Optimal Multi-Objective VAr Planning Using Accelerated Ant Colony and Analytical Hierarchy Process Methods

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Abstract:

The aim of reactive power(VAr) planning is to provide the system with sufficient VAr sources to enable the system to be operated under economically conditions .The VAr planning problem is a constrained ,multi-objective non-differentiable optimization problem .The VAr problem is first formulated as a multi-objective problem . This formulation considers different objective functions related to real power losses ,investment cost of VAr sources ,installation and maintenance cost ,voltage deviation and security margin with equality and inequality constraints .Second the objective functions are weighted by analytical hierarchy process (AHP) ,So the multi-objective optimization problem is converted into single objective function .Third the weak bus and heavy load bus oriented criterion are used to determine the candidate buses for installing new VAr sources .Then an ant colony algorithm which is based on the foraging behavior of ants is developed to solve this problem .This proposed method has been applied on the modified IEEE 14 bus system.

1 Introduction

The purpose of optimal VAr planning is to provide the system with sufficient VAr sources so that it can operate in an economically feasible operation condition while all load and operational constraints with respect to credible contingencies are met. The objective function can include various functions .In most papers the real power losses ,the investment and installation cost of VAr sources are considered as objective functions and different formulation and solution algorithm have been developed[1,2]. A common characteristic of these methods is that the value of VAr sources has always been treated as continuously differentiable and the system security hasn't been considered .It has been shown that the voltage collapse may occur due to the shortage of reactive power at some buses ,so in VAr planning approach the weak buses should be determined for installation of new VAr sources . Therefore in Ref.[3] a weak bus oriented criterion is applied to determined candidate buses .although the system voltage profile is considerably improved after VAr planning ,buy voltage at some buses may approach their upper limits which is not desire regarding the

voltage collapse .As a result the voltage deviation of each bus most be as small as possible to obtain a performance voltage index .It is also necessary to maximize the system security margin ,So the system to be able to tolerate more load demand without voltage collapse .In this study apart from different methods used all these objective functions are considered. Many of the existing solution algorithms for such problem belong to heuristic or approximate techniques .These solutions usually lead to local optima rather than global optima .To overcome this difficulty various techniques such as simulated annealing (SA) ,Genetic algorithm (GA) and tabu search (TS) ,… have been successfully applied for VAr planning [3-10] .In this paper an optimization technique based on ant colony (AC) method has been developed to find a global optimal solution for VAr planning. This technique is also a powerful tool for solving many classic combinational optimization problems like the traveling salesman problem ,quadratic assignment problem and the network routing problem [11-14] .In power systems the Ac algorithm has been applied to unit commitment problem[15] and optimal placement of capacitors in distribution system ,so far[16] .
In this paper the objective functions are weighted by analytical hierarchy process(AHP) ,which is introduced by T.L.Salty [17]. This paper is organized as follows .The next sections of the paper discuss the formulation of the VAr planning ,the ant colony algorithm ,analytical hierarchy process and how this techniques can be applied to solve the problem[14-20]. Finally the developed algorithm has been tested on the modified IEEE 14 bus system .

3-problem formulation

The VAr planning problem is formulated as a multi-objective mathematical programming problem in which all objective functions are simultaneously improved and all constraints satisfied .The objective function includes real power losses ,the investment cost of VAr sources ,voltage deviation and security margin .

3-1 Power loss and investment cost

The objective is to minimize the total real power losses arising from branches and to minimize the expenditures of VAr sources:

$$f_1 = \sum_{i \in \Omega_c} (d_i + S_{ci} q_{ci} + S_{ri} q_{ri}) + k_e \sum_{j=1}^{n_t} T_j P_{loss,j} \quad (1)$$

Where

k_e :converted real power to expense.

T_j : the duration of the system operating time under j load level.

$P_{loss,j}$: the system real power loss under j load level.

$\sum_{i \in \Omega_c} (d_i + S_{ci} q_{ci} + S_{ri} q_{ri})$: the total purchase cost of the new installment VAR sources.

Ω_c :a set of all candidate buses to install new VAR sources.

d_i :the installment cost at bus i.

S_{ci} :the unit costs of capacitor.

S_{ri} : the unit costs of reactor.

q_{ci} : added capacitive compensation ar bus i and it is an integer.

q_{ri} : added inductive compensation ar bus i and it is an integer.

3-2 Security margin

This objective function is concerned with the static voltage stability of the system and how to reduce the danger of voltage collapse .In this optimization problem the attempt is made to maximize the system security margin ,so the system to be able to tolerate more load demand without rise of voltage collapse .The security margin is defined as :

$$SM = \frac{\sum_{j \in J_L} S_j^{\lim it} - \sum_{j \in J_L} S_j^{initial}}{\sum_{j \in J_L} S_j^{\lim it}} \quad (2)$$

Where

SM: security margin of system.

$S_j^{initial}$: initial value of MVA load at bus j

S_j^{limit} : critical value of MVA load at bus j

J_L : set of all load buses .

The value of S_j^{limit} is determined using continuation power flow (CPF) ,in which the power consumption at each bus is continuously increased until approaching the point of voltage collapse .In order to maximize the above index ,the following function can be minimized instead ,

$$f_2 = 1 - SM = \frac{\sum_{j \in J_L} S_j^{initial}}{\sum_{j \in J_L} S_j^{lim\,it}} \qquad (3)$$

3-3 Voltage deviation

The voltage deviation of each load bus must be as small as possible to obtain a performance voltage index .The voltage deviation index is defined as :

$$f_3 = \underset{j}{Max} \frac{\left|V_j - V_j^{spec}\right|}{V_j^{spec}} \qquad (4)$$

where

J_L : set of all load buses.

V_j :voltage magnitude at bus j.

V_j^{spec} : ideal specific voltage magnitude at bus j ,which is usually 1 p.u.

The above objective functions are converted to the following single function ,in which coefficients w_1, w_2 and w_3 are the corresponding weights :

$$F = w_1 * f_1 + w_2 * f_2 + w_3 * f_3 \qquad (5)$$

4-Analytical hierarchy process method

To tackle the problem of VAr planning with multiple objectives the weighted sum strategy is employed to convert these functions into a single function by giving relative weighting values .The weighting factor of each objective is assessed via the analytical hierarchy process (AHP) approach [17]. As shown in table1. the AHP creates an intensity scale of importance to transform linguistic terms into numerical intensity values .

Table 1 :Intensity scale of importance

Intensity of importance	Definition
1	Equal importance
3	Weak importance of one over another
5	Strong importance
7	Very strong importance
9	Absolute importance
2,4,6,8	Intermediate values between adjacent scale

Assuming $f_1, f_2, ... f_P$ be the set of objectives considered, the quantified judgments on pairs on pairs of objectives f_i, f_j are then represented by an p by p Matrix:

$$A = \left[a_{ij}\right] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1P} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2P} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{1P}} & \frac{1}{a_{2P}} & \cdots & 1 \end{bmatrix} \qquad (6)$$

where the entries a_{ij} $(i, j = 1,2,..., p$ where p is the number of objective) are defiend by the following rules :

Rule 1 :if $a_{ij} = \alpha$,then $a_{ji} = \frac{1}{\alpha}$, where α is an intensity value determined by the operators ,as shown in table 1 .

Rule 2 :if f_i is judged to be of equal relative importance as f_j ,then $a_{ij} = 1$,and $a_{ji} = 1$,in particular , $a_{ii} = 1$ for all i .

Following the eigenvector method [17] ,an eigenvector of matrix A corresponding to the largest eigenvalue can then be obtained .The weighting vector is as follows :

$$W = [w_1, w_2, \cdots, w_i, \cdots, w_P] \quad (7)$$

5- Accelerated ant colony algorithm

Ants in real world cooperate to obtain an optimal path from their nest to a food sources .This is accomplished by means of pheromones which enables the ants to interact with another. Pheromones are deposited along the trails by the ants .The optimal trails are those accumulated by more pheromones.

If the optimization problem can be formulated as[14] :

$$\begin{aligned} &Min \quad J = f(x) \\ &x_{\min} \le x \le x_{\max} \quad ; \quad x = (x_1, x_2, \cdots, x_n) \in R^n \end{aligned} \quad (8)$$

As a first step to solve this problem we express the solution candidate x with a N-length binary string,

$$X \Leftrightarrow \{b_N, b_{N-1}, \cdots, b_1\} \quad (9)$$

To do so ,according to the maximum and minimum value of VAr sources to be installed in a candidate bus ,a binary string is selected .Each bit of this string can take value of 0 or 1 .By assigning such string to all candidate buses the problem can be defined as Eq() ,in which $b_j \in \{0,1\}$ for j=1,2,…, N: b_1 is the lowest bit and b_N is the highest bit in the string. An oriented graph C=(V,S) is defined with a set of nodes

$$V = \{v_s, v_N^0, v_{N-1}^0, ..., v_1^0, \; v_N^1, v_{N-1}^1, ..., v_1^1\}$$

And a set of oriented arcs

$$S = \{(v_N^0, v_{N-1}^0), ..., (v_j^0, v_{j-1}^0), (v_j^0, v_{j-1}^1), (v_j^1, v_{j-1}^0), (v_j^1, v_{j-1}^1), ...(v_2^1, v_1^1)\}$$

Where the node v_s is the unique initiative node; the nodes v_j^0 and v_j^1 for each j represent two Situations of the bit b_j , i.e., 0 and 1, respectively. From each of the nodes v_j^0 and v_j^1 for j=2,3,…,N, there exist and only exsit two arcs connecting to the nodes v_{j-1}^0 and v_{j-1}^1 respectively. Thus the complex nonlinear system optimization problem is mapped to a searching problem on the oriented graph C in the way of looking for a best path among all the paths originating from v_s and terminated at v_1^0 and v_1^1 respectively.

Let the ant A_i dispatched from an artificial ant colony $A = \{A_1, A_2, ..., A_m\}$ commence searching at the node v_s , passing through the path segments composed of N one-to-one interconnected oriented arcs, to form a path W_i consisting of the nodes sequence $\{v_N^{i_N}, v_{N-1}^{i_{N-1}}, ..., v_1^{i_1}\}$ for $i_1, i_2, ..., i_N \in \{0,1\}$, corresponding to a binary string $\{b_N^i \; b_{N-1}^i ... b_1^i\}$ where $b_j^i \in \{0,1\}$ for j=1,2,…, N. The sequence can be decoded to a solution candidate x_i :

$$\begin{aligned} &\phi(W_i) = \{b_N^i \; b_{N-1}^i \; ... \; b_1^i\} \\ &\Leftrightarrow x_i = \frac{X_i}{2^N - 1}.(X_{\max} - X_{\min}) + X_{\min} \end{aligned} \quad (10)$$

Where X_i is the decimal number to the string $\{b_N^i \; b_{N-1}^i ... b_1^i\}$, to guarantee all the solution candidates decoded from the searching paths satisfying the constraint $x_{\min} \le x \le x_{\max}$ under the mapping of Eq.(10)

The artificial ants conduct their search on the oriented graph C in the similar way as their natural counterparts. Each ant starts its travel in a random manner: at each node it reached, the ant selects one of the two path segments originating from the node in a probability ρ proportional to the pheromone φ accumulated on the path segment, and deposits a pheromone increment $\Delta\varphi$ to inform other ants to follow its tour route. The amount of the pheromone increment does not be deposited arbitrarily: it follows the law that the better the whole path (evaluated by calculating the objective value f(x) in (8) for x which is decoded from the binary string corresponding to this path), the more the deposited pheromone increment is. In this way of positive feedback , more and more artificial ants will concentrate on the

best path of the graph to find out the global optimal solution of the problem (8). The detail rules of the graph-based ant search and the pheromone update can be seen in [18].
In current commonly used basic ant colony algorithm, the total amount of pheromone created by an ant is uniformly assigned to each segment of the path it walked through .In our construction of the oriented graph , however , the uniform pheromone increment assignment strategy will result in a deteriorated searching behavior : because of the different contributions made by different path segments in a path to the corresponding solution candidate, assigning pheromone increments uniformly to all the path segments will induce the same probability in the choice of different searching step lengths in the following searching efforts. Such kind of searching behavior may not match the topological structure of the solution candidate (with a smaller objective value) the reasonable search effort in the next period should be made in a narrow region around it in order to speed up searching convergence in the probabilistic sense; for worse solution candidates (with a bigger objective value), on the other hand , in the next period a bigger search step should be set as an attempt for global optimality.
In light of the consideration mentioned above, we develop a heuristic pheromone increment assignment strategy to accelerate the searching procedure , by depositing the pheromone increment $\Delta\varphi_{i,j}$ on the path segment $\{v_i, v_j\}$ in the following way:

$$\Delta\varphi_{i,j}(f_s(t), k) = \frac{1}{1 + e^{\beta.k.f_s(t).(f_s(t)-(f_{\min}(t)+\delta))}}$$

where $f_{\min}(t)$ is the minimum objective value obtained in the last t searching periods, $f_s(t)$ is the objective value corresponding to the path covering $\{v_i, v_j\}$ the ant A_S walked through in the t-th searching period, k is the bit position mapped into a corresponding node in the graph C, and the adjustable parameters $\beta, \delta \rangle 0$.
From Eq.(6), it can be seen that the worse the solution candidate, or the lower the encoding bit position, the smaller the probability is in which the corresponding path segment will be selected by the following ants. In this way in the next searching period, the ants will be likely to take a small-scale searching step around the original solution candidate, in order to make use of valuable information obtained in the previous searching periods.

6- Solution algorithm

The proposed algorithm for solving the above problem is described as follows :
Step1 : Input the network data
Step2 : Define the candidate buses for installation of new VAr sources using the weak bus and heavy load bus-oriented criterions.
Step3 : Input the required information for ant colony method ,i.e. number of iteration(n) ,number of ant (Na) , δ and β coefficients.
Step4: Choose the N-bit string ,the number of bits are determined by maximum and minimum VAr sources to be installed to candidate buses .
Step5: Put constant pheromone on the routes of the oriented graph
Step6: Move each ant along routes and determine the amount of VAR sources at candidate buses.
Step7: Add the above values to values obtained in the previous iteration and run a load flow to check the constraints.
Step8: Determine the objective function for each ant. Perform a number of Na moves, then go to next step.
Step9: Determine the minimum value of the objective function in the present iteration.
Step10: Put pheromone along routes using Eq.( ). Check the stop criterion (No. of iteration), if not satisfied go to step 5 otherwise proceed to next step.
Step11: Print the results.

The flow chart is shown in Fig.1.

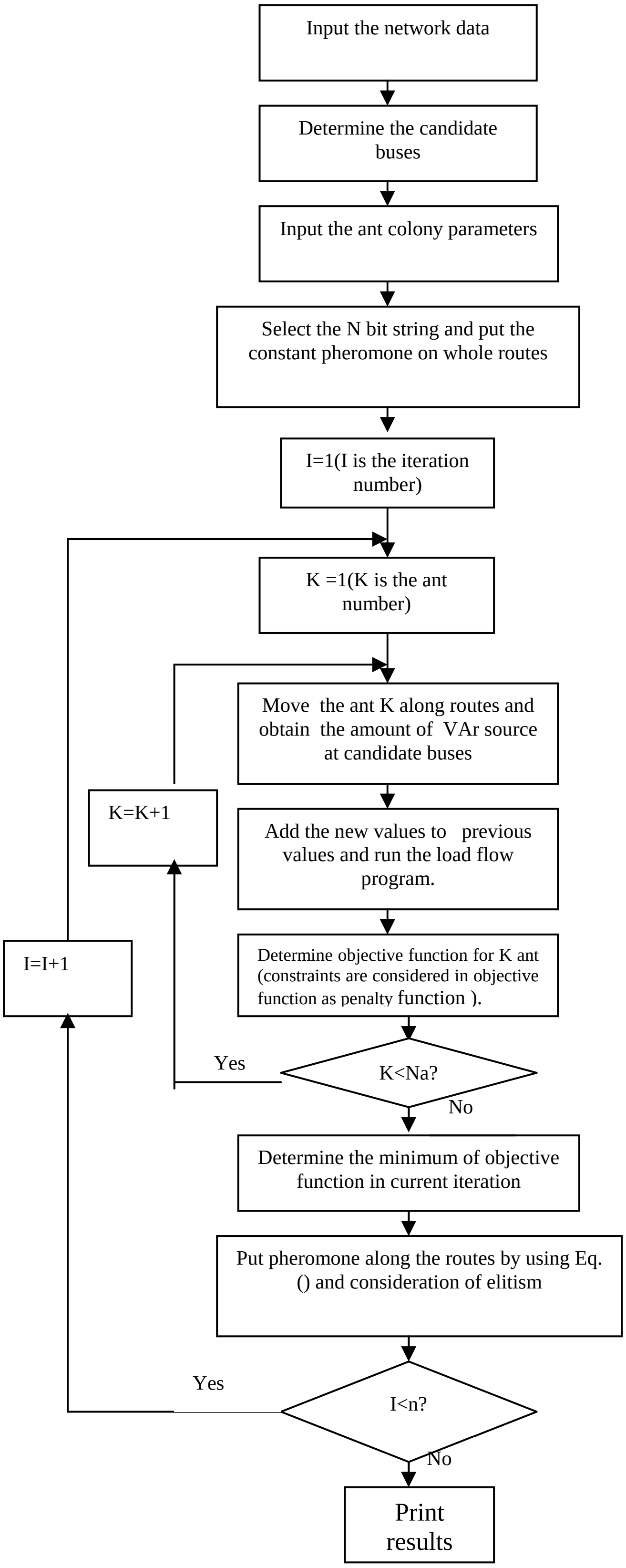

Fig1:The flow chart of the VAR planning program solution by AAC

7-Numerical results

To demonstrate the capability of the proposed algorithm it has been tested on the modified IEEE 14 bus system [3] having the following parameters : Energy loss cost weight Ke=2.3 NT$/kWh , and are limited to 150 bank .Each bank is set to 1 MVAr and the VAr source cost weights used are : Sci=2275 NT$/bank ,Sri=3280 NT$/bank and di= 84000NT$/location .The lifetime of the VAr source to be 10 years .The duration of of the summer peak load is estimated to be about 6 months per year and 8 hours per day ,so T_j=365*8(h)*10(y)*0.5=14600 .
Two cases have been considered .In case one the VAr planning is treated as a single objective optimization problem .The objective function includes power loss and investment cost reduction ,defined by Eq().
In second case ,all objective functions are considered using Eq.() .

Case 1

The results of case 1 are shown in Table2 and Table3.Table2 shows the configuration of the VAr sources (VAr locations ,sizes and types) .Table3 lists the power loss and values of different costs before and after planning .The total cost is reduced by 30.69% ,the power loss is reduced by 30.73% .The voltage profile is also shown in Fig.2

Case 2

In this case with reference to table in terms of intensity of importance of different objective function ,six situations are studied .The results of this study are shown in Table .As this table lists ,The values of weighting factors for each situation is calculated by AHP method and shown in row 4,5 and 6 .Row 7,8 and 9 of table correspond to the value of cost,security margin and maximum voltage deviation

Table2: Results of VAr locations, sizes and types

14	13	12	4	Bus no.
24	14	17	61	Installed banks

Table 3: Results of case1 (single objective)

Reduced rate(%)	Before planning	After planning	Objectives
30.73	39.4012	27.2920	Power loss (kW)
30.73	1304968524	903910940	Cost of energy losses (NT$)
------	------	599900	Cost of VAr sources (NT$)
30.69	1304968523	904510840	Total cost (NT$)

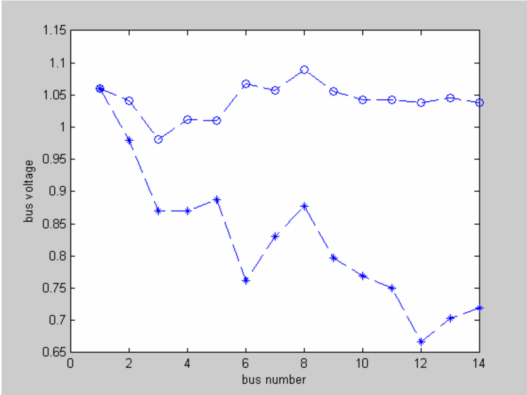

Fig.2 Voltage profile at buses before & after planning

-+- Voltage profile before planning

-o- Voltage profile after planning

. Table 2: results for multi-objective VAr planning on the IEEE 14 bus system.

Relative importance	**Situation 1**	**Situation 2**	**Situation 3**	**Situation 4**	**tuation 5**
Importance of f_1 respect to f_2	Strongly Preferred (5)	Equally Preferred (1)	f_2 Moderately preferred f_1 (1/3)	f_2 Very Strongly Preferred f_1 (1/7)	Equally Preferred (1)
Importance of f_1 respect to f_3	Extremely Preferred (9)	Between Strongly Preferred and Very Strongly Preferred (8)	f_3Moderately preferred f_1 (1/3)	f_3 Strongly Preferred f_1 (1/5)	f_3 Very Strongly Preferred f_1 (1/7)
Importance of f_2 respect to f_3	Very Strongly Preferred (7)	Between Strongly Preferred and Very Strongly Preferred (8)	Equally Preferred (1)	Between Equally Preferred and Moderately preferred (2)	f_3 Very Strongly Preferred f_2 (1/7)
w_1	0.613	0.471	0.143	0.0754	0.1429
w_2	0.335	0.471	0.429	0.5614	0.1429
w_3	0.0512	0.0588	0.429	0.365	0.7778
Cost value (NT$) **($f_1$)**	$8.9*10^8$	$9.049*10^8$	$9.18*10^8$	$9.2*10^8$	$9.16*10^8$
Security margin Index **(f_2)**	0.7427	0.7057	0.7037	0.6917	0.7093
Voltage deviation(pu) **(f_3)**	0.0879	0.0625	0.0359	0.0398	0.0341

8-Conclusion

This study developed an accelerated ant colony (AAC) method to solve the single objective and multi objective VAr planning problems. In the case of multi objective problem, the objective functions are weighted by analytical hierarchy process(AHP). The numerical results prove the ability of the proposed algorithm to find a desirable, global efficient solution to VAr planning problem.

9- References

[1] Y.T. Hsiao, C.C. Liu, H.D. Chiang and Y.L. Chen" A new approach for optimal VAr sources planning in large scale electric power systems" IEEE Trans. On power system, Vol.8, No.3,Agu. 1993.

[2]. Y.T.Hsiao et al,"A computer package for optimal multi-objective VAR planning in large scale power systems" IEEE Trans. On power system, Vol.9, No.2, 1994.

[3] Y.L. Chen " Weighted-norm approach for multi objective VAr planning" IEE Proc. Gener. Transt. Dist., Vol.145, No.4,July 1998.

[4] Y.L. Chen and Y.L. Ke " Multi objective VAr planning for large scale power systems using projection based two layer simulated annealing algorithms" Iee Prov.-Gen.Trasm. Distrib. Vol.151,No.4,July 2004.

[5]Y.-L Chen , C.-C.Liu,"Interactive fuzzy satisfying method for optimal multi-objective VAr planning in power systems" IEE 1994.

[6]K.Y.Lee, Y.M.Park "Optimization method for reactive power planning by using a modified simple genetic algorithm" IEEE Transactions on power systems, Vol.10, No.4, November 1995.

[7]L.L.Lai , J.T.Ma," Practical application of evolutionary computing to reactive power planning" IEE Proc.-Gener. Transm. Distrib.,Vol.145,No.6,Nov. 1998.

[8]K.Iba "Reactive power optimization by genetic algorithm" IEEE Transactions on power systems, Vol.9, No.2, May 1994.

[9] D.Q. Gan et. Al. " Large scale VAr optimization and planning by Tabu Search "Electric Power Research Vol.39, No.3, pp.5-8,1996.

[10] D.F. Pires,A.G. Martins and C.H. Antunes," A multiobjective model for VAr planning in radial distribution networks based on Tabu Search" IEEE Trans. on power systems. 2005

[11] M. Dorigo, L.M. Gambardella, " Ant colony system: A cooperative learning approach to the traveling salesman problem" IEEE Trans. On Evolutionary Computation,Vol.1,pp.53-56,1977.

[12 M. Dorigo, G. Di Caro, L.M. Gambardella, "Ant algorithm for discrete optimization", Artificial Life,Vol.5,pp.137-172,1999.

[13] S. Das, I. Mohanty, D.Z. Yang, " Ant colony algorithm for multicast routing in communication networks", Proceeding sixth International Joint Conference on Information Science, Durham, North California,2002.

[14].LI.Y.;"An Accelerated Ant Colony Algorithm for Complex Nonlinear System Optimization" ,Proceedings of the 2003 IEEE, International Symposium on Intelligent Control Houston, Texas. October 5-8, 2003.

[15] S. Phoomvuthisarn, S. Chusanapiputt, D. Nualhong, "Diversity control approach to ant colony optimization for unit commitment problem, "Analog and Digital Techniques in Electrical Engineering, IEEE Tencon 2004

[16] R. Annaluru, S. Das, A. Panwa, " Multi level ant colony algorithm for optimal placement of capacitors in distribution systems" Evolutionary Computation 2004, CEC 2004, congress Vol.2 ,19-23 June, pp. 1932-1937

[17] T. L. Satty, " The analytical hierarchy process: planning, priority setting, resource allocation" New York McGraw Hill1980.

[18]W.J. Getjahr , "A graph-based ant system and its convergence" Future Generation Computer System, Vol.16, No. 8,pp 873-888. June2000.

[19]T.Stutzle, H,H,Hoos," Max-Min ant system", Future Generation Computer Systems,Vol.16, Issue 8,pp 889-914 ,June 2000.

[20] J.Zhang, Q.Gao, X.Xu," A self-adaptive ant colony algorithm, control theory and applications " Vol.17,N.1,pp.1-8, 2000.