Power System Capacity Expansion Planning Using Monte Carlo Simulation and Genetic Algorithm

Ching-Tzong Su　　Guor-Rurng Lii

Institute of Electrical Engineering, National Chung Cheng University, Chiayi 621, TAIWAN
Fax: 886-52752013　　Tel: 886-52428162
Email : ieects@ccunix.ccu.edu.tw

Abstract -- This paper presents a new optimization approach for electric power system expansion planning. The expansion is performed by adding new transmission lines and/or generators such that system total cost associated with the expansion alternative is optimized and future load demand is satisfied. The proposed method adopts a Monte Carlo simulation technique, maximum-flow minimum-cut theorem, and optimization techniques to find a desired alternative for expansion. In the Monte Carlo simulation, a two-state model for the system components is employed. On the other hand, the system reliability is measured by the index of expected demand not served. To determine the expected demand not served, the labeling and augmentation algorithms and maximum-flow minimum-cut theorem are applied. The system reliability is expressed by the measure of expected demand not served. Which can then be transformed into the interruption cost. Consequently, an objective function composed of the interruption cost and installation cost to be optimized can be established. However, due to the characteristics of this problem and the adaptability and effectiveness of genetic algorithms (GAs), we employ GAs to resolve the optimization problem. Finally, to demonstrate the application of the proposed method, an IEEE five-bus test system is exemplified

1. INTRODUCTION

Network expansion deals with an ever growing need for more load demand. In order to meet this demand, the size of the network is incrementally expanded according to the customer requirements. In such an environment, it is critical that the new generators and transmission lines are added in a prudent manner to maximize the performance and reliability characteristics of the expanded network. There are few algorithms for optimizing network capacity expansions of electric power systems "it was shown by Billinton and Allan [1984], Sallam et al. [1990], Nara et al. [1992], Su et al. [1986a], Su et al. [1987], Su and Lii [1995]". In electric power systems, there are optimization problems. A trade-off between system installation cost and power interruption cost is required. An alternative is optimum when its associated total cost is minimum.

This paper presents a GAs based approach for the capacity expansion of composite (generation + transmission) power systems. GAs, termed as artificial intelligence approaches, are finding wide applications in resolving optimization problems. GAs are kinds of probabilistic, heuristic and stochastic algorithms that are able to find the global minima. Which have an advantage that the fitness function does not necessarily require the gradient. In that sense, the method is more flexible in solving the optimization problems for a composite power system. Monte Carlo method is employed to simulate the status of system components, and after the simulation, a graph exclusive of the failed elements is formed to replace the physical power network. To determine the demand served (and thus the demand not served) corresponding to the graph obtained at this simulation, the labeling and augmentation algorithms and the maximum-flow minimum-cut theorem are employed. Similar simulations are repeated for specified times, and from which we obtain the expected demand not served for the system.

2. PROBLEM STATEMENT

Reliability requirements vary greatly depending on the type of equipment or system under consideration. For any given apparatus there likely has trade-off between installation cost and interruption cost. The more the effort puts into making the apparatus reliable, the higher will be its initial or installation cost. On the other hand, the more reliable an apparatus is, the lower the cost for interruption and repair is likely to be. We might be tempted to ensure that the solution is optimal when the total cost (i.e., installation cost + interruption cost) is minimized.

For a power network, the *DNS* of one individual simulation may be stated as :

$$DNS = D - PS \tag{1}$$

where D : demand, in MW
PS : power supplied, in MW
DNS : demand not served, in MW

The *EDNS* computed from the simulation results may be stated as

$$EDNS = (\sum_{k=1}^{N_s} DNS_k) / N_S \quad (2)$$

where $EDNS$: expected demand not served, in MW
DNS_k : demand not served at the k-th simulation, in MW
N_s : total number of simulation computations

The objective of the proposed method is to find the optimal network expansion of the power system, such that the total cost consisting of interruption cost and installation cost can be minimized. The objective function of the optimization model may be defined as follows

$$Y = Y_1 + Y_2$$

$$= C_t * EDNS * 8760 + \sum_{i=1}^{N_a} (C_{1i} + C_{2i} * \frac{1-FOR}{FOR}) \quad (3)$$

where Y : total cost, in k$/year
Y_1 : interruption cost, in k$/year
Y_2 : installation cost, in k$/year
C_t : price of one MW-hour lost, in k$/MW-hour
N_a : total number of apparatus for the system
C_{1i}, C_{2i} : installation-cost coefficients for the i-th apparatus, in k$/MW and k$/km for generators and transmission lines, respectively.
$: a nameless, fictional monetary unit
FOR : forced outage rate

The system demand served can be determined by employing the maximum-flow minimum-cut theorem. Which states that the maximum flow equals the minimum cut, and the demand served is equal to the maximum flow.

3. THE EMPLOYED TECHNIQUES

3.1 Graph Formation

The data fed into the model consist of

(1) Generator : connection bus, rating of capacity and *FOR*.
(2) Transmission line : starting and end bus, rating of capacity and *FOR*.
(3) Load : connection bus and demand.

The physical network system is first represented as a base graph "it was shown by Su et al. [1986a], Su et al. [1987], Su et al. [1986b], Su et al. [1986c]". In this process, generators, lines and bus loads all become branches. Each branch representing the generator is connected to a common vèrtex called source S and is assigned a direction apart from the source. Each branch representing the bus load is connected to another common vertex called sink L, and is assigned a direction toward the sink. On the other hand, the branches representing the lines are assigned directions arbitrarily. It should be pointed out that the base graph established in this section is obtained for the normal system state.

3.2 Monte Carlo Simulation

Two-state model and the Monte Carlo simulation method are adopted for the system reliability assessment. It is assumed that any one of generators and lines is either in normal state or failure state, and the network state is a random variable. In common Monte Carlo analysis, sample values are drawn at random from the distributions of each of the input variables. The simulation consists of generating random numbers representing the values of the problem variables. The state of the branches representing the generators and lines is simulated by the random drawing of a number pertaining to a uniform probability function. If the random number is in [0, *FOR*], the branch is considered to be failed and the capacity is assumed to be zero at that time. Otherwise, it will be considered to be functioning and the capacity will be assumed in its rating, if the random number is in [*FOR*, 1]. The load of each branch representing the bus load is treated as a fixed amount. After this simulation process, a reduced graph exclusive of the failed elements is formed.

3.3 Labeling And Augmentation Algorithms

To determine the demand served, the leveling and augmentation algorithms "it was shown by Sullivan [1977]" are first employed. In labeling algorithm, the procedures for labeling a graph so as to identify an augmentation path are as follows :

(1) Label node S by $(S, +, \infty)$. The S identifies the node; the + indicates that the flow into the node can be increased; and the ∞ indicates that the amount of flow available to node S is infinite. S is now labeled and unscanned (unscanned means we have not yet extracted any flow from the node) and all other nodes are unlabeled and unscanned.
(2) Select any labeled and unscanned node i, then for any unlabeled and unscanned node j connected to i through branch m
(2a) Label node j by $(i, -, \Delta f_{mj})$, for $f_m(j,i) > 0$, and $\Delta f_{mj} = \min[I_i, P_m + f_m(j,i)]$; or label node j by $(i, +, \Delta f_{mj})$, for $f_m(i,j) > 0$, and $\Delta f_{mj} = \min[I_i, P_m - f_m(i,j)]$.
where I_i : the flow available at node i, in MW
P_m : the capacity of branch m, in MW
$f_m(i,j)$: the flow of branch m from node i to node j, in MW
The label contains a + if the flow can be increased

and a $-$ if the flow can only be decreased. Bus j is now labeled and unscanned.

(2b) Circle the $\pm$ index of bus i to indicate that it has been scanned.

(3) Repeat step (2) until node L is labeled, go to the augmentation algorithm; or until no more labels can be assigned, go to find the minimum cut.

The augmentation algorithm is a methodical procedure using the labeled graph for actually augmenting the flow. The process is started with the fictitious common demand node L, and the algorithm may be stated as follows

(1) Set j=L.
(2) Compare the Δf_{mj} between labeled node j and the preceding node i (this node is scanned by node j from labeling algorithm), then let $\Delta f_m = \min(\Delta f_{mi}, \Delta f_{mj})$.
(3) If i=S, let j=L and go to step (4); otherwise $i \neq$ S, let $j=i$ and return to step (2).
(4) If the label on the node j is $(i,+,\Delta f_{mj})$, then increase the flow through branch m by an amount Δf_m. However, if the label is $(i,-,\Delta f_{mj})$, then decrease the flow on branch m by an amount Δf_m.
(5) If the next labeled node considered is the source node S, let i=S, erase all labels and return to the labeling algorithm. However, if the next labeled node being considered is $i \neq$ S, let $j=i$, return to step (4).

3.4 Maximum-Flow Minimum-Cut Theorem

After finishing the labeling and augmentation algorithms aforementioned, all branches in a graph between labeled and unlabeled nodes are the minimum cut elements. The maximum-flow minimum-cut theorem "it was shown by Ford and Fulkerson [1962]" is stated as :

For all feasible flow patterns

$$\max(f_{S-L}) = \min_{Q}[c(q_{S-L})] \qquad (4)$$

where
- Q : the set of all such q_{S-L} cuts
- f_{S-L} : the flow from node S to node L, in MW
- q_{S-L} : a set of elements whose removal from the graph breaks all directed paths from node S to node L
- $c(q_{S-L})$: the sum of the capacities of all the elements defining the q_{S-L} cut, in MW

That is, for a graph, the maximum flow is equal to the sum of the capacities of the minimum cut elements.

3.5 Genetic Algorithms

Genetic Algorithms "it was shown by Michalewicz [1992]" are conceptually based on natural genetic and evolution mechanisms working on populations of solutions in contrast to other search techniques that work on a single one. The maximization process of GAs includes the following steps :

(1) String representation -- GAs have typical coding in binary. A string consists of bits; the number of bits is equal to the number of total candidate elements expanded for generator and line branches. Each bit is in the form of binary corresponding to the scheme estimated for adding or not of the apparatus. For example, the length of each binary string is set at 14 bits in the application example and shown as follows :

L_8	L_9	L_{10}	L_{11}	L_{12}	L_{13}	L_{14}	L_{15}	L_{16}	L_{17}	L_{18}	L_{19}	L_{20}	L_{21}

where L_i is the state of connected line (1 or 0) between two buses.

(2) Initial population generation -- Initial population of binary strings is created randomly.
(3) Fitness evaluation -- The solution strings and each candidate solution are tested in their environments. The fitness of each candidate solution is evaluated through an appropriate measure which is the negative value of the total cost function Y, i.e., the fitness function is equal to $-Y$.
(4) Selection and reproduction -- A set of old chromosomes are selected to reproduce a set of new chromosomes according to the probability which is proportional to their fitnesses. They are carried out to preserve better solution candidates.
(5) Crossover -- Crossover is performed on two chromosomes at a time that are selected from the population at random. To better the performance of GAs, the crossover rate is set at exponential change from low to high.
(6) Mutation -- Mutation involves selecting a chromosome and one of its bits at random and changing the bit selected from a 1 to a 0 or vice versa. It can be used to escape from a local minimum. To better the search effect of GAs, the mutation rate is set at exponential change from high to low. After mutation, the new generation is established and the procedure begins again with fitness evaluation of the population.

4. PROPOSED SOLUTION PROCEDURES

The solution procedures begin with a transformation of the expanding electric network into base graph and a random generation of pertinent chromosomes which satisfy the constraints of the problem. The Monte Carlo simulation method, labeling and augmentation algorithms, and maximum-flow minimum-cut theorem are used to compute the *EDNS* of the system for each chromosome and obtain an interruption cost associated with each chromosome. From the system *EDNS* and interruption cost as well as the installation cost, we determine the fitness (i.e., total cost) associated with each chromosome. Subsequently, GAs employ reproduction, crossover and mutation to create a new generation. The new generation provides new addition branches for the solution algorithm for another loop of computation. The process is repeated until the last generation specified is achieved. Figure 1 shows the flow chart of main computational procedures for the proposed method.

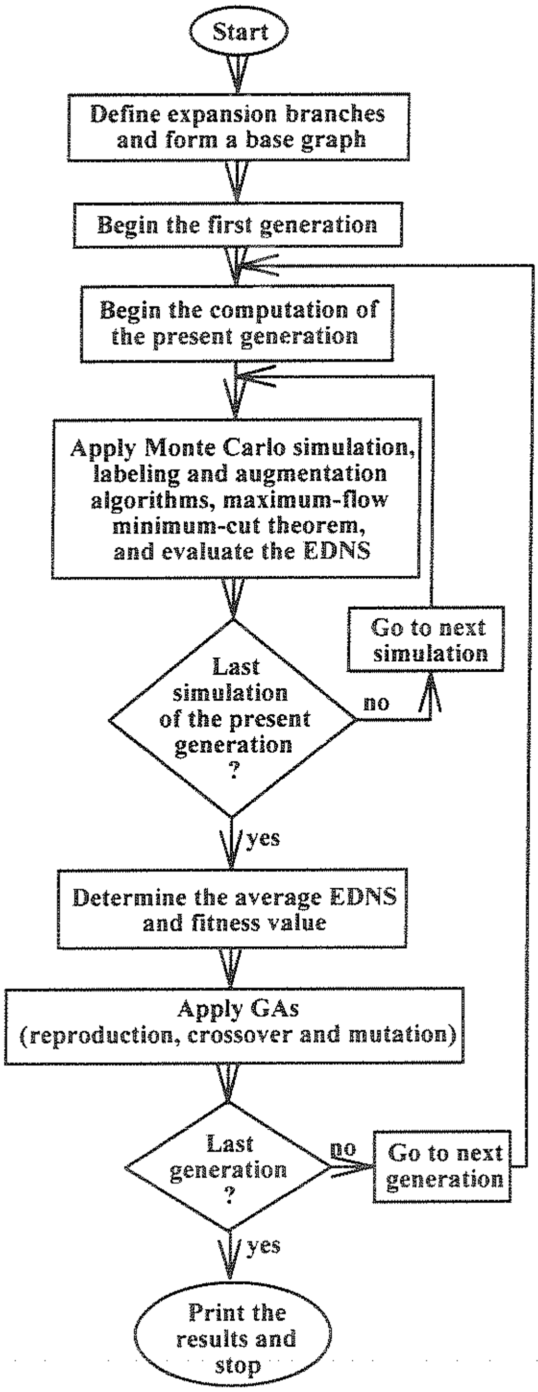

Figure 1. Computational procedures for the solution method

5. APPLICATION SYSTEM AND RESULTS

To illustrate the application of the proposed method, an IEEE five-bus test system is exemplified. The original system is a generation and transmission composite system as shown in Figure 2. It consists of two generators, seven transmission lines and four bus loads. Figure 3 shows the base graph transformed from Figure 2. In the solution process, the objective aims at minimizing the system total cost while satisfies the load demand. The input data for the generators, lines and loads are listed in Table 1, Table 2 "it was shown by Billinton and Allan [1984]" and Table 3, respectively. Table 4 shows the transmission lines available for capacity expansion. We forecast that the load demand will be 450 MW in the target year. Therefore, in order to satisfy this load demand, we will attempt to add two generators and a number of transmission lines. On the other hand, we assume that the annual installation-cost coefficients of C_{1i} are 5.00 k$/MW for the generators and 1.30 k$/km for 100-MW line, 1.00 k$/km for 75-MW line, 0.75 k$/km for 50-MW line, 0.40 k$/km for 25-MW line. Besides, the annual installation-cost coefficients of C_{2i} are $C_{2i} = 0.2400$ k$/MW for generators and $C_{2i} = 0.0228$ k$/km for transmission lines. The price of one MW-hour lost is given as $C_t = 0.0185$ k$/MW-hour "it was shown by Sallam et al. [1990]".

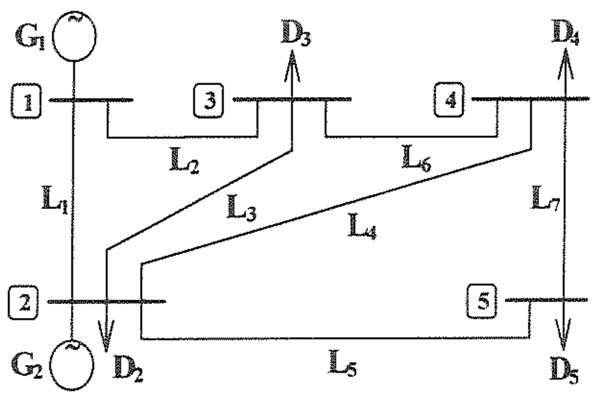

Figure 2. The IEEE five-bus test system

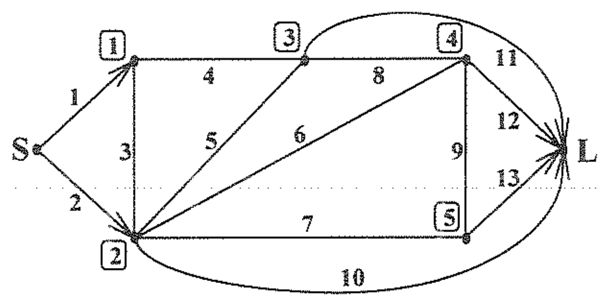

Figure 3. Base graph of the test system, which consists of 13 branches.

Table 1 Input data of generators

Element	Connection Bus	Capacity (MW)	*FOR*
G_1	1	150.0	0.02
G_2	2	50.0	0.03
$*G_6$	6	100.0	0.02
$*G_7$	7	150.0	0.03

* represents the added generators

Table 2 Input data of transmission lines

Element	Starting Bus	End Bus	Capacity (MW)	Length of Line (km)	*FOR*
L_1	1	2	100.0	40	0.22
L_2	1	3	50.0	30	0.32
L_3	2	3	25.0	25	0.39
L_4	2	4	50.0	45	0.32
L_5	2	5	75.0	65	0.29
L_6	3	4	25.0	20	0.39
L_7	4	5	25.0	20	0.39

Table 3 Input data of bus loads

Element	Connection Bus	Load Demand (MW)
D_2	2	25.0
D_3	3	50.0
D_4	4	50.0
D_5	5	75.0

Other input data used for the Genetic Algorithms include

population size : 10

crossover rate : from *exp*(0.10) to *exp*(0.75)

mutation rate : from *exp*(0.850) to *exp*(0.001)

The optimal solution can be achieved by taking 225 generations and 100 simulations for each generation, and the computational results are listed in Table 5. Table 5 shows that 9 of 14 available transmission lines are selected for expansion. For the target year, the total cost is 10462 k$ and *EDNS* is 48.0 MW. Because GAs belong to the stochastic search technique, Figure 4 shows the variation of optimal fitness value with respect to generation number with simulation number=100. It reveals that the optimal solution is attained at generation number = 225.

Table 4 Input data of available transmission lines for capacity expansion

Element	Starting Bus	End Bus	Capacity (MW)	Length of Line (km)	*FOR*
L_8	1	4	50.0	50	0.32
L_9	1	5	75.0	70	0.29
L_{10}	1	6	50.0	15	0.32
L_{11}	1	7	75.0	80	0.29
L_{12}	2	6	50.0	50	0.32
L_{13}	2	7	75.0	40	0.29
L_{14}	3	5	25.0	40	0.39
L_{15}	3	6	25.0	35	0.39
L_{16}	3	7	50.0	50	0.32
L_{17}	4	6	50.0	55	0.32
L_{18}	4	7	75.0	30	0.29
L_{19}	5	6	25.0	70	0.39
L_{20}	5	7	50.0	15	0.32
L_{21}	6	7	100.0	60	0.22

Table 5 Computational results attained by taking 225 generations and 100 simulations for each generation.

Element	Starting Bus	End Bus	Capacity added (MW)
L_8	1	4	50.0
L_{10}	1	6	50.0
L_{11}	1	7	75.0
L_{12}	2	6	50.0
L_{13}	2	7	75.0
L_{15}	3	6	25.0
L_{17}	4	6	50.0
L_{18}	4	7	75.0
L_{19}	5	6	25.0
Total Cost (k$)		10462	
EDNS (MW)		48	

6. CONCLUSIONS

This paper has presented a methodology and modeling technique for the capacity expansion planning of composite power systems. Based upon statistical simulation and optimization technique of GAs, the proposed method considers system component availabilities and a two-state model for the system components. Interruption cost and installation cost are taken into account by the presented model.

The solution method can coordinate the installation cost with the reliability worth while planning capacity expansion. Furthermore, due to the adaptive encoding strings of GAs, it enables the proposed method to be efficient for resolving more large power systems.

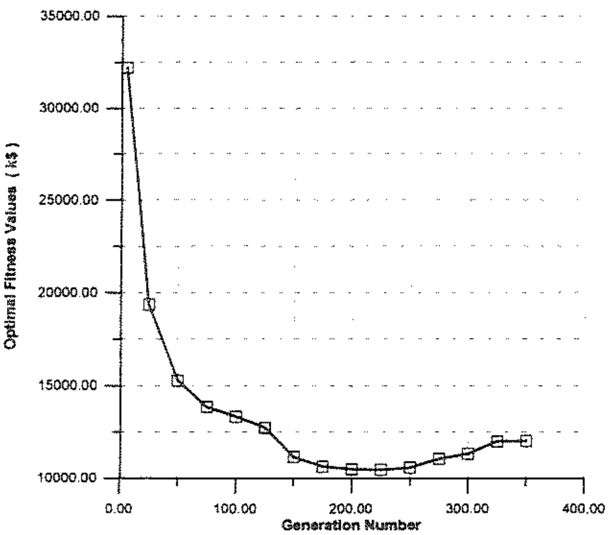

Figure 4. Variation of optimal fitness values with respect to generation number. Simulation number=100

7. REFERENCES

Billinton R., and R. N. Allan, *Reliability Evaluation of Power Systems*, Pitman Books, New York, 1984.

Ford, L. R., Jr., and D. R. Fulkerson, "*Flows in Networks*," Princeton University Press, New Jersey, 1962.

Michalewicz, Z., *Genetic Algorithms + Data Structures = Evolution Programs*, Heidelberg: Springer-Verlag, 1992.

Nara, K., et al., Implementation of genetic algorithm for distribution systems loss minimum re-configuration, *IEEE Trans. on Power Systems*, vol 7, num 3, 1044-1050, 1992.

Sallam, A. A., M. Desouky, and H. Desouky, Evaluation of optimal-reliability indices for electrical distribution systems, *IEEE Trans. Reliability*, vol 39, num 3, 259-264, 1990.

Su, C. T., T. S. Wu, T. H. Lee, and C. L. Huang, Statistical simulation method for production transmission system planning, *Journal of the Chinese Institute of Electrical Engineering*, vol 29, num 1, 48-57, 1986.

Su, C. T., T. H. Lee, T. S. Wu, and C. L. Huang, Production costing and reliability evaluation for composite systems with outages and uncertainties, *Electric Power Systems Research*, vol 10, num 3, 215-222, 1986.

Su, C. T., T. S. Wu, T. H. Lee, and C. L. Huang, Capacity planning with flow and reliability evaluation using Monte Carlo simulation, *IEEE Trans. on Reliability*, vol R-35, num 5, 518-522, 1986.

Su, C. T., T. S. Wu, C. L. Huang, and T. H. Lee, Transmission capacity expansion planning with economic dispatching and flow evaluation, *Journal of Franklin Institute*, vol 323, num 3, 285-295, 1987.

Su, C. T., and G. R. Lii, Reliability optimization design of distribution systems via multi-Level hierarchical procedures and generalized reduced gradient method, *In Proceedings of the IEEE International Conference on Energy Management and Power Delivery*, Singapore, 180-185, 1995.

Sullivan, R. L., *Power System Planning*, McGraw-Hill, 1977.