Resilience Metrics for Integrated Power and Natural Gas Systems

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***Abstract*—The integrated power and natural gas system (IPGS) is a promising technique against extreme weather. In this letter, a valley-shaped resilience model is proposed to evaluate the performance of IPGSs under extreme weather and inter-energy assistances between the electric power sector and the natural gas sector. Furthermore, a quantification metrics framework for IPGS resilience evaluation is raised. Novel metrics are proposed, especially the distortion rate (Θ) and linepack effect (Δt^*) for quantifying coupling tightness and assistance from natural gas transient in resilience perspective respectively. Evaluation on different restoration strategies is conducted to validate the effectiveness of the proposed metrics framework.**

***Index Terms*—Integrated power and natural gas system, resilience, resilience metrics, valley-shaped resilience model.**

I. Introduction

METRICS of resilience [1] are of crucial importance, which can provide a general discourse system for the evaluation on system resilience performance, comparison on effectiveness of alternative hardening strategies, assessment on the validity of potential restoration schemes, etc. A quantified resilience metrics framework is instructive for further research in resilience including resilient planning, pre-disaster hardening, and ex-post restoration.

Current research on the resilience of integrated power and natural gas system (IPGS) is mainly focused on the physical operation status, which makes the constraints of the optimization model. This resulted in the difficulty of comparing different resilience enhancement strategies as currently there has not been a systematic quantitative evaluation method for IPGS resilience. To make it clear, among literature focusing on the ex-post restoration strategies, [2] considers the electric power sector (EPS) and natural gas sector (NGS) separately, while [3], [4] takes the cost of non-served loads of EPS and NGS together. Also, [5] optimizes the total operation cost, and [6] formulates a multi-objective problem considering both supplied load amount and the system preparedness index. Thus, to select a practical resilience-oriented operation strategy for the real world IPGS, it is desirable to build an all-around evaluation framework.

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This letter proposes a valley-shaped resilience model for IPGS as well as presents an all-around quantified resilience performance evaluation framework. Moreover, we discovered that the natural gas linepack plays a tricky role in the resilience of IPGS. A special metric is proposed to capture this characteristic. The proposed valley-shaped model with novel metrics provides a new perspective of the IPGS resilience.

II. Definition and Quantification of Resilience Metrics in IPGS

A. The Valley-shaped Resilience Model

Fig.1 shows the valley-shaped resilience model in three cases, namely separated power and natural gas system (SPGS), IPGS and IPGS* (effect of linepack in consideration). Linear approximation is adopted for clarity. Note that Fig.1 is an illustration of EPS disruption, while NGS disruption as well as disruption of both systems can be included in the model.

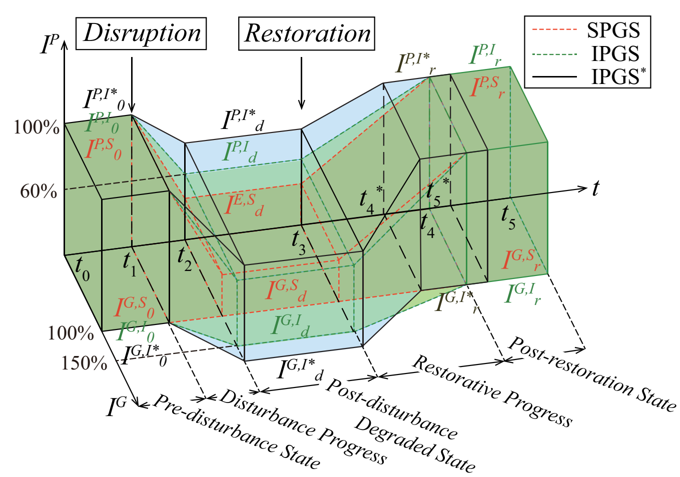

Fig. 1. Multi-phase valley-shaped model of IPGS resilience.

Resilience performances are depicted by system function indicators, which are defined from the demand side in this letter to better depict the enhancement of resilience from natural gas linepack. Weighting factors and normalization are adopted. $I^{P,S}$, $I^{P,I}$, and $I^{P,I*}$ denote the system function of EPS in SPGS, IPGS and IPGS* respectively, while $I^{G,S}$, $I^{G,I}$, and $I^{G,I*}$ denote the system function of NGS in SPGS, IPGS and IPGS* respectively. Altogether 5 phases are illustrated in the valley-shaped model, namely pre-disturbance state, disturbance progress, post-disturbance degraded state, restorative progress and post-restoration state. Subscripts $_0$, $_d$, and $_r$ represent pre-disturbance state, post-disturbance degraded state and post-restoration state. For the sake of simplicity, slight operational adjustments towards better resilience or economic performance are ignored in the model, thus system function indicators in phase I and V are shown as 100% in Fig.1.

B. Assistance Inside the IPGS

The inter-energy assistance between the EPS and the NGS is the profound reason of resilience enhancement of IPGS compared to SPGS, which has been proved by the Roppongi Hills microgrid in Japan [7]. We herein use simple illustrative examples to explain the mechanism of the inter-energy assistance inside IPGS during sector disruptions in Fig.2.

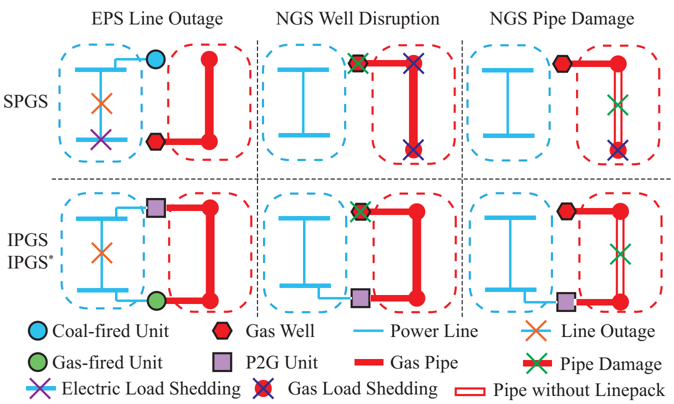

Fig. 2. Mechanism of inter-energy assistance inside IPGS.

Altogether 3 typical types of sector disruptions are summarized, namely EPS line outage, NGS well disruption and NGS pipe damage. As shown in Fig.2, load shedding is inevitable in case SPGS of all three types of disruptions, while loads are preserved in case IPGS and IPGS*.

The assistance from NGS to EPS happens when EPS line outage occurs. The assistance mechanisms include: (1) Due to the transmission path set up by P2G unit and gas-fired unit, an electric-energy $\rightarrow$ chemical-energy $\rightarrow$ electric-energy conversion is done while maintaining the electricity transmission from the supply end bus to the receiving end bus. (2) An increase in gas well supply enables the gas-fired unit to generate sufficient electricity for the receiving end bus. (3) Linepack in adjacent pipes are utilized for sufficient electricity generation of gas-fired units. The valley-shaped model in Fig.1 can be expained by the mechanisms. The increment of NGS system function from IPGS to SPGS in phase II, III and IV is due to mechanisms (1) and (2) because the increased gas consumption of gas-fired units can be respected as load increment in NGS. Moreover, mechanism (3) accounts for the increment of NGS system function from IPGS* to IPGS. The utilization of linepack took over the additional proportion of gas-fired units' consumption without violating the supply constraints of gas wells.

The assistance from EPS to NGS happens when NGS is incurred, including gas well disruptions and gas pipe damages. The EPS to NGS assistance mechanisms are similar to assistance mechanisms (1) and (2) from NGS to EPS, while the linepack effect (corresponding to the aforementioned mechanism (3)) does not exist because of the much faster transient process of EPS.

C. IPGS Resilience Metric System

As mentioned in the introduction, previous research focus on the single phase optimal operation [2]–[6] or single index optimization [2]–[5]. However, resilience is a multi-phase multi-objective problem, which need an all-around evaluation. Thus, an all-around IPGS resilience metric system based on the valley-shaped model is proposed to this end. Further, the coupling tightness of EPS and NGS is enabled to be viewed in the resilience perspective in the proposed metric system.

TABLE I
RESILIENCE METRIC SYSTEM OF VALLEY-SHAPED MODEL

Phase	Resilience metric	Symbol	Mathematical definition
II	Rapidity of system function degrading	Φ^P	$\frac{I_0^{P,I}-I_d^{P,I}}{t_2^P-t_1^P}$
	Degree of system function degrading	Λ^P	$I_0^{P,I}-I_d^{P,I}$
	Rapidity of assistance	Φ^G	$\frac{I_d^{G,I}-I_0^{G,I}}{t_2^G-t_1^G}$
	Degree of assistance	Λ^G	$I_d^{G,I}-I_0^{G,I}$
III	Extensiveness of degradation state	E^P	$t_3^P-t_2^P$
	Extensiveness of assistance	E^G	$t_3^G-t_2^G$
IV	Promptness of recovery	Π^P	$\frac{I_r^{P,I}-I_d^{P,I}}{t_4^P-t_3^P}$
	Promptness of regression	Π^G	$\frac{I_r^{G,I}-I_d^{G,I}}{t_4^G-t_3^G}$
II-IV	Severity of event (power)	V^P	$I_0^{G,S}\times\int_{t_1^P}^{t_4^P}\left[1-I_t^{P,I}\right]\mathrm{d}t$
	Severity of event (gas)	V^G	$I_0^{P,S}\times\int_{t_1^G}^{t_4^G}\left[I_t^{G,I}-1\right]\mathrm{d}t$
I-V	Distortion rate	Θ	$\frac{I_t^G}{I_t^P}$
II	Enhancement of degradation speed	$\Delta\phi^P$	$\frac{I_d^{P,I}-I_d^{P,S}}{t_2^P-t_1^P}$
	Enhancement of degradation	$\Delta\lambda^P$	$I_d^{P,I}-I_d^{P,S}$
	Enhancement of assistance speed	$\Delta\phi^G$	$\frac{I_d^{P,I}-I_d^{P,S}}{t_2^G-t_1^G}$
	Enhancement of assistance	$\Delta\lambda^G$	$I_d^{G,I}-I_d^{G,S}$
IV	Enhancement of recovery speed	$\Delta\pi^P$	$\frac{I_d^{P,I}-I_d^{P,S}}{t_4^P-t_3^P}$
	Enhancement of regression speed	$\Delta\pi^G$	$\frac{I_d^{G,I}-I_d^{G,S}}{t_4^G-t_3^G}$
IV	Linepack effect	Δt^*	$t_4-t_4^*$

Key resilience metrics for all-around IPGS resilience evaluation are presented in Tab. I. Two groups are divided according to the scope of evaluation, including IPGSs/IPGS*s resilience performance evaluation and IPGSs/IPGS*s resilience enhancement evaluation.

1) Metrics for Resilience Performance Evaluation: The metrics in the upper part of Tab.I depict the geometric feature of the valley-shaped model for resilience performance evaluation. Metrics in phase II describe the rapidity (Φ^P) and degree (Λ^P) of EPS function degradation, as well as the rapidity (Φ^G) and degree (Λ^G) of the assistance from NGS. As clearly illustrated in Fig.1, $\Phi^{P,I^*}\leq\Phi^{P,I}\leq\Phi^{P,S}$, $\Lambda^{P,I^*}\geq\Lambda^{P,I}\geq\Lambda^{P,S}$, $\Phi^{G,I^*}\geq\Phi^{G,I}\geq\Phi^{G,S}$ and $\Phi^{G,I^*}\geq\Phi^{G,I}\geq\Phi^{G,S}$ accord with the NGS to EPS assistance mechanisms. Further, Φ^P and Λ^P reflect the resistance to EPS disruption, while Φ^G and Λ^G represent the assistance from NGS under EPS disruptions. However, when NGS undergoes an disruption, Φ^G and Λ^G represent the resistance of NGS, while Φ^P and Λ^P reflect the assistance from EPS. All following indicators have the same dual characteristic, and only the EPS disruption case will be illustrated for the sake of simplicity. Metrics in phase III states the extensiveness of degradation state (E^P) and assistance (E^G), which embody the response time of system operators. Metrics in phase IV present the promptness of recovery in EPS (Π^P) and NGS (Π^G). These two metrics reflect the effectiveness of response and recovery strategies. Considering that the inter-energy assistance mechanisms inside IPGS, under same infrastructure repair scheme, the recovery speed of IPGS can be better than SPGS, i.e., $\Pi^{P,I} \geq \Pi^{P,S}$. Volume metrics of phase II-IV state the severity of the extreme event. V^P and V^G aim to reflect the total influence of the extreme weather from the perspective of EPS and NGS respectively. Distortion rate (Θ) models the whole process of IPGSs under extreme weather from phase I to V. Further, the maximum distortion rate index (Θ_{max}) provides a novel resilience perspective on coupling relationship of energy sectors.

2) Metrics for Resilience Enhancement Evaluation: As in the lower part of Tab.I, the metrics aims to evaluate the resilience enhancement of IPGS/IPGS* compared to SPGS. Note that the enhancement of IPGS* to IPGS can be quantified similarly. Metrics in phase II depict the discrepancy in rapidity of EPS system function degradation ($\Delta\phi^P$) and decrease in degree of EPS system function degradation ($\Delta\lambda^P$). Similar indices ($\Delta\phi^G$,$\Delta\lambda^G$) are defined for NGS assistance enhancement evaluation. Herein we define the metrics in the hypothetic occasion of EPS disruption, and it should be noted that the metrics are able to evaluate the NGS disruption circumstances. In NGS disruption situation, $\Delta\phi^P$ and $\Delta\lambda^P$ are for EPS assistance enhancement evaluation, while $\Delta\phi^G$ and $\Delta\lambda^G$ are for NGS system function drop evaluation. For the sake of simplicity, we present the definition in the EPS disruption case for metrics mentioned below. Metrics in phase IV denote the enhancement of recovery speed of EPS ($\Delta\pi^P$) and the regression speed of NGS ($\Delta\pi^G$). Moreover, a special metric, linepack effect (Δt^*) is proposed to evaluate the influence of linepack to IPGS by the length of restorative progress. The enhancement is positive in some of the EPS disruption cases because of the support of natural gas linepack, i.e., assistance mechanism (3). However, the linepack effect is not always positive. For some EPS disruption cases without suitable operation strategies and NGS disruption cases, the process of linepack rebuilding would cause a longer restoration time, which is negative, as shown in the application example.

D. Quantification of the Resilience Metrics

The mathematical definition of the proposed resilience metrics is based on the geometric features of the valley-shaped resilience model. To promote the continuity of research, indices Φ^P, Λ^P, E^P and Π^P follow the mathematical definition proposed in the previous work of power system resilience evaluation. Indices of NGS resilience evaluation, Φ^G, Λ^G, E^G and Π^G are quantified similarly. Indices V^P and V^G are defined by the volume change of EPS and NGS system performances, respectively, in order to quantify the overall impact of the extreme weather. Distortion rate Θ is quantified by the ratio of I^G and I^P. It is a whole-process index reflecting the dependency between EPS and NGS. Take the EPS disruption case as an example. From phase I to phase V, distortion rate Θ goes up and meets its maximum value in phase III, then goes down in phase V to the initial value. The maximum value Θ_{max} in phase III provides researchers a new perspective in coupling relationship of EPS and NGS. When NGS disruption happens, the distortion rate goes down at first and then regresses to its initial value. The minimum value Θ_{min} occurs in phase III, and depicts the dependency of NGS on EPS. The indices $\Delta\phi^P$, $\Delta\lambda^P$, $\Delta\phi^G$, $\Delta\lambda^G$, $\Delta\pi^P$ and $\Delta\pi^G$ are defined by the difference of IPGS to SPGS or IPGS* to SPGS. The index linepack effect (Δt^*) is defined by the discrepancy between IPGS* and IPGS, by considering the support of natural gas linepack.

Therefore, a systematic metrics framework for IPGS resilience evaluation is proposed. The framework includes the previous work for power system resilience as well as develops advanced metrics to provide new perspectives for resilience evaluation. Moreover, this valley-shaped resilience model and the quantified metrics framework can be applied in various areas and extended to other integrated energy systems.

E. Application of the Resilience Metrics

The application of the resilience metrics is stated below. (1) The all-around metrics provide a systematic framework for the multi-phase multi-objective IPGS resilience evaluation. Different operation strategies can be systematically compared, which is useful in real-life system operation strategy selection. (2) Metrics can be the operation objective of IPGS, e.g., Φ^P in phase II and Π^P in phase IV. (3) A novel resilience perspective on IPGS is presented by distortion rate Θ and linepack effect Δt^* for coupling tightness of energy sectors and enhancement of natural gas linepack, respectively, which can be further applied in planning, operation, and etc.

III. Application Example

The application example is conducted on a modified IEEE 33-bus-13-node IPGS. Altogether 3 coal-fired units and 5 gas-fired units are included. EPS disruption assumption is made. Natural gas linepack is considered as the model proposed in [8], in which linepack is in linear relationship with the pressure at the terminals of the pipe. Note that a complex model of linepack is also applicable. The basic settings of the comparative cases are presented in Tab.II. The evaluation results are shown in Tab.III.

TABLE II
OPERATION STRATEGIES OF CASES

Cases	Inter-energy Strategy	Linepack Strategy	Operation Strategy	
			Phase II	Phase IV
Base	×	×	Minimal operation cost*	
1	√	√	Minimal operation cost*	
2	√	×	Minimal operation cost*	
3	√	√	Minimal load shedding	Fastest restoration
4	√	×	Minimal load shedding	Fastest restoration

* Including the cost of load interruption.

By the comparison of Case 1 and 2, it clearly shows that the utilization of linepack is able to uplift the resilience performance of IPGS. Metrics in phase II, i.e., Φ^P, Φ^G, Λ^P

TABLE III
COMPARISON ON METRICS OF DIFFERENT SCENARIOS

Metric	Φ^P	Φ^G	Λ^P	Λ^G	Π^P	Π^G	V^P
Case 1	3.52	1.27	0.61	0.26	4.43	1.30	39.93
Case 2	3.84	1.19	0.57	0.21	3.29	1.05	47.08
Case 3	4.03	1.43	0.70	0.39	4.26	1.16	52.94
Case 4	3.96	1.39	0.68	0.30	4.53	1.24	56.61
Metric	V^G	Θ_{max}	$\Delta\phi^P$	$\Delta\lambda^P$	$\Delta\pi^P$	Δt^*	
Case 1	12.71	4.36	1.06	0.23	2.54	8h	
Case 2	9.11	3.34	1.38	0.19	1.40	-	
Case 3	16.22	4.62	1.57	0.32	2.47	-5h	
Case 4	14.67	3.90	1.50	0.30	2.64	-	

and Λ^G meet an increment by mechanism (3) mentioned in Section II-B. Moreover, the dependency of EPS on NGS also grows because the utilization of natural gas linepack somewhat enhances the coupling tightness of energy sectors. The linepack has an overall positive effect on the IPGS resilience performance in the comparison, and the recovery time of IPGS* has an 8-hour ahead compared with IPGS.

However, the effect of linepack may not always be positive according to the comparison of Case 3 and 4. In Case 3, though the maximum load shedding amount is reduced by the support of linepack compared with Case 4, the final recovery time of IPGS* has a 5-hour delay compared with IPGS. Moreover, the restoration speed (Π^P,Π^G) of IPGS* is lower than IPGS. By analyzing the all-around resilience metrics, we found that Φ^P, Φ^G, Λ^P, Λ^G and Θ_{max} of IPGS* are better than those of IPGS. The support of natural gas linepack is the critical reason. After the utilization of linepack, rebuilding needs to be done in the restorative progress. Therefore, the assistance mechanism (3) disappears in phase IV. Moreover, even P2G units are put into operation to support the linepack rebuilding process. This finally results in the delay of recovery.

Considering that resilience has multiple metrics, the single-objective or single-phase optimization of IPGS operation may lead to a sub-optimal operation result in a real-life IPGS. Therefore, by adopting the all-around metric system proposed in this letter, whether the Pareto optimality is achieved could be figured out in a systematic way.

IV. CONCLUSION

A valley-shaped resilience model for all-around resilience evaluation of IPGS is proposed in this letter. Further, based on the aforementioned model, a systematic metrics framework and the corresponding quantification methods are presented. All metrics proposed not only evaluate the resilience performance but also can be the objective of resilience-oriented optimization. In addition, distortion rate Θ is a novel resilience perspective for energy sector coupling relationship. And in the application example, we discover that it is a paradox in the utilization of natural gas linepack. The linepack used in the mitigation of system disruption may have a negative effect on the final restoration because of the linepack rebuilding process.

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