Optimization of Power Generation Rights Under the Requirements of Energy Conservation and Emission Reduction

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Abstract. In recent years, the energy crisis and greenhouse effect problem have caused wide public concern, if these issues cannot be resolved quickly, they will bring troubles to people's lives. In response, many countries around the world have implemented policies to reduce energy consumption and greenhouse gas emissions. In our country, the electric power industry has made great contribution to the daily life of people and the development of industry, but it is also an industry of high consumption and high emission. In order to realize the sustainable development of society, it is necessary to make energy conservation and emission reduction in the power industry as an important part of the realization of this goal. In this context, power generation trade has become a hot topic in energy conservation and emission reduction. Through the electricity consumption of the units with different power efficiency and coal consumption rate, it can achieve the target of reducing coal consumption, reducing network loss, reducing greenhouse gas emission, and increasing social benefit, and so on. This article puts forward a optimal energy model on the basis of guaranteeing safety and environmental protection. In this paper, they used the IEEE30, IEEE39, IEEE57 and IEEE118 node system as an example, and set up the control groups to prove the practicality of the presented model. The solving method of this model was interior-point method.

1. Introduction

In recent years, in order to reduce the power industry’s consumption of coal resources and make power generation trade can be carried out in the direction of energy-saving, many scholars put forward the relevant models. Early scholars have proposed the largest model of coal savings [1], while there are also scholars putting forward the smallest model of the network loss after transaction [2]. For a medium-sized power system and assuming that the power transmission capacity is 1010 kW · h/year, if the network loss reduces by 1%, then a year can save electricity 108 kW · h. Also, assuming that the average unit coal consumption rate is 350 g/kW · h, then the reduction of 1% loss means that a year will save 3.5 × 104t standard coal, which is a very impressive figure. Hence, reducing the network loss after transaction can also be used as a means of energy saving. However, there are some shortcomings in the two types of models; when the unit coal consumption after transaction is at minimum, the network loss may be larger. On the contrary, when the network loss after transaction network loss is at
minimum, the unit coal consumption may be larger. So the results of the power generation trade under the guidance of the two models may fail to achieve the best energy savings.

Although a few scholars have proposed the optimal energy saving model to comprehensively consider the coal consumption and the network loss [3], but they did not fully consider the situation that when the system is at the maximum after transaction, the carbon emissions may exceed. They also neglected that the load margin may be too small to lead to the risk in operation. As a result, this paper presents a more comprehensive model, taking the coal consumption and the network loss after transaction into account. It also introduces the static voltage stability constraint and the carbon displacement constraint under the constraint condition. It aims to achieve the largest goal of saving energy after transaction in the premise of ensuring the safety and environmental protection of the system.

2. Research Methods
The model proposed in this paper comprehensively considers the change of coal consumption and the network loss after transaction. In order to verify if the model can achieve the largest energy savings, two sets of control groups need to be set up: one is the optimal model for the coal consumption after transaction and the other is the optimal model for the network loss after transaction. Then the energy savings of the two models after transaction will be obtained and be compared with the model of this paper. In order to verify the necessity of introducing double constraint conditions, two sets of control groups need to be set up to avoid the problem of the safety and environmental protection of the system. The static voltage stability constraints will be removed in the first group of models, and carbon emissions constraints will be removed in another. Then observe if the energy saving, load margins, carbon emissions and other parameters of the two groups of models after transaction have changed.

Apparently, the model of this paper deals with the nonlinear problem which covers a variety of constraints, and the interior point method can deal with such problems well. Here we adopt an improved interior point algorithm - the central correction interior point method based on the constraint relaxation strategy to solve the problem of this model. Compared with the traditional interior point method, the algorithm can solve the numerical problems caused by the complementary difference, and improve the convergence of the interior point method [4]. We use IEEE30, IEEE39, IEEE57, IEEE118 node system as an example of this paper, using MATLAB software to write the internal point of the program and calculate the results of various models.

3. Establishing the optimal power generation trade model with energy saving

3.1. Objective function

\[
\min f_1 = KST^T \cdot (P_{gt0} + P_{gp}) + \alpha \cdot [(e1^T P_{gt0} + e1^T P_{gp}) - (e1^T P_{g0} + e1^T \lambda_g b)]
\]  (1)

| Variables | Meanings |
|-----------|----------|
| KST       | the coal consumption rate of the controllable generator, the row vector |
| Pgt0      | the active output column vector of the controllable generator in the system before the start of the transaction |
| Pgp       | the active output column vector of all controllable generators after transaction relative to that before the moment of transaction |
| \(\alpha\) | the commutation factor of the network loss of coal consumption, whose value is equal to the power of the unit MW·h. It needs to consume the standard tons of coal |
| e1T       | the row vector with M dimension is 1, here M is the number of all generators; |
| Pg0       | the active output column vector of all the generators before the start of the transaction |
3.2. Constraint condition

3.2.1. Power flow equations.

\[ L_0 + G(P_{g0}) + l_p G(P_{gp}) - \lambda_p b - f(x_p) = 0 \]  

(2)

Table 2 Interpretation of variables

| Variables | Meanings |
|-----------|----------|
| L0        | the input power column vector of each node at the starting time |
| G(.)      | the reflection of the controllable generator output vector to node input vector; |
| lp        | the output factor of the controllable generator at the peak of the load |
| lpG(Pgp)  | the active output increase of this node |
| f(.)      | the calculation formula of the input power of the node |
| xp        | the state variable of the node at the peak load, including the magnitude and phase angle of the voltage |

3.2.2. The active, reactive power constraints of generator.

\[ P_{g_{\text{min}}} \leq P_g + P_{gp} \leq P_{g_{\text{max}}} \]  

(3)

\[ Q_{g_{\text{min}}} \leq Q_{gp} \leq Q_{g_{\text{max}}} \]  

(4)

Table 3 Interpretation of variables

| Variables | Meanings |
|-----------|----------|
| Pgmax     | the upper limits of the active output of the generator at the peak load |
| Pgmin     | the lower limits of the active output of the generator at the peak load |
| Qgmax     | the upper limits of the reactive power output of the generator at the peak load |
| Qgmin     | the lower limits of the reactive power output of the generator at the peak load |
| Qgp       | the reactive power output of the generator at the peak load |

3.2.3 Node voltage amplitude constraint

\[ V_{p_{\text{min}}} \leq V_p \leq V_{p_{\text{max}}} \]  

(5)

Table 4 Interpretation of variables

| Variables | Meanings |
|-----------|----------|
Vpmax  the upper limits of the reactive power output of the generator at the peak of the load
Vpmin  the lower limits of the reactive power output of the generator at the peak of the load
Vp  the amplitude of the node voltage at the peak load

3.2. 4 Branch current constraint

\[ |I_{ij}(X_p)|^2 \leq I_{ij}\text{max}^2 \quad (6) \]
\[ |I_{ji}(X_p)|^2 \leq I_{ji}\text{max}^2 \quad (7) \]

**Table 5** Interpretation of variables

| Variables | Meanings |
|-----------|----------|
| Iij(·)    | the branch current that flows from node i to node j |
| Iji(·)    | the branch current that flows from node j to node i |

3.2. 5. Static voltage stability constraint

The constraint of the power flow of voltage at the critical point:

\[ L_0 + G(P_{\phi0}) + l_c G(P_{gp}) - \lambda_c b - f(x) = 0 \quad (8) \]

**Table 6** Interpretation of variables

| Variables | Meanings |
|-----------|----------|
| lc        | the output factor of the controllable generator at the voltage critical point |
| lcG(Pgp)  | the active output increment of the system at that point |
| xc        | the state variable of the node at the critical point |

Load margin constraints:

\[ \lambda_{\text{ref}} \leq \lambda_c \quad (9) \]
\[ \lambda_c = (P_{lc} - P_{l0}) / b_i \quad (10) \]

**Table 7** Interpretation of variables

| Variables | Meanings |
|-----------|----------|
| Plc       | the load of the voltage at the critical point |
| P0        | the load at the current operating time |
| bi        | the transition from the current operating point to the voltage at the critical point |
| \lambda_{\text{ref}} | the given minimum load margin threshold |
| \lambda_c | the load margin of the system of the voltage at critical point |

Load margin is generally used as a measure of static voltage stability, in which the greater the \( \lambda_c \) is, the better the stability of the voltage. Once the value is below the \( \lambda_{\text{ref}} \), the load will slightly increase, and the system is likely to face the risk of voltage collapse. We set \( \lambda_{\text{ref}} \) of IEEE13, IEEE39, IEEE57, IEEE118, the four node systems relatively as 0.9, 1.35,0.95,1.05.

The reactive power constraints of generators of voltage at stable critical point:

\[ Q_{g\text{min}} \leq Q_{gc} \leq Q_{g\text{max}} \quad (11) \]

Qgc is the reactive power output of generators of voltage at stable critical point.

3.2. 6. Carbon emissions constraints

The amount of carbon emissions in the system is set as \( C_e \), which is calculated as follows:

\[ C_e = C_i \cdot k_i \cdot P_d = 1.9774 \times 0.325 \cdot P_d \quad (12) \]
### Table 8 Interpretation of variables

| Variables | Meanings |
|-----------|----------|
| Ct        | the permissible carbon emissions of per unit of standard coal, which is 1.9774 t |
|           | the average coal consumption rate of power supply for the thermal power units, which indicates the amount of standard coal that is required to generate 1 MW·h of electricity, with the value of 0.325 t / MW·h |
| Kt        | the total load of the system |
| Pd        | the total load of the system |

Carbon emissions are defined as me, the formula is as follows:

\[ m_e = k_e \cdot P_{gp} \]  \hspace{1cm} (13)

In the formula: \( k_e \) is the carbon flux intensity vector of the units, we set the carbon emission intensity of the large coal-fired unit, the small coal-fired unit and the gas turbine unit relatively as 0.75t / MW·h, 1.15t / MW·h, 0.4t / MW·h.

Therefore, the constrain of the system's carbon emission is:

\[ K^T \cdot P_{gp} \leq C_e \]  \hspace{1cm} (14)

According to the above description, we set up the following power generation trade model to save energy to its limit:

**obj:** \( \min f_1 = K^T \cdot (P_{g0} + P_{gp}) + \alpha \cdot [(e^T \cdot P_{g0} + e^T \cdot P_{gp}) - (e^T \cdot P_{g0} + e^T \cdot P_{gp})] \)

**s.t.:**\[
\begin{align*}
(2) &- (9) \\
(11) \\
(14)
\end{align*}
\]

### 4. Case analysis

#### 4.1 The necessity of considering the coal consumption and the change of the network loss in the meantime

We decide to trade at the peak of the load.

**Table 9** The raw data of the test system

| Testing system | The coal consumption before transaction/t | The network loss before transaction/MW |
|----------------|------------------------------------------|--------------------------------------|
| IEEE30         | 116.21                                   | 9.75                                 |
| IEEE39         | 2531.36                                  | 48.45                                |

#### 4.1.1 The optimal power generation trade model to save the coal consumption(model 1 for short in the following paper)

**obj:** \( \min f_2 = K^T \cdot (P_{g0} + P_{gp}) \)

**s.t.:**\[
\begin{align*}
(2) &- (9) \\
(11) \\
(14)
\end{align*}
\]

Let \( M_t \) be the amount of coal after transaction, \( M_t = KST \cdot (P_{g0} + P_{gp}) \), \( t \) is for the settlement time, and \( t = 1h \) in this paper.

\( \Delta M \) is the change of the coal consumption, which is the amount of coal after the transaction minus the amount of coal after the transaction. \( P_{loss} \) is for the network loss after transaction. \( P_{loss} = [(e1TP_{g0} + e2TP_{gp}) - (e3TP_{d0} + e4TP_{pb})] \cdot t \); \( \Delta P_{loss} \) is the change of network loss, which is the loss before the transaction minus the loss after the transaction; \( Q \) is the energy saving, \( Q = \Delta M + \alpha \Delta P_{loss} \), \( \alpha = 0.325t/MW·h \). By trading the coal consumption after transaction will arrive at the minimum, so we can ensure that the best amount of coal will be achieved after transaction. According to this model, there are results as follows.
Table 10 The optimization results of model one

| Testing system | Mt/t   | ΔM/t | Ploss /MW | ΔPloss/M W | Q/t |
|----------------|--------|------|-----------|------------|-----|
| IEEE30         | 115.87 | 0.34 | 8.1       | 1.65       | 0.88|
| IEEE39         | 2530.44| 0.92 | 49.43     | -0.98      | 0.6 |

4.1.2 The optimal power generation trade model to reduce the network loss (model 2 for short in the following paper)

\[
\begin{align*}
\text{obj:} & \quad \min f_3 = (e_1^T P_{s0} + e_2^T P_{g0}) - (e_1^T P_{s0} + e_2^T \lambda b) \\
\text{s.t.:} & \quad (2) - (9), (11), (14)
\end{align*}
\]

Table 11 The optimization results of model 2

| Testing system | Mt/t   | ΔM/t | Ploss /MW | ΔPloss/M W | Q/t |
|----------------|--------|------|-----------|------------|-----|
| IEEE30         | 116.54 | -0.33| 5.85      | 3.9        | 0.94|
| IEEE39         | 2531.6 | -0.23| 48.28     | 0.17       | -0.17|

4.1.3 The optimal power generation trade model to save energy (model 3 for short in the following paper)

The model has been introduced in above two sections, so we do not discuss here. In the following table, C represents the carbon emissions after transaction, \( \lambda_c \) is the load margin of the system when the load is at the peak time after transaction.

Table 12 The optimization results of model 3

| Testing system | Mt/t   | ΔM/t | Ploss/M W | ΔPloss/M W | Q/t | C/(t/h) | Cref/(t/h) | \( \lambda_{\text{ref}} \) | \( \lambda_c \) |
|----------------|--------|------|-----------|------------|-----|---------|------------|-------------------|------------|
| IEEE30         | 116.31 | -0.1 | 6.48      | 3.27       | 0.9 | 273.19  | 273.19     | 0.9               | 0.9        |
| IEEE39         | 2530.5 | 0.85 | 48.28     | 0.17       | 0.9 | 5873.2  | 5919.72    | 1.35              | 1.3        |
| IEEE57         | 497.86 | -0.44| 25.23     | 8.76       | 2.4 | 916.99  | 1152.73    | 0.95              | 0.9        |
| IEEE11         | 1767.0 | 1.46 | 136.36    | 10.49      | 4.8 | 3752.63 | 3771.61    | 1.05              | 1.0        |

From the analysis of the data in three tables above, it can be seen that the coal consumption of the power generation trade is ordered: Model 2 > Model 3 > Model 1, and the network loss after transaction is ordered: Model 1 > Model 3 > Model 2. Although Model 3 after transaction is not the best in the coal consumption and the network loss among the three models, the amount of its energy savings is the largest, which fully proves that Model 3 has the best energy-saving effect.

4.2 The necessity of introducing double constraint conditions

4.2.1 The optimal model of energy saving without the introducing of carbon emission constraints

The model removes the constraint (14), and the result of the transaction is as follows:
Table 13 Trading results without the introduction of carbon emission constraints

| Testing system | Mt/t  | ΔM/t  | Ploss/MW | ΔPloss/MW | Q/t  | C/(t/h) | Cref/(t/h) | λref | λc |
|----------------|-------|-------|----------|-----------|------|---------|------------|------|----|
| IEEE30         | 115.75 | 0.46  | 5.4      | 4.35      | 1.87 | 283.56  | 273.19     | 0.9  | 0.91 |
| IEEE39         | 2530.44 | 0.92  | 45.43    | 3.02      | 1.9  | 6044.11 | 5919.7     | 1.35 | 1.35 |
| IEEE57         | 497.52 | -0.1  | 24.42    | 9.57      | 3.01 | 1236.98 | 1152.7     | 0.95 | 0.98 |
| IEEE118        | 1759.43 | 9.04  | 125.99   | 20.87     | 15.8 | 3991.68 | 3771.6     | 1.05 | 1.05 |

Analysis: As can be seen from the data in Table 13, there is a slight increase in the load margin of the system of the IEEE30 and IEEE57 node at the peak load without introducing carbon emissions constraints. But the carbon emissions of the four nodes have increased. They are more than the provisions of the emission limit, hence, the environmental protection of this model greatly reduces.

4.2.2 The optimal model of energy saving without the introduction of static voltage stability constraints

The model removes (8), (9), (11), and the following is the result of the transaction in this case. λ0 is the load margin when the system does not introduce a single constraint condition.

Table 14 Trading results without the introduction of static voltage stability constraints

| Testing system | Mt/t  | ΔM/t  | Ploss/MW | ΔPloss/MW | Q/t  | C/(t/h) | Cref/(t/h) | λref | λc |
|----------------|-------|-------|----------|-----------|------|---------|------------|------|----|
| IEEE30         | 116.93 | -0.72 | 4.92     | 4.83      | 1.33 | 263.19  | 273.19     | 0.85 | 0.63 |
| IEEE39         | 2527.67 | 3.69  | 38.13    | 10.32     | 7.04 | 5820.64 | 5919.7     | 0.67 | 0.29 |
| IEEE57         | 497.15 | 0.27  | 23.93    | 10.06     | 3.54 | 908.16  | 1152.7     | 0.62 | 0.58 |
| IEEE118        | 1758.49 | 9.98  | 101.75   | 45.1      | 24.64| 36716.1 | 3771.6     | 1.35 | 0.32 |

From the data analysis of Table 14, it can be seen that under the condition of carbon emission constraint, the final carbon emission is less than the double constraint condition, and the result of the transaction is more environmentally friendly. However, the load margin of the whole system is significantly lower than that before the constraint, especially in IEEE39 and IEEE118 node systems, whose load margins at the peak of load are 19% and 22% respectively, which are most likely to lead to the serious consequences of voltage collapse, affecting the stable and safe operation of the power system.

In Table 12, Table 13 and Table 14, compared with that under the double constrains, the total amount of energy saving of the system increases under the single constraint. However, when the static voltage stability constraint condition is not introduced, the load margin of the system at the peak load point is small and there is a certain operational risk; if the carbon emission constraint is not introduced, the environmental protection of the model will reduce, both of which fail to achieve the requirements of "stability" and "environmental protection" of power generation trade. Therefore, it is necessary to introduce the two constraints of static voltage stability and carbon emissions in power generation trade.

5. Conclusion

In this paper, the optimal energy saving transaction model considering both static voltage stability and carbon emission constraints is proposed from the perspective of energy saving and emission reduction. It is proved that the largest amount of energy saving can be obtained by considering both the network loss and coal saving, the system is more in line with the requirements of safety and environmental after transaction. Using the model to guide the power generation trade can effectively alleviate China’s current major issues of energy shortages and greenhouse gas emissions.
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Acknowledgments
This paper was supported by Major Program of National Natural Science Fundation of China(Grant No.51367014). We express our sincere gratitude to the professors and students who provided support and assistance for this paper.