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AC-Based Differential Evolution Algorithm for Dynamic Transmission Expansion Planning

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Abstract

This work proposes a method based on a mixed integer nonlinear non-convex programming model to solve the multistage transmission expansion planning (TEP). A meta-heuristic algorithm by the means of differential evolution algorithm (DEA) is employed as an optimization tool. An AC load flow model is used in solving the multistage TEP problem, where accurate and realistic results can be obtained. Furthermore, the work considers the constraints checking and system violation such as real and power generation limits, possible number of lines added, thermal limits and bus voltage limits. The proposed technique is tested on well known and realistic test systems such as the IEEE 24 bus-system and the Colombian 93-bus system. The method has shown high capability in considering the active and reactive power in the same manner and solving the TEP problem. The method produced improved good results in a fast convergence time for the test systems.

Keywords*: multistage transmission expansion planning, meta-heuristics, differential evolution algorithm, AC power flow model, violation checking, constraint programming*

1. Introduction

The future of the power network is to be a better grid in which the grid is flexible with different scenarios and robust to withstand different kinds of uncertainties or disturbances that may happen. The 10-years planning summary which is proposed by [1], which has been prepared by the Western Electricity Coordinating Council (WECC), the loads are expected to increase 14% between the years of 2017 and 2028. In other words, that percentage is 1.2% compound annual rate. On the other hand, the future of the generation units is expected to have an important change from the traditional ones, since the additions of the new generation units to replace the retired ones are renewable units. Only then the mandated state of the Renewable Portfolio Standards (RPSs) can be fulfilled.

With such a contemporary change, many issues are expected to rise in the near future of the power system. First of all, the load increment might change and affect the components of the power flow in the existing network. Furthermore, it might cause a potential overloads and stability problems. Such problems can violate the reliability criteria of the system. Second, most of the renewable energy resources are located in far places and not readily connected to the main power network. Additional transmission capacity is required in order to cater all the above problems [2]. Given the required task in TEP process, in order to find the optimal plan of TEP over a specified horizon, tedious and complex computational process and extensive parameters are required to be dealt with. It is worth mentioning that, the problem of transmission expansion planning has always been solved by the mathematical methods and meta-heuristic methods [3]-[7].

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When looking closely at the previous works one may notice that, the relaxed mathematical models using only the active part (real power and voltage angles) have always been used to solve the static and multistage TEP problem as presented in [8]-[10].

The TEP problem is represented based on a mixed integer nonlinear programming (MINLP) problem. Usually, the MINLP non convex nonlinear constraints are solved by using the Meta heuristic methods, considering their potential of finding high-quality solutions and some advantages: they are relatively simple, able to mix integer and non-integer variables and avoid local optima by exploring the structure of each problem with less computational effort [11].

Throughout the past decades, there have been many works proposed to solve the TEP problem. Some works have been significant to the problem, such as: a hierarchical decomposition approach for optimal transmission network expansion planning was introduced in [12]. Another important work was proposed by Olivier G.C at al. [13]. A general branch and bound algorithm was used to obtain a feasible integer solution for each investment sub-problem. Moreover, an application of an Improved Genetic Algorithm (IGA) was presented for solving the TEP problem [14]. Furthermore, a modified PSO technique incorporating a novel swarm initialization procedure for solving the TEP problem is presented in [15].

One of the powerful meta-heuristic algorithms that have been utilized to solve the TEP problem is the Differential Evolution Algorithm (DEA). The DEA has been successfully employed to solve the TEP problem. For instance, Lu et al. [16] presented a differential evolution based method for power system planning problem. The method had the ability to handle the integer variables and non-linear constrained multi-objective optimization problem. However, the approach was not robust enough due to several simplifications, such as, ignoring the security constraint and inability in handling the uncertainties in the deregulated environment. T. Sum-Im et al [17] employed the differential evolution algorithm (DEA) as an optimizing tool for the transmission expansion planning. However, it was applied directly to the DC power flow-based model in order to find a solution for static and multistage (TEP). The method yield acceptable results but by not using an AC power flow model, the DEA is only good for estimation but not accurate, since reactive power, security criteria and the uncertainties in power system are neglected. In order to cater the multi-stage TEP problem, a consideration of multi-time periods and finding possible sequences of transmission reinforcements are required. However, only a few have considered the multi-stage nature of the TEP problem [18- 22].

The use of the (complete) AC model for the multistage transmission expansion planning in the first phase is incipient and there is practically no technical literature about it. In contrast, only few studies have been conducted using the AC power flow model to solve the short term transmission expansion planning. For instance, reference [23] used an interior point method to solve the nonlinear programming problems during the solution steps of the AC Load flow algorithm. Another work in [24] solved the TEP problem by using a different method; it started with the solution of the DC model and then reinforcing the expanded transmission network using new transmission lines, as well as reactive power sources. Generally, promising results have been obtained from these works, which encourages the planners to consider the AC load flow in solving the multistage TEP problem. The scope of this work takes into account only the planning stage. All the generation units are assumed to be met locally. The operation cost and the operation constraints are not included in this work. This work calculates only the cost of the lines to be introduced to the network. The major contributions of this paper are enumerated as follows:

a. Using the complete AC load flow model in solving the multistage TEP problem, with consideration of the reactive power requirement of the system.
b. Introducing the proposed AC model and showing the performance of DEA.
c. Proposing a complete multistage planning framework which includes the optimization and considering the violation checking for the system along the planning horizon.

2. Multistage Transmission Expansion Planning Formulation

The complete AC power flow model can be applied to solve the problem of multistage transmission expansion planning. The investment cost of the plan is considered as an objective function, where $c(x)$ represents the cost of stage t. The transmission expansion investment plan is obtained with a reference to the base year bearing in mind the annual rate $I$and the values of the TEP investment cost in the base year t_0 with a horizon of Tstages are as follows:

$$c(x) = (1-I)^{t_1-t_0} c_1(x) + (1-I)^{t_2-t_0} c_2(x) + (1-I)^{t_3-t_0} \\ = \delta_{inv}^{1} C_1(x) + \delta_{inv}^{2} C_2(x) + \delta_{inv}^{3} C_3(x) \tag{1}$$

and:

$$\delta_{inv}^{t} = (1-I)^{t_t-t_0}$$

Strictly AC load flow model is applied in modeling the multistage TEP problem, where δ_{inv}^{t} is the discount factor used to find the every value of an investment at stage *t*. The objective function that considers the expansion cost of the transmission network is expressed in equation 2.

$$\min v = \sum_{t=1}^{T} \left[\delta_{inv}^{t} \sum_{(i,j)\in\Omega} c_{ij}{}^{t} n_{ij}{}^{t} \right] \tag{2}$$

Where $c_{ij}{}^{t}$ represents the circuit cost vector that can be added to the network and $n_{ij}{}^{t}$ represents the number of the added circuit's vector for stage *t*. *v*is the investment cost of the added lines for the entire planning horizon.

$$P(V,\theta,n) - P_G + P_D = 0 \tag{3}$$

$$Q(V,\theta,n) - Q_G + Q_D = 0 \tag{4}$$

Equation 3 and 4 represent the conventional equations of AC power flow considering *n*, the number of circuits (lines and transformers), as variables. The constraints of the real and reactive power in the generators are represented by equation 5 and 6, respectively; and 7 represents the voltage values.

$$P_{Gi}^{t,\min} \le P^{t}{}_{Gi} \le P_{Gi}^{t,\max} \tag{5}$$

$$Q_{Gi}{}^{t,\min} \le Q^{t}{}_{Gi} \le Q_{Gi}^{t,\max} \tag{6}$$

$$Vi^{t,\min} \le V^{t} i \le Vi^{t,\max} \tag{7}$$

The maximum and minimum values of the constraints (5, 6 and 7) are usually considered as the international standard IEC60038 stated, 105 and 95% of their nominal values, respectively. The limits of the apparent power flows for each branch are represented by equation 8 and 9.

$$(N+N^0)S^{to} \le (N+N^0)S^{\max} \tag{8}$$

$$(N+N^0)S^{from} \le (N+N^0)S^{\max} \tag{9}$$

The constraint of the capacities of the added circuits is represented by (10). *N* and N0 are diagonal matrices containing vector n and the existing circuits in the base case of the network, respectively. *n* is the vector containing the maximum allowable number of circuits that can be added.

$$0 \le n^{t} \le n^{t,\max} \tag{10}$$

$$N_{ij}^{t} \ge N_{ij}^{t-1} \tag{11}$$

$$N_{ij} = N_{ij}^{o} + n_{ij} \tag{12}$$

From the above equations one can notice that, the possibility of excluding any right of way is not included. On the other hand, the number of the new lines to be added in the new stage should be included in planning the next stage. The elements of vectors *P(V, u, n)* and *Q(V, u, n)* are calculated by equation 13 and 14, respectively.

$$P_i(V,\theta,n) = V_i \sum_{j\in N} V_J [G_{ij}(n)\cos\theta_{ij} + B_{ij}(n)\sin\theta_{ij}] \tag{13}$$

$$Q_i(V,\theta,n) = V_i \sum_{j\in N} V_J [G_{ij}(n)\sin\theta_{ij} - B_{ij}(n)\cos\theta_{ij}] \tag{14}$$

Where *i*, *j*represent buses and *N*is the set of all buses, *ij* represents the circuit between buses*i* and *j*. The bus admittance matrix elements (*G* and *B*) are:

$$G = \begin{cases} G_{ij}(n) = -(n_{ij} g_{ij} + n_{ij}^{0} g_{ij}^{0}) \\ G_{ij}(n) = \sum_{j\in\Omega i} (n_{ij} g_{ij} + n_{ij}^{0} g_{ij}^{0}) \end{cases} \tag{15}$$

$$B = \begin{cases} B_{ij}(n) = -(n_{ij} b_{ij} + n_{ij}^{0} b_{ij}^{0}) \\ B_{ij}(n) = b_i^{sh} + \sum_{j\in\Omega i} [n_{ij} (b_{ij} + b_{ij}^{sh}) \\ + n_{ij}^{0} (b_{ij}^{0} + (b_{ij}^{sh})^{0})] \end{cases} \tag{16}$$

Where Ω*i*represents the set of all buses directly connected to bus *i*;*gij*, *bij* and $b^{sh}_{ij}$are the conductance, susceptance and shunt susceptance of the transmission line or transformer *ij*(if ij is a transformer b^{sh}_{ij}=0), respectively, and bshij is the shunt susceptance at bus *i*. Note that in (15) and (16), the possibility of a different transmission line or transformer to be added in parallel with an existing one is considered, although the equivalent circuit parameters may be different [25].

$$p_{ij}^{from} = V_i^2 g_{ij} - V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}) \tag{17}$$

$$p_{ij}^{to} = V_j^2 g_{ij} - V_i V_j (g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}) \tag{18}$$

The real power generation limits are represented in (17) and (18). Where P^{from} and P^{to} are the real power flows vectors (*MVA*) in the branches and their limits.

$$\begin{aligned} Q_{ij}^{from} &= -V_i^2 (b_{ij}^{sh} + b_{ij}) \\ &\quad - V_i V_j (g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}) \end{aligned} \tag{19}$$

$$\begin{aligned} Q_{ij}^{to} &= -V_j^2 (b_{ij}^{sh} + b_{ij}) \\ &\quad + V_i V_j (g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij} \end{aligned} \tag{20}$$

The equation 19 and 20 represent the limits of the reactive power flows. Where Q^{from} and Q^{to} are the reactive power flows vectors in the branches in both terminals and their limits.

$$S_{ij}^{from} = \sqrt{(P_{ij}^{from})^2 + (Q_{ij}^{from})^2} \tag{21}$$

$$S_{ij}^{to} = \sqrt{(P_{ij}^{to})^2 + (Q_{ij}^{to})^2} \tag{22}$$

The limits of the apparent power flows are represented in (21) and (22). Where $S^{from}$and S^{to} are the apparent power flows vectors (*MVA*) in the branches and their limits. The Elements (*ij*) of the vectors of the Power Flows Limit Constraint in the branches which are considered as constraints in this formulation are given by (17): (22).

It is worth mentioning that, the multistage TEP problem has been treated differently in this work comparing to the previous works available in the literatures [18-22]. In this method, the base of every stage is the last stage topology and the additional lines that has been considered to be added. More accurate and comprehensive plans are obtained using this method. Figure 1 illustrates and shows how this method is normally done. It considers all the stages additional results which affect the solution quality unlike the other methods that only considers the original configuration as the main base for all the stages.

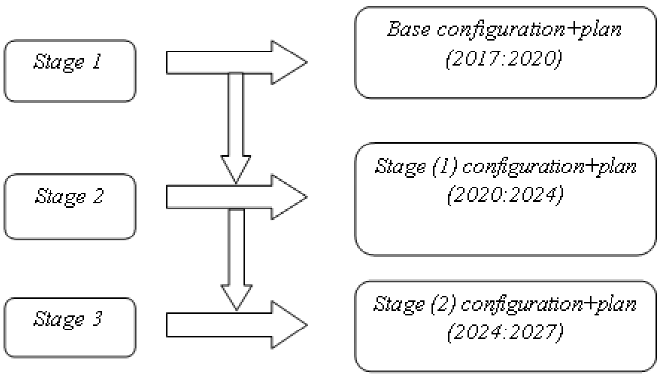

Figure 1. Multistage TEP based on different base configuration

The typical AC power flow formulation can be found in [20]. During the formulation of the problem, the number of circuits added in branch ij, and PG (the resizing value of the generation units) are considered as the most important decision variables. Therefore, it is a mixed integer nonlinear problem, where the solution includes integer value (added lines) and continuous value (PG).

3. Differential Evolution Algorithm

Differential evolution is a powerful EA algorithm for global optimization over continuous space. Recently, the DE has become one of the most widely used evolutionary algorithms for solving the optimization issues [26, 27].

Differential evolution algorithm is a parallel direct search method, which employs a population P of size NP, consisting of floating point encoded individuals or candidate solutions. It starts by initializing the population of the candidate solutions. A randomly chosen value from within their corresponding feasible bounds is assigned for all the decision parameters, in every vector of the initial population. Then, the mutation operator generates mutant vectors by perturbing a randomly selected vector with the difference of two other randomly selected vectors. Afterwards, the crossover process is employed to help increase the diversity among the mutant parameter vectors. The randomly generated parameters in mutation will be replaced by certain parameters of the individual target vector to generate a trial vector. Eventually, selection process compares the corresponding target vector and the fitness of the trial vector, and then chooses the better ones which provide the best solution.

Differential evolution algorithm has many strategies that can be employed for the optimization purpose. There are five variations, as originally proposed by Storn in [26], which are commonly used to solve the TEP problem.

4. Application of DEA in Multistage Transmission Expansion Planing Based on AC Load Flow

4.1. Problem Optimization and Control Parameters Setting

An important factor that strongly affects the convergence and the quality of the solutions of DEA is choosing the control parameters values. Storn and Price [26] had described how to choose suitable control parameters of Np, F and CR. To mention some, for Np, it must be between 5*D and 10*D but it must not be less than 4*D to make sure that DEA will have the enough mutually different vectors. They also recommended that F=0.5 and CR to be 1 or 0.9 to get faster convergence. The DEA procedure for optimizing the TEP problem is illustrated in Figure 2.

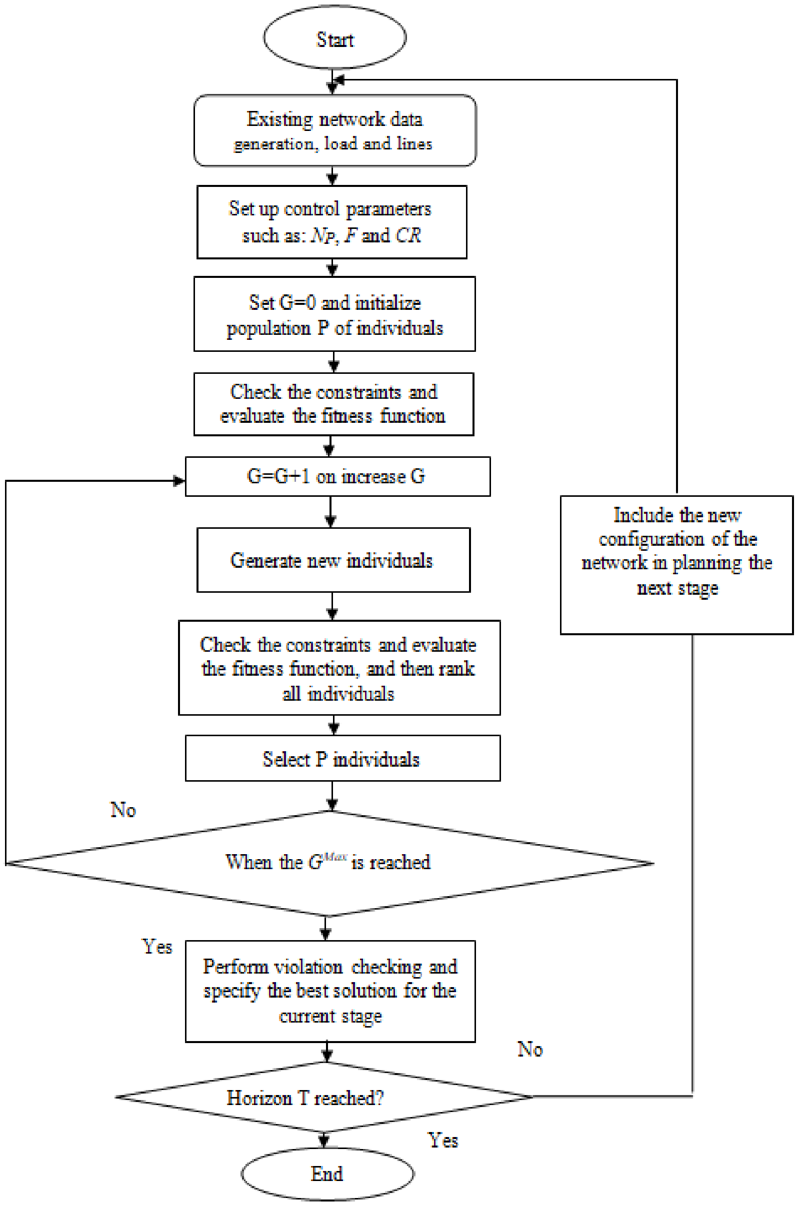

Figure 2. Implementation flow diagram

The proposed DEA procedure to solve the multistage TEP problem starts with checking the data of minimum and maximum sizes of the network, such as power generation, load demand and the transmission lines. A horizon of time stage planning (T) and an annual interest rate value (I). The lower and upper bounds of the initial population (xjmin and xjmax) are defined. DEA is very sensitive regarding the control parameters, a good choice for them; guarantee a faster convergence and good results. The algorithm continues by initializing the population of individuals and evaluating the fitness function, followed by checking the constraints. Next is the optimization step, where G=1 and applying mutation, crossover and selection to generate the new individuals. Then, the fitness function is evaluated and the algorithm checks if there is any violation of the AC load flow constraints. In case of any violation registered, the obtained solution is considered infeasible and the selected values of the control parameters should be changed. The procedure stops when the predefined convergence criterion is obtained or the maximum number of generation is reached. Otherwise, the algorithm repeats the optimization process and will continue searching. The optimization step for finding the best solution is repeated until the maximum number of generations (Gmax) is reached. The proposed technique can be implemented with various systems. It can be further implemented for a practical system since it deals with all the aspects of the real world networks.

4.2. Fitness Function Calculation

After generating the initial population, each individual will contain integer valued Nij and continuous valued PG. An AC load flow calculations is performed for every individual. Generally, the fitness function is employed for finding the best solution that satisfies all the constraints by checking for violations. In order to represent the violations of the equality and inequality constraints, penalty functions are applied in the fitness function as follows:

$$FF_{stage} = \frac{PF}{OF_{stage} + W_1 * P_1 + W_2 * P_2} \tag{23}$$

Where FF and OF are the fitness function and objective function of the TEP problem, respectively, and P1 and P2 are the equality and inequality constraint penalty functions, respectively. PF is the Penalty Factor for the violation of a constraint which is set to 10000 in this work. W1 and W2 are penalty weighting factors, which are set to 1.0 in this work. The modifications of the Newton Raphson AC power flow model to solve the multistage TEP problem and check the constraints violations are as follows:

$$\min v = \sum_{t=1}^{T} \left[\delta_{inv}^{t} \sum_{(i,j)\in\Omega} c_{ij}{}^{t} n_{ij}{}^{t} \right] \tag{24}$$

$$P_2 = \lambda_V \sum |V_V| + \lambda_{PG} \sum |V_{PG}| + \lambda_{QG} \sum |V_{QG}| + \lambda_{Sfrom} \sum |V_{Sfrom}| + \lambda_{Sto} \sum |V_{Sto}| + \lambda_n \sum |V_n| \tag{25}$$

$$P_1 = 0 \tag{26}$$

where:

$$V_{QG} = \begin{cases} 0 & if \quad Q_{Gi}^{Min} \le Q_{Gi} \le Q_{Gi}^{Max} \\ Q_{Gi} - Q_{Gi}^{Max} & if \quad Q_{Gi} > Q_{Gi}^{Max} \\ Q_{Gi} - Q_{Gi}^{Min} & if \quad Q_{Gi} < Q_{Gi}^{Min} \end{cases} \tag{27}$$

$$V_V = \begin{cases} 0 & if \quad Vi^{Min} \le Vi \le Vi^{Max} \\ V - V^{Max} & if \quad V > V^{Max} \\ V - V^{Min} & if \quad V < V^{Min} \end{cases} \tag{28}$$

$$V_{PG} = \begin{cases} 0 & if \quad P_{Gi}^{Min} \leq P_{Gi} \leq P_{Gi}^{Max} \\ P_{Gi} - P_{Gi}^{Max} & if \quad P_{Gi} > P_{Gi}^{Max} \\ P_{Gi} - P_{Gi}^{Min} & if \quad P_{Gi} < P_{Gi}^{Min} \end{cases} \quad (29$$

$$V_n = \begin{cases} 0 & if \quad 0 \leq n \leq n^{Max} \\ n - n^{Max} & if \quad n > n^{Max} \\ n - 0 & if \quad n < 0 \end{cases} \quad (30)$$

$$V_{Sfrom} = \begin{cases} 0 & if \quad (N+N^0)S^{from} \leq (N+N^0)S^{\max} \\ (N+N^0)S^{from} - (N+N^0)S^{\max} & if \quad (N+N^0)S^{from} > (N+N^0)S^{\max} \end{cases} \quad (31)$$

$$V_{Sto} = \begin{cases} 0 & if \quad (N+N^0)S^{to} \leq (N+N^0)S^{\max} \\ (N+N^0)Sto - (N+N^0)S^{\max} & if \quad (N+N^0)S^{to} > (N+N^0)S^{\max} \end{cases} \quad (32)$$

The value of P2 expresses the summation of the violation in every constraint. The constant λ has the same value of F (mutation factor). Another advantage of using the differential evolution algorithm is that, it can even start with impossible solution. In order to find the fitness function for the all stages, a simple derivation should be made as following:

$$Vio_{stage} = \frac{PF}{FF_{stage}} - OF_{stage} \quad (33)$$

$$violation = \sum_{t=1}^{T} Vio_{stage1} + Vio_{stage2} + Vio_{stageT} \quad (34)$$

To ensure that the obtained solution is feasible, the total violation in this equation must equal to 0. Otherwise the parameters should be changed to find the optimal solution.

$$OF_{total} = \sum_{t=1}^{T} \delta_{inv}^{t} . \, OF_{stage1-T} \quad (35)$$

$$FF_{total} = \frac{PF}{OF_{total} + Vio_{total}} \quad (36)$$

The violation of every stage and the total violation can be obtained by (33) and (34), respectively. Equation 35 expresses the total value of the objective function of the three stages and the total fitness function is obtained by equation 36. Note that, if there is no violation at the planning stage there will be no need to perform the TEP process since all the constraints are satisfied and system is working adequately.

5. Tests and Results

The plan consists of three planning stages P1, P2 and P3. The P1 stage is the first stage which is the period from 2017 until 2020 and 2017 is the base year for this stage. The P2 stage is the period from 2020 until 2024 and 2020 is the base year for the second stage. The P3 stage is the period from 2024 until 2027 and 2024 is the base year for the third stage. In this paper, the total transmission expansion investment plan is obtained with reference to the base year 2014 and the annual interest rate value I=10%. The maximum number of lines allowed to be added in parallel with the existing lines in this study is four lines in each branch. Note that, if there is no violation at the initial planning stage there will be no need to perform the TEP process since all the constraints are satisfied and the system is working adequately. Otherwise, the method attempts to obtain the feasible and then the optimum solution.

5.1. IEEE 24-Bus System

The IEEE 24 bus system is used in this work to test the proposed methodology for the multistage TEP problem. The system has 33 generators connected at 10 busses and 21 loads. The line investment cost and the system details can be found in [20]. The total load of this system is 2850 MW.

The proposed method has shown its ability in obtaining good results and high quality solutions. All DEA modes obtained competitive and promising results; DEA mode 3 has found the best topology for the expansion plan with the least investment cost. In addition, Figures (3) and (4) show the best obtained objective function and fitness function based on DEA mode 3. Furthermore, there is no violation registered and all the constraints are satisfied. Table 1 shows the additional lines to be added to the system along the planning horizon and the related initial cost of the expansion before considering the discount factors due to the installation delay.

Table 1. The Expansion Investment Cost Calculation of IEEE 24-bus Test System

Planning stage	Additional lines	Investment Cost, (MUS$)
Stage P1	$n_{1\text{-}2}=1$, $n_{6\text{-}10}=1$, $n_{17\text{-}18}=1$ and $n_{20\text{-}23}=1$	69
Stage P2	$n_{3\text{-}9}=1$ and $n_{17\text{-}18}=1$, $n_{6\text{-}7}=1$, $n_{10\text{-}12}=1$, $n_{14\text{-}23}=1$ and $n_{4\text{-}9}=1$	264
Stage P3	$n_{1\text{-}2}=1$, $n_{9\text{-}12}=1$, $n_{5\text{-}10}=1$, $n_{2\text{-}8}=1$, $n_{11\text{-}14}=1$, $n_{16\text{-}23}=1$ and $n_{8\text{-}9}=1$	324

The additional transmission lines determined by the proposed DEA method using mode 3 are as follows:

Stage P1: n1-2=1, n6-10=1, n17-18=1 and n20-23=1.

Stage P2: n3-9=1 and n17-18=1, n6-7=1, n10-12=1, n14-23=1 and n4-9=1

Stage P3: n1-2=1, n9-12=1, n5-10=1, n2-8=1, n11-14=1, n16-23=1 and n8-9=1.

Considering the discount factors due to the installation delay are equal to 1.0, 0.729 and 0.478 for the first, second and third stages, respectively. The final cost of the expansion plan can be obtained by applying (1) as shown in Table 2. Figure 3 shows the average convergence curve of the objective function for IEEE 24-Bus System by DEA3. Figure 4 shows the average convergence curve of the fitness function for IEEE 24-Bus System by DEA3

Table 2. The Final Expansion Investment Cost Calculation of IEEE 24-bus Test System

Stage No.	Cost (MUS$)
Stage P1	69
Stage P2	192.4
Stage P3	145.3
Total Cost	406.7

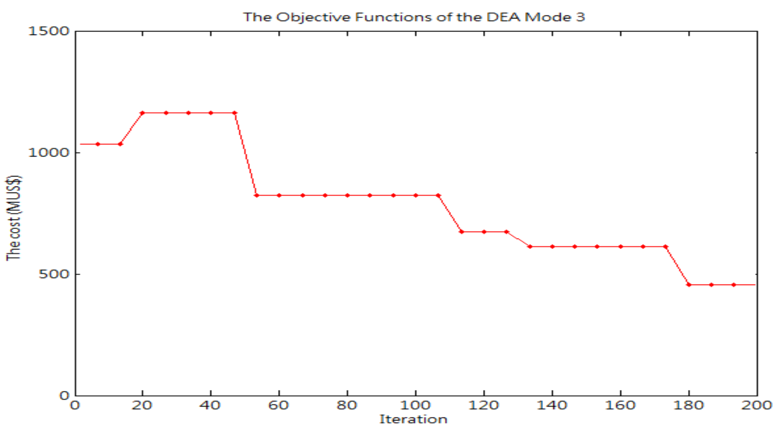

Figure 3. The average convergence curve of the objective function for IEEE 24-Bus System by DEA3

The new installed transmission lines along the planning horizon are depicted in Figure 5, where, the lines installed in the first, second and third stages are appeared in red, blue and green, respectively.

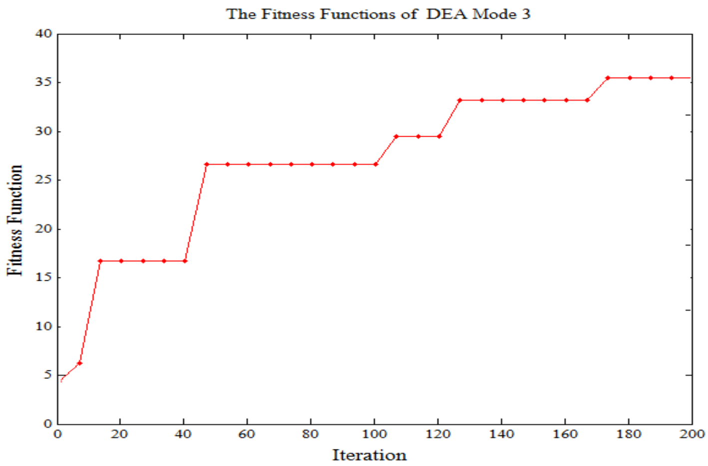

Figure 4. The average convergence curve of the fitness function for IEEE 24-Bus System by DEA3

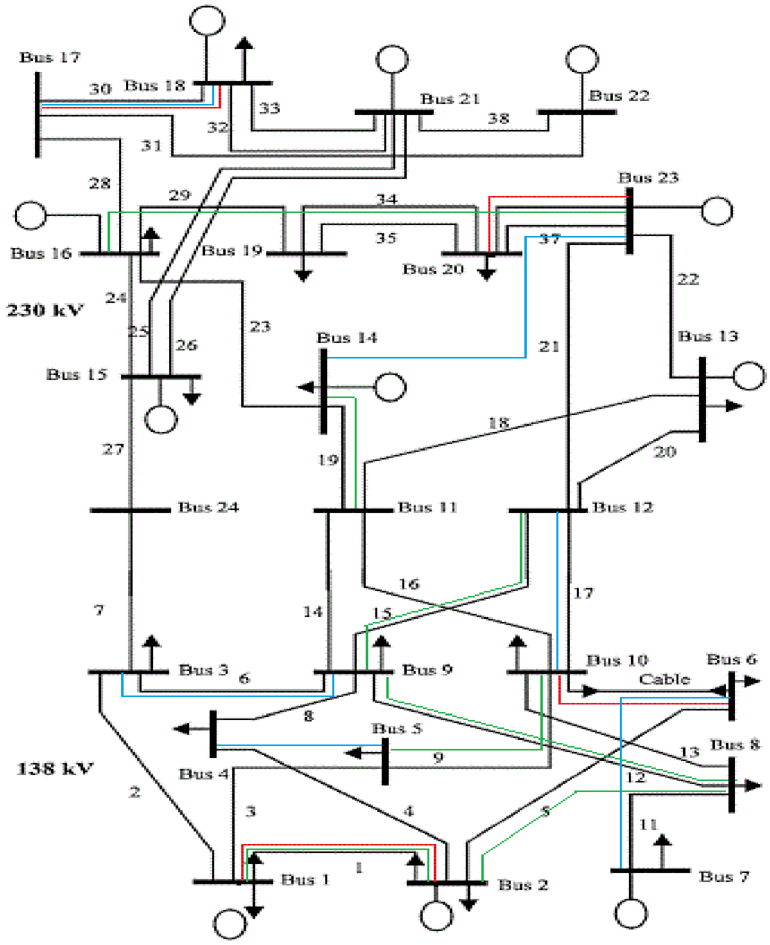

Figure 5. IEEE 24-bus system with the additional lines

5.2. Colombian 93-bus System

The system has 93 buses, 155 possible candidate right-of-ways and 14 559MW of total demand for the entire planning horizon. The required system data such as, generation, transmission lines and load data including the growth rate along the planning horizon (for the DC model) are available in [26]. It is important to note that some in the data of the system had to be introduced in order to use the AC model. The reactive power (in each bus) is 15% of the real power, the upper limits of the transmission lines are increased by 20%, and the resistance and susceptance are 10% and 1% of the reactance of the transmission line, respectively.

The DEA has shown its ability in obtaining good results and high quality solutions. In addition, all DEA modes obtained competitive and promising results. Furthermore, there is no violation registered and all the constraints are satisfied. Table 3 shows the additional lines to be added to the system along the planning horizon and the related initial cost of the expansion.

Table 3. The Expansion Investment Cost Calculation of Colombian 93-bus Test System

Planning stage	Additional lines	Investment Cost, (MS$)
Stage P1	$n_{57-81}=1$, $n_{45-81}=1$, $n_{55-57}=1$, $n_{85-91}=1$, $n_{43-88}=1$, $n_{8-67}=1$ and $n_{73-82}=1$	325.986
Stage P2	$n_{27-35}=1$, $n_{62-82}=1$, $n_{74-89}=1$, $n_{79-83}=1$, $n_{61-68}=1$, and $n_{72-73}=1$	108.722
Stage P3	$n_{19-86}=1$, $n_{43-88}=1$, $n_{15-20}=1$, $n_{30-64}=1$, $n_{31-72}=1$, $n_{30-65}=1$, $n_{55-82}=1$, $n_{68-86}=1$, $n_{19-58}=1$, and $n_{27-35}=1$	230.269

Among all the five modes, DEA mode 3 found the best topology for the expansion plan. Figure 6 and 7 show the best obtained fitness function and objective function based on DEA mode 3. The additional transmission lines determined by the proposed DEA method using mode 3 are as follows:

Stage P1: $n_{57-81}=1$, $n_{45-81}=1$, $n_{55-57}=1$, $n_{85-91}=1$, $n_{43-88}=1$, $n_{8-67}=1$ and $n_{73-82}=1$

Stage P2: $n_{27-35}=1$, $n_{62-82}=1$, $n_{74-89}=1$, $n_{79-83}=1$, $n_{61-68}=1$, and $n_{72-73}=1$

Stage P3: $n_{19-86}=1$, $n_{43-88}=1$, $n_{15-20}=1$, $n_{30-64}=1$, $n_{31-72}=1$, $n_{30-65}=1$, $n_{55-82}=1$, $n_{68-86}=1$, $n_{19-58}=1$, and $n_{27-35}=1$

The final cost of the expansion plan after considering the discount factor for each stage can be obtained by applying (1) as shown in Table 4.

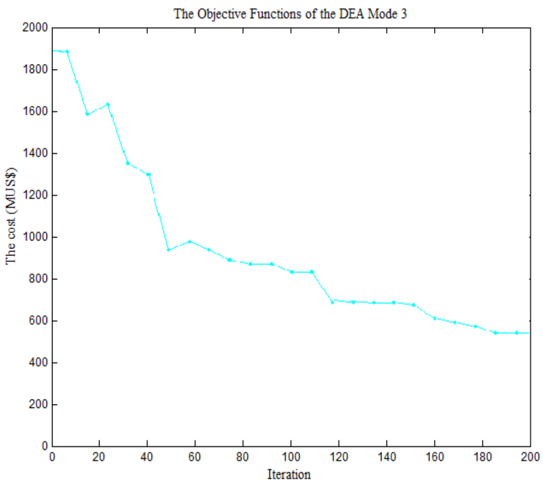

Figure 6. The average convergence curve of the objective function for Colombian 93-Bus System by DEA3

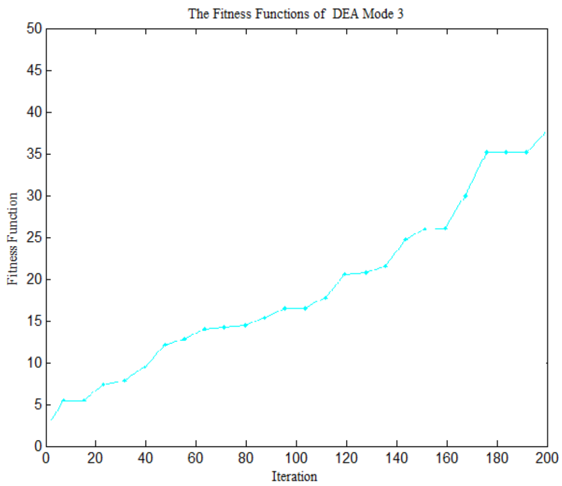

Figure 7. The average convergence curve of the fitness function for Colombian 93-Bus System by DEA3

Table 4. The Final Expansion Investment Cost Calculation of Colombian 93-bus Test System

Stage No.	Cost US$
Stage P1	325.986 M$
Stage P2	79.258 M$
Stage P3	110.068 M$
Total Cost	515.312M$

The Figure 8 shows the Colombian 93-bus system with the new installed transmission lines along the planning horizon. Where, the lines installed in the first, second and third stages are appeared in red, blue and green, respectively. Considering that DEA is stochastic evolutionary algorithm for global optimization over continuous space, the DEA has been run repeatedly and the tables 2 and 4 show the best obtained results. However, the suitable DEA control parameters for the multistage TEP problem are found to be within: mutation factor (*F*)=[0.69:0.7], crossover probability (*CR*)=[0.87:0.93] and population size (*NP*)=[*5*D*]. The maximum predetermined convergence criterion is set to 10^{-3}.

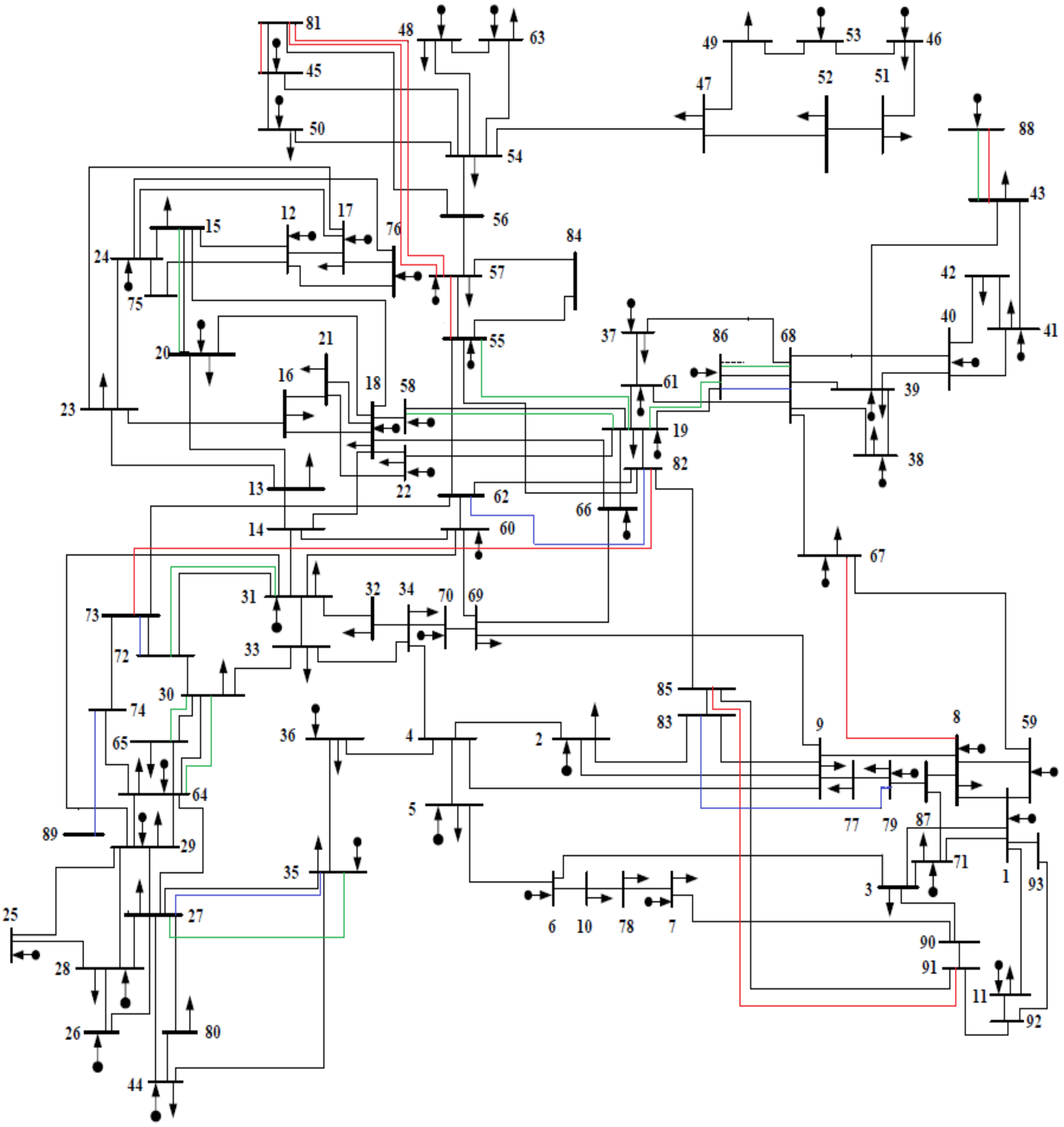

Figure 8. The 93-Bus Colombian System with the Additional Lines

6. Results Comparison

The obtained results clearly indicate that DEA procedure can be efficiently applied to solve the multistage TEP problem using AC power flow model. Comparing the proposed method to the works available in the literature as shown in Table 5, although the electrical aspects are not the same, an acceptable investment cost is found bearing in mind that, an AC power flow model is used which considers all the aspects of the power system while the works available in the literature have applied the DC model.

In the case of IEEE 24-bus system, the obtained results for every stage are acceptable. This work has yet to reduce the total investment cost the series of added lines. Actually, it is logical to have higher investment cost since the current work applied the AC power flow model which requires tedious work to deal with. Regarding the lines additions, the obtained topology from the proposed technique is not in agreement with the previous work [13] due to the differences of the applied methods.

For the Colombian 93 bus system, the proposed method has produced challenging and competitive to the previous results. In term of the lines additions, the proposed method results are close to the previous ones reported in [7], [13] and [19]. When comparing the proposed method to the previous works in term of the computationl times, the proposed method produces fast convergece. Table 5 shows the comparison that takes into account the investment cost and the total required computational time for every method.

It is important to note that at present the use of the AC power flow model in solving the multistage TEP problem is incipient and there are no previous studies about it. Therefore, the series of line additions found can be only considered best-quality topologies or suboptimum topologies. For that reason, there is no conclusive proof of the optimality of the results found.

Table 5. Comparison of the Obtained Plans versus Other Literatures

Applied Method	Cost (MUS$)
Colombian 93-bus system	
Current Method	515.312
DEA [17]	505.8
GA [9]	514.4
FSC[13]	492.167
IEEE 24-bus system	
Current Method	406.7
FSC[13]	360

In fact, dealing with the pure AC load flow model requires a higher objective function, considering the voltage and reactive power issues. Referring to Tables 5, the expansion cost of the current method is slightly higher than the other methods due to the mentioned factors. However, the obtained cost is still comparable economically to those of the previous works. Although the convergence speed is not an essential factor in the current problem formulation, the DEA showed high speed in obtaining the best solution. The time speed is an essential factor in case of considering reliability and security criteria along with the reactive power allocation. Generally, the proposed method performed efficiently in term of the solution quality which is simple to implement to solve the multistage transmission expansion planning problem.

6. Conclusion

This paper proposes a mixed integer nonlinear programming formulation for the multistage transmission expansion planning problem considering violation checking, where strictly pure AC load flow model is used. DEA has shown a good capability in providing a comparable and high quality solution; it even can start searching from an impossible solution. Popular and realistic test systems are used to show the accuracy and efficiency of the proposed model. The results show that it is possible to apply the AC power flow model to solve the multistage transmission expansion planning problem. Furthermore, there were no violation cases and all the constraints are satisfied which makes the system security constrained. It should be noted that, solving the large scale networks using the AC model is still challenging due to the voltage and reactive power problems. Generally, because of the non-convex nature of the transmission expansion planning problem, the global optimality of the obtained solutions is not guaranteed.

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