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Resilience-constrained Long-term Reserve Planning of Integrated Gas and Power Systems

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ABSTRACT

The increasing frequency of extreme weather events nowadays has posed a great threat to the reliable operation of integrated gas and power systems (IGPSs). Thus, a resilience-based approach is in urgent need for investment and operation for IGPSs to avoid the impacts of natural disasters. This paper presents a long-term reserve expansion model to enhance the resilience of IGPSs to extreme events. According to the spatial features of windstorms, the analytical resilience constraints are firstly formulated considering the energy interactions between the power system and the gas system. Moreover, the developed resilience constraints are added to the reserve optimization model to determine the investments of power units and gas storage. In the proposed model, both the operating constraints and investment constraints of IGPSs are considered. Finally, the proposed methods are validated using an integrated gas and power testing system.

Keywords: reserve expansion, integrated gas and power systems, resilience constraints, windstorms.

NOMENCLATURE

Abbreviations	
IGPSs	Integrated gas and power systems
NGS	Natural gas system
GPP	Gas-fired power plant
EELC	Expected electric load curtailments
CPP	coal-fired power plants

1. INTRODUCTION

In recent years, climate change has increased the frequency of various severe weather events, e.g. windstorms and thunder, which makes critical energy systems (CESs) more vulnerable to these risks [1]. The resilience, representing the ability of CESs to resist and adapt to the possible disturbances, has attracted widespread attention in both academia and industry [2]. As an effective measure to enhance system resilience, the long-term reserve expansion is in urgent need for CESs to deal with natural disasters.

Besides extreme events, the interactions between the power system and natural gas system (NGS) can bring new challenges to the reserve management of CESs. Compared to a single energy system, the component failures occurring in one system may spread to the other system [3]. A practical example of massive power blackouts in Taiwan, China in August 2017 attributed to the gas interruption to gas-fired units. Moreover, the expansion of gas reserves cannot only enhance the resilience of NGS but also have a great impact on reserve expansion of power systems [4]. Considering that, it is essential to develop a co-optimization model in integrated gas and power systems (IGPSs) to coordinate the reserve of NGS and power systems considering resilience constraints.

In the previous studies, the reserve and network expansion models of IGPSs have been studied extensively. In [5], a bi-level multi-state programming is proposed to considering the bi-directional energy conversion between the power system and NGS. Reference [6] proposes an expansion planning framework considering market interactions among various stakeholders. The multi-period framework is proposed in [7] and [8] to determine the optimal generation, transmission and gas network expansions. However, the previous studies mainly propose reserve expansion models of IGPSs under normal conditions without considering the impacts of extreme events. Faced with the increasing frequency of extreme events, several studies have considered the resilience issues in the reserve planning of IGPSs. In [9], a two-stage robust optimization-based co-expansion planning model is developed to enhance the resilience of IGPSs. Reference [10] proposes an optimization-based network hardening model to reinforce the power lines and gas pipelines against windstorms. However, only the costs caused by extreme events are added to the objective function whereas the resilience constraints are not considered in the planning model.

In this paper, a resilience-constrained optimization model is proposed to determine the long-term reserve expansion plan of IGPSs considering the coordination between NGS and power systems. Firstly, the analytical resilience constraints are developed considering the impacts of extreme events, i.e. windstorms. Moreover, the long-term reserve optimization model restricted by resilience constraints is proposed to determine the planning of power units and gas storage. The objective function of the proposed model is to minimize the total costs considering both the operating constraints and investment constraints of IGPSs. Finally, case studies illustrate the validity of the proposed model.

2. MODEL THE IMPACTS OF WINDSTORMS ON IGPSS

The IGPSs consist of power system and gas system connected through GPPs, as shown in Fig. 1. The electric network and gas pipelines are responsible for transmitting energy from power units and gas wells to satisfy the electric loads and gas loads of consumers.

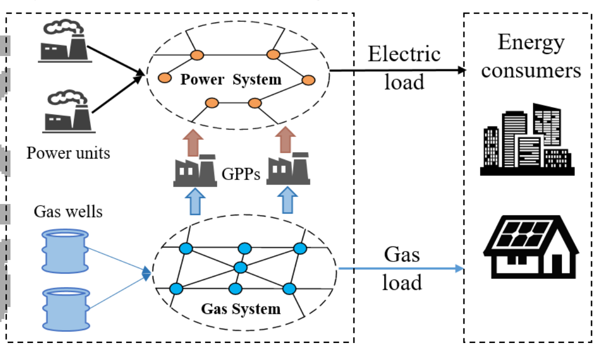

Fig 1. Description of integrated gas and power systems.

Due to the impacts of windstorms, the occurrence of component failures can increase significantly. Since the gas pipelines are usually buried underground, only the impacts of windstorms on the power lines are considered in this paper. The break-down of power lines may make power units disconnected from power system and reduce the available generation capacity, further resulting in load curtailments.

2.1 Component failure model under windstorms

Considering the impacts of windstorms, the fragility of power lines are closely related to the surrounding wind speeds [11]. According to the fragility curves in Fig. 2, the failure probability of power lines can be expressed as:

$$p_l(v) = \begin{cases} p_l^0, & \text{if } v \le v_{critical} \\ p_{l\_v}(v), & \text{if } v_{critical} < v \le v_{collasape} \\ 1, & \text{if } v > v_{critical} \end{cases} \quad (1)$$

where $p_l(v)$ denotes the failure probability of power line l as the function of wind speed of v; p_l^0 denotes the failure probability of line for good weather state; $p_{l\_v}(v)$ denotes the linear relation between unavailability and wind speeds between $v_{critical}$ and $v_{collasape}$.

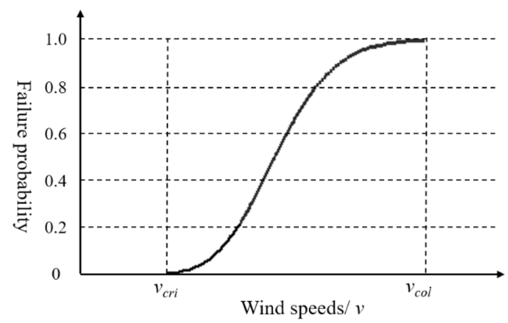

Fig 2. The fragility curves of power lines under windstorms.

2.2 Resilience constraints formulation

According to [10], the resilience of energy systems can be represented as the expected load curtailments after the occurrence of extreme events. In this paper, the expected electric load curtailments (*EELC*) at year t under windstorms can be expressed as:

$$EELC_t = \sum_{s=1}^{K_s}\sum_{b=1}^{K_b} P_s \cdot LC_{tsb} \cdot 1\left(LC_{tsb}\right) \cdot D_b \quad (2)$$

where P_s denotes the probability of contingency state s. LC_{tsb} represents the gas load curtailments for load block b at year t and state s. $1(LC_{tsb})$ is a binary variable, which equals to 1 if $1\left(LC_{tsb}\right) > 0$ and equals to 0 if $1\left(LC_{tsb}\right) \le 0$. K_s is the number of contingency states.

Considering the impacts of windstorms, the operation states of power lines can be either 0 or 1, where 1 corresponds to line connection and 0 corresponds to line outage. Supposing that there are FL failed lines after windstorms, the probability of state s can be calculated using the following equation:

$$P_s = \prod_{l=1}^{FL} p_l(v) \cdot \prod_{l=FL+1}^{L} \left(1 - p_l(v)\right) \quad (3)$$

where L is the total number of power lines.

After the disconnection of power lines caused by windstorms, the original power system may be split into several subsystems. Hence, the electric load curtailments LC_{ts} at year t and state s can be calculated according to the sum of inadequate generation capacity in each subsystem.

$$LC_{ts} = \sum_{h=1}^{H} \left(ED_{tsb}^{h} - \sum_{g} \overline{P_{tsg}^{h}} - \sum_{e} \overline{P_{tse}^{h}} \cdot Z_{te} \right) \quad (4)$$

where ED_{tsb}^{h} denotes the electric loads of subsystem h for load block b at year t and state s. $\overline{P_{tsg}^{h}}$ represents the generation capacity of unit g at year t and state s. $\overline{P_{tse}^{h}}$ and Z_{te} are the generation capacity and investment state of candidate unit e at year t and state s.

After determining the P_s and LC_{ts}, the $EELC_t$ at year t can be represented using (4).

3. LONG-TERM RESERVE EXPANSION MODEL CONSIDERING RESILIENCE CONSTRAINTS

In this section, the mathematical formulation resilience-constrained reserve expansion model is presented.

3.1 Objection function

The proposed planning model is to minimize the total costs in the planning horizon, including investment cost IC, operation costs OC and load curtailment costs CC.

$$\min\ TC = IC + OC + CC \quad (5)$$

The investment cost IC is the total costs of candidate power units, which can be represented as:

$$IC = \sum_{t} \sum_{e} \kappa_t \cdot \overline{P_{te}} \left(z_{et} - z_{e(t-1)} \right) \quad (6)$$

where $\kappa_t = 1/(1+d)^{t-1}$ is net present value and d is the discount rate.

The operation cost OC is the total costs of gas production for wells and power generation for units.

$$OC = \sum_{t} \sum_{b} \kappa_t \cdot \left(\sum_{g} C_g \cdot P_{gtb} + \sum_{e} C_e \cdot P_{etb} + \sum_{w} C_w \cdot W_{wtb} \right) \cdot D_b \quad (7)$$

where P_{gtb} and P_{etb} represent the power output of unit g and candidate unit e for load block b at year t. W_{wtb} denotes the production of gas well w for load block b at year t. C_g, C_e and C_w are energy production costs of unit g, candidate unit e and gas well w, respectively.

Load curtailment cost CC can be calculated as:

$$CC = \sum_{t} \left(\kappa_t \cdot EELC_t \cdot C_t^{E} \right) \quad (8)$$

where C_t^{E} is the cost for electric load curtailment.

3.2 Investment constraints

Once a candidate unit is installed, the investment will be equal to 1 for the remaining years. Hence,

$$Z_{e(t-1)} \le Z_{et} \quad (9)$$

The total installed power generation capacity in the power system should satisfy the energy demand and reserve capacity, which can be expressed as:

$$\sum_{e} \overline{P_{te}} \cdot Z_{et} + \sum_{g} \overline{P_{gt}} \ge ED_{tb} + ER_{tb} \quad (10)$$

where ER_{tb} represents the reserve requirement for load block b at year t.

3.3 Operation constraints

The operation of NGS needs to follow the constraints in (11)-(17). The nodal balance (11) describes that the gas leaving each node is equal to the gas injected at that node. The Weymouth equation (12) describes the relationship between pipeline flow and nodal pressures [1]. Nodal gas pressure and pipeline flow limits are shown (13) and (14). Constraints (15) and (16) describes the operation features of compressors. Production limits of gas wells are shown in (17).

$$\sum_{w} W_{mwtb} - \sum_{p} \tau_{ptb} - \sum_{c} \tau_{ctb} - GD_{mtb} = 0 \quad (11)$$

$$\tau_{ptb} \cdot \left| \tau_{ptb} \right| = M_p \cdot \left(\pi_{mtb}^2 - \pi_{ntb}^2 \right) \quad (12)$$

$$\underline{\pi_m} \le \pi_{mtb} \le \overline{\pi_m} \quad (13)$$

$$\underline{\tau_p} \le \tau_{ptb} \le \overline{\tau_p} \quad (14)$$

$$\Gamma_{ctb} = \pi_{cmtb} / \pi_{cntb} \quad (15)$$

$$\underline{\Gamma_c} \le \Gamma_{ctb} \le \overline{\Gamma_c} \quad (16)$$

$$0 \le W_{mwtb} \le \overline{W_{mw}} \quad (17)$$

where W_{mwtb} denotes gas production of gas well w for load block b at node m and year t. τ_{ptb} and τ_{ctb} represent the gas flow through pipeline p and compressor c for load block b at year t. GD_{mtb}

represents the gas load for load block b at node m and year t. π_{mtb} represents the nodal pressure for load block b at node m and year t. M_p is the transmission coefficient of pipeline p. $\underline{\pi_m}$ and $\overline{\pi_m}$ are the minimum and maximum gas pressures at node m, respectively. $\underline{\tau_p}$ and $\overline{\tau_p}$ are the minimum and maximum gas flows through pipeline p, respectively. Γ_{ctb} is the compressor ratio of compressor c for load block b at year t. $\underline{\Gamma_c}$ and $\overline{\Gamma_c}$ are the minimum and maximum compressor ratios of compressor c, respectively. $\overline{W_{mw}}$ is the maximum production of gas well w at node m.

The operation of power system needs to follow the constraints in (18)-(24). Equation (18) describes the nodal power balance constraint. Equation (19) calculates the line flow using DC model. Line flow constraints and nodal phase angle limits are shown in (20) and (22), respectively. Constraints (22) and (23) restrict the power output of coal-fired power plants (CPPs) and candidate units. The power output of gas-fired power plants (GPPs) is calculated by the corresponding gas supplied to them in (24).

$$\sum_e P_{ietb} + \sum_g \left(P_{igtb}^G + P_{igtb}^C\right) - \sum_l f_{ltb} = ED_{itb}^E \tag{18}$$

$$f_{ltb} = \left(\theta_{itb} - \theta_{jtb}\right) / x_l \tag{19}$$

$$-\overline{f_l} \le f_{ltb} \le \overline{f_l} \tag{20}$$

$$\underline{\theta_i} \le \theta_{itb} \le \overline{\theta_i} \tag{21}$$

$$0 \le P_{igtb}^C \le \overline{P_{ig}} \tag{22}$$

$$-\overline{P_{ie}} \cdot Z_{te} \le P_{ietb} \le \overline{P_{ie}} \cdot Z_{te} \tag{23}$$

$$P_{igtb}^G = GD_{mtb}^G \cdot \psi \tag{24}$$

where P_{igtb}^G and P_{igtb}^C are power outputs of CPPs and GPPs for load block b at node i and year t. f_{ltb} represents the power flow of line l for load block b at year t. ED_{itb}^E is the gas load for load block b at node i and year t. θ_{itb} is the phase angle of node i for load block b at year t. x_l is the reactance of line l. $\overline{f_l}$ is the maximum power flow of line l. $\overline{\theta_i}$ and $\underline{\theta_i}$ are the maximum and minimum phase angle of node i. ψ is the gas gross heating value.

3.4 *Resilience constraints*

In order to determine the long-term reserve considering the impacts of windstorms, the proposed optimization model also needs to satisfy the resilience constraints in (2).

3.5 *Linearization techniques*

The proposed reserve expansion model is formulated as a non-linear integer programming problem, which cannot be effectively solved [1]. In this paper, different linearization techniques are utilized to linearize the non-linear terms in the proposed model.

The non-linear term $\tau_{ptb} \cdot \left|\tau_{ptb}\right|$ of the pipeline flow equation in (12) is linearized using piecewise linearization techniques. The detailed explanations of piecewise linearization techniques can be found in [1].

The non-linear term $LC_{tsb} \cdot 1\left(LC_{tsb}\right)$ of the resilience constraints in (2) is linearized using big-M methods [12]. Firstly, the auxiliary variable RLC_{tsb} is introduced, which is equal to $LC_{tsb} \cdot 1\left(LC_{tsb}\right)$. Through the big-M method, the non-linear term $LC_{tsb} \cdot 1\left(LC_{tsb}\right)$ can be replaced with (25)-(27).

$$\left(\mathbf{1}\left(LC_{tsb}\right) - 1\right) \cdot M \le LC_{tsb} \le \mathbf{1}\left(LC_{tsb}\right) \cdot M \tag{25}$$

$$-M \cdot \mathbf{1}\left(LC_{tsb}\right) \le RLC_{tsb} \le M \cdot \mathbf{1}\left(LC_{tsb}\right) \tag{26}$$

$$LC_{tsb} - M \cdot \left(1 - \mathbf{1}\left(LC_{tsb}\right)\right) \le RLC_{tsb} \le LC_{tsb} + M \cdot \left(1 - \mathbf{1}\left(LC_{tsb}\right)\right) \tag{27}$$

On the basis, the proposed model can be transformed into the linear integer programming problem, which can be solved by Cplex.

4. CASE STUDIES AND DISCUSSIONS

The test system in this paper is composed of IEEE 30-node system and the modified Belgian 20-node gas system [14]. The network topology and the parameters of the test system can be found in [14]. Three GPPs at electric nodes 5, 8 and 13 are assumed to obtain gas supply from gas nodes 3, 7 and 20. Both the gas loads and electric loads have an average load growth rate of 5%. The discount rate is set as 5%. The planning horizon is set as 10 years. The data of six candidate power units is shown in Table I. The line fragility curve is determined according to [11], which is shown in Fig.3.

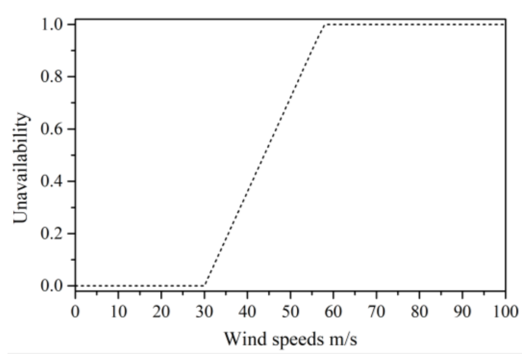

Fig 3. Relationship between failure probability of power lines and winds speeds

In order to evaluate the impacts of windstorms on the planning results of IGPSs, three cases are considered in this paper. Case 1 is the base one where the resilience constraints are not considered. The wind speeds of windstorms in cases 2 and 3 are set as 31m/s and 33m/s, respectively.

Table I. Candidate generating unit data

Power units	Node	Capacity (MW)	Investment costs	Operation costs
GU1	30	80	250	38
GU2	26	60	210	41
GU3	17	50	190	43
GU4	15	90	230	35
GU5	10	70	220	39
GU6	4	40	180	40

The total planning reserve at year 10 for different cases are illustrated in Fig. 4. The planning reserves of IGPSs at year 10 for cases 1, 2 and 3 are 90MW, 280MW and 390MW, respectively. Hence, it can be concluded that more reserve needs to be deployed when considering the resilience constraints of IGPSs. Moreover, the increase of wind speeds can increase the reserve requirements of IGPSs to enhance the resilience to windstorms.

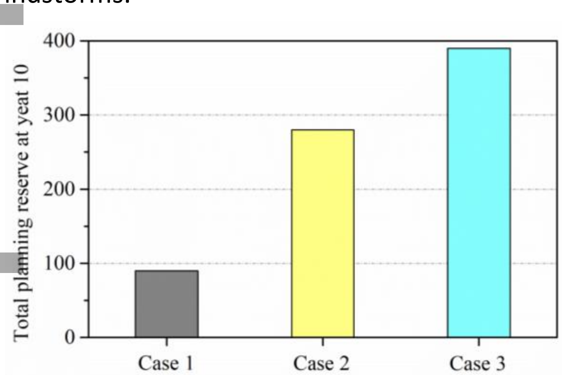

Fig 4. Total planning reserve at year 10 for different cases

Based on the determined planning results in Fig.5, the resilience evaluation results of cases 1 and 2 are compared under windstorms with 31m/s. The resilience evaluation results are illustrated in Fig. 5. It can be noted that the *EELC* values in case 1 are significantly larger than that in case 2, indicating that the power grids in case 1 are vulnerable to windstorms. Furthermore, the neglect of resilience constraints in long-term reserve planning may lead to unreasonable results since the results cannot satisfy resilience requirements. In contrast, the *EELC* values in case 2 are all smaller than the resilience requirements.

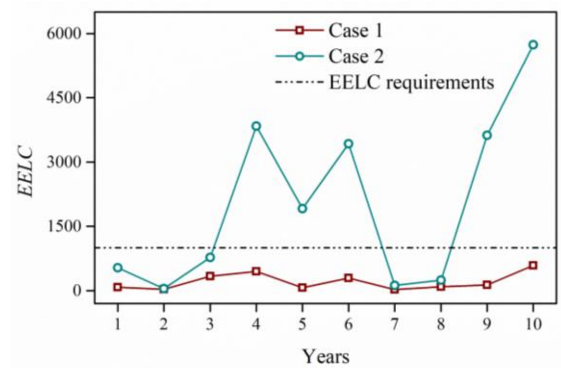

Fig 5. Comparison of resilience evaluation results between cases 1 and 2

5. CONCLUSIONS

This paper proposes a resilience-constrained long-term reserve expansion model to enhance the ability of IGPSs to resist windstorms. Firstly, the analytical resilience constraints of IGPSs are formulated considering the spatial features of windstorms. Moreover, the developed resilience constraints are added into the reserve optimization model to determine the reserve planning results, where both the operating constraints and investment constraints of IGPSs are considered. The simulation results show that the neglect of resilience constraints may lead to over-optimistic planning results. The results further illustrate the necessity to consider resilience constraints in the long-term reserve planning of IGPSs.

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