Transmission Expansion Planning using Bacterial Foraging Optimization Algorithm

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ABSTRACT:

Transmission expansion planning (TEP) refers to specifying the place, time, and number of new transmission lines that should be established, so that given the network available, one can fulfill the potential demand of the power system in the future in terms of both operation and economic aspects (given the system constraints). Nevertheless, TEP is intrinsically a large-scale, mixed integer, nonlinear, and non-convex problem, which basically has several local optima. Solving this problem is very difficult and its computation is very time-consuming. To solve such a problem, a powerful optimization method is needed. In this paper, to solve the TEP problem, a new optimization algorithm called bacterial foraging optimization algorithm (BFOA) has been used. The proposed method has been studied on a 6-bus network for different scenarios, with the results indicating efficiency of BFOA.

KEYWORDS: bacterial foraging optimization algorithm, transmission expansion planning, optimization, system constraints, power system.

1. INTRODUCTION

Considering the ever-increasing consumption of electricity, the power system should be able to provide electrical energy continuously and reliably. This problem can be resolved merely by enhancing the capacity of the current generation units or construction of new power plants. However, greater generation capacity in turn causes increased power transmission in transmission system lines, which can result in overload in the system [1]. This can expose the power system to the risks resulting from overload in the transmission system lines, which in turn can lead to increased loss in the transmission system, elevated equipment temperature, and even global outage. To transmit the excess electric power, a logical plan is required to develop the transmission system, which means installing more transmission lines in the current power system to ensure reliable and economical performance [2].

Solving TEP problem means developing scenarios for generation and demand in the future to investigate to what extent the network safety limitations are followed under these scenarios [3]. Further, determining the optimal network modification if required and suitable time for its implementation along the planning time horizon are also studied. This process may seem simple, but it does not involve many aspects that should be taken into account. As transmission expansion planning is a mixed-integer, nonlinear, non-convex, and multistage optimization problem, it is considered very complex. Designing and innovating a planning method that can encompass all these complexities are very difficult [4]. In many papers, two types of method are employed for TEP. Some methods try to determine and propose the optimal manner of network reinforcement using predetermined criteria. These criteria can only be network safety or encompass other objectives such as investment costs [2]. However, given the utilized criteria, more estimations may be required to modify the system. For this reason, other planning methods assume that a set of modifications are proposed and they retry to evaluate them and choose the most appropriate ones.

TEP process seeks to find the most optimal path among buses with generation units and electric demand centers (determined out of load prediction plan) using distribution posts, where the loads are fully supplied under both normal working conditions and in case of disturbance in the performance of some system elements [2]. Further, the minimum cost could be imposed to the system. Indeed, TEP is an optimization process, in which the location (power sending and receiving terminals) and type (voltage level, number of conductors, type of conductors) of the new transmission elements are determined along with their accessibility frequencies.

There are some problems for solving TEP, including the large number of solutions, which can cause convergence to local optimum. As TEP is a hybrid problem by nature, it can lead to enlargement of the number of choices. This may be computationally impractical or very time-consuming [5]. Among the studies, a group of papers have tried to improve the solutions by presenting new methods and applying different optimization algorithms to the problem. Use of genetic algorithm [6], taboo search algorithm [7], particle swarm optimization algorithm [8], and social spider optimization algorithm [9], etc. are among the methods used in this regard. In this paper, a method is introduced for TEP to achieve an accurate and optimal solution. To solve the problem, a new metaheuristic optimization method called BFOA is employed. Mathematical algorithms are not very suitable for large-scale power systems. Hybrid method enjoy suitable solutions, though the time required for obtaining the optimal solution is very long, and depends on the problem dimensions and number of its parameters. Heuristic methods are very suitable, easily to implement, and devoid of computational complexity.

The TEP methods can be categorized according to criteria related to uncertainty, time horizons, reorganization or non-reorganization. Hence, these methods can be deterministic/non-deterministic, static/dynamic for power systems and are known as heuristics, mathematical optimization and meta-heuristics methods. In [10] social spider optimization algorithm (SSA) has been used to solve the TEP. A suitable method for applying the constraints of the problem is also suggested. The proposed method is tested on 6, 46 and 87 bus networks and the results show efficiency of the proposed method.

A mixed integer programming (MIP) method for the TEP with regard to HVDC and HVAC lines, network security constraints, and cost is presented in [11]. The MIP-based model ensures that the optimal solution is achieved. There is also a way to reduce the search space.

In [12] the problem of planning the TEP is solved using the Imperialist Competitive Algorithm (ICA). This algorithm is based on the modeling of the social-political process of the imperialism phenomenon. This way, by imitating the social, economic, and political evolution of countries and by mathematical modeling, parts of this process provide regular operators in an algorithm that can help to solve complex optimization problems.

The TEP problem with respect to energy storage system (EES) is presented in [13]. so, Bandarz analysis is used to solve this problem. In [14] the TEP problem has been investigated considering the uncertainties of load and cost of investment. These uncertainties are modeled using limited and symmetric loads and a cautious approach has been used to reduce the probability of violating the constraints.

In [15] a three-level model is proposed to formulate the TEP problem that takes place at the lowest level of market resolution and at the mid-level of production capacity development and at the highest level of development of transmission capacity.

the TEP with purpose of minimizing planning and operational costs is proposed in [16]. in that paper, problem is solved in planning horizon with limited short-term operational issues and long-term reliability.

In [17], a differential evolution algorithm (DE) is used to search for the TEP problem. The answer is analyzed using a small number of planning scenarios. The DE algorithm is implemented separately for each scenario and a response is found for it. Then the cost of matching each response with other scenarios is calculated. At the end, the most flexible program is chosen as the answer of problem. The fact that only a few moments are analyzed is a limitation for this method.

In [18], a multi-stage stochastic multi-objective optimization framework has been introduced, which, with the help of an optimal AC distributor, manages the voltage immunity in the system's lasting state. In this method, systemic system uncertainties are considered, and they produce scenarios using the Monte Carlo simulation method. One advantage of this approach is to look at further stages of the planning horizon and involve many criteria in choosing the answer to the problem. The disadvantage of this method is that it does not model one of the uncertainties caused by RES resources and analyzes only a small number of scenarios. Additionally, there is no supervision over line overloads.

In this paper, a novel heuristic method called BFOA is used to solve the TEP problem. Proposed method is applied to a 6-bus standard network. The rest of this paper is as follow: section 2 is dedicated to problem formulation such as objective function and constraints, the BFOA is explained in section 3 and simulation results and conclusion are presented in section 4 and 5, respectively.

2. PROBLEM FORMULATION

2.1. The Necessities

To formulate the optimization problem and for desirable performance of the BFOA, factors such as different levels of voltage in the network, economic and technical justification for switching substations, system losses, and the limitations of the distribution subsystem should be taken into account.

2.2. Objective Function

The main objective is to minimize the total cost, which can be defined as follows:

$$C_{total} = C_{new\text{-}line} + C_{\exp\text{-}sub} + C_{chn\text{-}sub} + C_{up\text{-}sub} + C_{sw\text{-}sub} + C_{sp\text{-}line} + C_{loss} \tag{1}$$

Each of the above costs is:

$C_{\text{new-line}}$ represents the investment cost of new transmission lines, defined as follows:

$$C_{new-line} = \sum_{i \in L_c} C_L(x_i) L_i \tag{2}$$

Where, L_i shows the length of the i_{th} transmission line of the candidate line (km), L_c refers to the set of candidate lines, x_i denotes the type of transmission line of the i_{th} candidate line, and $C_L(x_i)$ represents the investment cost of each kilometer of the line of x_i type.

$C_{\text{exp-sub}}$ indicates the expansion cost. This means that with expansion of an interconnected network, some of the current substations may need to be developed, so that their practical limitaitons are not violated.

$$C_{\exp-sub} = \sum_{j \in L_t} C_T(y_j) \tag{3}$$

Where, L_t denotes the set of candidate transformers, y_j is the type of i_{th} candidate transformer, and $C_T(y_j)$ is the cost of investment of the transformer type y_j.

It is assumed that the voltage of each new distribution substation is known, and the cost of its supply is considered almost based on the minimum distance between the substation of interest with an adjacent line. In TEP, this cost should be calculated accurately. Based on the objective function terms and the relevant practical constraints, such a new distribution substation may be upgraded to a higher voltage level. If N_C represents the set of these upgraded substations, the upgrading cost should also be included in our model. This cost (C_x) is a function of the load capacity of that substation P_{DK}. Thus:

$$C_{chn-sub} = \sum_{k \in N_c} C_s(P_{DK}) \tag{4}$$

$C_{\text{up-sub}}$ is the cost of enhancing the voltage of a substation to higher levels given technical and economic factors. The cost of this upgrading is defined as follows:

$$C_{up-sub} = \sum_{l \in N_s} C_u(TP_l) \tag{5}$$

Where, N_s is the set of substations with multiple voltages, TP_l denotes the level of power transmitted by substation l, and $C_u(TP_l)$ represents the cost of upgrading for a substation with the transmission capacity of TP_l.

$C_{\text{sw-sub}}$ is the cost resulting from transformers in the candidate switching substations. Hence:

$$C_{sw-sub} = \sum_{n \in N_w} (C^f_{swn} + C^t_{sw}(TP_n)) \tag{6}$$

in this relation, N_w shows the set of switching substations selected out of the available candidate substations (determined by the user), C^f_{swn} shows the cost of substation n, irrespective of the voltage conversion necessities, and C^t_{sw} reveals the cost of required transformers, which depends on load capacity (TP_n) in the substation of interest.

$C_{\text{sp-line}}$ is the cost of splitting adjacent line and using it as the input/output for feeding each substation:

$$C_{sp-line} = \sum_{m \in N_{sp}} C_{spm} \tag{7}$$

In this relation, N_{sp} represents the set of options selected for splitting among the available candidate lines, and C_{spm} represents the cost of splitting (m).

C_{loss} is the total actual power losses, which is defined as follows:

$$C_{loss} = CP_{loss}\left(\left(\sum_{j \in L_t} R_t(y_j)\left(\frac{P_j}{\cos f}\right)^2\right) + \left(\sum_{i \in L_c} R_l(x_i) L_i \left(\frac{P_i}{\cos f}\right)^2\right) + \left(\sum_{k \in L_e} R_k \left(\frac{P_k}{\cos f}\right)^2\right)\right) \tag{8}$$

Where the first and third terms are the losses of new transformers, losses of new lines, and losses of transformers and the available lines. Furthermore, $R_t(y_j)$ denotes the resistance of transformer type y at position j, $R_l(x_i)$ represents the resistance of each unit of the length of line type x at the position of i, R_k reveals the resistance of transformer or line k, L_e is the set of available lines and transformers, CP_{loss} indicates the cost per each unit of loss, P_j the actual power transmitted through the new transformer j, P_i represents the actual power transmitted through the new line i, P_k shows the actual power transmitted through the transformer or line k, and $\cos\phi$ represents the mean power coefficient.

3. CONSTRAINTS

3.1. Power Transmission Limitations

For each transmission element (lines and transformers), the extent of power transmission should not exceed its allowable rate under both normal working conditions and during disturbance (in this research N-1).

$$b_k(\theta_i - \theta_j) \le \bar{P}_k^{No} \qquad \forall k \in (L_c + L_t + L_e) \tag{9}$$

$$b_k^m(\theta_i^m - \theta_j^m) \le \bar{P}_k^{Co} \qquad \forall k \in (L_c + L_t + L_e) \cap m \tag{10}$$

Where, $\bar{P}_k^{No}$ and $\bar{P}_k^{Co}$ are the allowable rate of power transmission of element k under normal working conditions and during disturbance. θ_i and θ_j represent the voltage angles of line k during normal working conditions, θ_i^m and θ_j^m are the voltage angles of line k following incidents of disturbance m, C shows the set of disturbances, and L_c, L_t, and L_e are predetermined.

3.2. Limitations of Distribution Substation

Each new substation as well as the current substations may have limitations given the number of their connections (lines/input or output feeders).

$$\sum_{i \in L_c} M_i^{\,j} \le \bar{M}^{\,j} \qquad \forall j \in n \tag{11}$$

Where, $\bar{M}^j$ shows the maximum allowable number of lines connected to bus j. M_i^j is also a counter, and if line i is connected to bus j, it would be equal to one otherwise zero. n is also predetermined.

3.3. Islanding Conditions

Power systems should be planned in a way that there is no islanding during normal working conditions and disturbance.

$$N_{island} = 0 \tag{12}$$

Islanding is identified by investigating the difference of the phase angle along each line. Elevation of the phase angle difference signifies islanding. This occurs because the end of the line of interest leads to a bus with load.

4. BACTERIAL FORAGING OPTIMIZATION ALGORITHM (BFOA)

Today, various algorithms including genetic algorithm, simulated annealing, ant colony, particle swarm, and artificial neural networks have been presented, which are highly applicable across various optimization problems.

Among the above algorithms, BFOA [19] is used to find the optimal rate of FACTS equipment and to minimize the losses of actual power, FVSI, L-index, minimize the total cost, improve the voltage profile, and enhance the voltage stability. The reason of selecting bacteria based exploration algorithm is that the dimensions of problem and its nonlinearity do not have a considerable effect on the efficiency of this algorithm. This algorithm can be converged to the final optimal solution in many problems, for which most analytical methods are not able to converge. Further, this algorithm benefits from various advantages including lower computational load, global convergence, shorter execution time, and ability of managing a larger number of objective functions compared to other evolutionary algorithms.

BFOA is considered a family of optimization algorithms inspired by the nature. The search of bacteria to find nutrients is a method to maximize the energy obtained in each time unit. Independent plant bacteria also communicate with each other through sending signals. Given the two previous points, a bacterium makes decision about exploring nutrients. This process in which each bacterium is searching for nutrients with small steps is called chemically directed movement. The main idea of BFOA is to mimic the chemical movement of virtual bacteria in the search space of the optimization problem.

The bacterium based exploration optimization can be described in the following steps: chemically directed motion, group motion, reproduction, elimination and scattering.

4.1. Chemically Directed Motion

This process simulates the motion of E. coli cell through floating and slithering using flagellum. The E. coli bacterium has a plasma membrane, cell wall, and capsule that contains the cytoplasm and nucleoid [19] which is shown in Fig. 1. Biologically, an E.coli bacterium can move in two different ways. It can swim within a certain direction in a period of time, or can slither, which performs these two functional states throughout its lifespan periodically. Assume that θ^i (j, k, l) represents the i_{th} bacterium in the j_{th} chemical reaction, k_{th} reproduction, and l_{th} step of elimination- scattering. C(i) is equal to the size of steps selected along a random direction through slithering (traversing the unit of length). Following computational view, the bacterial motion can be defined as follows:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \tag{13}$$

where Δ shows a vector along random direction, whose elements lie within the range of [-1,1].

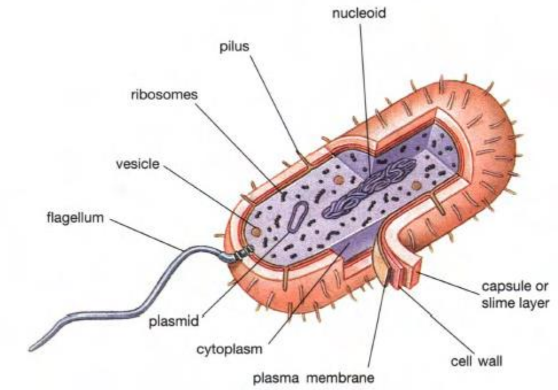

Fig. 1. Bacterial foraging E. coli [19]

4.2. Group Motion

A remarkable group behavior is observed among many motile bacteria including E. coli and Typhimurium, composed of complex and stable patterns dependent on space and time (swarm) in a semisolid nutrient environment. A group of E. coli cells organize themselves as a mobile ring, and move off inclined planes of nutrients upwards. When they are half way in their path, they form a semisolid network. When these cells are stimulated by high levels of succinate, they secrete an absorption aspartate, helping them to aggregate as a group and move as concentrated patterns of swarms with a high density of bacteria.

4.3. Reproduction

The bacteria that are less healthy eventually die when health your bacteria, irrespective of the gender, divide into two other bacteria and stand in the same position. This causes the population dimensions to remain constant.

4.4. Elimination and Scattering

In an environment where a population of bacteria live, gradual or dramatic changes may occur due to several reasons. Past events of death of all bacteria in a certain region or dear group scattering to a new part of that environment may occur. For example, considerable increase in the local temperature can demolish a group of bacteria which usually lie in a region with high concentrations of nutrients at low temperature. Such events can occur in a way that all bacteria present in a region die or group of them scatter into a new location.

To simulate this phenomenon in BFOA, some bacteria are demolished randomly and with a very low probability. Meanwhile, their substitutes lie throughout the entire search space randomly. The events of elimination and scattering can cause annihilation of the bacterial motion process. However, they can also help this process, as by implementing the scattering, the bacteria can line next to a suitable food source. From another perspective, the processes of elimination and scattering are parts of the long-term behavior of swarm-based motile creatures.

5. SIMULATION

In this part, TEP program is run in MATLAB software using BFOA. The simulations have been performed on a six-bus network with 11 transmission lines and three thermal units, as shown in Fig. 2. The information related to thermal units and the lines is presented in [20]. To solve the problem, direct-current load flow (DCLF) is used.

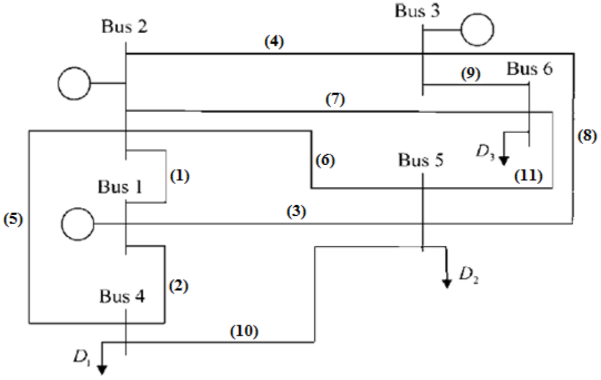

Fig. 2. The six-bus network [20]

Four scenarios have been considered to investigate different states, including normal network state, 20% increase in the load, 20% increase in the load with installing a transmission line, and 20% growth in the load with installing two transmission lines.

The results obtained for the network during normal working states and *N-1* for the 1st to 4th scenarios are revealed in Tables 1 to 4 in Appendix. Considering the capacity of each line, it is observed that in the first scenario when line number 2 (1-4) experiences an event, line 5 (2-4) has faced an overload of around 41%. In other states, no violation of the constraints has been observed.

Table 2 in Appendix presents the results of the magnitude of the current passing through the lines in terms of per-unit for the second scenario. In this state, the normal state of the network, line 5 experiences around 7% overload. In other states, other lines also face overload. For example, with cancellation of line 5, line 2 finds 47% overload. Hence, the network cannot operate in 20% of overload. Accordingly, the network should be expanded to enhance its power transmission. For this purpose, in the third and fourth scenarios, one and two new transmission lines are installed respectively. The aim is to find the optimal site for installing the lines. In the third scenario, after solving the problem, it was found that the new transmission line should be installed between buses 2 and 4 (parallel to line 5).

According to the results in Table 3, after installing the new line, it is observed that in the state the problem overload occurs only when line 5 faces an incidence. However, in other states, all of the lines operate within their allowable limits. Indeed, installing a line will not completely solve the problem. Therefore, two new transmission lines should be considered to solve this problem. In this state, two transmission lines, one between buses 2 and 4 (parallel to line 5) and another between buses 1 and 4 (parallel to line 2) are installed. In this state, as shown in Table 4, it is observed that no line experiences overload.

For a more complete comparison, the power passing through the lines in response to incidence is demonstrated in Figs. 3 to 13.

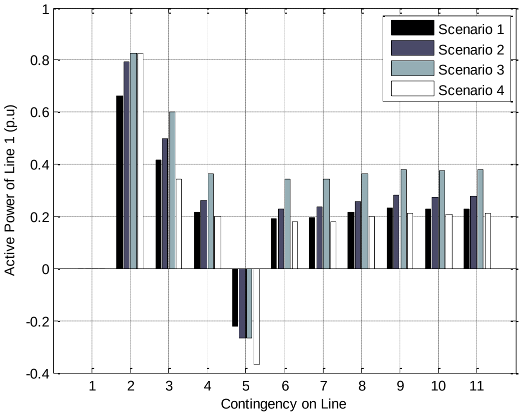

Fig. 3. The power passing through line 1 in response to incidence across different lines

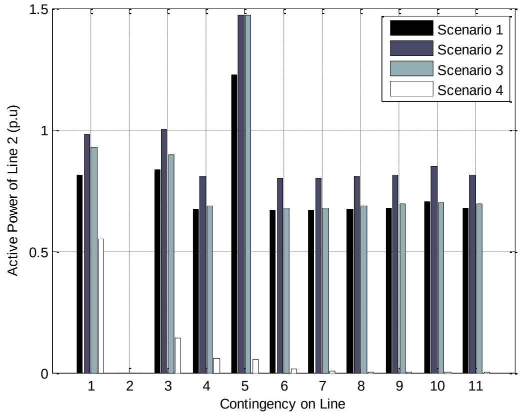

Fig. 4. The power passing through line 2 in response to incidence across different lines

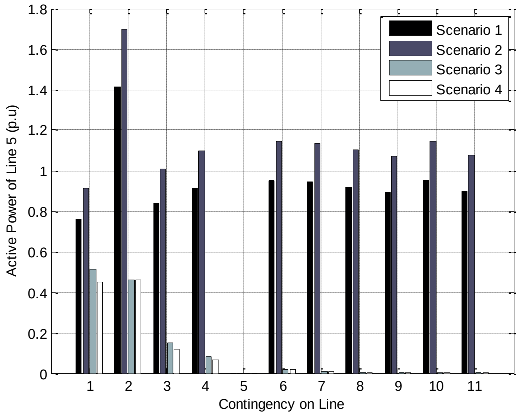

Fig. 7. The power passing through line 5 in response to incidence across different lines

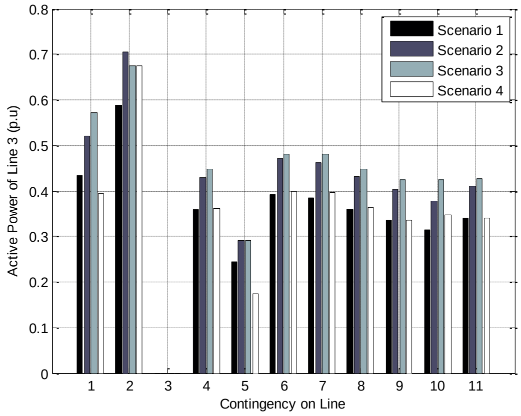

Fig. 5. The power passing through line 3 in response to incidence across different lines

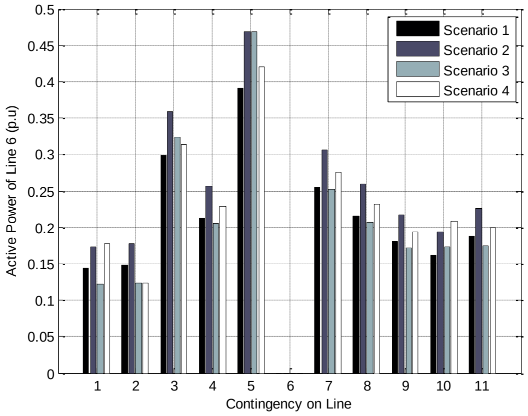

Fig. 8. The power passing through line 6 in response to incidence across different lines

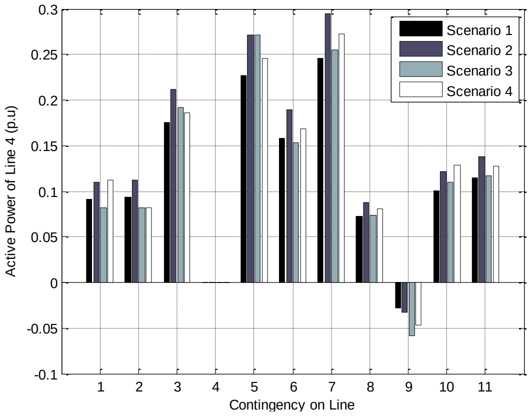

Fig. 6. The power passing through line 4 in response to incidence across different lines

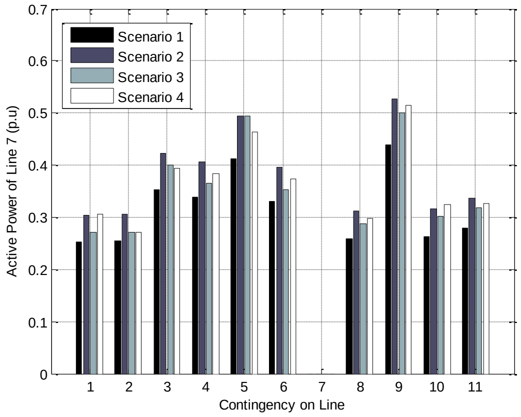

Fig. 9. The power passing through line 7 in response to incidence across different lines

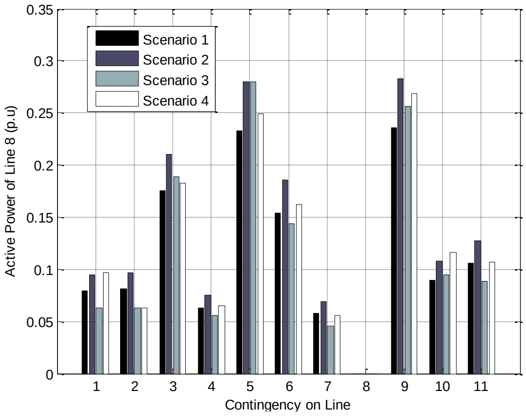

Fig. 10. The power passing through line 8 in response to incidence across different lines

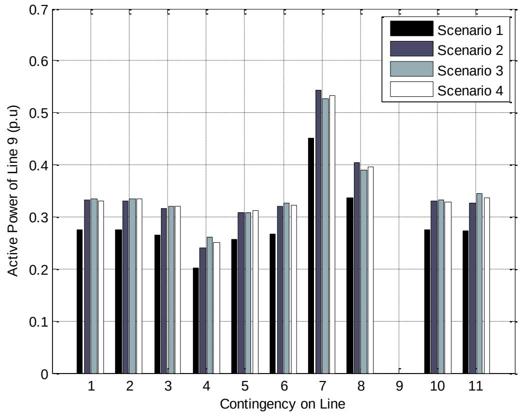

Fig. 11. The power passing through line 9 in response to incidence across different lines

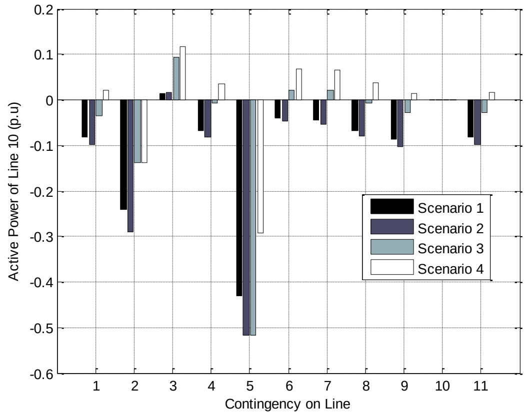

Fig. 12. The power passing through line 10 in response to incidence across different lines

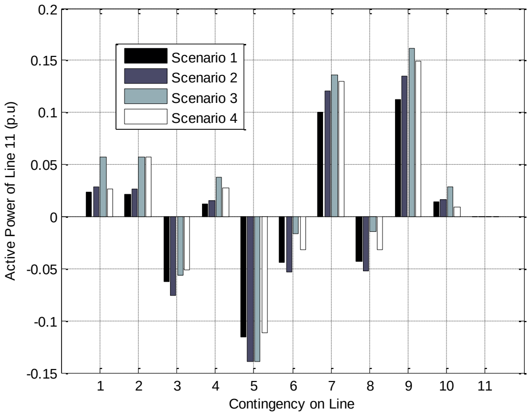

Fig. 13. The power passing through line 11 in response to incidence across different lines

6. CONCLUSION

Solving TEP problem means caring for the future demand and expanding the current network by following safety, technical and economic limitations and determining the optimal manner of network modification if required and determining the suitable time for its implementation along the planning time horizon.

In this paper, TEP problem was addressed for a six-bus network using BFOA. The simulations have been performed across four different scenarios. It was found that BFOA is efficient and is able to find the optimal and suitable solution for the problem.

It was also observed that in the first scenario when line 2 experiences an incidence, line 5 finds overload by around 41%, while in other states, no violation of the constraints was observed. Following 20% overload, installing a single transmission line cannot prevent overload in the network. Therefore, another line should also be installed. In the fourth scenario, a new transmission line was added, in which no line experienced overload and opted response was acceptable. Therefore, in the presence of these two new lines, the network can tolerate 20% overload.

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APPENDIX

Table 1. The magnitude of the current passing through the lines in terms of per-unit for the first scenario

Fault placement	1-2	1-4	1-5	2-3	2-4	2-5	2-6	3-5	3-6	4-5	5-6
-	0.2302	0.6785	0.3413	0.1152	0.8965	0.1879	0.2806	0.106	0.273	-0.083	-0.0008
1-2	-	0.8154	0.4346	0.0915	0.7611	0.1447	0.2526	0.0789	0.2763	-0.081	0.0237
1-4	0.6612	-	0.5887	0.0933	1.4153	0.1478	0.2547	0.0809	0.2761	-0.242	0.0219
1-5	0.4154	0.8345	-	0.1760	0.8382	0.2988	0.3523	0.1754	0.2643	0.0145	-0.063
2-3	0.2172	0.6746	0.3581	-	0.9148	0.2133	0.3390	0.0626	0.2010	-0.068	0.0126
2-4	-0.220	1.2272	0.2435	0.2265	-	0.3907	0.4117	0.2330	0.2572	-0.430	-0.116
2-5	0.1906	0.6668	0.3924	0.1577	0.9523	-	0.3306	0.1544	0.2669	-0.039	-0.044
2-6	0.1959	0.6683	0.3856	0.2460	0.9448	0.2550	-	0.0577	0.4520	-0.044	0.1006
3-5	0.2156	0.6742	0.3601	0.0728	0.9170	0.2163	0.2594	-	0.3366	-0.067	-0.043
3-6	0.2338	0.6795	0.3365	-0.028	0.8913	0.1806	0.4400	0.2355	-	-0.087	0.1127
4-5	0.2294	0.7056	0.3149	0.1010	0.9525	0.1619	0.2638	0.0897	0.2750	-	0.0138
4-6	0.2300	0.6784	0.3414	0.1151	0.8966	0.1880	0.2801	0.1063	0.2725	-0.083	-

Table 2. The magnitude of the current passing through the lines in terms of per-unit for the second scenario

Fault placement											
	1-2	1-4	1-5	2-3	2-4	2-5	2-6	3-5	3-6	4-5	5-6
-	0.2762	0.8142	0.4096	0.1383	1.0759	0.2254	0.3367	0.1272	0.3276	-0.099	-0.0010
1-2	-	0.9784	0.5215	0.1098	0.9133	0.1736	0.3031	0.0947	0.3316	-0.098	0.0284
1-4	0.7935	-	0.7064	0.1119	1.6984	0.1774	0.3056	0.0971	0.3313	-0.291	0.0262
1-5	0.4985	1.0014	-	0.2113	1.0058	0.3585	0.4227	0.2105	0.3172	0.0174	-0.076
2-3	0.2606	0.8095	0.4297	-	1.0978	0.2559	0.4068	0.0752	0.2412	-0.082	0.0152
2-4	-0.265	1.4727	0.2922	0.2718	-	0.4689	0.4941	0.2797	0.3086	-0.517	-0.139
2-5	0.2288	0.8002	0.4709	0.1892	1.1427	-	0.3967	0.1853	0.3203	-0.046	-0.053
2-6	0.2351	0.8020	0.4627	0.2952	1.1338	0.3060	-	0.0692	0.5424	-0.053	0.1208
3-5	0.2588	0.8090	0.4321	0.0874	1.1004	0.2595	0.3113	-	0.4039	-0.080	-0.052
3-6	0.2806	0.8154	0.4038	-0.033	1.0696	0.2167	0.5280	0.2826	-	-0.104	0.1352
4-5	0.2752	0.8468	0.3778	0.1212	1.1430	0.1943	0.3165	0.1077	0.3300	-	0.0166
4-6	0.2761	0.8141	0.4097	0.1381	1.0760	0.2256	0.3362	0.1275	0.3270	-0.099	-

Table 3. The magnitude of the current passing through the lines in terms of per-unit for the third scenario

Fault placement	1-2	1-4	1-5	2-3	2-4	2-5	2-6	3-5	3-6	4-5	5-6
-											
1-2	-	0.9288	0.5711	0.0819	0.5125	0.1227	0.2702	0.0628	0.3356	-0.036	0.0574
1-4	0.8262	-	0.6737	0.0820	0.4626	0.1229	0.2703	0.0629	0.3356	-0.139	0.0572
1-5	0.6017	0.8982	-	0.1920	0.1482	0.3235	0.4001	0.1885	0.3199	0.0943	-0.056
2-3	0.3642	0.6877	0.4479	-	0.0808	0.2051	0.3648	0.0561	0.2603	-0.007	0.0380
2-4	-0.265	1.4727	0.2922	0.2718	-	0.4689	0.4941	0.2797	0.3086	-0.517	-0.139
2-5	0.3426	0.6765	0.4807	0.1530	0.0208	-	0.3540	0.1439	0.3255	0.0222	-0.016
2-6	0.3428	0.6766	0.4805	0.2554	0.0104	0.2520	-	0.0451	0.5268	0.0220	0.1364
3-5	0.3635	0.6874	0.4489	0.0739	0.0050	0.2065	0.2876	-	0.3904	-0.007	-0.014
3-6	0.3792	0.6955	0.4251	-0.059	0.0024	0.1723	0.5014	0.2565	-	-0.028	0.1618
4-5	0.3765	0.6992	0.4242	0.1096	0.0012	0.1732	0.3029	0.0944	0.3316	-	0.0286
4-6	0.3781	0.6950	0.4268	0.1171	0.0006	0.1747	0.3187	0.0890	0.3445	-0.027	-

Table 4. The magnitude of the current passing through the lines in terms of per-unit for the fourth scenario

Fault placement											
	1-2	1-4	1-5	2-3	2-4	2-5	2-6	3-5	3-6	4-5	5-6
-											
1-2	-	0.5525	0.3949	0.1119	0.4524	0.1774	0.3056	0.0971	0.3313	0.0199	0.0262
1-4	0.8262	-	0.6737	0.0820	0.4626	0.1229	0.2703	0.0629	0.3356	-0.139	0.0572
1-5	0.3419	0.1447	-	0.1865	0.1185	0.3134	0.3935	0.1822	0.3207	0.1165	-0.051
2-3	0.1986	0.0587	0.3611	-	0.0678	0.2287	0.3843	0.0650	0.2514	0.0358	0.0274
2-4	-0.370	0.0530	0.1740	0.2455	-	0.4209	0.4631	0.2496	0.3123	-0.293	-0.112
2-5	0.1775	0.0144	0.3995	0.1688	0.0177	-	0.3727	0.1620	0.3232	0.0689	-0.032
2-6	0.1796	0.0072	0.3956	0.2730	0.0088	0.2758	-	0.0557	0.5337	0.0655	0.1295
3-5	0.1977	0.0036	0.3628	0.0802	0.0042	0.2310	0.2986	-	0.3967	0.0373	-0.032
3-6	0.2127	0.0018	0.3356	-0.047	0.0020	0.1937	0.5142	0.2691	-	0.0138	0.1490
4-5	0.2095	0.0009	0.3477	0.1287	0.0010	0.2080	0.3254	0.1162	0.3289	-	0.0088
4-6	0.2106	0.0004	0.3395	0.1271	0.0005	0.1991	0.3270	0.1074	0.3362	0.0171	-