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Impact Analysis of Seismic Events on Integrated Electricity and Natural Gas Systems

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Abstract—**Seismic events can cause devastating impacts on both overground and underground energy system infrastructure. This paper proposes a methodology to evaluate the impact of seismic events on the security of integrated electricity and gas system, mainly focusing on pipelines leakage and connection loss of electricity transmission lines. A stochastic model is used to formulate the damage level based on earthquake severity. The seismic impact on the integrated system is classified according to the levels of pipe leak and electricity line failure. Load curtailment due to limited generation capacity and overloaded transmission lines is thereafter quantified. Seismic intensity is generated randomly based on Monte Carlo simulation so that a certain seismic intensity can be related to relevant load curtailment. An integrated energy system with a 30-busbar electricity system and a 6-node natural gas network is used to demonstrate the effectiveness of the proposed method. The results clearly illustrate damage consequences under seismic events in terms of both probability and severity levels. This work can inform resilience enhancement scheme design based on the vulnerability performance and impact of both systems.**

Index terms—**Integrated electricity and gas system, Pipe leak, Seismic damage, transmission line outage.**

NOMENCLATURE

PGV	Peak ground velocity.
PGA	Peak ground acceleration.
G	Admittance matrix of gas pipes.
A	Connection matrix of the system.
P	Pressure matrix of gas nodes.
Q	Flow rate vector of gas nodes
EOD	Equivalent orifice diameter
t	Thickness of maximum possible annular space.
k	Annular disengagement constant of damaged pipes.
k_1, k_2	Local crack constant of pipe wall.
θ	Opening angle of damage orifice.
D	Diameter of the damaged pipe.
w	Width of split of damaged pipe.
P_i	The probability of *i* th leak scenarios.
d_i	Equivalent orifice diameter under the *i* th damage scenarios.
CHP	A Combined Heat and Power plant.
y	The efficiency of combined heat and power plant.
PG_{CHP}	The power output of CHP.
PG_{Gas}	The gas energy input of CHP.
CL	Connection loss of the power system under seismic stress.
D_{CL}	The damage expectation of connection loss.
CL_n	Connection loss of the worst damage state.
$P_{CL,i}$	Probability of the *i* th damage state.
CL_i	Connection loss of the *i* th damage state.
SF_n	The sensitive factor for branch flow over demand change.
$\Delta Branch\ i$	The changes of branch flow.
$\Delta Demand$	The changes of demand.

I. INTRODUCTION

THE interconnection of various energy vectors has widely grown in recent years, especially between electricity and natural gas systems. Many technologies, for instance, combined heat and power (CHP) unit, energy hub, and micro-grid enable the increasing combination of those two energy systems. In the meantime, due to the climate change, low probability high impact natural events could cause severe consequences to the interconnected energy systems. Any failure of the interconnections may lead to significant energy loss and the impact could propagate to the other networks. Therefore, the security of integrated electricity and gas system needs to be assessed.

Due to that seismic activities damage both overground and underground parts of energy systems, how integrated energy systems would behave and react regarding seismic activities should be taken into consideration. From the topological point of view, papers [1, 2] quantify the seismic impact on integrated electricity and gas systems in terms of connectivity loss, power loss and impact factor on affected population. Based on that, further research [3] shows that, compared to separate electricity and gas networks, the interdependency of gas and electricity system shows an increased vulnerability. Consequently, it can be concluded that in order to promote system security, the response and behaviours of integrated gas and electricity should be investigated with high priority.

Seismic modelling methods can be mainly categorized into three groups: direct methods, integral-equation methods, and asymptotic methods [4]. The first group refers to the mathematical expressions based on a numerical mesh [5-7], the second group is related to wave filed that oriented from point sources [8, 9] while the last group also considers wave filed but only approximates certain magnitude of seismic events [10-12]. In this paper, the intensity of seismic activities is modelled by wave propagation described as peak ground acceleration (PGA) and peak ground velocity (PGV). These variables are related to landslides, surface faulting and liquefaction-induced lateral spreading [13, 14]. It can be obtained that the higher the seismic level, the higher the PGA magnitude would be. The relationship between PGA, PGV and seismic intensity can be found in [15].

TABLE I
RANGES OF PGA, PGV AND SEISMIC INTENSITY

Intensity	Ⅰ	Ⅱ ~ Ⅲ	Ⅳ	Ⅴ	Ⅵ	Ⅶ	Ⅷ	Ⅸ
PGA (%g)	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124
PGV (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116

For typical gas networks, seismic activities mainly affect pipelines by causing gas leakage. This type of damage may not directly lead to destructions but would cause energy supply loss of gas generation due to insufficient supply. In fact, because of various types of forces, there is a large difference between the seismic response of buried pipes and above ground infrastructures [13]. In natural gas systems, ground movements normally result in pipeline leaks. To evaluate the leakage rate, paper [16] defines an equivalent diameter μ to describe gas leakage, which points out that general gas leakage usually varies from 0 to 10mm/m. Although simplified analysis procedures are analysed, the unduly amount of assumptions evolved may lead to inaccurate results. Thus, after modifying some assumptions, a modified analysed method for buried pipes underground motion is presented [17], in which various types of fault movements are investigated. Nevertheless, though the physical performance of buried pipelines is distinguished, how gas leakage can be correlated with seismic intensity is still not clear. Paper [18] takes gas supply networks as an example and designs a probability density evolution approach to evaluate the seismic reliability of networks. However, in this model, the connectivity reliability is obtained but ignored the gas flow conditions.

As for electrical systems, seismic activities significantly impede the security of generation plants, substations and distribution circuits. The destruction of these elements may result in a significant load loss [14, 19, 20]. To evaluate the regional economic loss of disturbed electricity lifelines, paper [6] proposes a seismic performance quantification scheme based on a linear programming model. This method enables an input-output analysis that can not only validate the economic loss but also contribute to loss mitigation. The intensity detection of a seismic explosion is realised with the air-shock wave impact of drilling and blasting operations on electricity power lines in paper [21]. However, more detailed considerations of electricity power lines structure, shock resistance should be applied regarding the impact of seismic explosion loads. In paper [22], the repair costs and system downtime are analysed based on MATPOWER. The drawback of this model is that only the vulnerability of transformers and plants are analysed while system branches are ignored. Referring to graph theory, a seismic vulnerability assessment strategy for interdependent critical systems is developed in paper [3]. The structural vulnerability is quantified by evaluating the seismic impact on population and energy supply. The shortcoming of this method is that the graph theory can only evaluate the structural vulnerability but ignores the change of power flows.

This paper designs a novel method to assess the performance of integrated natural gas and electricity systems under seismic stress. The connection loss of transmission lines and seismic leakage of gas pipelines is extensively assessed, where the first task is achieved by building a probabilistic model and the second is estimated by modelling several damage scenarios. It proposes a novel seismic damage quantification method considering both seismic losses caused by the lack of generation and demand curtailment while meeting network power flow constraints. The vulnerability of system branches is thereafter assessed, based on the analysis of each branch disconnection impact on load curtailment.

The main contribution of this paper is;

- This designed scheme specifies seismic damage by investigating the energy flow changes within the entire integrated energy system. Then, the seismic impact on system components and system functionality are clearly described. But existing research mainly concerns with connectivity loss based on graph theory and ignores damage to system components and functionality,
- Instead of investigating economic loss by building a simplified model for energy systems, this proposed scheme relates a certain intensity of seismic activities to a certain amount of load loss. Consequently, the damage caused by seismic stress is more precisely quantified.
- The load loss is estimated by decreased generation capacity caused by gas leakage and load curtailment while meeting transmission line capacity. It allows system operators to comprehend how seismic damage would affect energy system capability and integrity. In addition, it considers the seismic impact on both system generation and demand, thus fully examining the consequences on the whole supply chain.
- The weight of branches on system security is assessed by using an evaluation method. Based on that, system resilience can be enhanced by strengthening the most vulnerable branches, thus providing the possibility to design system strengthening strategies with lower budget but higher efficiency.

The rest of the paper is organized as follows: Section II investigates the seismic response of the gas network. In Section III, the response of electricity systems to seismic events is studied and in Section IV, a case study is presented. A discussion on substation is introduced in V. Section VI concludes this paper.

II. THE SEISMIC BEHAVIOUR OF GAS NETWORK

This section investigates the performance of gas pipelines under seismic events. A mathematical expression of pipe leakage is presented, in which the seismic damage is separated into two aspects: the damage quantity and damage quality. The first aspect can be related to different seismic intensity while the other aspect specifies the leakage rate. Consequently, a relationship between the gas leakage rate and the seismic intensity is established.

A. The damage to buried pipelines

To quantify the seismic loss of gas networks, a relationship needs to be established between the seismic intensity and overall pipeline leakage. In this paper, for the gas networks, the seismic behaviour is classified by three steps: Firstly, the seismic intensity is quantified and related to certain PGV. Subsequently, equation (1) allows the classification of how many damage holes would be generated by the seismic stress. Then, the expectation of the size of damage holes and how much the gas pressure P would be affected can be obtained. Consequently, the loss of flow rate Q can be found. In this paper, 5 damage scenarios are deployed to estimate the leakage loss.

To address gas leakage caused by the seismic stress, the relationship between the damage quantity, or damage ratio, and seismic intensity is classified first. Normally, the damage ratio of the gas network can be described by the damage rate, which represents the number of damage points per kilometres of pipelines within the entire system. According to paper [14], for ductile iron, the damage rate is classified by PGV as

$$Damage\ rate = \frac{\text{Damage points}}{\text{Km}} = 0.00003 \times (\text{PGV})^{2.25} \quad (1)$$

Thus, the intensity of seismic activities can be related to a certain damage ratio of a gas network.

B. The estimation of leakage amount

However, although the damage rate for overall pipelines is obtained, the gas leakage amount for each damage orifice on pipes still need to be investigated.

For typical seismic activities, the peak horizontal particle velocity is positively correlated with pipeline damage ratio [23]. Thus, the damage ratio can be assumed to grow linearly as the intensity of seismic stress increases. Normally the gas flow within a pipeline can be classified as,

$$AGA^TP + Q = 0 \quad (2)$$

Where G is the admittance matrix of gas pipes, A is the connection matrix of the system, P is the pressure matrix of gas system node, and Q is flow rate vector of nodes.

However, to model the gas pipeline leakage, a general hydraulic method would require many unknown variables to quantify the leakage loss, for instance, the pressure drop, outlet flow and inlet pressure. Even if the inlet pressure is assumed to be constant, there would still be an unduly number of unknown variables [24]. Thus, instead of classifying pressure variation due to seismic damage, this paper maintains the leakage loss by investigating the equivalent orifice diameter (EOD) of damaged pipes. A leak damage expectation based on EOD analysis would be specified regarding the probability of various leakage scenarios.

For standard buried pipelines, seismic stress mainly causes five types of damage: annular disengagement, round crack, longitudinal crack, local crack of the pipe wall and local tear of the pipe wall. The EOD of damaged pipe regarding different scenarios can be derived as [25],

$$d_1 = 2\sqrt{tkD} \quad (3)$$

$$d_2 = 2\sqrt{\theta D} \quad (4)$$

$$d_3 = 2\sqrt{LD\theta/\pi} \quad (5)$$

$$d_4 = 2\sqrt{k_1k_2D} \quad (6)$$

$$d_5 = 2\sqrt{kwD} \quad (7)$$

Where d_1, d_2, d_3, d_4, d_5 are the EOD for these five scenarios respectively, D is the diameter of the damaged pipe, θ is the opening angle, L is the length of the crack and can be taken as the length, w is the width of split and t, k, k_1k_2 are constant that set as 10~16 mm, 1% and 5% respectively. Because the opening angle θ and width of split w are largely determined by pipeline material, their values are set to 0.1° and 12 mm from observations.

The probabilities of that 5 damage scenarios regarding different pipe materials are shown in table 2. For each type of pipe, the possible damage scenarios are listed with its probability. Subsequently, the overall expectation of EOD for a single pipe leak would be,

$$EOD = \sum_{i=1}^{n=5} P_i d_i \quad (8)$$

Where P_i refers to the probability of different leak scenarios, d_i is EOD under the five damage scenarios.

TABLE II
THE PROBABILITY OF LEAK SCENARIOS FOR PIPELINES OF VARIOUS MATERIALS [25]

Pipe Material	Annular disengagement	round crack	longitudinal crack	Local loss of pipe wall	Local tear of pipe wall
Cast Iron	0.3	0.5	0.1	0.1	N/A
Ductile Iron	0.8	N/A	0.1	0.1	N/A
Riveted Steel	0.6	N/A	0.3	0.1	N/A
Welded Steel	N/A	N/A	N/A	N/A	1.0
Joint Concrete	1.0	N/A	N/A	N/A	N/A

Hence, a specific relationship is established between the seismic intensity and general natural gas loss. When the diameter and material of pipelines are classified, the gas leakage can be obtained accordingly.

C. The coupling of electricity and gas system

In this paper, the electricity system and gas network is integrated by a single transportation pathway. A Combined Heat and Power plant (CHP) is assumed to be installed in the gas network to convert gas to electricity at node *C*, and its efficiency would be PG_{CHP}, the power output of CHP, over PG_{Gas}, the gas energy input of CHP.

$$y = \frac{PG_{CHP}}{PG_{Gas}} \quad (9)$$

III. SEISMIC RESPONSE OF ELECTRICITY SYSTEM

This section designs a seismic loss estimation methodology for electricity systems, which mainly considers the seismic damage to lines. A probabilistic model of loss expectation regarding each level of seismic arrack is proposed. Then, the system performance quantification schemes are developed.

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A. Connection Loss

Although the seismic behaviour of various types of electricity infrastructures have been assessed, a scheme that quantifies the performance of overall systems is desirable to address the power flow change within the entire system. For electricity systems, seismic events mainly affect its functionality by damaging components such as generation plant, substation and distribution circuits. This scheme mainly considers the seismic damage on distribution branches, as it's the key feature to establish reliable energy supply and satisfy customer demand. generally, seismic events disturb distribution branches by shaking pylons and destroying conductors, and thus the connection cables can be considered as the most vulnerable targets of the transmission system that faces seismic threats.

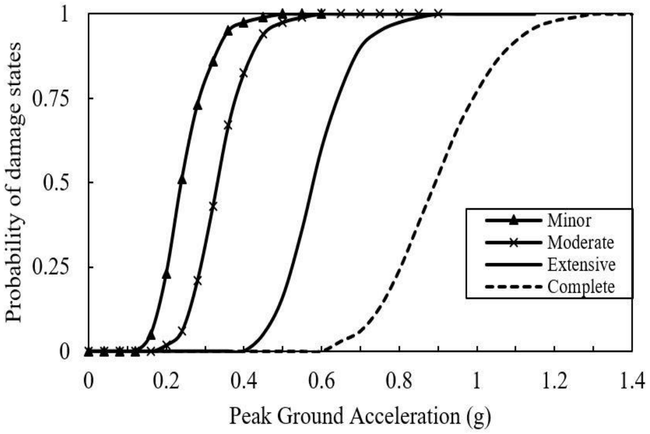

Fig. 1. Fragility curve of transmission lines

As shown in figure 1, paper [14] provides a probability model of the electricity system under earthquake attacks. Based on statistical analysis, this scheme concludes the seismic impact on distribution branches into four damage stages: minor damage $d1$, moderate damage $d2$, extensive damage $d3$, and the complete destruction $d4$. Consequently, for a given level of ground acceleration, these curves in Figure 1 describe the probability of reaching or exceeding each damage state. For distribution branch, each damage state refers to a certain level of connection loss. $d1$ refers to 4% connection loss (CL), $d2$ refers to 12% CL while $d3$, $d4$ represents for 50% CL, 80% CL respectively. Subsequently, for the same PGA, more severe damage states correspond to the lower probability of occurrence [1].

TABLE III
DAMAGE ALGORITHM FOR THE ELECTRICITY SYSTEM

Damage state	Median(g)	β
slight/minor	0.28	0.30
moderate	0.40	0.20
extensive	0.72	0.15
complete	1.10	0.15

Although each level of seismic stress is related to a certain distribution of damage states, a damage expectation is necessary to obtain a certain percentage of transmission loss due to seismic events.

B. Damage Expectation of connection loss of electricity systems

TABLE IV
SEISMIC DAMAGE TO THE ELECTRICITY SYSTEM

Damage state	Loss estimation	
	Connection loss (CL)	***Probability***
Slight	4%	P_1
Moderate	12%	P_2
Extensive	50%	P_3
Complete	80%	P_4

To establish the overall CL for a certain level of PGA, the damage expectation should be determined. However, the four damage states are not completely independent. Because a more severe damage state contains lower damage stages, the damage expectation D_{CL} can be characterised as,

$$D_{CL} = P_n CL_n + \sum_{i=2}^{n-1} \left(P_{CL,i-1} - P_{CL,i}\right) CL_{i-1} \tag{10}$$

Where i∈ $[15 \ldots, n]$ refers to four damage states.

Thus, if the magnitude of PGA is specified, the failure rate of branches within the entire system can be obtained properly.

C. Load Loss Estimation

Due to seismic stress, line failures would significantly affect energy system security, especially the problem of unbalanced energy generation and demand. Referred to unsatisfied load demand, necessary load curtailment should be considered.

Thus, this scheme mainly considers load curtailment in two aspects: Firstly, the decrease of generators' capacity caused by gas leakage and isolated power plants would lead to unsatisfied load demand. Secondly, when a line failure occurs, other lines would be overloaded due to increasing power flow. Thus, proper load curtailment is conducted to relieve the overloading. This paper curtails load that cannot be satisfied based on each demand sensitivity factor to a system component. The demand sensitivity factor can be classified as,

$$SF_n = \frac{\Delta Branch\ i}{\Delta Demand} \tag{11}$$

Where $\Delta Branch\ i$ is the power flow fluctuation along the branch i while $\Delta Demand$ represents for the amount of the curtailed load.

D. The implementation process

The overall implementing steps of this seismic damage assessment scheme for integrated electricity and gas system is illustrated in figure 3. For a given level of seismic events, the PGA and PGV are explicit values, and subsequently, the leakage rate and the number of failure branches can be obtained. The locations of gas leakage and failure electricity branches are randomly selected. The integrated power flow within the entire network is then conducted to determine load curtailment. Due to the overloading transmission lines and limited generation capacity, proper load curtailment strategies should be employed related to a certain intensity of seismic activities. Furthermore, a resilience enhancement strategy for system branches would be proposed based on the analysis of loss load due to transmission lines' outage. Subsequently, the implementation steps can be specified as,

1. Generating seismic intensity randomly

2. Maintaining the pipeline leakage loss and connection loss within the natural gas network and electricity system respectively.
3. Classify reduced generation capacity including both CHP output and power plant.
4. Determine the load curtailment due to decreased generation capacity and overloading transmission line.
5. Relating the amount of load curtailment to the intensity of generating seismic activity.
6. The vulnerability assessment of transmission lines.

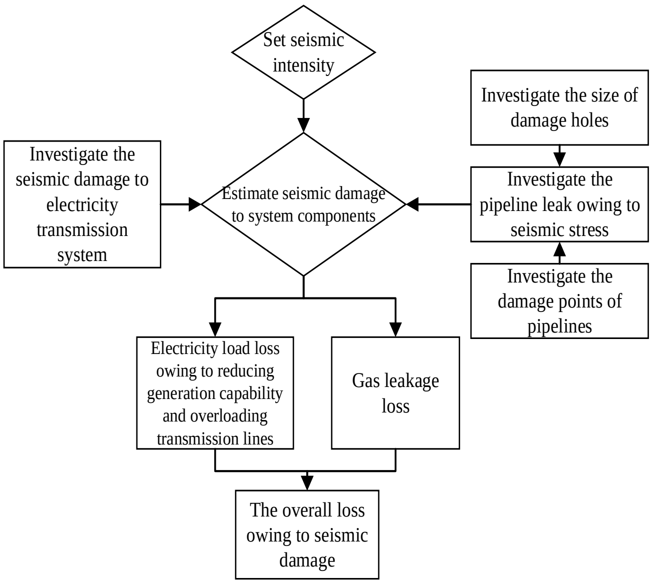

Fig. 2. Implementing steps of seismic damage.

Ⅳ. CASE STUDY

A. The test system

In this section, a combined 6 nodes gas network and IEEE 30 busbars electricity network is used for demonstrating the developed model. As shown in figure 3, the gas network contains the main gas supply, 4 demand nodes and 7 pipelines. A gas-fired CHP *C* is located at node *C* of the gas network and then connected to busbar 2. The efficiency of gas-fired generation deployed at busbar 2 is set to 80%.

The Monte Carlo simulation is conducted 10000 iterations to simulate the performance of the integrated system under seismic damage, regarding the randomly generated intensity of seismic activity. During each iteration 1) for the gas network, the pipe leakage is generated, randomly at the pipes in the system, and thus the generation of this gas supply can be determined. 2) For the electricity system, the expected line loss ratio can be calculated by equation (10) under the simulated seismic intensity. The lost lines are randomly selected from the 41 branches. Thus, the system power flow changes and lost loads can be accordingly quantified. Furthermore, the importance of each branch will be illustrated by a box plot figure, which compares each branches' disconnecting impact within all the simulations.

Table 5 shows the original demand of system electricity bus bars, the overall original load would be classified as 189.2 MW. Loss load assessment would then be distinguished and investigated in the following analysis.

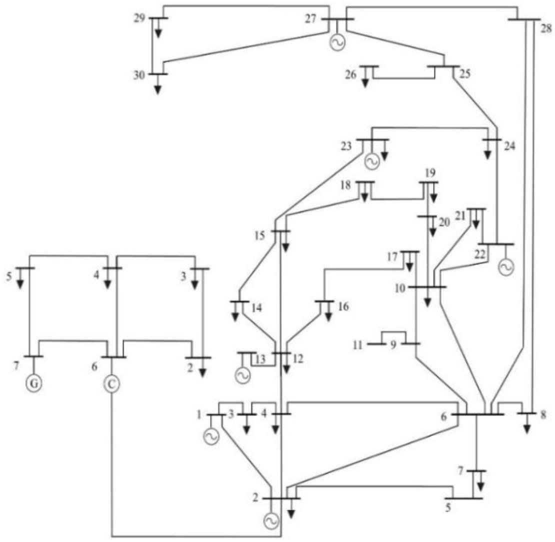

Fig. 3. The test system

As for the gas network, its demand nodes 2, 3, 4 and 5 are set with maximum gas flow mode (generating as much as the substation can to satisfy those load demand), in which their gas demand (50, 100, 150 and 100 MW) would be satisfied at any time. The gas supply obtains a fixed capacity that equals to 600 MW. Subsequently, to minimise the decline of gas transferred to electricity, the CHP at node *C*, which has 200 MW original demand, is operated under Max pressure mode.

TABLE V
ORIGINAL LOAD DEMAND

Bus No	Demand (MW)	Bus No	Demand (MW)
2	21.7	**17**	9
3	2.4	**18**	3.2
4	7.6	**19**	9.5
7	22.8	**20**	2.2
8	30	**21**	17.5
10	5.8	**23**	3.2
12	11.2	**24**	8.7
14	6.2	**26**	3.5
15	8.2	**29**	2.4
16	3.5	**30**	10.6
		Total	189.2

B. Result analysis

In this section, the sampled seismic intensity is set to Ⅷ, thus PGA is 0.45g (45%g) and PGV is 60 cm/s. Considering equation (10), since each PGA can be related to a certain probability of several damage states, the damage expectation of CL is then classified as 12.5% of 41 branches (5.125), which indicates the number of failed transmission lines is 5. Hence, 5 failure lines are randomly selected from 41 branches. In addition, another variable that is affected by seismic damage is the generation of CHP output. For the seismic intensity of 60 cm/s, the damage rate among the gas network is determined as 0.00003. If the overall length of gas pipes is

3.5 km, there will be 1 damage point. The locations of gas leaks are randomly generated among all gas pipelines. Assume all pipes within the gas network are constructed by Ductile Iron, based on the probabilities of that 5 damage scenarios, the damage expectation of EOD can then be estimated as 5cm. Subsequently, system leakage loss due to seismic damage is maintained based on *Pipeline Studio*, a pipeline analysis software that can model a wide range of steady-state and transient analysis of pipe systems. Based on the Benedict-Webb-Rubin equation, the hydraulic analysis function of natural gas and the liquid pipeline is employed.

TABLE VI
OUTFLOW OF GAS NETWORK DUE TO SEISMIC DAMAGE

Components	Mode of control	Pressure (BARG)	Flow (MW)
CHP6	Max pressure	110	62.3~69.8
Gas demand2	Max flow	109.3	50
Gas demand3	Max flow	109.4	100
Gas demand4	Max flow	109	150
Gas demand5	Max flow	109.9	100
Leak	Leak sim	109.1	130.2~137.5
Supply7	Max flow	109.4	600

As shown in Table 6, the gas leakage varies from 130.2 MW to 137.5 MW, consequently, the energy transferred from gas to electricity would be 49.84~55.84 MW. Since the busbar 2 within the electricity system maintains a 12 MW's capability, the overall generation in busbar 2 would be 61.84~67.84 MW. For instance, the upper left figure converges in the area with the highest density, which is between -20~0 MW, and this interval can be seen as the effect of 0.45g seismic activity. However, the results indicate that owing to the seismic activities, the power flow carried by system branches can maintain an extreme value that may reach the limit of its capacity. Thus, the main reasons for the extreme value are: i) Although only 5 transmission lines have failures, most remaining branches are not effective enough to satisfy load demand: ii) Some branches could obtain more power flow when the directions of power flows on other branches reverse.

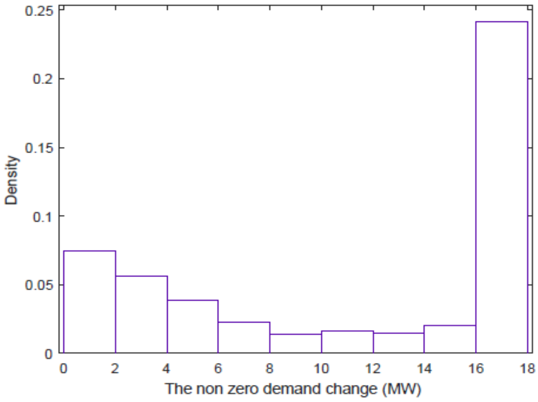

Fig. 4. The non-zero demand change for bus 21

Thus, the conclusion is that some of the system branches could be required to satisfy more demand when seismic damage occurs. Subsequently, when this condition happens, overloading transmission lines would be generated, and the necessary load curtailment scheme should be applied to meet the transmission lines' capacity limit.

A sample demand change that related to overloading transmission lines and the shortage of generation capacity is illustrated in figure 4. This figure illustrates the PDF of the quantity of none zero load curtailment (changeless conditions removed) on bus 21 in 10000-time simulation, in which *x* axis refers to the amount of its demand change while *y* axis is the probability density among 10000-time simulation. When proper load curtailment is employed, the power demand curtailment on bus 21 can be generally assessed as higher than 16 MW, which is nearly 100% of its overall demand. The relatively high probability for bus 21 to completely lose its demand (17.5 MW) indicates the high possibilities for its load gets completely curtailed owing to seismic activities.

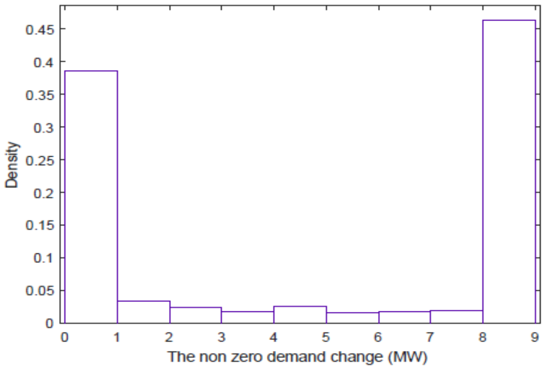

Fig. 5. The non-zero demand change for bus 24

Same as figure 4, figure 5 shows the overall non-zero demand change (changeless conditions removed) for bus 24. As the result illustrates, load curtailment between 8~9 MW maintains a higher occurrence. Although the most likely demand curtailment for bus 24 is 8.9 MW, its demand curtailment lower than 1 MW has a high probability as well. The reason for that case can be there is a high probability for bus 24 gets completely isolated from the main grid while line failures may only obtain a minor impact on it.

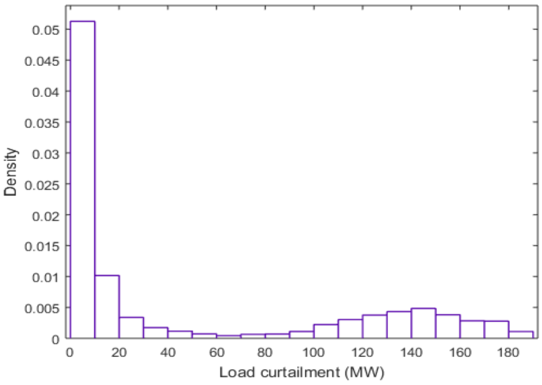

Fig. 6. The lost load for the whole system under seismic intensity VIII

To conclude the seismic impact on the integrated electricity and gas system, the lost load is assessed by summarising load curtailment. As shown by figure 6, for seismic activities that maintain Ⅷ intensity, the expectation interval of load curtailment would be 46.25~48.73 MW, which indicates that there would be the highest possibility for this system to have load curtailment of 46.25~ 48.73 MW.

Figure 6 also illustrates that, since there is also a high probability for a zero load curtailment condition, the probability for this integrated system to maintain its full

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functionality is relatively high. The states that represent the loss load between 10 and 20 MW have a relatively high chance, which may relate to the contribution of the isolated load. When load isolation occurs, the load would be considered as completely lost. Nevertheless, this condition may occur more frequently than predicted, and in that case, the quantity of loss load would vary from 3.2 MW to 30 MW, which leads to a downward trend between 0~30 MW. There is another peak of 100~180 MW, and in that case, the majority of system load get curtailed, this system will be divided into several islanded networks. Because this paper mainly refers to the distribution circuit, the islanded networks would be seen as completely lost. Moreover, regarding the whole system, the most possible load curtailment due to isolated networks would be around 140 MW.

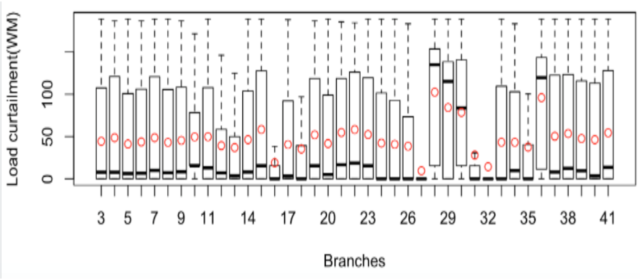

Fig. 7. The loss load due to branch outage

Since 5 branches are disconnected in each simulation, the load curtailment related to each branch disconnection can be identified. Figure 7 is a box plot that compares load curtailment for every faulty transmission line. Red marks represent average values while black lines describe the median values. The outliers have been removed. It can be observed that branches 28, 29, 30 and 36 contribute to the highest load curtailment far larger than other. Consequently, branches 28, 29, 30 and 36 can be seen as the most vulnerable transmission lines in this system. Besides, for most remaining transmission lines, the median of their load curtailment obtains similar values, which indicates that these branches may have a similar contribution to system security.

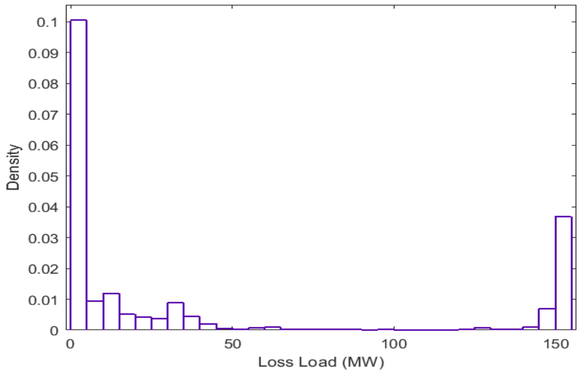

Fig. 8. System lost load under the seismic intensity of VI

When seismic intensity is set to Ⅶ (0.30g), the CL would be 50%×4%+25%×12%=5% of 41 branches. This indicates that the failure of 2 lines would be generated by a seismic attack. Regarding the gas network, since PGV is between 16-31 cm/s, the damage points of pipelines would be less than 1. Consequently, the gas pipeline network is assumed to have no damage. Fig. 8 shows the electricity load loss under Ⅶ seismic stress, where the results can be divided into two categories: 1) minor loss case from 0-50 MW, 2) severe loss load case from 145-155MW. In the minor case, the most likely expectation interval is between 7.63-9.98 MW while for the severe case, the most likely expectation interval is between 152.34-155.01MW.

C. Multi connection case

Since the previous test system integrates the electricity and gas system only by a single connection, this section provides a more realistic test case with more interconnections. As shown in figure 9, three CHPs are installed at the Gas nodes 2, 6, 3 to convert energy from gas to electricity, subsequently, they are operated under Max pressure mode.

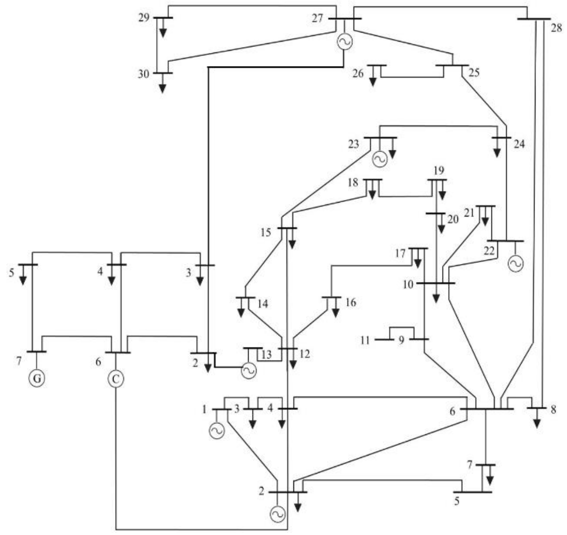

Fig. 9. The test system with Multi internal connections

For seismic stress with intensity Ⅷ, the overall loss load is shown in figure 10. The confident interval of load curtailment is classified as 68.52~71.03 MW. Thus, the most possible load loss for this system can be seen as between 68.52~71.03 MW. Comparing to the test system with a single interconnection, this system seems more vulnerable to seismic stress. The reason for that is probably that more interconnections between the two systems allow a more severe mutual effect under seismic stress.

Similar to figure 8, Figure 11 indicates that the most vulnerable branches are branch 16, 28-33 and 36. Those branches near to interconnections between the electricity and gas system are extremely vulnerable (such as branch 16, 36). Comparing to the result of a single connection case, more branches behave vulnerably to seismic stress and the estimated overall load loss is much higher. This may indicate that more interconnections between electricity and gas system may lead to higher vulnerability.

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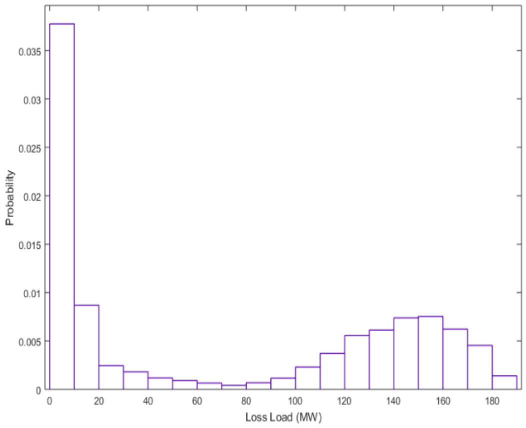

Fig. 10. The lost load for the whole system

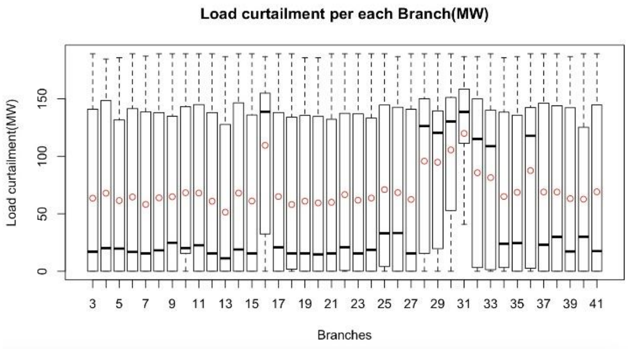

Fig. 11. The lost load due to branch outage

A brief case study on substations is added here. By assuming the distance between seismic epicentre and different substations are all the same, then all the substations would experience a PGA of 0.45g. After 10000 times of Monte Carlo simulation, the PDF of load loss is given in figure 12. The results can be categorised into two kinds: 1) minor loss case from 0-60 MW, 2) severe loss load case from 140-180MW. In the minor case, the most likely expectation interval is between 25.38-27.93 MW and for the severe case, the most likely expectation interval is between 167.93-171.43MW.

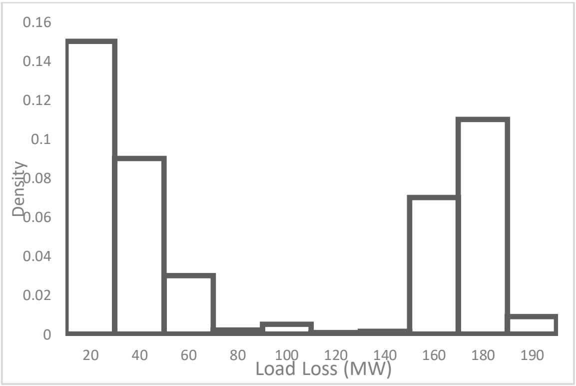

Fig. 12. The lost load due to substation damage

V. DISCUSSION ON SUBSTATIONS AND POWER PLANTS

As there are so many types of substations, over-ground, pole mounted and underground, they should be differentiated modelled in examining seismic attacks. For a generic substation, the state-of-art research takes transformers and bushings as the most critical elements. Finite-element analyses indicate that the interaction between these two critical elements has a significant effect on seismic vulnerability of substations [1, 2]. Thus, there are three steps to assess substation vulnerability under seismic stress. Firstly, the vulnerability of transformers and bushings within different types of substation can be investigated. Then, substations are modelled as branches but with different fragility curves compared to real branches. Finally, the position of seismic epicentre and its PGA logarithmic attenuation is considered regarding substation locations. Divided into four different damage states by HAZUS MR4, the fragility curve of High Voltage substations raises rapidly with rising PGA.

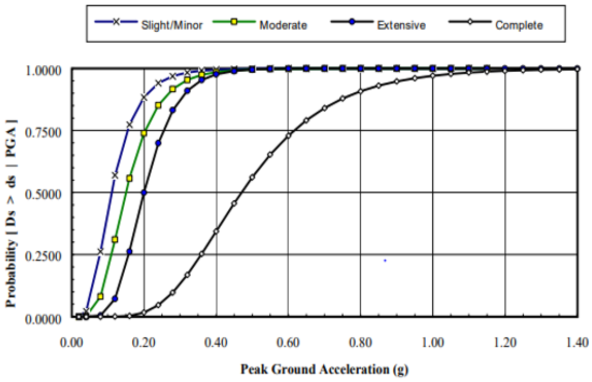

Fig. 13. The fragility curves for high voltage substations [14]

Similar to substations, there are many types of power plants with completely different physical features. Traditional generation plants, such as coal and natural gas, they are big in geographical size with numerous components, cooling tower, turbine, generators, and structural constructions. Hydropower plants are built within dams, which are normally very resilient to seismic attacks. For renewable generation, such as wind farms and solar farms, their features are different from the traditional generation. Wind farms are vulnerable to seismic attacks, as wind turbines can be analogue to pylons. However, considering the completely different physical features, there is no one general method that can be applied to all of them. Expensive research should be conducted into each type of with reliable data.

Ⅵ. CONCLUSION

In this paper, a statistic model of seismic activity is developed and applied to integrated electricity and natural gas systems. It considers the impact of seismic events on both electricity transmission line and gas pipes, quantified in terms of load loss. the key findings are:

- The damage caused by seismic attacks can cause certain load loss of the integrated electricity and gas system. Thus, system security can be enhanced by applying proper strengthen strategies.
- For short pipelines in gas networks, seismic intensity lower than Ⅶ may not cause direct load loss but with increasing length, the consequence would become severe.
- For systems with more interconnections between electricity and gas, severer load loss is caused by Ⅷ level seismic events, which indicates more interconnections may lead to higher vulnerability. It is due to due to the cascading impact of failures.

This paper mainly focuses on the fragility of transmission lines, but the framework can be easily applied to other network assets, such as substations, which will be further explored in our future research. This research can help system operators to assess the performance of their integrated energy systems under seismic attacks and thus they can deploy proper branch strengthening schemes and measures to enhance the system resilience.

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