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Identification of Vulnerable Components In Integrated systems Under the Background of Resilience

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***Abstract*—Under the background of the resilience of integrated systems, the identification of vulnerable components is of great significance to the operation of integrated systems when they are exposed to extreme weather. This paper proposes a method to identify the vulnerable lines and natural gas sources considering the interdependency of power systems and natural gas systems. A transient-state-based integrated system model is constructed firstly to more accurately describe the system model. Then the vulnerability factors are designed to reflect the impact degree of outages of natural gas sources on the vulnerability of lines of power grids. In light of complex network theory, the topological and operational vulnerability index is further presented to evaluate the resilience of integrated systems. Furthermore, network efficiency and system transmission efficiency are adopted to measure the impact of line outages and natural gas malfunctions on the integrated system to verify the identified vulnerable lines. Finally, a case study composed of the IEEE 30-bus system and a 20-bus Belgian gas network is utilized to illustrate the effectiveness of the proposed model.**

Keywords*— resilience, integrated systems, vulnerability identification, complex network theory

I. INTRODUCTION

As the increasing penetration rate of gas-fired generation and power to gas(P2G) devices[1], the interdependency of electricity and natural gas renders it necessary to take the mutual impact of different systems into account. Many blackouts happen in power systems are due to the impact delivered from another energy system, e.g., in 2021, the main cause of the Texas blackout lies in the insufficient natural gas supply due to freeze-offs of wellheads, which, in turn, resulted in a shortage of fuel on the power system side[2] In the context, embedding the impact of natural gas systems into the analysis of the reliability and resilience of power systems is demanding.

Resilience is generally-accepted defined as “the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event”[3]. Several instances of extreme natural disasters necessitate a transfer from the reliability-based integrated system operation to a resilience one for the operators. Power systems are elaborated planned and operated to resist random outage of any one or two components, called N-1/N-2 criterion, but under extreme weather, multiple components can be malfunctioning simultaneously. Under such circumstances, resilience is utilized to measure the capability to hedge against extreme weather.

The identification of vulnerable components is one of the key steps to assess the resilience of a system. Many works of literature have been carried out on the identification of vulnerable components in power systems. In [4]-[6], transmission lines with topological vulnerability are dynamically identified from the perspective of the network topology. [7]-[9]has been devoted to constructing various characteristic indicators to assess the vulnerability of nodes or lines. From the perspective of system operation, [10][12] establish vulnerability identification models in virtue of the notion of “entropy of power flow”, which can reflect the distribution of power flow to some extent.

However, all of the aforementioned literature merely identify vulnerable components in power systems. Little research has focused on the integrated operation and interdependent impact of multiple energy systems considering the transient characteristic of gas flow. To fill the research gap, a vulnerability identification framework composed of a topological vulnerability index, operational vulnerability index as well as the verification method considering different types of attacks, is proposed based on the transient-state gas flow model(TSGF). With an elaborated case study, the effectiveness of the proposed method is further proved.

II. THE OPTIMIZATION MODEL OF INTEGRATED SYSTEMS WITH THE TRANSIENT-STATE MODEL

In this section, the optimization model of integrated systems with transient-state gas flow is introduced. The objective of this model includes the sum of operation and load shedding costs. And the constraints are composed of the operational limits from both power grids and natural gas networks [13].

A. Objective

The objective developed takes the sum of natural gas consumption cost, consumption cost of conventional units in power systems, and load shedding cost.

$$\min \sum_{i=1}^{N_g}(C_{g,i}^p(A_{g,i})+C_{g,i}^s(\Delta A_{g,i})+\sum_{j=1}^{N_e}(C_{e,j}^p(P_{e,j})+C_{e,j}^s(\Delta P_{e,j}) \quad (1)$$

Where $C_{g,i}^p(\bullet)$ and $C_{g,i}^s(\bullet)$ denote the natural gas consumption cost function and gas shedding cost function respectively. $A_{g,i}$ and $\Delta A_{g,i}$ represent the amount of natural gas supply and curtailment magnitude at node *i*. And $C_{e,i}^p(\bullet)$ and $C_{e,i}^s(\bullet)$ are the generation cost and load shedding cost, while $P_{e,i}$ and $\Delta P_{e,i}$ express the amount of the electricity output and curtailment. N_g and N_e each records the nodes of the natural gas network and power systems.

B. Constraints

The constraints constructed in this paper can be divided into two types: constraints lie in power systems and constraints are about natural gas systems.

(1) Constraints in Power Systems with DC power flow(DCPF)

Firstly, we discuss the constraints that are concerning about power systems, as shown in (2)-(5):

$$P_{c,j}+P_{gas,j}-L_{c,j}+\Delta L_{c,j}-P_{in,j}=0 \quad (2)$$

$$Q_{c,j}+Q_{gas,j}-Q_{c,j}+\Delta Q_{c,j}-Q_{in,j}=0 \quad (3)$$

$$P_{in,j}=V_j\sum_{k=1}^{N_e}V_k(G_{jk}\cos\theta_{jk}+B_{jk}\sin\theta_{jk}) \quad (4)$$

$$Q_{in,j}=V_j\sum_{k=1}^{N_e}V_k(G_{jk}\sin\theta_{jk}-B_{jk}\cos\theta_{jk}) \quad (5)$$

$$V_j^{\min}\le V_j\le V_j^{\max} \quad (6)$$

$$P_{c,j}^{\min}\le P_{c,j}\le P_{c,j}^{\max} \quad (7)$$

$$Q_{c,j}^{\min}\le Q_{c,j}\le Q_{c,j}^{\max} \quad (8)$$

$$P_{Gas,j}^{\min}\le P_{Gas,j}\le P_{Gas,j}^{\max} \quad (9)$$

$$Q_{Gas,j}^{\min}\le Q_{Gas,j}\le Q_{Gas,j}^{\max} \quad (10)$$

Where Eq.(2) and Eq.(3) represent the nodal active and reactive power balance of the power system, respectively. Eq.(4) and Eq.(5) denote the active and reactive power injection equation. $P_{gas,j}$ and $Q_{gas,j}$ are the active and reactive power generated by the gas-fired unit. And $P_{in,j}$ $Q_{in,j}$ are the active and reactive power of the node j. V_j is the magnitude of the voltage of the node j. θ_{jk} is the angle difference between the node j and the node k.

(2) Constraints in Natural Gas Systems with Transient-State Gas Flow(TSGF)

Constraints in natural gas systems mainly comprise of nodal gas flow balance, nodal gas flow injection balance, relation equation between pipeline flow rate and node pressure, and compression equation about compressor respectively, as shown in:

$$A_{g,i}-A_{gas,i}-L_{g,i}+\Delta A_{g,i}-A_{in,i}=0 \quad (11)$$

$$\frac{4R\cdot\psi\cdot\rho_n}{\pi\cdot d^2}\cdot(A_{in,i}-A_{in,k})+\frac{1}{z_s}(\frac{\pi_i+\pi_k}{2})=0 \quad (12)$$

$$P_{gas,j}=\eta_{g2p}A_{gas,i}G_{HV} \quad (13)$$

$$\frac{\pi_i^2-\pi_k^2}{2\cdot l}+\frac{32v^2\rho_n^2}{F^2\pi^2d^5}\cdot\tilde{A}_{ik}\cdot|\tilde{A}_{ik}| \quad (14)$$

$$h_{ik}=b_{ik}f_{ik}[(\frac{\pi_i}{\pi_k})^{z\left(1-\frac{1}{r}\right)}-1] \quad (15)$$

$$\tau_{ik}=a+bh_{ik}+c_{ik}^2 \quad (16)$$

$$A_{g,i}^{\min}\le A_{g,i}\le A_{g,i}^{\max} \quad (17)$$

$$\pi_i^{\min}\le\pi_i\le\pi_i^{\max} \quad (18)$$

$$C_{ik}^{\min}\le\frac{\pi_i}{\pi_k}\le C_{ik}^{\max} \quad (19)$$

$$0\le\Delta A_{g,i}\le A_{g,i} \quad (20)$$

$$0\le\Delta P_{e,j}\le P_{e,j} \quad (21)$$

where $A_{gas,i}$ is the amount of natural gas consumed by the gas-fired unit. $L_{g,i}$ is the gas load located at node *i*. $A_{in,i}$ is the amount of gas injection at node *i*. f_{ik} and τ_{ik} are the gas flow through the pipeline and consumed by the compressor respectively. η_{g2p} is the generation efficiency of the gas-fired unit. G_{HV} is the heat rate of natural gas. M_{ik} is the pipeline transmission parameter. b_{ik} is the compression constant. *z* and *r* are the compressor coefficient and heat coefficient respectively. *a*, *b* and *c* are the consumption coefficients of the compressor. $C_{ik}^{\min}$ and $C_{ik}^{\max}$ are maximum and minimum compressor rates. R is the gas constant. ψ is the pipeline temperature; d is the diameter of the pipeline, and l is the distance of the pipeline. $\tilde{A}_{ik}$ is the average flow in the pipeline, v is the travel velocity of gas flow, and F is the fanning transmission gas factor.

III. Identification of Vulnerable Components

A. Vulnerability Factors

In this paper, three types of vulnerable indices are constructed, categorized by the coupling vulnerability factor, the topological vulnerability factor, and the operational vulnerability factor.

1) The coupling vulnerability factor

When the gas source *s* malfunctions, we denote that the power flow on the transmission line *k* is $PF_{k,s}$ and the change of power flow is shown as (22):

$$\Delta PF_{m,s}=|PF_{m,s}-PF_{m,0}| \quad (22)$$

Where $PF_{m,0}$ implies the power flow on the line *k* before the gas source *s* is malfunctioning.

And the sum of the change of power flow on all lines is shown as :

$$\Delta PF_m = \sum_{m=1}^{N_{pl}} | PF_{m,s} - PF_{m,0} | \tag{23}$$

And the power flow change ratio is defined as:

$$R_{m,s} = \frac{\Delta PF_{m,s}}{\Delta PF_m} \tag{24}$$

Then we define the power flow distribution entropy as:

$$H_m = \sum_{m=1}^{N_{pl}} -R_{m,s} \ln R_{m,s} \tag{25}$$

N_{pl} represents the number of transmission lines in power systems. H_s can reflect the impact of gas source outage on the distribution of power flow.

Based on the (25), we can further define the gas source vulnerability factor as:

$$V_s = \frac{\Delta PF_s}{H_s} = \frac{\sum_{m=1}^{N_{pl}} | PF_{m,s} - PF_{m,0} |}{\sum_{m=1}^{N_{pl}} -r_{m,s} \ln r_{m,s}} \tag{26}$$

After the normalization of V_m , we can define the coupling vulnerability factor of the power line *m* as:

$$V_1(m) = \sum_{s=1}^{N_s} \overline{V_s} \Delta PF_{m,s} \tag{27}$$

where N_s represents the number of natural gas sources, $\overline{V_s}$ is the normalized value of V_s .

The coupling vulnerability factor reflects the impact of outages of natural gas sources on the power lines. A larger $V_1(k)$ for a specific line shows that the line is more vulnerable to the outage of natural gas sources.

2) The topological vulnerability factor

According to the max flow principle[14]. The transmission capacity between the node *m* and *n* is defined as the minimum capacity possessed by all the lines between these two nodes. Thus we can define the transmission capability between *i* and *j* is:

$$TC_{i,j} = \min_{a,b \in S_{i,j}} \{tc_{a,b}\} \tag{28}$$

Where $tc_{a,b}$ is the capacity of line *a* -*b*. And $S_{i,j}$ denotes the nodes set of shortest paths between (*i*, *j*).

From the Eq.(28), we can further define the topological vulnerability factor as:

$$V_2(k) = \sum_{i=1}^{N_{eg}} \sum_{j=1}^{N_{ed}} TC_{i,j} I_{i,j}^m \tag{29}$$

where $I_{i,j}^m$ is an integer variable to indicate if the line *m* lies in the shortest paths between *m* and *n*. N_{eg} and N_{ed} are the number of nodes at which generators and loads are located, respectively.

3) The operational vulnerability factor

Firstly, we define the power flow pulse ratio as:

$$R_{a,m} = \frac{\Delta PF_{a,m}}{\sum_{a=1}^{N_{eb}} \Delta PF_{a,m}} = \frac{| PF_{a,m} - PF_{a,0} |}{\sum_{a=1}^{N_{eb}} | PF_{a,m} - PF_{a,0} |} \tag{30}$$

Where $r_{a,m}$ can measures the impact of the outage of line *m* on the power flow on line *a*. $PF_{a,0}$ and $PF_{a,m}$ are the power flow under the base case and after the line *k* is malfunctioning.

Considering all the lines will suffer from the power flow pulse, we can obtain the power flow distribution entropy caused by the outage of line *m*:

$$H_m = \sum_{a=1}^{N_{eb}} -r_{a,m} \ln r_{a,m} \tag{31}$$

Based on (31), we can define the operational vulnerability factor as:

$$V_3(m) = \frac{| PF_{m,0} |}{H_m} = \frac{| PF_{m,0} |}{\sum_{a=1}^{N_{eb}} -r_{a,m} \ln r_{a,m}} \tag{32}$$

4) The comprehensive vulnerability index

To comprehensively evaluate the system's vulnerability, we can composite the aforementioned three factors to construct the comprehensive vulnerability index as:

$$V(m) = V_1(m)(\alpha_1 V_2(m) + \alpha_2 V_3(m)) \tag{33}$$

where α_1 and α_2 are pre-defined weight coefficients.

The comprehensive vulnerability index takes concurrently count of the topological and operational impact of outages from natural gas systems on the lines of power grids. A line with the larger $V(m)$ value indicates that it is more vulnerable to outages from the natural gas system.

IV. Assessment and Validation

The vulnerability reflects the deteriorative trend of the system performance under attacks. We further adapt the network efficiency and the system transmission efficiency to indicate the system performance.

1) The network efficiency

In complex networks, the efficiency of the node pair (*a*, *b*) $E_{a,b}$ is defined as the reciprocal of the shortest distance between *m* and *n*:

$$E_{a,b} = \frac{1}{d_{a,b}} \tag{34}$$

Where $d_{a,b}$ is the shortest distance between *a* and *b*.

To weigh the transmission efficiency of the network as a whole, we define the average efficiency of all node pairs in the network as the overall network efficiency:

$$E = \frac{1}{N_e(N_e - 1)} \sum_{a,b \in N_e} \frac{1}{d_{a,b}} \tag{35}$$

Eq.(35) only considers the topological structure. To integrate the physical characteristic of integrated systems, we can substitute the shortest distance with the shortest electrical distance, and regard outputs and loads as the weight coefficients to define the network efficiency under the ***k*-th** attack:

$$E(k) = \frac{1}{N_{eg} N_{ed}} \sum_{a=1}^{N_{eg}} \sum_{b=1}^{N_{ed}} \frac{\min\{\omega_a, \omega_b\}}{d_{a,b}^k} \tag{36}$$

where ω_a is the weight coefficient of the generator node a . And ω_b is the weight coefficient of the generator node b. $d^k_{a,b}$ is the shortest electrical distance under the k-th attack.

2) the system transmission efficiency

We further select the system transmission efficiency indicator to reflect the difference in load levels before and after the attack:

$$L(k)=\frac{\sum_{i=1}^{N_{is}^k}\sum_{j=1}^{N_i^k}P_d^k(j)}{\sum_{j=1}^{N_{ed}}P_d^0(j)} \tag{37}$$

where N_{is}^k is the number of isolated islands formed after the k-th attack. N_i^k is the number of nodes in the isolated island i. $P_d^k(j)$ is the load level at the node j under the k-th attack. And $P_d^0(j)$ is the load level before the attack.

V. CASE STUDY

A. Basic Settings

To validate the correctness and effectiveness of the proposed model, an electricity-gas coupling system composed of an IEEE 30-bus system and a 20-bus Belgian gas network is elaborated. And the generators at the node 1, 8, and 13 in the IEEE 30-bus system are set as gas-fired generators connected to the nodes 10, 7 and 16 in the natural gas system, respectively. The rest of the generators in the power system are all regarded as conventional generators.

B. Result analysis

1) Analysis of the vulnerability of transmission lines

According to the identification method of vulnerability for transmission lines, we can calculate the vulnerability index for each line and Fig. 1 shows the lines with the 10-th highest vulnerability indices.

TABLE I. IDENTIFICATION RESULT OF THE VULNERABILITY

The order of vulnerability indices	Line Number	Vulnerable Index
1	6	0.168
2	8	0.114
3	9	0.108
4	10	0.106
5	2	0.093
6	28	0.079
7	5	0.067
8	23	0.052
9	9	0.051
10	16	0.018

It can be seen from TABLE I that the vulnerability indices vary obviously among all lines. It means that the identification method can easily distinguish the lines with high vulnerability values from those with relatively low vulnerability values.

2) The validation of vulnerability lines

We further validate the vulnerability through successively attacks each line Two attack modes, i.e., random attacks and deliberate attacks, are incorporated to examine the system performance. Random attacks mean that we randomly choose a certain number of lines to be on outages. And lines with the highest vulnerability values are outages with deliberate attacks. And the network efficiency is shown in TABLE II.

TABLE II. THE NETWORK EFFICIENCY UNDER DIFFERENT ATTACK MODES

The number of attacks	under deliberate attack mode	under random attack mode
1	0.835	0.991
2	0.807	0.988
3	0.769	0.983
4	0.479	0.978
5	0.293	0.958
6	0.224	0.944
7	0.180	0.940
8	0.151	0.930
9	0.131	0.925
10	0.076	0.907

From TABLE II., we can see that after 10 times random attacks, the network efficiency only drops to 90% whereas that goes down below 20% very quickly under the deliberate attacks. It means that the vulnerable lines are vital to the performance of the whole system. And we further explore the system transmission efficiency, under those circumstances, the result is shown below.

TABLE III. THE SYSTEM TRANSMISSION EFFICIENCY UNDER DIFFERENT ATTACK MODES

The number of attacks	under deliberate attack mode	under random attack mode
1	0.980	1
2	0.973	1
3	0.940	0.987
4	0.940	0.987
5	0.844	0.987
6	0.724	0.880
7	0.653	0.868
8	0.523	0.838
9	0.453	0.838
10	0.432	0.838

From TABLE III, we can easily observe that the system transmission falls below 50% after 10 times deliberate attacks, nevertheless, the percentage is merely 82% with random ones. The result proves that the overall system transmission efficiency is tightly dependent on the resilience of the identified vulnerable lines.

Furthermore, vulnerable indices for natural gas sources are calculated. The result is demonstrated in TABLE IV.

TABLE IV. RESULTS OF VULNERABLE INDEXES FOR NATURAL GAS SOURCES

Rank	Number	Vulnerable Index
1	4	0.502
2	2	0.187
3	5	0.154
4	6	0.087
5	1	0.054
6	3	0.019

The result reveals that the reliability of gas sources 4, 2, 5 is curial to the resilience of the whole integrated system. We should take related measures to ensure their reliability, e.g., weatherization and infrastructure hardening.

In light of the ranking above, we severally choose deliberate attacks on sources 4, 2, 5, and take the system transmission efficiency to assess the system performance. The result is shown in TABLE V.

TABLE V. VARIATION OF SYSTEM TRANSMISSION EFFICIENCY UNDER DIFFERENT SCENARIOS

The number of attacks	Outage of source 4	Outage of source 2	Outage of source 5	Normal state
1	0.780	0.684	0.691	1
2	0.754	0.603	0.610	0.990
3	0.710	0.554	0.602	0.974
4	0.543	0.532	0.598	0.960
5	0.533	0.520	0.523	0.940
6	0.455	0.511	0.519	0.544
7	0.380	0.324	0.518	0.531
8	0.243	0.310	0.423	0.453
9	0.210	0.255	0.231	0.324
10	0.205	0.198	0.201	0.215

TABLE V illustrates the system performance with the increasing number of deliberate attacks. The result shows that the rates of descent of the system transmission efficiency are positively related to the vulnerable index, i.e., the system transmission efficiency falls steepest when the natural gas source with the largest vulnerable index is malfunctioning.

VI. CONCLUSION

As the strengthening independence of power systems and natural gas systems, the two systems' safety operation is spontaneously correlated. The increasingly frequent occurrence of extreme weather imposes a large challenge on the resilience of integrated systems. In the context of resilient demand, we propose a set of indexes to identify vulnerable components composed of power transmission lines and natural gas sources from the perspective of the system coupling, structure, and operation, respectively. And based on three types of factors, we further construct the comprehensive vulnerability index to realize the precise evaluation of critical components. Last but not the least, we adopt the system transmission efficiency and network efficiency to investigate the impact of different attacks on the identified vulnerable components in the system. The case study reveals that the identified vulnerable power transmission lines and natural gas sources are of significance to the resilience of the integrated system since their outage will remarkably deteriorate the system's performance. Thus we should take careful measures to guarantee their reliability to enhance the overall resilience to an acceptable level.

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