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Artificial Bee Colony (ABC) Algorithm based Transmission Expansion Planning with Security Constraints

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Abstract

These days Transmission Network Expansion Planning (TNEP) is a noteworthy power system optimization issue in light of the fact that the modern electric power systems comprise of large-scale, very complex interconnected transmission systems which must be planned essentially. TNEP problem is a non-linear, non-convex optimization problem. Such problems can be easily solved using meta-heuristic optimization technique. This paper outlines solution of TNEP problem using Artificial Bee Colony (ABC) algorithm, a meta-heuristic optimization technique. ABC algorithm is mainly based on foraging behaviour of honey bees. The main purpose is to minimize the investment cost of network planning while satisfying the prevailing constraints. The ABC method is tested with 132 kV 5 bus MSETCL Network system in Amravati Region, Garver's six bus system and IEEE 24 bus system with and without considering security constraints. The results obtained by this method are found to be superior as compared to those obtained using other methods reported in the literature.

Keywords: BC Algorithm, Indian Power System, Meta-Heuristic, Optimization, TNEP

1. Introduction

Transmission system is one of the most important parts of the electric power industry. It is not only because it provides a linkage between the first and the last stages of the electrical system (generation and distribution), but also a non-discriminative, secured and reliable environment to suppliers and consumers. Therefore, a good transmission system expansion plan is always needed. Nowadays modern electric power systems consist of large-scale and highly complex interconnected transmission systems. Hence the TNEP problems are now significant power system optimization problem. The TNEP problem is a large-scale, complex and nonlinear combinatorial problem of mixed integer nature. In this, the number of candidate solutions to be evaluated increases exponentially with the increase in the system size. In order to plan power systems in both an economic and efficient manner, accurate solution of the TNEP problem is essential. Therefore, applied optimization methods should be sufficiently efficient when solving such problems.

TNEP is a problem of mixed integer nature with nonlinear combinatorial strategy. With a specific end goal to design power systems in both a monetary and productive way a precise arrangement is fundamental. In this way, when tackling such issues, proposed optimization techniques ought to be adequately effective. To unravel this proficiency issue, various computational procedures have been proposed lately. In this section, to take care of the issue of coordinated and multi-stage TNEP Genetic Algorithm (GA) is exhibited. To strengthen and assess the resultant expansion plan from genetic algorithm evaluation of reliability is performed with security constraints. To limit the investment cost on transmission systems by fulfilling the constraints, for example, load shedding restrictions, expansion parameter and load active power

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balance, and the objective is detailed. The proposed model will be executed in MATLAB/Simulink working stage and the execution will be evaluated with the current procedures.

TNEP problem are of two types, Static Transmission Network Expansion Planning (STNEP) and Dynamic Transmission Expansion Network Planning (DTNEP) based on planning horizon. The algorithm proposed for solving STNEP problems are classified in three types as (a) mathematical optimization methods, (b) heuristic methods and (c) meta-heuristic methods. Similarly for DTNEP problem it is classified into two types as (a) mathematical optimization methods and (b) meta-heuristic methods. The meta-heuristic optimization techniques are superior as compared to others because there is no chance to get trapped in sub optimal solution[1].

In 1970 Garver applied the linear programming technique to solve TNEP problem. It consists of two parts as (a) Linear Flow Estimation and (b) New Circuit Selection[2]. After this many new techniques were applied for solving TEP problems.This includes dynamic programming[3], hierarchical decomposition[4] and interactive method[5]. The hierarchical decomposition methods cope up with the non-convexity of the TNEP problem. Genetic Algorithm (GA) is nothing but the search algorithm based on the natural genetics and natural selection. It includes three operators to get the best solution, viz., selection, crossover and mutation. GA can easily enhance the existence of non-linearity against pure mathematical model[6]. Application of Greedy Randomized Adaptive Search Procedure (GRASP) which is one of the heuristic techniques is presented in[7]. Taboo Search algorithm[8], Simulated Annealing[9], Adaptive particle swarm optimization technique[10] were applied for solving TNEP problems. With respect to different aspects such as modelling, approaches for solving TEP, reliability, electricity market and tools for optimization the review is presented in[11]. The review outcomes offer a widespread background of the planning issues and the corresponding solution approaches that may also lead to provide the future directions relating to this work. Uncertainty in wind and load is considered in stochastic programming which is a cost effective approach to model the transmission expansion planning[12].

The Artificial Bee Colony (ABC) algorithm is mainly based on population search procedure. It is used to solve convex, non-linear and complex optimization problems. It is also used to solve unit commitment problem[13], optimal allocation of Distributed Generation[14]. This paper demonstrates the application of ABC algorithm to transmission expansion problem. The remaining paper is organized as follow: Section 2 describes the mathematical model for transmission expansion planning. Section 3 presents overview of Artificial Bee Colony Algorithm and its implementation to TNEP problem. Section 4 presents the case studies and results, and finally conclusions are presented in Section 5.

2. Mathematical Model for TNEP

Here the DC model is used for modelling the static transmission expansion planning problem. In DC power flow model some assumptions are made for simplicity viz. i) It completely ignores the reactive power balance equations ii) It also assumes all voltage magnitudes are identically one per unitiii) Ignores line losses iv) Also ignores taps dependence in the transformer reactances. Hence it reduces the power flow equations to sets of easy equations. For single-stage transmission expansion planning problem, the power grid is usually represented by the DC power flow model. The problem formulation TNEP can be given as below[15]:
Objective function:

$$min v = \sum_{l \in \Omega} c_l n_l \quad (1)$$

Subject to

$$S f^k + g = d \quad (2)$$

$$f_l^k - \gamma_l (n_l^0 + n_l)(\Delta\theta_l^k) = 0,$$

For $l \in 1,2......, nl \,\&\, l \neq k$ (3)

$$f_l^k - \gamma_l (n_l^0 + n_l - 1)(\Delta\theta_l^k) = 0,$$

For $n = k$, (4)

$$\left| f_l^k \right| \leq (n_l^0 + n_l)\overline{f}_l,$$

For $l \in 1,2......, nl \,\&\, l \neq k$ (5)

$$\left| f_l^k \right| \leq (n_l^0 + n_l - 1)\overline{f}_l, \text{ For } l = k \quad (6)$$

$$0 \leq n_l \leq \overline{n_l} \quad (7)$$

$n_l \geq 0$, and integer, for $l \in 1,2......, nl \,\&\, n \geq l \,\&\, l \neq k$

$(n_l + n_l^0 - 1) \geq 0$, and integer, for l=k

$l \in \Omega$ and k=0, 1 NC

Where,

k=0, represents the base case without any line outage.

v: Total transmission investment cost,

g: The vector of generation at each node,

d: The vector of corresponding demands at that node,

s: Branch-node incidence matrix of the power system,

f^k: Vector with elements, f_l^k,

γ_l: Suceptance of the circuit that can be added to l^{th} right of way,

n_l: The number of circuits added in l^{th} right-of-way,

n_l^0 : Number of circuits in the base case,

$\Delta\theta_l^k$: Phase angle difference in l^{th} right-of way when k^{th} line is out,

f_l^k : Total real power flow by the circuit in l^{th} right-of-way when k^{th} line is out,

$\overline{f}_l$: Maximum allowed real power flow in the circuit in l^{th} right of-way,

$\overline{n}_l$: Maximum number of circuits that can be added in l^{th} right-of-way,

Ω : Set of all right-of-ways,

nl: Total number of lines in the circuit,

NC: Number of credible contingencies

In above stated problem formulation, Equation (1) represents the total investment cost of new lines added, Equation (2) represents the power balance constraint at each node, Equations (3) and (4) represent the real power flow equations in DC network, Equations (5) and (6) represent the line real power flow constraints, Equation (7) represents the restriction on the construction of line per corridor Right of Way (ROW). ROW is a strip of land used to construct, operate, maintain and repair the transmission line facilities by electrical transmission utility

3. Overview of ABC Algorithm

Transmission network expansion planning has always done either by mathematical optimization models or heuristic models, or recently by meta-heuristic algorithms. In 2005 Karaboga, introduced the Artificial Bee Colony (ABC) algorithm which is a swarm based meta-heuristic algorithm used for optimizing numerical problems. It was mainly inspired by the intelligent foraging behaviour of honey bees. Artificial Bee Colony (ABC) algorithm is a meta-heuristic optimizing technique in which a colony of artificial bees cooperate each other to find high quality solution for optimization problems. ABC algorithm is widely used for various problems where either the conventional algorithms are not able to find suitable solution or the time used by conventional algorithms is not acceptable[16].

The ABC algorithm consists of three groups of bees as employed bee, onlooker bee and scout bee. In ABC algorithm each cycle of the search consists of the three major steps. Firstly the employed bee goes in search of food source. Then they share the information with onlooker bee waiting in the hive to choose the food source and then the scout bee goes in search of food source randomly after the food gets exhausted. So the bees hunting for food and share the information regarding the food with other bees waiting in the hive called employed bee. The bees waiting in the dance area to make decision for choosing the food source called onlooker bee and the bees carrying random search of food again called scout bees.

In ABC algorithm, probable solution of the optimization problem is represented by the position of a food source, and the fitness solution of the problem a corresponding nectar amount of a food source.

3.1 Advantages of ABC algorithm

- It mainly based on intelligent behaviour of honey bee swarm.
- It is quite simple, flexible and robust technique.
- It is a global optimization algorithm.
- It can be also used for combinatorial optimization problems.
- It can be used for unconstrained and constrained optimization problems.
- It employs only three control parameters (population size, maximum cycle number and limit) that are to be predetermined by the user.

The Artificial Bee Colony (ABC) Algorithm generates the initial population P of Ns vector of Candidate solutions as

$$P = [X_1,.... X_i,.... X_{NB}]^T \quad (8)$$

Each candidate solution X_i is a D-dimensional vector, containing as many integer-valued parameters in Equation (8)

Where,

D: the number of optimized parameters

$$X_i = \left[x_{1,i},...x_{j,i},....x_{D,i}\right] \quad (9)$$

Where,

$i = 1, \ldots\ldots\ldots\ldots, Ns$

Equation (9) is used for searching new position from the old in memory. Now the new candidate food position is updated by the employed bee.

$$v_{ij} = x_{ij} + \phi_{ij} * \left(x_{ij} - x_{kj}\right) \quad (10)$$

Where,

$\O_{ij}$: a random number between [-1 1]

$k \in \{1, 2, \ldots\ldots\ldots N_s\}$

$j \in \{1, 2, \ldots\ldots\ldots D\}$

is randomly chosen index

Now the probability of the food source selected by the onlooker bee is obtained by the Equation (10) associated with that food source,

$$pp_i = \frac{fitness_i}{\sum_{j=1}^{N_s} fitness_j} \quad (11)$$

Where,

N_s: Number of food source

$fitness_i$: Fitness value of the solution *i* which is proportional to the nectar amount of the food source in the position *i*.

The food source whose nectar is exhausted by the employed bees is replaced by the scout bees by random search. If the food position is not advanced during set number of cycles called limit, then it is assumed that the food source gets exhausted. Then the new food source is searched by the scout bees which are nothing but the employed bees whose food source has been exhausted. They again go in search of food randomly to find the next food source.

For each candidate source position v_{ij} is produced and checked for its quality. If it is found that the present food source has better nectar than old one, then it is replaced by the old one in the memory.

The general algorithmic structure of ABC optimization approach is as follows:

- Initial Phase
- REPEAT
  Employed Bee Phase
  Onlooker Bee Phase
  Scout Bee Phase
  Memorize the best solution
  Achieved so far
- UNTIL (Cycle=Max. Cycle Number)

3.2 Implementation of ABC in TNEP Problem

The implementation of ABC algorithm in TNEP problem is as follows:

3.2.1 Input Parameters and Initialization Step

The main parameters required for implementing ABC algorithm in TNEP problem are number of employed and onlooker bees, number of food source, population size. It also needs the upper and the lower bound of candidate solution. First of all it generates randomly distributed initial population of size Ns as per Equation (7). In transmission expansion planning,

$X_i = [n_{1,i}, \ldots\ n_{j,i}, \ldots\ n_{D,i}]$

Where,

$i = \{1, 2, \ldots \ldots \ldots \ldots N_s\}$

n_{ij}: The number of possible transmission lines between each branch j and i

D: The number of parameters optimized

3.2.2 Employee Bee Search Phase

In this phase, the food source gets optimized using Equation (9) by employed bees. Penalty factor technique is implemented to handle the constraints. After this objective function value is calculated and the best solution obtained is retained in the memory.

3.2.3 Onlooker Bee Search Phase

Depending upon the probabilities found out using Equation (10), onlooker bee search for the food in swarm. If it is found that the new food source is better than the old one then its position is updated by using Equation (9).

3.2.4 Scout Bee Search Phase

The solution obtained in above onlooker bee search phase is not improved after further number of cycles then the scout bees go in search of new source randomly and replaces the exhausted source. Then it memorizes the best solution obtained so far and gives better solution. After reaching to maximum number of cycles the algorithm is terminated otherwise jump to step (2).

3.2.5 Applying Security Constraint

The solution obtained after application of ABC algorithm is further refined by applying Security constraints. The Normalized Performance Index (NPI) is used which is a ratio between the decrease in the overloads after line addition to the cost of that line, which is used to select best line among the list of candidate lines[17].

- Assume the base case and run DC power flow.
- Evaluate the base case overload index and new overloaded index, then calculate the normalized performance index.
- Select the line with maximum value of NPI repeat the procedure until overloads are removed.
- Arrange all the lines in decreasing order of their cost to apply redundancy criterion.
- If this removal does not create overloads in the network for base case then remove the line.

3.3 Redundancy Criterion

Redundancy criterion is used to remove unwanted lines in the expansion planning. In this all the added lines are sorted in descending order of their costs and check for the possibility of removal of redundant lines from the list of added candidate lines. Firstly simulate the removal of one line at a time from the list of added lines, and run the power flow. If this removal does not create overloads in the network then remove the line from the list of chosen candidate lines. Repeat the process until all the chosen candidate lines are tested.

4. Case Studies

The proposed ABC algorithm is implemented on Indian power system i.e., 5 bus network in Amravati region. The power world simulator is a tool to visualize the system through the use of colorful animated online diagrams. This simulator uses the graphics and animation to represent the system in which the red colored pie charts shows that those lines are extremely overloaded, the orange colored lines are overloaded beyond 80% and the blue colored lines are within overload limit.

4.1 132 kV 5 Bus (MSETCL) Network in Amravati Region

In this case a real 132kV 5 bus network in Amravati region is solved by Static transmission expansion planning. This is a single stage planning problem in which all the expansion are done in single stage of planning horizon.

In this 5 bus system there is generation of 390MW and 50MW at bus 1 and bus 5 respectively. The original 5 bus network is shown in Figure 1. In Figure 1, it is seen that two lines are overloaded. So there is need of expansion of transmission system. The corresponding data for the given 5 bus system are given in Table 1 and 2[17].

After application of this algorithm to this 5 bus system, total eight lines are obtained. Applying redundancy criterion, it is found that out of these eight lines two lines are redundant i.e., line between bus 2 and 3 and line between bus 3 and 4. So these two lines are omitted and actually six lines are added as single line between bus 1 and 2, between bus 1 and 3, between bus 1 and 5, between bus 3 and 5 and two lines between bus 4 and 5. The total investment cost obtained in this case is 101.55 Crores (INR). The 132kV 5 bus network after static expansion planning is shown in Figure 2. It is evident from the blue colour pie chart line that the system is in stable condition.

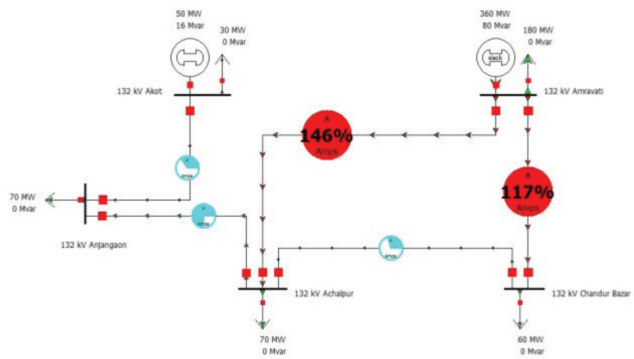

Figure 1. Original 132KV 5 bus network

Table 1. Bus data for 132kV 5 bus network

Bus	Bus Name	Generation (MW)	Demand (MW)
1	Amravati	390	180
2	Achalpur	-	70
3	Chandur Bazar	-	60
4	Anjangaon	-	70
5	Akot	50	30

Table 3 shows the comparative result for 132kV 5 bus network by GA and ABC. It is concluded that the ABC algorithm gives better result than GA with the minimum investment cost[17].

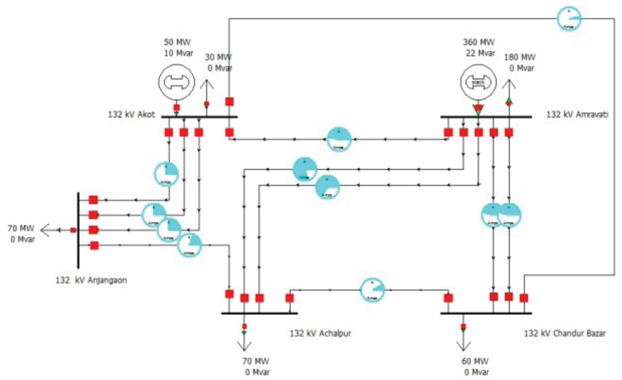

Figure 2. 132KV 5 bus network after static expasion planning.

Table 2. Line data for 132 kV 5 bus network

Line	No. Existing Lines	Reactance (p.u.)	Investment Cost (Crore INR)	Capacity (MW)
1-2	1	0.4025	19.632	75
1-3	1	0.4025	11.660	75
1-4	0	0.4025	25.440	75
1-5	0	0.4025	38.160	75
2-3	1	0.4025	9.837	75
2-4	1	0.4025	9.422	75
2-5	0	0.4025	23.320	75
3-4	0	0.4025	22.470	75
3-5	0	0.4025	38.160	75
4-5	1	0.4025	11.872	75

Table 3. Comparative result of GA and ABC for TNEP for Indian power system

Algorithms	Genetic Algorithm (GA)	Artificial Bee Colony (ABC) Algorithm
Number of lines	n_{1-3}=1, n_{1-2}=2, n_{1-4}=1, n_{2-5}=2, n_{4-5}=2	n_{1-2}=1, n_{1-3}=1, n_{1-5}=1, n_{3-5}=1, n_{4-5}=2
Total Number of Lines Added	8	6
Investment Cost [Crores INR]	146.54	101.55
Investment Cost [US $]	10715	7425
	[1 US $ = 73.12 INR]	

4.2 Garver's Six Bus System

The configuration of Garver's six bus system before expansion is shown in Figure 3. The single stage planning problem is solved by ABC algorithm. The planning horizon and the new bus i.e., sixth bus are added with generation capacity of 600MW to mitigate the future demand. The system has 15 candidate branches and a total demand of 760 MW. Maximum possible number of possible lines per corridor is five. The cost is shown in US $. The line data is given in[10] and bus data in Table 4.

4.2.1 Without Security Constraints

In this case total eight lines are obtained. Out of which one line is found to be redundant after applying redundancy criterion i.e., line between bus 2 and bus 3.

The optimal solution obtained without considering security constraints is US$ 196,000 which is better than the solution obtained by GA[18]. The result obtained without considering security constraints is shown in Figure 4. The blue and orange colour lines show that the system is stable.

4.2.2 With Security Constraints

Power system must be secure even after planned and unplanned line outages. An important aspect that must be considered in the TNEP is the system security. It ensures that the system will be secure even after any single line outages. The *N-1* contingency analysis looks at the system state after a single line outage. This is considered to be a minimum security requirement in TNEP[18].

In Garver's six bus system, total twelve new lines are obtained after application of the ABC algorithm. After applying redundancy criterion to this six bus system it is found that two lines are redundant i.e. line between bus 3 and bus 5 and line between bus 4 and bus 6. Hence they are omitted. Finally ten lines are added as one line between 1 and bus 3, one line between bus 1 and 4, one line between bus 1 and bus 5, one line between bus 2 and 3, one line between bus 2 and bus 4, one line between bus 2 and bus 6 one line between bus 3 and 4, one line between bus 3 and bus 6, one line between bus 4 and bus 5 and one line between bus 5 and bus 6. The total investment cost of new transmission line after implementing the ABC algorithm to the six bus system. considering security constraints is US $ 236,000 which is better than the results found by GA[18]. The Garver's six bus system after static expansion planning considering security constraints is shown in Figure 5. The blue colour lines show that the system is fully stable.

Table 4. Bus data for Garver's six bus system

Bus	Generation (MW)	Demand (MW)
1	150	80
2	-	240
3	360	40
4	-	160
5	-	240
6	600	-

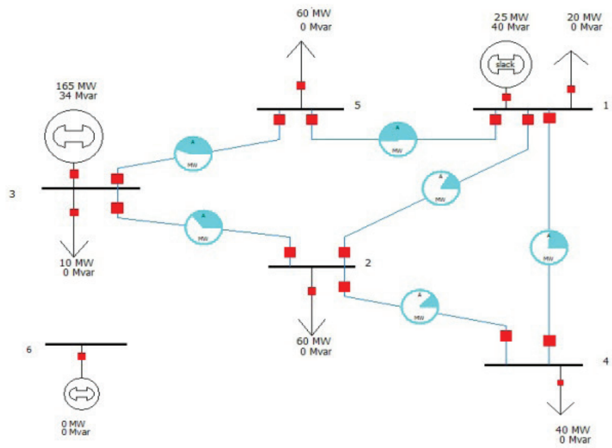

Figure 3. Original network of Garver's six bus system.

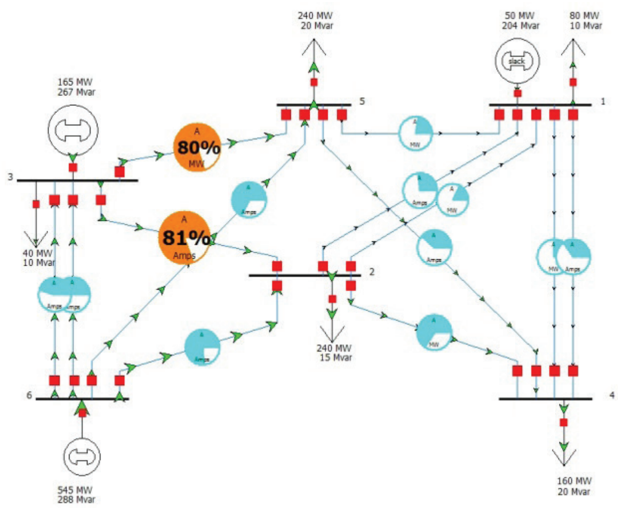

Figure 4. Garver's six bus system after static expansion planning without considering security constraints.

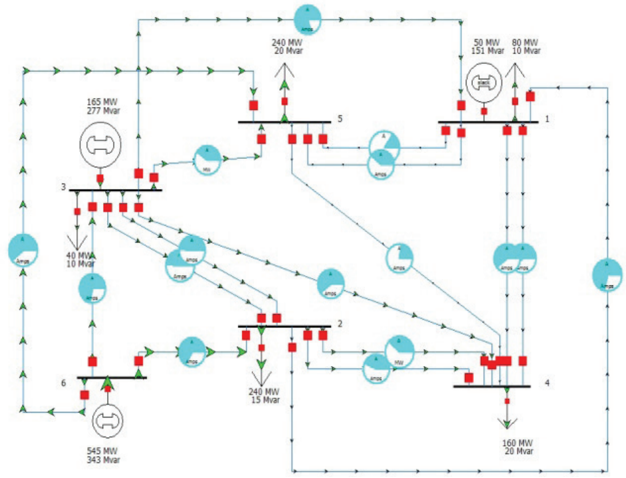

Figure 5. Garver's six bus system after static expansion planning with security constraints

4.2.3 IEEE 24 Bus Systems

This system consists of total 24 buses along with 41 ROW. The Original topology for this IEEE 24 bus system is shown in Figure. 6. The overloaded lines are shown by the red colour. The maximum allowed number of circuits per right-of-way is five. The line data and bus data for e IEEE 24 bus system is taken from[10].

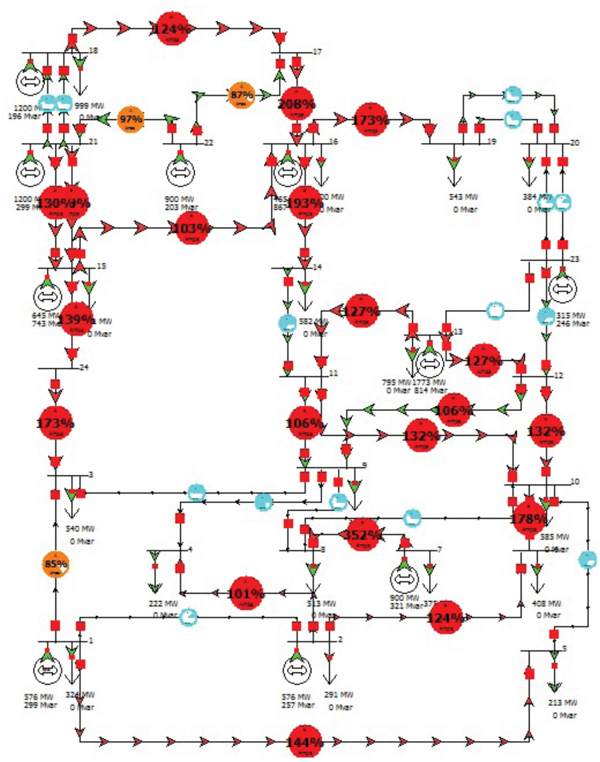

Figure 6. IEEE 24 bus systems.

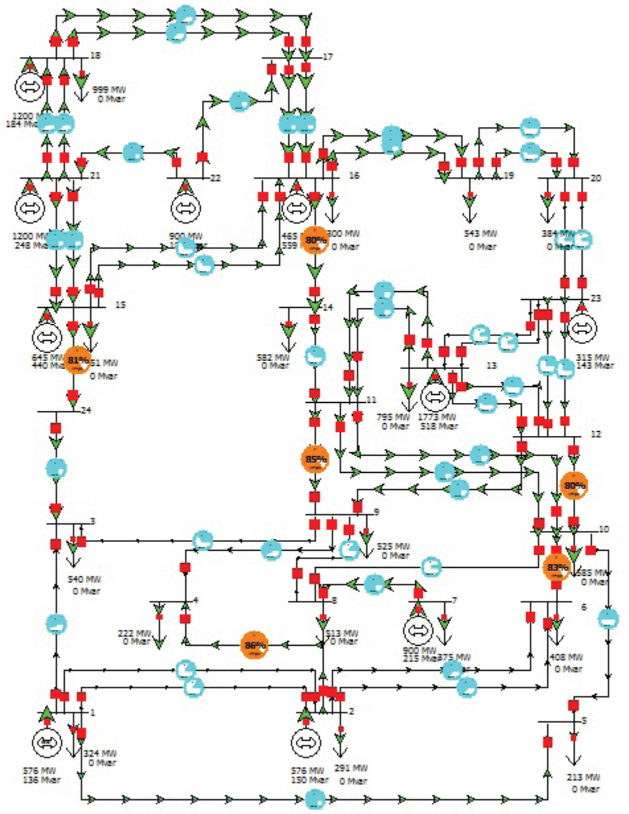

Figure 7. IEEE 24 bus system after static expansion planning without security constraints.

i) TNEP Without Security Constraints

In this case total twelve lines are obtained out which one line is found to be redundant after applying redundancy criterion i.e., line between bus 21 and bus 22. Finally eleven lines are added as single line between 1 and bus 2, bus 2 and bus 6, bus 10 and bus 11, bus 11 and13, bus 12 and bus 13, bus 12 and bus 23, bus 13 and 23, bus 15 and 16, bus 16 and bus 17, bus 16 and bus 19, bus 17 and 18. The optimal solution obtained without considering security constraints is [10^6 US$] 364.95 which is better than the solution obtained by PSO[10] and GA[19]. The result obtained without considering security constraints is shown in Figure 7. The blue and orange colour lines show that the system is stable.

ii) With Security Constraints

In this case, total twenty two new lines are obtained after application of the ABC algorithm. After applying redundancy criterion to this IEEE 24 bus system it is found that two lines are redundant i.e. line between bus 5 and bus 10 and line between bus 6 and bus 10. Hence these lines are omitted. Finally twenty lines are added as one line each between 3 and bus 9, bus 8 and 9, bus 8 and bus 10, bus10 and 11, bus 10 and bus 12, bus 11and bus13, bus 12 and 13, bus 12 and 23, bus 15 and bus 21, bus 17 and bus 18, bus 17 and bus 22, bus 1 and bus 8, bus 2 and bus 8, bus 13 and 14, bus 14 and 23, bus 16 and bus 23 and two lines between bus 19 and bus 23.

5. Conclusions

In this paper, artificial bee colony algorithm is implemented on Indian five bus practical power system, Garver's six bus system and IEEE 24 bus system for static expansion planning. For very first time Indian five bus practical system's expansion is done with the proposed method. It is found that the results obtained using the proposed

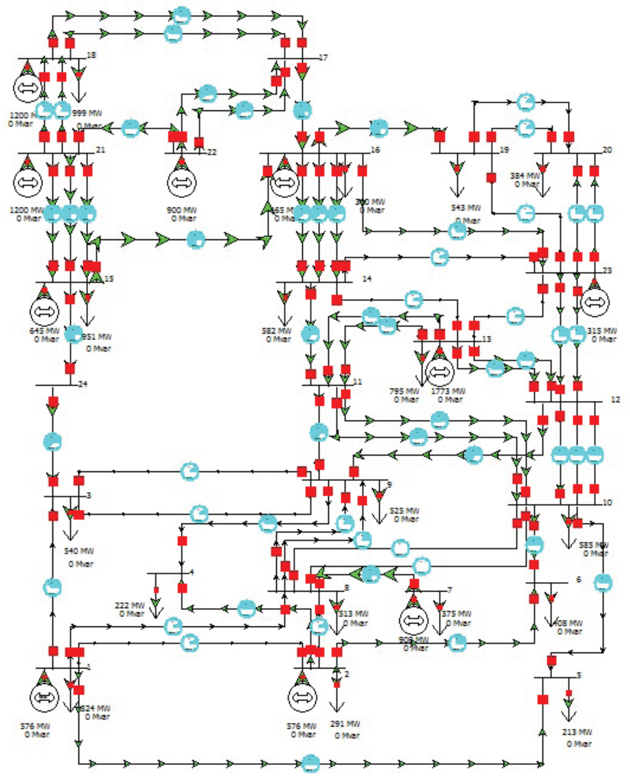

Figure 8. IEEE 24 bus system after static expansion planning with security constraints.

method are superior than the results obtained by previously presented algorithms in literature. For Indian power system the results obtained using ABC algorithm are 30.70% more economical than those obtained using GA. For Garver's six bus system the results obtained are 28.98 % and 20.80% more economical than obtained using GA for without and with security constraints respectively. For IEEE 24 bus system it is 6.42% and 3.38% more economical than GA for without and with security constraints respectively. ABC algorithm being a meta-heuristic optimization technique, its principal advantage is that it does not fall in sub optimal solution and gives global optimal solution.

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