive power of generator in i^{th} bus

K: Reactive power efficiency rate (usually between 5-10%)

IV. Unbalanced Three Phase Power Flow

In unbalanced three-phase power flow, the following components are modeled by their equivalent circuits in term of inductance, capacitance, resistance and injected current.

a) Distributed Generators: DGs are modeled as constant P and variable Q.
b) Transformers: transformers are modeled as equivalent circuit with fictitious current injections.
c) Capacitors: Capacitors are represented by their equivalent injected currents.
d) Demands or Loads: system loads are basically considered asymmetrical; because of single-phase loads and unequal three phase loads.

In this paper a network-topology-based on three-phase distribution power flow algorithm is used. Two matrices are used to obtain the power flow solution. They are the Bus Injection to Branch Current (BIBC) and the Branch Current to Bus Voltage (BCBV) matrices [19].

V. Distributed Generation Modeling

Generally, depending on the contract and control status of a generator, it may be operated in one of the following modes:

- To output power at a specific power factor (PQ node).
- To output power at a specific terminal voltage (PV Node).

In general, DGs can be modeled four ways:

- PV model that each three phase can be controlled instantaneously.
- PQ model that each three phase can be controlled instantaneously.
- PV model that each phase could be controlled separately.
- PV model that each phase could be controlled separately.

We have used a reactive power compensation for modeling of SVCs and PV nodes[9]. Fig2 shows model of DGs based on kind of their control.

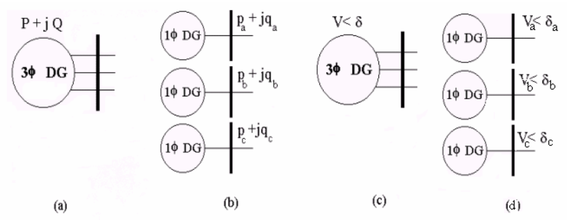

Fig. 2. Model of DSs
a). PQ Model with instantaneously control
b). PQ Model with separately control
c). PV Model with instantaneously control
d). PV Model with separately control

VI. Ant Colony System Mechanism

Ants are insects, which live together. Since they are blind animals, they find the shortest path from nest to food with aid of the pheromone. The pheromone is the chemical material deposited by the ants, which serves as critical communication media among ants, thereby guiding the determination of next movement. On the other hand, ants find the shortest path, based on intensity of pheromone deposited on different paths. For better understanding, assume that ants want to move from A to B and vice versa, to obtain food (Fig3).

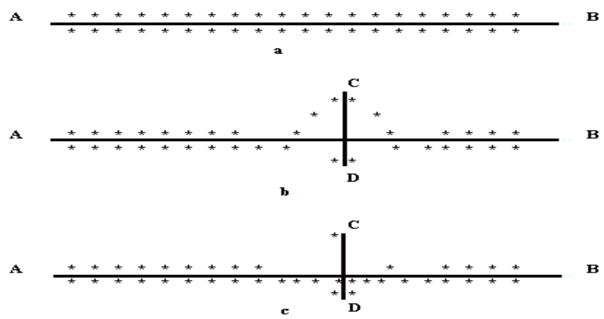

Fig. 3. An example of finding the shortest path by ants

At first, if there is no obstacle, all of them will walk to the straight path (Fig 3.a). Now, assume that there is an obstacle, in this case, ants will not be able to follow the original trial in their movement. Therefore, randomly, they turn to left (ACB) and to right (ADB) (Fig 3.b). Since ADB path is shorter than ACB, the intensity of pheromone deposited on ADB is more than the other. So ants will be increasingly guided to move on the shorter path (Fig 3.c). This behavior forms the fundamental paradigm of ant colony system.

As it was indicated in Fig3, the intensity of deposited pheromone is one of the most important factors for ants to find the shortest path. Therefore, this factor should be used to simulate behavior of ants. Generally, the following factors are used to simulate ant systems:

- Intensity of pheromone
- Length of path

To select the next path, state transition probability is defined as follows:

$$P_{ij} = \frac{(\tau_{ij})^{\gamma_1}(1/L_{ij})^{\gamma_2}}{\sum(\tau_{ij})^{\gamma_1}(1/L_{ij})^{\gamma_2}} \quad (9)$$

After selecting the next path, trail intensity of pheromone is updated as:

$$\tau_{ij}(k+1) = \rho\tau_{ij}(k) + \Delta\tau_{ij} \quad (10)$$

Where:

τ_{ij} :intensity of pheromone between nodes i and j, L_{ij}: length of path between nodes i and j,

ρ : a coefficient such that (1-ρ) represents the evaporation of trail between time k and k+1.

γ_1 and γ_2: control parameters for determining weight of trail intensity and length of path.

VII. Ant Colony Algorithm

This section presents a new approach based on ant algorithm for solving optimization problems. Optimization problem is defined as:

$$\begin{aligned} &Min \quad f(X) \\ &s.t \\ &h_i(X) = 0 \qquad i = 1,2,3,..., N_{eq} \\ &g_i(X) \geq 0 \qquad i = 1,2,3,..., M \end{aligned} \tag{11}$$

Where:
N_{eq}: number of equality constraints,
M: number of inequality constraints,
X: state variables.
In order to apply ant colony algorithm the following steps should be repeated.

Step 1: Creation of global initial population for Colonies and Global Trail Intensity

An initial population of ant colonies, X_i that must meet constraints, is selected randomly. At initialization phase it is assumed that trail intensity between each two colonies are the same

$$\begin{aligned} &Global\_Initial\_Colony\_Population = [X_1, X_2, ..., X_N] \\ &X_{i\min} \leq X_i \leq X_{i\max} \\ &Global\_Initial\_Intensity = [\tau_{ij}]_{N*N} \end{aligned} \tag{12}$$

where N is the number of Colonies.

Step 2: Creation of local initial population for each Ant colony and local Trail Intensity

In this step for each ant colony, initial population is created randomly. Also local trail intensity between ants in each colony is generated.

$$\begin{aligned} &Local\_Initial\_Population = [Y_1, Y_2, ..., Y_M] \\ &X_i - \delta \leq Y_i \leq X_i + \delta \\ &Local\_Trial\_Intensity = [\tau_{ij}]_{M*M} \end{aligned} \tag{13}$$

In this equation M is the number of ants in each colony and δ is the radius of local area search.

Step 3: Determination of next path

Determination of next path for each colony of ants depends on the direction of global and local paths. Namely, at first each colony of ants has to find local and global path as follows:

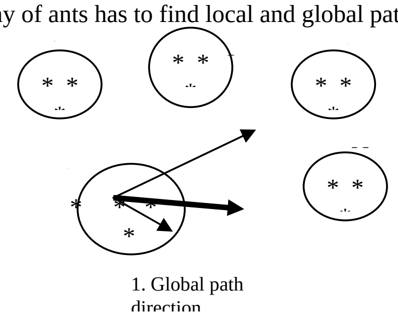

Fig. 4. Determination of next path for ant colony

The movement direction of any of ants is a combination of two preceding directions (eq.9).

Selection of global and local path is based on (1). Since in some optimization problems, L_{ij} is not known, we can define its inverse as follows:

$$\phi_{ij} = F(X_i) - F(X_j) \tag{14}$$

Transition probabilities are defined as:

$$P_{ij} = \frac{(\phi_{ij})^{\gamma_1} (\tau_{ij})^{\gamma_2}}{(\sum_{j=1}^{K} (\phi_{ij})^{\gamma_1} (\tau_{ij})^{\gamma_2})} \tag{15}$$

Value of K is equal to N and M for global and local transition probabilities respectively.
The roulette wheel is used for stochastic selection. After selection of local and global paths, trail intensity is updated as follows:

$$\begin{aligned} &\Delta\tau_{ij} = P_{ij} \\ &\tau_{ij}(k+1) = \rho\tau_{ij}(k) + \Delta\tau_{ij} \end{aligned} \tag{16}$$

Next path is determined based on local and global paths as follows:

$$X_i(k+1) = X_i(k) + rand*(X_{Local} - X_i(k)) + rand*(X_{Global} - X_i(k)) \tag{17}$$

New paths are compared with their limits.

Step 4: Check of convergence

After all of Ant colonies, find their next path, convergence is checked by:

$$\sqrt{\sum_{i=1}^{N} (X_i(k+1) - X_i(k))^2} < \varepsilon \tag{18}$$

If convergence condition is satisfied stop and print the results, otherwise go to step 3.

VIII. Flow Chart of Algorithm

Fig 5 shows flowchart of ant colony algorithm that described in previous section.

The first step is to create an initial population (Global initial population) for the colonies of ants based on control variables (In this paper active and reactive power of DGs, reactive power of capacitors and tap of LTC), which are between their limits. Then an initial population (Local initial population) will be created for each colony. In order to determine the next path for each ant, global and local paths should be known. Global and local paths determinations are similar. Using the trail intensity, global and local transition probabilities are calculated based on the difference between the cost of colonies and the difference between the costs of ants in each colony respectively. Afterward, global and local paths are determined with roulette wheel. If convergence is met, it will stop and otherwise the path determination steps are repeated. Unbalanced three-phase power flow presented in [19] is used to calculate the active power losses.

IX. Simulation

In this section the proposed method is applied to optimal operation management of distribution on two distribution test feeders.

In following section results for two cases are presented. It is assumed that energy price in substation is 4 cent per kWh and Capital cost of capacitor banks can be considered as deterioration rate and is written as follows:

$$C_{ci}(Q_{ci}) = Q_{ci} \times 11600 \ {}^{\$}\!/_{M}\ \text{var} \div (H \times 15 \times 8760\ )hrs \\ = Q_{ci} \times .1324 \ {}^{\$}\!/_{M}\ \text{var}\ .hr \tag{19}$$

Where H represents average duty cycle of capacitor banks and value of $\frac{2}{3}$ is considered for it in this study.

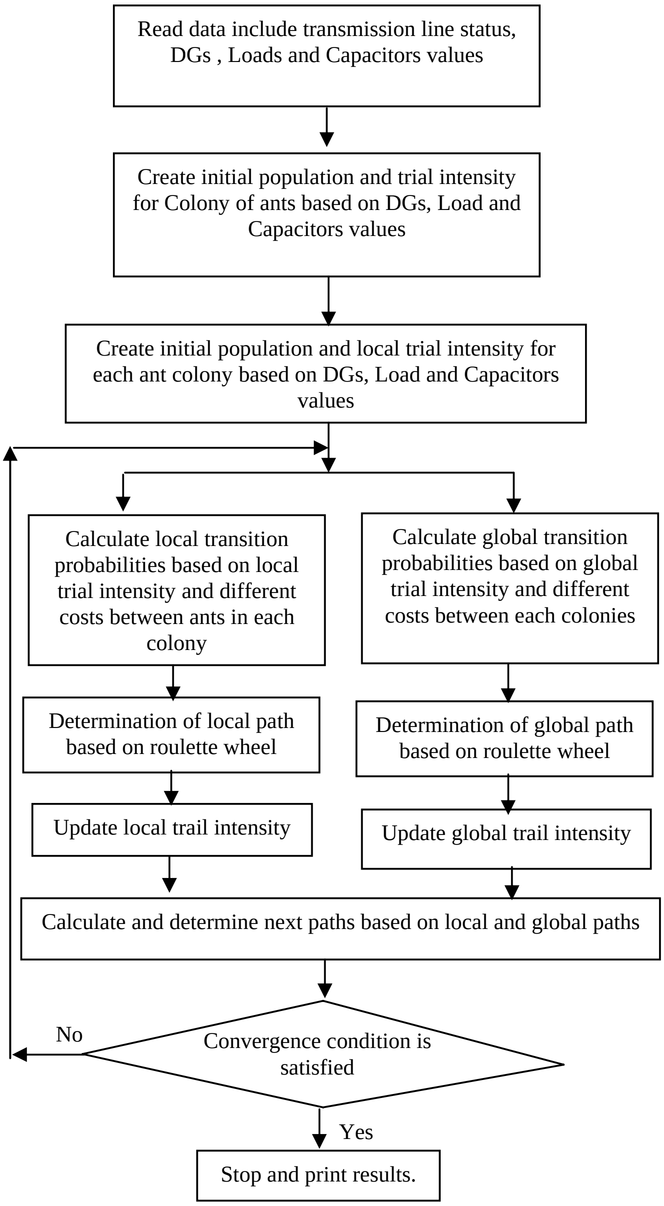

Fig. 5 Flowchart of proposed algorithm

Case 1: IEEE 34 bus radial test feeders

Figure 6 shows the IEEE 34 bus radial distribution test feeders, where the lines and loads specification are presented in [21].

For this system it is assumed that there are three DGs connected at 9, 23 and 27 respectively, which their specification are presented in Table II.

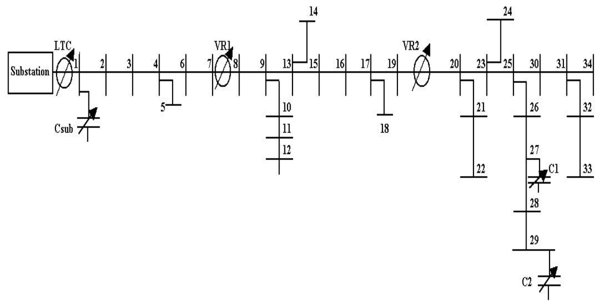

Fig. 6 Single Line Diagram

TABLE II
CHARACTERISTIC OF GENERATORS

	G1	G2	G3
Maximum Active Power(kW)	100	400	600
Maximum Reactive Power (Kvar)	80	320	480
Minimum Reactive Power (Kvar)	-60	-240	-360
Location	6	16	29
Kind of DG	Micro Turbine CHP	Large Wind Turbine	Combustion Turbine CHP

Table III give the comparison of results the proposed method with Genetic Algorithm.

TABLE III
COMPARISON RESULTS

	ACO	GA
Objective function Value ($/h)	50.451	52.1954
Losses (Kw)	9.5528	17.5441
Tap of Substation Transformer	1.0131	1.003
Tap of Voltage Regulator 1	0.98	1.008
Tap of Voltage Regulator 2	1.03	1.021
Active Power of DG1 (Kw)	0	5.72
Active Power of DG2 (Kw)	400	380.72
Active Power of DG3 (Kw)	499.99	355.43
Reactive Power of DG1 (Kvar)	1.74	29.65
Reactive Power of DG2 (Kvar)	91.9974	153.23
Reactive Power of DG3 (Kvar)	95.81	417.22
Reactive Power of Capacitor 1(Kvar)	450	0
Reactive Power of Capacitor 2(Kvar)	0	0
Execution Time (S)	300	700

Case 2. A realistic 23 bus 20 Kv network

The method is applied to a rural network as shown in Figure 7. This system is used to supply power demand in the village located in the north of Iran. Line and load characteristics are shown in Tables IV and V respectively. Line impedance Matrix is presented in equation (11). As there is no DG in this networks currently, two typical DGs have been considered in buses 13 and 21 which their specification have been presented in Table VI. In this system there is one-capacitor (800Kvar), which is located in bus 14.

$$Z_{Line}(\Omega/m) = (1e-4)\begin{bmatrix} 7+j7 & .2+j.15 & .2+j.15 \\ .2+j.15 & 7+j7 & .2+j.15 \\ .2+j.15 & .2+j.15 & 7+j7 \end{bmatrix} \tag{20}$$

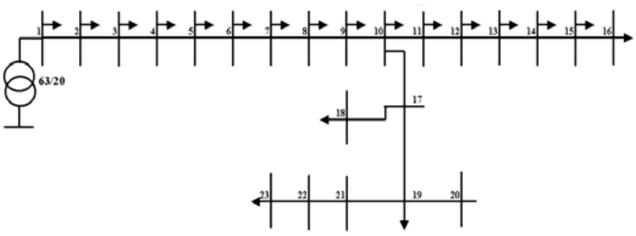

Fig.7 Single Line Diagram of rural network

TABLE IV
LINE CHARACTERISTICS

No	From	To	Length (m)
1	1	2	40
2	2	3	280
3	3	4	140
4	4	5	120
5	5	6	330
6	6	7	725
7	7	8	210
8	8	9	210
9	9	10	55
10	10	11	60
11	11	12	1000
12	12	13	1020
13	13	14	870
14	14	15	865
15	15	16	865
16	10	17	1400
17	17	18	1700
18	17	19	70
19	19	20	70
20	18	21	1060
21	21	22	1500
22	22	23	520

TABLE V
LOAD CHARACTERISTICS

No	Pa(Kw)	Qa(Kvar)	Pb(Kw)	Qb(Kvar)	Pc(Kw)	Qc(Kvar)
1	0.00	0.00	0.00	0.00	0.00	0.00
2	105.00	78.75	114.45	85.84	95.55	71.66
3	83.33	62.50	90.83	68.13	75.83	56.88
4	83.33	62.50	90.83	68.13	75.83	56.88
5	83.33	62.50	90.83	68.13	75.83	56.88
6	83.33	62.50	90.83	68.13	75.83	56.88
7	83.33	62.50	90.83	68.13	75.83	56.88
8	83.33	62.50	90.83	68.13	75.83	56.88
9	83.33	62.50	90.83	68.13	75.83	56.88
10	83.33	62.50	90.83	68.13	75.83	56.88
11	105.00	78.75	114.45	85.84	95.55	71.66
12	105.00	78.75	114.45	85.84	95.55	71.66
13	83.33	62.50	90.83	68.13	75.83	56.88
14	83.33	62.50	90.83	68.13	75.83	56.88
15	21.00	15.75	22.89	17.17	19.11	14.33
16	333.33	250.00	363.33	272.50	303.33	227.50
17	133.33	100.00	145.33	109.00	121.33	91.00
18	83.33	62.50	90.83	68.13	75.83	56.88
19	105.00	78.75	114.45	85.84	95.55	71.66
20	105.00	78.75	114.45	85.84	95.55	71.66
21	50.00	37.50	54.50	40.88	45.50	34.13
22	0.00	0.00	0.00	0.00	0.00	0.00
23	105.00	78.75	114.45	85.84	95.55	71.66

TABLE VI
CHARACTERISTIC OF GENERATORS

	G1	G2
Maximum Active Power	1000	1000
Maximum Reactive Power	800	800
Minimum Reactive Power	-600	-600
Location	13	21
Kind of DG	Combustion Turbine CHP	Combustion Turbine CHP

A comparison between the proposed algorithm (ACO) and Genetic Algorithm is available in Table VII.

TABLE VII
COMPARISON RESULTS

	ACO	GA
Objective function Value ($/h)	254.0269	254.0296
Losses (Kw)	31.1441	31.2657
Tap of Substation Transformer	1.03	1.0291
Active Power of DG1 (Kw)	764.3091	760.53
Active Power of DG2 (Kw)	237.49	231.84
Reactive Power of DG1 (Kvar)	200.21	203.144
Reactive Power of DG2 (Kvar)	208.535	210.1121
Reactive Power of Capacitor (Kvar)	800	800
Execution Times (S)	200	423

As shown in Tables III and VII, the proposed method can be used to apply to optimal operation management of distribution networks. The results of these Tables can be summarized as follows:

1. The execution time of proposed method is sufficiently short (with regard to GA) and will give a general idea that the method can be implemented without any restriction in realistic networks.
2. The method can be applied to a wide variety of similar optimization problems. On the other hand, this method can be used to non-differential and non-continuous objective function and constraints.
3. Objective function value and active power losses in the proposed method is less than GA.
4. Because most of dispersed generations owned and controlled by private sections, necessary mechanisms must be applied for supervision and control of optimal operation in power systems. In this paper costs pertaining to active and reactive power generation offered by owners of dispersed generations have been used as a decisive factor for optimal control of them. Results achieved in last sections show that we can apply these methods to control dispersed generations and be sure that high benefits will be gained from them.

X. CONCLUSION

As the number of DGs will be increasing, their impacts on power system to be studied. One of the most important issues in distribution system is distribution management system (DMS), which can be affected by DGs. In this paper a new approach for optimal operation management of distribution networks with regard to DGs presented. The simulation result showed that the method could be implemented in practical distribution networks.

The execution time of proposed method is sufficiently short and will give a general idea that the method can be implemented without any restriction in realistic networks. Since the most of DGs owned by private section, active and reactive power generation costs of DGs considered as optimal parameter control of them.

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