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Implementation of the pumped-storage unit on static transmission network expansion planning problem considering emission

Chandrakant Rathore*

This paper presents the impact of the pumped-storage (PS) unit on the static transmission network expansion planning problem (STNEP). The aim of this work is to minimize the total cost and emission produced by the CO_2. The total cost is the summation of the transmission line cost and the fuel cost of the generating units. In growing power industry the generation sources are the main equipment, as there are various types of the generating sources. Their selections are done to achieve a more eco-friendly and economical. Hence, the impact of emissions on the STNEP needs to be analyzed. The proposed problem is tested on the IEEE 24-bus system and the gbest-guided artificial bee colony (GABC) optimization algorithm is applied to this problem. The results obtained indicate that the PS unit is effective to reduce the total cost and CO_2 emission level.

Keywords: *Artificial bee colony optimization, DC power flow, investment cost, pumped-storage, transmission expansion planning.*

NOMENCLATURE

a_i, b_i, c_i are the fuel cost coefficients
CL_{ik} is construction of line in US $
$E_{emission}$ represents the total emission produced by generators
$Emission_i$ represents the emission produced by i^{th} generating unit
F represents the objective function
FC is fuel cost in US $/h
f is the vector with elements f_{ik} (power flows)
f_{ik}^{max} is the line flow limit
n_{ik}^{o}, n_{ik}^{max} and n_{ik} are the number of existing circuits, maximum number of added circuits in branch, the total integer number of circuits added to the branch i-k
N_g and N_b represents set of all generators and number of bus
P_d is the corresponding demands
P_{gi}, P_{gi}^{max} and P_{gi}^{min} represents the real power generation at bus i, the maximum and lower limit of generation capacity at bus i
$P_{p,g}$ is the vector of generation at each node
$P_{p,g,i}$ $P_{p,g,i}^{\min}$ and $P_{p,g,i}^{\max}$ represents the power generation by the PS unit at bus i, the lower and maximum limit of generation capacity of the PS unit at bus i
$Q_{p,i}$ is the water flow by the PS unit at bus i
TC is total cost in US $
TLC is transmission line cost in US $
N_g represents the number of generating units
$Q_{p,g,i}$, $Q_{p,g,i}^{\min}$ and $Q_{p,g,i}^{\max}$ represents the water discharge by the PS unit at bus i, the lower and maximum limit of water discharge of the PS unit at bus i

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

$V_{p,u,i}$, $V_{p,u,i}^{\min}$ and $V_{p,u,i}^{\max}$ represents the volume of the water storage at upper reservoir of the PS unit at bus *i*, the lower and maximum limit of volume of the water storage at upper reservoir of the PS unit at bus *i*
$V_{p,l,i}$, $V_{p,l,i}^{\min}$ and $V_{p,l,i}^{\max}$ represents the volume of the water storage at lower reservoir of the PS unit at bus *i*, the lower and maximum limit of volume of the water storage at lower reservoir of the PS unit at bus *i*
$V_{p,u,o}$ and $V_{p,l,o}$ represents the initial volume of the water storage at upper reservoir and lower reservoir of the PS unit at bus *i*,
$V_{p,u,i}$, and $V_{p,l,i}$ represents the volume of the water storage at upper reservoir and lower reservoir of the PS unit at bus *i*,
θ_i and θ_k are the voltage angle at *i* and *k* buses
γ_{ik} is the susceptance between buses *i* and *k*
Ω represents set of all right-of-way paths for candidate's network expansion,

1.0 INTRODUCTION

Increasing in the electric power generation means utilization of more fossil-fuels, as at present maximum power generations are done using coal. This fossil-fuel produces dangerous gases such as CO_2, NO_2 and SO_2. The minimization of these gases is by utilizing more renewable power resources like solar, wind, hydro and hydro-pumped storage in power generation. However, these renewable energy sources are uncertain in nature, but due to their less economy and eco-friendly now-a-days their utilization has been increased. Hence, it is required to study the impacts of these resources on the transmission network expansion planning (TNEP) problem. In the existing literature maximum work has been carried with wind farm integration [1] and a little work has been done with the hydropower incorporation on the TNEP problems [2].

The transmission network expansion planning (TNEP) problem determines 'when', 'where' and 'which' type of new transmission facilities are required in the power system. It also ensures that there are no overload paths while building the new lines during the specified planning period [3]. TNEP is categorized as the static TNEP and dynamic TNEP problems. The static TNEP is a single period planning problem, however, the dynamic TNEP is multi-period planning problem.

Garver is the first who has applied linear programming method [3] to solve the TNEP problem. Thereafter, various optimization techniques [4-16] have been applied to the static and the dynamic TNEP problems.

From the literature review, it has been found that only few researchers have worked on the TNEP problem considering emission of CO_2 [17, 18]. In [17], the impact of CO_2 emission on the TNEP problem has been presented. In addition to that they have proposed two different models of CO_2 emission cost, and the objective is to minimize the sum of annual generator operating cost and annualized transmission investment cost. In [18], the TNEP problem has been considering the environmental issue. The objective is to minimize the transmission line investment cost and emission produced by CO_2.

The implementation of the PS unit to solve the unit commitment (UC) problem has been widely studied in [19-21]. In [19], the UC problem has been solved considering the PS unit to minimize the emission and the fuel cost of the thermal generating units. In [20], the hydrothermal UC problem has been solved considering two PS units to minimize the sum of the fuel cost and the start-up cost. The UC problem has been solved considering two PS hydro electricity plants to minimize the sum of the fuel cost, the start-up cost and the shutdown cost in [21].

However, the impact of the pumped-storage (PS) unit has been not reported on the TNEP problem study yet. Hence, there is a need to study the impact of the PS unit on the TNEP problem.

The gbest-guided artificial bee colony (GABC) optimization algorithm [22-23], which is inspired by food foraging behavior of honey bees-based search procedure is used to solve the proposed STNEP problem.

The main contributions of this paper are as follows:

1. To study the impact of the PS unit on the STNEP problem.
2. To analysis the impact of CO_2 emission on the STNEP problem.
3. Implementation of the GABC optimization algorithm for the STNEP problem.
4. To study the impact of the PS unit on the total cost and emission level of the CO_2.

The rest of the paper is organized as follows: section 2 describes the mathematical model for STNEP; section 3 presents an overview of gbest-guided artificial bee colony (GABC) algorithm and its implementation on STNEP problem; section 4 presents the results obtained; discussion on the results are elaborated in section 5; the conclusion is discussed in section 6.

2.0 MATHEMATICAL MODEL FOR THE PROPOSED TNEP PROBLEM

2.1 Static TNEP model

The objective function of the STNEP problem is to minimize to the total cost and the emission level of CO_2. The DC power flow model is used as follows [3-16, 24],

Minimize

$$F = W_i \times (TLC + FC) + W_e \times E_{emission} \quad ....(1)$$

The terms in (1) are explained as follows:

The term TLC in the proposed objective function (1) is the traditional STNEP cost model i.e. cost of new transmission line [3-16] and is given as

$$TLC = \sum_{i,k\hat{I}\Omega} C_{Lik}(n_{ik}) \quad ....(2)$$

The term FC is the fuel cost of the generating units and it is represented by the quadratic function [25] which is given by:

$$FC = \sum_{i}^{N_g} a_i + b_i P_{gi} + c_i (P_{gi})^2 \quad ....(3)$$

The term $E_{emission}$ gives the emission produced by the generators and it is calculated [17] by using (4)

$$E_{emission} = \sum_{i}^{N_g} Emission_i \times P_{gi} \quad ....(4)$$

where, W_i and W_e the weighing factor and their values are selected as $W_i + W_e = 1$ Subjected to

$$f - P_g - P_{p,g} = P_d \quad ....(5)$$

$$f_{ik} - \gamma_{ik}(n_{ik}^o + n_{ik})(\theta_i - \theta_k) = 0 \quad ....(6)$$

$$|f_{ik}| \le (n_{ik}^o + n_{ik}) f_{ik}^{max} \quad ....(7)$$

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad ....(8)$$

$$0 \le n_{ik} \le n_{ik}^{max} \quad ....(9)$$

$$P_{p,g,i}^{min} \le P_{p,g,i} \le P_{p,g,i}^{max} \quad ....(10)$$

$$Q_{p,g,i}^{min} \le Q_{p,g,i} \le Q_{p,g,i}^{max} \quad ....(11)$$

$$V_{p,u,i}^{min} \le V_{p,u,i} \le V_{p,u,i}^{max} \quad ....(12)$$

$$V_{p,l,i}^{min} \le V_{p,l,i} \le V_{p,l,i}^{max} \quad ....(13)$$

$$V_{p,u,i} = V_{p,u,0} - Q_{p,i} \quad ....(14)$$

$$V_{p,l,i} = V_{p,l,0} + Q_{p,i} \quad ....(15)$$

Equation (5) represents the power balance constraint, (7) represents the power flow limit for each branch which is calculated by using (6). Equation (8) represents the power generation limit of thermal generating units, (9) represents the link expansion limit, (10) represents the power generation limit of the PS unit, (11) gives the water flow limit constraint, (12) and (13) gives the upper and lower water storage level limits of a reservoir. Equations (14) and (15) represent the water balance between the upper and lower reservoir.

3.0 OVERVIEW OF GABC OPTIMIZATION ALGORITHM

There are various numbers of nature-inspired algorithms that have been applied for solving the optimization problems. Gbest-guided artificial bee colony (GABC) algorithm is one of them, which is based on intelligent behavior of honey bee swarm. In [26], the authors have proposed ABC algorithm consists of three groups of bees namely employed bees, onlooker bees, and scout bees. The position of a food source signifies a possible solution of the optimization problem.

3.1 Pseudo-code of the GABC algorithm to solve STNEP problem

The steps to be followed to solve STNEP problem using GABC optimization algorithms are as:

Step-1: Initialize the algorithm control parameters and read the systems data.

Step-2: Generate the initial population vector

An initial population $Pop = [X_1, \ldots X_i, \ldots, X_{Us}]^T$ of Us food source positions is generated randomly in the multi-dimensional search space where Ns represent the size of the population and $X_1, X_2, \ldots, X_i, \ldots X_{Us}$ are candidate solutions. Each possible solution vector is given by

$$X_i = \left[Tl_{i1}, Tl_{i2}, \ldots, Tl_{iL}, P_{g,i1}, P_{g,i2}, \ldots, P_{g,iG} \right]$$

(i = 1, 2, 3,….,Us), L and G indexes represents the possible candidate lines and the number of generating units.

All this decision variables represented by X_i are distributed uniformly between their minimum limit and maximum limit.

Step-3: Evolution

The fitness of each possible food source position is analyzed by calculation the objective function value.

Step-4: Set iteration count (m) =1

Step-5: For each employed bee

5.1: Calculate the new candidate food source position using (16). If the new position created value exceeds its ranges, the decision variable is set within its range value.

$$z_{ij} = x_{ij} + \Phi_{ij}\left(x_{ij} - x_{ki}\right) + \beta_{ij}\left(y_i - x_{ij}\right) \quad \text{....(16)}$$

where the term β_{ij} is gbest term and is a uniform random number in [0, C]. C is a non-negative constant. Φ_{ij} is a random number between [-1, 1], $k \in \{1, 2 \ldots U_s\}$ and $j \in \{1, 2 \ldots D\}$ are randomly chosen indexes.

5.2: Determine the fitness value using (1) and simultaneous run DC load flow.

5.3: Check the system constraints using (5) to (15), apply the penalty factor method to handle constraints.

5.4: Apply greedy selection mechanism for choosing between the best solution and the worst solution.

5.5: Memorize the best solution.

Step-6: Calculate the probability values $prob_i$, using (17).

$$prob_i = \frac{fitness_i}{\sum_{j}^{U_s} fitnees_j} \quad ....(17)$$

where, $fitness_i$ is the fitness value of the solution *i*, U_s is the number of food source.

Step-7: For each onlooker bees

7.1: According to the probability values (17) selecta candidate food source position.

7.2: With this selected position perform the steps 5.2 to 5.5.

Step-8: Depending upon the trail counter replaces the abandoned food sources by using (18) as found by the scout bees and follow the steps 5.2 to 5.3.

$$x_{ij} = x_{jmin} + rand(0,1) \times \left(x_{jmax} - x_{jmin} \right) \quad ....(18)$$

Step-9: Memorize the best solution (food source) achieved so far.

Step-10: Repeat the step 5 to 9 until the stopping criteria is reached.

Step-11: Display the best solution.

The control parameters of the GABC optimization algorithm to obtain the optimal solution for the IEEE 24-bus system is as follows: employed bees are 50% of colony size, 500 onlooker bees, C is 1.5, limit value is 4 and the maximum number of iterations is 500.

4.0 THE SYSTEM UNDER STUDY AND RESULTS

4.1 System under study

The multi-objective STNEP problem is solved in MATLAB™ environment by applying the GABC optimization technique. The modified IEEE 24-bus system is adopted for this work. Original IEEE 24-bus network data is taken from [27]. The generator cost characteristic and emission data are extracted from [25], [17]. The emission cost is not considered in this paper. The details regarding the emission factor and PS unit are shown in the Table 1. It is considered that the maximum number of three new parallel lines may be installed in each possible expansion path. In this work, it is considered that the water availability is equal around all the buses. However, as per [21] the PS unit must be installed at the highest load bus. Hence, the PS unit is installed at bus 10. To demonstrate the proposed work, five different cases have examined. These cases are elaborated as:

- The proposed STNEP problem is solved without generation rescheduling in case-1.
- In case-2, the generating units are allowed to vary between their minimum and a maximum generating limit.
- The impact of emission is analyzed in case-3.
- In case-4, the fuel cost of the generating units is incorporated.
- Integration of the PS unit at load bus is analyzed in case-5.

In case-1 and case-2, the objective is to minimize the cost of new transmission line only. In case-3, the objective is to minimize the emission (CO_2 produced) only. From case-4 to case-5, the objective is to minimize both total cost of the system and emission produced.

TABLE 1				
DETAILS OF CO_2 EMISSION FACTORS AND PUMPED-STORAGE UNIT DATA				
Emission factors				
Generation Type [17]	Coal	CCGT	Nuclear	Hydro
tCO_2/MWh	0.88	0.37	0	0
Panjiakou, Pumped-storage unit data [20]				
Usable water volume (m^3)	$6.5e^{10}$	Power output function (MW)	$P_{p,g} = -1.3036 + 0.6538Q_p - 0.0945e^{-5}Q_p^2$	
Water flow (m^3/s)	$Q_p^{max} = 357.50$ and $Q_p^{min} = 48.00$	Generating power production (MW)	$P_{p,g}^{max} = 232.30$ and $P_{p,g}^{min} = 29.58$	

4.2 Numerical Results

In these studies, case-1and case-2 is analyzed by considering $W_i = 1$ and $W_e = 0$. Case-3 is analyzed by considering $W_i = 0$ and $W_e = 1$. Similarly, cases 4 to 5 are examined by keeping $W_i = 0.5$ and $W_e = 0.5$. The simulation results and scheduling for all the cases for IEEE 24-bus system are enumerated in the Table 2 and Table 3. The capability of the GABC optimization algorithm is demonstrated and validated through simulation of the cases 1-5.

The comprehensive results for all the cases are described below:

Case-1: In this case, the proposed static TENP problem (1) is solved and the result obtained with the GABC optimization algorithm has transmission line cost (TLC) 390 million US \$ with additions of 12 new lines to the base network and the added line network topology is: $n_{1-5} = 1$, $n_{3-24} = 1$, $n_{6-10} = 1$, $n_{7-8} = 2$, $n_{14-16} = 1$, $n_{15-24} = 1$, $n_{16-17} = 2$, $n_{16-19} = 1$ and $n_{17-18} = 2$.

TABLE 2							
OVERALL SUMMARY OF RESULTS OBTAINED FOR THE PROPOSED STNEP PROBLEM BY THE GABC ALGORITHM							
Cases		**Results of STNEP**					
		TLC, million US \$	**FC, million US \$/h**	**TC, million US \$**	**Emission, tCO_2/h**	**Total new lines added**	
$W_i = 1$ and $W_e = 0$	1	390	-	390	-	12	
	2	152	-	152	4306.580	5	
$W_i = 0$ and $W_e = 1$	3	4,860	-	4,860	3115.418	96	
$W_i = 0.5$ and $W_e = 0.5$	4	322	14.585	336.585	3670.886	8	
	5	160	13.892	173.892	3398.017	6	

TABLE 3

DISPATCH OF GENERATING UNITS FOR ALL SCENARIOS OF THE PROPOSED STNEP PROBLEM

Cases	Generating Units (MW)											Total Load at level (MW)	Total Gen-erations (MW)
	P_{g1}	P_{g2}	P_{g7}	P_{g13}	P_{g15}	P_{g16}	P_{g18}	P_{g21}	P_{g22}	P_{g23}	$P_{p,g}$		
1	576	576	900	1773	645	465	120	1200	900	315	-	8550	8550
2	570.420	570.890	900.000	1577.580	644.790	464.520	942.140	1189.330	65.540	1624.760	-	8550	8550
3	413.890	413.890	818.480	1734.417	604.753	424.753	1199.971	1199.971	771.973	967.904	-	8550	8550
4	576	576	900	1677.776	643.047	465	853.992	853.992	900	1104.215	-	8550	8550
5	576	576	593.820	1773	645	349.250	791.770	791.770	593.820	1627.230	232.310	8500	8549.966

Case-2: In this case, the optimal solution found by the GABC optimization algorithm has TLC = 152 million US \$ with additions of 5 new lines to the base network and the added line network topology is: n_{6-10} = 1, n_{7-8} = 2, n_{10-12} = 1 and n_{14-16} = 1. Emission of CO_2 = 4306.580 tCO_2/h

Case-3: In this case, the impact of emission is analyzed on the proposed problem. The results obtained are: TLC = 4,860 million US \$ and emission of CO_2 = 3115.418 tCO_2/h, with 96 new lines added to base network. The results are displayed in Table 2. The bar chart shown in Figure 1 gives the detail about the quantity of CO_2 released into the atmosphere for cases 3 to 5. This figure shows the variations are taking place in the volume of CO_2 released.

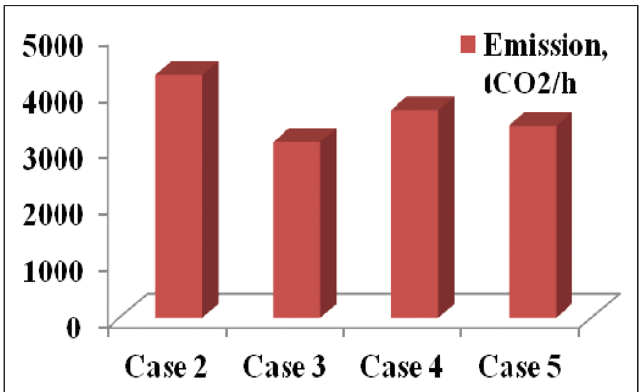

FIG 1. BAR CHART OF THE EMISSION LEVEL OF CO_2 FOR CASES 2 TO 5

Case-4: The fuel cost of generating units is included in the objective function in this case study. The result obtained has: TLC = 322 million US \$, the fuel cost of the generation units (FC) = 14.585 million US \$/h, total cost (TC) = 336.585 million US \$ and the amount of CO_2 released is 3670.886 tCO_2/h, with the line configuration: n_{2-6} = 2, n_{3-24} = 1, n_{7-8} = 2, n_{9-12} = 1, n_{14-16} = 1 and n_{16-17} = 1, with 8 new lines added to the base network. The results are displayed in Table 2.

Case-5: The impact of the PS unit on the transmission line cost and emission level of CO_2 is analyzed. The solutions found by the GABC algorithm is TLC = 160 million US \$, FC = 13,892,899.718 US \$/h, TC = 173,892,899.718 US \$ and CO_2 emissions of 3398.017 tCO_2/h. The following six lines are added to base network: n_{1-5} = 1, n_{6-10} = 1, n_{7-8} = 2, n_{14-16} = 1 and n_{16-17} = 1. The amount of water discharge is 357.500 m^3/s, the water storage volume in upper and down reservoir is 2,713,000 m^3, 7,287,000 m^3 respectively.

5.0 DISCUSSION ON THE RESULTS

The results obtained by the GABC algorithm have been compared with the existing published results. The comparison has done in case-1 and case-2 as for other cases results have not been reported so far. The comparison details are shown in the Table 4. The observations observed from all the cases analyzed are enumerated below:

Case-1* and *Case-2: It is observed from the Table 4 that the solution obtained by the GABC algorithm for case-1 yields a better result than CHA [28] technique and same as HSA [15] technique. In case-2, the result obtained by the GABC optimization technique is better than the New DA [29] technique and competent to techniques such as B and B [27], and CBGA [30]. It proves that the GABC algorithm is more efficient than the other evolutionary algorithms. It is also observed from the results that the transmission line cost is lesser in case-2 compared to case-1.

The cost convergence curves or both the cases are shown in Figure 2, 3 and 4. It is concluded that the algorithm achieves its optimal solutions after 50 iterations.

TABLE 4

COMPARISON OF THE RESULTS FOR CASES 1 AND 2

Methods	Optimal cost (million US $) IEEE 24-bus system	
	Case-1	Case-2
B & B [27]	-	152
HSA [15]	390	-
CHA [28]	438	-
New DA [29]	-	224
CBGA [30]	-	152
GABC	**390**	**152**

Bold values denote the optimal solution found.

Case-3* and *Case-4: In this case-3, it is ascertained that minimization of emission level only leads to the high cost of transmission lines. However, from the case-4, it is observed that the inclusion of the fuel cost of the generating units increases the total cost of the system and also quantity of CO_2 emission level.

Case-5: It is observed that with the integration of the PS unit the cost of new transmission lines, fuel cost and total system cost has reduced 50%, 4.7% and 48.3% respectively as compared with case-4 study. Also, emission level has minimized to 7.4% of 3670.886 tCO_2/h as obtained in case-4. It shows that pumped-storage unit injection helps to minimize the total cost as well as the emission of CO_2 also.

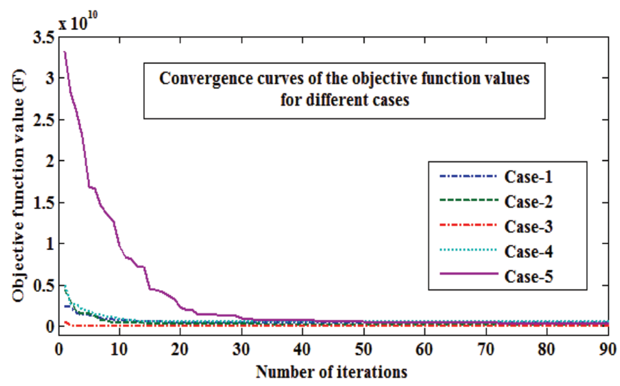

FIG 2. OBJECTIVE FUNCTION CONVERGENCE CURVES FOR ALL 5 CASES

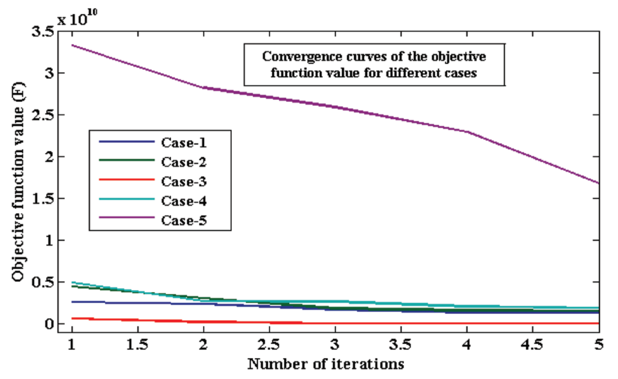

FIG 3. OBJECTIVE FUNCTION CONVERGENCE CURVES FOR ALL 5 CASES FOR ITERATIONS 0-5

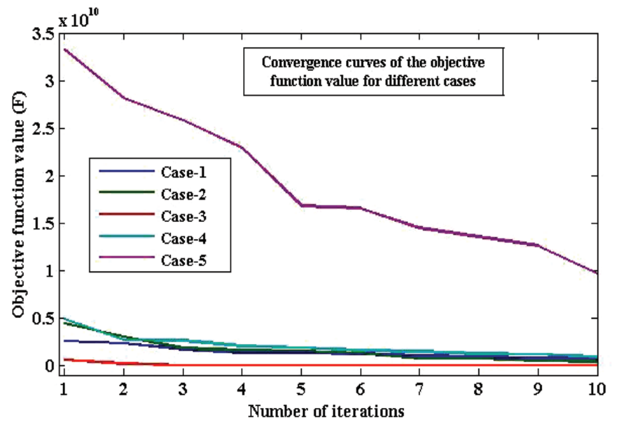

FIG 4. OBJECTIVE FUNCTION CONVERGENCE CURVES FOR ALL 5 CASES FOR ITERATIONS 0-10

6.0 CONCLUSIONS

This paper, deals with the multi-objective optimization problem which minimizes the total system cost along with the quantity of CO_2

produced by the generating units. The GABC optimization algorithm is adopted to solve this multi-objective STNEP problem. The following points are drawn from all the cases studied:

1. The GABC optimization technique results have been compared with previously published work. The comparison shows that the algorithm yields a better result than the optimization technique such as CHA and New DA. However, the results found are competent with B and B, HSA and CBGA optimization algorithm.
2. The results illustrate that minimization of emission alone is not economically feasible as it leads to more investment cost. However, to minimize both cost and emission proper tuning is required.
3. The study shows that the emission level, the total cost, the fuel cost and the transmission line cost get reduced with the integration of the pumped-storage unit.

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