Optimal Energy Reserve Scheduling in Integrated Electricity and Gas Systems Considering Reliability Requirements

Hengyu Hui, Minglei Bao, Yi Ding, Yang Yang, and Yusheng Xue

***Abstract*—With the growing interdependence between the electricity system and the natural gas system, the operation uncertainties in either subsystem, such as wind fluctuations or component failures, could have a magnified impact on the reliability of the whole system due to energy interactions. A joint reserve scheduling model considering the cross-sectorial impacts of operation uncertainties is essential but still insufficient to guarantee the reliable operation of the integrated electricity and natural gas system (IEGS). Therefore, this paper proposes a day-ahead security-constrained unit commitment (SCUC) model for the IEGS to schedule the operation and reserve simultaneously considering reliability requirements. Firstly, the multi-state models for generating units and gas wells are established. Based on the multi-state models, the expected unserved energy cost (EUEC) and the expected wind curtailment cost (EWC) criteria are proposed based on probabilistic methods considering wind fluctuation and random failures of components in IEGS. Furthermore, the EUEC and EWC criteria are incorporated into the day-ahead SCUC model, which is nonconvex and mathematically reformulated into a solvable mixed-integer second-order cone programming (MISOCP) problem. The proposed model is validated using an IEEE 30-bus system and Belgium 20-node natural gas system. Numerical results demonstrate that the proposed model can effectively schedule the energy reserve to guarantee the reliable operation of the IEGS considering the multiple uncertainties in different subsystems and the cross-sectorial failure propagation.**

***Index Terms*—Integrated electricity and natural gas system (IEGS), natural gas reserve, electric reserve, expected unserved energy cost, expected wind curtailment, multi-state model, operational reliability.**

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H. Hui, M. Bao, and Y. Ding (corresponding author) are with the College of Electrical Engineering, Zhejiang University, Hangzhou, China (email: huihengyu@zju.edu.cn; baominglei@zju.edu.cn; yiding@zju.edu.cn).

Y. Yang is with the Department of Industrial Systems Engineering and Management, National University of Singapore, Singapore (email: yang.yang97@u.nus.edu).

Y. Xue is with State Grid Electric Power Research Institute, Nanjing, China (e-mail: xueyusheng@sgepri.sgcc.com.cn).

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I. Introduction

THE development of natural gas-fired generating units (NGUs) strengthens the interactions between power systems and natural gas systems. The adjustable capacity of the natural gas system plays an important role in the operational reliability management for the integrated electricity and natural gas system (IEGS). Specifically, resources with adjustable potential in natural gas systems such as gas storages and line packs can significantly enhance the operational reliability of IEGS if scheduled properly [1]-[4]. Nevertheless, with improper scheduling or operating approaches, both wind power uncertainties and random failures in either power systems or gas systems can significantly affect the reliable operation of IEGS. For instance, a gas well outage may cause the interruption of gas supply for NGUs and further lead to load interruption in power systems. In August 2017, the disruptions of gas supplied to six NGUs in Tatan power plant caused a massive power blackout in Taiwan, China [5]. In August 2019, due to the sudden failure of an NGU and insufficient system reserves, there was a widespread frequency drop of the power system in England and Wales. The offshore wind turbine generators (WTGs) that could not withstand low frequency were largely off-grid, resulting in major power outages [6]. Therefore, it is necessary to simultaneously schedule the reserves of power and natural gas systems to enhance the reliability for the entire system.

The reserve scheduling of the IEGS has been studied in some research. Reference [7] conducts the economic dispatch model of an IEGS with deterministic reserve demand considering wind power and power-to-gas process. In [1], the deterministic reserve requirement is constrained in the power system when scheduling the IEGS. However, these deterministic methods may be not reliable, because they neglect the variable impact of uncertainties in different subsystems at different times. In this context, the stochastic methods can take different scenarios of failures and their probabilities into account when scheduling the energy reserve and operation for the IEGS. In [8], the proposed coordinated stochastic model incorporates the stochastic power system conditions considering random outages and forecasting errors into the security-constrained unit commitment (SCUC). Reference [9] establishes a stochastic dispatch model for the IEGS based on its proposed security risk constraints to determine the reserve capacity. In [10], a risk-averse adjustable uncertainty set is proposed to describe the stochastic wind error and is incorporated into the day-ahead scheduling to arrange the reserve and operation for IEGS. Reference [11] also proposes a robust day-ahead dispatch model for the IEGS to manage reserve and operation considering renewable uncertainties and $N-1$ contingencies in power systems. In [12], an SCUC model is proposed to dispatch the distributed gas storage considering possible $N-k$ contingencies in power systems. However, these research mainly focuses on the uncertainties in a single energy system. References [9] and [10] only consider the uncertainties of wind power. References [8], [11], and [12] only consider the uncertainties in the power system. Therefore, the uncertainties of multiple components in different subsystems and possible failure propagation due to energy interactions are not considered comprehensively, which may lead to over-optimistic optimization results. To solve the problem, this paper focuses on the impact of multi-type uncertainties in different subsystems and subsequent failure propagation to conduct a stochastic optimal dispatch for the energy reserve and operation of the IEGS.

The studies on the reliability-constrained reserve scheduling under multiple uncertainties have been carried out in a single energy system. Taking the power system as an example, the uncertainties in the power system include wind power uncertainty, probability of generating unit failure, and so on. In this context, the method based on probabilistic criteria has been developed to quantify the operational reserve under multiple uncertainties. In [13], probabilistic criteria such as the expected unserved energy cost (EUEC) considering random failures of generating units are incorporated into the unit commitment model to determine the appropriate quantity of the up reserve (UR) for power systems. Moreover, with the increasing penetration of wind power, the down reserve (DR) is essential to cope with system imbalances, which is the reserve capacity for the sudden decrease of load demand or increase of renewable energy output [14], [15]. The EUEC has limited influences on the dispatch of the DR, and the DR is mainly constrained by the expected wind curtailment cost (EWC) criterion. In [15]-[17], both the EUEC and the EWC are proposed to schedule the UR and the DR in power systems considering wind power uncertainties. However, these criteria neglect the random failures of components in natural gas systems and are no longer suitable for the IEGS. On one hand, the contingencies in natural gas systems directly challenge the operational reliability of the IEGS. On the other hand, they may break the bridge between natural gas systems and power systems by reducing the gas supply of NGUs, and consequently lead to load shedding in power systems. Therefore, when considering the cross-sectorial failure propagation, the previous methods may not be applicable for the reserve scheduling of the IEGS. In this context, it is urgent to develop new probabilistic reliability criteria for co-optimizing the multi-energy reserve in the IEGS.

To formulate the probabilistic criteria considering uncertainties, it is essential to select reasonable models to characterize the operating states of components. The probabilistic criteria in the aforementioned researches are usually formulated utilizing two-state generating unit models, where the units can only be in well-functioning state or failure state. However, utilizing simple two-state models of generating units in reliability analysis may yield pessimistic appraisals [18]. Multi-state models have been utilized to characterize the output of WTGs and the random failure nature of generating units and gas wells [19]-[21]. In [19], the multi-state model is utilized to describe the random failures of generating units in a distributed generation system. In [20], simulation results show that the wind speed distribution can be discretized into a multi-state model with reasonable accuracy for reliability analyses. Therefore, it is important to build novel reliability criteria considering the multi-state operating characteristics of components in IEGS.

This paper proposes a probabilistic method to schedule the operation and reserve simultaneously under the reliability criteria considering wind fluctuation and random component failures. Compared with the previous studies, the main contributions of the proposed model can be summarized as follows.

1) A novel model is proposed to incorporate reliability criteria into the SCUC model of IEGS to schedule the electric reserve and the gas reserve simultaneously. The probabilistic reliability criteria for IEGS include the EUEC and the EWC, which are formulated considering cross-sectorial failure propagation.

2) The multi-state models of generating units and gas wells considering both DR and UR are proposed in this paper. The multi-state model can reflect the operation of components more precisely under partial fault conditions compared with the two-state model, where the units can only be in full functioning or failure state [18], [22].

3) The nonconvex constraints of natural gas systems are reformulated by the second-order cone (SOC) relaxation, which can be solved using the mixed-integer second-order cone programming (MISOCP) method. The MISOCP can effectively solve the nonconvex natural gas flow equations with a limited relaxation error, and helps with the joint reserve management of IEGS.

II. Reserve Scheduling in IEGS Considering Failure Propagation

A. Impacts of Random Failures in Natural Gas Systems on Power Systems

The reliable operation of the IEGS is threatened by multiple contingencies such as extreme weather [23], human error [5], and misoperation. With the developing coupling between subsystems of IEGS, the failure in one system may propagate to its interacted system [24]. Figure 1 illustrates the failure propagation from natural gas systems to power systems and its impact on reserve scheduling.

The corresponding propagation steps are presented bellow.

Step 1: a contingency causes an initial failure of components in natural gas systems, and the natural gas generation may not satisfy the total gas demands.

Step 2: due to the shortage of natural gas, the gas supplied to NGUs is reduced or completely cut off.

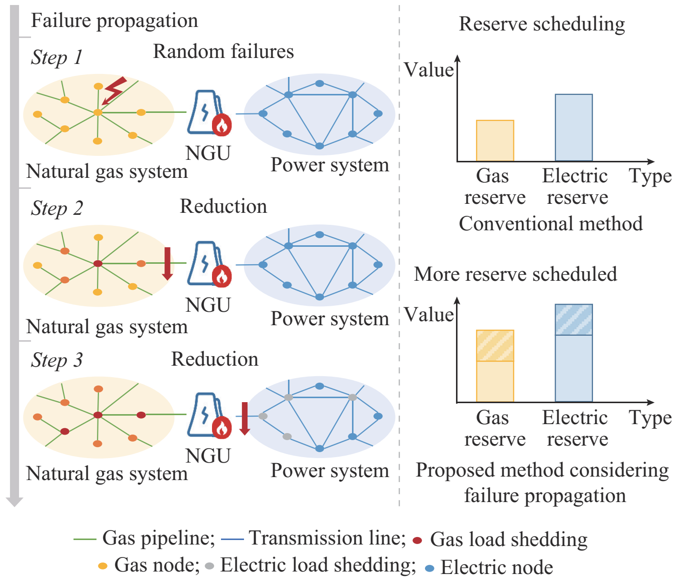

Fig. 1. Framework of failure propagation from natural gas systems to power systems and its impact on reserve scheduling.

Step 3: because of the interruption of the gas supplied to NGUs, the electricity output of NGUs drops rapidly, resulting in electric load shedding.

It can be observed that random failures in natural gas systems could affect not only the reliable operation of natural gas systems but that of electricity systems. If the impact of the failure propagation is ignored, the scheduled energy reserve is insufficient when actual failures occur, causing serious consequences such as blackouts. Therefore, it is essential to comprehensively consider the uncertainties in both subsystems and the failure propagation when scheduling the energy reserve for the IEGS.

B. Outline of This Paper for Reserve Scheduling

The outline for reserve scheduling of the IEGS is illustrated in Fig. 2. A multi-state model is proposed at first to characterize the output and reserve capacity of components in Section III. Three types of reserve are considered in this paper, i. e., electric UR, electric DR, and gas reserve. Moreover, two types of generating units are considered in this paper, i. e., WTG and fossil-fuel generating units (FGUs). In Fig. 2, k_{egn}, k_{gwn}, and k_{wn} are the states of the FGU *egn*, gas well *gwn*, and WTG *wn*, respectively; $P_{eg,t}$, $P_{w,t}$, and $P_{gw,t}$ are the generation powers of the FGU *egn*, gas well *gwn*, and WTG *wn*, respectively; and $\boldsymbol{s}$ is the operational state of the IEGS aggregated by the states of these components. These parameters are presented and utilized in the multi-state model of components, i. e., constraints (1)-(6) in Section III. Based on the multi-state model of components, the reliability criteria are formulated considering the failure propagation.

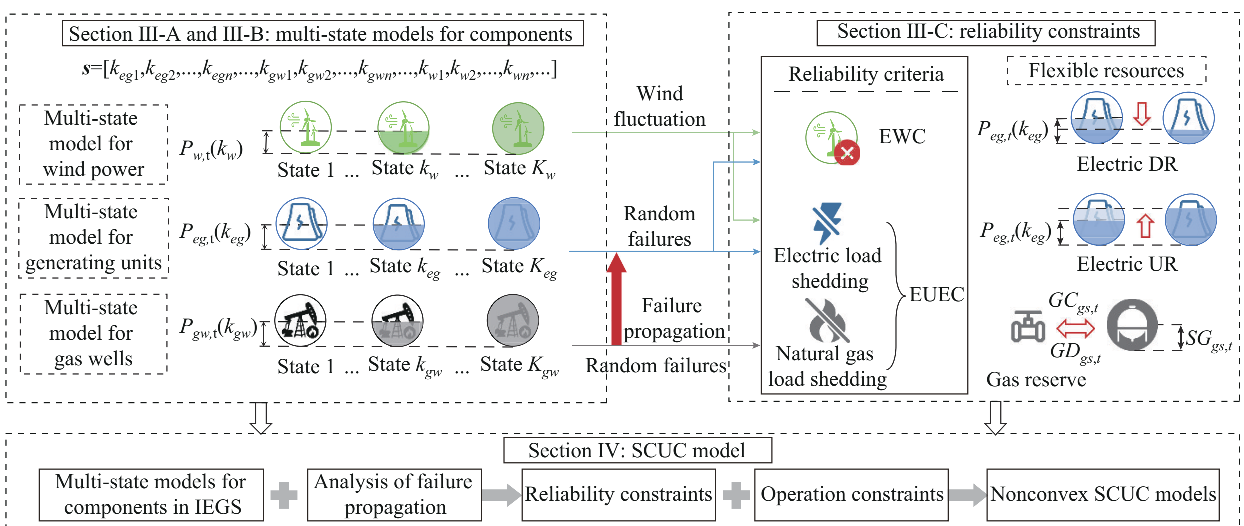

Fig. 2. Outline for reserve scheduling of IEGS.

In Section IV, the reliability criteria are incorporated into the SCUC model. Besides the reliability criteria, the optimal scheduling model for operation and reserve arrangement in IEGS satisfies power system constraints, natural gas system constraints, and gas storage constraints.

The proposed model is a nonconvex problem and Section V introduces the solution methodology for it. Section VI analyzes the impact of failure in power systems on natural gas systems. Consequently, the energy reserve and operation can be scheduled under reliability criteria in Section VII. Section VIII concludes this paper.

III. Probabilistic Criteria Based on Multi-state Models

A. Multi-state Model for FGUs and Gas Wells

The operating state of components in power systems or natural gas systems is usually characterized by two-state models. However, in reality, an operating component may be in an intermediate state between well-functioning and full failure. For instance, an FGU may generate the scheduled power but do not have sufficient dispatchable capacity. In these failure states, not only the operating power could change, but also the maximal dispatchable generating capacity (MADGC) and the minimal dispatchable generation capacity (MIDGC) would be affected, which has a pessimistic impact on the reliability of systems during real-time operation [25]. Therefore, multi-state models for the components in IEGS are introduced to describe the operating states in more details, especially partial failure.

Meanwhile, both the UR and the DR should be formulated in the multi-state models. UR is the reserve capacity designed to provide an increased rate of generation. DR is the reserve capacity for the sudden decrease of load demand or increase of renewable energy output [15], [26]. With the high penetration of wind power, it is necessary to utilize the DR to cope with system imbalances. Therefore, a four-state model for FGUs and gas wells considering both the UR and the DR is shown in Fig. 3, where $R_{eg,t}^{up}$ is the scheduled UR for FGU eg at interval t; $R_{eg,t}^{dn}$ is the scheduled DR for FGU eg at interval t; and $R_{eg,t}$ is the scheduled generation for FGU eg at interval t.

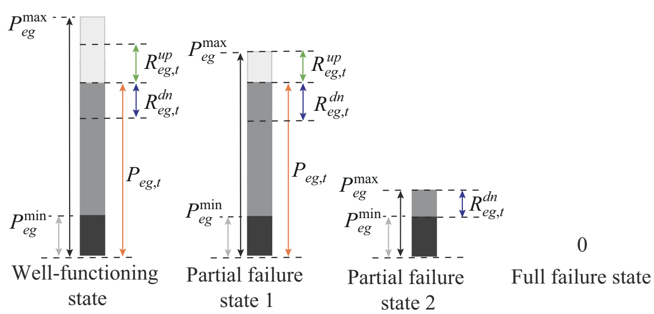

Fig. 3. Multi-state model for FGUs.

In the well-functioning state, the MADGC is equal to the generation schedule plus the UR. The MIDGC is equal to the generation schedule minus the DR. In partial failure state 1, the maximal generation level is inferior to the generation schedule plus the UR. The minimal generation level is inferior to the generation schedule minus the DR. It indicates that the FGU can satisfy the requirement of generation scheduling and provide sufficient DR, but cannot provide sufficient UR for the operational time period t. The MADGC should be equal to the maximal generation capacity in partial failure state 1. In partial failure state 2, the maximal generation level is inferior to the scheduled generation. It indicates that the FGU can neither satisfy the generation scheduling requirement nor provide sufficient UR during time period t for power systems. The MADGC should be equal to the maximal generation level in partial failure state 2. Besides, the minimal generation level could be larger than the MADGC minus the DR. It is possible that the FGU cannot provide sufficient DR during time period t. In the complete failure state, both the maximal and minimal generation levels are zero, and the generation output is also zero. Therefore, the MADGC and MIDGC under different states during the operational time period t can be evaluated as:

$$P_{eg,t}^{\max,s} = \min\left\{P_{eg,t} + R_{eg,t}^{up}, P_{eg}^{\max}(k_{eg})\right\} \tag{1}$$

$$P_{eg,t}^{\min,s} = \max\left\{P_{eg,t} - R_{eg,t}^{dn}, P_{eg}^{\min}(k_{eg})\right\} \tag{2}$$

where $P_{eg}^{\max}(k_{eg})$ and $P_{eg}^{\min}(k_{eg})$ are the maximal and minimal generation capacities of the FGU eg in state k_{eg}, respectively.

Similar to the multi-state model of FGUs, the dispatchable generating capacity of a gas well gw for each state k_{gw} during time period t can be evaluated as:

$$P_{gw,t}^{s} = \min\left\{P_{gw,t}, P_{gw}^{\max}(k_{gw})\right\} \tag{3}$$

where $P_{gw,t}$ is the scheduled generation of a gas well gw during time period t; and $P_{gw}^{\max}(k_{gw})$ is the maximal generation capacity of a gas well gw in state k_{gw}. In this paper, we assume that gas wells do not provide UR or DR like fossil-fuel FGUs.

B. Multi-state Models for Wind Power Output

Considering the fluctuation of wind speeds, the power output of WTGs is usually represented by multi-state models. It has been proven that the 6-state wind speed model can be utilized for reliability analysis with reasonable accuracy [20]. Generally, the wind speed for a WTG can be expressed as:

$$\begin{cases} V_{w,t}(k_w) = \mu_{w,t} + (k_w - 3)(5\delta_{w,t}/3) \\ pr_{w,t}(k_w) = pr(V_{w,t}(k_w)) \end{cases} \quad k_w = 1, 2, \ldots, 6 \tag{4}$$

where $\mu_{w,t}$ and $\delta_{w,t}$ are the mean value and variance of wind speed distribution of WTG w during time period t, respectively; and $V_{w,t}(k_w)$ and $pr_{w,t}(k_w)$ are the wind speed and corresponding probability of WTG w in state k_w at time period t, respectively.

The power output of a WTG may vary continuously and intermittently from zero to the rated value depending on the wind speed at the wind farm. The output of a WTG can be determined from its power curve, which is a plot of output power against wind speed [27]. The mathematical expression for a typical power curve of a WTG can be expressed as:

$$P_{w,t}(k_w) = \begin{cases} 0 & 0 \le V_{w,t}(k_w) < V_w^{ci} \cup V_w^{co} < V_{w,t}(k_w) \\ P_w^{rate}(A_w + B_w V_{w,t}(k_w) + C_w V_{w,t}^2(k_w)) & \\ & V_w^{ci} \le V_{w,t}(k_w) < V_w^{r} \\ P_w^{rate} & V_w^{r} \le V_{w,t}(k_w) \le V_w^{co} \end{cases} \tag{5}$$

where V_w^{ci}, V_w^{co}, and V_w^{r} are the cut-in speed, cut-out speed, and rated speed of WTG w, respectively; and P_w^{rate} is the rated power of WTG w when the wind speed is between the rated speed and cut-out speed. These parameters including A_w, B_w, and C_w can be found in [28]. Together with (4) and (5), the power output of WTGs can be discretized and expressed with multi-state models.

C. Formulation of Reliability Constraints

The operational reliability of the IEGS is affected by uncertainties of components and the energy interaction between subsystems. In view of that, the reliability constraints of natural gas systems are first established based on the multi-state model of gas wells. Furthermore, the reliability constraints of power systems are formulated with consideration of the failure propagation as well as the multi-state models of FGUs and WTGs.

Therefore, the reliability constraints of the IEGS are depended on the operational states of each FGU, WTG, and gas well. The operational state of the IEGS is the state space aggregated by the states of these components. The power output of each FGU and gas well can be in different states during real-time operation. These states can be assembled together to represent states of the IEGS as:

$$\boldsymbol{s}=[k_{eg1},k_{eg2},...,k_{egn},...,k_{gw1},k_{gw2},...,k_{gwn},...,k_{w1},k_{w2},...,k_{wn},...] \tag{6}$$

For a specific state $\boldsymbol{s}$ of the IEGS, the probability is equal to the production of the probability of FGU states, gas well states, and WTG states.

1) Formulation of Reliability Criteria in Natural Gas Systems

The expected unserved natural gas cost (EUNG) in state $\boldsymbol{s}$ is equal to the total natural gas demand minus the total MADGC of the natural system. The total natural gas demand in EUNG excludes the gas supplied to NGUs. This is because operators always cut off gas supplied to NGUs first to ensure other natural gas loads as much as possible when the total natural gas demand exceeds the MADGC [1], [29]. Therefore, the EUNG considering different states during time period t can be evaluated as:

$$EUNG_t=\sum_{s\in NS}(DG_t-\sum_{gs}RGD_{gs,t}-\sum_{gw}P^{s}_{gw,t})\varsigma^{s}_t\cdot VOLL_g\cdot\Delta t\prod_{gw}pr^{s}_{gw,t} \tag{7}$$

where DG_t is the natural gas demand s during time period t; $RGD_{gs,t}$ is the releasing rate of a gas storage gs during time period t in contingencies; ς^s_t equals to 1 only when NGUs are completely cut off and there is still a shortage of natural gas; $VOLL_g$ is the penalty price of natural gas load shedding; $pr^{s}_{gw,t}$ is the probability that the gas well gw is in state $\boldsymbol{s}$ during time period t; and NS is the set of different states.

2) Formulation of Reliability Criteria in Power Systems Considering Failure Propagation

The reliability criteria in power systems include the expected unserved electric load cost (EUEL) and the EWC. The EUEL in state $\boldsymbol{s}$ is equal to the total load demand minus the total MADGC of the power system and the total wind power output. Moreover, the operating state of NGUs closely interacts with the gas supplied to them. When a component in the natural gas system fails, the gas supplied to NGUs will be reduced. Consequently, the failure propagation could reduce the output of NUGs and have an impact on the EUEL. The EUEL considering different states during time period t can be evaluated as:

$$EUEL_t=\sum_{s\in NS}\Bigg[DE_t-\sum_{eg\in CGU}P^{\max,s}_{eg,t}-\sum_{w}P_{w,t}-\max\Bigg\{0,\sum_{eg\in NGU}P_{eg,t}-\Big(DG_t-\sum_{gs}RGD_{gs,t}-\sum_{gw}P^{s}_{gw,t}\Big)\eta_{g2e}\Bigg\}\Bigg]\cdot\xi^{s}_t\cdot VOLL_e\cdot\Delta t\prod_{eg}pr^{s}_{eg,t}\prod_{gw}pr^{s}_{gw,t}\prod_{w}pr^{s}_{w,t} \tag{8}$$

where DE_t is the electrical demand during time period t; η_{g2e} is the conversion efficiency from gas to electricity; ξ^s_t is a binary variable and equals to 1 if there is electricity load interruption in state $\boldsymbol{s}$ during time period t; $VOLL_e$ is the penalty price of electricity load shedding; and $pr^s_{eg,t}$ and $pr^s_{w,t}$ are the probabilities that the FGU eg and WTG w are in state $\boldsymbol{s}$ during time period t, respectively.

Equation (8) indicates that if the gas shortage is less than the gas supplied to NGUs, the power generation of NGUs will be reduced. Furthermore, if the gas shortage is greater than the gas supplied to NGUs, the gas supplied to NGUs will be completely cut off and NGUs cannot generate power.

Moreover, the EWC under state $\boldsymbol{s}$ is equal to the total wind power output plus the total MIDGC subtract the total load demand. The EWC considering different states during time period t can be evaluated as:

$$EWC_t=\sum_{s\in NS}\Bigg(\sum_{eg}P^{\min,s}_{eg,t}+\sum_{w}P_{w,t}-DE_t\Bigg)\psi^{s}_t\cdot VOLL_w\cdot\Delta t\cdot\prod_{eg}pr^{s}_{eg,t}\prod_{w}pr^{s}_{w,t} \tag{9}$$

where ψ^s_t is a binary variable and equals to 1 if there exists wind curtailment in state $\boldsymbol{s}$ during time period t; and $VOLL_w$ is the potential loss price of the wind curtailment.

IV. Formulation of Probabilistic SCUC in IEGS

Based on the multi-state model of components in IEGS, the SCUC model considering the probabilistic constraints is proposed to schedule the generation, operating reserve of FGUs, and gas storage.

A. Objective Function

The objective of the probabilistic SCUC model is to minimize the operation cost of the IEGS, including the power system cost (the operation cost, reserve cost, startup cost, and shutdown cost of all FGUs) and natural gas system cost (generation cost of gas wells and operation cost of gas storage).

$$\min f=\sum_{t}\sum_{eg}[EC_{eg}(P_{eg,t},x_{eg,t})+R^{up}_{eg,t}\cdot RC^{up}_{eg,t}+R^{dn}_{eg,t}\cdot RC^{dn}_{eg,t}]+\sum_{t}\sum_{eg}(SU_{eg}\cdot y_{eg,t}+SD_{eg}\cdot z_{eg,t})+\sum_{t}\sum_{gw}\rho_{gas}P_{gw,t}+\sigma_{gs}\sum_{t}\sum_{gs}(GC_{gs,t}+GD_{gs,t}) \tag{10}$$

where EC_{eg} is the operation cost of the FGU eg; $R^{up}_{eg,t}$ and $R^{dn}_{eg,t}$ are the UR and DR costs of the FGU eg during time period t, respectively; SU_{eg} and SD_{eg} are the startup and shut down costs of FGU eg, respectively; $x_{eg,t}$, $y_{eg,t}$, and $z_{eg,t}$ are binary variables and equal to 1 if the FGU eg is online, start up, and shut down at time period t, respectively; and ρ_{gas} and σ_{gs} are the price of natural gas and the operation cost of gas storage, respectively.

B. Constraints

The operation of the IEGS should be constrained by the power system constraints, natural gas system constraints, gas storage constraints, and the aforementioned reliability constraints.

1) Power System Constraints

The constraints for the operation of power systems include the power balance constraint, the transmission line constraint, the phase angle constraint, and the operation constraints of FGUs.

The power balance at each bus can be expressed as:

$$\sum_{i \in N}\left(\sum_{eg \in NG_i} P_{eg,t} + \sum_{w \in NW_i} P_{w,t} - \sum_{d \in NL_i} DG_{d,t}\right) - \sum_{j \in \phi_i} B_{ij}(\theta_{i,t} - \theta_{j,t}) = 0 \tag{11}$$

where NG_i, NW_i, and NL_i are the sets of FGUs, WTGs, and loads at bus i, respectively; B_{ij} is the admittance of the transmission line between bus i and bus j; and $\theta_{i,t}$ is the phase angle of bus voltage at bus i during time period t.

The power flow between bus i and bus j can be evaluated as:

$$\left|B_{ij}(\theta_{i,t} - \theta_{j,t})\right| \le \left|F_{ij}^{\max}\right| \tag{12}$$

where $F_{ij}^{\max}$ is the maximal power flow of the transmission line between bus i and bus j.

The phase angle at each bus should be constrained by:

$$\theta^{\min} \le \theta_{i,t} \le \theta^{\max} \tag{13}$$

where $\theta^{\max}$ and $\theta^{\min}$ are the maximal and minimal phase angles of bus voltage, respectively.

Moreover, the constraints for the operation of FGUs include the output limits in (14), reserve limits in (15), ramping constraints in (16), minimal online and offline time periods limits in (17) and (18), and binary variable functions in (19).

$$P_{eg}^{\min} x_{eg,t} \le P_{eg,t} \le P_{eg}^{\max} x_{eg,t} \tag{14}$$

$$\begin{cases} R_{eg,t}^{up} \le x_{eg,t} \cdot \min\{P_{eg}^{\max} - P_{eg,t}, r_{eg}^{+}\} \\ R_{eg,t}^{dn} \le x_{eg,t} \cdot \min\{P_{eg,t} - P_{eg}^{\min}, r_{eg}^{-}\} \end{cases} \tag{15}$$

$$\begin{cases} P_{eg,t} - P_{eg,t-1} \le r_{eg}^{+}[1 - x_{eg,t}(1 - x_{eg,t-1})] \\ P_{eg,t-1} - P_{eg,t} \le r_{eg}^{-}[1 - x_{eg,t-1}(1 - x_{eg,t})] \end{cases} \tag{16}$$

$$\begin{cases} \sum_{t=1}^{T_{eg}^{up}} (1 - x_{eg,t}) = 0 \\ \sum_{\tau=t}^{t+T_{eg}^{on}-1} x_{eg,\tau} \ge T_{eg}^{on}(x_{eg,t} - x_{eg,t-1}) \quad t \in [T_{eg}^{up}+1, T - T_{eg}^{on}+1] \\ \sum_{\tau=t}^{T} [x_{eg,\tau} - (x_{eg,t} - x_{eg,t-1})] \ge 0 \quad t \in [T - T_{eg}^{on}+2, T] \end{cases} \tag{17}$$

$$\begin{cases} \sum_{t=1}^{T_{eg}^{dn}} x_{eg,t} = 0 \\ \sum_{\tau=t}^{t+T_{eg}^{off}-1} (1 - x_{eg,\tau}) \ge T_{eg}^{off}(x_{eg,t-1} - x_{eg,t}) \quad t \in [T_{eg}^{dn}+1, T - T_{eg}^{off}+1] \\ \sum_{\tau=t}^{T} [1 - x_{eg,\tau} - (x_{eg,t-1} - x_{eg,t})] \ge 0 \quad t \in [T - T_{eg}^{off}+2, T] \end{cases} \tag{18}$$

$$\begin{cases} y_{eg,t} - z_{eg,t} = x_{eg,t+1} - x_{eg,t} \\ y_{eg,t} + z_{eg,t} \le 1 \end{cases} \tag{19}$$

where $P_{eg}^{\max}$ and $P_{eg}^{\min}$ are the maximal and minimal generation capacities of FGU eg, respectively; r_{eg}^{+} and r_{eg}^{-} are the up and down ramping rates of FGU eg, respectively; T_{eg}^{up} and T_{eg}^{dn} are the initial times of startup and shutdown of FGU eg, respectively; and T_{eg}^{on} and T_{eg}^{off} are the minimal online and offline time periods of FGU eg, respectively.

2) Natural Gas System Constraints

The components of natural gas networks are similar to those of power systems in IEGS, which consists of the gas flow balance constraint, the pipeline flow constraints, nodal gas pressure constraint, and gas well generation limits.

The nodal gas flow balance can be expressed as:

$$\sum_{gw \in GW_m} P_{gw,t} - DG_{m,t} - \sum_{eg \in NGU_m} P_{eg,t}/\eta_{g2e} - \sum_{n \in \phi_m} GF_{mn,t} + \sum_{gs \in GS_m} (GD_{gs,t} - GC_{gs,t}) = 0 \tag{20}$$

where GW_m, NGU_m, and GS_m are the sets of gas wells, NGUs, and gas storages at bus m, respectively; $DG_{m,t}$ is the natural gas demand at bus m during time period t; $GF_{mn,t}$ is the gas flow of pipeline between node m and node n at time period t; and $GC_{gs,t}$ and $GD_{gs,t}$ is the storing and releasing rates of a gas storage gs during time period t, respectively.

The pipeline flow $GF_{mn,t}$ can be expressed as:

$$sgn(GF_{mn,t}) \cdot GF_{mn,t}^2 = C_{mn}^2(\pi_{m,t}^2 - \pi_{n,t}^2) \tag{21}$$

$$sgn(GF_{mn,t}) = sgn(\pi_{m,t}, \pi_{n,t}) = \begin{cases} 1 & \pi_{m,t} > \pi_{n,t} \\ -1 & \pi_{m,t} < \pi_{n,t} \end{cases} \tag{22}$$

$$\left|GF_{mn,t}\right| \le GF_{mn}^{\max} \tag{23}$$

where π_m is the nodal gas pressure at node m; and $GF_{mn}^{\max}$ is the maximal gas flow of pipeline between node m and node n.

The nodal gas pressure should be constrained by:

$$\pi_m^{\min} \le \pi_{m,t} \le \pi_m^{\max} \tag{24}$$

where $\pi_m^{\min}$ and $\pi_m^{\max}$ are the minimal and maximal gas pressures at node m, respectively.

Moreover, the output of gas wells can be limited by:

$$P_{gw}^{\min} \le P_{gw,t} \le P_{gw}^{\max} \tag{25}$$

where $P_{gw}^{\min}$ and $P_{gw}^{\max}$ are the minimal and maximal generations of a gas well gw, respectively.

3) Natural Gas Storage Constraints

The natural gas storage constraints include the storing rate limits of gas storage in (26), the releasing rate limits of gas storage in (27), and the gas storage limits in (28). Equation (29) denotes the amount of natural gas been stored during time period t. Equation (30) denotes that the gas storage at the final hour should be equal to that of the initial hour.

$$0 \le GC_{gs,t} \le GC_{gs}^{\max} \tag{26}$$

$$0 \le GD_{gs,t} \le GD_{gs}^{\max} \tag{27}$$

$$SG_{gs}^{\min} \le SG_{gs,t} \le SG_{gs}^{\max} \tag{28}$$

$$SG_{gs,t} = SG_{gs,t-1} + \eta_{gs}^{c} \cdot GC_{gs,t} - GD_{gs,t}/\eta_{gs}^{d} \tag{29}$$

$$SG_{gs,0} = SG_{gs,NT} \tag{30}$$

where $GC_{gs}^{\max}$ and $GD_{gs}^{\max}$ are the maximal storing and releasing rate of gas storage gs, respectively; $SG_{gs,t}$ is the current level of a gas storage gs during time period t; $SG_{gs}^{\min}$ and $SG_{gs}^{\max}$ are the minimal and maximal gas capacities of gas storage gs, respectively; and η_{gs}^{c} and η_{gs}^{d} are the storing and releasing efficiencies, respectively.

The natural gas storage provides IEGS with adjustable supply or demand when there is a deficit or surplus of natural gas production. In accordance with the electric reserves, the gas reserves can consist of two directions of reserves, i.e., gas UR and gas DR [30]. In this paper, the two directions of gas reserves are provided by gas storages. Specifically, gas UR is the gas releasing process of gas storages for the increase of gas load demand. Gas DR is the gas storing process of gas storages for the decrease of gas load demand. Equations (31)-(33) represent the gas reserve limits.

$$\begin{cases} 0 \le RGD_{gs,t} \le GD_{gs}^{\max} \\ 0 \le RGC_{gs,t} \le GC_{gs}^{\max} \end{cases} \tag{31}$$

$$\begin{cases} SG_{gs,t}^{r1} = SG_{gs,t-1} - RGD_{gs,t}/\eta_{gs}^{d} \\ SG_{gs,t}^{r2} = SG_{gs,t-1} + \eta_{gs}^{c} \cdot RGC_{gs,t} \end{cases} \tag{32}$$

$$\begin{cases} SG_{gs}^{\min} \le SG_{gs,t}^{r1} \le SG_{gs}^{\max} \\ SG_{gs}^{\min} \le SG_{gs,t}^{r2} \le SG_{gs}^{\max} \end{cases} \tag{33}$$

where $RGC_{gs,t}$ and $RGD_{gs,t}$ are the gas DR and UR capacities of gas storage gs, respectively; and $SG_{gs,t}^{r1}$ and $SG_{gs,t}^{r2}$ are the levels of gas storage gs after providing the gas DR and UR, respectively.

4) Unserved Energy and Wind Power Curtailment Constraints

The energy supplied by the IEGS consists of natural gas energy and electricity energy. Therefore, the EUEC in IEGS is equal to the sum of the EUNG in (7) and the EUEL in (8). Considering the reliability requirements, the EUEC in IEGS should be constrained by a certain value in (35), and the EWC in power systems is constrained by (36).

$$EUNG_t + EUEL_t = EUEC_t \tag{34}$$

$$EUEC_t \le EUEC_t^{\max} \tag{35}$$

$$EWC_t \le EWC_t^{\max} \tag{36}$$

where $EUEC_t^{\max}$ and $EWC_t^{\max}$ are the set maximum values of the EUEC and the EWC during time period t, respectively.

V. Solution Methodology

The proposed model is a mixed-integer nonlinear optimization problem since there are nonconvex items in (1)-(9) and (21)-(23). In order to find out the global optimal solution of the problem, the big-M linearization method and the SOC relaxation are utilized to convert the problem into an MISOCP. The piecewise constraints (1)-(9) are reformed into linear constraints by the big-M linearization method, and the nonconvex constraints (21)-(23) are relaxed to standard SOC constraints.

A. Big-M Linearization Method

The big-M linearization method is used to reformulate the piecewise constraints (1)-(9) into linear expressions. For instance, the minimum function in (1) should be eliminated and replaced by linear expressions. Assume that:

$$RC_{eg,t}(k_{eg}) = (P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up})\gamma_{eg,t}(k_{eg}) \tag{37}$$

where $\gamma_{eg,t}(k_{eg})$ is a binary variable defined as:

$$\gamma_{eg,t}(k_{eg}) = \begin{cases} 1 & 0 \le P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up} \\ 0 & 0 > P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up} \end{cases} \tag{38}$$

Therefore, the minimum function in (1) can be replaced with:

$$\begin{aligned} P_{eg,t}^{\max,s} = \min\left\{P_{eg,t} + R_{eg,t}^{up}, P_{eg}^{\max}(k_{eg})\right\} = \\ P_{eg}^{\max}(k_{eg}) - (P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up})\gamma_{eg,t}(k_{eg}) = \\ P_{eg}^{\max}(k_{eg}) - RC_{eg,t}(k_{eg}) \end{aligned} \tag{39}$$

Equation (37) contains items that are the products of continuous and binary variables, which can be replaced with:

$$(P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up})/M \le \gamma_{eg,t}(k_{eg}) \tag{40}$$

$$\gamma_{eg,t}(k_{eg}) \le 1 + (P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up})/M \tag{41}$$

$$-M\gamma_{eg,t}(k_{eg}) \le RC_{eg,t}(k_{eg}) \le M\gamma_{eg,t}(k_{eg}) \tag{42}$$

$$P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up} - M(1-\gamma_{eg,t}(k_{eg})) \le RC_{eg,t}(k_{eg}) \tag{43}$$

$$RC_{eg,t}(k_{eg}) \le P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t}^{up} + M(1-\gamma_{eg,t}(k_{eg})) \tag{44}$$

where M is a very big positive number.

Using the same method, the minimum function in (3) and the maximum functions in (2) and (8) can be linearized. Constraints (7)-(9) which also contain the items that are the products of continuous and binary variables can be linearized by similar methods in (40)-(44).

B. SOC Relaxation

The nonconvex constraints (21)-(23) need to be relaxed into standard SOC constraints. Equations (21)-(23) can be reformulated as (45)-(48) with newly introduced binary integers instead of the sign function:

$$GF_{mn,t}^2 = (I_{mn,t}^+ - I_{mn,t}^-)C_{mn}^2(\pi_{m,t}^2 - \pi_{n,t}^2) \tag{45}$$

$$I_{mn,t}^+ + I_{mn,t}^- = 1 \tag{46}$$

$$-(1 - I_{mn,t}^+)\cdot GF_{mn}^{\max} \le GF_{mn,t} \le (1 - I_{mn,t}^-)\cdot GF_{mn}^{\max} \tag{47}$$

$$(1 - I_{mn,t}^+)\pi_{m,\min}^2 \le \pi_{m,t}^2 - \pi_{n,t}^2 \le (1 - I_{mn,t}^-)\pi_{n,\max}^2 \tag{48}$$

where $I_{mn,t}^+$ and $I_{mn,t}^-$ are binary variables equal to 1 if the gas flow is from node m to node n and from node n to node m during time period t, respectively.

Equation (45) is further relaxed to (50) with the new ancillary variable $\gamma_{mn,t}$.

$$\gamma_{mn,t} = (I_{mn,t}^+ - I_{mn,t}^-)(\pi_{m,t}^2 - \pi_{n,t}^2) \tag{49}$$

$$\gamma_{mn,t}C_{mn} \ge GF_{mn,t}^2 \tag{50}$$

Constraint (50) is a standard SOC constraint that can be solved using the SOC programming method. Equation (49) can be linearized in similar methods in (40)-(44) to (51)-(54).

$$\gamma_{mn,t} \ge \pi_n^2 - \pi_m^2 + (\pi_{m,\min}^2 - \pi_{n,\max}^2)(I_{mn,t}^+ - I_{mn,t}^- + 1) \tag{51}$$

$$\gamma_{mn,t} \ge \pi_m^2 - \pi_n^2 + (\pi_{m,\max}^2 - \pi_{n,\min}^2)(I_{mn,t}^+ - I_{mn,t}^- - 1) \tag{52}$$

$$\gamma_{mn,t} \le \pi_n^2 - \pi_m^2 + (\pi_{m,\max}^2 - \pi_{n,\min}^2)(I_{mn,t}^+ - I_{mn,t}^- + 1) \tag{53}$$

$$\gamma_{mn,t} \le \pi_m^2 - \pi_n^2 + (\pi_{m,\min}^2 - \pi_{n,\max}^2)(I_{mn,t}^+ - I_{mn,t}^- - 1) \tag{54}$$

So far, the nonconvex constraints of the proposed model are reformulated by linear simplification and SOC relaxation. Now, the model only has linear constraints and standard SOC inequalities, which can be solved using the

MISOCP method.

The architecture of the proposed SCUC model considering the reliability requirements and its reformulation methods is shown in Fig. 4. In reliability constraints, a multi-state model is proposed at first to characterize the wind fluctuation and uncertainties of components in natural gas systems and power systems. Based on the multi-state model, the reliability criteria are formulated considering the failure propagation. Incorporating the reliability constraints with the basic operation constraints of the IEGS constitutes the proposed SCUC model. Furthermore, the solution methodology in this section reformulates the proposed model into a solvable MISOCP problem.

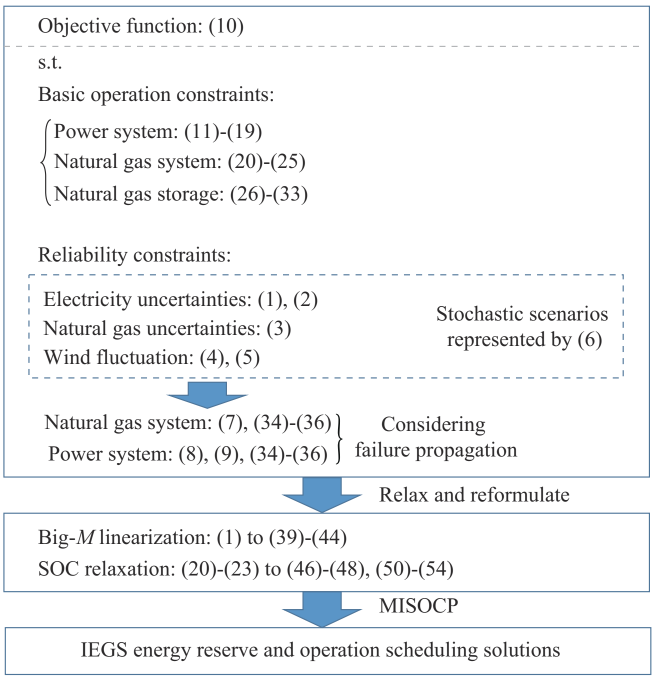

Fig. 4. Architecture of proposed SCUC model considering reliability requirements.

VI. Impact Analysis of Failures in Power Systems on Natural Gas Systems

The impacts of random failures in natural gas systems on power systems are analyzed and considered in Sections II and III. However, random failures in power systems can also affect the reliable operation of natural gas systems. Components such as gas wells in natural gas systems may consume electric power from power systems to maintain the normal operation. If the power system cuts off the electricity supply to these components in contingencies, the reliable operation of natural gas systems is further at risk. In this context, the energy reserve in both subsystems should corporate to maintain the reliable operation of the IEGS.

In this section, the reliability criteria of power systems are formulated at first. Then, the reliability analysis of natural gas systems considering the impacts of power systems is presented.

A. Reliability Analysis of Power Systems

In this section, the power supply of gas wells is provided by power systems and is regarded as an electric load in power systems. The electricity consumption of gas wells has a positive relationship with the amount of gas production, which can be modeled as:

$$DE_{gw,t}=\eta_{g2e}P_{gw,t} \tag{55}$$

where $DE_{gw,t}$ is the electricity consumption of gas well gw during time period t.

Moreover, the gas production of gas wells closely interacts with the electric power supplied to them. In order to ensure the reliable operation of NGUs, the power supplied to gas wells is guaranteed at first in contingencies. In this context, the electric power to gas wells will be reduced or cut off only when the electric load curtailment exceeds the summation of electric loads except the summation of electric power to gas wells as shown in (56).

$$DE_t-\sum_{eg}P_{eg,t}^{\max,s}-\sum_{w}P_{w,t}>DE_t-\sum_{gw}DE_{gw,t} \tag{56}$$

Therefore, the EUEL in state s is equal to the total load demand minus the total MADGC of the power system and the total wind power output. When the electric load curtailment exceeds the summation of electric loads except the summation of electric power to gas wells, the EUEC reaches its maximum value. The EUEL considering different states during time period t can be evaluated as:

$$EUEL_t=\sum_{s\in NS}\left[DE_t-\max\left(\sum_{eg}P_{eg,t}^{\max,s}+\sum_{w}P_{w,t},\sum_{gw}DE_{gw,t}\right)\right]\cdot \xi_t^s\cdot VOLL_e\cdot\Delta t\prod_{eg}pr_{eg,t}^s\prod_{gw}pr_{gw,t}^s\prod_{w}pr_{w,t}^s \tag{57}$$

B. Reliability Analysis of Natural Gas Systems Considering Impacts of Power Systems

The EUNG in state s is equal to the total natural gas demand minus the total MADGC of the natural system. Moreover, the operating state of gas wells closely interacts with the electric power supplied to them. When interruptions reduce the electric power supplied to gas wells, the gas generation will reduce. Consequently, the failure propagation could reduce gas production and have an impact on the EUNG. Therefore, the EUNG considering different states during time period t can be evaluated as:

$$EUNG_t=\sum_{s\in NS}\left[DG_t+\sum_{eg\in NGU}P_{eg,t}/\eta_{g2e}-\sum_{gs}RGD_{gs,t}-\min\left(\sum_{gw}P_{gw,t}^s,\left(\sum_{eg}P_{eg,t}^{\max,s}+\sum_{w}P_{w,t}\right)\Big/\eta_{g2e}\right)\right]\cdot \varsigma_t^s\cdot VOLL_g\cdot\Delta t\prod_{eg}pr_{eg,t}^s\prod_{gw}pr_{gw,t}^s\prod_{w}pr_{w,t}^s \tag{58}$$

VII. Case Study

The proposed model is validated using a 30-bus 20-node IEGS shown in Fig. 5. The system consists of an IEEE 30-bus system and a Belgium 20-node natural gas system. In the test system, except for NGUs and WTGs, all other generating units are coal-fired generating units (CGUs). The selected wind farm from [15] is connected to node B8. The ramping rates, the minimum up and down time of NGUs and CGUs, generation cost coefficients, electricity load curve, and gas demand are taken from [12]. The electricity load shedding cost is set to be 1000 \$/MWh. The natural gas load shedding cost is set to be 240 \$/kcf [31]. The wind curtailment is set to be 200 \$/MWh [9]. The initial gas storage and the maximal natural gas storage in natural gas systems are 600 kcf and 1200 kcf, respectively. The maximal charging rate and discharging rate for the natural gas storage system are set to be 600 kcf/h. The conversion ratio from natural gas to electricity is set to be 0.24 MWh/kcf for all NGUs. The multi-state models of NGUs and CGUs including their performance rates and corresponding probabilities are taken from [18]. The multi-state models of gas wells including their performance rates and corresponding probabilities are taken from [22]. The gas price is set to be 5 \$/kcf. The reserve price for CGUs is set to be 50 \$/MW. The operation cost of gas storage is set to be 0.5 \$/(kcf/h) [12]. In order to better characterize the impact of natural gas system failures and power system failures on the IEGS system, the failure probability of components in the power system and natural gas system has been adjusted to some extent. The failure probability of components in the power system is set to increase linearly within a day. The highest probability at the end of the day is twice the lowest probability at the beginning of the day. The failure probability of components in the natural gas system is set to decrease linearly within a day. The highest probability at the beginning of the day is twice the lowest probability at the end of the day.

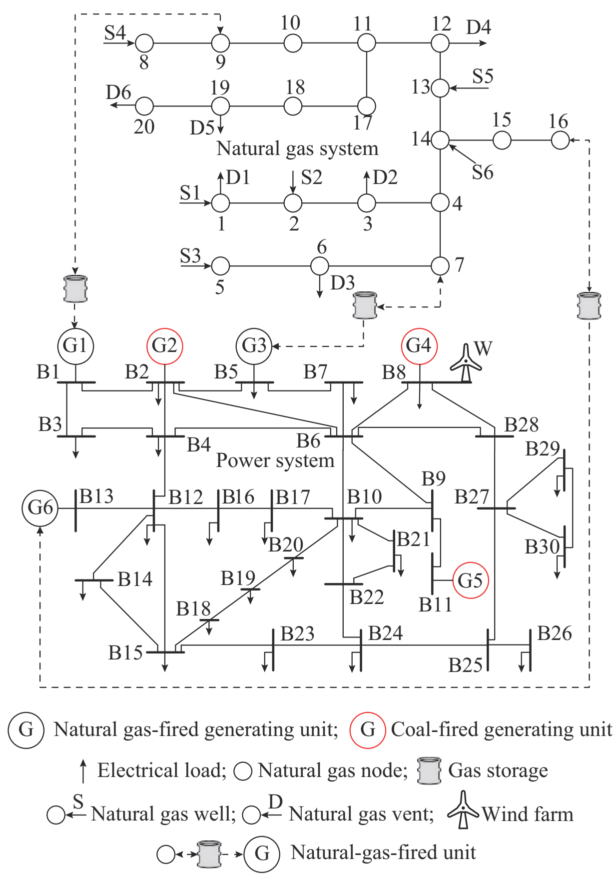

Fig. 5. Diagram of 30-bus 20-node IEGS.

To illustrate the effectiveness of the proposed technique, three cases are conducted. Case 1 is to investigate the impacts of reliability criteria on the energy reserve scheduling results. Case 2 is to analyze the impacts of uncertainties in subsystem and the failure propagation on the reserve scheduling of the IEGS. Case 3 is to analyze the impact of failures in power systems on natural gas systems.

A. Case 1: Effectiveness of EUEC and EWC Criteria

In this case, in order to investigate the impacts of reliability criteria on the energy reserve scheduling results, two scenarios are presented based on the proposed SCUC model.

In Scenario I, the upper bound of the EUEC, i.e., $EUEC_t^{max}$ in (35), is changed to show how it varies with the UR and the gas storage scheduling.

In Scenario II, the upper bound of the EWC, i.e., EWC_t^{max} in (36), is changed to show how it varies with the DR scheduling.

Figure 6 shows the results of Scenario I. The arranged UR capacity and the arranged gas storage capacity increase with the decrease of the EUEC. As the average hourly EUEC decreases from \$20000 to \$15000, the scheduled gas storage increases, while the scheduled UR capacity hardly increases. On one hand, the operating cost of gas storage (0.5 \$/(kcf·hour)) is less than the cost of the UR (averagely 50 \$/MWh). On the other hand, the proposed model can optimize the generation scheduling of units at first without arranging the UR. For instance, an event distribution of the scheduled power among generating units can reduce the EUEC in $N-1$ contingencies. As the average hourly EUEC decreases from \$15000 to \$5000, both the gas storage and the UR increase to guarantee the reliable operation of the IEGS. As the EUEC continues to decrease from \$5000, the scheduled UR increase, while the gas storage has reached the maximum of around 1200 kcf and cannot continue to increase.

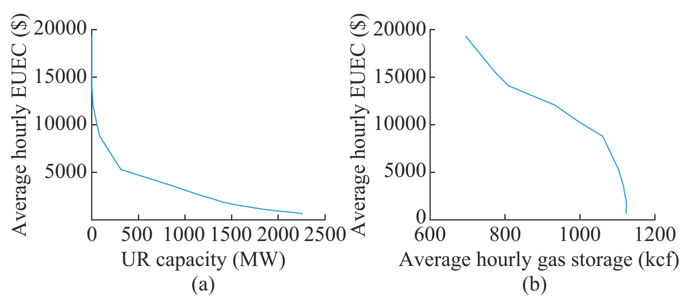

Fig. 6. Relationships between EUEC and energy reserve in Scenario I. (a) Average hourly EUEC for different scheduled UR capacities. (b) Average hourly EUEC for different scheduled gas storage capacities.

Figure 7 shows the results of Scenario II. The arranged DR capacity increases with the decrease of the EWC. The scheduled gas storage capacity is less affected by the EWC. The limited impact of the gas storage capacity on the EWC is that the gas storage may maintain a margin for possible surplus gas. Especially when NGUs provide the DR and reduce their gas demand in contingencies, natural gas will be redundant.

In general, the proposed model can effectively schedule the UR, the DR, and the gas storage with the proposed model and reliability criteria. The arranged UR capacity and the arranged gas storage capacity increase with the decrease of the EUEC, and the arranged DR capacity increases with the decrease of the EWC.

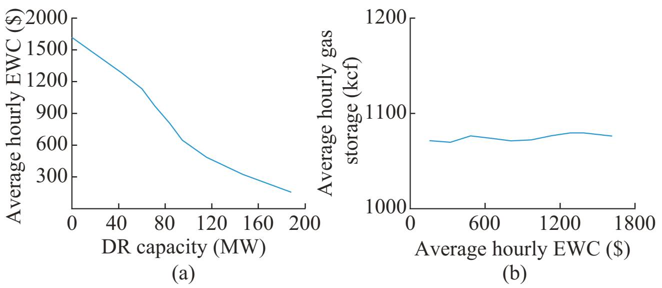

Fig. 7. Relationships between EWC and energy reserve in Scenario II. (a) Average hourly EWC for different scheduled DR capacities. (b) Average hourly EWC for different scheduled gas storage capacities.

B. Case 2: Effectiveness of Proposed Model

In this case, four scenarios are presented to illustrate the impact of uncertainties in different subsystems and failure propagation on the operational reliability of the IEGS.

1) Scenario I: a deterministic unit commitment (DUC) is conducted in this scenario. The UR and DR capacity requirements are set according to a deterministic value. Uncertainties in natural gas systems and their impacts on power systems are not considered.

2) Scenario II: uncertainties in natural gas systems and their impacts on power systems are not considered in the formulation of reliability criteria. Based on the reliability criteria in power systems, an SCUC is conducted.

3) Scenario III: uncertainties in both subsystems are considered but failure propagation is neglected in the formulation of reliability criteria, which means NGUs in this scenario always obtain a stable gas supply. Based on the reliability criteria without consideration of the failure propagation, an SCUC is conducted.

4) Scenario IV: uncertainties in both subsystems and the failure propagation are considered in the formulation of reliability criteria. NGUs in this scenario may be cut off due to random failures in natural gas systems. Based on the proposed reliability criteria, an SCUC is conducted.

In Scenario I, the DR requirement for wind power is set as 50% of the stochastic wind forecasting error. The UR for energy shortage is set as 15% of the electricity load. In Scenarios II, the upper bounds of reliability criteria, i.e., $EUEC_t^{\max}$ and $EWC_t^{\max}$, are set according to the total DR and UR capacity in Scenario I for comparison. In Scenarios III and IV, the reliability constraints are the same as those in Scenario II for comparison. All four scenarios are run using CPLEX 12.5 under MATLAB on a Windows-based PC with four threads clocking at 2.40 GHz and 8 GB RAM.

1) Impact of Random Failures in Natural Gas Systems on Reliability

By comparing scheduling results of Scenarios II and III, it can be concluded that random failures in natural gas systems have a considerable impact on the operational reliability of the IEGS. After considering the failure of the natural gas system, the average hourly EUEC is reduced from \$17258.2 to \$1510.2, a reduction of 90% as shown in Table I. The reasons mainly include the following three aspects.

TABLE I
OPERATION SCHEDULING RESULTS OF DIFFERENT MODELS IN CASE 2

Scenario	Problem scales				Computing time (s)	Scheduled results					
	Number of binary variables	Number of continuous variables	Number of quadratic constraints	Number of constraints		Total cost ($)	Daily UR capacity (WM)	Daily DR capacity (WM)	Average hourly gas storage (kcf)	Average hourly EUEC ($)	Average hourly EWC ($)
I	456	4104	456	7786	1.55	1057401	1546.0	103.9	604.7	25591.5	1052.4
II	1344	5760	456	10570	95.23	1075988	1546.5	103.8	604.7	17258.2	808.7
III	1632	6048	456	12298	150.81	1095814	1689.8	103.8	1124.1	1510.2	808.7
IV	1920	6336	456	14026	205.00	1106375	1836.0	103.8	1124.1	1123.4	808.7

1) In order to reduce the possible natural gas load shedding caused by random failures in natural gas systems, the natural gas storage increases and always maintains at a high level as shown in Fig. 8. The average hourly gas storage increases from 604.7 kcf to 1124.1 kcf, an increase of 85.9%. The sufficient gas reserve minimizes the loss of the natural gas load shedding and improves the reliability of the IEGS directly.

2) From the EUEC criteria in (34), it can be observed that the power system could increase the UR for the operational reliability of the integrated system. As shown in Table I, the daily UR capacity in the power system increases from 1546.5 MW to 1689.8 MW, an increase of 9.3%. Especially when the probability of random failures in natural gas systems is high, more UR is arranged in power systems. As shown in Fig. 9, from the 1st hour to the 8th hour, during which the probability of random failures in natural gas systems is high, the scheduled UR in Scenario III is evidently more than that in Scenario II, resulting in the reduction of the possible failure loss of the IEGS.

3) The generation proportion of NGUs and CGUs is more balanced in Scenario III. As shown in Fig. 10, Scenario III increases the generation of CGUs and decreases that of the NGUs. Consequently, the IEGS's demand for natural gas is reduced and the possible natural gas load shedding in contingencies also decreases.

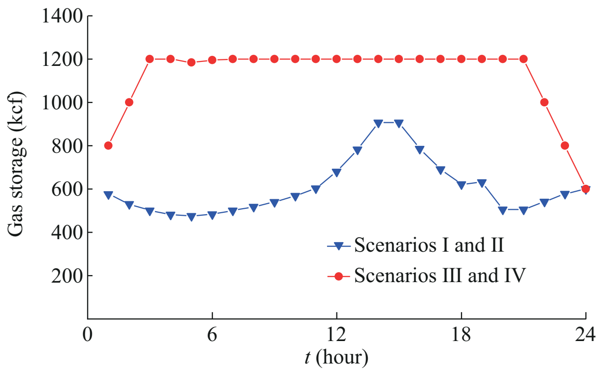

Fig. 8. Gas storage arrangements in different scenarios.

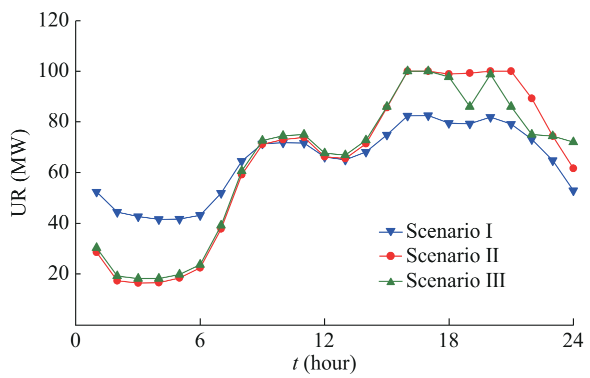

Fig. 9. UR arrangements in different scenarios.

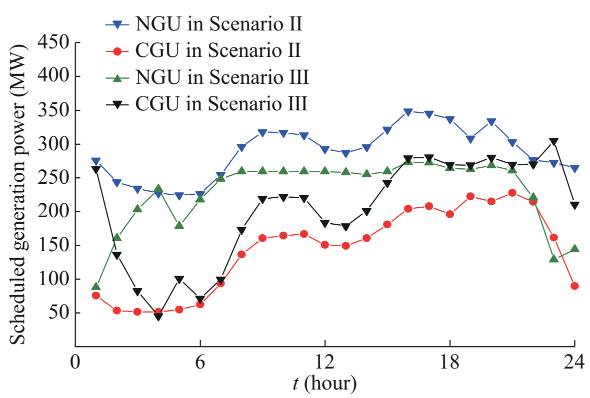

Fig. 10. Scheduled generation power of NGUs and CGUs in Scenario II and Scenario III.

2) Impact of Failure Propagation on Reliability

By comparing the scheduling results of Scenario III, and Scenario IV, it can be concluded that the failure propagation affects the operational reliability of the IEGS. With consideration of the failure propagation, the average hourly EUEC is reduced from \$1510.2 to \$1123.4, a reduction of 25.6% as shown in Table I. The daily UR capacity increases from 1689.8 MW to 1836.0 MW, an increase of 8.7%. It indicates that when considering the failure propagation, the energy supply of NGUs may be cut off in contingencies, resulting in the increase of the UR in power systems. Especially in the time when the failure probability of components in the natural gas system is high or the natural gas reserve is insufficient, Scenario IV schedules more UR. As shown in Fig. 11, from the 1st hour to the 8th hour, Scenario IV schedules significantly more UR compared with Scenario III. Moreover, in the first and last periods of scheduling, when the natural gas storage is not high, Scenario IV arranges additional UR.

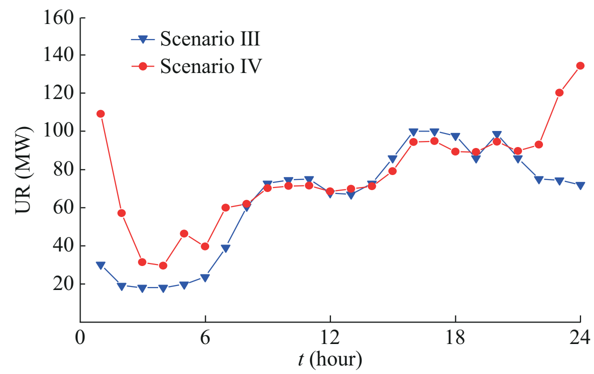

Fig. 11. UR arrangements in Scenarios III and IV.

3) Problem Scales and Computing Time

Table I shows that the number of continuous variables, continuous variables, and constraints increases, as the uncertainties considered in Scenario I to Scenario IV increase. The enlargement of the problem scale is caused by reliability criteria considering random failures in natural gas systems and failure propagation. The computing time also increases with the enlargement of the problem scale.

It can be concluded that scheduling the reserve capacity without considering the random failures in natural gas systems and the failure propagation may contribute to low operational reliability. Therefore, the proposed approach can schedule the operation and reserve for IEGS effectively with high operational reliability.

C. Case 3: Impact of Failures in Power Systems on Natural Gas Systems

In order to illustrate the impact of failures in power systems on natural gas systems, a new case (Case 3) is developed in the case study, where two scenarios are presented to illustrate the impact of failures in power systems on natural gas systems.

1) Scenario I: uncertainties in both subsystems are considered but failure propagation is neglected in the reliability criteria, which means NGUs in this scenario always obtain a stable gas supply. Based on the reliability criteria without consideration of the impact of failures in power systems on natural gas systems, an SCUC is conducted. This scenario is the same as Scenario III in Case 2.

3) Scenario II: uncertainties in both subsystems and the impact of failures in power systems on natural gas systems are considered in the reliability criteria. Gas wells in this scenario are regarded as electric loads in power systems and may be cut off due to random failures in power systems. Based on the reliability criteria considering the impact of failures in power systems on natural gas systems, an SCUC is conducted.

In Scenarios I and II, the reliability constraints are the same for comparison.

By comparing the scheduling results of Scenarios I and II, it can be concluded that the random failures in power systems can also affect the natural gas systems. As shown in Table II, with consideration of the impacts of power systems on natural gas systems, the daily UR capacity increases from 1689.8 MW to 1708.4 MW, an increase of 1.1%. The average hourly EUEC is reduced from $1510.2 to $1123.4, a reduction of 2.3%.

TABLE II
OPERATION SCHEDULING RESULTS OF DIFFERENT MODELS IN CASE 3

Scenario	Total cost ($)	Daily UR capacity (WM)	Daily DR capacity (WM)	Average hourly gas storage (kcf)	Average hourly EUEC ($)	Average hourly EWC ($)
I	1095814	1689.8	103.8	1124.1	1510.2	808.7
II	1100812	1708.4	103.8	1125.0	1123.4	808.7

VIII. CONCLUSION

The coupling of electricity and natural gas systems leads to the fact that uncertainties in any system may affect the reliable operation of the integrated system. The blackouts in Taiwan, China and other accidents indicated that failure in arranging the energy reserve considering energy interactions may result in major power outages. Therefore, this paper proposes a probabilistic method to schedule operation and reserve resources simultaneously and related operational reliability criteria. The proposed reliability criteria take a comprehensive consideration of the operational uncertainties in IEGS, including wind fluctuation, random failures of multi-state components, and failure propagation across the systems. Case studies show that the proposed technique can effectively schedule the operation and energy reserve of IEGS considering reliability requirements. The scheduled energy reserve capacities in both systems are higher compared with conventional approaches, when components in natural gas systems may fail. In general, with the developing interdependence between the electricity system and the natural gas system, this research is useful for guiding the operation and energy reserve arrangement for IEGS in the future smart grid.

REFERENCES

[1] C. M. Correa-Posada and P. Sanchez-Martin, "Integrated power and natural gas model for energy adequacy in short-term operation," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3347-3355, Nov. 2015.

[2] M. Bao, Y. Ding, C. Shao *et al*., "Nodal reliability evaluation of interdependent gas and power systems considering cascading effects," *IEEE Transactions on Smart Grid*, vol. 11, no. 5, pp. 4090-4104, Sept. 2020.

[3] S. Wang, Y. Ding, C. Ye *et al*., "Reliability evaluation of integrated electricity-gas system utilizing network equivalent and integrated optimal power flow techniques," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 6, pp. 1523-1535, Nov. 2019.

[4] N. Jia, C. Wang, W. Wei *et al*., "Decentralized robust energy management of multi-area integrated electricity-gas systems," *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 6, pp. 1478-1489, Nov. 2021.

[5] Xinhua. (2017, Aug.). Massive power outage in Taiwan caused by human error. [Online]. Available: http://www.xinhuanet.com/english/2017-08/15/c_136528707.htm

[6] Ofgem. (2019, Sept.). Technical report on the events of 9 August 2019. [Online]. Available: https://www.ofgem.gov.uk/system/files/docs/2019/09/esotechnicalreport-final.pdf

[7] G. Li, R. Zhang, T. Jiang *et al*., "Security-constrained bi-level economic dispatch model for integrated natural gas and electricity systems considering wind power and power-to-gas process," *Applied Energy*, vol. 194, pp. 696-704, May 2017.

[8] A. Alabdulwahab, A. Abusorrah, X. Zhang *et al*., "Stochastic security-constrained scheduling of coordinated electricity and natural gas infrastructures," *IEEE Systems Journal*, vol. 11, no. 3, pp. 1674-1683, Sept. 2017.

[9] Z. Chen, Y. Zhang, T. Ji *et al*., "Stochastic dynamic economic dispatch of high wind-integrated electricity and natural gas systems considering security risk constraints," *CSEE Journal of Power and Energy Systems*, vol. 5, no. 3, pp. 324-334, Aug. 2019.

[10] L. Yao, X. Wang, T. Qian *et al*., "Robust day-ahead scheduling of electricity and natural gas systems via a risk-averse adjustable uncertainty set approach," *Sustainability*, vol. 10, no. 11, p. 3848, Oct. 2018.

[11] F. Liu, Z. Bie, X. Wang, "Day-ahead dispatch of integrated electricity and natural gas system considering reserve scheduling and renewable uncertainties," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 646-658, Apr. 2019.

[12] Y. He, M. Shahidehpour, Z. Li *et al*., "Robust constrained operation of integrated electricity-natural gas system considering distributed natural gas storage," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 3, pp. 1061-1071, Jul. 2018.

[13] G. Liu and K. Tomsovic, "Quantifying spinning reserve in systems with significant wind power penetration," *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2385-2393, Nov. 2012.

[14] H. Wu, M. Shahidehpour, Z. Li *et al*., "Chance-constrained day-ahead scheduling in stochastic power system operation," *IEEE Transactions on Power Systems*, vol. 29, no. 4, pp. 1583-1591, Jul. 2014.

[15] Y. Yang, M. Bao, Y. Ding *et al*., "Impact of down spinning reserve on operation reliability of power systems," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 4, pp. 709-718, Jul. 2020.

[16] N. Zhang, C. Kang, Q. Xia *et al.*, "A convex model of risk-based unit commitment for day-ahead market clearing considering wind power uncertainty," *IEEE Transactions on Power Systems*, vol. 30, no. 3, pp. 1582-1592, May 2015.

[17] C. Shao, X. Wang, M. Shahidehpour *et al*., "Security-constrained unit commitment with flexible uncertainty set for variable wind power," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, pp. 1237-1246, Jul. 2017.

[18] A. Lisnianski, D. Elmakias, D. Laredo *et al*., "A multi-state Markov model for a short-term reliability analysis of a power generating unit," *Reliability Engineering & System Safety*, vol. 98, no. 1, pp. 1-6, Feb. 2012.

[19] Y.-F. Li and E. Zio, "A multi-state model for the reliability assessment of a distributed generation system via universal generating function," *Reliability Engineering & System Safety*, vol. 106, pp. 28-36, Oct. 2012.

[20] R. Karki, P. Hu, and R. Billinton, "A simplified wind power generation model for reliability evaluation," *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 533-540, Jun. 2006.

[21] A. Moshari, A. Ebrahimi, and M. Fotuhi-Firuzabad, "Short-term impacts of DR programs on reliability of wind integrated power systems considering demand-side uncertainties," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2481-2490, May 2016.

[22] M. Bao, Y. Ding, C. Singh *et al*., "A multi-state model for reliability assessment of integrated gas and power systems utilizing universal generating function techniques," *IEEE Transactions on Smart Grid*, vol. 10, no. 6, pp. 6271-6283, Nov. 2019.

[23] M. Bao, Y. Ding, M. Sang *et al*., "Modeling and evaluating nodal resilience of multi-energy systems under windstorms," *Applied Energy*, vol. 270, p. 115136, Jul. 2020.

[24] Z. Bao, Q. Zhang, L. Wu *et al*., "Cascading failure propagation simulation in integrated electricity and natural gas systems," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 5, pp. 961-970, Sept. 2020.

[25] Y. Ding, L. Cheng, Y. Zhang *et al*., "Operational reliability evaluation of restructured power systems with wind power penetration utilizing reliability network equivalent and time-sequential simulation approaches," *Journal of Modern Power Systems and Clean Energy*, vol. 2, no. 4, pp. 329-340, Dec. 2014.

[26] J. M. Arroyo and F. D. Galiana, "Energy and reserve pricing in security and network-constrained electricity markets," *IEEE Transactions on*

Power Systems, vol. 20, no. 2, pp. 634-643, May 2005.

[27] Y. Ding, C. Shao, J. Yan *et al*., "Economical flexibility options for integrating fluctuating wind energy in power systems: the case of China," *Applied Energy*, vol. 228, pp. 426-436, Oct. 2018.

[28] P. Giorsetto and K. F. Utsurogi, "Development of a new procedure for reliability modeling of wind turbine generators," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, no. 1, pp. 134-143, Jan. 1983.

[29] M. Bao, Y. Ding, X. Yin *et al*., "Definitions and reliability evaluation of multi-state systems considering state transition process and its application for gas systems," *Reliability Engineering & System Safety*, vol. 207, p. 107387, Mar. 2021.

[30] L. He, Z. Lu, J. Zhang *et al*., "Economic dispatch of multi-area integrated electricity and natural gas systems considering emission and hourly spinning reserve constraints," *International Journal of Electrical Power & Energy Systems*, vol. 132, p. 107177, Nov. 2021.

[31] P. N. Biskas, N. G. Kanelakis, A. Papamatthaiou *et al*., "Coupled optimization of electricity and natural gas systems using augmented Lagrangian and an alternating minimization method," *International Journal of Electrical Power & Energy Systems*, vol. 80, pp. 202-218, Sept. 2016.

Hengyu Hui received his B.Eng. degree in electric engineering from Zhejiang University, Hangzhou, China, in 2019. He is currently pursuing his Master's degree in Zhejiang University, Hangzhou, China. His research interests include operation of integrated energy system and demand response.

Minglei Bao received his B.S. degree in electrical engineering from Shandong University, Jinan, China, and the Ph.D. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 2016 and 2021, respectively. He is currently a Post-Doctor at Zhejiang University, Hangzhou, China. His research interests include reliability analysis of integrated energy system, complex network, and power market.

Yi Ding received his B.Eng. degree from Shanghai Jiao Tong University, Shanghai, China, and the Ph.D. degree from Nanyang Technological University (NTU), Singapore, both in electrical engineering. He is a Professor in the College of Electrical Engineering, Zhejiang University (ZJU), Hangzhou, China. Before he joined in ZJU, he was an Associate Professor in the Department of Electrical Engineering, Technical University of Denmark (DTU), Lyngby, Denmark. He also held research and teaching positions in University of Alberta, Edmonton, Canada and NTU. He was a Consultant as Energy Economist for Asian Development Bank in 2010. He is an Editorial Member of Journal of Modern Power Systems and Clean Energy. He is also a Guest Editor for the special section of IEEE Transactions on Power Systems. He is a Member of IEC working groups for micro-grid standards. His research interests include power system planning and reliability evaluation, smart grid, and complex system risk assessment.

Yang Yang received his B.Eng. degree and the Master's degree in electric engineering from Zhejiang University, Hangzhou, China, in 2017 and 2020, respectively. He is currently pursuing his Ph.D. degree in National University of Singapore, Singapore. His research interests include reliability analysis of integrated energy system and power market.

Yusheng Xue received his Ph.D. degree in electrical engineering from the University of Liege, Liege, Belgium, in 1987. He became an Academician of Chinese Academy of Engineering in 1995. He is now the Honorary President of State Grid Electric Power Research Institute (SGEPRI), Nanjing, China. His research interests include nonlinear stability, control, and power system automation.