

Transmission Expansion Planning Considering Network Adequacy and Investment Cost Limitation using Genetic Algorithm

M. Mahdavi, E. Mahdavi

Abstract—In this research, STNEP is being studied considering network adequacy and limitation of investment cost by decimal codification genetic algorithm (DCGA). The goal is obtaining the maximum of network adequacy with lowest expansion cost for a specific investment. Finally, the proposed idea is applied to the Garvers 6-bus network. The results show that considering the network adequacy for solution of STNEP problem is caused that among of expansion plans for a determined investment, configuration which has relatively lower expansion cost and higher adequacy is proposed by GA based method. Finally, with respect to the curve of adequacy versus expansion cost it can be said that more optimal configurations for expansion of network are obtained with lower investment costs.

Keywords—TNEP, Network Adequacy, Investment Cost, GA

I. INTRODUCTION

TRANSMISSION network expansion planning (TNEP) is an important part of power system planning that its main objective is to acquire the most optimal plan for the network expansion. It determines where, when and which kind of transmission line must be added to the network. TNEP should be satisfied required adequacy of the lines for delivering safe and reliable electric power to load centers along the planning horizon [1-3]. Calculation of investment cost for network expansion is difficult because it is dependent on the various reliability criteria [4]. Thus, the long-term TNEP is a hard, large-scale combinatorial optimization problem. Transmission expansion planning is a hard and highly non-linear combinatorial optimization problem that generally, can be classified as static or dynamic. Static expansion determines where and how many new transmission lines should be added to the network up to the planning horizon. If in the static expansion the planning horizon is categorized in several stages we will have dynamic planning [5, 6].

In the majority of power systems, generating plants are located far from the load centers. In addition, the planned new projects are still far from completion. Due to these factors, investment cost for transmission network is huge. Thus, the STNEP problem acquires a principal role in power system planning and should be evaluated carefully because any effort to reduce transmission system expansion cost significantly improves cost saving. After Garver's paper that was published in 1970 [7], much research has been done on the field of

TNEP problem. Some of them such as [1-3], [6], [8-25] is related to problem solution method. Some others, proposed different approaches for solution of this problem considering various parameters such as uncertainty in demand [5, 26], reliability criteria [4, 27, 28], and economic factors [29]. Also, some of them investigated this problem and generation expansion planning together [30, 31]. Recently, different methods such as GRASP [3], Bender decomposition [6], HIPER [17], branch and bound algorithm [32], sensitivity analysis [15], genetic algorithm [1, 11, 20], particle swarm optimization [24], simulated annealing [16, 25] and Tabu search [12] have been proposed for the solution of STNEP problem. In all of these methods, the problem has been solved regardless to network adequacy and limitation of investment cost. In Ref. [8], authors proposed a neural network based method for solution of the TNEP problem with considering both the network losses and construction cost of the lines. But the transmission network adequacy for a limited investment cost has not been investigated in this study. In Ref. [10], the network expansion costs and transmitted power through the lines have been included in objective function and the goal is optimization of both expansion costs and lines loading. In addition, the objective function is different from those which are represented in [6, 11, 12], [15-17], [20, 32]. However, the transmission network adequacy considering a specific investment has not been studied.

In Ref. [33], the voltage level of transmission lines has been considered as a subsidiary factor but its objective function only includes expansion and generation costs and one of the reliability criteria i.e.: power not supplied energy. Moreover, expansion planning has been studied as dynamic type and the network adequacy and investment cost limitation have not been considered. Finally, in pervious author's papers [34, 35], the expansion cost of substations with the network losses have been considered for the solution of STNEP problem. The results evaluation in [34] was shown that the network with considering higher voltage level save capital investment in the long-term and become overload later. In [35], it was shown that the total expansion cost of the network was calculated more exactly considering effects of the inflation rate and load growth factor and therefore the network satisfies the requirements of delivering electric power more safely and reliably to load centers. However, the network adequacy in transmission expansion planning has not been studied.

The network adequacy is necessary to provide load demands when the network is expanding because its lack (i.e. lines overloading) causes to load interrupting. Consequently, if transmission lines of expanded network overloads later, the

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network satisfies the requirements of delivering electric power more safely and reliably to load centers. It is well-known that the transmission network adequacy correlates with the investment cost. i.e.: the network adequacy increases by rising investment cost and using the exact planning and the proper algorithm. On the other hand, with a low costing, the network operates weakly to support load demand and becomes overloaded early. Therefore, with compromising between two parameters, i.e. investment cost and network adequacy rate and finally defining a curve which show network adequacy versus expansion cost, static transmission network expansion planning can be implemented in order to have a network with maximum efficiency from the technical and economical viewpoint.

In this paper, transmission expansion planning has been studied by including the adequacy of transmission lines and expansion cost in objective function and maximum investment cost in constrains of the STNEP problem using decimal codification genetic algorithm (DCGA). It should be noted that with performing DC load flow according to load growth for years after expansion, if only a line of the network is overloaded in each year, network adequacy is missed. Also, the best solution that obtains from GA method is the configuration for network expansion which has a respectively lower cost and higher adequacy that will be lately overload. With respect to this fact that investment cost for expansion of the network is determined by network owner, the case study has received various amount of this parameter.

II. MATHEMATICAL MODEL OF THE STNEP PROBLEM

In this study, in order to consideration of transmission lines condition after expansion from the loading viewpoint, the adequacy of transmission network is included in STNEP objective function. Therefore, the proposed objective function is defined as follows:

$$C_E = \sum_{i,j \in \Omega} CL_{ij} n_{ij} + C_o T \quad (1)$$

Where:

C_E : Optimal expansion cost of network.

CL_{ij} : Construction cost of each line in branch i-j.

n_{ij} : Number of new circuits in corridor i-j.

Ω : Set of all corridors.

T : Required time for missing the expanded network adequacy (in year).

C_o : Annual worth of transmission network adequacy (\$/year). Determination of this parameter is based on importance of network adequacy for network owners.

Several restrictions have to be modeled in a mathematical representation to ensure that the mathematical solutions are in line with the planning requirements. These constraints are as follows (see Refs. [5, 34] for more details):

$$Sf + g - d = 0 \quad (2)$$

$$f_{ij} - \gamma_{ij} (n_{ij}^0 + n_{ij}) (\theta_i - \theta_j) = 0 \quad (3)$$

$$0 \leq n_{ij} \leq \overline{n_{ij}} \quad (4)$$

$$C \leq C_{\max} \quad (5)$$

$$N-1 \text{ Safe Criterion} \quad (6)$$

Where, $(i, j) \in \Omega$ and:

S : Branch-node incidence matrix.

f : Active power matrix in each corridor.

d : Demand vector.

N : Number of network buses.

θ : Phase angle of each bus.

γ_{ij} : Total susceptance of circuits in corridor i-j.

n_{ij}^0 : Number of initial circuits in corridor i-j.

$\overline{n_{ij}}$: Maximum number of constructible circuits in corridor i-j.

f_{ij} : Maximum of transmissible active power through corridor i-j which will have two different rates according to voltage level of candidate line.

C_{\max} : Maximum investment for expanding the network.

In this study, the objective function is different from those which are mentioned in [1-20], [23-29], [31, 32, 34, 35] and the goal is obtaining the number of required circuits for adding to the existed network so that it have been maximum adequacy with minimum investment cost during the specified horizon year. Thus, problem parameters of the problem are discrete time type and consequently the optimization problem is an integer programming problem. For the solution of this problem, there are various methods such as classic mathematical and heuristic methods [5-21]. In this work, the decimal codification genetic algorithm is used to solve the STNEP problem due to flexibility, simple implementation and the advantages which were mentioned in [34].

III. DCGA AND CHROMOSOME STRUCTURE OF THE PROBLEM

Standard genetic algorithm is a random search method that can be used to solve non-linear system of equations and optimize complex problems. The base of this algorithm is the selection of individuals. It doesn't need a good initial estimation for sake of problem solution. In other words, the solution of a complex problem can be started with weak initial estimations and then be corrected in evolutionary process of fitness. The standard genetic algorithm manipulates the binary strings which may be the solutions of the problem. This algorithm can be used to solve many practical problems such as transmission network expansion planning [35, 35]. The genetic algorithm generally includes the three fundamental genetic operators of reproduction, crossover and mutation. These operators conduct the chromosomes toward better fitness. There are three methods for coding the transmission lines based on the genetic algorithm method [34, 35]:

1) Binary codification for each corridor.

2) Binary codification with independent bits for each line.

3) Decimal codification for each corridor.

Although binary codification is conventional in genetic algorithm but in here, the third method has been used due to following reasons [35]:

1) Avoiding difficulties which are happened at coding and decoding problem.

2) Preventing the production of completely different offspring from their parents and subsequent occurrence of divergence in mentioned algorithm.

In this method crossover can take place only at the boundary of two integer numbers. Mutation operator selects one of existed integer numbers in chromosome and then changes its value randomly. Reproduction operator, similar to standard form, reproduces each chromosome proportional to value of its objective function. Therefore, the chromosomes which have better objective functions will be selected more probable than other chromosomes for the next population (i.e., Elitism strategy). In this work, each gene in the chromosome includes number of transmission circuits (the both of constructed and new circuits) at each corridor. Fig. 1 shows a typical chromosome with 12 corridors. Flowchart of the proposed approach for the solution of TNEP problem using DCGA is shown in Fig. 2.

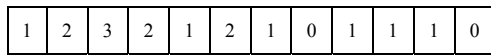


Fig. 1 A typical chromosome structure

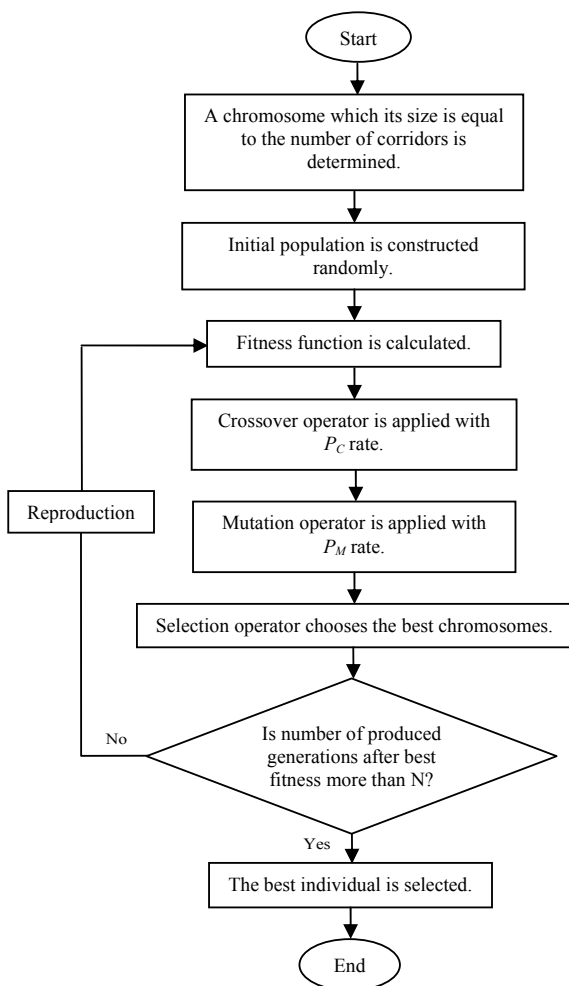


Fig. 2 Flowchart of the proposed method

A. Selection, Crossover and Mutation Process

This operator selects the chromosome in the population for reproduction. The more fit the chromosome, the higher its probability of being selected for reproduction. Thus, selection

is based on the survival-of-the-fittest strategy, but the key idea is to select the better individuals of the population, as in tournament selection, where the participants compete with each other to remain in the population. The most commonly used strategy to select pairs of individuals that has applied in this paper is the method of roulette-wheel selection [36]. After selection of the pairs of parent strings, the crossover operator is applied to each of these pairs.

The crossover operator involves the swapping of genetic material (bit-values) between the two parent strings. Based on predefined probability, known as crossover probability, an even number of chromosomes are chosen randomly. A random position is then chosen for each pair of the chosen chromosomes. The two chromosomes of each pair swap their genes after that random position. Crossover may be applied at a single position or at multiple positions. In this work, because of choosing smaller population multiple position crossover is used with probability of 0.9.

Each individuals (children) resulting from each crossover operation will now be subjected to the mutation operator in the final step to forming the new generation. The mutation operator enhances the ability of the GA to find a near optimal solution to a given problem by maintaining a sufficient level of genetic variety in the population, which is needed to make sure that the entire solution space is used in the search for the best solution [35]. In a sense, it serves as an insurance policy; it helps prevent the loss of genetic material. This operator randomly flips or alters one or more bit values usually with very small probability known as a mutation probability (typically between 0.001 and 0.01). In a binary coded GA, it is simply done by changing the gene from 1 to 0 or vice versa [37]. In DCGA, as in this study, the gene value is randomly increased or decreased by 1 providing not to cross its limits. Practical experience has shown that in the transmission expansion planning application the rate of mutation has to be larger than ones reported in the literature for other application of the GA. In this work mutation is used with probability of 0.1 per bit. After mutation, the production of new generation is completed and it is ready to start the process all over again with fitness evaluation of each chromosome. The process continues and it is terminated by either setting a target value for the fitness function to be achieved, or by setting a definite number of generations to be produced. In this study, a more suitable criteria termination has accomplished that is production of predefined generations after obtaining the best fitness and finding no better solution. In this work a maximum number of 3500 generations has chosen.

IV. CASE STUDY

Garver's network is used as a test system to demonstrate the effectiveness of the proposed idea. This network is shown in Fig 3. In this network, existed lines are 400 kV with capacity 750 MW. Resistance and reactance of each line are 0.000035 and 0.000124 Ω/Km , respectively. Other required data of the network are detailed in [35]. Finally, the planning horizon year is 2021 (10 years ahead).

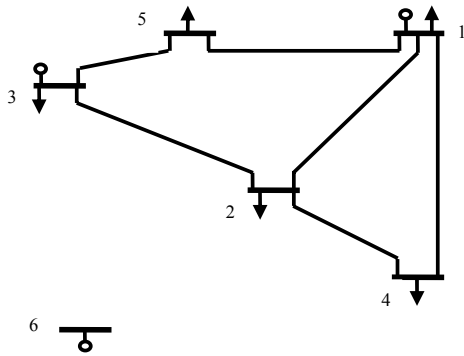


Fig. 3 Garver's 6-bus network

The proposed method is applied to the case study system for different rate of investment costs (C_{\max} = 20 to 90 million dollars) and the results are given in Tables 1-3. It should be noted that the rate of C_{\max} is determined by network owner. Thus, with respect to this cost, the planner should propose a design which has relatively more adequacy and lower expansion cost.

TABLE I

PROPOSED CONFIGURATIONS WITH RESPECT TO C_{\max} =20-45 MILLION \$US

	C_{\max} =20 & 25	C_{\max} =30	C_{\max} =35	C_{\max} =40	C_{\max} =45
Corridor	Number of circuits	Number of circuits	Number of circuits	Number of circuits	Number of circuits
2-6	0	2	3	3	3
3-5	0	1	1	2	2
4-6	3	2	2	2	4

TABLE II

PROPOSED CONFIGURATIONS WITH RESPECT TO C_{\max} =50-90 MILLION \$US

	C_{\max} =50	C_{\max} =55 & 60	C_{\max} =65	C_{\max} =70- 80	C_{\max} =85 & 90
Corridor	Number of circuits	Number of circuits	Number of circuits	Number of circuits	Number of circuits
2-6	3	4	4	4	4
3-5	2	3	3	2	3
3-6	0	0	1	0	1
4-6	4	3	3	3	4
5-6	0	0	0	1	1

TABLE III

EXPANSION COSTS AND YEARS OF MISSING THE NETWORK ADEQUACY FOR C_{\max} =20-90 MILLION \$US

C_{\max}	Expansion cost	T
20 & 25	17.849 MSUS	9 years after expansion (2020)
30	27.837 MSUS	14 years after expansion (2025)
35	33.787 MSUS	16 years after expansion (2027)
40	37.824 MSUS	18 years after expansion (2029)
45	42.724 MSUS	20 years after expansion (2031)
50	47.245 MSUS	20 years after expansion (2031)
55 & 60	53.762 MSUS	22 years after expansion (2033)
65	54.622 MSUS	23 years after expansion (2034)
70-80	68.890 MSUS	24 years after expansion (2035)
85 & 90	80.796 MSUS	25 years after expansion (2036)

From the above Tables it can be seen that, with increasing the investment cost, more lines are added to the network and subsequent network adequacy increases (the lines of network is overloaded later). But, a balance must be created between value of network adequacy and investment cost. i.e. configuration which has relatively higher adequacy and lower investment cost should be proposed for network expansion. Fig. 4 which has been obtained with respect to Tables 1-3, shows the relation of network adequacy with investment cost.

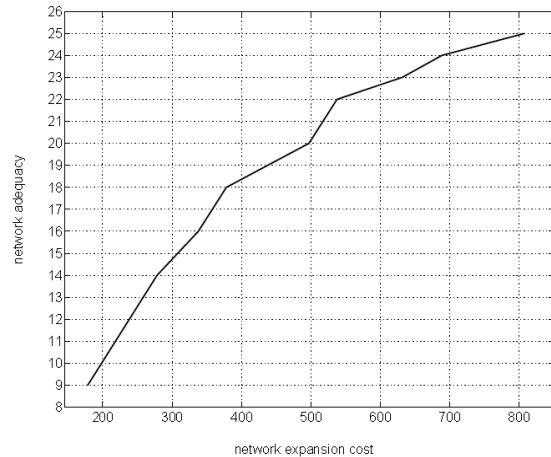


Fig. 4 The curve of adequacy versus expansion cost

According to Fig. 4, it can be seen that network adequacy does not increase proportional to growth of investment cost and for higher investment costs is faced to saturation. Thus, it seem that expansion of network with lower investment costs is caused the network posses higher adequacy in comparison with expansion on network with higher investment costs.

V. CONCLUSION

In this paper, by including the transmission network adequacy and maximum investment cost in the objective function and constrains of STNEP problem, an optimal network arrangement is obtained for the network expansion using a decimal coded genetic algorithm (DCGA) method. The proposed arrangement satisfies a maximum adequacy for the feeding of loads with minimum expansion cost. As it is expected, increasing the investment cost (in fact, adding more lines to network) is caused network that is better from overloading point of view is gained. But by limiting this cost that is more near to fact, it can be concluded that if the expansion cost is increased, network which is better from adequacy point of view is not obtained. Because, simulation results shows the optimal configuration is more near to lower amounts of expansion cost.

APPENDIX

A. Selection, Crossover and Mutation Process

Load growth coefficient = 1.07

Number of initial population = 5

End condition: 3500 iteration after obtaining best fitness ($N=3500$).

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