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GABC optimization algorithm for solving simultaneous transmission expansion planning and substation expansion planning

Chandrakant Rathore*

This paper presents the Gbest-guided Artificial Bee Colony (GABC) optimization technique for solving the transmission and substation expansion planning simultaneously. The motive of the proposed approach is to minimize the summation of the Transmission line Investment Cost (TIC) and the Operation Cost (OC). The OC is the combination of the fuel cost of generating units and the total wind power uncertainty cost (TWC). To reduce the power demand now-a-days more renewable energy resources are integrating in the system by the system operator. Hence, this work also adopted the wind power uncertainty factor. The DC power flow model is used to formulate the mathematical structure of Simultaneous Transmission and Substation Expansion Planning (STSEP) problem. To have more complexity on the proposed problem load uncertainties are also considered. The proposed model is tested on the modified IEEE 24-bus reliability test system. Different case studies are considered to demonstrate the effectiveness of the adopted study. Detailed analyses on the numerical results are briefly presented. The results obtained indicate that with load variations the total cost of the system has increased, as well as the selection of lines and substations have also varied.

Keywords: *DC power flow, gbest-guided artificial bee colony, transmission expansion planning, substation expansion planning, wind power*

NOMENCLATURE

a_i and b_i	cost coefficient of the i^{th} generator
c and k	scale factor and shape factor (units of wind speed)
$C_{dwi}(.)$	direct cost function of i^{th} wind farm (US $/h)
$C_{dwi}(.)$	direct cost function of i^{th} wind farm (US $/h)
$C_{pwi}(.)$ and $C_{rwi}(.)$	underestimation and overestimation cost functions of the i^{th} wind farm (US $/h)
C	is a non-negative random number
CB	set of all candidate buses
CL_{ik}	investment cost of new transmission lines between branch i-k (US $)
d_{wi}	direct cost coefficient for the i^{th} wind farm (US $/MWh)
f_{ik}	active power flow in the *i-k* branch (MW)
f_{ik}^{max}	active power flow limit on the *i-k* branch (MW)
FC	fuel cost of generating units (US $)
$f_v(v)$	Weibull probability density function

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*Research scholar, Electrical Engineering Department, S.V. National Institute of Technology, Suart - 395007, India.
E-mail: chandrakant.r@rediffmail.com, Phone: 09537667415

$F_v(v)$	cumulative distribution function
k_{pi} and k_{ri}	underestimation and over estimation cost coefficient for the i^{th} wind farm (US $/MWh)
N_g and N_w	number of generating units and wind farm
N_b	number of buses
N_{lk}	set of lines connected to *k*
n_{ik}^{o} and n_{ik}	initial number of lines and new lines added to the *i-k* branch
n_{ik}^{max}	maximum number of lines that can be added to the *i-k* branch
P_{gi}	active power generation at the i^{th} bus (MW)
P_{gi}^{min} and P_{gi}^{max}	active power generation lower and upper limit at the i^{th} bus (MW)
P_{dk}	active load at bus *k* (MW)
P_{wi}	scheduled wind power from the i^{th} wind farm (MW)
$P_{wi, av}$	available wind power from the i^{th} wind farm (MW)
P_r and P_w	rated wind power and output power of the i^{th} wind farm (MW)
v, v_{ci}, v_{co} and v_r	wind speed ,cut-in, cut-out and rated wind speed (m/s)
TC	total cost (US $)
TIC	transmission line investment cost (US $)
TWC	total wind power utilization cost (US $)
z_b	binary variable related to the candidate buses: 1 if bus *i* is selected, 0 otherwise
γ_{ik}	susceptance of a branch between buses *i-k*
θ_m and θ_n	phase angle at buses *m* and *n* (rad)
Ω	set of all candidate lines

1.0 INTRODUCTION

With an increase in electricity power consumption growth, maintaining the system reliability and fulfillment of the required load demand becomes difficult for the system operator. The utilization of renewable energy resources have increased in the present scenario, but uncertainty nature has created additional burden to the system operator. Hence, this leads to go for transmission expansion planning (TEP), generation expansion planning (GEP) and substation expansion planning (SEP) with least costs and fulfilling various operational constraints. This work comprises of the simultaneous solution of the TEP and SEP problem.

The TEP determines “what”, “where”, and “when” new transmission facilities to be installed to meet the system requirements [1].

The SEP determines the required expansion capacities of the existing substations as well as the locations and the sizes of new substations together within the required time, so that the loads may get uninterruptible power supply [2].

The TEP problem has been solved by using a linear programming method in [3] and thereafter many different optimization techniques have been implemented to solve this problem, detailed literature reviews have been presented in [4-5].

However, due to the nonlinearity nature of the optimization problems the classical methods have been unable to give the optimal solution. Hence, now-a-days heuristics and meta-heuristics techniques have been implemented to solve TEP problems.

Different problems and issues such as load uncertainty, reliability constraint, security constraint and the integration of wind farm have been studied by researches in [6-12]. In [12], authors have solved the static TEP problem considering the uncertain nature of wind power and various costs associated with it.

The SEP problem has been solved by researchers in [13, 2, and 14]. The authors in [13] have presented a novel approach for finding the optimal location and sizing of the HV/MV substations. A fuzzy-based load uncertainty model has been considered and to solve the optimization problem genetic algorithm has used. The authors in [2] have solved the SEP problem by implementation of genetic algorithm. The objective function has the cost of substations, the cost of loss, the low-line and high-line cost. A multi-stage model for solving the sub-transmission system expansion planning with placement of distributed generators using mixed integer nonlinear programming method has been presented by the authors in [14]. However, the authors in [15] have solved the simultaneous transmission and substation expansion planning problem for two modified test systems. The authors have used the mixed-integer linear programming method to minimize the investment cost and the expected operation cost.

However, the incorporation of the wind power uncertainty cost for solving the simultaneous transmission expansion planning and substation expansion planning (STSEP) problem has not studied by researchers on the TEP problem.

As it is seen from the literature that the gbest-guided artificial bee colony (GABC) optimization method has been not applied to solve the TEP problem. Hence, in this work it is considered. The GABC optimization algorithm is the modified version of the ABC algorithm [16], which also consists of three groups of artificial bees and it is inspired by the food foraging behavior of honey bees also a population-based search optimization method [17, 18]. The algorithm has been implemented for solving power system problems such as load flow [19], unit commitment [20] and economic load dispatch [21].

It is found from the literature reported till now that the transmission expansion planning and substation expansion planning problem has been solved separately considering various problems/ issues due to the complexity of simultaneous planning. Hence, it this paper the STSEP problem is examined considering uncertainties in wind power and load nature. In the proposed work the meta-heuristic optimization algorithm called GABC is implemented to solve the DC power flow based STSEP problem as in literature shows that it has fast computational capability and able to handle large complex problems. The modified IEEE 24-bus reliability test system is used for the validation of the algorithm. The results obtained are compared and analyzed.

The main contribution of this study is to address the following issues:

(1) To study the combined impact of TEP and SEP problem simultaneous.

(2) To analyze the effect of wind power uncertainty on the simultaneous transmission and substation expansion planning (STSEP) problem.

(3) To evaluate the effect of load uncertainty on the STSEP problem.

(4) To examine the performance of the GABC optimization algorithm on the proposed problem.

The rest of the paper is organized as: In section 2, the overview of GABC optimization algorithm is described. The proposed problem formulation is presented in section 3. In section 4, the system under consideration and numerical results are presented. Conclusion is discussed in section 5.

2.0 BRIEF OVERVIEW OF BASIC ABC AND GABC ALGORITHM

2.1 Introduction

Artificial Bee Colony (ABC) is one of the popular meta-heuristic algorithms, which is inspired by the collective intelligent behavior of honey bees for hunting for food. The ABC algorithm has been introduced and developed by Basturk B and Karaboga D [16]. It consists of three artificial bees groups, namely employed bees, onlooker bees and scout bees. The position of each food source signifies a probable and possible solution of the defined optimization problem. The nectar amount of the food source represents the quality or fitness of the solution.

The steps mentioned below are repeated until a termination criterion is reached.

2.1.1 Initialization of the parameters

The algorithm has few input/control parameters such as population size (Np), the number of the food source, the number of employed and onlooker bees, the number of trials after which a food source is assumed to be abandoned called as a limit, and finally the stopping criterion (maximum number of iterations).

2.1.2 Initialization of the population

After initializing the input parameters, the ABC algorithm generates arbitrarily distributed the initial population Pop of Np vectors of candidate solutions as (1),

$$\mathrm{Pop} = [\mathrm{Sol}_1, \ldots \mathrm{Sol}_i, \ldots.., \mathrm{Sol}_{Np}]^T \qquad ....(1)$$

where $\mathrm{Sol}_i = [u_{i1}, \ldots, u_{ij}, \ldots.., u_{iD}]$ represents the ith food source of D-dimensional vector, then each food source is generated as follow:

$$u_{ij} = \mathrm{lower}_{\mathrm{boundj}} + \left(\mathrm{upper}_{\mathrm{boundj}} - \mathrm{lower}_{\mathrm{boundj}}\right) \times \mathrm{rand},$$

$$\text{for } j=1 \ldots D \text{ and } i=1 \ldots Np \qquad ....(2)$$

2.1.3 Employed bees phase

At this position, each employed bee finds the new food source position Newsol_{ij} by utilizing the old position using (3)

$$\mathrm{New\ sol}_{ij} = u_{ij} + w_{ij} \times (u_{ij} - u_{kj}) \qquad ....(3)$$

where w_{ij} is a random number between [-1, 1], and k ϵ {1, 2…, Np} and j ϵ {1, 2…, D} are randomly chosen indexes. After the selection of a new position, the nectar amount is compared between the new and old position; if the new position is found better than the old position, the new position is retained, otherwise it is discarded. The greedy selection method is used for the choice of the best and the worst.

2.1.4 Onlooker bees phase

The onlooker bees select a food source according to the probability calculated by (4) associated with that food source.

$$\mathrm{probability}_i = \frac{\mathrm{fitness}_i}{\sum_{j=1}^{Np} \mathrm{fitness}_j} \qquad ....(4)$$

where $\mathrm{fitness}_i$ is the fitness value of ith solution, and Np is the number of the food source. Similar to the employed bees phase, the onlooker bees also modify their position using (3) and repeat the same.

2.1.5 Scout bees phase

If a location source of food cannot be enhanced further through a specified number of trials, then the food source is assumed to be abandoned. The value of the predetermined number of trials is an important control parameter of algorithm ABC, which is called a limit for the abandonment. Assume that the abandoned source is u_{ij} and j ϵ {1, 2…, D}, then the new food source found by the scout bees to be replaced by the abandoned position by using (5),

$$u_{ij} = u_{j\min} + \mathrm{rand}[0,1] \times (u_{j\max} - u_{j\min}) \qquad ....(5)$$

For each candidate source position Newsol_{ij} is produced and estimated by the artificial bee, its quality is compared with its old position. If the new position is found better than the old position, it replaces the old position and if not the old position is retained in memory. In the complete process it is considered that at each cycle at maximum only one scout bee goes outside for hunting a new food source.

2.2 Gbest Artificial Bee Colony Algorithm (GABC)

In ABC algorithm, the solution a search equation described as in (3), and the probability of getting a random solution for the best and the worst solution are same. Also, (3) has good exploration, but poor exploitation. In order to achieve good optimization, performance the exploration and exploitation abilities should be equally balanced. Therefore, to achieve this (3) is modified to improve the exploitation as follows [18]

$$\text{New sol}_{ij} = u_{ij} + w_{ij}\left(u_{ij} - u_{kj}\right) + \psi_{ij}(y_j - u_{ij}) \qquad \text{....(6)}$$

where the term added in (3) is gbest term, y_j is the j^{th} element of the global best solution, and ψ_{ij} is a uniform random number in [0, C], where C is a non-negative constant. By adding this term the exploitation ability of ABC algorithm is increased, and the modified ABC algorithm has named as gbest-guided ABC (GABC) algorithm. The value of C plays an important role in improving the exploitation, and the higher value provides better exploitation capability.

3.0 PROPOSED PROBLEM FORMULATION

The objective of the STSEP problem is to minimize the total cost. The assumptions made for the proposed problem are:

1. A lossless DC power flow is adopted to model the STSEP problem.
2. The wind farm is installed at the load bus.
3. The operating and investment costs of the substations are not considered.

3.1 The proposed STNEP Model

The objective of the proposed STSEP problem is to minimize the summation of the transmission line investment cost (TIC) and the operation cost (OC) subjected to various economic and technical constraints. The operation cost consists of the fuel cost of generation units and the total wind power utilization cost. The total cost (TC) is formulated as follows:

Minimize Total cost (TC),

$$TC = \sum_{i,k\in\Omega} C_{Lik}\left(n_{ik}\right) + \left\{ 12\times 8760\times \left[\sum_{i}^{N_g}\left(a_i + b_i P_{gi}\right) + \sum_{i}^{N_w}\left(\begin{array}{l} C_{wdi}\left(P_{wi}\right) + C_{pwi}\left(P_{wi,av} - P_{wi}\right) + \\ C_{rwi}\left(P_{wi} - P_{wi,av}\right) \end{array} \right) \right] \right\} \qquad \text{....(7)}$$

The terms in (7) are explained as follows:

The transmission line investment cost (TIC) is the traditional TEP cost model which has been used widely in [22-25]. The fuel cost of the generating units is represented by the quadratic function which is given by [26, 15]. The total wind power utilization cost (TWC) [20, 21, 12, 27], which is the summation of the direct cost C_{wdi} (P_{wi}), the underestimation cost (penalty cost) C_{pwi} ($P_{wi,av}$-P_{wi}) and the overestimation cost C_{rwi} (P_{wi}-P_{wiav}) (reserve cost) component. These cost components are calculated by using (8), (9) and (10) as below:

$$C_{wdi}\left(P_{wi}\right) = d_{wi} P_{wi} \qquad \text{....(8)}$$

$$C_{pwi}\left(P_{wi,av} - P_{wi}\right) = k_{pi}\left(P_{wi,av} - P_{wi}\right) \qquad \text{....(9)}$$

$$C_{rwi}\left(P_{wi} - P_{wi,av}\right) = k_{ri}\left(P_{wi} - P_{wi,av}\right) \qquad \text{....(10)}$$

Subject to the following equality and inequality constraints: These constraints are organized as

1. *Power balance constraint:* The power supplied by the thermal generators and wind farm must satisfy the load for that period,

$$\sum_{\forall i\in N_{lk}} f_i - \sum_{\forall i\in N_g} P_{gi} - \sum_{\forall i\in N_w} P_{wi} = P_{dk} \quad k = 1,\ldots,N_b \qquad \text{....(11)}$$

2. *Maximum power flow limits:* In order to maintain system stability, the line loading should be less than its thermal limit.

$$\sum_{\forall i\in N_{lk}} \left|f_i\right| \le \left(n_i^o + n_i\right) f_i^{max} \qquad \text{....(12)}$$

In the DC power flow model, power flow between branches in (12) is calculated by using (13),

$$f_{ik} = \gamma_{ik}\left(n_{ik}^{o} + n_{ik}\right)\left(\theta_m - \theta_n\right),\ m \neq n,\ \forall m, n \in N_b \quad ....(13)$$

3. *Power generation limits:* Each power generating source has generation range represented as,

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad ....(14)$$

$$0 \leq P_{wi} \leq P_{wri} \quad ....(15)$$

4. *Line expansion limits:* The expansion of new parallel lines should be within the range specified as

$$0 \leq n_{ik} \leq n_{ik}^{max} \quad ....(16)$$

5. *Candidate line selection:* This means that if a candidate line is selected, the candidate bus/buses connected to that line must be chosen as well.

$$z_b \geq n_{i,k} \quad i, k \forall \Omega,\ b \in CB \quad ....(17)$$

3.2 Wind speed and turbine generator model

Wind energy is highly sensitive to the wind speed and due to the unpredictable nature of wind, and many related models are studied. However, it is seen from the previous literature that [28] the Weibull distribution is commonly used to represent the wind speed characteristics. Therefore, in this paper also the Weibull probability density function (PDF) is used. The Weibull probability density function and the cumulative distribution function (CDF) are calculated by (18) and (19) respectively.

$$f_V(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp^{-\left(\frac{v}{c}\right)^{k}}, 0 < v < \infty \quad ....(18)$$

$$F_V(v) = \int_0^v f_V(\tau)\, d\tau = 1 - \exp^{-\left(\frac{v}{c}\right)^{k}} \quad ....(19)$$

Once the intermittent nature of the wind is considered as an arbitrary variable, the output power of the wind energy conversion system (WECS) may also be considered as a random variable. The output of the WECS [27] with different wind speeds is stated as:

$$P_w = 0,\ \text{for } v < v_{ci} \text{ and } v > v_{co} \quad ....(20)$$

$$P_w = P_r\left(\frac{v - v_{ci}}{v_r - v_{ci}}\right),\ \text{for } v_{ci} \leq v \leq v_r \quad ....(21)$$

$$P_w = P_r,\ \text{for } v_r \leq v \leq v_{co} \quad ....(22)$$

3.3 Implementation of the GABC algorithm to the STSEP problem

This part gives the brief information about the implementation optimization techniques to solve the proposed STSEP problem. The main steps to be followed are:

1. Read all the network data and the algorithm control parameters.
2. Create the random initial population vector of possible optimal solution using (1) according to the case study under consideration.
3. The GABC optimization algorithm iterates over the employed bees, onlooker bees and scout bees phase until the termination criterion is reached.
4. Run DC load flow for every change in food source position by simultaneously checking for the system constraints using (11)-(17). The penalty factor method is used to handle the system constraints.

4.0 RESULTS

4.1 System under study

The STSEP problem is solved in MATLAB™ environment by applying GABC optimization techniques. The modified IEEE 24-bus system is adopted for this work. The original IEEE 24-bus network data are taken from [29]. The generator cost characteristic and the new candidate data are extracted from [26, 15]. It is considered that the maximum number of one new parallel line may be installed in operative for 12 years. Bus 1 is the slack bus for all cases.

The modified IEEE 24-bus test system is laid out in Figure 1. It consists of 10 generating units, 17 loads and 38 lines including two voltage levels: 138 kV and 230 kV. The original IEEE 24-bus network data is taken from [29]. There are five new candidate buses and 26 new candidate lines for this study.

Three new load centers at buses 25, 26 and 27 and also one new generating unit at bus 27 is considered over the planning period [15]. The new candidate lines and buses are represented in Figure 1 by red dashed lines. The generator cost characteristic is extracted from [26]. The candidate line data are displayed in the Table 1.

It is considered that the maximum number of one new parallel line may be installed in each possible expansion path. It is considered that the constructed lines are operative for 12 years.

In this work, the wind farm is installed at bus number 4 [10]. The maximum wind power penetration of 300 MW is considered. The details of wind generator parameters used are taken from [30].

The following control parameters are selected for the best solution of GABC algorithm: population size (colony size) Np = 50, Onlooker bees = 750, the limit = 4, C = 1.5 and the maximum number of iterations = 500. To achieve the best result, 20 trails have been taken with these control parameters.

4.2. Results

The proposed work is illustrated through four different cases. These cases are elaborated as:

- The STSEP problem is solved in case-1.
- With the integration of wind farm the problem is solved in case-2.
- In case-3 and case-4, the problem is solved under ± 10% and ± 5% load uncertainty factor.

The comprehensive results for all the cases are described below:

Case-1: In this case, the result obtained with the GABC optimization algorithm has the transmission line investment cost (TIC) of 801.740 million US $, the fuel cost (FC) of generating units is 10,652.728 million US $ and the total cost (TC) is 11,454.468 million US $ with additions of 25 new lines to the base network. The candidate lines selected are: CL_5, CL_7, CL_8, CL_9, CL_{10}, CL_{12}, CL_{13}, CL_{14}, CL_{15}, CL_{16}, CL_{17}, CL_{18}, CL_{21},CL_{25}, CL_{36}, CL_{37}, CL_{39}, CL_{40}, CL_{42},CL_{47}, CL48, CL_{49}, CL_{52}, CL_{56}, CL_{58} and candidate buses 30 and 31 are chosen as the optimal plan.

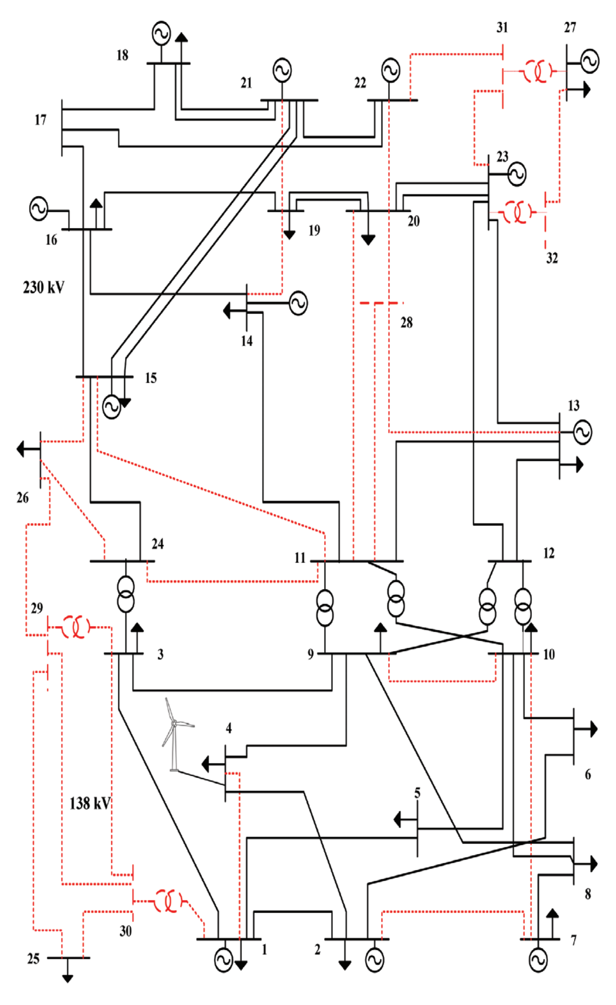

FIG. 1 THE MODIFIED IEEE 24-BUS RELIABILITY TEST SYSTEM

TABLE 1

CANDIDATE LINES DATA

Candidate lines	**From**	**To**	**r (p.u)**	**x (p.u)**	**b (p.u)**	**Maximum line limit**	**Capacity (MW)**	**Investment cost (million US $)**
CL$_1$	1	2	0.0026	0.0139	71.9424	1	175	3
CL$_2$	1	3	0.0546	0.2112	4.7348	1	175	55
CL$_3$	1	5	0.0218	0.0845	11.8343	1	175	22
CL$_4$	2	4	0.0328	0.1267	7.8927	1	175	33
CL$_5$	2	6	0.0497	0.192	5.2083	1	175	50
CL$_6$	3	9	0.0308	0.119	8.4034	1	175	31
CL$_7$	3	24	0.0023	0.0839	11.9190	1	400	50
CL$_8$	4	9	0.0268	0.1037	9.6432	1	175	27
CL$_9$	5	10	0.0228	0.0883	11.3250	1	175	23
CL$_{10}$	6	10	0.0139	0.0605	16.5289	1	175	16
CL$_{11}$	7	8	0.0159	0.0614	16.2866	1	175	16
CL$_{12}$	8	9	0.0427	0.1651	6.0569	1	175	43
CL$_{13}$	8	10	0.0427	0.1651	6.0569	1	175	43
CL$_{14}$	9	11	0.0023	0.0839	11.9190	1	400	50
CL$_{15}$	9	12	0.0023	0.0839	11.9190	1	400	50
CL$_{16}$	10	11	0.0023	0.0839	11.9190	1	400	50
CL$_{17}$	10	12	0.0023	0.0839	11.9190	1	400	50
CL$_{18}$	11	13	0.0061	0.0476	21.0084	1	500	66
CL$_{19}$	11	14	0.0054	0.0418	23.9234	1	500	58
CL$_{20}$	12	13	0.0061	0.0476	21.0084	1	500	66
CL$_{21}$	12	23	0.0124	0.0966	10.3520	1	500	134
CL$_{22}$	13	23	0.0111	0.0865	11.5607	1	500	120
CL$_{23}$	14	16	0.005	0.0389	25.7069	1	500	54
CL$_{24}$	15	16	0.0022	0.0173	57.8035	1	500	24
CL$_{25}$	15	21	0.0063	0.049	20.4082	1	500	68
CL$_{26}$	15	24	0.0067	0.0519	19.2678	1	500	72
CL$_{27}$	16	17	0.0033	0.0259	38.6100	1	500	36
CL$_{28}$	16	19	0.003	0.0231	43.2900	1	500	32
CL$_{29}$	17	18	0.0018	0.0144	69.4444	1	500	20
CL$_{30}$	17	22	0.0135	0.1053	9.4967	1	500	146
CL$_{31}$	18	21	0.0033	0.0259	38.6100	1	500	36
CL$_{32}$	19	20	0.0051	0.0396	25.2525	1	500	55
CL$_{33}$	20	23	0.0028	0.0216	46.2963	1	500	30
CL$_{34}$	21	22	0.0087	0.0678	14.7493	1	500	94
CL$_{35}$	1	4	0.0006	0.015	66.6667	1	175	7.72
CL$_{36}$	1	30	0.00336	0.084	11.9048	1	400	3.12
CL$_{37}$	2	7	0.00084	0.021	47.6190	1	175	10.82

CL_{38}	3	29	0.00336	0.084	11.9048	1	400	3.12
CL_{39}	3	30	0.00068	0.017	58.8235	1	500	8.76
CL_{40}	7	10	0.0008	0.02	50.0000	1	175	10.29
CL_{41}	9	10	0.00064	0.016	62.5000	1	175	8.24
CL_{42}	11	15	0.00088	0.022	45.4545	1	500	11.13
CL_{43}	11	24	0.00044	0.011	90.9091	1	500	5.66
CL_{44}	11	28	0.00096	0.024	41.6667	1	500	12.35
CL_{45}	13	28	0.00044	0.011	90.9091	1	500	5.66
CL_{46}	14	19	0.00068	0.017	58.8235	1	500	8.76
CL_{47}	15	26	0.00068	0.017	58.8235	1	500	8.76
CL_{48}	19	21	0.00056	0.014	71.4286	1	500	7.21
CL_{49}	20	22	0.00056	0.014	71.4286	1	500	7.21
CL_{50}	20	28	0.00044	0.011	90.9091	1	500	5.66
CL_{51}	22	31	0.00044	0.011	90.9091	1	500	5.66
CL_{52}	23	31	0.00044	0.011	90.9091	1	500	5.66
CL_{53}	23	32	0.00336	0.084	11.9048	1	400	3.12
CL_{54}	24	26	0.00044	0.011	90.9091	1	500	5.66
CL_{55}	25	29	0.00068	0.017	58.8235	1	500	8.76
CL_{56}	25	30	0.00044	0.011	90.9091	1	500	5.66
CL_{57}	26	29	0.00056	0.014	71.4286	1	500	7.21
CL_{58}	27	31	0.00336	0.084	11.9048	1	400	3.12
CL_{59}	27	32	0.00056	0.014	71.4286	1	500	7.21
CL_{60}	29	30	0.00068	0.017	58.8235	1	500	8.76

Case-2: The result obtained has TIC of 851.920 million US \$, FC is 10,077.863 million US \$, the total wind power utilization cost (TWC) is 174.694 million US \$ and TC is 11,104.477 million US \$ with additions of 26 new lines to the base network. The candidate lines selected are: CL_3, CL_5, CL_7, CL_8, CL_9, CL_{10}, CL_{11}, CL_{12}, CL_{13}, CL_{15}, CL_{16}, CL_{17}, CL_{18}, CL_{21}, CL_{25}, CL_{26}, CL_{35}, CL_{39}, CL_{41}, CL_{42}, CL_{47}, CL_{49}, CL_{51}, CL_{54}, CL_{56}, CL_{58} and candidate buses 30 and 31 are chosen as the optimal plan. The total cost convergence curves for case-1 and case-2 are shown in Figure 2. It is noted that for both the cases the GABC optimization technique gives better results in less number of iterations. The results obtained with statistical analysis are displayed in the Table 2. It is observed from this table that the total cost obtained by the GABC technique found 3%, 5% reduction in the total cost and the fuel cost compared with case-1.

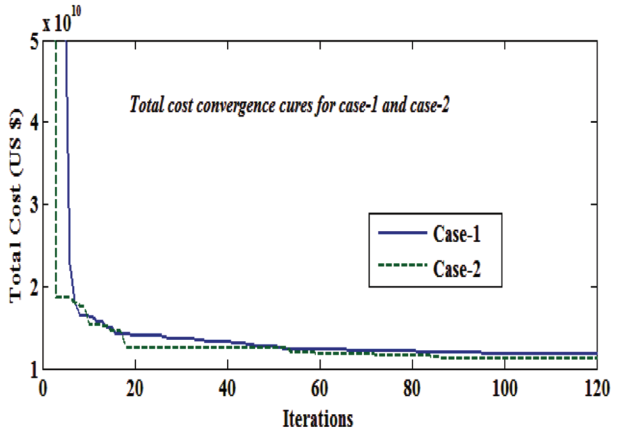

FIG. 2 TOTAL COST CONVERGENCE CURVES FOR CASE-1 AND CASE-2

Case-3: In this case, the STSEP problem is analyzed with considering ±10% load uncertainly and the wind power uncertainty. The results are examined at maximum load condition (3(a)), minimum load condition (3(b)) and the load at minimum total cost (3(c)).

3(a): The result obtained with the GABC optimization algorithm at maximum load has TIC of 715.170 million US $, FC is 14,854.950 million US $, TWC is 174.716 million US $ and TC is 15,744.837 million US $ with additions of 22 new lines to the base network. The candidate lines selected are: CL_3, CL_8, CL_9, CL_{10}, CL_{11}, CL_{13}, CL_{15}, CL_{16}, CL_{17}, CL_{18}, CL_{21}, CL_{23}, CL_{26}, CL_{27}, CL_{41}, CL_{47}, CL_{48}, CL_{49}, CL_{52}, CL_{55}, CL_{57}, CL_{58} and candidate buses 29 and 31 are chosen as the optimal plan. The total load demand is 10135.910 MW.

TABLE 2

SUMMARY OF THE RESULTS FOR CASES 1 AND 2

Results	Case-1	Case-2
TIC, million US $	801.740	851.920
FC, million US $	10,652.728	10,077.863
TWC, million US $	0	174.694
TC, million US $	11,454.468	11,104.477
Average	12,117,263,850.897	11,629,741,599.952
Worst	13,156,809,227.687	12,568,513,505.965
Std	617,366,965.548	499,395,675.689
Total new lines connected	25	26
Candidate buses selected	30 and 31	30 and 31

3(b): The GABC optimization algorithm found TIC of 1,016.280 million US $, FC is 12,056.920 million US $, TWC is 77.154 million US $ and TC is 13,150.354 million US $ with additions of 35 new lines to the base network. The candidate lines selected are: CL_2, CL_5, CL_6, CL_{10}, CL_{12}, CL_{13}, CL_{14}, CL_{16}, CL_{17}, CL_{18}, CL_{24}, CL_{25}, CL_{26}, CL_{28}, CL_{30}, CL_{32}, CL_{33}, CL_{37}, CL_{38}, CL_{40}, CL_{41}, CL_{42}, CL_{44}, CL_{46}, CL_{47}, CL_{48}, CL_{49}, CL_{50}, CL_{51}, CL_{52}, CL_{54}, CL_{55}, CL_{56}, CL_{57}, CL_{58} and candidate buses 28, 29, 30 and 31are chosen as the optimal plan. The total load demand is 8625.798 MW.

3(c): The results found has TIC of 108.196 million US $, FC is 11,379.277 million US $, TWC is 17.255 million US $ and TC is 12,633.787 million US $ with additions of 30 new lines to the base network. The candidate lines selected are: CL_2, CL_3, CL_5, CL_6, CL_8, CL_{10}, CL_{12}, CL_{13}, CL_{14}, CL_{15}, CL_{16}, CL_{17}, CL_{18}, CL_{20}, CL_{21}, CL_{22}, CL_{23}, CL_{26}, CL_{36}, CL_{37}, CL_{40}, CL_{41}, CL_{48}, CL_{49}, CL_{51}, CL_{54}, CL_{56}, CL_{57}, CL_{58}, CL_{60} and candidate buses 28, 30 and 31 are chosen as the optimal plan. The total load demand is 9810.649 MW.

The total cost convergence curves for case-3 are shown in Figure 3. This curve indicates that the GABC algorithm is able handle the complexity of the proposed problem. The overall summary results for case-3 are mentioned in the Table 3. It is noted from this table that with variations in load profile the total cost as well as the selection of the candidate lines and buses also gets changed.

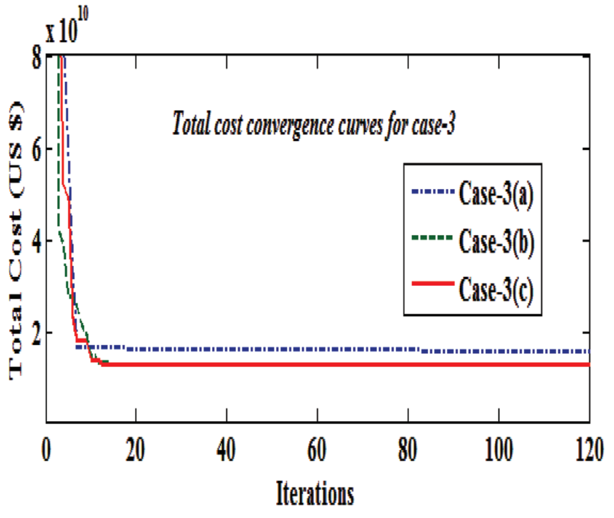

FIG. 3 TOTAL COST CONVERGENCE CURVES FOR CASE-3

Case-4: In this case, the STSEP problem is analyzed with considering ±5% load uncertainly and the wind power uncertainty. The results are evaluated at maximum load condition (4(a)), minimum load condition (4(b)) and the load at minimum total cost (4(c)).

TABLE 3

SUMMARY OF THE RESULTS FOR CASE-3 CONSIDERING ±10% LOAD UNCERTAINTY

Results	**3(a)**	**3(b)**	**3(c)**
	Maximum load (10135.910 MW)	**Minimum load (8624.960 MW)**	**Load at minimum total cost (9810.649 MW)**
TIC, million US $	715.170	1,016.280	1,081.960
FC, million US $	14,854.950	12,056.920	11,379.277
TWC, million US $	174.716	77.154	172.550
TC, million US $	15,744.837	13,150.354	12,633.787
Total new lines conn-ected	22	35	30
Candi-date buses selected	29 and 31	28, 29, 30 and 31	28, 30 and 31

4(a): The result obtained with the GABC optimization algorithm at maximum load has TIC of 1,050.890 million US $, FC is 11,849.724 million US $, TWC is 174.720 million US $ and TC is 13,075.334 million US $ with additions of 28 new lines to the base network. The candidate lines selected are: CL$_{2}$, CL$_{4}$, CL$_{5}$, CL$_{6}$, CL$_{9}$, CL$_{10}$, CL$_{12}$, CL$_{13}$, CL$_{14}$, CL$_{15}$, CL$_{16}$, CL$_{17}$, CL$_{18}$, CL$_{20}$, CL$_{21}$, CL$_{22}$, CL$_{25}$, CL$_{28}$, CL$_{35}$, CL$_{42}$, CL$_{43}$, CL$_{47}$, CL$_{49}$, CL$_{51}$, CL$_{54}$, CL$_{55}$, CL$_{57}$, CL$_{58}$ and candidate buses 29 and 31 are chosen as the optimal plan. The total load demand is 9769.200 MW.

4(b): The result obtained has TIC of 912.370 million US $, FC is 12,426.893 million US $, TWC is 135.710 million US $ and TC is 13,474.973 million US $ with additions of 29 new lines to the base network. The candidate lines selected are: CL$_{1}$, CL$_{2}$, CL$_{3}$, CL$_{5}$, CL$_{6}$, CL$_{9}$, CL$_{10}$, CL$_{12}$, CL$_{13}$, CL$_{14}$, CL$_{15}$, CL$_{16}$, CL$_{18}$, CL$_{20}$, CL$_{21}$, CL$_{23}$, CL$_{27}$, CL$_{29}$, CL$_{33}$, CL$_{35}$, CL$_{39}$, CL$_{41}$, CL$_{42}$, CL$_{48}$, CL$_{51}$, CL$_{54}$, CL$_{56}$, CL$_{57}$, CL$_{58}$ and candidate buses 29,30 and 31 are chosen as the optimal plan. The total load demand is 8925.460 MW.

4(c): The optimization algorithm obtained TIC of 826.850 million US$, FC is 1, 113. 008 million US $, TWC is 172.560 million US$ and TC is 12,137.418 million US $ with additions of 23 new lines to the base network. The candidate lines selected are: CL$_{2}$, CL$_{3}$, CL$_{5}$, CL$_{7}$, CL$_{8}$, CL$_{10}$, CL$_{12}$, CL$_{13}$, CL$_{15}$, CL$_{16}$, CL$_{17}$, CL$_{18}$, CL$_{21}$, CL$_{23}$, CL$_{26}$, CL$_{36}$, CL$_{48}$, CL$_{49}$, CL$_{51}$, CL$_{54}$, CL$_{56}$, CL$_{57}$, CL$_{58}$ and candidate buses 29, 30 and 31 are chosen as the optimal plan. The total load demand is 9717.801 MW. The total cost convergence curves for case-4 are shown in Figure 4. The overall summary results for case-4 are mentioned in the Table 4. Similar kind of response is found here also as in case-3.

TABLE 4

SUMMARY OF THE RESULTS FOR CASE-4 CONSIDERING ±5% LOAD UNCERTAINTY

Results	**4(a)**	**4(b)**	**4(c)**
	Maximum load (9769.200 MW)	**Minimum load (8925.460 MW)**	**Load at minimum total cost (9717.801 MW)**
TIC, million US $	1,050.890	912.370	826.850
FC, million US $	11,849.724	12,426.893	11,138.008
TWC, million US $	174.720	135.710	172.560
TC, million US $	13,075.334	13,474.973	12,137.418
Total new lines connected	28	29	23
Candidate buses selected	29 and 31	29, 30 and 31	29, 30 and 31

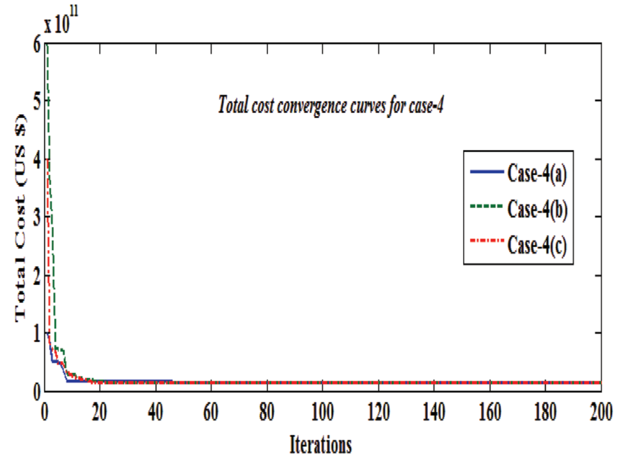

FIG. 4 TOTAL COST CONVERGENCE CURVES FOR CASE-4

5.0 CONCLUSION

A mathematical structure is formulated for solving the transmission expansion planning and substation expansion planning. It is tested on the modified IEEE 24-bus reliability test system. The consideration of load uncertainties as well as the wind power uncertainty is the main contribution of the paper. The important points concluded from all the cases studied are following:

1. With the integration of wind farm the total load demand is shared between it and other generating units this leads to the reduction in the total cost and the fuel cost of the system.
2. The total cost has increased with the variations in load nature.
3. The optimal solution found by the GABC optimization technique is analyzed and it is noted that the GABC algorithm finds better solution in less number of iterations. Hence, this proves the efficiency of the GABC technique for handling large complex problems.

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