The Resilience Assessment Method of Electric-gas System under Earthquake Disaster

Yi Zheng
Shibei Power Supply Company,State Grid Shanghai Municipal Electric Power Company
Shanghai, People's Republic of China
lessyie0527@163.com

Jing Wu
Shibei Power Supply Company,State Grid Shanghai Municipal Electric Power Company
Shanghai, People's Republic of China
13310033122@163.com

JiaHong Fu
Shibei Power Supply Company,State Grid Shanghai Municipal Electric Power Company
Shanghai, People's Republic of China
715440771@qq.com

YiWen Shen
Shibei Power Supply Company,State Grid Shanghai Municipal Electric Power Company
Shanghai, People's Republic of China
blueriver_ka_en2@hotmail.com

Han Wang*
Key Laboratory of Smart Grid of Ministry of Education Tianjin University
Tianjin, People's Republic of China
2663671815@qq.com

Hang Li
Key Laboratory of Smart Grid of Ministry of Education Tianjin University
Tianjin, People's Republic of China
2419091330@qq.com

Kai Hou
Key Laboratory of Smart Grid of Ministry of Education Tianjin University
Tianjin, People's Republic of China
hdbhyj@tju.edu.cn

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***Abstract*—Earthquake disasters can cause damage to various types of infrastructure of the electric-gas system, and in severe cases, power outages and gas outages. Taking into account the uneven distribution of earthquakes in space, this paper constructs an earthquake disaster model based on the three-level latent focal region division scheme and an electric-gas system component failure probability model based on earthquake intensity distribution. Then, a planning-oriented resilience assessment framework of electric-gas system under earthquake disaster is proposed. Finally, this paper uses the electric-gas system composed of the IEEE RTS79 grid and the modified 14-node gas grid to verify the proposed resilience assessment framework.**

***Keywords* —resilience, earthquake disaster, electric-gas system, planning-oriented**

I. INTRODUCTION

In recent years, earthquakes occur frequently all over the world, which poses a great threat to the energy system. Wenchuan Earthquake in China paralyzed the Northwest Sichuan Power Grid, and the instantaneous load loss of the entire Sichuan Province reached 31.8%. In 1971, the San Fernando, California earthquake caused heavy losses to buried gas pipelines in the San Fernando Valley. Under the impact of earthquake disasters, the component failure probability of the electric and the natural gas transmission network will be greatly increased, and as their coupling relationship getting deeper, the cascading effect of different energy systems under earthquake cannot be ignored. In this context, it is necessary to comprehensively analyze the impact of the earthquake on the electric-gas system and evaluate the resilience of the electric-gas system under earthquake.

Due to the need to consider the faults in both power system and natural gas system, the progress of the research about electric-gas system resilience under earthquake is slow. Reference [1] evaluates the impact of earthquake on power system, while it does not consider the natural gas system coupled with it. Reference [2] evaluates the resilience of island integrated energy system under earthquake disaster from three aspects of robustness, rapidity and redundancy, however, the spatial distribution characteristics of earthquake is not considered.

At present, there is a lack of systematic method to evaluate the resilience of electric-gas system under earthquake. This paper aims to solve this problem. The main contributions of this paper include: a feasible earthquake disaster model is built and the resilience assessment framework of electric-gas system under earthquake is proposed.

The rest of the paper is organized as follows. Section II introduces the earthquake disaster model. Then, the soving method of component failure probability and the resilience assessment framework of electric-gas system under earthquake are developed in Section III. A case composed of IEEE RTS79 grid and the modified 14-node gas grid is analyzed in Section IV, and conclusions are drawn in Section V.

II. EARTHQUAKE DISASTER MODEL

The most important characteristic parameters of an earthquake are hypocentral location, earthquake magnitude M and earthquake intensity I. The hypocentral location is the starting position of the earthquake, M refers to the magnitude of the earthquake itself, and I represents the degree of damage caused by the earthquake. The purpose of earthquake disaster modeling is to describe the distribution of the three.

A. Earthquake Activity Model

In order to describe the spatial multi-level heterogeneity of earthquake activity, China GB18306-2015 proposes a three-level latent focal region division scheme: firstly, the earthquake zones used for the statistics of earthquakeity parameters are divided; then the background sources with different background earthquakeity characteristics are divided in the earthquake zone; finally, the tectonic sources are divided in the background sources according to the local tectonic conditions [3] (the tectonic sources are generally distributed along the earthquakeity faults). Fig. 1 shows the three-level division model of the latent focal region, where M_u is the upper magnitude limit, and the red line represents the active fault.

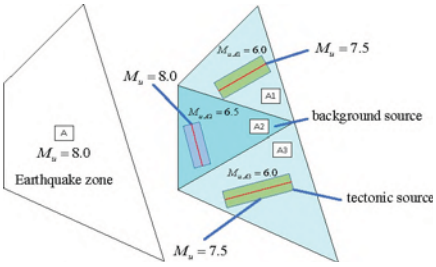

Fig. 1. Schematic diagram of three-level division of latent focal region

The earthquakes that may occur in the earthquake zone are equally divided into several magnitude grades. Then, set $M_j \in [M_j - \Delta M/2, M_j + \Delta M/2]$ as the center value of the j th magnitude grade, where ΔM is the magnitude interval. Taking M_j to represent the j th magnitude grade, the magnitude distribution of the earthquake zone is:

$$P(M_j) = \frac{2\exp[-\beta(M_j - M_0)]}{1-\exp[-\beta(M_u - M_0)]} \cdot sh(\frac{\beta}{2}\Delta M) \tag{1}$$

where $P(M_j)$ represents the probability that the earthquake occurred belongs to the j th magnitude grade; $\beta = b\ln 10$, b is the coefficient of the G-R relationship in the earthquake zone; M_0 is the lower limit of the magnitude of the earthquake zone, generally taken as 4.

In the following part of this paper, background source and tectonic source are collectively referred to as latent focal region. The probability that an earthquake is located in a certain latent focal region is determined by its earthquake activity weight, and within the latent focal region, the probability of an earthquake occurring at each location is equal.

The earthquake activity weight of latent focal region can be obtained from the following equation [4]:

$$\alpha_i = \begin{cases} A_i \times (M_{u,i} - M_0), & M \le M_{u,i} \\ 0, & M > M_{u,i} \end{cases} \tag{2}$$

where α_i is the absolute activity weight of the i th latent focal region; A_i is the area of the i th latent focal region; $M_{u,i}$ is the upper limit of the magnitude.

After determining the earthquake activity weights of all latent focal regions, the probability that the j th magnitude earthquake in the earthquake zone occurs at the point (x, y) in the i th latent focal region can be directly calculated:

$$\begin{aligned} P(x,y,M_j) &= P(M_j)\cdot P((x,y)|M_j) \\ &= P(M_j)\cdot \frac{\alpha_i}{\sum \alpha}\cdot\frac{1}{A_i} \end{aligned} \tag{3}$$

B. Earthquake Intensity Attenuation Model

In order to characterize the inhomogeneity of seismic intensity attenuation along different directions, the elliptical attenuation model is used for statistical analysis along the long axis and the short axis [5]. The earthquake intensity of each point in the short axis or long axis direction is given by:

$$I = A + BM + C\lg(r + r_0) \tag{4}$$

where r is the epicenter distance; A, B, C, r_0 are regression parameters.

Remember the interval of earthquake intensity $[i-0.5, i+0.5]$ is earthquake intensity zone i, where $i \in \{6,7,8\}$. Intensity zone can be divided by determining the ellipse parameters of each interval's boundary. For this reason, the long and short axis radius of the isointensity line of the boundary and the direction of the earthquake long axis are required.

The long and short axis radius of the boundary line in the earthquake intensity zone can be derived from the following equation:

$$r = 10 \wedge (\frac{I - A - BM}{C}) - r_0 \tag{5}$$

The principle of determining the direction of earthquake long axis is as follows: the direction of the long axis of the earthquake in the tectonic source is consistent with the direction of the active fault of the tectonic source; the direction of the long axis in the background source is consistent with that of the tectonic source nearest to the source.

III. THE RESILIENCE ASSESSMENT METHOD OF ELECTRIC-GAS SYSTEM CONSIDERING THE IMPACT OF EARTHQUAKE

A. Component Failure Probability Model

Earthquake disasters have strong destructive power on the transformer, overhead transmission line and gas pipeline, so this study only considers the damage of these three types of component.

(1) Failure probability model of transformer

Assuming that the failure probability of a single transformer under an earthquake is p_u, and there are n backups, the actual failure probability of the transformer is:

$$P_u = p_u^{\,n+1} \tag{6}$$

(2) Failure probability model of overhead transmission line

Assuming that the transmission line spans K earthquake intensity zones, the failure probability of the towers in each intensity zone is the same. Considering that the towers on the same transmission line are connected in series, the failure probability of the entire line is:

$$u = 1 - \prod_{j=1}^{K}(1-u_j)^{n_j} \tag{7}$$

where u_j is the failure probability of the tower in intensity zone i; n_j is the number of towers located in the j th earthquake intensity zone.

(3) Failure probability model of gas pipeline

The failure probability of gas pipelines is analyzed by earthquake damage rate [6]:

$$\begin{aligned} P_f &= 1 - e^{(-R_f L)} \\ R_f &= C_d C_g 10^{0.8(I-9)} \end{aligned} \tag{8}$$

where R_f is the earthquake damage rate; C_d is the influence coefficient of pipe diameter; C_g is the site soil influence coefficient; L is the length of the pipeline.

When a gas pipeline spans multiple earthquake intensity zones, the earthquake damage rate in different parts of the pipeline may be different. For this reason, this study divides the gas pipeline into N micro-element pipelines of length ΔL. ΔL being small enough, the earthquake intensity of the micro-element pipeline can be judged by the intensity zone which its midpoint in.

B. The Resilience Assessment Framework of Electric-gas System

(1) System-level resilience index

An earthquake may break out at any place and with any magnitude in the earthquake zone, so the decision maker must take all possible earthquake scenarios into account when making planning scheme. Each earthquake scenario will lead to different fault states of the electric-gas system, resulting in different load reductions.

The system-level resilience index R_{sys} is used to measure the system resilience under earthquake:

$$R_{sys} = \sum_{w=1}^{W} P_w E[Q_w] \tag{9}$$

where W is the set of potential earthquake scenarios; P_w is the probability that the earthquake occurred in earthquake zone is w; $E[Q_w]$ is the impact of the electric-gas system under the earthquake w, that is, the expected value of the minimum load reduction of the system under each fault state; Q_w is the sum of the electrical load reduction and the converted gas load reduction.

This paper uses the impact increment-based state enumeration method (IISE) to solve $E[Q_w]$. This method increases the weight of low-order fault states, thereby greatly reducing the impact of ignoring high-order states on calculation accuracy [7]. Based on the IISE method, equation (9) can be rewritten as:

$$R_{sys} = \sum_{w=1}^{W} P_w \sum_{j=1}^{J} \sum_{s\in\Omega_j} \left(\prod_{i\in s} pfail_{w,i}\right) \Delta I_{w,s} \tag{10}$$

where Ω_j is the failure scenario set of j order; J is the highest failure order enumerated by IISE method; $pfail_{w,i}$ is the failure probability of component i under earthquake w; $\Delta I_{w,s}$ is the impact increment of fault scenario s under earthquake w.

(2) Planning-oriented resilience assessment framework

Fig. 2 shows a schematic diagram of the resilience assessment framework of the electric-gas system under earthquake, where R_{set} is the setting upper limit value of resilience index.

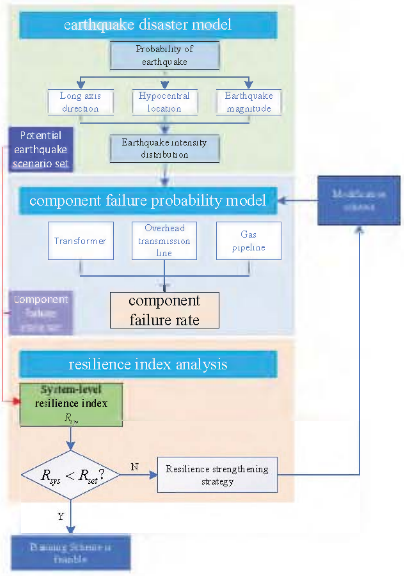

Fig. 2. resilience assessment framework of electric-gas system

It can be seen from the figure that the entire framework can be divided into three modules: earthquake disaster model, component failure probability model, and resilience index analysis.

IV. CASE STUDY

A. Case Scenario Introduction

In this paper, the electrical-gas system composed of IEEE RTS79 grid and the modified 14-node gas grid is selected as an example. It is assumed that four gas power plants are available in the electrical-gas system, and their installed capacity accounts for 41.06%. Fig. 3 shows the schematic diagram of the system for reference.

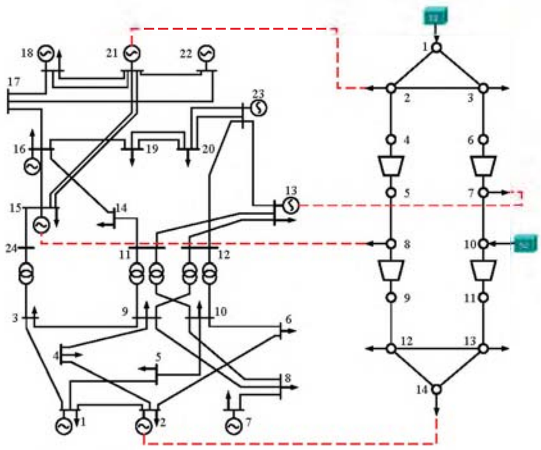

Fig. 3. Schematic diagram of the electric-gas system

The electric-gas system is attached to a constructed earthquake zone. The power and natural gas subsystems actually overlap each other, so their positions on the axes are shown in Fig.4 respectively.

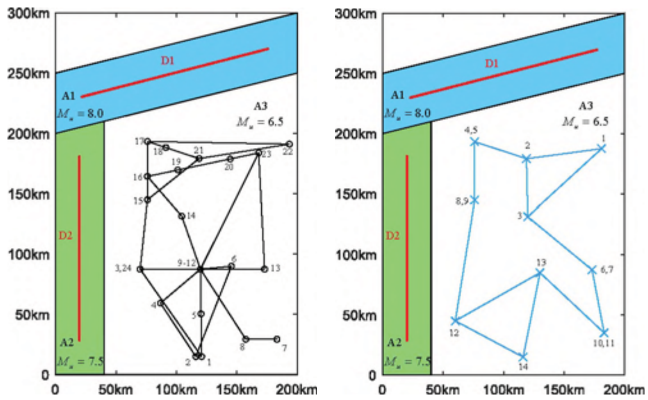

Fig. 4. Location diagram of the electric-gas system in the earthquake statistics area

As Fig. 4 shows, there are two active faults D1 and D2 as well as tectonic sources A1 and A2 distributed along D1 and D2 respectively in the rectangular earthquake zone measured as 200m×300m, while the remaining area is the background source A3.

It's assumed that the earthquake zone is located in the strong earthquake zone of qinghai-Tibet, China. Reference [8] gives the intensity attenuation parameters. Besides, the relevant parameters of component fault probability based on earthquake intensity are given in Table I.

TABLE I. COMPONENT FAULT PARAMETERS OF ELECTRIC-GAS SYSTEMS

fault parameter	earthquake intensity		
	6	7	8
Transmission tower failure probability	6.446E-05	5.040E-04	2.570E-03
Transformer failure probability	2.546E-06	7.027E-06	1.826E-04
earthquake damage rate of pipeline	0.0001	0.001	0.01

B. Resilience Analysis of Electrical-Gas System under Specific Earthquake Scene

An earthquake of magnitude grade $7.5 \sim 8.0$ is supposed to occur at point $(100, 230)$. Fig. 5 shows the location of the electrical-gas system in the earthquake intensity distribution diagram.

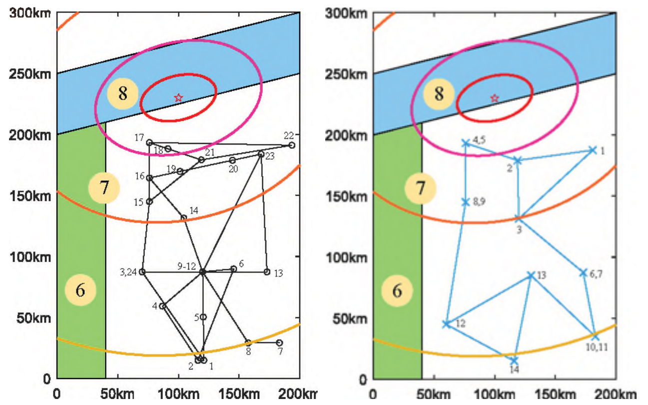

Fig. 5. Schematic diagram of seismic intensity distribution

(1) Calculation of Component Failure Probability

Set the tower spacing d as 100m and the micro-element pipeline length ΔL as 500m, then the failure probability of each type of component under earthquake can be figured out. Taking transmission line 13-23 as an example, the calculation process is as fallows:

The length of the transmission line 13-23 is 96.56km, and there are 203(n1) towers and 118(n2) towers located in the intensity zone 6 and intensity zone 7 respectively. These towers are connected in series, so the failure probability of transmission line 13-23 is given by the following equation:

$$pfail_{line}(13-23) = 1-(1-p_{I=6})^{n_1} \times (1-p_{I=7})^{n_2} \approx 0.07 \quad (12)$$

where $p_{I=6}$ and $p_{I=7}$ represent the tower failure probability in the intensity zone 6 and intensity zone 7 severally.

The calculation process of transformer and gas pipeline failure probability is quite similar to that of transmission line, which is not detailed here.

(2) Load Reduction Optimization Algorithm

Fig. 6 shows the load reduction optimization algorithm based on decoupled frame, in which the load reduction model of the electrical subsystem is solved by MATPOWER, while the load reduction model of the natural gas subsystem is calculated by the nonlinear solver.

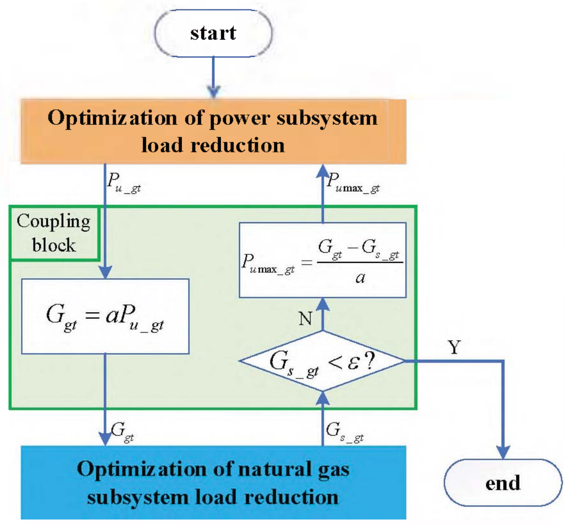

Fig. 6. Decoupling optimization framework for load reduction of electric-gas system

(3) The Solving of Resilience Index

In this paper, IISE method and traditional state enumeration method (SE) are compared in solving $E[Q_w]$. MCS is selected as standard results for comparison and the convergence criterion is set to 10^6 sampled failure scenarios. The calculation results are given in TABLE II, where SE2 and IISE2 respectively represent the result obtained by the IISE and the SE methods, which are based on a 2^{th} order of enumerated failure scenarios.

TABLE II. SYSTEM-LEVEL RESILIENCE INDEX UNDER THE SPECIFIC EARTHQUAKE SCENARIO

method	$E[Q_w]$ (MW)	error	calculating time(s)
MCS	9.629	-	71927.748
SE2	0.936	90.279%	115.446
IISE2	9.905	2.866%	116.081

It can be seen from Table II that IISE2 and SE2 require much less calculation time than MCS, while IISE2 has much higher calculation accuracy than SE2. IISE2 can give consideration to both speed and accuracy, so it is reasonable and efficient to choose IISE2 for calculation.

C. Resilience Analysis of Electrical-Gas System Considering Potential Earthquake Scenarios

In order to comprehensively consider all possible earthquake scenes in the earthquake zone, the epicenter location and magnitude grade are enumerated. Assuming that earthquakes may occur in (x_0, y_0), where $x_0 \in 0,1,2,...,200$ and $y_0 \in 0,1,2,...,300$. At each potential epicenter point, there are K magnitude grades to be enumerated, where $K = (M_u - M_0) / \Delta M$.

Obviously, the area of the latent focal region in equation (3) should be replaced by the number of the enumerated potential epicenter points in this region, so that the total probability of earthquakes in all enumerated points is equal to 1.

$E[Q_w]$ of all potential earthquake scenes can be calculated by IISE2, and the system-level resilience index R_{sys} is 0.08073. If R_{sys} exceeds the specified threshold, planners ought to take component reinforcement measures to reduce the resilience index.

V. CONCLUSION

The innovations of this paper are to build an earthquake model based on the three-level latent focal region division scheme and to solve the component failure probability according to the earthquake intensity distribution. In addition, a resilience assessment method of electric system under earthquake is proposed, and this method is applied to an example for verification.

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