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Operation Optimization of Energy Internet considering Transmission Characteristics of Natural Gas

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Con il continuo esaurimento dei combustibili fossili e il loro impatto negativo sull'ambiente, lo sviluppo delle energie rinnovabili e l'efficienza energetica sono imminenti, e il concetto di energia Internet è stato proposto. A causa della continua diminuzione dei costi del gas naturale, la proporzione di turbine a gas sul lato della generazione di energia è in continuo aumento. Nella pianificazione del sistema di alimentazione tradizionale, l'affidabilità dell'approvvigionamento di gas naturale non è generalmente considerata. Questa ipotesi potrebbe non essere vera poiché l'accoppiamento tra rete naturale e sistema energetico continua a essere rafforzato. Pertanto, è di grande importanza considerare le caratteristiche del gas naturale nell'ottimizzazione di Internet Energy.

Questa tesi studia le prestazioni della turbina a gas, che è il mezzo di accoppiamento della rete di gas naturale e del sistema di alimentazione. Vengono analizzate le prestazioni dei componenti principali nella turbina a gas, comprese le relazioni matematiche tra i compressori, i combustori, le turbine, ecc. E le variabili di ciascun componente. Il modello complessivo della turbina a gas viene stabilito in base alla relazione tra queste variabili e quindi questo modello viene utilizzato per analizzare le prestazioni della turbina a gas influenzate dall'ingresso di gas. Otteniamo la curva che indica la relazione tra la velocità del rotore o potenza e l'ingresso del gas. Quando c'è mancanza di gas, la turbina a gas avrà un calo improvviso della produzione; Simultaneamente, simuliamo l'operazione effettiva aumentando la velocità del rotore per aumentarne l'uscita. Aumentando la velocità del rotatore, dovremmo allo stesso tempo aumentare l'immissione di gas per mantenere l'aumento della potenza.

In secondo luogo, viene studiata l'operazione congiunta della rete di gas naturale e del sistema di alimentazione. Le prestazioni dei componenti chiave nella rete di gas naturale e nei sistemi di alimentazione sono analizzate in dettaglio. I modelli matematici precisi vengono utilizzati per modellare i componenti chiave e i componenti non critici sono semplificati. I vincoli della pressione dei nodi nella rete del gas naturale, l'uscita del pozzo di gas, la trasmissione della condotta sono presi in considerazione nel processo di modellizzazione. Sulla base della rete del sistema di alimentazione dei nodi IEEE 24 e della rete di gas naturale a 20 nodi del Belgio, viene stabilito un modello di simulazione dell'operazione combinata di accoppiamento gas-elettricità e si ottiene uno schema economico ottimale dell'operazione combinata gas-elettricità considerando le caratteristiche di trasmissione del gas naturale.

Uno studio del controllo del sovraccarico di emergenza del sistema di alimentazione mediante turbine a gas è nella terza parte. Quando si verifica un guasto nel sistema di alimentazione e la linea di trasmissione viene interrotta, il flusso di corrente che avrebbe dovuto essere sopportato dalla linea di demarcazione viene deviato verso altre linee nel sistema, causando l'interruzione di queste linee e l'ulteriore aggravamento la gravità del sovraccarico, che porta a una serie di errori complessi. Il metodo tradizionale di controllo del sovraccarico causerà la perdita di energia ad alcuni utenti. Considerando le rapide caratteristiche di rampa delle turbine a gas, possiamo regolare rapidamente l'uscita della turbina a gas per eliminare il sovraccarico della linea e per proteggere l'elettricità dell'utente non ne è stata compromessa. In questa tesi, basata sul precedente modello di accoppiamento gas-elettricità, lo schema di ottimizzazione viene confrontato in termini di velocità ed economia. Si è concluso che una quantità di carburante insufficiente inciderà sulla velocità di rampa della turbina a gas e abbiamo bisogno di sacrificare l'ecomonia in qualche modo per ottenere la soluzione più veloce.

Abstract

With the continuous depletion of fossil fuels and their adverse impact on the environment, the development of renewable energy and energy efficiency are imminent, and concept of Energy Internet has been put forward. Due to the continuous decrease of natural gas costs, the proportion of gas turbines on the power generation side has been continuously increasing. In traditional power system scheduling, the reliability of natural gas supply is generally not considered. This assumption may not be true as the coupling between natural network and power system continues to be strengthened. Therefore, it is of great significance to consider the characteristics of natural gas in the optimization of Energy Internet.

This thesis first studies the performance of gas turbine, which is the coupling medium of natural gas network and power system. The performance of the main components in the gas turbine is analyzed, including the mathematical relationships among the compressors, combustors, turbines, etc., and the variables of the each component. The overall gas turbine model is established based on the relationship between these variables and then this model is used to analyze gas turbine performance influenced by gas input. We get the curve indicating the relationship between the rotor speed or power output and the gas input. When there is lack of gas, the gas turbine will have a sudden drop in output; Simultaneously, we simulate the actual operation increasing the rotor speed to increase its output. When increasing the rotator speed , we should at the same time increase the gas input to keep the increased output.

Secondly, the joint operation of natural gas network and power system is studied. The performance of key components in natural gas network and power systems is analyzed in detail. The precise mathematical models are used to model the key components and the non-critical components are simplified. Constraints of the pressure of the nodes in the natural gas network, output of gas well, pipeline transmission are taken into account in the modeling process. Based on the IEEE 24 node power system network and the Belgium 20 node natural gas network, a gas-electricity coupling combined operation simulation model is established, and an optimal economic scheme of gas-electricity combined operation is obtained considering natural gas transmission characteristics.

A study of emergency overload control of the power system using gas turbines is in the third part. When a fault occurs in the power system and the transmission line is cut off, the power flow that should have been borne by the cut-off line is diverted to other lines in the system, causing these lines to go out of operation and further aggravating the severity of the overload, leading to a series of complex faults. The traditional overload control method will cause some users to lose power. Considering the fast ramp-rate characteristics of gas turbines, we can quickly adjust the gas turbine output to eliminate the line overload, and to protect the user's electricity not been affected. In this thesis, based on the previous model of gas-electricity coupling, the optimization scheme is compared in terms of speed and economy. It is concluded that insufficient fuel quantity will affect the ramp-rate of the gas turbine and we need to sacrifice ecomony someway to get the fastest solution.

Chapter 1

1 Background

1.1 Introduction

Fossil energy plays a central role in the traditional energy system. However, it is not sustainable and is increasingly lacking. High-speedy and rugged energy utilization methods, while aggravating the energy crisis, also have extremely adverse effects on the environment. The development of renewable energy as a substitute for fossil energy has become an inevitable trend in promoting social transformation and development. The Energy Internet aims to reduce the dependence of economic development on traditional fossil fuels, maximize the utilization efficiency of renewable energy, and fundamentally change the current energy production and consumption modes. The proposal of the Energy Internet breaks the supply and demand boundary between traditional energy industries, and maximizes the promotion of interconnection, interoperability, and complementarity of the types of primary and secondary energy sources such as coal, petroleum, natural gas, heat, and electricity; it provides large-scale access to new energy and distributed energy, realizing the plug-and-play operation of electrical equipment; it also realizes optimal regulation and efficient use of energy flow through local area autonomous consumption and wide-area peer-to-peer interconnection, and establishes an open and flexible industry and business forms. Energy Internet is the product of the deep integration of energy and internet. It has received extensive attention from the academic community and the industry[1-4].

The Energy Internet is actually composed of four complex network systems, namely power systems, transportation systems, natural gas networks, and information networks. It has the following features[5]:

1. Support the transition from fossil energy to renewable energy;

2. Support large-scale distributed power supply access;

3. Support large-scale hydrogen energy storage and other energy storage equipment access;

4. Use Internet technology to transform the power system;

5. Support the transition to electrified transportation.

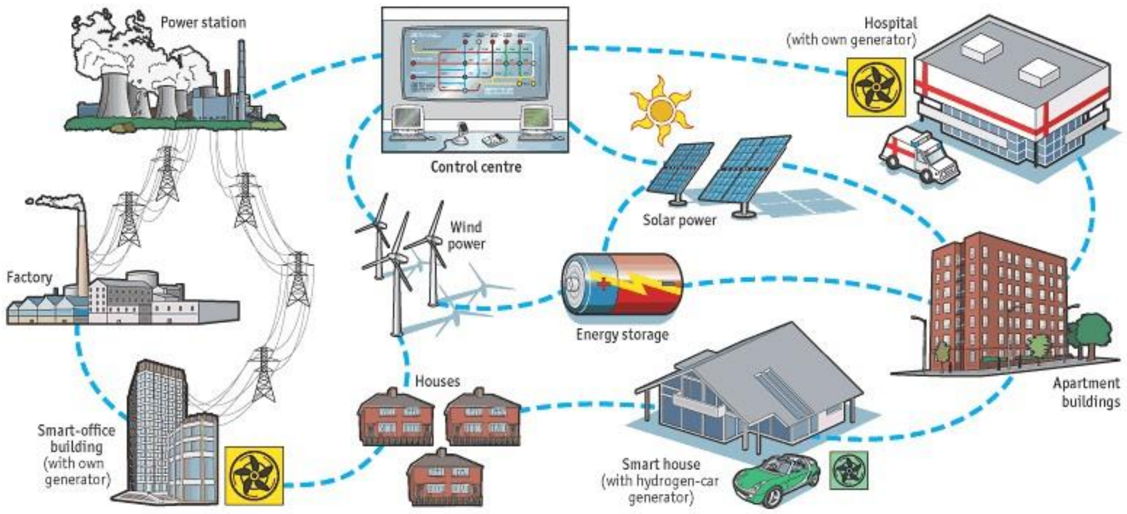

Figure 1-1 Structure of Energy Internet

The Energy Internet is a comprehensive energy-sharing technology that uses renewable energy, smart transmission technology, Internet information technology, and system planning and analysis technologies, and integrates power grids, natural gas networks, thermal networks, and electrified transportation networks to form a highly energy-efficient energy sharing network. The ideal operation mode of the energy internet should be a joint operation mode that is dominated by power grids and involves multiple industries such as energy producers and consumers, energy network operators, and energy agents. With the deep integration of energy and information, the energy industry will develop new business models in energy, materials and equipment, energy production, trading, consumption, and energy assets in the process of becoming highly efficient in the interconnection. The energy interconnection open platform is an integrated information processing platform with a comprehensive security strategy and interconnected features. Under this platform, the interconnection information network is equipped with massive information collecting and sensing devices within the power grid, gas networks, thermal networks, and transportation network to collect various energy equipment operating status and real-time operating status of each energy system. The multi-energy coordination management system coordinates and manages various energy transactions and energy resource allocations from the perspectives of the energy, gas, thermal, and electricity industries, and ensures the coordinated operation and management of multiple energy transactions and energy resources from the perspectives of safe system operation, maximum energy value, and multi-energy trading standards and regulations to guarantee the safe and efficient supply of energy and the healthy development of the energy Internet[6-8].

The power system, as a hub for the transformation of various energy sources, is the core of the Energy Internet. Compared with other primary energy sources, the impact of natural gas on the environment is relatively small. In addition, combined cycle gas units have significant advantages such as high efficiency, fast response and short construction time. In recent years, with the continuous progress and improvement of horizontal wells and fracturing technology and the emergence and deepening of the “shale gas revolution”, the cost of natural gas has been declining, and the proportion of gas-fired generating units on the power generation side is expected to increase. In this way, the operation of the natural gas network will directly affect the economic operation and reliability of the power system. On the other hand, with the recent power to gas (P2G) technology, the excess output of renewable energy generators can be converted into methane and injected into natural gas networks for transportation and utilization. Therefore, it can be predicted that, as one of the most important primary energy sources, the proportion of natural gas in the future energy consumption is expected to increase significantly. The future energy internet will be the result of highly coupled natural gas networks and power systems, and their relationship will also be much closer[5].

In traditional power system operation and dispatching, the reliability of natural gas supply is generally not considered, ie it is assumed that the supply of natural gas is not limited when the generation unit needs. In fact, natural gas supply is constrained by pipeline capacity and gas storage capacity; therefore, with the increase in the proportion of gas-fired power generation, this assumption does not always hold.

At the same time, unlike electricity, natural gas has a slow transmission speed in its network, and has a certain transmission delay. Also because of the compressibility of natural gas, it can be stored in the transmission pipeline in a short time without special storage devices. This makes it impossible to simply deal with the traditional power system scheduling problem when considering the coupling of natural gas networks and power systems.

1.2 Literature Survey

Gas turbines have entered the power generation industry since the 1950s. After more than a century of development, the performance of gas turbines has been greatly improved. At present, there are many researches on gas turbines. In today's gas turbine industry, the United States is in a leading position. This is mainly because the United States has given great support to the research and development of gas turbines, and has invested a lot of funds, such as the IHPTET plan, ATS plan and CAGT plan. Japan is also one of the countries that can produce FA-type gas turbines and has a new Daylight plan to promote the development of gas turbines. Currently, there are four companies that have cutting-edge technologies for gas turbine manufacturing: GE in the United States, Siemens in Germany, Alstom in France, and Mitsubishi in Japan. These companies now produce third-generation gas turbines. The model and parameters of a typical simple-cycle gas turbine are shown in Table 1-1[9].

Table 1-1 Typical simple-cycle gas turbine models and parameters

Company	Model	Basic Power (kW)	Thermal efficiency (%)	Compression rate	Air flow (kg/s)	Turbine Temperature (℃)
GE Power system	PG6111 (FA)	75900	34.9	15.6	202.8	602.8
	PG6591C	42300	36.27	19.0	117.0	569.4
Siemens Power Generation	V94.2	182300	35.18	13.8	519.8	567.2
	V94.3	265900	38.60	17.0	655.9	584.4

Mitsubishi Heavy Industries	M701DA	144100	34.8	14.0	440.9	542.2
	M701G	271000	38.70	21.0	737.1	587.2
Alstom	GT8C2	57000	34.01	17.6	200.0	508

The performance of gas turbines varies. According to the performance and characteristics of different gas turbines, domestic and foreign scholars have conducted a series of research and analysis. The reference [9] establishes the mathematical model of the gas turbine system, adopts the method of fuzzy identification to fit the compressor characteristic curve. The reference [10] establishes the mathematical model of natural gas supply system that is convenient for simulation and calculation. The reference [11] studied the characteristics of gas turbines using component modeling methods, focusing on the non-iterative modeling method based on the volumetric method. The reference [12] uses the modular modeling method to process compressors and gas turbines in stages; the dynamic mathematical model of each module is established according to the conservation law, and programming is performed using the ACSL simulation language. The reference [13] studies the performance of single-axis constant-speed, simple-cycle gas turbines for power generation, and establishes equations based on the various balances that should be satisfied during its operation. In reference [14], the volume inertia link iss added to the gas turbine model, which simplifies the steps in the calculation of the dynamic process, eliminating the need for iterative calculations to solve the calculation of the right function of the first-order inertia link, thus avoiding possible non-convergence caused by the use of iterative calculations. The reference [15] uses the sequential module method for IGCC systems to calculate and establish the performance models for each unit. The reference [16] combines the advantages of the sequential module method and the simultaneous equation method, introduces the simultaneous optimization algorithm of gas turbine system simulation, and proposes two levels of three models: strict model, simple model, and system-linked network model, which can use the advantage of the stand module method and can better reflect the complex fluid network characteristics of the system. Through a series of modeling studies on gas turbines, it can simulate and predict its dynamic characteristics as a reference for actual operation of gas turbines.

Another important issue in the coupling of power systems and natural gas networks is the coordinated operation of the two systems. Power systems and natural gas networks have similar and different characteristics. When two networks are linked through some coupling links, how the two systems work together requires specific research. The reference [17] proposes the concept of energy hub, which integrates electricity, natural gas, and other forms of energy. It consists of energy conversion equipment and energy storage equipment, enabling the conversion and storage of multiple energy sources. This concept can be used to model various physical entities including power plants, substations, and microgrids. The energy hubs are connected to each other through transmission lines, natural gas pipelines, and other devices to form a multi-energy network system, in which energy is consumed or converted. The reference [17] also proposes the concept of a coupling matrix to describe the mutual transformation of different energy sources in an energy hub. The coefficients in the coupling matrix are derived from the conversion efficiency between different energy sources and the dispatch factor, which is a decision variable that determines how energy is transformed into each other. The reference [18] takes the electric/gas/thermal micro energy system as the object, and studies the issues of micro gas turbine modeling, energy coordination strategy, unified power flow solution, and optimization of power flow. The reference [19] establishes the mathematical model in integrated energy systems of electricity, gas and thermal power based on existing cumbersome problems in the modeling of gas networks with compressors, considering different control methods, and an improved analysis method is proposed. In reference [20] the analysis of interconnected links centered on regional mixed energy stations is conducted based on energy hubs conceptually, and a comprehensive solution model of REGHS energy flow is formed. Reference [21] proposes a multi-stage joint planning model for power system and gas networks with the goal of minimizing investment costs and operating costs. The incremental linear model is used to convert the original model into a mixed-integer linear optimization problem. In reference [22], the problem of hybrid systemization of power grids is described from a technical and economic point of view respectively, and the dynamic modeling of natural gas pipeline networks is performed. At the same time, the method of considering the dynamic process of gas turbines connected to the pipeline network is given. These scholars have analyzed the operating characteristics of the two networks through a certain mathematical model, which helps us to have a better understanding of the energy interconnection and provide guidance for actual operation.

Finally, the transmission line overload in power systems is a problem that needs much attention. Many scholars have done a lot of research on this issue. The reference [23] introduces the overload criteria of the safety and stability control device, and introduces the specific methods for increasing the mis-proof criteria from power system and the criteria design ascepts. The reference [24] proposes the control law of the load of the line overload automatic control unit for the actual needs of the power system, and provides the control criteria of the line breakage, short circuit and disconnection of the voltage transformer (TV) and the overload control of the line. The reference [25] combines the configuration and operating requirements of the actual grid safety and stability control system, and gives the optimal emergency control model under transient stability. The reference [26] proposes a new algorithm for power flow tracking in combination with the superposition theorem and the principle of proportional distribution, and applies it to line overload emergency control. At present, the investigation of the transmission line overload has not yet come to an end. With the increasing level of energy interconnection, the impact of line overload is also increasing, and we need to continue to study this issue further.

Chapter 2

2 Gas turbine performance in gas-electric coupled system

At present, China mainly uses coal to generate electricity. The issue of pollution emissions from coal power generation has attracted increasing attention as the scale of power generation continues to expand. Coal-fired power plants have become the largest air pollution source in China. Therefore, more environmentally friendly and efficient power generation technologies (such as hydroelectric power generation, wind power generation, solar power generation, nuclear power generation and gas turbine power generation, etc.) have gradually received attention. From 1996 to 2004, China's total energy production and consumption and its composition are shown in the following two tables. From this we can see the changes in energy production and consumption in different forms[27].

Table 2-1 China’s total energy production and composotion from 1996 to 2004

Year	Total energy production (10,000 tons of standard coal)	Percentage of total energy production (%)			
		Raw coal	Crude oil	Natural gas	Hydropower
2004	184600	75.6	13.5	3	7.9
2003	159912	74.5	15.1	2.9	7.5
2002	138369	71.2	17.3	3.1	8.4
2001	120900	68.6	19.4	3.3	8.7
2000	106988	66.6	21.8	3.4	8.2
1999	109126	68.3	21	3.1	7.6
1998	124250	71.9	18.5	2.5	7.1
1997	132410	74.1	17.3	2.1	6.5
1996	132616	75.2	17	2	5.8

Table 2-2 China’s total energy comsumption and composotion from 1996 to 2004

Year	Total energy consumption (10,000 tons of standard coal)	Percentage of total energy consumption (%)			
		Raw coal	Crude oil	Natural gas	Hydropower
2004	197000	67.7	22.7	2.6	7
2003	170943	67.6	22.7	2.7	7
2002	148222	65.6	24	2.6	7.8
2001	134914	65.3	24.3	2.7	7.7
2000	130297	66.1	24.6	2.5	6.8
1999	130119	68.0	23.2	2.2	6.6
1998	132214	69.6	21.5	2.2	6.7
1997	137798	71.7	20.4	1.7	6.2
1996	138948	74.7	18.0	1.8	5.5

Compared with coal, China's use of natural gas and hydropower resources remains to be further improved. In 2000, the hydropower generation in China was 222.4 billion kWh, the utilization of hydropower resources was 11.56%, and the natural gas output was 27.2 billion, which was less than 5% of the resources. In 2004, the proportion of China's natural gas and hydropower in energy production was 3% and 7.9%, and the proportion of energy consumption was only 2.6% and 7%. The use of clean energy resources such as coalbed methane, wind power and solar power have just started, and their role have not been given enough attention[27].

As a heavy-duty power generation equipment, gas turbines use natural gas, fuel oil, and synthesis gas as fuels to generate electricity. Gas turbine combined cycle has high efficiency, low pollution, small floor space, short construction period, flexible operation, and suitable for peaking time and other significant advantage. In recent years, newly-added power generation in developed countries has basically replaced conventional coal-fired thermal power generation with high-performance natural gas combined-cycle power generation. With the construction of natural gas transmission projects such as West-to-East gas transmission, the development of China’s gas turbine power plants has encountered unprecedented The opportunities for gas turbine combined cycle units have been rapidly developed in China, especially in the Pearl River Delta and Yangtze River Delta regions. Many large-scale gas turbine combined cycle power plants have been completed and put into operation, and a considerable number are being planned and constructed[28].

The total size of China's national economy was ranked second in the world in 2013, and the total installed capacity of power generation equipment has reached 1.23 billion kW, ranking first in the world. However, per capita power generation and per capita electricity consumption in China are approximately 1/4~1/3 compared with developed countries such as United States, Britain, Germany and France. In order to realize China's industrialization, urbanization, and agricultural modernization, China's power industry will continue to expand its scale. It is predicted that by 2030, China's total installed capacity of power generation will double again, reaching approximately 2.5 billion kW.

Natural gas-fired gas-fired steam combined cycle is a highly efficient clean power generation technology that humans have mastered. The most advanced combined-cycle power plant currently has an efficiency of 60% to 61%, and NOx emissions are reduced to 15mL/m3 or even less, and there is no SOx and dust emission. The specific emission of carbon dioxide is only about 40% of the supercritical coal-fired power stations. The energy efficiency of the thermoelectric cooling and multi-feed system consisting of natural gas-fired gas turbines can reach 75%, which is the main form of distributed generation and regional energy systems. With the development of our national economy and the advancement of urbanization, the demand for gas turbines in China's power industry will be enormous[29].

In 2013, China's natural gas consumption was four times that of 2004, reaching 167.6 billion m^3, and the State Council recently proposed to reach 400 billion m^3 by 2020. The current situation of the use of natural gas in countries around the world is about 1/3 of the total power generation amount. According to this proportion, by 2020, China’s natural gas industry can provide power for 160 million kW gas-steam combined-cycle power plant. At present, China is developing IGCC power station, polygeneration, and coal chemical industry in an orderly manner, among which gas turbines are also used. With gas turbines needed in the petrochemical and metallurgical industries, the market size of heavy-duty gas turbines and other industrial needs can reach 4000 to 500 billion yuan.

The early development of gas turbines in China (1950-1970) was the study of Soviet technology, and we conducted independent research and development on the basis of digestion and absorption. After the reform and opening up, China mainly used cooperative production methods in the gas turbine industry, and no longer developed its own gas turbine products. In 1985, China introduced the LM2500 naval gas turbine from the United

States and gained some experience in operation and maintenance. Since 1993, China and Ukraine have cooperated to introduce the newly-developed UGT25000 gas turbine gas turbine and signed a production and manufacturing technology licensing contract. Since then, China has owned high-power gas turbines.

Since 2002, China's gas turbine industry has entered a new period of development, through the introduction of advanced gas turbine technology, on this basis of digestion and absorbtion, to achieve the localization of equipment manufacturing and production, and through innovation to achieve intellectual property autonomy. During the six years from 2001 to 2007, China formed three gas turbine cooperation consortia: Shanghai Electric (Group) Corporation cooperated with Siemens, Harbin Power Equipment Co., Ltd. cooperated with General Motors Corporation, Dongfang Electric Corporation cooperated with Mitsubishi Corporation. China has carried out a lot of scientific research on gas turbines, and the gap between the technological field of gas turbine development and the international advanced level is gradually narrowing[30].

In general, China began to develop gas turbines early but developed slowly, and there is still a long way to go compared with the advanced level in the world. Therefore, in order to meet the needs of China's gas turbine development strategy, it is of great significance to study the operating rules and experience of gas turbines.

2.1 Mathematical model of gas turbine

Gas turbine is a complex system. It consists mainly of three parts: the compressor, the combustor and the turbine. There are also other parts like cooling system, gas control system, but we ignore them in this thesis.

System modeling methods are usually two kinds, one is the white box method and the other is black box method. Here we adopt white box method, which means we need to establish part by part and then study the overall performance.

To establish an appropriate model for gas turbine, we have the following assumptions:

1) Compressor inlet temperature is equal to atmospheric temperature

2) The gas in the compressor and turbine is regarded as the ideal gas

3) The cooling air is drawn at the outlet of the compressor and is not considered for work in the turbine.

4) The losses in the compression and expansion process are considered by the isentropic and isentropic efficiency.

2.1.1 Compressor model

The compressor is one of the main components of the gas turbine, and its role is to supply high pressure air to the gas turbine combustion chamber continuous.

The import flow of compressor is decided by its rotor speed and blade angle. We can demonstrate import flow as a function of rotor speed, blade angle and environmental parameters:

$$G_c = \frac{p_1 \cdot g(aiv)}{\sqrt{T_1}} \cdot \frac{\rho_1}{\rho_{R1}} \cdot \frac{n}{n_r} \cdot \frac{G_R}{kG_R} \qquad (2\text{-}1)$$

Where p_1 is the inlet pressure, $g(aiv)$ is blade angle function, T_1 is inlet temperature, n is rotor speed and n_r is the reference rotor speed.

Here we set inlet temperature T_1 equal to 300K and outlet temperature T_2 equal to 382.2K, which comes from the equation $T_2 = T_1(1 + \frac{\pi_c^{m_c} - 1}{\eta_c})$, and think that π_c, η_c and m_c are all constant because their appropriate values make little difference.

For the air pressure, we take inlet pressure p_1 equal to 0.98 times of atmospheric pressure and at the same time outlet pressure p_2 equals to π_c times of inlet pressure.

To simplify this function, we can assume that function of blade angle equals to per unit 1. Looking up historical and engineering data and we can draw a much simpler function: $G_C = 0.0217n$, which only depends on the rotor speed.

For the air enthalpy, we have the following function:

$$1.01t + (2500 + 1.84t) * d \qquad (2\text{-}1)$$

Where t is centigrade temperature and d is moisture content. We find that d equals to 0.023kg per kg air in 300K and 0.06kg in 288.2K.

So we can get the compressor power consumption:

$$N_c = G_c(H_2 - H_1) \tag{2-3}$$

2.1.2 Combustor model

The main role of the combustion chamber in a gas turbine is to burn the high pressure air obtained by the compressor by burning the fuel and eventually to form a high pressure and high temperature gas. The chemical reaction in the combustion chamber is an oxidation reaction. Here we consider the gas is C_8H_{16} and burning with O_2.

The high pressure air coming out of the compressor partly enters the combustion chamber and the other part is withdrawn for cooling air. The cooling air is used to cool the turbines of the rotor, stator and blades. So the air enters the combustion chamber equals to: $G_{b1} = G_c(1-X)$, and the mixed outlet flow equals to $G_{b2} = G_{b1} + G_f$, where G_f is gas flow amount.

For the cooling coefficient X, we use this figure as assistance and in the circumstance we set is X approximately 5%.

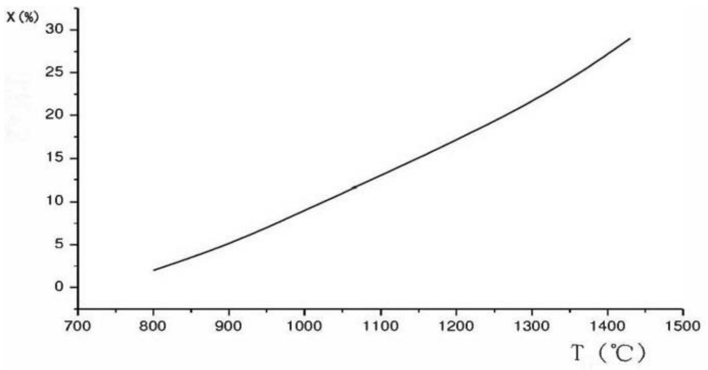

Figure 2-1 Relationship between cooling coefficient and temperature

Outlet pressure of combustor p_3 equals to 0.98 times of inlet pressure p_2.

For the combustion process, we have the following equation:

$$G_{b1}(H_{b1}^{T_2} - H_{b1}^{T_b}) + G_f(H_f^{T_f} - H_f^{T_b}) + \eta G_f H_f^{T_b} = (G_{b1} + G_f)(H_{b2}^{T_3} - H_{b2}^{T_b}) \tag{2-4}$$

Where T_b is temperature when we test gas heat and T_f is fuel inlet temperature; η is combustion efficiency; T_3 is combustor outlet temperature and is unknown.

From this equation, we can get combustion chamber outlet enthalpy equals to:

$$H_{b2}^{T_3} = \frac{G_{b1}(H_{b1}^{T_2} - H_{b1}^{T_b}) + G_f(H_f^{T_f} - H_f^{T_b}) + \eta G_f H_f^{T_b}}{G_{b1} + G_f} + H_{b2}^{T_b} \tag{2-5}$$

To calculate the enthalpy of gas in a particular temperature, we consider the gas fuel is all C8H16 and air is adequate so the gas fuel is completely combusted. We use the following table to calculate the enthalpy of gas[9]:

Table 2-3 Enthalpy coefficients of different gases

	CO_2	H_2O	N_2	AIR	C_8H_{16}
a	0.1965×10^3	-0.4345×10^2	-0.2731×10^2	-0.3302×10^2	-0.1149×10^1
b	0.4343×10^1	0.8421×10^1	0.4343×10^1	0.7281×10^1	0.6985×10^1
c	0.1025×10^1	-0.2370×10^{-2}	-0.8690×10^{-3}	-0.1434×10^{-2}	0.3506×10^{-3}
d	-0.7134×10^{-3}	0.4960×10^{-5}	0.9296×10^{-6}	0.2348×10^{-5}	0.4713×10^{-6}

And with these coefficients we can calculate:

$$H^T = 4186.8\times(a + bT + cT^2 + dT^3) \tag{2-6}$$

$$H_{tot} = \sum_i^m \varphi_i H_i \tag{2-7}$$

Where φ is volume fraction of each part.

By solving the cubic equation we can get the combustor outlet temperature T_3.

2.1.3 Turbine model

Turbine is the component conversing heat of the gas into the turbine rotor mechanical power. Part of the mechanical work is used to drive the compressor to work, the excess part is used as a valid power output, to drive the outside of the various loads.

Mixed gas inflates in turbine to promote mechanical power, so the outlet of mixed gas equals to its inlet flow, which is $G_t = G_{b2}$.

We set its outlet pressure p_4 equals to 0.98 times of atmospheric pressure and outlet temperature T_4 equal to 0.892 times of combustor outlet temperature T_3.

To get the power that turbine produces, we can use the following equation: $N_t = G_t(H_3 - H_4)$, H can be calculated with the function we draw in combustor model section.

2.1.4 Load and rotor model

There are several kinds of load model. Here we use velocity adjustable load model:

$$N_l = kn^2 \tag{2-8}$$

The gas turbine we study is a uniaxial system so we can draw the following rotor differential equation[2]:

$$J\omega \frac{d\omega}{dt} = N_t - N_c - N_l \tag{2-9}$$

With this equation, we connect the whole system with the rotor speed, and when the circumstance changes, rotor speed will change correspondingly[31].

2.1.5 Overal model

The compressor compresses the air into the gas turbine. Its outlet temperature and pressure are the inlet temperature and pressure of the combustot. The fuel enters the combustor and the compressed air is mixed and burned with fuel. The temperature and pressure at the inlet and outlet follow their internal chemical and physical equations. The outlet temperature is the inlet temperature and pressure of the turbine, and the relationship between the temperature and pressure of the inlet and outlet of the turbine follows its internal chemical and physical relationship. By linking all the mathematical equations through the relationship between the various variables within the gas turbine, a general gas turbine mathematical model is established.

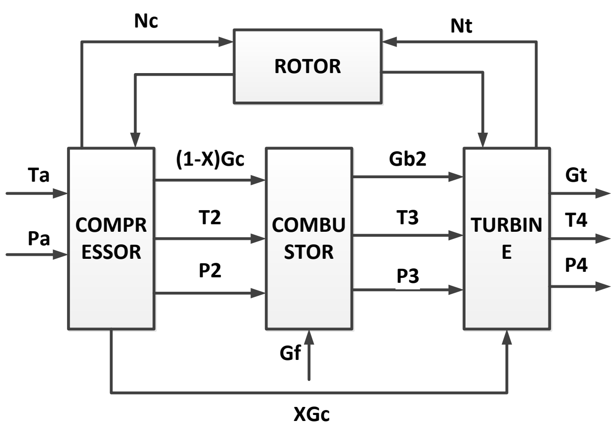

Figure 2-2 Overall structure of gas turbine

Figure 2-2 shows the overall model of gas turbine. We connect these four parts with the relation of temperature, pressure and rotor speed.

2.2 Simulation and analysis of gas turbine performance in gas-electricity coupling

We use Matlab to simulate this gas turbine model and study different cases to analyze the characteristics of gas turbine and its impact on power system.

2.2.1 Input and output characteristics

We change the amount of input gas fuel and see the steady output of rotor speed as follows:

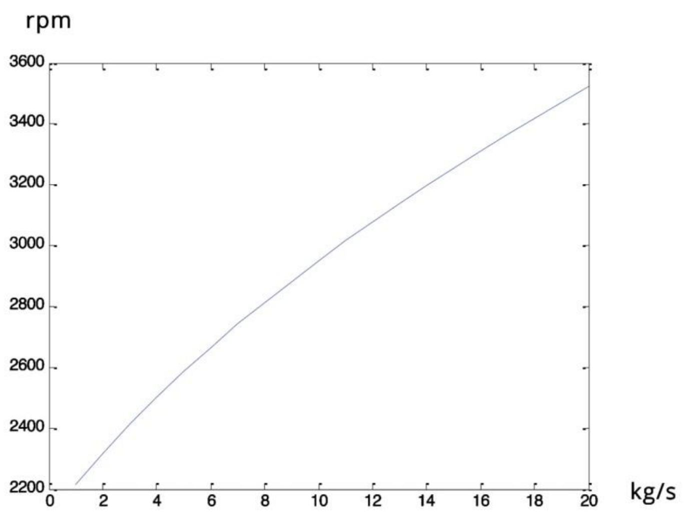

Figure 2-3 Relationship between rotor speed and gas supply

When we increase the gas we put in, the rotor speed will increase correspondingly.

As we can see, the relationship of rotor speed and gas supply is not linear. Obviously, when gas supply is excessive, it will not be completely combusted and there will be a lot left. So when we operate optimal scheduling of gas network and power system, we can not consider the gas supply is infinite and can satisfy all our demands.

2.2.2 Emergency Response

We change the amount of gas fuel input immediately from 12kg/s to 8 kg/s, and the rotor speed changes as follows:

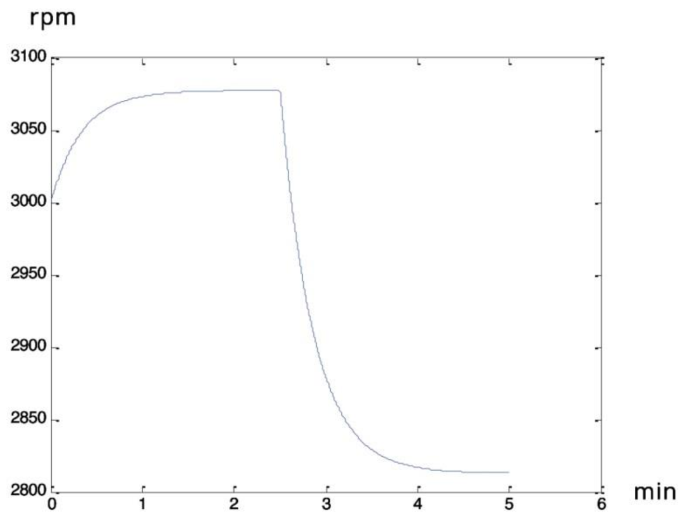

Figure 2-4 Respond of rotor speed when gas supply decreases

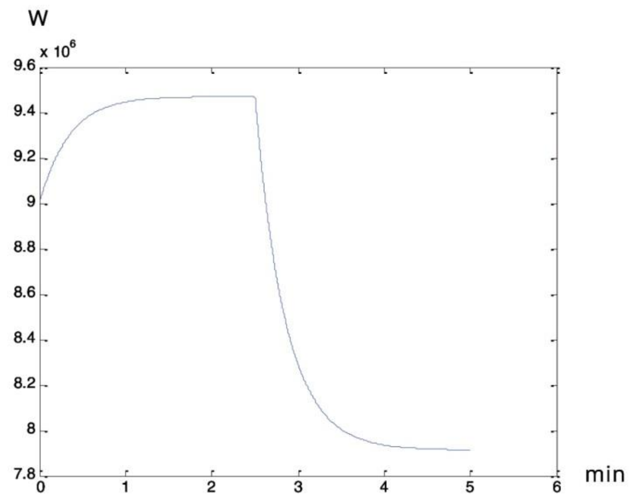

Figure 2-5 Respond of output power when gas supply decreases

The rotor speed will rapidly drop from about 3080 r/min to 2820 r/min with output power dropping from 9.5 MW to 7.9 MW.

When there are emergencies occur in gas networks, ignoring the dynamic characteristic of gas, gas supply is cut immediately, the power gas turbine produces will drop rapidly following the curve of Figure 2-5, which will influent power flow and the steady of power system.

If the gas turbine is applied to stable supply for long periods of time, this quick decrease will increase the power grid fluctuation risk. Electrical staff needs to cut some loads to maintain normal power flow and this will cause partial power outages. On the other hand, they can increase some other plants' power output to remain stable. However, this may exert the pressure that lines undertake, and may cause overload.

2.2.3 Peaking Function

When we want to increase the output power of gas turbine, we can take methods such as raising the rotor speed immediately. The following figure is the respond when we change the speed immediately.

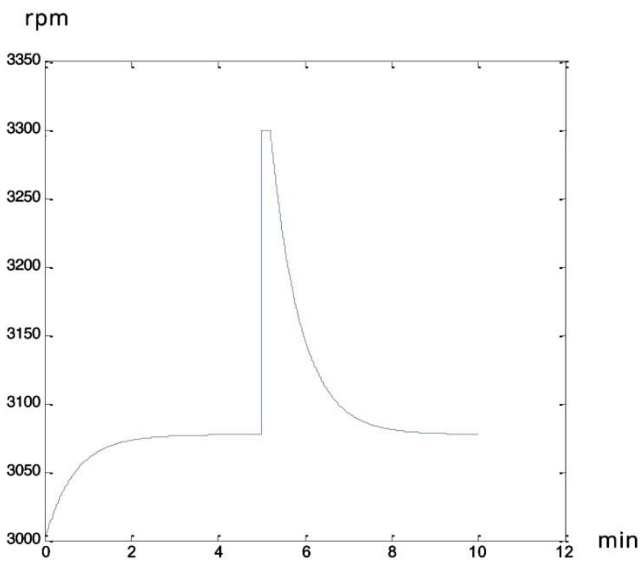

Figure 2-6 Respond when raise rotor speed

It can be seen from the figure that after the rotor has increased the speed with the help of the external equipment, since the gas quantity of the gas turbine has not been increased in time, after the external force is removed, the rotor speed of the gas turbine will rapidly decrease and return to the previous stable speed.

This simulation simulates the need to increase the output of the gas turbine and increase the output of the rotor in a short period of time by using external means to accelerate the rotation of the rotor. However, the amount of gas should be increased accordingly. Otherwise, after the removal of the external force, the rotor speed of the gas turbine will still return to the original level. This has a certain guiding significance for the actual operation of gas turbine power plants.

2.3 Summary of this chapter

On the basis of the previous study of gas turbine, this chapter summarizes the general variable relationships according to the mechanism of each component within the gas turbine, and links the mathematical equations of various components of the gas turbine through the relationship between them and the requirements used in the power system are simplified for some parameters and variable equations that have little impacts on the results, and a simple and effective mathematical model is established to facilitate the use in the power system and to simulate some of the performance of the gas turbine:

1) A gas turbine mathematical model that is easy to use in the power system is established based on the relationship between the various components within the gas turbine;

2) The gas turbine output (rotor speed) curves corresponding to different fuel intake volumes are obtained by simulation. The output of the gas turbine will increase with the increase of the gas volume, but it is not a linear relationship and this can help us in the modeling of power systems when using this model;

3) We do simulations of the change in output performance (rotor speed, output force) of the gas turbine when the intake gas amount is insufficient. When the supply of fuel is insufficient due to inadequate pressure in the gas network or pipeline pressure, the rotational speed and output of the gas turbine will suddenly drop and eventually stabilize at a low rotational speed level;

4) Simulation of the actual operation of a gas turbine power plant that needs to rapidly increase the gas turbine output. With the help of external equipment, the gas turbine rotor speed can increase rapidly, but at the same time it needs to increase the amount of fuel to maintain the increased output. Otherwise, after the external force is removed, the gas turbine rotor speed will quickly drop to the original level.

Chapter 3

3 Optimized operation of the gas-electric coupled network

As already mentioned, with the continuous deepening of the “shale gas revolution”, the proportion of gas-fired power generation in total power generation capacity is expected to increase significantly in the future. During a short period of five years from 2006 to 2010, shale gas production in the United States increased by more than 20 times. At present, 23% of the total natural gas in the United States is supplied by shale gas. The United States' "shale gas revolution" has changed the pattern of the world natural gas market, which may cause a significant drop in the price of natural gas, which in turn will promote the rapid development of gas-fired power generation. It can be foreseen that as one of the most important primary energy sources, the proportion of natural gas in the future energy consumption is expected to increase significantly. Therefore, the future Energy Internet will be the product of a highly coupled natural gas network and power system. Some countries began to try to unify the management of natural gas networks and power systems. For example, in 2009, Australia merged its domestic power system operators and natural gas network operators and established a national energy market operating agency responsible for the unified planning and management of power networks and natural gas networks.

A hybrid energy system consists of a natural gas network and a power system. Figure 3-1 shows the main components of the hybrid energy system. Natural gas networks mainly include natural gas pipelines, pressure regulating valves and compressor stations. Natural gas enters the pipeline from the supply source and is then transported to the user through the pipeline network. The natural gas flow is adjusted by controlling the pressure of different nodes in the pipeline network and the position of the pressure regulating valve or valve spool. Usually the compressor station consists of an engine, a gas turbine and a compressor[32].

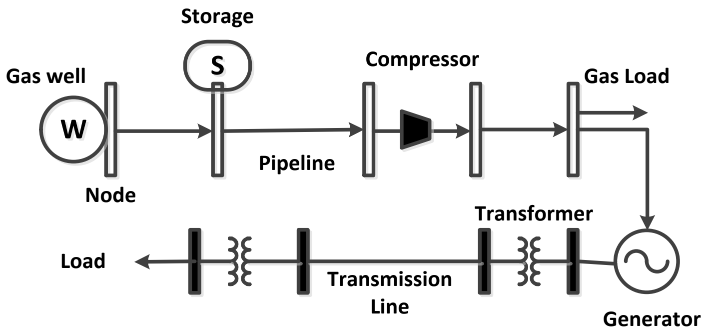

Figure 3-1 Model of gas network and power system

Power systems and natural gas networks are, to a certain extent, very similar. They are all used to transport energy from the supply side to the consumer side. They can be summarized as follows: supply side (power station or natural gas field); transmission (high-voltage power grid or high pressure pipe network); distribution (medium/low voltage network or medium/low pressure pipe network); user (power user or gas user)[33].

However, there are some differences between the two networks. Natural gas is always in the form of primary energy and comes directly from the natural gas field. Electricity is secondary energy that is converted from primary energy at the power station. Natural gas is sent from the natural gas field (supply side) to users through the pipeline network, and electricity is transmitted through the transmission line. In addition, natural gas pipelines can store some natural gas for use at peak load period, while electricity cannot be efficiently stored.

With the increasingly close connection between them, to some extent, the two networks operate as one. Figure 3-2 shows the joint operation of a hybrid gas-electric system.

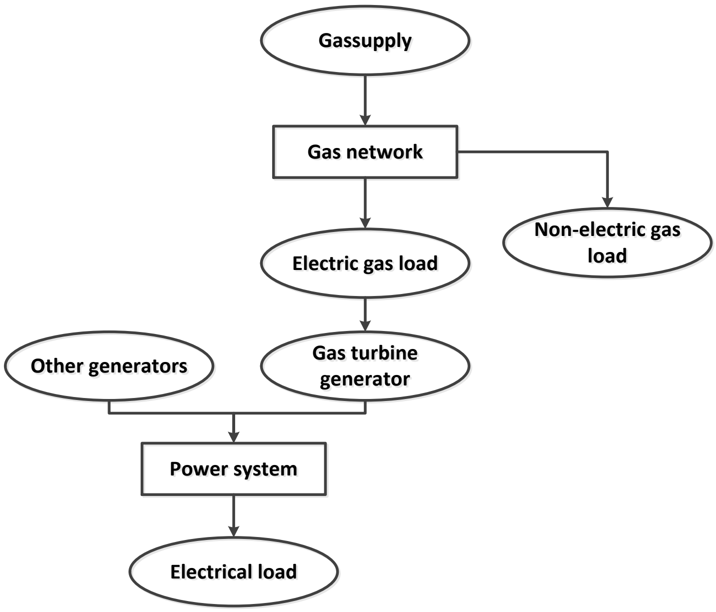

Figure 3-2 Joint operation of gas network and power system

3.1 Gas-electricity coupled network model

As shown in the figure below, the natural gas network consists of natural gas wells, gas storage tanks, natural gas pipelines, compressors, and natural gas loads. After natural gas is mined and processed, it is mainly delivered to users through natural gas pipelines. However, since the natural gas will rub against the pipeline wall during the flow, the pressure will gradually decrease after a certain transmission distance (usually 80-160km). In order to ensure that natural gas can be delivered to the load side normally, a compressor must be installed in the natural gas system to boost the pressure. The role of compressors in natural gas networks is similar to transformers in power systems. In the modeling of natural gas networks, the constraints of each link must be considered.

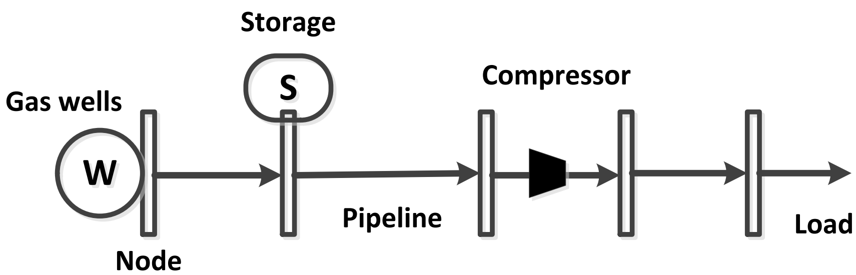

Figure 3-3 Structure of gas network

3.1.1 Natural gas network modeling

3.1.1.1 Natural gas source and gas storage

The role of natural gas sources and gas storage tanks is like the power supply and batteries in the power grid. It is the energy source of the entire network and will not be elaborated here.

3.1.1.2 Compressor

There are many ways to classify compressors. According to their driving force, compressors in actual natural gas networks can be divided into two types: gas compressors and electric compressors. Their structures are shown in the figure below:

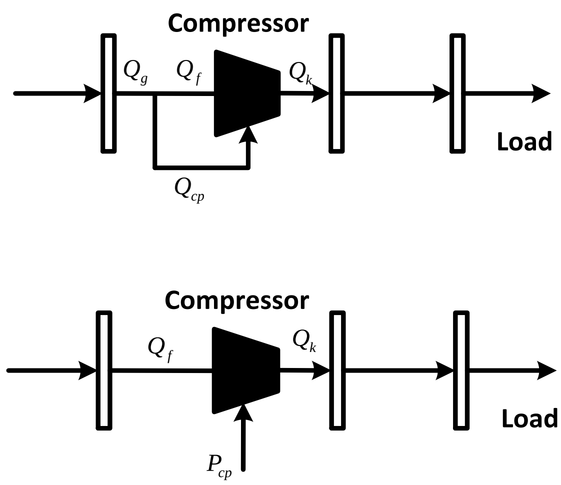

Figure 3-4 Structure of compressor

For the electric compressor, its driving force comes from the outside, that is, the electric energy supplied by the outside to the compressor drives the compressor to work, and does not require the consumption of natural gas, then its intake air amount is equal to the export volume:

$$Q_f = Q_k \quad (3\text{-}1)$$

For the gas compressor, a part of the natural gas that enters the compressor needs to be used to drive the compressor. The gas volume at the outlet is smaller than the intake air amount. The actual gas volume relationship is:

$$Q_f = Q_k \quad (3\text{-}2)$$

$$Q_g = Q_{cp} + Q_f \quad (3\text{-}3)$$

Where Q_{cp} is the amount of natural gas consumed for the compressor to work

3.1.1.3 Pipeline

The gas pipeline network is classified according to the gas transmission pressure and can be divided into 7 levels: high pressure gas pipeline A, high pressure gas pipeline B, secondary high pressure gas pipeline A, secondary high pressure gas pipeline B, medium pressure gas pipeline A, medium pressure gas pipeline B, low pressure gas pipeline[34].

Table 3-1 Gas pipeline pressure classification

Pressure levels	A(MPa)	B(MPa)
High pressure gas pipeline	2.5-4.0	1.6-2.5
Secondary high pressure gas pipeline	0.8-1.6	0.4-0.8
Medium pressure gas pipeline	0.2-0.4	0.01-0.2
Low pressure gas pipeline	Less than 0.01	

In the derivation of the natural gas pipeline equations, the following assumptions are made[35]:

(1) The gas flow in the pipeline is stable, that is, the flow rate of gas in any section of the pipeline is equal to a constant, and it will not change with time and distance;

(2) Since the energy loss due to frictional losses becomes thermal energy, and the thermal energy is lost through the wall to the surrounding medium, the gas temperature T remains nearly constant, so it can be assumed that the flow is isothermal;

(3) If it has been assumed that the flow is isothermal, it can be assumed that the temperature T of the fluid in the pipeline is known. In fact, if an average temperature is used, then the energy equation in the system of equations can be removed and the solution can be simplified. It is also possible to discard the various changes in the equation of motion and the continuity equation over time, and the kinetic energy of the gas in the pipeline is neglected.

(4) The compression coefficient in the equation of state can be considered as a constant over the entire length of the pipeline because the average pressure and temperature of the

gas in the gas pipeline does not vary so much so that the coefficient of variation in the equation is very small. So small changes can be ignored.

(5) If the pipe section is already given, then the inclination angle of this pipe will remain unchanged;

(6) The thermal expansion and contraction of the pipe wall is neglected here;

(7) The friction coefficient also remains constant along the length of the pipe.

The gas pipeline network is generally in a constant flow state. The calculation of the constant flow is the core of the pipeline network operation and is also an important part of the gas pipeline network simulation. Under normal circumstances, in gas pipeline network engineering design, the flow within a certain period of time is regarded as a constant flow, assuming that each parameter does not change according to time; because it is a stable flow, the flow value will not change because of time changes, then the pressure drop equation (stability flow equation) is expressed as:

$$P_{1i}^2 - P_{2i}^2 = K_i \frac{Q_i^\alpha}{d_i^\beta} l_i = s_i Q_i^\alpha \qquad (3\text{-}4)$$

Where n is natural gas pipeline number, P_{1i}, P_{2i} are the natural gas absolute pressures (Pa) at the beginning and end of the i-th pipe; K_i is the coefficient relevant of the pipeline friction resistance coefficient, gas density, temperature, compression factor, etc. l_i is the length of the i-th pipe (m); Q_i is the flow of the i-th pipe (Nm); d_i is the inner diameter of the i-th pipe (m); s_i is the resistance coefficient of the i-th pipe.

The gas pipeline pressure in general cities is below 1.6MPa, so the basic calculation formula for high and medium pressure gas pipelines:

$$\frac{P_1^2 - P_2^2}{L} = 1.27 \times 10^7 f \frac{Q_0^2}{d^5} \rho_0 \frac{T}{T_0} \qquad (3\text{-}5)$$

Where P_1, P_2 are the absolute pressures (kPa) at the beginning and end of the pipeline; L is the length of the pipeline (km); f is the coefficient of friction of the pipeline; Q_0 is the flow of the pipeline under standard conditions (Nm); d is the inside diameter (mm); ρ_0 is the density of natural gas under standard conditions (kg/Nm); T is the absolute temperature of natural gas (K); T_0 is the absolute temperature of natural gas (K) under standard conditions.

The basic calculation formula for low pressure gas pipelines:

$$\frac{P_1 - P_2}{L} = 6.26 \times 10^4 f \frac{Q_0^2}{d^5} \rho_0 \frac{T}{T_0} \quad (3\text{-}6)$$

3.1.1.4 Gas flow

According to Kirchhoff's first law, the flow of any node is zero algebraicly, which means that the load at any node is equal to the sum of the inflow and outflow of the node, expressed, in matrix form is:

$$[\frac{L_d}{L_e}] = L = AQ \quad (3\text{-}7)$$

Where L is natural gas load vector of the natural gas pipeline network; L_d is non-electric natural gas demand vector; L_e is electricity natural gas demand vector; A is reduced branch-node correlation matrix; Q is flow vector in the branch.

Take the following as an example:

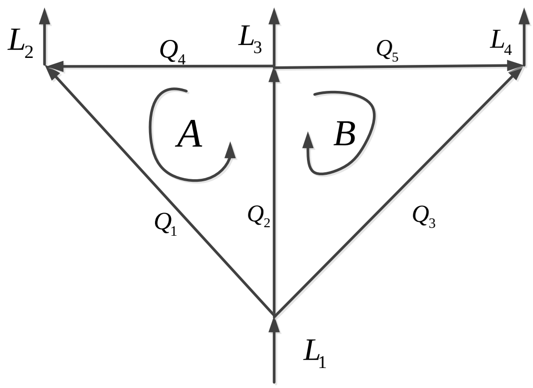

Figure 3-5 Natural gas pipeline network topology

According to Kirchhoff's law, the pipe network node equation in this example is:

$$\begin{bmatrix} 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 & -1 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \end{bmatrix} = \begin{bmatrix} L_2 \\ L_3 \\ L_4 \end{bmatrix}$$

The symbol stipulates: when the branch air flow enters this node, the sign is positive, otherwise, the sign is negative.

3.1.2 Power system modeling

The active power flow equation of the power system is[36]:

$$P_i = V_i \sum_{j \in i} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}), \quad i = 1, 2, \ldots n \tag{3-8}$$

Branch active power flow can be expressed as:

$$P_{ij} = V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) - t_{ij} G_{ij} V_i^2 \tag{3-9}$$

Where: t_{ij} is the transformer non-standard transformation ratio of the branch ij; θ_{ij} is the phase angle difference of the node voltage at both ends of the branch ij; and G_{ij}, B_{ij} are the real and imaginary parts of the node admittance matrix element.

$$\theta_{ij} = \theta_i - \theta_j \tag{3-10}$$

$$G_{ij} + jB_{ij} = -\frac{1}{r_{ij} + jx_{ij}} = -\frac{r_{ij}}{r_{ij}^2 + x_{ij}^2} + j\frac{x_{ij}}{r_{ij}^2 + x_{ij}^2} \tag{3-11}$$

Where: r_{ij}, x_{ij} are the resistance and reactance for the branch ij, when $i = j$, we have:

$$G_{ii} = -\sum_{\substack{j \in i \\ j \neq i}} G_{ij} \tag{3-12}$$

$$B_{ii} = -\sum_{\substack{j \in i \\ j \neq i}} B_{ij} \tag{3-13}$$

According to the simplification condition of the P-Q decomposition method, the AC power flow is simplified, and the following DC power flow equation can be obtained:

$$P_i = \sum_{j \in i} B_{ij} \theta_{ij} \tag{3-14}$$

Written as a matrix, it is:

$$P = B\theta \tag{3-15}$$

Where P is the node injection power vector, and $P_i = P_{Gi} - P_{Di}$, P_{Gi}, P_{Di} are the generator output and load of the node, θ is the node voltage phase angle vector; B is the imaginary part of the node admittance matrix.

Similarly, substituting the simplified condition of the P-Q decomposition into the branch power flow equation, we can get:

$$P_{ij} = -B_{ij}\theta_{ij} = \frac{\theta_i - \theta_j}{x_{ij}} \tag{3-16}$$

Written as a matrix, it is:

$$P_l = B_l \Phi \tag{3-17}$$

Where: P_l is the vector of the active power flows for each branch; Φ is the phase difference vector at each end of each branch; B_l is a diagonal matrix composed of admittances for each branch. Let the number of branches of the system be l, then B_l is an l-order square matrix.

3.1.3 Gas-electricity coupling

A gas turbine is a key part of a coupled natural gas network and power system. It is an energy converter.

For gas turbines, the relationship between gas flow and the real power it emits can be expressed by the following equation:

$$P = \mu(Q)QH = C_1Q^3 + C_2Q^2 + C_3Q + C_4 \tag{3-18}$$

Where $\mu(Q)$ is the efficiency of the gas turbine is related to the amount of intake air; H is the calorific value of natural gas; C_1, C_2 and C_3 are gas turbine performance factors.

3.2 Optimized operation considering natural gas transmission characteristics

The optimal operation of the power system refers to the use of existing equipment to improve current distribution in the power network by adjusting current operating modes, while ensuring that the power quality of the power grid complies with the standards and the system operates safely and reliably to get smaller system fuel consumption or active power loss. As a highly practical energy-saving scheduling technology, the optimal operation of the power system involves the distribution of the load of active power and reactive power, common problems such as start-stop planning of the unit, optimal power flow problems, and reactive power optimization problems. It is all about pursuing an optimal operating index.

3.2.1 Objective function

The optimization goal of the model proposed in this study is to achieve the lowest joint operation cost of the two networks under the constraint of meeting the safety operation of natural gas networks and power systems. The specific optimization objectives are:

$$\min: \sum_i K_i G_{g,i} + \sum_j K_j G_{e,j} \tag{3-19}$$

Where K_i and K_j are the price of the raw materials required for the unit gas turbine and thermal power generation, respectively, $G_{g,i}$ and $G_{e,i}$ are the output of the gas turbine and the thermal power generator.

3.2.2 Restrictions

3.2.2.1 Output Constraints of Natural Gas Wells

Natural gas is extracted from gas wells and is subject to a series of constraints such as gas well pressure and equipment capacity, which limits the amount of natural gas generated from gas wells per unit time:

$$\underline{W}_w \le pg_w \le \overline{W}_w \tag{3-20}$$

Where $\underline{W}_w$ and $\overline{W}_w$ are the min and max output of gas wells.

3.2.2.2 Natural gas network node pressure constraints

The pressure of each node of the natural gas network must be within a reasonable and safe operating range. It has the following constraints:

$$\underline{P}_i \le p_i \le \overline{P}_i \tag{3-21}$$

Where $\underline{P}_i$ and $\overline{P}_i$ are min and max node pressures.

3.2.2.3 Gas storage output limit

In the event of a breakdown of the natural gas network or large fluctuations in gas load, the gas storage tank can be used as an alternative to the gas source to provide natural gas to the network to ensure sufficient natural gas load supply. Natural gas network gas storage tanks are limited by storage capacity and natural gas injection and output flow restrictions. Here, the following limits are set for gas intake:

$$\underline{S}_s \le store_s \le \overline{S}_s \tag{3-22}$$

Where $\underline{S}_s$ and $\overline{S}_s$ are the min and max output of gas storages.

3.2.2.4 Compressor restrictions

The original model of the compressor is a non-convex and non-linear expression describing the relationship between compressor boost ratio and energy consumption. Since the focus of this article is on the optimization of operational discussions, and the compressor consumes very little energy (electric energy or natural gas), the compressor model is simplified, ie the energy consumed by the compressor is ignored and only the boosting relationship between the compressor intake and outlet is retained. It has the following limitations:

$$1 \le \Gamma \le \overline{\Gamma}_c \tag{3-23}$$

Where $\overline{\Gamma}_{co}$ is the max compression ratio.

The DC power flow model is used for the power system. The main considerations are the output constraints of the generator and the constraints of the power flow:

3.2.2.5 Generator output limit

The limit for generators is:

$$\underline{G}_g \le G_g \le \overline{G}_g \tag{3-24}$$

Where $\underline{G}_g$ and $\overline{G}_g$ are the min and max output of generators.

3.2.2.6 power flow limits

The capacity of each line is limited by the line itself:

$$-flow_{\max} \le P_{ij} = \frac{\theta_i - \theta_j}{x_{ij}} \le flow_{\max} \tag{3-25}$$

Where $flow_{\max}$ is the max power flow allowed.

3.3 Simulation

This topic is modeled on the basis of the IEEE 24-node power system and the Belgian 20-node natural gas network. The Belgian 20-node natural gas network is as follows[37]:

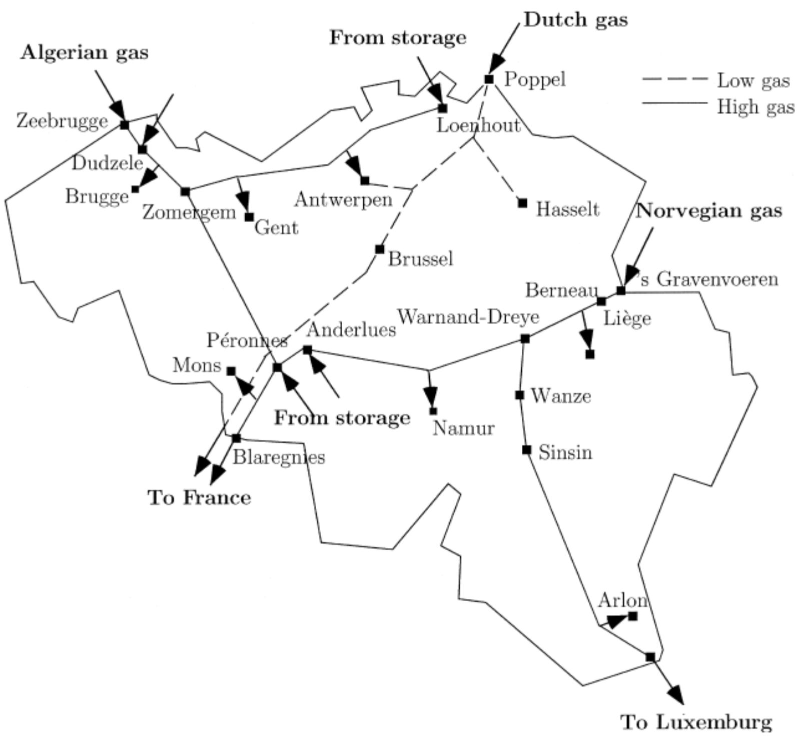

Figure 3-6 Belgian Natural Gas Network

Here only the high gas part is used. The load of the node is as follows:

Table 3-2 Belgian 20-node network load

Node	Connected pipe	Load（$10^6 m^3$/day）
Antwerpen	6	4.034
Arlon	19	0.222
Brugge	3	3.918
Gent	7	5.256
Liege	10	6.365
Mons	15	6.848
Namur	12	2.120
Luxemburg	20	1.919

The structure of the IEEE24 node power system is not described in detail here. The natural gas network and the power system are coupled through the gas turbine. The specific coupling network structure is as follows:

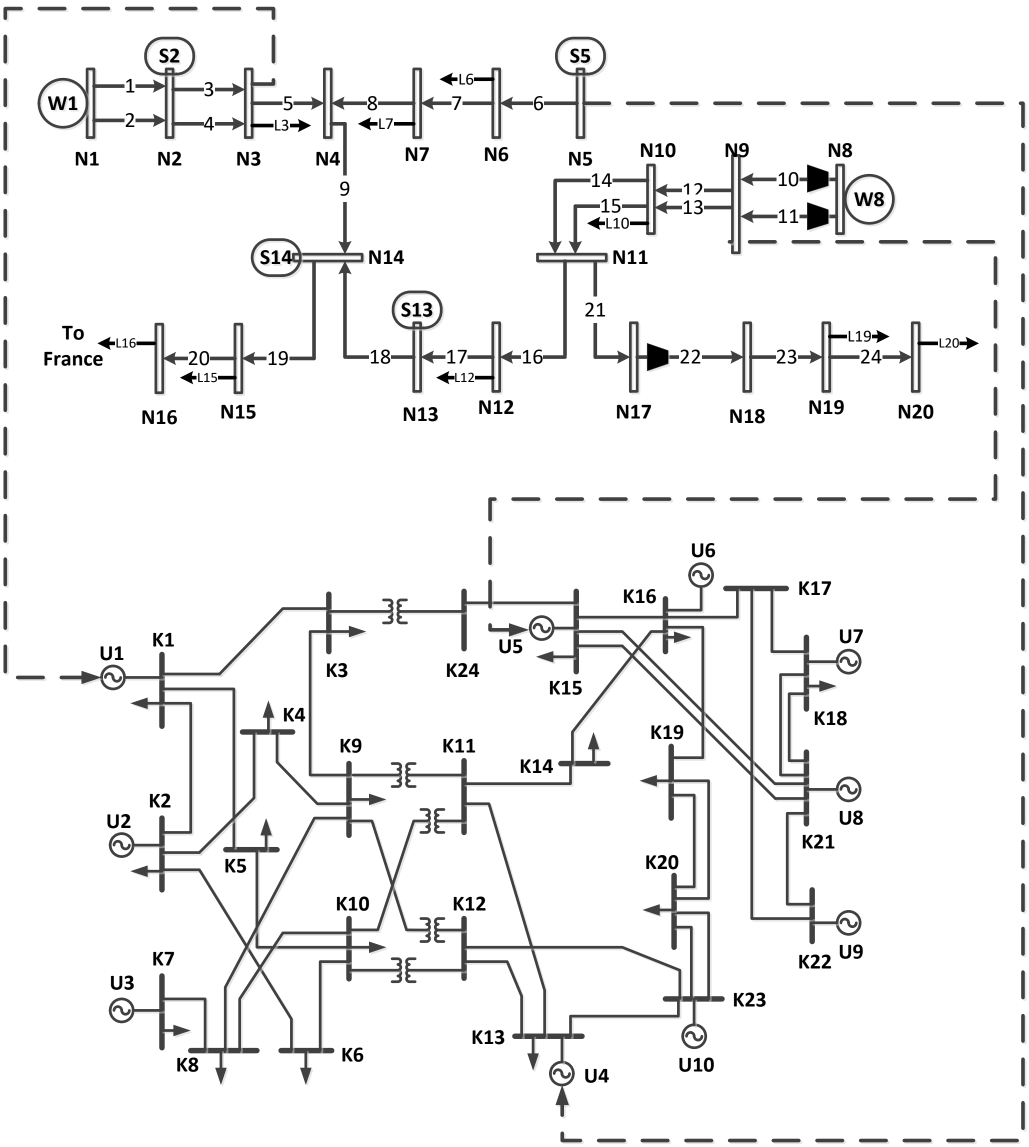

Figure 3-7 Joint operation system of natural gas network and power system

This model makes some modifications and adjustments to the standard model, in which the generators connected to busbars 1, 13 and 15 of the IEEE 24-node power system are gas turbine generators. The fuel for the gas turbines is supplied by nodes 3, 5 and 9 of the natural gas network respectively. The rest of buses 2, 7, 16, 18, 21, 22 and 23 are all connected to thermal power generators. The detailed data of all generators are as follows[38]:

Table 3-3 Power system generator output limit

Generator	Connected bus	Max output（GW）	Min output（GW）
U2	2	0.192	0.06
U3	7	0.3	0.025
U6	16	0.155	0.055

U7	18	0.4	0.1
U8	21	0.4	0
U9	22	0.3	0
U10	23	0.6	0

The power flow constraints and line impedances of the power system transmission lines are as follows:

Table 3-4 Power system transmission line parameters

Line	Start	End	Max Flow（GW）	Impedance（p.u.）
TL1	1	2	0.175	0.0139
TL2	1	3	0.175	0.2112
TL3	1	5	0.175	0.0845
TL4	2	4	0.175	0.1267
TL5	2	6	0.175	0.192
TL6	3	9	0.175	0.119
TL7	3	24	0.4	0.0839
TL8	4	9	0.175	0.1037
TL9	5	10	0.175	0.0883
TL10	6	10	0.175	0.0605
TL11	7	8	0.175	0.0614
TL12	8	9	0.175	0.1651
TL13	8	10	0.175	0.1651
TL14	9	11	0.4	0.0839
TL15	9	12	0.4	0.0839
TL16	10	11	0.4	0.0839
TL17	10	12	0.4	0.0839
TL18	11	13	0.5	0.0476
TL19	11	14	0.5	0.0418
TL20	12	13	0.5	0.0476
TL21	12	23	0.5	0.0966
TL22	13	23	0.5	0.0865
TL23	14	16	0.5	0.0389
TL24	15	16	0.5	0.0173
TL25	15	21	0.5	0.049
TL26	15	21	0.5	0.049
TL27	15	24	0.5	0.0519
TL28	16	17	0.5	0.0259
TL29	16	19	0.5	0.0231
TL30	17	18	0.5	0.0144
TL31	17	22	0.5	0.1053
TL32	18	21	0.5	0.0259
TL33	18	21	0.5	0.0259
TL34	19	20	0.5	0.0396
TL35	19	20	0.5	0.0396
TL36	20	23	0.5	0.0216

TL37	20	23	0.5	0.0216
TL38	21	22	0.5	0.0678

For the Belgian 20-node natural gas network, which contains 2 gas wells and 4 gas tanks, and their related parameters are as follows:

Table 3-5 Gas wells and gas storages parameters

Gas source	Connected node	Max Output（$10^6 m^3$/day）
W1	1	25
W2	9	20
S1	2	8.4
S2	5	4.8
S3	14	0.96
S4	13	1.2

The pressure limit for each node of the natural gas network is as follows:

Table 3-6 Natural gas network node pressure limit

Node	Max Pressure（bar）	Min Pressure（bar）
1	77	30
2	77	30
3	80	30
4	80	30
5	77	30
6	80	30
7	80	30
8	66.2	30
9	66.2	50
10	66.2	50
11	66.2	30
12	66.2	30
13	66.2	30
14	66.2	30
15	66.2	50
16	66.2	50
17	66.2	25
18	63	25
19	66.2	25
20	66.2	25

According to the equation (3-5), it is difficult to program. Here, the parameters such as the length of the line and the diameter of the pipe are firstly substituted into the equation (3-5) and it’s simplified as follows:

$$c_{ij} * (P_i^2 - P_j^2) = Q_{ij}^2 \qquad (3\text{-}26)$$

Where c_{ij} is a simplified parameter calculated from the parameters of the pipeline, the specific values are as follows:

Table 3-7 Natural gas pipeline network simplified parameters

Pipeline	Start node	End node	c_{ij}
1	1	2	9.07027
2	1	2	9.07027
3	2	3	6.04685
4	2	3	6.04685
5	3	4	1.39543
6	5	6	0.100256
7	6	7	0.148655
8	7	4	0.226895
9	4	14	0.659656
10	8	9	7.25622
11	8	9	0.108033
12	9	10	1.81405
13	9	10	0.0270084
14	10	11	1.45124
15	10	11	0.0216067
16	11	12	0.863836
17	12	13	0.907027
18	13	14	7.25622
19	14	15	3.62811
20	15	16	1.45124
21	11	17	0.051445
22	17	18	0.00641977
23	18	19	0.00170320
24	19	20	0.0278190

Because the hybrid optimization of natural gas networks and power systems is a large-scale hybrid nonlinear optimization problem, the pipeline equations are nonlinear and non-convex equations, which increases the complexity of the model. In the general optimization model, these nonlinear equations need to be linearized to reduce the complexity of the model. However, the hybrid nonlinear optimization solver can be used in GAMS without linearizing the nonlinear equations, which can reduce the difficulty of solving and improve the speed of the solution.

Taking the lowest joint operation cost as the optimization goal, the operation plan with the lowest cost under the requirements of safe and stable operation is obtained. The operating parameters of the natural gas network are as follows:

Table 3-8 Joint operating parameters of natural gas network

Node	Gas output（$10^6 m^3$/day）	Gas load（$10^6 m^3$/day）	Node pressure（bar）
1	21.140		75.993
2	7.038		75.911
3		3.918	75.695
4			72.856
5	2.386		70.803
6		4.034	70.427
7		5.256	70.569
8	3.858		50.000
9			50.701
10		6.365	50.454
11			50.559
12		2.120	51.977
13	0		54.862
14	0		57.603
15		6.848	50.856
16		3.582	50.000
17			50.253
18			51.025
19		0.222	50.722
20		1.919	50.477

The output of each generator is as follows:

Table 3-9 Power system generator output

Generator	Type	Output（GW）
U1	Gas	0.392
U2	Coal	0.165
U7	Coal	0.025
U13	Gas	0.391
U15	Gas	0.005
U16	Coal	0.155
U18	Coal	0.400
U21	Coal	0.400
U22	Coal	0.300

U23	Coal	0.600

The join of natural gas directly affects the power system's operation plan. Because the coal price is lower, the total power generation of the gas turbine is reduced. At the same time, due to the constraints of the power system and natural gas network, the output is in a safe and stable operation.

The above operating results will change with the changes in the prices of natural gas (gas turbine power generation) and coal (thermal power generation).

When the coupled nodes (gas turbine connection points) of the natural gas network and the power system change, the joint operation scheme of the two systems changes: the generators connected to the busbars 1, 15 and 18 of the IEEE 24-node power system are gas turbine generators, and the gas turbines fuel is supplied by node 3, node 5, and node 9 of the natural gas network respectively. At this time, the scheme with the lowest joint operating cost of the two systems becomes:

Table 3-10 New joint operating parameters of natural gas network

Node	Gas Output（$10^6 m^3$/day）	Load（$10^6 m^3$/day）
1	8.990	
2	8.396	
3		3.918
4		
5	4.779	
6		4.034
7		5.256
8	7.582	
9		
10		6.365
11		
12		2.120
13	0.600	
14	0.479	
15		6.848
16		0.044
17		
18		

19	0.222
20	1.919

The output of each generator is as follows:

Table 3-11 New power system generator output

Generator	Output（GW）
U1	0.392
U2	0.190
U7	0.300
U13	0.391
U15	0.005
U16	0.155
U18	0.100
U21	0.400
U22	0.300
U23	0.600

3.4 Summary of this chapter

This chapter examines the joint optimization of natural gas networks and power systems. The main accomplishments are:

(1) Analyzed the main components of the natural gas network and power system, established a mathematical model of the key components of the natural gas network and power system, and considered the constraints of the natural gas network and power system, including the gas wells and the output limitation of gas storage tanks in natural gas networks, gas pipeline equations, natural gas network nodes pressure limit, generator output constraints, line flow constraints, etc., established a joint operation model of gas-electricity coupling;

(2) The IEEE24-node power system and the Belgian 20-node natural gas network are selected as the basis of the case study. The two models are jointly built in the GAMS software, and the nonlinear equations in the model are solved by using the nonlinear solver that comes with the GAMS software. This study simulates the operational parameters of the natural gas network and power system when the two networks have the lowest joint operating cost, and analyzes the impact of the natural gas network on the power system.

Chapter 4

4 Gas turbine-based emergency overload control

4.1 Transmssion line overload

The overload of the power system is divided into normal overload and accidental overload. Normal overload generally utilizes the short-term overload capacity of the equipment, and eliminates overload by adjusting the operating mode within the allowable time range of the equipment; when the accidental overload occurs, the control equipment limits or eliminates the overload, and the safety and stability control devices implement control measures such as cutting generators, load shedding, lifting or dropping DC power to limit equipment overload.

Many of the major blackouts that occurred in history have been related to accidental overloads. Some typical examples are as follows:

1) On Aug. 14, 2003, a large-scale power outage occurred in the surrounding areas of the Great Lakes in the eastern United States. The blackouts involved areas of Connecticut, New York, Ohio, Massachusetts, Michigan, northern New Jersey and New England in the United States, and also caused power outages in areas such as Ontario in Canada. The entire power outage lasted only 7 minutes, but it caused at least 263 power stations to stop, causing a loss of load of 61,800 MW. The number of users affected by the accident reached 50 million, causing direct economic losses of 6 billion U.S. dollars and indirect economic losses of 30 billion U.S. dollars.

2) In November 2006, Western European Power Grid adopted an incorrect method to repair a 380 kV tie line to cause heavy load. After the misoperation of the staff caused the

overload of the line load to increase and exit the operation, the current transfer caused rapid failures. With large-scale proliferation, nine 380kV and four 220kV lines have been withdrawn from operation within 14s, resulting in large-scale blackouts.

3) In November 2009, all three lines of the 750kV transmission line in Itaipu, Brazil, were disconnected due to the poor weather conditions. Although emergency machine operations have been carried out, there is still a lot of currents shifting to other transmission lines in the south and southeastern power grids, causing chain trips, followed by a series of failures that eventually led to widespread power outages[39-40].

Analyzing the above typical blackout accidents shows that: before the accident, the line protection action was out of operation due to various reasons, and then this portion of the current that should have been taken by the removal line was transferred to other tie lines in the network, causing overload of these lines. Withdrawing from the operation further exacerbated the seriousness of the current transfer of the system, causing a series of complicated failures. Eventually, the system was forced to disconnect due to the failure of voltage and frequency to maintain normal operation, resulting in a large-scale power outage.

The rapid control of overload of transmission lines can be divided into three categories in terms of control measures or control means: 1) cutting loads and generators; 2) FACTS and HVDC control; 3) corrective switch conversion. These three methods have their own characteristics. We will discuss them in detail below.

1) Cutting loads and generators

Cutting loads and generators, as the name suggests, is to take measures to adjust the generator output and load size to eliminate transmission line overload. In the power system, reactive power often adopts the method of stratified partitioning and local balance compensation, and only a large amount of active power is transmitted on the power transmission line. Therefore, the current overload control is mainly directed at the analysis of active power. How to adjust the output of the generator and the load to reduce the active power of the branch belongs to the category of active safety correction, mainly divided into two categories: sensitivity method and optimization method.

Traditional overload optimization is a static, open-loop optimization method. However, taking into account these following factors, the traditional optimization method does not satisfy our need for overload control. It is very likely that there will be problems such as overloading even more serious after adjustment.

a) There is an error in the measurement device itself in the power system;

b) In the optimization modeling, in order to simplify the model and speed up the model solution, the DC power flow model is mostly used, and the DC power flow model itself has a lot of approximations, and the error is large;

c) Control variables also have some dynamic constraints when adjusting, such as the ramp rate of the unit, which is more difficult to consider in traditional optimization models;

d) The large number of intermittent energy sources and the development of the electricity market have made the operating status of the system more frequent;

e) The widespread use of a large number of non-linear power electronic devices makes the system's operating state after adjustment more difficult to predict.

2) FACTS and HVDC control[41-43]

As we all know, FACTS and HVDC devices can significantly improve the steady state performance and transient performance of power systems, including improving power flow and voltage control capabilities, enhancing the maximum available transmission capacity of transmission lines,, and improving system transient stability. Compared with the load control strategy of cutting generators, the use of FACTS and HVDC devices for overload control has the following advantages: First, the adjustment speed of FACTS and HVDC is very fast. In emergency control, just the adjustment of control parameters can quickly change its operating status, and can control the system flow in a wide range; secondly, the adjustment cost of FACTS and HVDC is very low, which does not involve the rearrangement of the generator output and the load to increase the additional adjustment costs of the system operations; finally, the interference introduced by the FACTS and HVDC adjustment process to the system is also very small.

The FACTS device has strict requirements on the installation location. As far as China is concerned, FACTS is not often used in the power system. On the contrary, due to the reverse distribution of energy and load in China, direct current transmission has been widely used. How to use HVDC to carry out emergency control of the power system overload, especially the coordination among multiple DCs, will become a research hotspot in the future.

3) Corrective Switching

Corrective switching, that is, changing the position of the transmission line switch, bus switch, and shunt element switch, can quickly change the system's power flow and voltage distribution. Corrective switching is just a running operation and does not require additional effort to readjust the generator output or load. Therefore, similar to the FACTS and HVDC control, the corrective switching has obvious economic advantages. In addition, because the corrective switching can quickly change the system's power flow and voltage distribution, it can be used as a quick control method in emergency situations.

4.2 Principle of emergency overload control for gas turbines

The use of gas-fired generator sets for power grid peak shaving has the following advantages: (a) Short construction period and low water consumption; (b) Simple and compact unit, small occupied space, low operation and maintenance costs; (c) The start-up and shutdown of the unit is simple, rapid, and flexible. It is suitable for two-shift operation. It has high environmental value, and no ash and dust emissions. Compared with the coal-fired units with the same capacity, the emission of carbon dioxide and other gases is much lower.

Considering the characteristics of the rapid start-stop of gas turbines, it is also necessary to consider the energy efficiency of natural gas resources. Building a gas-steam combined cycle unit and making full use of the waste heat of the gas exhaust, generating high temperature and high pressure steam through the waste heat boiler can improve the overall efficiency of the circulating unit, and even reach over 60%, and increase the power supply reliability of the unit at the same time. Meanwhile it can reduce nitrogen oxide emissions, and can achieve less than 10ppm emissions. Because the gas-fired-steam combined-cycle unit is based on a single-cycle gas turbine and the boiler steam turbine unit is added, the combined start-stop agility of the combined-cycle unit is reduced compared with a single cycle. But compared with the conventional coal-fired unit,the peak shaving performance of it is still much higher. Therefore, the use of a combined-cycle unit not only helps solve the problem of peak shaving in China's power grids, but also improves the economic efficiency of the generating units[44].

The startup of the gas turbine can reach very high speeds. According to the length of the start-up time, the gas turbine can be started in three ways: normal start, quick start and emergency start.

The gas turbine normally adopts normal start. Normal start is a kind of start according to the setting procedure. Warm-up is required during the start-up process and acceleration rate and loading rate of the unit are strictly controlled to avoid excessive thermal stress in the machine. Therefore, this method requires a long time to start, for heavy-duty unit it’s about 5-10min (excluding loading time, the same below); light structure needs about 1-5min; micro gas turbine only takes 20-40s. In some cases, it is required that the unit be put into operation as soon as possible, even at the expense of the life of some hot aisles, which is so-called quick start method, and the extreme situation will take emergency start. In order to meet the need for peaking of a simple-cycle gas turbine power plant, some units are also equipped with a quick start in addition to the normal start-up. This is also a kind of start-up according to the setting procedure, but the acceleration rate and load rate in the program are increased, and the reduction of warm-up time is achieved. Therefore, the start-up time is shortened and the thermal stress in the process is still within an acceptable level[45].

Considering the above-mentioned characteristics of the quick start-up speed of the gas turbine, when there is fault occuring in the power grid and the line is overloaded, the overload control can be performed by adjusting the output of the gas turbine, so as to avoid the occurrence of a long-term power outage.

The use of gas turbines for emergency overload control must consider the transmission characteristics of natural gas and the supply of natural gas limited by pipeline capacity and gas storage capacity. When the supply is low, the ramp rate of gas turbines is bound to reach the maximum speed. The assumption that the natural gas supply is not restricted when the units need is no longer correct in the traditional power system operation scheduling. This problem is particularly noticeable when the problem of fast overload is considered.

In this study, we consider the use of gas turbines for emergency overload control of transmission lines. When a fault occurs on the line, the protection action cuts the line, causing the topology of the power grid to change, and the power flow is redistributed. The power of some lines exceeds the maximum power allowed to flow, and this line is overloaded. At this time, the use of gas turbines to change the output with fast speed features, can reduce line overload condition with the fastest speed.

4.3 Simulation

The model used here is still the coupling network of natural gas network and power system used in Chapter 3, which is in the normal operation mod, and in this case we consider the situation of transmission line overload.

When a fault occurs in the line between bus 1 and bus 2, the protection action is taken, and then the line is cut off, and the power flow is redistributed. In this short time, the generator output and load are assumed to be unchanged. After calculation, the redistributed power flow of each line is as follows:

Table 4-1 Distribution of power flow after power line fault removal

Lines	Power Flow(GW)	Lines	Power Flow(GW)
TL2	0.089	TL21	0.197
TL3	0.194	TL22	0.153
TL4	0.033	TL23	0.311
TL5	0.035	TL24	0.043
TL6	0.035	TL25	0.255
TL7	0.156	TL26	0.255
TL8	0.041	TL27	0.156
TL9	0.123	TL28	0.273
TL10	0.102	TL29	0.060
TL11	0.100	TL30	0.266
TL12	0.138	TL31	0.247
TL13	0.133	TL32	0.091
TL14	0.133	TL33	0.091
TL15	0.154	TL34	0.061
TL16	0.142	TL35	0.061
TL17	0.163	TL36	0.125
TL18	0.158	TL37	0.125
TL19	0.118	TL38	0.293

TL20	0.121

According to Table 4-1, the power flow in line 3, that is, between bus 1 and bus 5, is 0.194 GW, which exceeds the maximum capacity that the line can withstand, and the line overload occurs. Through overload identification and emergency control measures, it is avoided that the protection action cuts the line and causes a more serious flow shift. At this time, overload control is required.

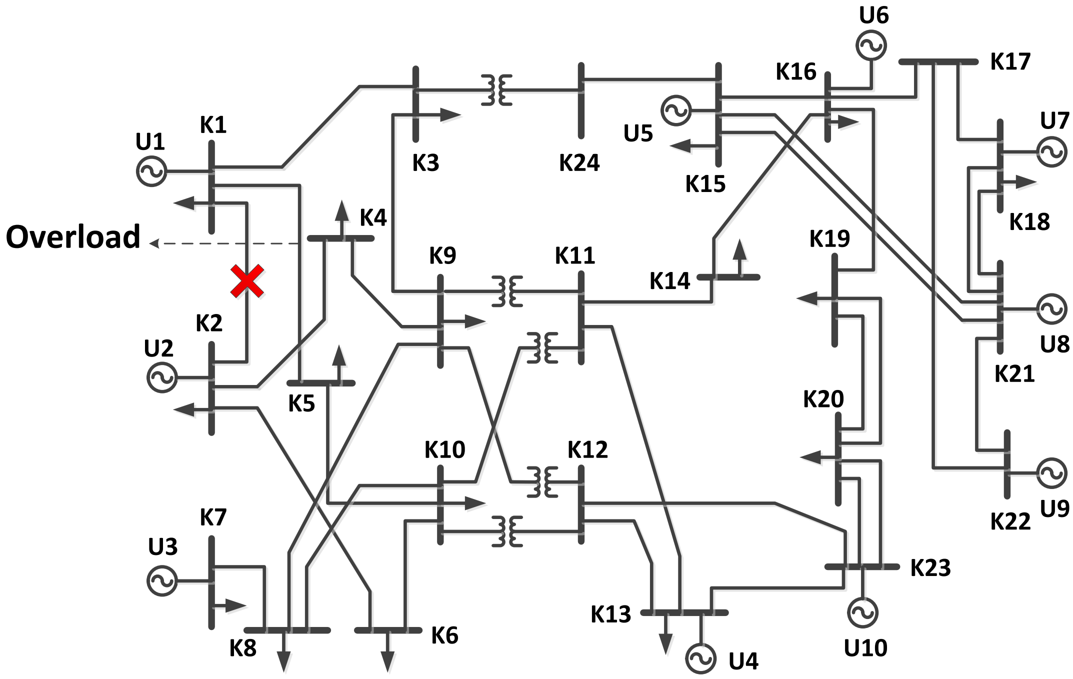

Figure 4-1 Power system line overload

In this thesis, we consider the use of gas turbines for emergency control of line overload. When a fault occurs on the line, the protection action cuts the line, causing the topology of the power system to change, and the power flow is redistributed. The power flow of some lines exceeds the maximum power allowed to flow, and the line is overloaded. At this time, we take advantage of gas turbines' high ramp rate to adjust their output to solve the line overload conditions with the fastest speed.

The traditional overload control is still aimed at optimizing the economic efficiency. Specifically, under the premise that the overload can be eliminated within a certain period of time (5 min or 10 min), the operating cost under the new stable condition is guaranteed to be the lowest. This project hopes to quickly solve the overload problem through the gas turbine. At this time, the objective function is no longer the lowest operating cost, but the shortest adjustment time, eliminating the overload situation in the fastest time. Since the ramp rate of the gas turbine is affected by the intake gas amount, when the intake gas amount is insufficient, the ramp rate of the gas turbine will also decrease, and the desired speed cannot be achieved. Therefore, when considering the use of a gas turbine for overload control in this subject, the gas turbine ramp rate is a key factor.

In addition, due to the delay in the transmission of natural gas, and the time of power system failure, fault removal, and emergency overload control is very short. So in such an extremely short time, the state of the natural gas network has almost no major changes, even if the pressure on the nodes or the compressor is adjusted, it cannot affect the gas turbine unit's gas intake, so it can be assumed that the gas turbine unit gas intake is a constant value and still equal to the gas supply to the gas turbine unit before the fault occurs.

4.3.1 Control strategy considering economy

For the traditional emergency overload control strategy for gas turbine units, the optimization goal is to minimize the new operating costs. The optimization objective function is:

$$\min:\sum_i K_i G_{g,i,new} + \sum_j K_j G_{e,j} \tag{4-1}$$

Where: K_i and K_j are the price of the raw materials required for the unit gas turbine and thermal power generation, and $G_{g,i,new}$ and $G_{e,i}$ are the output of the adjusted gas turbine unit and the output of the prior thermal power generator.

The constraints are:

1) Power flow equation

The DC power flow equations of equations are still used here.

2) After adjustment of the gas turbine generator units, the power flow of each line of the grid is less than the power flow constraint:

$$-flow_{\max} \le P_{ij,new} \le flow_{\max} \tag{4-2}$$

$P_{ij,new}$ is the power flow of each transmission line after adjustment, and $flow_{\max}$ is the maximum capacity of the transmission line.

3) After the adjustment, the output of the gas turbine generator unit is less than the maximum output constraint of the generator:

$$G_{g,new} = G_g \pm ramp\_rate * t \tag{4-3}$$

$$\underline{G}_g \le G_{g,new} \le \bar{G}_g \tag{4-4}$$

Where: $ramp\_rate$ is the ramp rate of the gas turbine unit, t is the adjustment time, $G_{g,new}$ is the new output of the gas turbine unit after adjustment, and $\underline{G}_g$ and $\bar{G}_g$ are the output lower and upper limits of the gas turbine generators.

4) The gas turbine unit's ramp rate is less than the maximum ramp rate:

$$ramp\_rate \le ramp\_rate_{\max} \tag{4-5}$$

Where $ramp\_rate_{\max}$ is the maximum ramp rate of the gas turbine generator unit.

5) The adjustment time does not exceed 5 minutes:

$$0 < t \le 5\min \tag{4-6}$$

4.3.2 Control strategy considering rapidity

For the strategy of using the shortest time to eliminate line overload, it is clear that the objective function has the shortest adjustment time for emergency overload, that is:

$$\min : t \tag{4-7}$$

The constraints are:

1) Power flow equation

The DC power flow equations of equations are still used here.

2) After adjustment of the gas turbine generator units, the power flow of each line of the grid is less than the power flow constraint:

$$-flow_{\max} \le P_{ij,new} \le flow_{\max} \tag{4-8}$$

$P_{ij,new}$ is the power flow of each transmission line after adjustment, and $flow_{\max}$ is the maximum capacity of the transmission line.

3) After the adjustment, the output of the gas turbine generator unit is less than the maximum output constraint of the generator:

$$G_{g,new} = G_g \pm ramp\_rate * t \qquad (4\text{-}9)$$

$$\underline{G}_g \le G_{g,new} \le \bar{G}_g \qquad (4\text{-}10)$$

Where: $ramp\_rate$ is the ramp rate of the gas turbine unit, t is the adjustment time, $G_{g,new}$ is the new output of the gas turbine unit after adjustment, and $\underline{G}_g$ and $\bar{G}_g$ are the output lower and upper limits of the gas turbine generators.

4) The gas turbine unit's ramp rate is less than the maximum ramp rate:

$$ramp\_rate \le ramp\_rate_{\max} \qquad (4\text{-}11)$$

Where $ramp\_rate_{\max}$ is the maximum ramp rate of the gas turbine generator unit.

This thesis has done four sets of simulation analysis on this issue, comparing the differences in the two control strategies, and taking into account the impact of natural gas intake, the gas intake of the four gas turbine units is sufficient, nearly sufficient, nearly insufficient and insufficient.

The optimization results are as follows:

1) Sufficient gas intake

When the gas intake of the gas turbine is sufficient, the ramp rate of the gas turbine unit is large enough. Specific climbing rate values are as follows:

G1： ±0.06 GW/min，G13： ±0.06 GW/min，G15:±0.035 GW/min

With the goal of solving the overload problem as soon as possible and the goal of the new stable operation cost as the minimum, the solution for solving the overload is as follows:

Table 4-2 Control plans when gas intake is sufficient

	Output changes			Time
	G1	G13	G15	
Rapidity	-0.033GW	0.033GW	0	0.55min
Economy	-0.033GW	0.033GW	0	0.55min

Gas generator G1 reduced its output by 0.033 GW, gas turbine G13 increased its output by 0.033 GW, and gas turbine G15 output remained unchanged. When the gas turbines are all adjusted for output with the maximum climbing rate, the shortest time for eliminating line overload is 0.55 min, and the optimization result with the lowest target for new operating costs is the same as the result with rapidity as the goal. The new trend after adjustment is as follows:

Table 4-3 New power flow after overload control

Lines	Power Flow/GW		Lines	Power Flow/GW	
	Rapidity	Economy		Rapidity	Economy
TL2	0.075	0.075	TL21	0.198	0.198
TL3	0175	0175	TL22	0.147	0.147
TL4	0.032	0.032	TL23	0.310	0.310
TL5	0.036	0.036	TL24	0.038	0.038
TL6	0.059	0.059	TL25	0.256	0.256
TL7	0.163	0.163	TL26	0.256	0.256
TL8	0.042	0.042	TL27	0.163	0.163
TL9	0.104	0.104	TL28	0.271	0.271
TL10	0.101	0.101	TL29	0.055	0.055
TL11	0.100	0.100	TL30	0.266	0.266
TL12	0.139	0.139	TL31	0.249	0.249
TL13	0.132	0.132	TL32	0.091	0.091
TL14	0.137	0.137	TL33	0.091	0.091
TL15	0.159	0.159	TL34	0.064	0.064
TL16	0.151	0.151	TL35	0.064	0.064
TL17	0.172	0.172	TL36	0.128	0.128
TL18	0.172	0.172	TL37	0.128	0.128
TL19	0.116	0.116	TL38	0.295	0.295
TL20	0.134	0.134			

The flow of each line does not exceed the maximum power flow constraint, and the overload condition of the line is eliminated. It can be seen that when the gas supply is sufficient, the ramp rate of the gas turbine is large enough, and the fastest speed and most economical cost can be satisfied at the same time.

2) Nearly sufficient gas intake

When the intake gas volume of the gas turbine is nearly sufficient, the maximum ramp rates of the three gas turbines are:

G1：±0.04 GW/min，G13：±0.04 GW/min，G15:±0.035 GW/min

Gas turbine ramp rates have been reduced when compared to sufficient gas intake.

Similarly, we compare the results of two optimizations:

Table 4-4 Control plans when gas intake is nearly sufficient

	Output changes			Time
	G1	G13	G15	
Rapidity	-0.033GW	0.033GW	0	0.829min
Economy	-0.033GW	0.033GW	0	0.829min

The optimization results at this time are the same as those in simulation 1), with G1 reducing the output by 0.033 GW, G13 increasing the output by 0.033 GW, G15 keeping the output unchanged, and the shortest elimination overload time is 0.829 min. At this time, both G1 and G13 have the maximum ramp speed to adjust the output, and at the same time achieve the goal of the lowest new operating cost, indicating that at this time, the reduction of the gas turbine ramp rate caused by the lack of intake gas can still meet the rapid and economical requirements of overload control.

3) nearly insufficient gas intake

When the gas intake of the gas turbine is nearly insufficient, the maximum ramp rates of the three gas turbines are:

G1：±0.03 GW/min，G13：±0.04 GW/min，G15:±0.035 GW/min

The optimization results obtained by the two optimization objectives at this time are:

Table 4-5 Control plans when gas intake is neraly insufficient

	Output changes			Time
	G1	G13	G15	
Rapidity	-0.032GW	0.043GW	-0.011GW	1.067min
Economy	-0.033GW	0.033GW	0	1.1min

When the gas turbine intake air volume is nearly insufficient, the economical optimal solution is still G1 to reduce output by 0.033 GW, G13 to increase output by 0.033 GW, G15 remains unchanged, and with the maximum ramp rate it requires 1.1 min to get the most ecomonical goal. However, if you want to eliminate the overload situation as quickly as possible, the plan is to reduce G2 output by 0.032 GW, G13 to increase output by 0.043

GW, G15 to reduce output by 0.011 GW, and the minimum time required at this time is 1.076 min, but the most economical goal is no longer satisfied. It can be seen that the decrease of ramp rate of the gas turbine has an impact on the overload control.

4) Insufficient gas intake

When the gas turbine intake gas volume is insufficient, the gas turbine ramp rate at this time is lower than when the gas volume is sufficient. The specific values are as follows:

G1： ±0.03 GW/min，G13： ±0.02 GW/min，G15:±0.035 GW/min

The optimization results obtained by the two optimization objectives at this time are:

Table 4-6 Control plans when gas intake is insufficient

	Output changes			Time
	G1	G13	G15	
Rapidity	-0.033GW	0.033GW	0	0.829min
Economy	-0.033GW	0.033GW	0	0.829min

When the gas turbine intake is insufficient, the most economical solution is still G1 to reduce the output of 0.033GW, G13 to increase the output of 0.033GW, G15 remains the same, with the maximum ramp rate, requires 1.65min; if we want to have the fastest speed to eliminate the overload, the plan is G1 to reduce output 0.034GW, G13 to increase output 0.023GW, G15 to increase output 0.011GW, the minimum time required at this time is 1.137min, but the most economical goal is no longer satisfied, and the time difference is large.

From the four sets of overload contorl plans, it can be seen that the previous overload control plan takes 5 minutes as the upper limit of the time to solve the problem, and under the condition that the time limit is satisfied, a new scheme with the lowest stable operating cost is sought. In this thesis, even if the gas turbine's ramp rate is reduced, it can still meet the requirements of solving the line overload problem within 5 minutes. Therefore, the economical optimal solutions given by the four sets of simulations are the same, that is, the gas turbine G1 reduces output by 0.033 GW, and the gas turbine G13 increases output by 0.033. GW, gas turbine G15 keeps its output unchanged.

From the point of view of solving the problem of line overload at the fastest speed, when the intake of the gas turbine is sufficient, the gas turbine can solve the line overload problem in the shortest time, and at the same time achieve the lowest new operating cost; but when the gas turbine intake is insufficient , at this time, the most economical solution is not the fastest solution. In order to quickly solve the overload problem, it is necessary to sacrifice certain economical efficiency. This verifies that the method of not considering the limitation of natural gas supply in the optimal operation of traditional gas-electricity coupled systems is not perfect. When the transmission of natural gas is limited by the pressure of pipelines, gas wells output, etc., the output of gas turbines and the ramp rate will be affected, and will change the operating scheme of the gas-electricity coupling system.

4.4 Summary of this chapter

This chapter studies the role of gas turbines in the overload control of power systems, and uses the characteristics of fast ramp rate of gas turbines to perform emergency overload control. Simulations have found that the problem of line overload can be solved by gas turbine generators in the shortest time when the gas intake of gas turbine is sufficient., while achieving the lowest adjustment cost; but when the gas intake of the gas turbine is insufficient, the best economic solution is not the fastest solution. In order to quickly solve the overload problem, it is necessary to sacrifice a certain economical interests.

This chapter verifies that the method of not considering the limitation of natural gas supply in the optimal operation of traditional gas-electric coupling system is not perfect. When optimizing the operating scheme, the transmission characteristics of natural gas must be considered.

Chapter 5

5 Conclusions and Suggestions

5.1 Conclusions

The coupling of natural gas network and power system is an important part of the Energy Internet. Studying the transmission characteristics of natural gas on the optimal operation of gas-electric coupling system has very important significance for the power system. This thesis reviews the coupling relationship between natural gas network and power system from the aspects of gas-electric coupling medium, the joint operation of gas-electric networks and the role of gas turbines in emergency overload control of electrical transmission lines, and draws some results and conclusions.

1) The mathematical relationship between the main components of the gas turbine and its various variables is analyzed in detail, and a simple but effective mathematical model of the gas turbine is established to facilitate the use in the power system simulation; the relationship between the gas turbine output and the intake gas volume is obtained by simulation, learning the performance change of the gas turbine when the intake gas quantity is insufficient. The output of the gas turbine will suddenly drop due to insufficient gas supply; We simulate the operation of the operator who needs to quickly increase the gas turbine output. While increasing the rotational speed, it is necessary to increase the amount of fuel to maintain the increased output.

2) Taking the optimal operation of natural gas network and power system as research objects, considering the constraints of the natural gas network and power system, including the limitation of the gas well output and gas storage tanks, gas pipeline equations, pressure limitations of the gas network nodes, generator output constraints and power flow

constraints, etc., and a joint operation model for gas-electric coupling is established. With economical optimization as the optimization goal, an economically optimal joint operation plan is obtained.

3) When the gas turbine's gas intake is sufficient, the gas turbine can solve the line overload problem in the shortest time, and at the same time achieve the lowest adjustment cost; but when the gas turbine intake gas volume is insufficient, the most economic solution is not the quickest one. The quickest plan requires the sacrifice of certain economical efficiency in order to quickly solve the overload problem. When the transmission of natural gas is limited by pipelines, gas well pressures, etc., the output and ramp rate of the gas turbine will be affected, and the operation plan of the gas-electric coupling system will be changed.

5.2 Suggestions

China has proposed to promote the revolution in energy production and energy consumption, vigorously develop non-coal energy, and form a multi-wheel-drive energy supply system for traditional energy and new clean energy. It can be foreseen that with the increasing investment of various countries in the Energy Internet, there will be more and more scholars starting researches of Energy Internet technology, and the continuous innovation of technology has also made various ideas possible.

Advanced energy storage technology will make large-scale energy storage become a reality, which will have a great impact on the entire Energy Internet, especially the power system, and will undergo revolutionary changes in the transmission and distribution sectors. At the same time, as the scale of the Energy Internet continues to expand and its topology is complex and dynamic, how to achieve coordinated management and control of multi-energy systems is a very important issue. In addition, the continuous development of power electronics technology has made energy transmission links more economical and flexible. Research on flexible HVDC transmission, control and protection technologies, and power grid fault diagnosis and restoration are among the key issues. Finally, with the rapid development of big data technology and artificial intelligence technology, the Energy Internet will also become more and more intelligent. How to effectively use the information technology for data collection, management, and analysis of the Energy Internet deserves much attention.

There are many areas of Energy Internet design. The development of the Energy Internet requires breakthroughs in various aspects as mentioned above to provide technical support for the changes in the energy industry in the future.

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