Economic Incentive to Transmission Investment Considering Environmental Cost

Xiao Gao

State Grid Energy Research Institute CO., LTD, Beijing, China

gaoxiao@sgeri.sgcc.com.cn

Abstract. The economic incentive to transmission investment considering environmental cost is investigated in this paper. The definition of economically stimulating signals to transmission investment is given. Based on the transmission line optimal investment planning model proposed in Brazil, the transmission planning model with economic stimulation is proposed. What’s more, the external cost of environment is taken into account in this above transmission planning model. This model is suitable for the merchant transmission plan. And it also provides transmission investors a decision-making reference. The effectiveness of the economic stimulation to transmission investment considering environmental cost is verified by the 5-bus system.

1. Introduction
With the continuous deepening of China's power market reform, transmission investment has gradually been liberalized. Under the commercial transmission investment mode, various entities such as transmission management agencies, power users, power generators, and intermediate agents participate in transmission investment and compete. Transmission investment plan using single government approval with consideration of electricity supply and demand will be difficult to adapt to the market. In transmission investment planning, cost is an important factor affecting economic efficiency [1]. Low investment is an important economic goal, and investors need to coordinate the reduction of network losses, reduce the probability of network congestion and other requirements on the transmission line [2~6]. But with the development of society, transmission investment planning needs to consider more. At present, in China and all over the world, energy conservation and environmental protection issues have received much attention. The power industry is an important industry for environmental pollution control. At present, pollution discharges and penalties are imposed on power generation plants to suppress pollutant emissions.

This kind of control method is based on the discharge of pollutants, which is a means of punishment afterwards. Whether it can effectively control the pollution have a great relationship with punishment, corporate affordability and social responsibility of enterprises. So the problem of sewage discharge can not be solved fundamentally. Considering the environmental cost of power generation in the transmission investment plan has two advantages. On one hand, the power transmission channel from power plants with large pollution will reduce, and also its power generation and sewage discharge will reduce. On the other hand, the capacity of the low-pollution generators including renewable power generation will expand.
The economic incentive to transmission investment considering environmental cost is researched in this paper based on the concept of economic incentive and a line investment planning model considering the loss reduction and elimination of congestion in Brazil. A simple example with the 5-bus system analyzes the role of economic stimulation.

2. Transmission grid investment economic incentive
The economic incentives for investment can be explained as the relationship between the expected return on investment returns and the behavior of the transmission grid investors during the period in which the number of participants in the cost sharing and the state of the system remain constant. The amount of investment that investors anticipate they can afford will provide feedback to investors. They expect to cost less for the transmission invest. And this expectation will lead them to take planned measures to achieve their goals as much as possible. In the economic incentive model of investment, the incentive source is the investment amount, the incentive target is the transmission investor, and the goal of the incentive object is to minimize the cost. The investor will adopt different behaviors to achieve this goal.

In the power grid, a decision-making factor in transmission line investment is the supply and demand capacity of electricity. Changes in generation capacity or load capacity may both cause transmission investment construction. When the grid load increases, even if the load bus does not change, if the transmission line cannot meet the increased load, it is necessary to invest in the construction of a new transmission line to avoid congestion and solve system safety problems. If a load substation is built in a new geographic location, that is, a load node is added, a corresponding transmission line must be constructed to ensure that the power users of this node use power normally.

There is a close relationship between the capacity of the generators and the load demand. And the decisions of the construction of the new generators are based on the predicted future load. When the ultimate output power of the original generators cannot meet the demand increase, the grid operators will purchase electricity from other power grids with increasing the power injected by other power grids, and encourage the power producers to invest in new generators.

In the long run, power generation construction can cause the construction of power transmission lines. If the power generation and load buses of the grid are unchanged, and the transmission capacity can meet the transmission requirements of the new power generation and load, no additional new lines are needed. If the power generation bus is unchanged and the original line transmission capacity cannot meet the transmission requirements of the newly added power generation and load, it is necessary to invest in the construction line. If a new generation bus is added, it is necessary to invest in the construction of the corresponding transmission line.

The important issue that investors face after deciding to build a new transmission line is where to build lines. Considering the total investment, reducing the network loss, effectively eliminating the transmission congestion, and conducive to energy saving and emission reduction and other factors, the construction plan of the new line can be determined.

3. Transmission line investment planning model
The economic incentives for transmission investment are reflected in the line investment planning model, which can realize the reliability and economical optimal transmission expansion decision.

3.1. Transmission Line active power flow function
The investment planning model proposed by Brazilian scholars selects the optimal line to be built with the goal of minimizing the total cost of investment and construction [6]. Given the power generation bus, the DC power flow model of the active power flow $P_{jk}$ of branch $j-k$ is as follows.

$$P_{jk} = b_{jk} \theta_{jk}, \forall (j,k) \in E \quad (1)$$
The susceptance of the branch j-k is $b_{jk}$, and $b_{jk} = \frac{1}{x_{jk}}$. And the voltage phase angle difference between bus j and bus k is $\theta_{jk}$.

If considering transmission losses, the DC model can be expressed as follows.

$$P_{jk} = b_{jk} \theta_{jk} + g_{jk} \frac{\theta_{jk}^2}{2}, \forall (j,k) \in E$$

(2)

The conductance of the branch ij is $g_{ij}$, and the set of branches that already exist in the grid is E. In the grid expansion plan, if the transmission power loss function is not considered, and the active power flow function of an alternative line is as follows.

$$P_{jk} = \varphi_{jk} b_{jk} \theta_{jk}, \forall (j,k) \in D$$

(3)

Considering the transmission loss, the active power flow function of an alternative line is as follows.

$$P_{jk} = \varphi_{jk} (b_{jk} \theta_{jk} + g_{jk} \frac{\theta_{jk}^2}{2}), \forall (j,k) \in D$$

(4)

In the above equation, the line construction decision function is $\varphi_{jk}$, and the set of alternative lines in the grid expansion plan is D.

$$\varphi_{jk}(x_{jk}) = \frac{e^{\alpha x_{jk}} - 1}{e^{\alpha x_{jk}} + 1}$$

(5)

Among them, the slope of the curve is $\alpha$. After a series of observations and statistics about $\alpha$, when $\alpha$ is 1 the function has good convergence and power flow results. If $\alpha$ is too large, the derivative value of the curve function is large, and the optimal power flow cannot converge. If $\alpha$ is too small, the curve function loses its characteristics, so the optimal power flow result will also be affected. So the value of $\alpha$ is 1.

Figure 1. The characteristics of curve function $\varphi_{jk}$. 
The value of the argument of function \( \varphi_{jk} \) is \([0, 20]\). According to the characteristics of this function shown in Fig. 1, the function value is close to 1 when the argument value is close to 8. And the upper limit of the argument is taken as 20 in order to make the function value as close as possible to 1. This function can be simulated using a neural network algorithm. For an alternative line in the extended transmission plan, if \( 0 \leq x_{jk} \leq 20 \), the function is continuous in the interval \([0, 1]\). If \( 11 \leq x_{jk} \leq 20 \), \( \varphi_{jk} = 1 \). And if \( 0 \leq x_{jk} \leq 0.0001 \), \( \varphi_{jk} = 0 \). If \( 0.0001 \leq x_{jk} \leq 11 \), \( \varphi_{jk} \) reflect the trend of the active power loss of lines.

### 3.2. Environmental cost function

Environmental cost refers to the cost of measures required to manage the environmental impact of corporate activities and other costs incurred by the company in implementing environmental objectives and requirements in accordance with the principle of environmental responsibility. As for power generators, the former part is the external cost of power generation, mainly refers to the external economic losses caused by sewage in power generation. And the latter part is the internal cost of power generation, including the cost of power generation enterprises to invest equipment and maintain operations for reducing emission and to pay sewage charges to relevant departments.

At present, the internal environmental cost of power generation has been included in the operation and maintenance costs of power generation. It is digested from the generating price. However, the external environmental costs of power generation have not been internalized, and the economic losses caused by certain pollutant emissions have not been included in the government sewage charges. In this case, this cost should be reflected in the transmission planning. The external environmental cost of the power plant can be calculated as follows [7].

\[
c_E = \sum_{i=1}^{I} \beta_i \lambda_i G
\]

Where \( i \) indicates the type of pollution discharge, there are \( I \) types, \( G \) indicates the amount of electricity generation, \( \lambda_i \) indicates the amount of pollutants discharged when the unit electricity generating, and \( \beta_i \) indicates the pollution loss caused by unit pollutants. Due to the differences in economic development levels and the differences in population density and pollution emissions in different regions, it is difficult to quantify the external pollution losses of power generators. According to calculation from the World Bank and the China Renewable Energy Development Project, the power pollution losses in 2010 ranged from 1-8 cents/kWh [7].

### 3.3. Transmission investment planning model

The optimal model for transmission system planning is expressed as follows.

\[
\text{Min} \sum_{n=1}^{n} (c_n + c_{En}) G_n + \sum_{(j,k) \in D} c_{jk} \cdot \varphi_{jk} (x_{jk})
\]

\[\text{S.t.} \quad G_j - \sum_{(j,k) \in E} P_{jk} - \sum_{(j,k) \in D} P_{jk} = d_j \]

\[|P_{jk}| \leq P_{jk}^{\text{max}}, \quad \forall (j,k) \in D, E \]

\[G_j^{\text{max}} \leq G_j \leq G_j^{\text{min}} \]

\[0 \leq x_{jk} \leq 20, \quad \forall (j,k) \in D \]
where, the number of generator sets is $n_g$, the operating cost of generator set $n$ is $c_n$ yuan/MW/year, the environmental cost of generator set $n$ is $c_{En}$ yuan/MW/year, the expansion cost of transmission line $jk$ is $c_{jk}$ yuan/year, the independent variable of the function is $x_{jk}$, the amount of power generated by the generator set of node $j$ is $G_j$, the expected load demand of node $j$ is $d_j$, the active power of the branch $jk$ is $P_{jk}$, the active power of the existing line is obtained by the formula (1) or (2), and the alternative line to be built is obtained by the formula (3) or (4).

The first term of the objective function represents the operating cost and environmental cost of the generators. And the second term represents the fixed cost of the system. The constraint first condition reflects the system power balance. The second condition reflects the transmission capacity limit of the line, and the line will not congest if the condition is satisfied. The third condition indicates that the power generation capacity limit is satisfied. The forth condition reflects the value range of the line construction decision function independent variable. The solution to this planning problem shows one of the candidate lines to be built with the largest active power flow. And the investment amount of the newly added transmission line is determined.

4. An example analysis

Figure 2 shows a 5-node test system with two generators and three loads. The line parameters are shown in Table 1. Node 1 is reference node, the remaining nodes are PQ nodes, and node 6 is a new grid node. In the monthly trading market, the monthly fixed price of the active power is 40,000 yuan/MW.

![Figure 2. A five node system.](image)

| Start node i | End node j | Branch resistance | Branch reactance | half of charging capacitor | cost (million yuan) | line capacity (MW) |
|--------------|------------|-------------------|-----------------|--------------------------|-------------------|-------------------|
| 1            | 2          | 0.10              | 0.40            | 0.03                     | 4                 | 100               |
| 1            | 4          | 0.15              | 0.60            | 0.025                    | 6                 | 80                |
| 1            | 5          | 0.05              | 0.20            | 0.01                     | 3                 | 100               |
| 2            | 3          | 0.05              | 0.20            | 0.02                     | 3                 | 100               |
| 2            | 4          | 0.10              | 0.40            | 0.02                     | 4                 | 100               |
| 3            | 5          | 0.05              | 0.20            | 0.025                    | 3                 | 100               |

The load of each node of the power grid and the output power of the generator set are shown in Table 2. And external environmental costs and operating costs are calculated based on the generator's annual utilization time of 4700 hours. According to this data, the power generation capacity of the original power grid cannot meet the load demand, and the power generation node 6 is added, and it is necessary to invest in a new power transmission line. The alternate line parameters between the nodes
are shown in Table 3. This test system is small, and it can be assumed that the geographical locations of the power plants are not far apart, and the external environmental costs of the power plants are not too much different, assuming about 400 yuan/MWh.

| Start node i | End node j | Branch resistance | Branch reactance | cost (million yuan) | line capacity (MW) |
|--------------|------------|-------------------|------------------|---------------------|-------------------|
| 1            | 3          | 0.09              | 0.38             | 3.8                 | 100               |
| 1            | 6          | 0.17              | 0.68             | 6.5                 | 70                |
| 2            | 5          | 0.08              | 0.31             | 3.3                 | 100               |
| 2            | 6          | 0.08              | 0.30             | 3                   | 100               |
| 3            | 4          | 0.15              | 0.59             | 5.6                 | 82                |
| 3            | 6          | 0.12              | 0.48             | 4.8                 | 100               |
| 4            | 5          | 0.16              | 0.63             | 6.15                | 75                |
| 4            | 6          | 0.08              | 0.30             | 3                   | 100               |
| 5            | 6          | 0.15              | 0.61             | 6                   | 78                |
Acknowledgments
This work was financially supported by Science and technology project of SGCC “Investigation of Retail Electricity Price Policies and its Application under the Reform of Electric Sale Side”

References
[1] L S Hyman, Transmission, congestion, pricing and incentives, IEEE Power Engineering Review, 19 (1999) 4-10.
[2] N K Edward, Stimulating new transmission investments, The Electricity Journal, 15 (2002) 76-80.
[3] B R Stein, Transmission investment: nourishing a gnarly tree, The Electricity Journal, 18 (2005) 25-32.
[4] K D Rajat, Transmission investment valuations: weighing project benefits, The Electricity Journal, 17 (2004) 55-67.
[5] A H Seddighi, A Ahmadi-Javid, Integrated multiperiod power generation and transmission expansion planning with sustainability aspects in a stochastic environment, Energy, 47 (2015).
[6] E J Oliveira, I C Silva, J L R Pereira, et al., Transmission system expansion planning using a sigmoid function to handle integer investment variables, IEEE Transactions on Power Systems, 20 (2005) 1616-1621.
[7] J X Wang, W H Gao, X F Wang, H Y Chen, Improved JASP Model of Generation Planning with Environment Cost, Journal of Xi’an Jiaotong University, 42 (2008) 1015-1020.