Power System Resilience Assessment Considering of Integrated Natural Gas System

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Keywords: Critical Infrastructure, Interdependence, Resilience, Performance.

Abstract

Power system and natural gas (NG) system are two critical infrastructures (CI) that modern society depends on. The power system designed with conventional reliability criterion can neither effectively anticipate nor respond to high impact, low probability (HILP) events such as earthquake. At the same time, increasingly utilization of NG for electricity generation leads to rising intersystem coupling of power system and NG system. The interdependence imposes power system potential risk, such as failure propagation trigged by gas network contingency. Taken together with power system intrinsic complexity, these factors could operate to amplify disruptive effects. In this context, this paper aims to develop an effective model and approach to assess power system resilience considering associated fuel supply system based on two performance metrics: Expected Demand Not Supplied (EDNS) and Probability of Load Curtailments (PLC). It develops models of NG system, power system and their interdependence for quantitative measurement purpose, and generates an integral simulation frame using non-sequential Monte Carlo simulation. Finally, it conducts case studies on modified Belgian gas transmission system and IEEE-24 reliability test system to justify the validity of the proposed approach.

1 Introduction

Our modern society depends deeply on critical infrastructure (CI) systems, which provide basic service for the society function and development, such as water, energy, health care, transportation, communication, and finance. The energy system especially power system and NG system is of vital importance since it supplies primary and second energy to all other sectors including itself for necessary operation. Power system is the backbone of several other key sectors. Blackouts in a power system could lead to disastrous consequences. Thus high reliability is the primary criteria of power supply to enable normal society function. However, threats to the power system reliability are both internal and external, such as threats from fuel supply system and extreme events.

The natural gas (NG) system is also a lifeline utility system playing a critical role in achieving social wellbeing. It is an essential energy source for activities of business, industry, agriculture and residents, especially an increasing fuel supply for power generation for a variety of reasons, such as technological advancements, environmental friendliness and economic profit. According to EIA's data, in 2014, 21.6% of world electricity production was from NG, the second largest preliminary single fuel, compared to about 12.1% in 1973 [7]. Obviously, the power system and NG system are linked more closely physically and economically, which could present challenges to both systems. The conventional viewpoint of treating NG or power system as a stand-alone energy supply is inadvisable. This highlights the necessity to model and analyse the interdependence between NG system and power system for risk mitigation and fast system restoration.

In addition to risks placed by interdependence among CIs, another challenge that power system faces comes from HILP events occurring more frequently in recent years, such as 2008 China ice storm [15], 2011 Japan earthquake and 2011 Thailand floods. The impact from HILP events complicates the power system analysis process as they are extensive and significantly uncertain in scale, space and time. The diversity of physical impact mechanism on different CIs intensifies uncertainties further. What's more, HILP events are predicted to happen more frequently and intensely in the future [6].

The CI internal complexity, rising interdependence as well as environmental risks resulting from HILP events could operate together to amplify disruptive effects. In this context, the resilience concept is emerging and has drawn much attention, and some work has been done sparsely across different fields, such as U.S, UK and "Future Resilient Systems" in Singapore-ETH Center [4]. However, in the process of power system resilience assessment, there is still a lack of consideration of this joint impact in a compatible way due to its complexity and interdisciplinary characteristics.

In order to address the issue, this paper aims to generate a preliminary integral analysis frame for power system performance assessment considering the impact of fuel supply systems under a wide range of uncertainties with an interdisciplinary viewpoint.

The remainder of this paper is structured as follows. Section 2 develops system models and proposes approach used. Section 3 covers case studies and simulation results. Section 4 draws conclusions and proposes future work.

2 System modelling

2.1 NG system modelling

A NG system can be modelled as a directional graph made of nodes and components. Node is the terminal of one or more components or the point where the gas is injected in or extracted from the system. Node connecting component is the element that connects two nodes, such as pipeline and compressor.

The steady-state gas flow rate through a horizontal pipeline is governed by pressure drop along the pipeline, and can be expressed as [9, 11]:

$$M_k^{ij} = S_{ij} \times 3.2387 \frac{T_0}{\pi_0} \sqrt{S_{ij} \frac{\left(\pi_i^2 - \pi_j^2\right) D_k^5}{f_k G L_k T_{ka} Z_a}} \tag{1}$$

where M_k^{ij} is the flow rate through pipeline *k*, *SCF/hr*; T_0 is standard temperature, $^{\circ}R$; π_0 is standard pressure, *psia*; π_i and π_j are pressure of node *i*, *j* respectively, *psia*; D_k is the diameter of pipeline *k*, *inch*; f_k is friction factor; *G* is gas specific gravity; L_k is pipeline length, *km*; T_{ka} is gas average temperature, $^{\circ}R$; Z_a is gas compressibility factor; S_{ij}=1 if $\pi_i>\pi_j$, else S_{ij}= -1.

For a high-pressure NG network, Equation (1) can be rewritten as [14]:

$$M_k^{ij} = S_{ij} C_k \sqrt{S_{ij}\left(\pi_i^2 - \pi_j^2\right)} \tag{2}$$

where $C_k = \frac{\varepsilon 18.062 T_0 D_k^{8/3}}{\pi_0 \sqrt{G L_k T_{ka} Z_a}}$, and ε is the pipeline efficiency.

The gas flow rate through a compressor is determined by its horsepower consumption that can be expressed by the following equation without heat transfer [9]:

$$HP_c^{ij} = \frac{\pi_i M_c^{ij} \alpha_c}{\eta_c(\alpha_c - 1)} \left[\left(\frac{\pi_j}{\pi_i} \right)^{\frac{\alpha_c - 1}{\alpha_c}} - 1 \right] \tag{3}$$

where π_i, and π_j are the suction and discharge pressure respectively, *psia*; M_c^{ij} is the flow rate through compressor *c*, *SCF/hr*; η_c is compressor efficiency; α_c is specific heat ratio (c_p/c_v, where c_p is the heat capacity at constant pressure, c_v is the heat capacity at constant volume).

The gas required by a gas-driven compressor *c* can be approximately calculated by:

$$\tau_c = \alpha_c^{ij} + \beta_c^{ij} HP_c^{ij} + \gamma_c^{ij} \left(HP_c^{ij} \right)^2 \tag{4}$$

where α_c^{ij}, β_c^{ij}, γ_c^{ij} are compressor gas consumption coefficients.

The active power L_c^{ij} consumed by an electricity-driven compressor *c* can be calculated by [8]:

$$L_c^{ij} = HP_c^{ij} \left(\frac{0.000007457}{3600} \right) \tag{5}$$

For a NG network consists of *n* nodes and *m* components, node gas flow balance can be expressed as the algebraic sum of gas injected and extracted:

$$\Delta M_i = \sum_{j=1}^{n} a_{ij} M_k^{ij} + \sum_{j=1}^{n} b_{ij} M_c^{ij} - M_{gs}^i + M_{gl}^i = 0 \quad i = 1, \cdots, n \tag{6}$$

where M_{gs}^i and M_{gl}^i are gas injection and load at node *i* respectively, *SCF/hr*.

$$a_{ij} = \begin{cases} 0 & \text{if node } i \text{ is not connected to node } j \\ 1 & \text{if node } i \text{ is connected to node } j \end{cases}$$

$$b_{ij} = \begin{cases} 0 & \text{if node } i \text{ is not connected to node } j \\ 1 & \text{if node } i \text{ is compressor suction node} \\ -1 & \text{if node } i \text{ is compressor discharge node} \end{cases}$$

A compressor can be specified by compression ratio, inlet or outlet pressure, or flow rate. For a compressor *c* with given compression ratio R_c^{ij}:

$$\Delta R_c^{ij} = \frac{\pi_j}{\pi_i} - R_c^{ij} = 0 \tag{7}$$

Assume node *n* is the reference node with given node pressure while other *n*-1 node pressures are left unknown, and there are n_c compressors with given compression ratio. Let column vector *X* represent the *n*-1+ n_c unknown variables in the system:

$$X = [\pi, HP]^T = \left[\pi_1, \cdots, \pi_{n-1}, HP_1, \cdots HP_{n_c} \right]^T \tag{8}$$

$$F(X) = \left[\Delta M, \Delta R \right]^T \tag{9}$$

Newton-Raphson method is used to solve the equation set. The iteration equations are as follows:

$$X^{l+1} = X^l + \Delta X^l \tag{10}$$

$$J^l \Delta X^l = -F(X)^l \tag{11}$$

where *J* is Jacobian matrix; *ΔX* is variable correction vector; *l* is number of iterations.

$$J^l = \begin{bmatrix} \left.\frac{\partial \Delta M_1}{\partial \pi_1}\right|_l & \cdots & \left.\frac{\partial \Delta M_1}{\partial \pi_{n-1}}\right|_l & \left.\frac{\partial \Delta M_1}{\partial HP_1}\right|_l & \cdots \left.\frac{\partial \Delta M_1}{\partial HP_{n_c}}\right|_l \\ \vdots & & \vdots & \vdots & \vdots \\ \left.\frac{\partial \Delta M_{n-1}}{\partial \pi_1}\right|_l & \cdots & \left.\frac{\partial \Delta R_1}{\partial \pi_{n-1}}\right|_l & 0 & \cdots \quad 0 \\ \vdots & & \vdots & \vdots & \vdots \\ \left.\frac{\partial \Delta R_{n_c}}{\partial \pi_1}\right|_l & \cdots & \left.\frac{\partial \Delta R_{n_c}}{\partial \pi_{n-1}}\right|_l & 0 & \cdots \quad 0 \end{bmatrix} \tag{12}$$

By alternately solving Equation (10) and (11), the unknown variables can be determined. Substituting the results into Equation (2) and Equation (3), flow rates through pipelines and compressors can be calculated.

Contingencies in a gas network such as leak, explosion and component failure are not rare, especially under HILP events. Most of the time, a NG system can step into a new steady state through redispatch or adjustment without disturbance to end customers. However, in some cases, load curtailment is inevitable due to the operating constraints. In practical, optimal shedding strategies are developed with different objective, such as minimum cost, priority list or minimum load shedding, which is adopted in this paper. The optimal gas flow (OGF) is formulated as:

$$Min\sum_{i=1}^{n} M_{lc}^{i} \qquad (13)$$

subject to Equation (2), Equation (3) and

$$M_{gs,\min}^{i} \le M_{gs}^{i} \le M_{gs,\max}^{i} \qquad \forall i \in \Omega_s \qquad (14)$$

$$\pi_{\min}^{i} \le \pi^{i} \le \pi_{\max}^{i} \qquad \forall i \in \Omega \qquad (15)$$

$$-M_{k,\max} \le M_k \le M_{k,\max} \qquad \forall k \in \Phi^p \qquad (16)$$

$$HP_{\min}^{i} \le HP_{p}^{i} \le HP_{\max}^{i} \qquad \forall i \in \Phi^c \qquad (17)$$

where M_{lc}^{i} is gas load curtailment at node *i*, *SCF/hr*; $M_{gs,\min}^{i}$ and $M_{gs,\max}^{i}$ are gas supply bounds of node *i*, *SCF/hr*; $\pi_{\min}^{i}$ and $\pi_{\max}^{i}$ are operation pressure bounds of node *i*, *psia*; $M_{k,max}$ is flow rate bound of pipeline *k*, *SCF/hr*; Ω, Ω_s, Φ^p, Φ^c are set of NG network nodes, supply nodes, pipelines and compressors respectively.

To tackle this non-convex optimal issue, a new variable Π is introduced where $\Pi=\pi^2$. Besides (14), (16) and (17), the objective function (13) also subjects to:

$$\Pi_{\min}^{i} \le \Pi^{i} \le \Pi_{\max}^{i} \qquad \forall i \in \Omega \qquad (18)$$

$$\left(M_k\right)^2 = (2I-1)\left(\Pi_i - \Pi_j\right)C_k^2 \qquad \forall (i,j) \in \Omega, \forall k \in \Phi^p \qquad (19)$$

$$M_K \le 2IM_K \qquad \forall k \in \Phi^p \qquad (20)$$

where $\Pi_{\min}^{i} = \left(\pi_{\min}^{i}\right)^2$, $\Pi_{\max}^{i} = \left(\pi_{\max}^{i}\right)^2$, $\Pi^{\mathrm{i}} = \left(\pi^{\mathrm{i}}\right)^2$, $\Pi^{\mathrm{j}} = \left(\pi^{\mathrm{j}}\right)^2$, and $I = \begin{cases} 0 & if \;\; \Pi^i < \Pi^j \\ 1 & if \;\; \Pi^i > \Pi^j \end{cases}$.

To solve the modified optimization problem, an existed mixed integer programming solver SCIP (Solving Constraint Integer Programs) [1] is used.

2.2 Power system modelling

Determination of the most optimal state with given objective, such as minimum fuel cost or network loss, is the optimal power flow (OPF) problem.

The general mathematical formulation of OPF can be:

$$\left.\begin{aligned} \min \;\; & f(x) \\ s.t. \;\; & g(x) = 0 \\ & h(x) \le 0 \end{aligned}\right\} \qquad (21)$$

The equality constraint is the power flow constraint, while the inequality constraint includes generator generation bounds, voltage magnitude bounds, transmission line capacities, reactive power source bounds and so on.

The OPF problem can be solved by AC or DC power flow. For AC version, the state variable vector *x* is the voltage angles and magnitudes ungiven, generators' active and reactive generation. For DC version, it is the voltage angles and generators' active generation. In this paper, the DC OPF function in Matpower 6.0b1 is employed for its calculation efficient as Monte Carlo simulation will introduce a considerable amount of calculation with a large-scale system.

2.3 Interdependence modelling

The power system and NG system are physically linked bi-directionally through GFPGs and compressors driven by electricity. The active power consumed by a compressor is a function of its horsepower, which is presented by Equation(5). A GFPG acts as a gas consumer in the NG system. The NG mass flow it consumes can be calculated by the following equation[2]:

$$M_{egl}^{i} = \frac{HR}{GHV} \qquad \forall i \in \Omega \qquad (22)$$

where M_{egl}^{i} is gas demand for electricity generation, *SCF/hr*; *HR* is heat rate, *BTU/hr*; *GHV* is gross heating value, *BTU/SCF*.

The heat required for generation is a function of the active power generated by the GFPG, which can be formulated by:

$$HR = \alpha_g^i + \beta_g^i P_g^i + \gamma_g^i \left(P_g^i\right)^2 \qquad \forall i \in \Phi_g \qquad (23)$$

where P_g^i is generated active power, *MW*; α_g^i, β_g^i, γ_g^i is heat rate coefficients for GFPG; Φ_g is set of GFPG.

2.4 Proposed approach

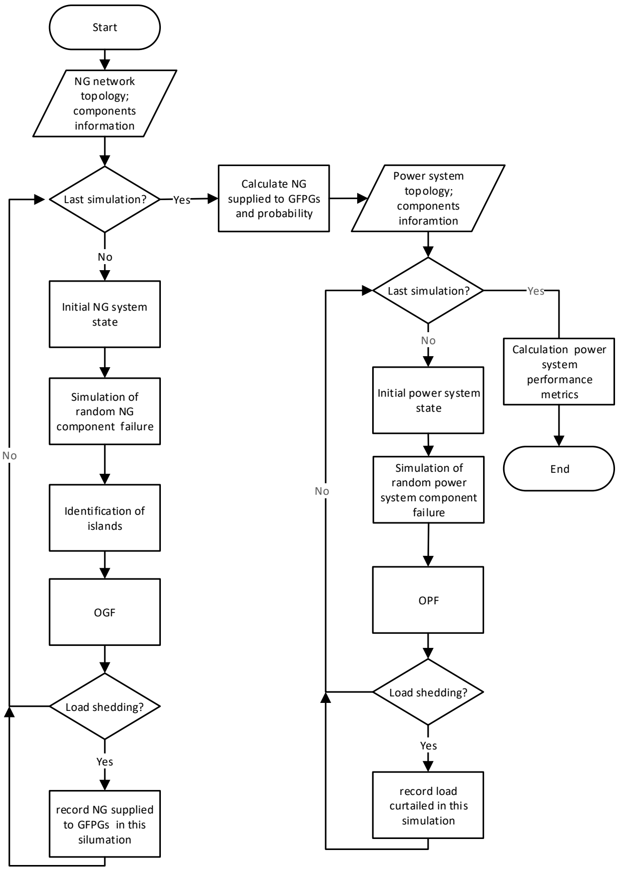

Figure 1: Flowchart of combined analysis procedure

The integrated simulation (Figure 1) starts from an initial NG system state with known network topology, load demand and supply information. In every simulation round, the NG system operation state is generated randomly according to components' failure rate and repair time. Then, if the system is islanded, subsystems should be analysed one by one. For every island, if needed, the OGF would be run to calculate the load curtailment in order to determine the NG supplied to GFPGs. By the simulation end, probability distributions of NG supplied to GFPGs can be calculated.

With simulation results of NG system, as well as given network topology and component data, power system simulation also starts from initial system state. The random system operation state is generated using non-sequential Monte Carlo simulation. If necessary, OPF would be run with the objective function of minimum load shedding. After completion of all simulations rounds, power system performance metrics can be calculated. It should be noticed the GFPG outage model is shifted from two states to multi states with the impact of associated NG supply system.

3 Case study

The analysed energy system consists of modified Belgian NG transmission system [3] and IEEE-24 reliability test system[12]. It is assumed that two 155 MW GFPGs are located at bus 15 and bus 16 in the power system, and the gas are supplied from node 12 (Namur) and node 20 (Petange) of the NG network, respectively, as shown in Figure 2.

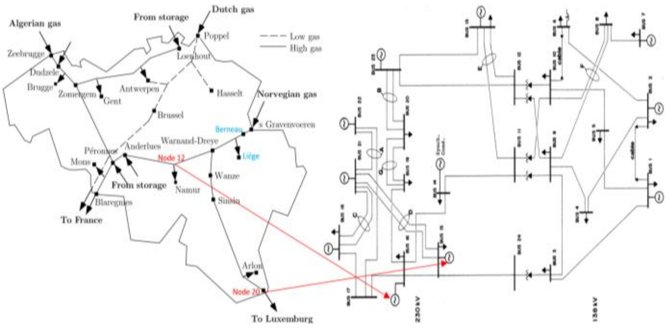

Figure 2: Belgian gas transmission system

The modified NG system includes 20 nodes and 24 pipelines described in Table 1 and Table 2.

Node	Town	Supply$_{min}$ (Mm^3/day)	Supply$_{max}$ (Mm^3/day)	Demand (Mm^3/day)	P$_{max}$ (*Bar*)	P$_{min}$ (*Bar*)
1	Zeebrugge	17.39	8.87	0	77	0
2	Dudzele	12.6	0	0	77	0
3	Brugge	0	0	5.88	80	30
4	Zomergem	0	0	0	80	0
5	Loenhout	7.2	0	0	77	0
6	Antwerpen	0	0	6.05	80	30
7	Gent	0	0	7.88	80	30
8	Voeren	33.02	20.34	0	66.2	50
9	Berneau	0	0	0	66.2	0
10	Liège	0	0	9.55	66.2	30
11	Warnand	0	0	0	66.2	0
12	Namur	0	0	0.775	66.2	0
13	Anderlues	1.8	0	0	66.2	0
14	Péronnes	1.44	0	0	66.2	0
15	Mons	0	0	10.27	66.2	0
16	Blaregnies	0	0	23.42	66.2	50
17	Wanze	0	0	0	66.2	0
18	Sinsin	0	0	0	66.2	0
19	Arlon	0	0	0.33	66.2	0
20	Petange	0	0	0.775	66.2	25

Table 1: Nodes of Belgian gas transmission system

Pipeline	From Node	To Node	Length (*km*)	C$_k$	Capcity (Mm^3/day)
1	1	2	4.0	3.01169	125.08
2	1	2	4.0	3.01169	125.08
3	2	3	6.0	2.45898	102.13
4	2	3	6.0	4.91796	102.13
5	3	4	26.0	1.18128	49.06
6	5	6	43.0	0.31663	13.15
7	6	7	29.0	0.38556	16.01
8	7	4	19.0	0.47633	19.78
9	4	14	55.0	0.81219	33.73
10	8	9	5.0	2.69374	111.88
11	8	9	5.0	0.32869	13.65
12	9	10	20.0	1.34687	55.94
13	9	10	20.0	0.16434	6.83
14	10	11	25.0	1.20467	50.03
15	10	11	25.0	0.14699	6.11
16	11	12	42.0	0.92943	38.6
17	12	13	40.0	0.95238	39.56
18	13	14	5.0	2.69374	111.88
19	14	15	10.0	1.90476	79.11
20	15	16	25.0	1.20467	50.03
21	11	17	10.5	0.22681	9.42
22	17	18	26.0	0.08012	3.33
23	18	19	98.0	0.04127	1.71
24	19	20	6.0	0.16679	6.93

Table 2: Pipelines of Belgian gas transmission system

In order to assess the effect of fuel supply system, the following two scenarios are simulated for comparison: independent power system, the power system with integration of associated NG system. Two power system performance metrics are employed: the Expected Demand Not Supplied (EDNS) and Probability of Load Curtailments (PLC).

In the independent scenario, the power system is simulated under the assumption that the NG system is 100% reliable. All generators are modelled by two states. In the integrated scenario, the GFPGs outputs and corresponding probabilities are determined by the NG system and power system together. In this paper, it is assumed that the active power generated by a GFPG has a linear relationship with NG input [13].

GFPG	Bus	Capacity (*MW*)	α_g^i	β_g^i	γ_g^i
1	15	155	0	8.13457	0
2	16	155	0	8.13457	0

Table 3: Heat rate coefficients for GFPG

The NG network simulation is conducted following the procedures described in Section 2. For illustrative purpose, it is assumed that all NG demands are interruptible and have the same priority. The failure rate and repair time of all the pipelines are assumed to be the same as λ_p=0.2 *failures/year·km* and r_p=*48hours* [5]. The pipeline failure probability can be calculated as:

$$\mu_p = \frac{8760}{r_p} \tag{24}$$

$$U_p = \frac{\lambda_p}{\lambda_p + \mu_p} \tag{25}$$

where μ_p is repair rate of the pipeline, *repairs/year*; U_p is the pipeline unavailability.

Table 4 presents the probability distribution of NG not supplied for node 12 and 20.

Node 12		**Node 20**	
NG Supplied (%)	**Probability**	**NG Supplied (%)**	**Probability**
0.00%	0.924242424	0.00%	0.811818182
11.81%	0.038181818	21.27%	0.000909091
43.96%	0.023333333	100.00%	0.187272727
66.93%	0.003030303		
100.00%	0.011212121		

Table 4: NG network simulation result

The simulation result demonstrates that contingencies in NG system could result in a cut-off or reduction of gas supplied to GFPGs with relatively higher probabilities. The probabilities of NG disruption at node 12 and 20 are 0.924242424 and 0.811818182 respectively, both the highest one. The probability of reduced NG supply at node 12 is as high as 0.064545454, which is almost six times of 100% NG supply.

When considering the fuel supply impact, the GFPGs are more likely to trip or operate in derated states compared to 100% reliable fuel supply. Table 5 provides comparison of the GFPGs generation output and corresponding probabilities in combined scenario and independent scenario.

GFPG at bus 15			
Combined Scenario		**Independent Scenario**	
Generation(*MW*)	**Probability**	**Generation(*MW*)**	**Probability**
103.7338833	0.002909091	0	0.04
68.13525807	0.0224	155	0.96
18.30601905	0.036654545		
0	0.050763636		
155	0.887272727		

GFPG at bus 16			
Combined Scenario		**Independent Scenario**	
Generation(*MW*)	**Probability**	**Generation(*MW*)**	**Probability**
32.96493424	0.000872700	0	0.04
0	0.219781818	155	0.96
155	0.779345455		

Table 5: GFPG output and probability

It can be seen clearly that in combined scenario the probability of success state at full capacity 155 is decreased while the failure probability is increased significantly in comparison with the independent scenario. Further, it is more obvious for the GFPG at bus 16. The reason is that its fuel is supplied by node 20 in the NG system, which has much longer distance from main NG sources. In other words, in the NG system, node 20 is more vulnerable to contingencies than node 12, which is determined by the network topology.

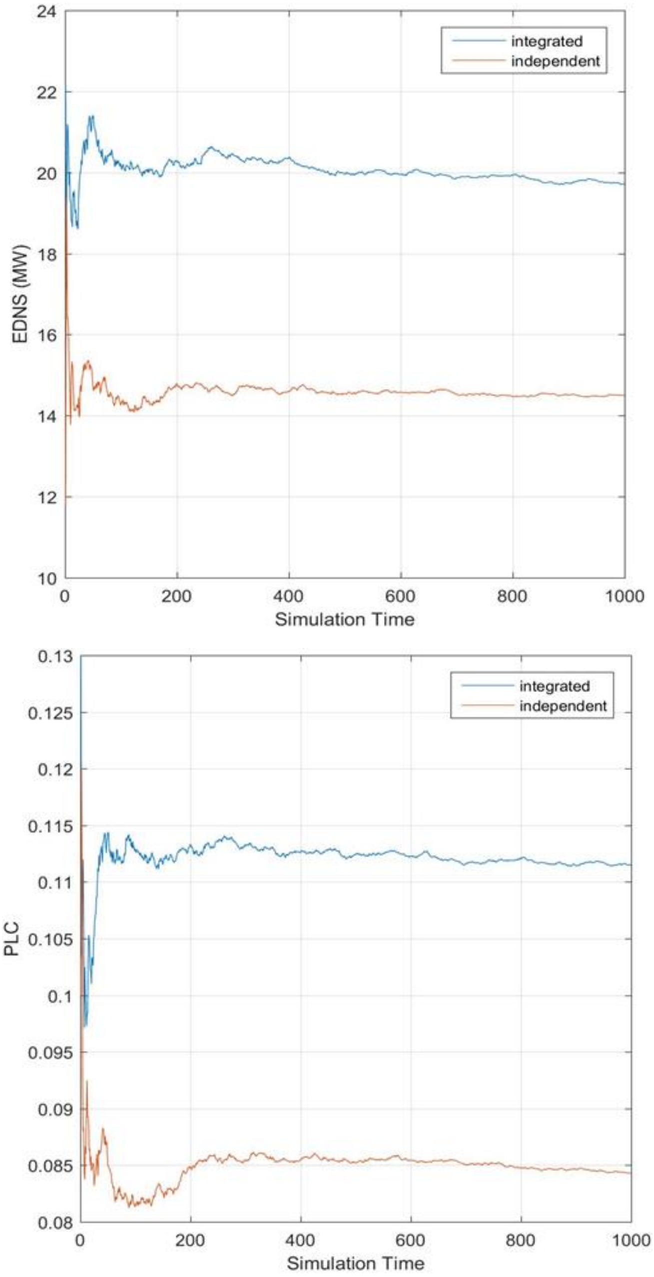

Figure 3: Power system performance metrics

The effect placed by the NG system lead to reduced system performance, which can be displayed by significant increase of EDNS and PLC. ENDS increases sharply by 41.2856% from 14.5857 *MW* to 20.6075 *MW*, while PLC increases by 33.3529% from 0.08527 to 0.11371 as shown in Figure 3. This result can be easily explained. In the combined scenario, increased GFPG failure probabilities in turn increase the probability of the power system load curtailment. The increase is more obvious if large capacity GFPGs are connected to topology weak NG system. The system ENDS also becomes larger due to increased failure probabilities and decreased outputs.

Simulation results reveal two key insights: first, the interdependence impact is significant and should not be ignored; second, the interdependence worsens power system performance. Therefore, the power system becomes less resilient considering fuel supply system. Neglecting this factors in the resilience assessment of power systems would result in the underestimation of the problem.

4 Conclusion and future work

Although there is still debates around the power system resilience definition and assessment approach, it becomes a hot topic and has vital importance as an integral part of society preparedness for HILP events.

Against this background, this paper provides a preliminary method for power system performance assessment considering the impact of fuel supply systems. Conclusions can be drawn from the simulation results analysis. First, obtained results show that the interdependence among the power system and NG system plays an important role in the performance of power system. Second, contingencies in NG system have a high, non-negligible, negative impact on power system performance. It can be easily observed from the perspective of EDNS and PLC. The simulation results also verified the effectiveness of approach developed in this paper.

Although the suggested method enhances the understanding of the role of significant interdependence, there are several questions remaining unclear. In order to fully explore this topic, additional efforts are required in the future.

First, physical models of impact mechanism must be developed for different types of HILP events to different kinds of CI components. For this purpose, information form the geographical information system and meteorological system would be integrated.

Second, although general resilience metrics are available, they are not sufficiently valid predictors. Individual metrics must be developed according to the threat and system characteristics. It should be shifted towards multi-attributed quantification including of restoration process.

Third, cascading effects will be taken into account because interdependence among CIs makes the power system more vulnerable to cascading failures under HILP events as disruption in one system could propagate to the other.

Moreover, human factor will be included, such as operator behaviour, which plays a vital role in an emergency.

Acknowledgements

This work is supported by the Future Resilient System (FRS) at the Singapore-ETH centre (SEC), which is funded by the National Research Foundation of Singapore (NRF) under its Campus for Research Excellence and Technological Enterprise (CREATE) program.

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