Integrated Power System Planning of Multiple Resources with Natural Gas Network and Power Sources

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Abstract. In order to promote all types of energy utilization, interaction between supply and demand as well as efficient operation, a new generation of energy systems which treats the electricity grid as the core came into being. Unlike traditional power system, the electricity network and gas network in the new generation of energy systems are closely linked through gas-fired units, and influence each other. Therefore, to ensure the safe operation of the future electricity network and natural gas network, the integrated framework for generation, electricity network and gas network expansion planning need to be carried out. Under the premise of meeting the electricity network and gas network safe operation constraints, we propose a multi-stage planning model for the combined generation, electricity network and gas network, in which investment cost and operating cost of the combined system are minimized. Combined generation, electricity network and gas network expansion planning is a large-scale, high-dimensional, non-convex and nonlinear optimization problem, which is difficult to solve. To solve this problem, we propose an incremental piecewise linear method to convert the original model into a large-scale mixed-integer linear optimization problem, allowing the use of sophisticated mathematical optimization method to quickly obtain the optimal solution.

1. Introduction

Compared with the traditional power system, the new generation energy system with power grid as the core closely connects the power network and the natural gas network through gas turbine [1-2]. At this time, if the interaction between the two energy systems is ignored, it is difficult to ensure the economy, security and reliability of the planning scheme if the power network or natural gas network is planned separately. Therefore, under the background of the coming of the new generation energy system with power grid as the core, carrying out the theoretical research on the joint planning of power network and natural gas network will provide an important theoretical basis for the future power system planning, which is a significant forward-looking work.

A dynamic model for joint planning of power grid and natural gas network considering the maximization of social welfare is proposed in [3-4]. In order to improve the robustness of the planning scheme in different scenarios, the adaptive cost is used as an objective function to quantify the risks caused by uncertain factors such as load forecasting and fuel cost. In addition, in order to achieve the goal of connecting a large number of distributed gas generating units into the distribution network more reasonably, a joint planning method is proposed for power distribution network and natural gas network planning.
network [5-7]. However, the above two kinds of natural gas pipeline flow models either ignore the air pressure, which cannot guarantee the optimal solution. In this paper, a piecewise linearization method is proposed to model the gas flow in natural gas pipeline. This method can ensure the global optimal solution of the planning model under the condition of controllable error.

The domestic research on the joint planning of power network and natural gas network is still blank. Based on the existing research results abroad, this paper establishes a joint planning model of natural gas network, power supply and power grid. In order to solve the shortcomings of the existing research results, this paper proposes a piecewise linearization method to transform the nonlinear gas pipeline flow constraints into linear constraints, thus transforming the original complex nonlinear nonconvex programming problem into a mixed integer linear programming (MILP) problem.

2. Planning modeling of natural gas network, power supply and power grid

2.1. Natural gas network model

As shown in Figure 1, the natural gas network is mainly composed of natural gas source, natural gas pipeline, pressurizer, storage and natural gas load. Natural gas is mainly transported to users through natural gas pipeline after being exploited and processed. However, due to the friction between natural gas flow and pipeline wall in the flow process, the pressure will gradually decrease after a certain transmission distance. In order to ensure that the natural gas can be transported to the load side normally, a pressurizer should be installed in the natural gas system to boost the pressure. The role of pressurizer in natural gas network is similar to transformer in power system. Because the planning is a long time scale problem, the role of energy storage constraints is mainly reflected in the short time scale operation problem. In order to avoid too much calculation, this paper ignores the modeling of energy storage in long time scale modeling. The following is the modeling of other elements in the natural gas network.

![Figure 1. Components of natural gas network.](image)

After the natural gas is extracted from the gas well, it needs to be purified through the refinery. Due to the limitation of gas pressure and equipment capacity at the gas well, the upper and lower limits of gas output per unit time of natural gas source are shown as:

$$W_{S_{	ext{min}}}' \leq W_{S_{	ext{h}}} \leq W_{S_{	ext{max}}}'$$

(1)

The pressure of each node in the natural gas network must be within the safe and reasonable operation range, and its mathematical expression is shown as:

$$\pi_{i_{\text{min}}} \leq \pi_{i_{\text{h}}} \leq \pi_{i_{\text{max}}}$$

(2)

The relationship between natural gas flow and pressure at both ends can be given by:

$$\text{sgn}(\pi_{i_{\text{h}}}, \pi_{j_{\text{b}}})fp_{p_{\text{h}j}}^2 = \phi_p(\pi_{i_{\text{h}}} - \pi_{j_{\text{b}}}) - F_{\text{p}_{\text{max}}}^{\text{max}} \leq fp_{p_{\text{h}j}} \leq F_{\text{p}}^{\text{max}}$$

(3)

The original model of the pressurizer is a non convex nonlinear expression describing the relationship between the pressurization ratio and the energy consumption. Since the focus of this paper is to study the expansion of natural gas pipeline, and the energy consumed by the pressurizer is very small (electric energy or natural gas), the model of pressurizer is simplified, and only the relationship
between the inlet and outlet of the pressurizer is retained, and the transmission capacity of the pressurizer is limited.

\[ \pi_{jdt} \leq \Gamma_c \pi_{jdt} \]  

(4)

2.2. Planning model of natural gas network, power supply and power grid

The planning objective of the proposed model is to minimize the net present value of investment and operation costs of natural gas network and power system in the planning level year, and meet the safety operation constraints of natural gas network and power network. Among them, the investment cost includes power investment cost, transmission line investment cost and natural gas pipeline investment cost. It should be noted that the operation cost of the generator only considers the non-gas unit, while the operation cost of the gas unit takes into account the cost of purchasing natural gas. The specific expression of the objective function can be given by:

\[
\begin{align*}
\text{Min} & \sum_{t} \sum_{i \in \text{SCG}} \frac{1}{(1+d)^{(t-1)}} GIC_G (x_{it} - x_{i(t-1)}) + \\
& \sum_{t} \sum_{i \in \text{SCG}} \frac{1}{(1+d)^{(t-1)}} GIC_G (y_{it} - y_{i(t-1)}) + \\
& \sum_{t} \sum_{p \in \text{SCG}} \frac{1}{(1+d)^{(t-1)}} GIC_G (z_{pt} - z_{p(t-1)}) + \\
& \sum_{t} \sum_{b \in \text{SCG}} \sum_{i \in \text{SWS}} \frac{1}{(1+d)^{(t-1)}} DT_{bt} \text{POC}_t P_{bdt} + \\
& \sum_{t} \sum_{b \in \text{SCG}} \sum_{i \in \text{SWS}} \frac{1}{(1+d)^{(t-1)}} DT_{bt} \text{GOC}_h w_{SH} \\
\end{align*}
\]  

(5)

3. Linearization of gas flow equation in natural gas pipeline

The joint planning model of natural gas network, power supply and power grid is a large-scale mixed integer nonlinear optimization problem, in which the nonlinear non convex gas pipeline flow equation is the key factor to increase the complexity of the model. In order to reduce the difficulty of solving the joint planning model of natural gas network, power supply and power grid, the flow equation of natural gas pipeline is linearized by incremental piecewise linearization method, and then the original model is transformed into a mixed integer linear optimization problem of large programming.

The specific linearization process is as follows:

(1) According to the scale and characteristics of the solution model, the appropriate number of linearized segments is determined after a balance is made between the accuracy of linearization and the amount of calculation.

(2) Calculate the discrete points needed for piecewise linearization.

(3) Find the value of \( f(x) \) corresponding to each discrete point.

(4) Linearization calculation, which can be given by:

\[
\begin{align*}
 f(x) & = f(x_1) + \sum_{k=1}^{NPL-1} \left[ f(x_{k+1}) - f(x_k) \right] \delta_k \\
 x & = x_1 + \sum_{k=1}^{NPL-1} (x_{k+1} - x_k) \delta_k \\
 \delta_{k+1} & \leq \eta_k \delta_k \\
 0 & \leq \delta_k \leq 1 \\
\end{align*}
\]  

(6)
Compared with the traditional methods, the proposed method has greatly improved the mean square error and interpolation error, and the expression of natural gas pipeline tidal current (3) can then be transformed into:

\[ \text{sgn}(\sigma_{jhtb} - \sigma_{jhtb})f_{pht}^2 = \phi_p(p_{s_{htb}} - p_{s_{jhtb}}) \]  (10)

After linearizing the left end of (10) by incremental piecewise linearization method, it can be given by:

\[ f_{p_{htb}} = f_{p_{pl1}} + \frac{NPL-1}{\sum_{k=1}^{NPL-1}} \left( f_{p_{p,k+1}} - f_{p_{pk}} \right) \delta_{pht} = \phi_p(p_{s_{htb}} - p_{s_{jhtb}}) \]  (11)

\[ f_{p_{pht}} = f_{p_{pl1}} + \frac{NPL-1}{\sum_{k=1}^{NPL-1}} \left( f_{p_{p,k+1}} - f_{p_{pk}} \right) \delta_{pht} \]  (12)

In the same way, the linearization constraints of the flow equation in the pipeline to be selected can also be obtained. Finally, the original model is transformed into a mixed integer linear optimization problem.

4. Conclusions
This paper introduces the natural gas network and models the key factors that need to be considered in the natural gas network planning. Then, to minimize the investment and operation costs, a joint planning model of natural gas network, power supply and power grid is proposed. In order to overcome the difficulty of solving the joint programming model caused by non convex nonlinear pipe flow equation, an incremental linearization method is proposed to transform the original model into a MILP model which is easy to solve.

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