Transmission Planning Considering Reliability and Economic Performances in A Deregulated Environment

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Abstract- **The optimal design of transmission system expansion planning is an important part of the overall planning task of electric power system under competitive electricity market environments. Taking the cost-benefit analysis theory in economics as a basis, this paper analyzes the economy and reliability of the power transmission network at the beginning. Then, a mathematical model Cost/Benefit is proposed, and it is calculated by genetic algorithms which is introduced in section Ⅳ. Finally, it is tested and analyzed by Gaver-6-node system. Furthermore, the results indicate the feasibility and effectiveness of the method proposed in the paper.**

Index terms- **Transmission expansion planning; cost-benefit analysis; reliability; genetic algorithms (GAs)**

I. INTRODUCTION

There has been a world-wide trend towards restructuring and deregulation of the power industry over the last decade. The competition in the wholesale generation market and the retail market together with the open access to the transmission network can bring many benefits to the consumers, such as lower electricity prices and better services. However, this competition also brings many new technical issues and challenges to the planning of restructured power systems.

Power market environment access has moved the industry from conventional monopolistic electricity markets to competitive markets. In a competitive market, the price of the delivered energy and the quality of electrical energy including voltage quality and reliability of service are the main factors for business success. A key factor in today's competitive environment is an orientation toward customer's needs and willingness to pay for quality.

Traditionally, the most widely practiced method for expansion planning is the least-cost planning (also known as integrated resource planning or integrated demand-supply planning). It minimizes the present worth of investment cost while meeting the design criteria. As a result of the deregulation, new challenges have emerged in power system planning with regard to market constraints and increased uncertainties. There have been some new planning methods trying to meet such challenges. Most of these new methods try to minimize the total cost while meeting the system reliability requirement. This study knocks a new door carefully with a methodology for deciding cost-benefit ratio for an optimal transmission system expansion planning.

II. COST-BENEFIT ANALYSES

Nowadays, the transmission planning should not be divorced from the environment of the power market [1]. Users who purchase the electricity also purchase an important attribute –reliability of the power supply. They have the right to seek compensation when they suffered economic loss due to the power supply reliability. Therefore, in the power market it is not difficult to understand that the total cost of electricity supply should not be only consisted by the cost of the investment and operating costs in the expansion of the power grid constructions, but also the losses of customers due to insufficient supply or the interruption caused by power shortage, that is, the power outage cost on the demand side. The outage cost on demand side is an economic reflection directly illuminates the electricity supply reliability. Obviously, high reliability and low cost is a contradiction, in this paper, we will use reliability cost-benefit analysis method to coordinate them. This method can balance the reliability and economic performances of the power grids in order to determine which kind of investment option can obtain the best total benefit.

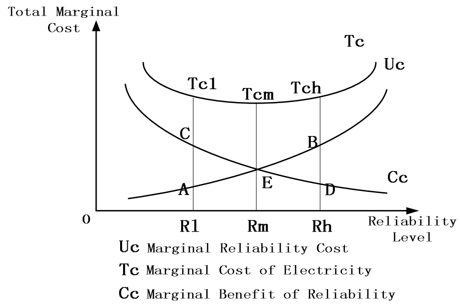

Fig.1 Reliability cost-benefit Curves

Reliability cost is defined as the cost of investment that power supply departments should spend, including line investment costs, operating costs and costs of network losses so as to reach a certain level of power supply reliability for the power grid. In this thesis reliability benefit is defined with the benefit derived from the improvement of the reliability. Because the social and economic benefit is difficult to calculate under a certain level of reliability, so the benefit is expressed with the outage cost which is derived from economic losses of customers because of the shortage of power or power service interrupted. Customer outage cost relates not only the time when the outage happens, but also the outage capacity, power shortage duration, frequency of power shortages, and so on. Outage cost is a function of these factors. Obviously, if the outage cost per unit remains constant, the lower the cost of power shortage the higher the reliability of benefits.

Outage cost[2] is an important index in the study of electricity reliability and economic losses. Relationship between Outage cost and reliability can be explained by Fig.1.

Outage cost can be calculated as follows:

$$R_{benefit} = \sum_{i=1}^{n} IEAR_i \times EENS_i = \sum_{i=1}^{n} \left(\frac{\sum_{k=1}^{m} L_{ik} \times f_k \times C_{ik}(d_k)}{\sum_{k=1}^{m} L_{ik} \times f_k \times d_k} \times EENS_i\right) \quad (1)$$

where

$IEAR_i$ - Evaluation of interrupted energy assessment rate of node i;

$EENS_i$ -Expected energy not supplied of node i during the study period;

n - Total node of the Grid Load;

m -Total number of the faults lead to Customer outage in node i;

L_{ik} - The lack of capacity on node i caused by the fault of k;

f_k -The frequency of the fault k;

d_k -The duration of the fault k;

$C_{ik}(d_k)$ -Corresponding outage cost per unit, it can be calculated by Comprehensive outage cost function of users.

During the research period EENS can be calculated by the function below:

$$EENS = \sum_{r \in NL} P_{Lr} \cdot \sum_{q,r \in F} APNS_{q,r} \cdot \prod_{j \in A} P_{qj} \cdot \prod_{k \in H} \left(1 - P_{qk}\right) \quad (2)$$

where

P_{Lr} - The probability of load level r;

$APNS_{q,r}$ - The lack of load capacity on state q, load lever r;

F- A set of all fault states which leads to the shortage of power supply per unit;

A - A set of all fault equipments in power system;

NL- A set of the load level during the research period;

P_{qj} - Failure outage or maintenance outage rate of the j-th equipment on the q-th state of the power system;

P_{qk} - Failure outage or maintenance outage rate of the k-th equipment on the q-th state of the power system;

P_{qj} , P_{qk} -can be calculated by functions below:

$$P_{qj} = \frac{\lambda_j}{\lambda_j + \mu_j}, P_{qk} = \frac{\lambda_k}{\lambda_k + \mu_k} \quad (3)$$

Where λ_j , μ_j , λ_k and μ_k , are the j and the k equipment failure rate and maintenance rate or planning maintenance rate and the corresponding maintenance rate respectively.

III. MATHEMATICAL MODEL FOR TRANSMISSION NETWORK PLANNING

A. MATHEMATICAL MODEL

By comparing and analyzing various models, the model which is adopted in this paper is listed below:

$$\min \quad J = \frac{Cost}{Benefit} \quad (4)$$

Subject to:

$$AP + G + P_C = P_L \quad (5)$$

$$P_{ij} - b_{ij}\left(\theta_i - \theta_j\right) = 0 \quad (6)$$

$$\left|P_{ij}\right| \le \bar{P}_{ij} \quad (7)$$

$$0 \le G \le \bar{G} \quad (8)$$

$$0 \le P_C \le P_L \quad (9)$$

$$0 \le n_{ij} \le \bar{n}_{ij} \quad (10)$$

where

$$Cost = C_{XL} + C_{OP} + C_{LOSS} \quad (11)$$

$$C_{XL} = \sum_{i=1}^{Ni} C_i L_i \quad (12)$$

$$C_{OP} = \alpha C_{XL} \quad (13)$$

$$C_{LOSS} = \sum_{l=1}^{N} \left(\frac{\theta_i - \theta_j}{x_l \times U}\right)^2 R_l \times t \times \delta \quad (14)$$

$$Benefit = \beta \times \Delta EENS \times IERA \quad (15)$$

and

Cost- Reliability cost;

Benefit-Reliability benefit;

C_{XL} - Investment cost of transmission lines;

C_{OP} - Operation and maintenance cost;

C_{LOSS} - Cost of network losses;

β - Weighted coefficient of outage cost range from 0 to 1, in this paper it is 0.7;

θ_i , θ_j - The phase angle of the ij ends;

$\Delta EENS$ - Variable quantity of excepted energy not supplied caused by transmission lines which is put into use or cut off;

IEAR- Assessment rate of interrupted energy in power system;

$n_{ij}, \bar{n}_{ij}, P_{ij}, \bar{P}_{ij}$ - The number of multipliable lines, the limit number of the lines, branch power, branch capacity respectively;

b_{ij} - Branch admittance;

P - Node power;

$G, \bar{G}$ -Generator Power and Maximum Output of Generator;

A- Incidence matrix between node and branch;

P_L -Load of node;

P_c - Reduction on load quantity;

C_i - Investment cost per unit of line i;

L_i - Length of line i;

N_i - The total number of the lines to be built in power network;

U - Net voltage;

t -Running time;

δ -Electricity price;

N- The total number of lines in power network;

R_i - Resistor of line i.

B. MODEL FEATURE

Compared with the traditional power grid planning mathematical models, the proposed has many advantages and characteristics：

（1） This model takes a comprehensive consideration of reliability cost and reliability benefit, coordinates the relationship between reliability and economic performances. The objective function overcomes so many shortcomings of traditional methods which overlook the benefit of reliability.

（2） It reflects the overall social benefit, and its physical meaning and significance of mathematics are clear and easy to be understood.

（3） The ratio of reliability of the cost benefit is selected for index of the selectable lines, namely $J = Cost / Benefit$, $Benefit = IERA \times EENS$ .Index J is inversely proportional to the size of IERA, therefore, the change of IERA just change the index size, there is no change in the order of the selected lines, so it will not affect the planning results.

（4） This model can enable power grid planners to know that which site to increase lines can get maximum benefit. Compared with other models, this one can reflect the impact of new lines to the entire network better.

IV. OVERVIEW OF GENETIC ALGORITHMS (GA)

GA theory has been extensively presented in many papers in recent years covering a number of applications in power systems. GA is a robust optimization method that works above a set of candidate solutions (individuals) named population and perform a number of operations based on genetic mechanical. Such operators recombine the information contained in the individuals and then, they create new populations. Figure 2 presents the GA basic structure, where P(t) represents the population at the generation t.

```
Start
    -   t=0
    -   Build P(t)
    -   Evaluate P(t)
    While( stop criterion is not achieved) do
          -            t= t+1
          -            Select the parents from P(t-1)
          -            Build P(t) performing genetic
          -             Evaluate P(t)
           operators to the parents
    End
End
```

Fig.2 GA basic structure

GA uses a selection mechanism which has as its main objective the selecting of “good” individuals from the current population and inserting them into a mating pool. As in the evolutionary theory [3], GA performs the mechanisms of crossover and mutation, which have the purpose of recombining the genetic material existing in the mating pool, so that better individuals may be created and the search enlarged to other regions of the space. Normally, the average quality of the next population is greater than the previous one. Besides the well-known basic GA operating principles, several modifications and improvements, considered critical to the performance of the optimization process, have been applied with success as a way to make the solution of the different problems feasible. Thus, it is necessary to include the knowledge about the problem into the algorithm. Therefore, a GA developed for a specific problem might fail when used in another problem.

A GA with these characteristics has been used with success in a variety of power system applications, such as reactive power planning, unit commitment etc [4].

One of the most important references published about GA, gives the basis of its application to engineering optimization problems.

A typical GA might have, at least, the following features:

（1） A defined representation of the individuals (or chromosomes), that can be Binary, Decimal or by Floating Point. More specifically, for the STNEP problem, the Decimal representation is more adequate, as may be subsequently seen.

（2） A fitness function, which depends on the objective function that is being optimized. Thus, better individuals (higher fitness values) must be those having the lower values of the objective function;

（3） A selection mechanism to choose individuals according to some procedure, defining the parents of the next population;

（4） A crossover mechanism to create new individuals from that Selected by the selection mechanism;

（5） A mutation mechanism to restore the genetic material lost and guides the exploration to new regions of the search space.

There are many alternatives to implement these features. The next section presents the details of the Improved Genetic

Algorithm (IGA) implemented for the special application with which we are dealing.

V. ALGORITHM OF THE SOLUTION

Before using any of the GA models, the problem must be represented in a suitable format that allows the application of the GA operators. The GA works by maximizing a single variable, the fitness function. Hence, the objective function and some of the constraints of the transmission planning must be transformed into some measure of fitness [5].

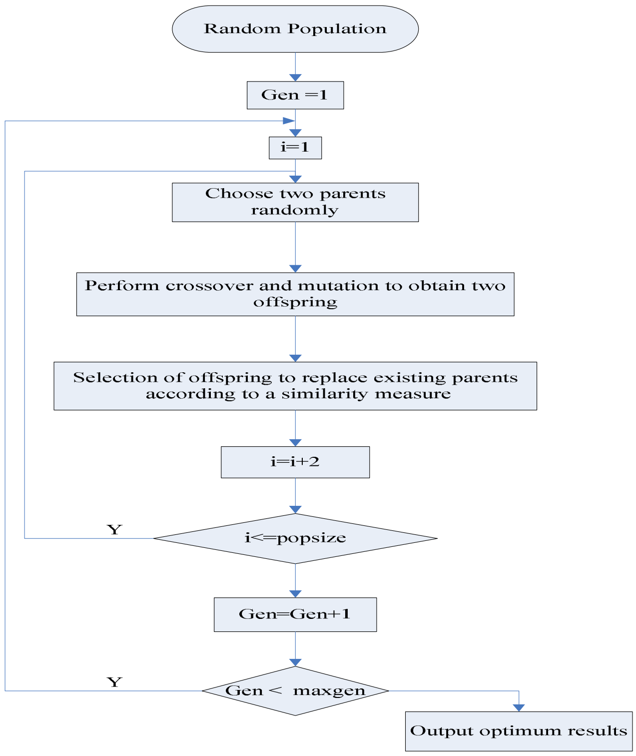

Fig.3 Genetic Algorithm

VI. CASE STUDY

The proposed decision process described in section 3 was tested on Graver-6-bus system. Its initial network and the distribution of power and load are shown in Fig.4, while the maximum load and power input are arranged in table1. In the study, the line is priced at 70 million Yuan/ (km• circuit), fault rate of the line is 0.05 times / (year• km• circuit), repair rate is $9.13*10^{-4}$ year/ (times• circuit), interrupted energy assessment rate (IEAR) is 30.0 Yuan/kWh, Load duration is 3,500 hours, α is 0.1, β is 0.7. Genetic algorithms (GAs) method is used in this study. Option 4 is a traditional plan, that is, the line investment and operating costs are taken into consideration as objective function, which subjected to the limits of power flow. By analyzing, the terms of its new lines can be drawn for the 2-6 (4), 3-5, 4-6 (2), with its energy expectation not supplied ($EENS^*$) is 267.1 (MWh/year). Therefore, Outage cost* goes to IEAR× $EENS^*$ = 267.1×30 = 8.013 (million Yuan), while its cost can be reached as

$$\cos t^* = C_{XL} \times \frac{i(1+i)^n}{(1+i)^n - 1} + C_{op} + C_{LOSS} = 55.21 \text{ (Million Yuan)}$$

Where i is the annual interest rate, which is 6% in this study; n is the investment recovery period, which is 10 years here.

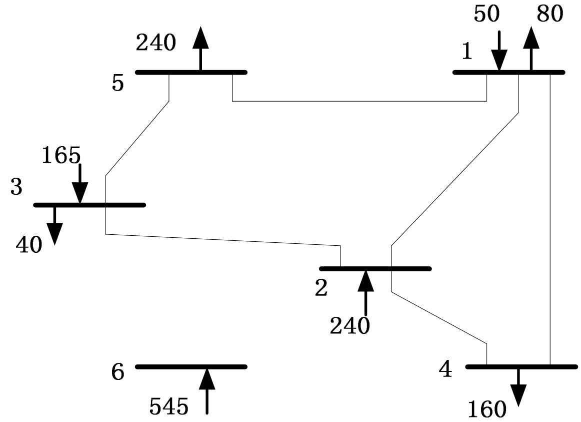

Fig. 4 Initial network of the Garver-6-bus system

Table1 Bus parameters of the Garver-6-bus system

Node number	Input(MW)	Load power(MW)
1	50.0	80.0
2	0.0	240.0
3	165.0	40.0
4	0.0	160.0
5	0.0	240.0
6	545.0	0.0

Table2 Planning result (with IEAR=30 Yuan (kWh^{-1}))

Alter-natives	cost	Outage cost	EENS	Total cost	Cost	Benefit	J	Rem-ark
Option 1	77.584	3.078	102.6	80.662	22.374	4.932	4.536	**Opti-mal**
Option 2	85.867	2.553	85.1	88.42	30.657	5.457	5.618	
Option 3	91.665	1.827	60.9	93.492	36.455	6.183	5.896	

cost, Outage cost, Total cost, Cost, Benefit：million Yuan；EENS: MWh/ year

where

$$\cos t = C_{XL} \times \frac{i(1+i)^n}{(1+i)^n - 1} + C_{OP} + C_{LOSS} \qquad (16)$$

$$\text{Outage cost} = IEAR \times EENS \qquad (17)$$

Total cost is the sum of cost and Outage cost, $Cost = \cos t - \cos t^*$ which means the increased reliability cost compared with the traditional model Option four. $Benefit = Outage \cos t^* - Outage \cos t$, which means the increased reliability benefit compared with the traditional model Option four, Cost/Benefit is the reliability cost-effectiveness ratio. From table 2, it is easy to see that in several solutions which are obtained by the genetic algorithm the Option one Cost/Benefit ratio is the smallest, therefore it is chosen as the optimal solution, and simultaneously it also satisfies the minimum Total cost.

Table3 .Number of new lines for the Garver-6-bus system

	Option 1	Option 2	Option 3	Option 4
New lines	2-5,2-6(4) 3-5(2),4-6(3)	2-6(4),3-5 (2),4-6(3), 5-6	2-4,2-5,2-6(4),3-5,4-6(2),5-6	2-6(4),3- 5,4-6(2)

VII. CONCLUSIONS

In this paper, a new power network planning method based on the reliable restraint (including planning methods and mathematical model) which can transform the reliability index of power network into economic index and take it as a part of objective function is put forward. This model can enable power grid planners to know that which site to increase lines can get maximum benefit. Compared with other models, the proposed can reflect the impact of new lines to the entire network better. The results of the case study also reveal that the model is effective.

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