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IMPACT OF NATURAL GAS INFRASTRUCTURE FAILURE ON ELECTRIC POWER SYSTEMS CONSIDERING THE TRANSMISSION DYNAMICS OF NATURAL GAS

Zheng QIao[1], Jinhang Wang[2], Hongbin Sun[1*], Yue Wu[2], Qinglai Guo[1]

1 Department of Electrical Engineering, Tsinghua University, 100084, China

2 State Grid Jilin Electric Power Supply Company

ABSTRACT

Due to the strengthening of the coupling between the power system and the natural gas system, this paper aims to study the impact of natural gas system infrastructure failure on the power supply of the power system. A quasi-dynamic model adapted to the different time scales of the coupled natural gas and electricity system is established. The effectiveness of the calculation method is demonstrated by comparison with the simulation results of SYNERGI software. The case study shows that if the power system can know the failure in the natural gas system in advance, there is some buffer time to take control measures.

Keywords: Coupled natural gas and electricity system, natural gas infrastructure failure, quasi-dynamic model, buffer time.

NONMENCLATURE

Abbreviations	
AC	Alternating Current
ATC	Available transfer capability
IESs	Integrated energy systems
PDEs	Partial differential equations
Symbols	
a,b,c	Combustion cons d tant of gas turbine
A	Cross-sectional area of pipe (m^2)
B_{ij}	Susceptance of the nodal admittance matrix
d	Diameter of the gas pipeline (m)
g	Gravity unit (m/s^2)
G_{ij}	Conductance of the nodal admittance matrix
GHV_g	Calorific value of natural gas
HR_g	Heat consumption of gas turbine
i,j	Index of electric system buses
k,m	Index of natural gas system nodes
L_g	Gas load of the gas turbine
$p_{com}^{in}, p_{com}^{out}$	Inlet and outlet pressure of compressor
p	Pressure
P_i	Active power injected at ith node
P_g	Active power of gas turbine
$q_{km}^{in}, q_{km}^{out}$	Inlet and outlet gas flow of pipe km
q	Volume flow rate under standard conditions
Q_i	Reactive power injected at ith node
R	Ideal gas constant
S	Compression ratio of compressor
t	Time
Δt	Time step
T	Temperature of natural gas
U_i	Voltage magnitude at ith node
v	Velocity of natural gas (m/s)
$\tilde{v}$	Average velocity of gas through valve
x	Length
Δx	Length step
X_0	The valve of X under standard conditions
Z	Compression factor of natural gas
α	Horizontal angle of the pipe
θ_i	Voltage phase angle at ith bus
λ	Resistance coefficient of gas pipeline
ξ	Loss factor of the valve
ρ	Density of natural gas

1. INTRODUCTION

Due to the rapid development and widespread use of gas turbines, the proportion of natural gas in the primary energy generation of power systems is increasing. The gas load of power systems also accounts for a very large proportion in the load of natural gas systems. Therefore, the interdependence of the two systems is getting stronger. The failure in one system may affect the operational security of another system through the coupling element, so it is necessary to perform a comprehensive security analysis of the coupled system.

Now there have been some literature carried out these interdependence and interactions on different aspects. Ref [1] studies the effect of compressors to enlarge the transmission capacity of the network and establishes a reliability model considering the joint operation of electrical and gas systems. The relevant indices of connection nodes for the gas-fired power plants are calculated in Ref [2] to examine the impact of the natural gas network on the operation of the power system. Sheng C and Guoqiang S, etc. proposes the concept of static security domain of the integrated natural gas and power system and studies the ATC of power system considering the static safety constraints of the coupled systems [3]. They also define the security region of IESs as a set of energy flow injections which the energy flow equations and security constraints are satisfied [4].

These documents did not analyze the operation security of the coupled system after some failure or disturbance. Ref [5] analyzes the impact of natural gas infrastructure contingencies on the gas supply of gas-fired power plants. Ref [6] studies the impact of the natural gas system on the power system by analyzing the operating status of power system after failure in the contingency set of natural gas system occurs. The unexpected fault of the device is regarded as an attack in Ref [7] and they proposes an optimization model to give an optimal defense configuration. Although these documents considering the failure in the coupled system, they all adopt static models.

However, the transmission dynamics of natural gas are much slower than that of the power system. Therefore, the failure of the power system will quickly affect the natural gas system, but there may be a certain buffer time before the failure of the natural gas system propagates to the power system. So this paper aims to study the impact of natural gas infrastructure contingencies on the power system considering the natural gas pipeline transmission dynamics. The remaining part of the paper is organized as follows. Section 2 formulates a quasi-dynamic model of coupled natural gas and electricity system. Section 3 simplifies the transmission equation of the natural gas pipelines and details the calculation method. Section 4 verifies the method proposed above and analyze the impact of natural gas infrastructure failure on the power system through some case studies. Section 5 concludes.

2. QUASI-DYNAMIC ENERGY FLOW MODEL

There is a large time scale difference between the transmission process of the power system and the natural gas system. When the power system is in a fast dynamic process, the natural gas system can be approximated as a steady state. When the natural gas system is in a slow dynamic process, the power system often reaches several new steady states. The purpose of this paper is to focus on the slow dynamics of natural gas pipeline transmission. A quasi-dynamic energy flow model is established, that is, the power system adopts the AC power flow equation, while the natural gas system adopts the dynamic differential equation.

2.1 Natural gas system

2.1.1 Gas transmission in pipeline

The transfer process of natural gas in pipeline is described as a set of PDEs with the laws of momentum, mass balance and state equation [8].

$$\frac{\partial(\rho\cdot v)}{\partial t}+\frac{\partial(\rho\cdot v^2)}{\partial x}+\frac{\partial p}{\partial x}+\rho\cdot g\cdot\sin\alpha+\frac{\lambda}{d}\frac{v^2}{2}\rho=0 \quad (1)$$

$$\frac{\partial(\rho\cdot v)}{\partial x}+\frac{\partial\rho}{\partial t}=0 \quad (2)$$

$$p=R\cdot Z\cdot T\cdot\rho \quad (3)$$

2.1.2 Valve model

The change of the valve opening degree will have a certain disturbance effect on the hydraulic power [9]. But its dynamic process is much faster than the gas transmission dynamics in the pipe, which is ignored here.

The relationship between the gas flow and the pressure difference through the valve can be derived as:

$$\tilde{v}^2=\frac{2(p_k-p_m)}{\xi\cdot\rho} \quad (4)$$

2.1.2 Compressor model

The compressors provide the pressure that natural gas transmission required. Generally the compression ratio is controlled as a fixed value.

$$S=p_{com}^{out}/p_{com}^{in} \quad (5)$$

2.2 Coupled components of natural gas and power system

The coupled components considered here are gas turbines in the gas-fired power plants. The coupling equation can be expressed by the heat rate curve.

$$HR_g = a + b \cdot P_g + c \cdot P_g^{\,2} \tag{6}$$

$$L_g = HR_g / GHV_g \tag{7}$$

3. CALCULATION OF DYNAMIC GAS FLOW

In order to simplify the calculation, some assumptions are made. First, the transmission speed is much less than the speed of sound. So the second item of Equ.(1) can be ignored. Next, the pipeline is assumed to be laid horizontally. Then the fourth item of Equ.(1) is zero. Finally, set $\rho v A = \rho_0 q$, converted the velocity to the form of the volume flow rate under standard conditions. The Equ.(1)-(2) are simplified to Equ.(8)-(9).

$$\frac{\rho_0}{A}\frac{\partial q}{\partial t} + \frac{\partial p}{\partial x} + \frac{\lambda}{2d}\frac{\rho_0^{\,2}}{\rho \cdot A^2} q^2 = 0 \tag{8}$$

$$\frac{\rho_0}{A}\frac{\partial q}{\partial x} + \frac{Z_0}{Z}\frac{T_0}{T}\frac{\rho_0}{p_0}\frac{\partial p}{\partial t} = 0 \tag{9}$$

Using Wendroff different format to approximate the partial differential equations [8], the formula can be expressed as following.

$$\begin{aligned}\left(q^{out}_{km,t+1} + q^{in}_{km,t+1}\right) + K_1 \times \left(p_{m,t+1} - p_{k,t+1}\right) + \\ K_2 \times \left(q^{out}_{km,t+1} + q^{in}_{km,t+1}\right)^2 + C1_t = 0\end{aligned} \tag{10}$$

$$K_3 \times \left(q^{out}_{km,t+1} - q^{in}_{km,t+1}\right) + \left(p_{m,t+1} + p_{k,t+1}\right) + C2_t = 0 \tag{11}$$

Where $K_1 = \dfrac{A \cdot \Delta t}{\Delta x \cdot \rho_0}$, $K_2 = \dfrac{\lambda}{8d}\dfrac{\rho_0 \cdot \Delta t}{\rho \cdot A}$, $K_3 = \dfrac{Z}{Z_0}\dfrac{T}{T_0}\dfrac{p_0 \cdot \Delta t}{A \cdot \Delta x}$ are constant parameters associated with the chosen differential step size. And the variables at time t are known, using $C1_t$ and $C2_t$ o simplify the expression. Where,

$$C1_t = -\left(q^{out}_{km,t} + q^{in}_{km,t}\right) + K_1\left(p_{m,t} - p_{k,t}\right) + K_2\left(q^{out}_{km,t} + q^{in}_{km,t}\right)^2$$

$$C2_t = K_3\left(q^{out}_{km,t} - q^{in}_{km,t}\right) - \left(p_{m,t} + p_{k,t}\right)$$

4. NUMERICAL STUDIES

Firstly, set up a test system to verify the calculation method of dynamic gas flow proposed in the section 3 by comparing the results with the simulation results of SYNERGI software. The structure and parameters of the test system are shown in the figure 1.

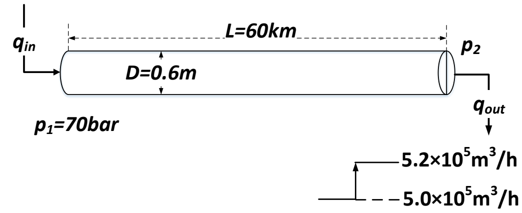

Fig 1 Test system

Assume that the pressure at the head of this pipe is controlled constant and the outlet gas load is stepped up. Set the differential step as △t = 30s, △x = 10km to calculate the inlet gas flow and the pressure at the end through the method proposed in this paper.

The results are shown in figure 2 and are compared with those simulated by SYNERGI software. It can be seen from the figure that the trend of the calculation result by the proposed model is basically the same as the simulation result of the SYNERGI software. In order to compare the errors calculated by the two methods more clearly, the figure 4 shows the two curves and the error between them. The comparison verifies the correctness of the calculation model.

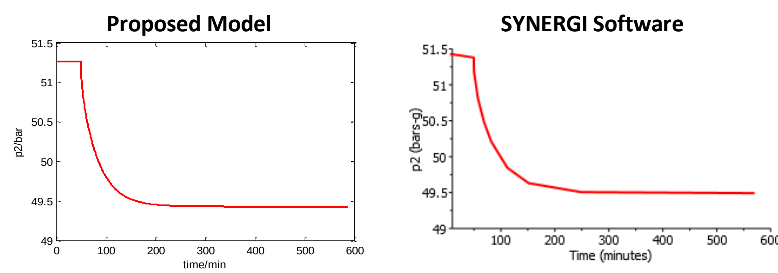

Fig 2 Node pressure at the end of the pipe

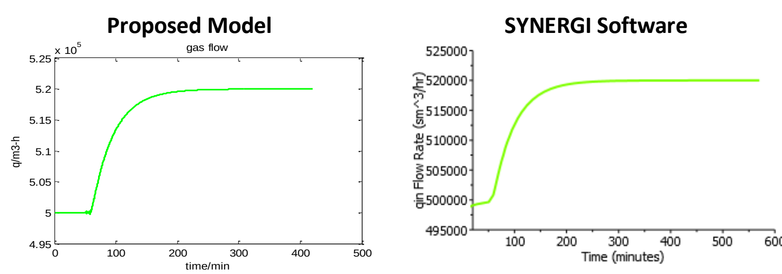

Fig 3 Inlet gas flow of the pipe

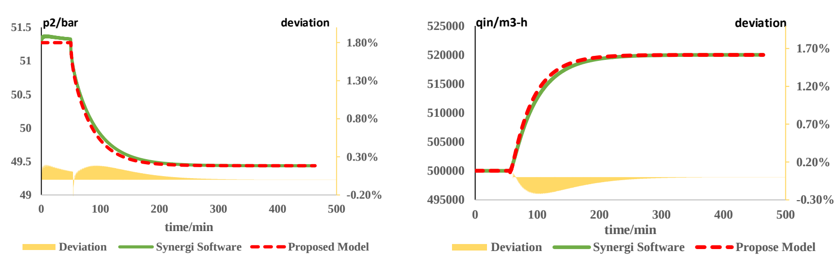

Fig 4 Error between the two method

Next, analyze the impact of the contingency of the natural gas infrastructure on the power system through a simple coupled system. The structure of the natural gas is shown in figure 4 which is referred from Ref [5]. The main parameters of the pipe is shown in table 1.

Table 1 Parameters of the pipe

No.	1	2	3	4	5	6	7
Length(km)	50	40	30	20	20	30	40
Diameter(mm)	600	500	500	500	500	500	500

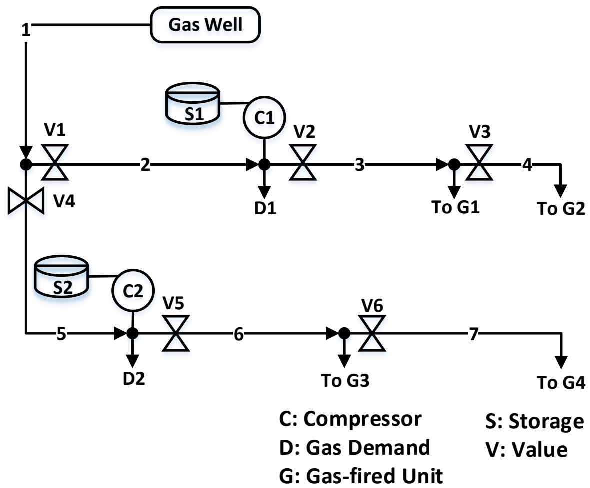

Fig 4 Structure of the natural gas sytem

This paper assumes the same priority for all loads. The effect of valve failure at different positions on the gas-fired units is shown in figure.

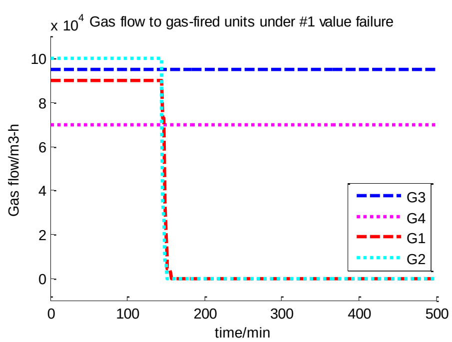

Fig 5 Gas flow to gas-fired units under valve 1 failure

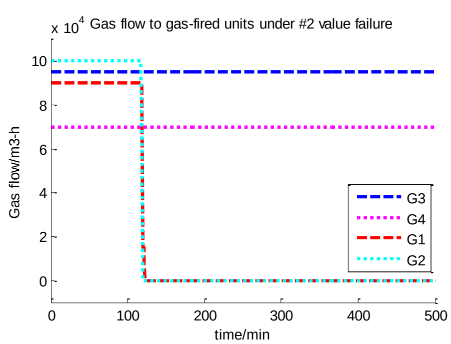

Fig 6 Gas flow to gas-fired units under valve 2 failure

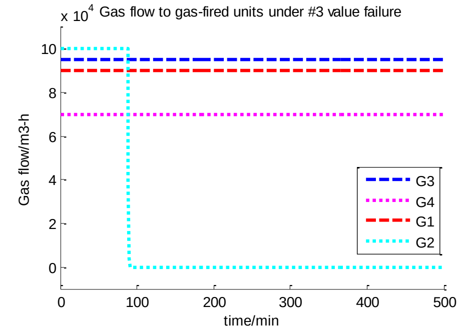

Fig 7 Gas flow to gas-fired units under valve 3 failure

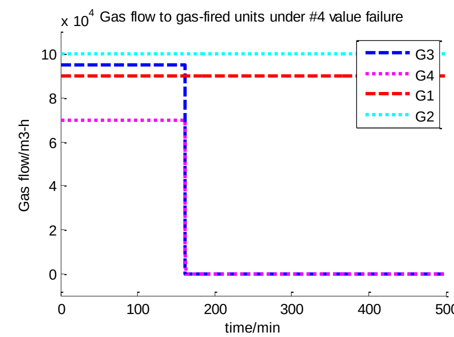

Fig 8 Gas flow to gas-fired units under valve 4 failure

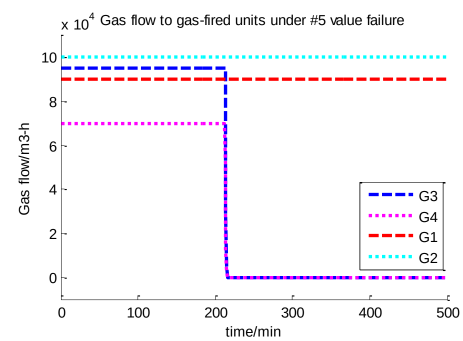

Fig 9 Gas flow to gas-fired units under valve 5 failure

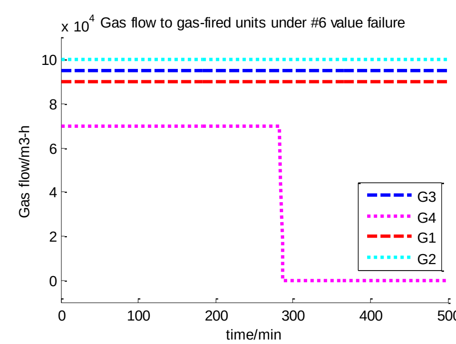

Fig 10 Gas flow to gas-fired units under valve 6 failure

It can be seen from this simple case study that, when the number of the affected load nodes is the same, for example in figure 6 and 9, or figure 7 and 10, the longer the distance between the failure infrastructure and the affected load, the longer the buffer time of this load. When multiple loads are affected at the same time, all loads are affected for the same time due to the assumption that the load has the same supply priority. And the shorter the failure infrastructure is from the nearest affected node, the shorter the buffer time, as shown in figures 5-7, or figures 8-10.

At the same time, the results of this case show that under the current operating pressure level, even the shortest pipe 4 (20km), when the valve at the head malfunctions, there is a one and a half hours buffer time for the affected load.

5. CONCLUSIONS

As the proportion of natural gas in the primary energy generation of power systems is gradually increasing, the failure of natural gas system facilities may have a very bad impact on the operational security of the power system. Since the time scale of natural gas transmission is quite different from that of electric power, there may be some buffer time before the natural gas system failure propagates to the power system. In this paper, a quasi-dynamic model adapted to different time scales of coupled natural gas and electricity system is proposed. The correctness of the calculation method is proved by comparison with the simulation results of mature commercial software SYNERGI. At the same time, the results of the case study show that at the level of the gas transmission network, if the power system can know in advance that the valve in natural gas system has malfunctioned, it can still have sufficient buffer time to take control measures to avoid the effect of the failure on the power system.

Next step we would study the effects of different pressure levels (such as the gas distribution network) and the length of the pipeline on the buffer time of the affected nodes. And the impact on the power system of the gas supply contract signed by gas-fired power plants.

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REFERENCE

[1] Jorge Munoz, Noemi Jimenez-Redondo, Juan Perez-Ruiz, Julian Barquin. Natural Gas Network Modeling for Power Systems Reliability Studies, IEEE Bologna Power Tech Conference, 2003.

[2] T.D.Diagoupis, E.N.Dialynas, L.G.Daoutis. Reliability Assessment of Natural Gas Transmission Systems and their Impact on the Operational Performance of Electric Power Systems, 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion, 2012.

[3] Sun Guoqiang,. Chen Sheng, Zheng Yuping, Wei Zhinong. Available Transfer Capability Calculation Considering Electricity and Natural Gas Coupled Energy System Security Constrains. Automation of Electric Power Systems, vol.39, no.23, pp.26-32, 2015.

[4] Sheng Chen, Zhinong Wei, Guoqiang Sun, Yonhui Sun. Steady-state Security Regions of Electricity-gas Integrated Energy Systems, 2016 IEEE Power and Energy Society General Meeting (PESGM), 2016.

[5] MOHAMMAD SHAHIDEHPOUR, YONG FU, THOMAS WIEDMAN. Impact of Natural Gas Infrastructure on Electric Power Systems. PROCEEDINGS OF THE IEEE, vol.93, no.5, pp.1042-1056, 2005.

[6] Zheng Qiao, Lin Jia, Wei Zhao, Qinglai Guo, etc. Influence of N-1 contingency in natural gas system on power system, 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), 2017.

[7] Cheng Wang, Wei Wei, Jianhui Wang, Feng Liu, etc. Robust defense strategy for gas-electric system against malicious attacks, IEEE TRANSACTIONS ON POWER SYSTEM, vol.32, no.4, pp.2953-2965, 2017.

[8] Xiaomeng Ai, Jiakun Fang, Shenzhi Xu. An optimal energy flow model in integrated gas-electric systems considering dynamic of natural gas system, Power System Technology, vol.42, no.2, pp.409-416, 2018.

[9] Tang Yue, Tang Lingdi, Liu Erhui. 3D simulation and transient model for regulating period of gate valve, Journal of Drainage and irrigation machinery engineering, vol.30, no.2, 2012.