RESILIENCE ANALYSIS OF ELECTRICITY-GAS INTEGRATED HYBRID ENERGY SYSTEM UNDER EXTREME EVENTS

Wenhao WANG[1]* Jianmei SUN[2]

The power system or natural gas system is vulnerable to natural disasters. In this regard, this paper studies the resilience of the electricity-gas integrated hybrid energy system under earthquake-like extreme events. Based on the historical seismic data, the k-means algorithm is used to cluster typical fault scenarios to obtain three types of extreme earthquake event scenarios. Examples simulations are carried out on the IEEE30-node power system and the 18-node natural gas system to verify the effectiveness of the resilience analysis method. The results show that the power grid will suffer greater losses under earthquake extreme events. The main reason is that the gas storage device faces the risk of damage and leakage while meeting the emergency power supply load, which causes the problem of insufficient gas storage, resulting in a greater recovery load on the power system. The proposed method effectively evaluates the resilience of the electricity-gas integrated hybrid energy system in earthquake disaster.

Keywords: electricity-gas integrated hybrid energy system (IHES); extreme events; earthquake disaster; resilience analysis

1. Introduction

Energy is the foundation of economic and social development. Natural gas, electricity and other energy sources constitute a multi-energy system. In order to solve the above problems, it is necessary to carry out overall planning and coordination optimization of system scheduling while considering the further improvement of system state security, reliability and energy efficiency. Among them, system planning, and operation is the process of realizing the coordinated operation of various systems by utilizing energy advantages and complementary energy system efficiency in emergency situations [1]. Coupling responses widely exist in the entire power system. The interference of the internal components of the coupling system will seriously affect the operational safety of the electricity-gas system. The electricity-gas interconnection transmission mechanism can not only

[1] * Eng., College of Economics and Management, Shanghai University of Electric Power, Han, China, corresponding author, E-mail：w18811654562@126.com.
[2] PhD Eng., College of Economics and Management, Shanghai University of Electric Power, Han, China, E-mail：13472787768@139.com

alleviate the crisis of energy shortage, but also improve system connectivity and ability to withstand extreme disasters.

Extreme power outages such as earthquakes, tsunamis, and typhoons have occurred frequently, causing huge economic losses and social impacts. The main characteristics of extreme natural disasters are different from other accidents. These things are unpredictable and may not happen, and are characterized by high risk, low probability, and high impact. One of the characteristics of tsunamis and earthquakes is that in various extreme disasters, the damage caused to system power equipment has uncertainty that is difficult to define [2]. For example, in 2008, a major earthquake occurred in Sichuan, China, and the power grid suffered unprecedented damage. The substation system is easily affected by earthquakes, and it is difficult to restore and rebuild after damage, which will affect the social functions and economic development of the affected areas for a long time.

With the rapid development and continuous attention of IHES, the integration of various energy subsystems has been continuously strengthened. In the case of extreme disasters, the combined components of the electric-gas hub composite energy system use electric energy conversion technology to realize joint supply. Electricity-gas systems improve the performance of gas systems, restore combustion systems and respond to disasters. This plays an important role in maintaining the basic social functions of modern cities [3]. It can be seen that measures such as improving energy utilization, revitalizing energy centers, and coordinating recovery will play a positive role in the post-disaster recovery capabilities of the system.

In order to assess the extent to which gas-fired systems increase distribution system resilience, extensive research is required on an extreme-disaster resilience assessment framework for electricity-gas IHES [4]. In short, these issues must be addressed: There is no regulatory framework for qualitative and quantitative analysis and resilience assessment of integrated energy and gas systems. Therefore, it is necessary to establish corresponding theories and evaluation methods. This paper analyzes the resilience of electricity-gas IHES under earthquake extreme natural disaster events. The research mainly focuses on two aspects, one is the resistance during the disaster, and the other is the recovery after the disaster, so as to judge the resistance of the electrical-gas IHES under disasters such as earthquakes.

2. Electricity-gas IHES

Fig. 1 shows the typical structure of the electricity-gas IHES. The devices cooperate with each other to realize the mutual conversion of energy.

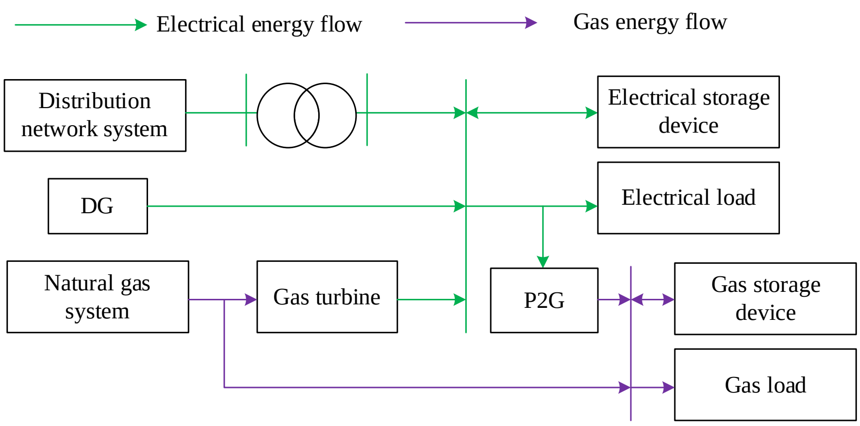

Fig. 1 Electricity-gas IHES

The operation form of gas storage facilities is the output of natural gas, which is mainly divided into two stages: the peak load stage of mechanical energy generation, which must be supplemented by gas turbines to convert energy and other electrical energy into load transmission. At this point, it is the stage of electric gas regulation; In the low load stage, energy is stored in the natural gas device because it cannot be stored, which is the gas to electricity stage [5, 6]. The above-mentioned gas storage device (GSD) generally takes gas storage cabinets and gas pipelines as examples.

If the storage capacity remains unchanged at the end of one operating cycle, the device can operate normally in the next operating cycle. Natural gas reserves are generally expressed as the gas input volume, gas output volume and gas storage volume at a certain moment. The corresponding constraint conditions of the gas storage device are shown:

$$\begin{cases} S_{a,t} = S_{a,t-1} + X_{a,t} - O_{a,t} \\ S_{a,0} = S_{a,T} \\ 0 \le X_{a,t} \le v_{a,t} X_{a,max}, \forall a \in \psi, t \in [1,T] \\ 0 \le O_{a,t} \le \xi_{a,t} O_{a,max} \\ 0 \le v_{a,t} \le \xi_{a,t} O_{a,max} \\ 0.2 S_a \le S_{a,t} \le 0.95 S_a \end{cases} \quad (1)$$

Where $\xi_{a,t}$ represents the gas-filled state of the GSD at time *t*, and is an integer variable of 0-1; $v_{a,t}$ represents the gas-released state of the GSD at time *t*, and is an integer variable of 0-1; $O_{a,max}$ is the maximum gas-released volume of the GSD, in cubic meters; $X_{a,max}$ is the maximum gas-filled volume of the GSD, in cubic meters; S_a is the rated capacity of the GSD; $S_{a,t}$ is the capacity of the GSD at time *t*, in cubic meters.

In the gas-to-electricity stage, the coupling element gas engine of the energy hub is mainly used for the overall energy conversion. The intermediate efficiency evaluation is based on the conversion efficiency, and the formula for converting natural gas into electricity is as follows:

$$P_n^{gas} = \eta_{gas-ele} Q_n^{gas} H_g \tag{2}$$

Where H_g represents the calorific value of natural gas; Q_n^{gas} is the natural gas flow rate consumed by the *n*th gas turbine; $\eta_{gas-ele}$ represents the conversion efficiency; P_n^{gas} represents the electricity generated by the *n*-th gas turbine.

In the electricity-to-gas stage, P2G technology is mostly used to convert electrical energy, and then generate methane, which is then stored and utilized. The energy conversion relationship is:

$$Q^{P2G} = P_{P2G} \eta_{gas-ele} / HHV_{CH_4} \tag{3}$$

Where $\eta_{gas-ele}$ represents the energy conversion efficiency of the electricity-to-gas stage, generally between 0.5 and 0.6; HHV_{CH_4} represents the high calorific value of methane gas.

3. Earthquake disaster scene set

When evaluating the resilience of integrated electric and natural gas energy systems, key failure scenarios should be selected. Depending on the characteristics of the disaster, the probability of failure of components such as electricity and gas pipelines varies. Therefore, choosing typical earthquake damage scenarios can make the durability evaluation results of energy and gas integrated power systems convincing [7].

First, this paper uses the Monte Carlo method to simulate earthquake disaster information. The past earthquake data and disaster data such as gradient and epicentral distance are determined by principal component analysis. The second is to extract peak seismic acceleration characteristics such as PGM, related formulas, failure rates of components and equipment, and reference curve models to calculate the vulnerability of the seismic integrated power system in various scenarios [8,9]. Finally, based on vulnerability, the typical fault scenarios are divided into k-means clustering and system information degradation, and three types of extreme earthquake disaster scenarios are obtained.

3.1. Disaster simulation and feature extraction

As far as daily life is concerned, earthquake extreme disasters occur as a low-probability and highly random event. It is difficult for us to accurately predict earthquake events. At the same time, past historical data information also has great limitations. In this paper, the disaster information is simulated by combining the historical earthquake data with the Monte Carlo method, and a corresponding disaster model is established. The calculation formulas of epicentral distance, earthquake level and earthquake peak acceleration are as follows:

$$N_r = -ln(1-P_r) \tag{4}$$

$$M = \frac{a-\log(N_r)}{b} \tag{5}$$

$$\begin{aligned} ln(PGA) = 2.2 + 0.81*(M-6) - 1.27*ln(\sqrt{R^2+9.3^2}) + \\ 0.11*\max[ln\frac{R}{100},0] - 0.0021*\sqrt{R^2+9.3^2} \end{aligned} \tag{6}$$

Where PGA represents the peak seismic acceleration(g，1g=9.81m/s^2); b represents the slope relationship between earthquake frequency and magnitude distribution; a represents the level of seismic activity(kN • m^{-1} • s^{-1}); N_r represents times of the magnitude M of the simulated random number; M represents the earthquake level (ML); R represents the epicentral distance (km); P_r represents a random number between 0 and 1.

3.2. K-means clustering and system information entropy to generate typical fault scene set

Firstly, the disaster features are extracted, and then the fault probability of the electricity-gas IHES under the earthquake disaster is analyzed through the vulnerability curve, so as to generate the corresponding disaster failure scenarios [10]. The typical fault scenes are divided, and the iterative method is used for optimal division [11]. The specific formula is as follows:

$$C_i = \arg_j min\left\| f(I_i) - \theta_j \right\|_2^2 \tag{7}$$

Where I_i represents representative seismic hazard characteristic values, $f(I_i)$ represents vulnerability curve corresponding to disaster characteristic values and earthquake disaster situations, θ_j represents random initial cluster centers.

In addition, according to the calculation results of the information entropy value of the IHES, the W (earthquake level) value of the IHES must be restricted, that is, it must satisfy $W_{min} \le W \le W_{max}$. The entropy beyond this value range corresponds to the reduction of defective scenes, and the output after pruning is adjusted according to the sampling distribution of defective scenes.

By discarding the fault scenes whose system entropy is out of bounds, the fault scenes with high probability of occurrence and which may have a serious impact on the fault result are considered. After this scene restores the default settings, the remaining scenarios have a high probability of fault and serious consequences, forming a set of typical fault scenes and strengthening the resilience assessment of the gas-electricity integrated system [12, 13].

Finally, the fault of the system, the earthquake of the whole scene is composed of different types: the damage degree of the electric system is less than 4.5%, while the damage degree of the gas-to-electricity system is very small, less than 5% for electricity and gas. An earthquake measuring 4.5 to 6 on the Richter scale. There have been very few failures of the gas system and major damage to the electrical system. Electric combined powertrains have a failure rate of about 20%. When the earthquake reaches magnitude 6 or above, the natural gas will be severely damaged, the power system will be severely damaged, and the energy integrated power system will suffer a loss of about 30% [14-17].

4. Earthquake Model Based on Markov State

Markov chain is a key method to reach different states in the process of state restoration and transfer of electric-gas IHES. It can be divided into four types: normal operating state, gas-to-electricity state, power-to-gas state and fault state [18]. according to the system operating state. To better understand the state transition process, an approximation is made: gas-to-electricity is static, which means that the gas system typically uses gas turbines to provide this level. How to generate electrical charge to maintain the load level of the electrical system. The gas-electricity holding state refers to the state that electric energy is still converted into gas energy even if the power supply is restored and the pipeline is not restored [19]. By combining the earthquake disaster scenario with the formed Markov state model, four different state transition models of the system are established, including three Markov state transition models.

First, when the magnitude is less than 4.5, a Markovian state transition model is formed from normal and faulty states in the power grid restoration process. State transitions are performed using failure rates λ and repair rates μ . The specific transition steps are shown in Fig. 2.

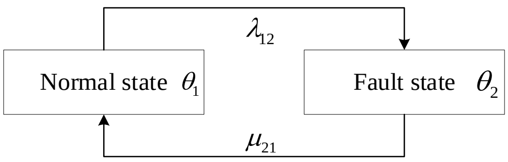

Fig. 2 Two-state model of the magnitude 4.5 seismic coupling system

Followed by earthquakes of magnitude 4.5 to 6, the cycle process of the integrated power system shifts from the Markovian state to the three-state, and then from the Markovian state to the lawful state, the three states of normal operation, electricity and gas, and fault state Markov state transitions. The specific transmission steps are shown in Fig. 3.

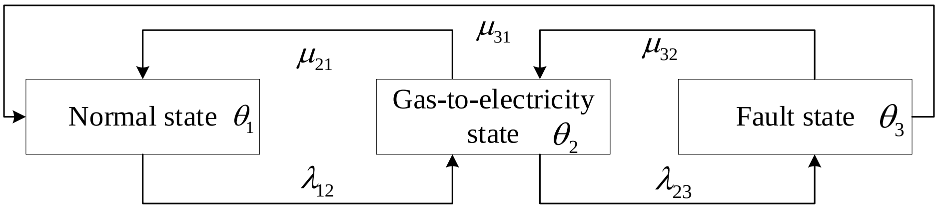

Fig. 3. Three-state model of the seismic coupling system from magnitude 4.5 to magnitude 6

Fig. 3 shows the establishment of normal operation state, determination of normal operation state, determination of gas based on electricity, determination of electricity based on gas, and failure state in case of an earthquake of magnitude 6 or above. The four-state Markov model and its specific transfer process are shown in Fig. 4.

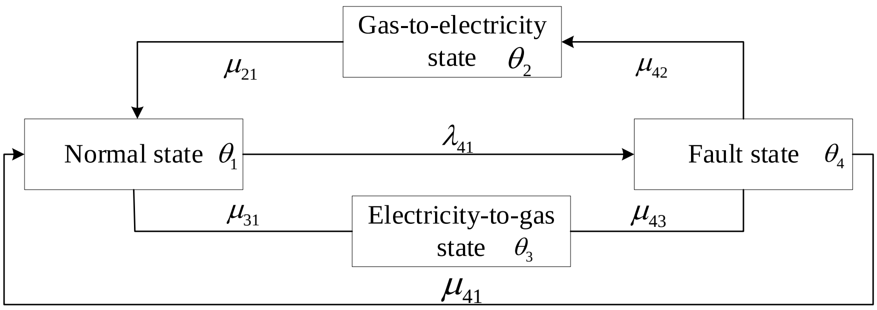

Fig. 4 Four-state model of seismic coupling system above magnitude 6

Finally, the state probability vector of the three-state model and the four-state model can be obtained through the following formula: $V_3 = [\theta_1, \theta_2, \theta_3]^T$, and the state transition vector is $V_4 = [\theta_1, \theta_2, \theta_3, \theta_4]^T$.

$$\sum_{i=1}^{n} \theta_i = 1 \quad 0 \le \theta_i \le 1 \tag{8}$$

$$\theta_i = \sum_{j=1}^{n} Q_{ji} \theta_j \quad i = 1, 2, \cdots, n \tag{9}$$

$$(P_i - I)V_i = 0 \tag{10}$$

$$P_3 = \begin{bmatrix} 1-\lambda_{12} & \lambda_{12} & 0 \\ \mu_{21} & 1-\mu_{21}-\lambda_{23} & \lambda_{23} \\ \mu_{31} & \mu_{32} & 1-\mu_{31}-\mu_{32} \end{bmatrix} \tag{11}$$

$$P_4 = \begin{bmatrix} 1-\lambda_{14} & 0 & 0 & \lambda_{14} \\ \mu_{21} & 1-\mu_{21} & 0 & 0 \\ \mu_{31} & 0 & 1-\mu_{31} & 0 \\ \mu_{41} & \mu_{42} & \mu_{43} & 1-\mu_{41}-\mu_{42}-\mu_{43} \end{bmatrix} \quad (12)$$

Where I is the identity matrix; V_i is the state probability vector of the *i*-th state model; P_i is the state transition matrix of the *i*-th state model; θ_i represents the *i*-th transition vector in the state transition vector A representing different system operating states; Q_{ji} represents the probability of state transfer from θ_j to θ_i in the electric-gas integrated energy system.

5. Static evaluation method of resilience of electrical integrated energy system

The electricity-gas IHES consists of two subsystems: the electrical distribution and the gas network. When the IHES encounters extreme disasters such as earthquakes, floods, and typhoons, the power topology cannot be changed, and the power distribution system cannot be reconfigured due to the failure of various subsystem components. The large-scale devastation of extreme disasters can lead to systemic failures that lead to increasingly severe economic losses. The concept of resilience is thus born, and the problem of restoring normal power supply to a faulty system when extreme events occur has received more and more attention [20].

From a systemic risk perspective, resilience and reliability are often viewed as additional indicators. Reliability here means low system damage and short-term availability. Generally speaking, the number of power outages per year and the duration of power outages can quantify the size of the indicator. Durability and reliability are completely different. In extreme cases such as earthquakes, typhoons, and heavy rains, the power distribution system will be damaged, and its resilience will be reduced. However, this does not mean that the power can be turned off, but an automatic touch switch can be used to achieve the purpose of reconfiguring the system circuit with high reliability. To put it simply, the research objects of these two indicators are different, and can be understood as two branches of systemic risk.

After extreme events, the inherent resilience curve of the system is related to the degree of resilience, adaptability and efficiency of the combination of subsystems. Trend charts are divided into three-state models and four-state models. First, the three-state model does little damage to gas systems but does damage to electrical systems. Second, under the four-state model, electric and natural gas systems are at risk. The change trends of system elasticity corresponding to the two state models are shown in Figs. 5 and 6. The black line is a general plot of the electrical system recovery time curve as a function of hazard. It represents important steps in the system, but not all resistance curves. Red is the earthquake-induced change in the elasticity of the gas system. The size of the impact is related to the type of earthquake. Gas systems generally suffer less damage than electric systems.

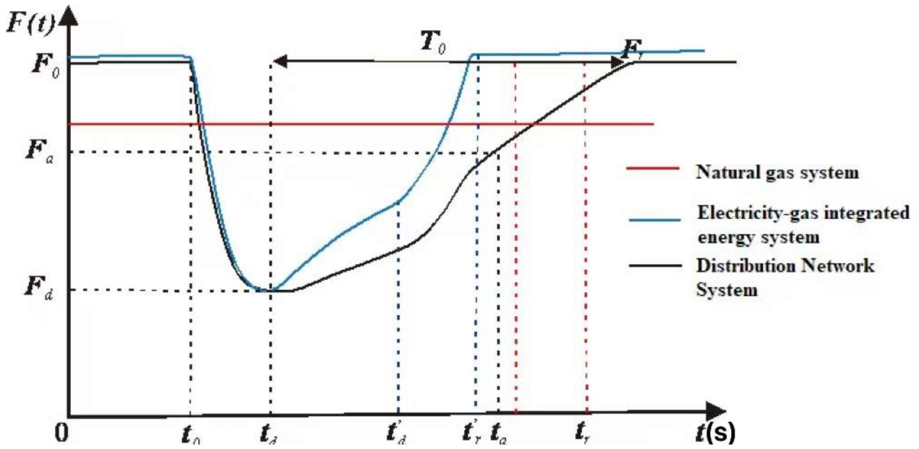

Fig. 5 System resilience change in three-state mode

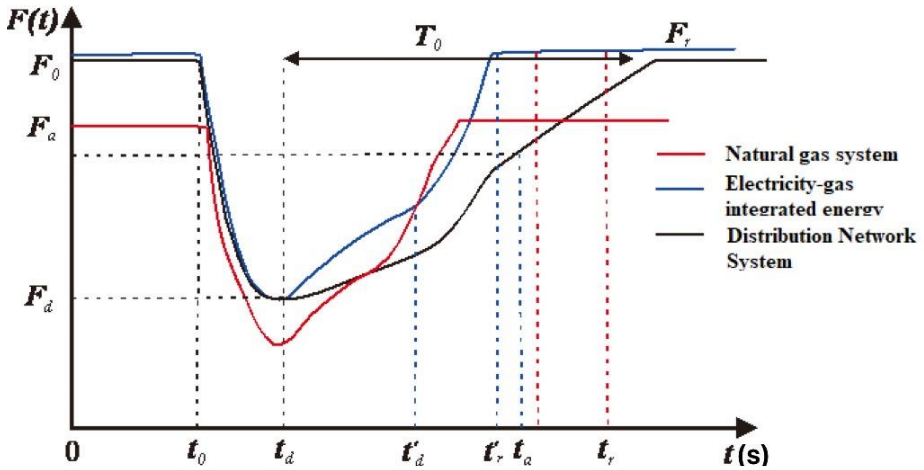

Fig. 6 System resilience change in four-state model

t is the time of disaster recovery; F is the restoring force. F_0, F_a, F_r respectively represent the initial values of distribution network system resilience, the initial values of natural gas system resilience, the initial values of electricity-gas integrated energy system resilience. F_0 is the lowest value of distribution network system resilience. The line segments of all resilience curves can be divided into the following times: the disaster time is the time when the system loses the most; t_0 is the recovery step 1, during which the recovery of the maximum non-critical load guarantees the recovery of all critical loads. T_0 corresponds to the black curve of restoring the elasticity of the IHES. The power supply in the disaster area continues to be loaded between the electrical-gas system, and the electrical energy level is continuously restored. The stages of resilience change can be divided into pre-disaster events, post-disaster events, recovery phase 1(t_d) and recovery phase 2($t_d^{'}$), t_a is auxiliary time points, without practical significance. When an earthquake occurs, the power system itself will accelerate according to the degree of energy recovery, especially the strategy of rapid power supply and rapid maintenance through the control of contact switches to control system components. Disasters affect power outages, and the fault is restored at $t_r^{'}$, and the system power capacity is restored to its original state. Likewise, the red and blue curves are the elasticity curves for the gas cycle system and the electricity-gas IHES. In the event of an earthquake disaster, the gas storage of the electricity-gas IHES transmits energy through gas pipelines to accelerate the recovery of the natural gas system. In recovery step 2, the distribution network is connected to the gas system, thereby accelerating recovery.

6. Case Analysis

Using Python software to simulate earthquake disaster scenarios, three different clusters can be obtained in Fig. 7 below, which also represent the changes in fault scenarios with changes in earthquake levels. Between earthquake levels, natural gas and electric power systems Certain failures will occur, corresponding to various damage degrees. From an overall point of view, the corresponding damage degrees are about 5%, 20%, and 30%.

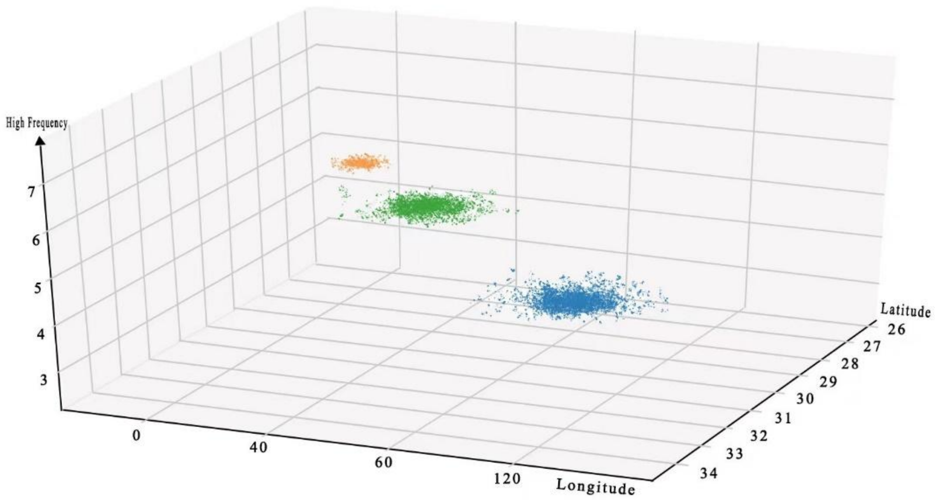

Fig. 7 Earthquake disaster scene set

The research takes the IEEE30-node power system as a simulation example, which is an 18-node natural gas system. Table 1 shows the specific efficiency parameters.

Table 1

Efficiency of electricity-gas IHES

Efficiency	Three-state model	Four-state model
$\eta_{ele,ele}$	0.9	0.9
$\eta_{gas,ele}$	0.7	0.85
$\eta_{ele,gas}$	0	0.6
$\eta_{gas,gas}$	0.9	0.8

The indicators of post-disaster electricity-gas comprehensive energy system resilience were quantified. Tables 2 and 3 show the system results.

Table 2

Resilience index weight set

Index	Three-state model	Four-state model
Robustness	$\mu_1 = \{0.277,0.277, 0.208,0.287\}$	$\mu_2 = \{0.333,0.229, 0.211,0.227\}$
Rapidity	$\mu_2 = \{0.454,0.546\}$	$\mu_2 = \{0.498,0.502\}$
Degree of recovery	1	1
Coupling	1	1

Table 3

Quantification results of electrical coupling system

index	Three-state model	Four-state model
Energy efficiency ratio	0.593	0.404
Residual load ratio	0.818	0.434
Network damage	0.789	0.639
Connectivity factor	0.648	0.440
Critical load recovery speed	0.655	0.631
Repair rate	0.636	0.785
Electrical-Pneumatic Coupling Index	0.490	0.870
Adaptation rate	0.973	0.980

On the basis of index quantification, simulation analysis is carried out through software, and the change curve of electrical coupling system with fault recovery time under earthquake conditions is shown in Fig. 8 below.

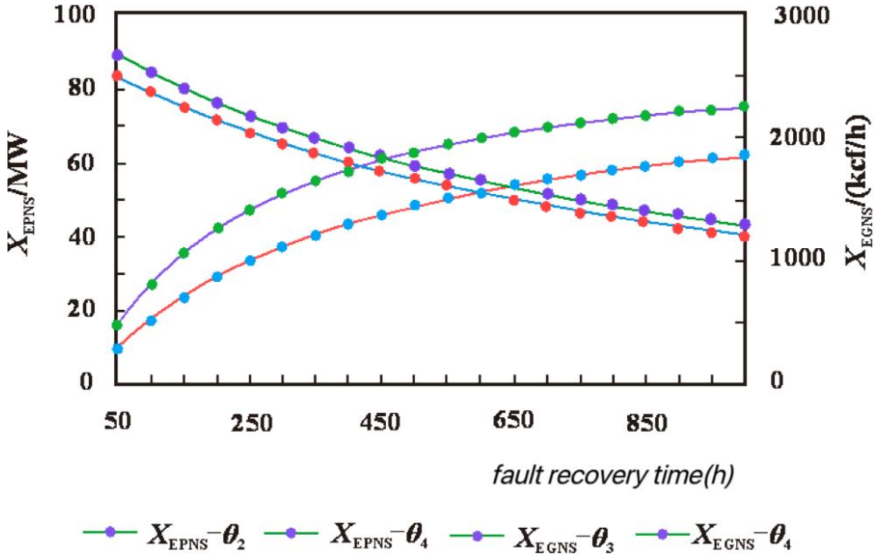

Fig.8 Variation curve of electrical coupling system with fault recovery time under earthquake conditions (Kcf/h mean Khz/h)

X_{EPNS} represents the energy transmitted by the gas storage of the electrical coupling system through natural gas pipelines. X_{EGNS} means electricity density. In the event of extreme events such as earthquakes, the power grid will suffer greater losses. The reason is that the GSD needs to supply emergency power loads while storing gas, and the part that suffers from damage and leakage will cause the problem of insufficient gas storage, resulting in the power system restores a greater load.

Compared to the post earthquake power system resilience analysis model in reference [21], this article considers the resilience analysis model of the electrical coupling system, which is more practical and provides the reasons why the electrical coupling system is more difficult to recover in the event of an earthquake. It also quantifies various indicators of the resilience of the post disaster electricity gas integrated energy system. And the resilience of the post disaster electrical coupling system was analyzed in terms of time dimension, providing a reference for the time of post disaster emergency rescue. This article proposes a research perspective on the resilience of integrated energy systems in reference [22], which aims to address the issue of inconsistent time scales for different energy transmission, establish a new multidimensional and multi-level resilience evaluation index and rating system, and more accurately measure the resilience of the system.

7. Conclusions

The power system feeding capacity mitigation problem characterized by extreme weather disasters and destructive earthquakes with different uncertainties, using the disaster scenarios, coupling connections and evaluation methods in this paper, such as subsystem coordination combined with electric-gas system conversion electricity-gas, the perspective is completely related to the maturity of the technology, it has advantages in improving gas conversion technology and gas generator equipment capabilities, a robustness assessment framework for comprehensive assessment of the IHES is proposed. The purpose of the research is to determine the ability of the power system to overcome the destructive impact of extreme events on the electricity-gas IHES, accurately evaluate the resilience of the system, and propose appropriate improvement programs. This paper mainly studies the basic framework of earthquake disaster simulation. The disaster data is simulated by Monte Carlo method, and the characteristic information of earthquake disaster is extracted by principal component analysis and formula method. Taking the earthquake scenario as an example, this paper constructs all three types of seismic event scenarios using information and weight groups and evaluates the resilience of the electricity-gas IHES and verifies the model validity through simulation experiments. However, due to limitations in research content, only one extreme environment, earthquake, has been analyzed, and there is still significant room for development. With the continuous deepening of research, the stability of electrical coupling systems will also be further improved.

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