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STATIC-TRANSMISSION NETWORK EXPANSION PLANNING CONSIDERING ENERGY STORAGE SYSTEMS

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Abstract—This paper presents the impact of energy storage systems (ESSs) on the static transmission network expansion planning problem (STNEP). The aim of this work is to minimize the total cost and as well as to analysis the impact of ESSs on the emission produced by CO_2. The total cost is the summation of the transmission line investment cost (TLC), the capital cost of energy storage systems (ESSC), the fuel cost (FC) and the CO_2 emission cost (EC) of generating units. In the growing power industry generation sources are the main equipment, as there are various types of generating sources. Their selections are done to achieve a more eco-friendly and economical. The deployment of ESSs leads its utilization on power system problems. Hence, the impact of ESS on the STNEP needs to be analyzed. The proposed problem is tested on a modified IEEE 24-bus system and the gbest-guided artificial bee colony (GABC) optimization algorithm is applied to solve this problem. The results obtained indicate that placement of ESSs leads to reduce the total cost and CO_2 emission level.

Keywords— Energy storage systems; Emission; Gbest-guided artificial bee colony; Static transmission network expansion planning problem;

I. 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 pumped-hydroelectric storage in the 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. The growing development of large-scale energy storage systems (ESSs) may reduce the uncertainty of the renewable power generation and helps to improve the system operation. Hence, it is required to study the impacts of these resources on the transmission network expansion planning (TNEP) problem. The transmission expansion planning determines “what”, “where”, and “when” new transmission facilities to be installed to meet the system requirements [1].

The TEP problem has been solved as an optimization problem since 1970’s [2]. The detailed, comprehensive reviews about the TEP problem have been presented in [3-4]. Various optimization techniques such as linear programming [2], dynamic programming [5] and many others [6-15, 16] have been applied by researchers to solve the static TEP and the dynamic TEP problem. However, these methods suffer to achieve the optimal solution due to non-linearity and stochastic modeling. Hence, the present practice is to implement heuristics and meta-heuristic techniques to solve TEP problems, which provide rapid calculation and fast convergence.

From the literature review, it has been found that only few researchers have worked on the TNEP problem the considering emission of CO_2 [17-18]. In [17], authors have presented the impact of CO_2 emission on the TNEP problem. 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. Author’s in [18] have solved the TNEP problem considering the environmental issue. The objective is to minimize the transmission line investment cost and emission produced by CO_2. However, in both the papers the impact of ESS has not been considered.

As per report presented in [19-22] the utilization of ESSs may defer or eliminate some utility upgrades. Keeping a point of view on TNEP problems, it may be feasible to install ESSs instead of transmission lines to serve the future peak load with reduced overall cost. Some researches in [23] and [24] have demonstrated the application of deploying energy storage system in TNEP. In [23], the objective is to minimize the transmission network investment cost by the help of ESS. In [24], authors have extended the work [23] by considering losses and actual costs of ESSs. In both papers for modelling TNEP disjunctive model and to solve the objective function by a mixed-integer linear programming method has been used. As per survey reported in [3-4] the disjunctive model and mixed-integer linear programming method has been used after approximations. Hence, to overcome these approaches in this work widely used DC power flow model and meta-heuristic optimization algorithm is considered.

Also, in both the papers the authors have not considered the impact of CO_2 emission while solving the TNEP problem. However, so far the application of energy storage systems such as large-scale battery stations to minimize the emission produced by dangerous gases has been not studied in literature. Therefore, this work proposes a methodology to minimize the total cost and study the impact of ESSs on the

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emission level. The GABC optimization algorithm is the modified version of the ABC algorithm, which is also a population-based search optimization method [25, 26]. The algorithm has been implemented for solving power system problems such as load flow [27], unit commitment [28] and economic load dispatch [29]. Studies reveal that the algorithm is robust and has fast convergence. Hence, in this work it is considered.

The main contributions of this study are as follows:

1. To analysis the impact of CO_2 emission on the STNEP problem.
2. Implementation of the GABC optimization algorithm for the STNEP problem.
3. To study the impact of megawatt-scale battery stations (MBS) on the total cost and emission level of CO_2.

The rest of the report is organized as follows: Section 2 describes the proposed mathematical model for STNEP. Section 3 presents an overview of gbest-guided artificial bee colony (GABC) algorithm and its implementation on the STNEP problem. The numerical results and discussions are presented in section 4. The conclusion drawn is discussed in section 5.

II. PROPOSED PROBLEM FORMULATION

The objective of the STSEP problem is to minimize the total cost under various economic and technical constraints.

A. The proposed STNEP Model

In this work, the objective is to minimize the summation of the transmission line investment cost (TLC), the fuel cost (FC) and the emission cost (EC) produced by the thermal generators, the capital cost of ESSs (ESSC) and it is formulated as follows:

Minimize, Total cost (TC)

$$TC = \overbrace{\sum_{i,k\in\Omega} T_{L,ik} n_{ik} C_{t,ik}}^{TLC} + \overbrace{8760 \times \sum_{i=1}^{N_g} e_{co2} E_{emission,i}}^{EC} \quad (1)$$
$$+ \overbrace{8760 \times \sum_{i=1}^{N_g} \left(a_i + b_i P_{g,i} + c_i \left(P_{g,i}\right)^2 \right)}^{FC} + \overbrace{\sum_{i=1}^{N_{ess}} \left(\beta_i ness_i + \beta_{mbs,i} P_{mbs,i} \right)}^{ESSC}$$

The constraints incorporated in solving process are organized as follows:

$$\sum_{\forall i \in N_{lk}} f_i - \sum_{\forall i \in N_g} P_{gi} - \sum_{\forall i \in N_{ess}} P_{essi} = P_{dk}, \ k = 1, \ldots, N_b \quad (2)$$

$$\sum_{\forall i \in N_{lk}} |f_i| \le \left(n_i^o + n_i\right) f_i^{max} \quad (3)$$

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad (4)$$

$$0 \le P_{mbsi} \le P_{mbsi}^{max} \quad (5)$$

$$0 \le n_{ik} \le n_{ik}^{max} \quad (6)$$

$$0 \le ness_i \le ness_i^{max} \quad (7)$$

Equation (2) represents the power balance constraint i.e, the power supplied by the thermal generators and ESSs must satisfy the load. The maximum power flow limits is given by (3), this represents the line loading should be less than its thermal limit. The power generation limits are given by (4) and (5), it represents that generation sources must generate power in their ranges. The line expansion constraint is represented by (6). The ESSs installed at particular location should be within the range specified as given by (7).

where,

a_i ,b_i and c_i	cost coefficient of the i^{th} generator
$C_{t,ik}$	the capital cost of transmission between i-k branch (US $/mile)
$P_{mbs,i}$	power capacity cost of MBS (US $/MW)
e_{co2}	The cost of emission produced by i^{th} generator (US $/t$CO_2$)
$E_{emission,i}$	emission produced by i^{th} generator (tCO_2/h)
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
f_{ik}	active power flow in the i-k branch (MW)
f_{ik}^{max}	active power flow limit on the i-k branch (MW)
N_g and N_{ess}	number of generating units and ESSs
$ness_i$ and $ness_i^{max}$	initial number of ESSs and maximum number of ESSs installed at i^{th} bus
N_b and N_{lk}	number of buses and set of lines connected to k
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)

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P_{mbsi} and P_{mbsi}^{max}	active power generated and upper limit of power generated by MBS at bus i (MW)
$T_{L,ik}$	Length of transmission between i-k branch (mile)
Ω	set of all candidate lines

III. OVERVIEW OF GBEST-GUIDED ARTIFICIAL BEE COLONY (GABC) ALGORITHM

Gbest-guided artificial bee colony (GABC) is the popular meta-heuristic algorithms, which is inspired by the collective intelligent behavior of honey bees for hunting for food. It is modified version of ABC algorithm. The ABC algorithm has been introduced and developed by Basturk B and Karaboga D [30]. 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 GABC algorithm follows the steps mentioned below are repeated until a termination criterion is reached.

A. 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 are 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 $X_i = \left[Tl_{i1}, Tl_{i2}, \ldots\ldots, Tl_{iL}, P_{g,i1}, P_{g,i2}, \ldots.., P_{g,iG} \right]$ (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 = 1

Step-5: For each employed bee

5.1: Calculate the new candidate food source position using (8). If the new position created value exceeds its ranges, the decision variable is set within its range value.

$$z_{ij} = x_{ij} + \Phi_{ij}\left(x_{ij} - x_{ki}\right) + \beta_{ij}\left(y_i - x_{ij}\right) \tag{8}$$

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 ∈ {1, 2…Us} and j ∈ {1, 2…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 (2) to (7), 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 (9).

$$prob_i = \frac{fitness_i}{\sum_{j}^{U_s} fitnees_j} \tag{9}$$

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

Step-7: For each onlooker bees

7.1: According to the probability values (9) select a 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 (10) as found by the scout bees and follow the steps 5.2 to 5.3.

$$x_{ij} = x_{j\min} + rand(0,1) \times \left(x_{j\max} - x_{j\min}\right) \tag{10}$$

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

Step-10: Repeat the step 5 to 9 until the stopping criteria (maximum number of iterations) 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.

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IV. NUMERICAL RESULTS AND DISCUSSION

The proposed static TNEP study is performed in a MATLAB environment by applying the GABC optimization algorithm. The modified IEEE 24-bus system is adopted for this work. The original IEEE 24-bus network data is taken from [31]. The generator cost characteristic and emission data are extracted from [17, 32]. It is assumed that the maximum number of three new parallel lines may be installed in each possible path. The capital cost of transmission lines are considered as 1,000,000 US \$/mile and emission allowance price is taken as 19.25 US \$/tCO2 [17]. At present the cost of ESSs are high [33, 24] as megawatt-scale battery stations (MBS) are assumed to be deployed. Hence, their unit power capacity cost ($\beta_{mbs,i}$) the fixed cost (β_i) and efficiency is considered as 200 US \$/kW, 800 US \$/kW and 80% respectively. All buses are considered applicable for deploying ESSs. The maximum capacity of MBS is 300 MW.

A. Results

The objective of the proposed STNEP problem is tested under four different cases as below:

- In case-1, the STNEP problem is solved only with generation rescheduling.
- In case-2, the fuel cost of the thermal generating units is incorporated.
- The impact of CO_2 emission level cost is analyzed in case-3 and this is considered as a base case.
- Integration of ESSs at load bus is analyzed in case 4.

The demonstration of all cases under consideration is analyzed on a modified IEEE 24-bus system. The capability of the GABC optimization algorithm is demonstrated and validated through simulation of the cases 1-4. The overall summary of simulation results are displayed in the Table I.

The extensive result analysis for all the cases are enumerated below:

Case-1: In this case, the optimal solution found by the GABC optimization algorithm has the transmission line investment cost (TLC) of 131,000,000 US \$ by adding 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 $n_{11-13} = 1$.

Case-2: In this study, the fuel cost (FC) of the thermal generating unit is included in the objective function. The optimal solution obtained has TLC = 393,000,000 US \$, FC = 75,436,775,696.801 and the total cost (TC) = 75,829,775,696.801 with additions of 12 new lines to the base network and the added line network topology is: $n_{3-24} = 1$, $n_{6-10} = 1$, $n_{7-8} = 1$, $n_{8-9} = 1$, $n_{10-12} = 1$, $n_{12-13} = 1$, $n_{14-16} = 1$, $n_{15-21} = 1$, $n_{15-24} = 1$, $n_{16-17} = 1$ and $n_{1-8} = 2$. The CO_2 emission quantity is 3614.738 tCO_2/h. The detail results are presented in the Table I.

Case-3: In this example, the impact of CO_2 emission level is analyzed and the emission cost (EC) of the thermal generating unit is included in the objective function. The optimal solution obtained has TLC = 393,000,000 US \$, FC = 75,431,179,607.977 US \$, EC = 611,484,537.966 US \$ and TC = 76,435,664,145.943 US \$ with additions of 12 new lines to the base network and the added line network topology is: $n_{3-24} = 1$, $n_{6-10} = 1$, $n_{7-8} = 1$, $n_{8-9} = 1$, $n_{10-11} = 1$, $n_{11-13} = 1$, $n_{14-16} = 1$, $n_{15-21} = 1$, $n_{15-24} = 1$, $n_{16-17} = 1$ and $n_{1-8} = 2$. The CO_2 emission quantity is 3614.738 tCO_2/h. The cost convergence curve is drawn in Fig. 1.

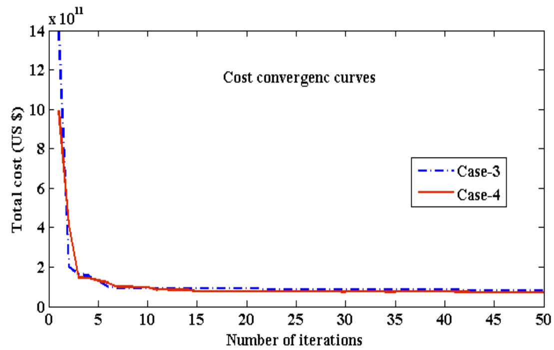

Fig. 1. Cost convergence curves for case-3 (base case) and case-4

Case-4: In this case, the objective is to analysis the impact of energy storage systems on the total cost and emission level of the system. The ESSs are installed at each load bus [24]. The location of MBS is selected on the basis of the minimum total cost at a particular load bus. It is noted from Fig. 2 that the optimal location of the MBS is at bus 8.

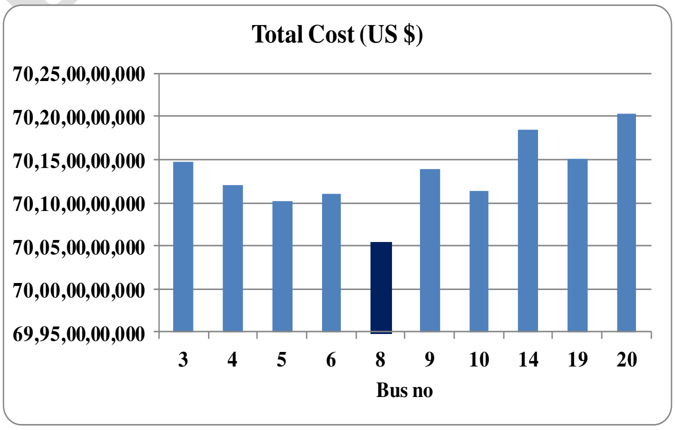

Fig. 2. Bar chart showing the impact of MBS on the total cost

The solution obtained with MBS has TLC = 316,000,000 US \$, FC = 69,091,991,504.728 US \$, EC = 598,853,490.418 US \$, the ESS capital cost (ESSC) = 47,993,530.418 US \$ and TC = 70,054,838,525.777 US \$ with additions of 10 new lines to the base network and the added line network topology is: $n_{3-24} = 1$, $n_{6-10} = 1$, $n_{7-8} = 1$, $n_{10-11} = 1$, $n_{11-13} = 1$, $n_{14-16} = 1$, $n_{15-24} = 1$, $n_{16-19} = 1$ and $n_{1-8} = 2$. The CO_2 emission quantity is 3551.287 tCO_2/h.

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The cost convergence curves are shown in Fig. 1. This curve portrays that the GABC optimization method is able to find the optimal solution within 100 iterations. From Fig. 3 it is noted that as the penetration level of ESSs varies the scheduling of other generating units gets affected.

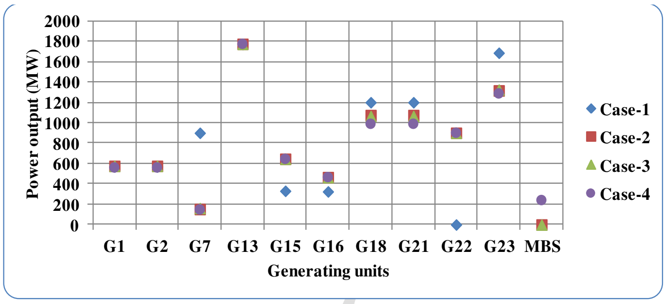

Fig. 3. Chart showing dispatch of generating units for all cases of the proposed STNEP problem

TABLE I. OVERALL SUMMARY OF RESULTS OBTAINED FOR THE PROPOSED STNEP PROBLEM BY GABC ALGORITHM

Results of STNEP	Cases Studied			
	Case-1 With TLC	Case-2 With TLC + FC	Case-3 With TLC + FC + EC	Case-4 With TLC + FC + EC + ESSC
TLC, US $	131,000,000	393,000,000	393,000,000	316,000,000
FC, US $	-	75,436,775,696.801	75,431,179,607.977	69,091,991,504.728
EC, US $	-	-	611,484,537.966	598,853,490.418
ESSC, US $	-	-	-	47,993,530.418
TC, US $	131,000,000.000	75,829,775,696.801	76,435,664,145.943	70,054,838,525.777
Average, US $	178,900,000	76,284,051,743.408	76,892,068,948.413	70,211,018,088.274
Worst, US $	229,000,000	77,242,414,221.433	77,720,733,060.423	70,358,738,698.938
Standard deviation, US $	31,472,916.046	607,385,481.917	553,470,962.464	106,231,655.126
Emission, tCO_2/h	-	3,614.738	3,626.191	3,551.287
Total new lines added	5	12	12	10

B. Discussion on the results

Elaborated studies are presented through various the simulation results obtained by the GABC optimization algorithm. The following major outcomes are ascertained from the cases studied.

- The algorithm used is competent to handle the complexity of the proposed problem.
- It is noted that from Figs. 4 and 5, that the CO_2 emission level and the total cost of the system have decreases with integration of ESSs into the system as compared to without ESSs.
- It is observed from the Table I, that the transmission line cost, the fuel cost, the emission cost, the total cost and emission level has reduced to 19.60%, 8.40%, 2.06%, 8.34% and 2.06% respectively with integration ESSs as compared to case-3. This clearly indicates that the higher capacity of energy storage system leads to more reduction in the costs as well as in emission level. However, the expense on the ESSs made towards increases with higher capacity.

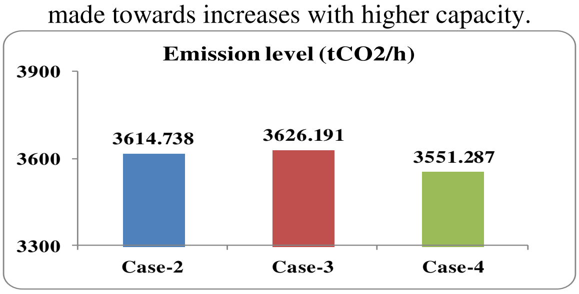

Fig. 4. Comparison of emission quantity for different cases

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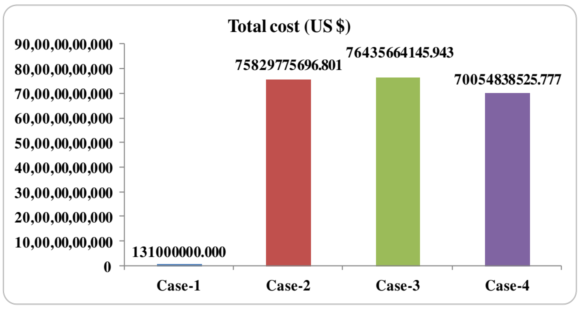

Fig. 5. Comparison of the total cost for different cases

V. Conclusion

An effective approach to minimize both the total cost and level of emission by the placement of ESSs are presented in this work. The GABC optimization technique is adopted to solve the proposed problem. The productivity of the applied methodology is presented through different case studies. The below mentioned points are concluded from the studies:

- The results obtained by the GABC optimization algorithm shows that it is capable to handle complex problems. It is also observed from the cost convergence curves that the algorithm is able to find the optimal solution in less number of iterations.
- The placement and sizing of ESSs in to the system places an important role to achieve the objective.
- With the integration of large ESS unit, emission level get reduces which leads to decrement in the total cost, the fuel cost and the emission cost.

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