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OPTIMAL SCHEDULING OF RESERVE AND GAS STORAGE IN INTEGRATED ELECTRICITY AND GAS SYSTEM CONSIDERING RELIABILITY REQUIREMENTS

Yang Yang[1*], Yi Ding [1], Hengyu Hui[1]

1 College of Electrical Engineering, Zhejiang University

ABSTRACT

To keep the reliability of the integrated electricity and natural gas system (IEGS), operating reserve and gas storage are both useful support to cope with contingencies in IEGS. This paper proposes a day-ahead SCUC model for the IEGS to schedule the operating reserve and gas storage simultaneously. The multi-state models for generating units and gas wells are firstly established. Based on the multi-state models, the expected unserved energy cost (EUEC) criterion is proposed based on probabilistic methods considering random failures of generating units and gas wells. Then, the EUEC criterion is incorporated into the day-ahead SCUC model, which is nonconvex and mathematically transformed into a solvable mixed integer linear programming (MILP) problem. The proposed model is studied using a 6-bus-6-node IEGS with natural gas storage.

Keywords: integrated electricity and natural gas system, operating reserve, natural gas storage, expected unserved energy cost.

1. INTRODUCTION

The increasing environmental pollution, carbon emission have fostered the consumption of natural gas, which is a clean and high efficient energy source. The proportion of natural gas in the global primary energy consumption will be 28% by 2030 [1]. The natural gas-fired generating units (NGUs) take account of 42% of the total generation capacity at the end of 2016 in the USA[2]. The large share of NGUs in the power systems strengthens the coupling between power system and natural gas system (NGS), entailing the needs for constructing the integrated electricity and natural gas system (IEGS). Operational strategies are required for the economical and reliable operation of IEGS.

The IEGS has been studied in many researches, including the optimal power and gas flow problems, expansion planning problems and optimal dispatch problems [3]. In [4], a novel mixed-integer linear programing(MILP) formulation was given for coupling power and gas networks taking into account the gas traveling velocity and compressibility. In [5], an integrated model was proposed for assessing the impact of interdependency of electricity and natural gas networks on power system security. In [6], a systematic and comprehensive planning model has been developed to co-plan the expansion of gas power plants, electricity transmission lines and gas pipelines. In [7], new techniques for controlling dynamic gas flows on pipeline networks were applied to examine day-ahead scheduling of electricity generation dispatch and gas compressor operation.

Operating reliability is another important issue for the study of IEGS. The coupled relationship between NGS and power system entails the random failures in NGS to affect the reliability of power systems [2]. For instance, a gas well outage may cause the interruption of gas supply for the NGUs and further lead to the load interruption in the power system. In Aug. 2017, the disruptions of gas supplied to six NGUs in Tatan power plant have caused a massive power blackout in Taiwan, China[8]. Therefore, it is important to consider the random failures of IEGS when scheduling the operating reserve and gas storage of the system.

This paper proposes a probabilistic method to schedule operating reserve and natural gas storage simultaneously under operating reliability requirements considering random failures of gas wells and generating

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units. Firstly, the multi-state models of the generating units and gas wells are proposed. On the basis, the EUEC criterion, which reflects the operating reliability of IEGS, is formulated based on the multi-state models of the generating units and gas wells. Moreover, the EUEC criterion is incorporated into the SCUC model of IEGS to schedule the reserve and gas storage simultaneously. Case study illustrates the validity of the proposed model.

2. MULTI-STATE MODELS FOR GENERATING UNITS AND GAS WELLS

The stochastic behaviors of generating units and gas wells during real-time operation are caused by random failures, which include two cases: full failure and partial failure. These random failures can fully or partially change the maximal dispatchable generating capacity (DGC) of generating units and gas wells during real-time operation[9]. A typical four-state model for generating units is shown in Fig.1.

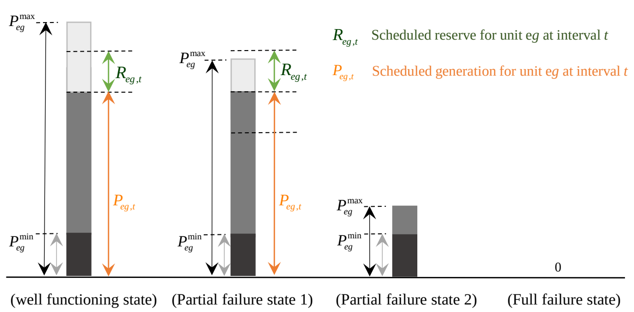

Fig 1 multi-state model for generating units

In the well-functioning state, the DGC is equal to the generation schedule plus reserve. In partial failure state 1, the maximal generation level of unit is inferior to the generation schedule plus the reserve. It indicates that the generating unit can satisfy the requirement of generation scheduling, but cannot provide sufficient reserve for the operational time period *t*. The DGC should be equal to the maximal generation capacity under partial failure state 1. In partial failure state 2, the maximal generation level is inferior to the scheduled generation. It indicates that the generating unit can neither satisfy the generation scheduling requirement nor provide reserve at the time period t for the power system. The DGC should be equal to the maximal generation level under partial failure state 2. In the complete failure state, both the maximal and minimal generation levels are zero and therefore the generation output is also zero. The DGC of each state k_{eg} in the operational time period *t* can be evaluated as:

$$P_{eg,t}^{\max,s} = \min(P_{eg,t} + R_{eg,t}, P_{eg}^{\max}(k_{eg})) \quad (1)$$

where $P_{eg,t}$ and $R_{eg,t}$ are the scheduled generation and scheduled reserve of the generating unit *eg* in the operational time period *t*, respectively. $P_{eg}^{\max}\left(k_{eg}\right)$ represents the maximal generation capacity of the generating unit *eg* under state k_{eg}.

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

$$P_{gw,t}^{s} = \min(P_{gw,t}, P_{gw}^{\max}(k_{gw})) \quad (2)$$

where $P_{gw,t}$ is the scheduled generation of a gas well *gw* in the operational time period *t*. $P_{gw}^{\max}\left(k_{gw}\right)$ represents the maximal generation capacity of a gas well *gw* under state k_{gw}.

2.2 Estimation of expected unserved energy cost

The power output of each generating unit and gas well can be in different states during real-time operation. These states can be assembled together to represent the states of the whole power system as:

$$s = [k_{eg1}, k_{eg2}, ..., k_{egn}, ..., k_{gw1}, k_{gw2}, ..., k_{gwn}, ...] \quad (3)$$

where k_{egn}, k_{gwn} are the states of the unit *egn* and gas well *gwn*, respectively. For a specific state *s* of power system, the probability is equal to the production of the probability of generating unit states and gas well states. The expected unserved energy cost (EUEC) in IEGS under state *s* is equal to the electricity load curtailment cost and natural gas load curtailment cost. The EUE considering different states at time period *t* can be evaluated as:

$$\begin{aligned} EUEC_t = \sum_{s\in NS} [(DE_t - \sum_{eg} P_{eg,t}^{\max,s}) \cdot VOLL_e \times \xi_t^s + \\ (\sum_{eg\in NGU} P_{eg,t}^{s} / \eta_{g2e} + DG_t - \sum_{gw} P_{gw,t}^{s} + \sum_{gs} GC_{gs,t} - GD_{gs,t}) \\ \cdot VOLL_g \times \varsigma_t^s] \\ \times \Delta t \times \prod_{eg} pr_{eg,t}^{s} \times \prod_{gw} pr_{gw,t}^{s} \end{aligned} \quad (4)$$

where ξ_t^s and ς_t^s are binary variables and equal to 1, if there exist electricity and gas load interruption under state *s* at time period *t, respectively*. DE_t and DG_t represent the electrical and natural gas demand at time period *t*, respectively. $GC_{gs,t}$ and $GD_{gs,t}$ refer to the storing and releasing rate of a gas storage *gs* at time period *t*. $VOLL_e$ and $VOLL_g$ denote the penalty price of shed electricity load and gas load, respectively. *NGU* and η_{g2e} represent natural gas-fired unit and the conversion efficiency from gas to electricity, respectively. $pr_{eg,t}^{s}$ and $pr_{gw,t}^{s}$ refer to the probability that the generating unit *eg* and gas well *gw* under state *s* at time period *t*. *NS* represents the set of different states.

The EUEC criterion can reflect the operating reliability of the IEGS. Incorporating the EUEC criterion into the SCUC model enables the IEGS being scheduled under operating reliability requirements.

3. FORMULATION OF PROBABILISTIC SCUC IN IEGS

Based on the multi-state model of generating units and gas wells, the SCUC considering the probabilistic constraints of EUEC to schedule the operating reserve of generating units and gas storage.

3.1 Objective function

The objective of the probabilistic SCUC model in IEGS minimizes the operation cost of IEGS, including the power system cost (operation cost and reserve cost of non-NGU as well as the startup cost, shutdown cost of all generating units) and natural gas system cost (generation cost for as wells and operation cost of gas storage). In this paper, the output of NGU is determined by the gas flow on its connected node and do not provide operating reserve for the power system.

$$\begin{aligned}\min f =& \sum_{t}\sum_{eg\notin NGU} EC_{eg}(PE_{eg,t}, x_{eg,t}) + R_{eg,t}\cdot RC_{eg,t} \\ &+\sum_{t}\sum_{eg} SU_{eg}\cdot y_{eg,t} + SD_{eg}\cdot z_{eg,t} \\ &+\sum_{t}\sum_{gw}\rho_{gas}\cdot PG_{gw,t} + \sigma_{gs}\cdot\sum_{t}\sum_{gs}(GC_{gs,t}+GD_{gs,t})\end{aligned} \tag{5}$$

where EC_{eg} represent the operation cost of non-NGU *eg*. $PE_{eg,t}$ and $RC_{eg,t}$ refer to the electrical generation and reserve cost of non-NGU *eg* at time period *t*, respectively. SU_{eg} and SD_{eg} represent the startup and shutdown cost of generating unit *eg*. $x_{eg,t}$, $y_{eg,t}$ and $z_{eg,t}$ are binary variables and equal to 1, if generating unit *eg* is online, start-up and shut-down at time period *t*, respectively. $PG_{gw,t}$ represents the gas generation of a gas well *gw* at time period *t*. ρ_{gas} and σ_{gs} refer to the price of natural gas and the operation cost of gas storage.

3.2 Constraints

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

3.2.1 Power system constraints

The constraints considered for the operation of power systems include the power balance constraint in (5), transmission line constraint in (6), phase angle constraint in (7), output limit for generating units in (8), reserve limit for generating units in (9), ramping constraints in (10), minimal online and offline time periods limits in (11) and (12), and binary variable functions in (13).

$$\sum_{i\in N}\Big(\sum_{eg\in NG_i} PE_{eg,t} - \sum_{d\in NL_i} D_{d,t}\Big) - \sum_{j\in\phi_i} B_{ij}(\theta_{i,t}-\theta_{j,t}) = 0 \tag{6}$$

$$\left|B_{ij}(\theta_{i,t}-\theta_{j,t})\right| \le \left|F_{ij}^{\max}\right| \tag{7}$$

$$\theta^{\min} \le \theta_{i,t} \le \theta^{\max} \tag{8}$$

$$PE_{eg}^{\min}\cdot x_{eg,t} \le PE_{eg,t} \le PE_{eg}^{\max}\cdot x_{eg,t} \tag{9}$$

$$R_{eg,t} \le x_{eg,t}\cdot\min(PE_{eg}^{\max} - PE_{eg,t}, r_{eg}^{+}) \tag{10}$$

$$\begin{cases} PE_{eg,t} - PE_{eg,t-1} \le r_{eg}^{+}\cdot[1 - x_{eg,t}\cdot(1-x_{eg,t-1})] \\ PE_{eg,t-1} - PE_{eg,t} \le r_{eg}^{-}\cdot[1 - x_{eg,t-1}\cdot(1-x_{eg,t})] \end{cases} \tag{11}$$

$$\begin{cases} \sum_{t=1}^{T_{eg}^{up}}(1-x_{eg,t}) = 0 \\ \sum_{\tau=t}^{t+T_{eg}^{on}-1} x_{eg,\tau} \ge T_{eg}^{on}\cdot(x_{eg,t}-x_{eg,t-1}),\ t\in[T_{eg}^{up}+1, T-T_{eg}^{on}+1] \\ \sum_{\tau=t}^{T}[x_{eg,\tau} - (x_{eg,t}-x_{eg,t-1})] \ge 0,\ t\in[T-T_{eg}^{on}+2, T] \end{cases} \tag{12}$$

$$\begin{cases} \sum_{t=1}^{T_{eg}^{dn}} x_{eg,t} = 0 \\ \sum_{\tau=t}^{t+T_{eg}^{off}-1}(1-x_{eg,\tau}) \ge T_{eg}^{off}\cdot(x_{eg,t-1}-x_{eg,t}),\ t\in[T_{eg}^{dn}+1, T-T_{eg}^{off}+1] \\ \sum_{\tau=t}^{T}[1-x_{eg,\tau} - (x_{eg,t-1}-x_{eg,t})] \ge 0,\ t\in[T-T_{eg}^{off}+2, T] \end{cases} \tag{13}$$

$$\begin{cases} y_{eg,t} = x_{eg,t}\cdot(1-x_{eg,t-1}) \\ z_{eg,t} = x_{eg,t-1}\cdot(1-x_{eg,t}) \end{cases} \tag{14}$$

where B_{ij} and $F_{ij}^{\max}$ are the admittance and maximal power flow of the transmission line between bus *i* and bus *j*, respectively. $\theta_{i,t}$ is the phase angle of bus voltage at bus *i* in the time period of *t*. $\theta^{\max}$ and $\theta^{\min}$ represent maximal and minimal phase angle of bus voltage. $PE_{eg}^{\max}$ and $PE_{eg}^{\min}$ represent maximal and minimal generation capacity of generating unit *eg*. r_{eg}^{+} and r_{eg}^{-} represent the up and down ramping rates of generating unit *eg*. T_{eg}^{on} and T_{eg}^{off} refer to the initial time of startup and shutdown of generation unit *eg*. T_{eg}^{up} and T_{eg}^{dn} refer to minimal startup and shutdown time period of generating unit *eg*.

3.2.2 Natural gas system constraints

The components of natural gas network are similar to those of the power system in IEGS, where the natural gas wells function as generating units, pipelines function as transmission lines. The natural gas-fired units connect the two interdependent systems as a coupled infrastructure, whose output is proportional to the gas inflow rate. The constraints considered for the operation of the natural gas systems include the pipeline flow constraints in (14) and (15), nodal gas flow balance constraint in (17), nodal gas pressure constraint in (18) and gas well generation limits in (19).

$$\mathrm{sgn}(GF_{mn,t})\cdot GF_{mn,t}^2 = C_{ij}^2\cdot(\pi_m^2-\pi_n^2) \tag{15}$$

$$\mathrm{sgn}(GF_{mn,t}) = sng(\pi_m,\pi_n) = \begin{cases} +1, \pi_m > \pi_n \\ -1, \pi_m < \pi_n \end{cases} \tag{16}$$

$$\left|GF_{mn,t}\right| \le GF_{mn}^{\max} \tag{17}$$

$$\sum_{gw\in GW_m} PG_{gw,t} - DG_{gw,t} - \sum_{eg\in NGU_m} PE_{eg,t}/\eta_{g2e} - \sum_{n\in\phi_m} GF_{mn,t} + \sum_{gs\in GS_m}(GD_{gs,t}-GC_{gs,t}) = 0 \tag{18}$$

$$\pi_m^{\min} \le \pi_{m,t} \le \pi_m^{\max} \tag{19}$$

$$PG_{gw}^{\min} \le PG_{gw,t} \le PG_{gw}^{\max} \tag{20}$$

Where π_m is the nodal gas pressure at node *m*. $GF_{mn,t}$ represents the gas flow of pipeline between node *m* and mode *n* at time period *t*. $GF_{mn}^{\max}$ represents the maximal gas flow of pipeline between node *m* and node *n*. $\pi_m^{\min}$ and $\pi_m^{\max}$ represent minimal and maximal gas pressure at node m. $PG_{gw}^{\min}$ and $PG_{gw}^{\max}$ represent the minimal and maximal generation of a gas well *gw*, respectively.

3.2.3 Natural gas storage constraints

The natural gas storage provides the IEGS with adjustable supply or demand when there is a deficit or surplus of natural gas production. The natural gas storage constraints include the storing rate limits of gas storage in (20), the releasing rate limits of gas storage in (21), the gas storage limits in (22). Equation (23) denotes the amount of natural gas been stored at time *t*. Equation (24) denotes that the gas storage at the final hour should be equal to that of the initial hour.

$$0 \le GC_{gs,t} \le GC_{gs}^{\max} \tag{21}$$

$$0 \le GD_{gs,t} \le GD_{gs}^{\max} \tag{22}$$

$$SG_{gs}^{\min} \le SG_{gs,t} \le SG_{gs}^{\max} \tag{23}$$

$$SG_{gs,t} = SG_{gs,t-1} + \eta_{gs}^c\cdot GC_{gs,t} - GD_{gs,t}/\eta_{gs}^d \tag{24}$$

$$SG_{gs,0} = SG_{gs,NT} \tag{25}$$

where $SG_{gs,t}$ represents the gas storage of a gas storage *gs* at time period *t*. $GC_{gs}^{\max}$ and $GD_{gs}^{\max}$ are the maximal storing and releasing rate of a gas storage *gs*. $SG_{gs}^{\min}$ and $SG_{gs}^{\max}$ are the minimal and maximal gas capacity of a gas storage *gs*. η_{gs}^c and η_{gs}^d are storing and releasing efficiency.

3.2.4 Energy unserved constraints

The overall EUEC in the IEGS should be constrained by a certain value.

$$\sum_{t\in NT} EUEC_t \le EUEC^{\max} \tag{26}$$

where $EUEC_t$ is the expected unserved energy cost at time period *t*. $EUEC^{\max}$ is the maximal accumulative expected unserved energy cost from the initial hour to the final hour.

4. SOLUTION METHODOLOGY

The proposed method cannot be solved using MILP method, because there exist non-linear items in constraints (1)-(4) and (15). However, they can be linearized, so that the MILP can be adopted.

Firstly, the function of *min* in (1) and (2) should be eliminated and replaced by linear expressions. Assuming that:

$$RC_{eg,t}(k_{eg}) = (P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t})\cdot\gamma_{eg,t}(k_{eg}) \tag{27}$$

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

$$\gamma_{eg,t}(k_{eg}) = 1,\ if\ \ 0 \le P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t},\ otherwise\ 0 \tag{28}$$

Equation (26) contains items that are the products of continuous variables and binary variable, which can be replaced with the following linear expressions:

$$(P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t})/M \le \gamma_{eg,t}(k_{eg}) \tag{29}$$

$$\gamma_{eg,t}(k_{eg}) \le 1 + (P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t})/M \tag{30}$$

$$-M\cdot\gamma_{eg,t}(k_{eg}) \le RC_{eg,t}(k_{eg}) \le M\cdot\gamma_{eg,t}(k_{eg}) \tag{31}$$

$$P_{eg}^{\max}(k_{eg}) - P_{eg,t}^0 - r_{eg,t}^{up} - M\cdot(1-\gamma_{eg,t}(k_{eg})) \le RC_{eg,t}(k_{eg}) \tag{32}$$

$$RC_{eg,t}(k_{eg}) \le P_{eg}^{\max}(k_{eg}) - P_{eg,t} - R_{eg,t} + M\cdot(1-\gamma_{eg,t}(k_{eg})) \tag{33}$$

where *M* is a very big positive number.

In Equation (2) and (3), which also contain the items that are the products of continuous variables and binary variable can be linearized in similar methods in (29)-(33).

Furthermore, Equation (14) is in quadratic form, which can be linearized using the piecewise linear approximation method proposed in [10] as follows:

$$p_m = \pi_m^2 \tag{34}$$

$$sgn(GF_{mn,t})\cdot GF_{mn,t}^2 = \sum_{k\in K}(c_{mn,k}\cdot gf_{mn,k} + b_{mn,k}\cdot\varsigma_{mn,k}) = C_{ij}^2\cdot(p_m - p_n) \tag{35}$$

$$\sum_{k\in K}\zeta_{mn,k} = 1 \tag{36}$$

$$\zeta_{mn,k}\cdot gf_{mn,k}^{\min} \le gf_{mn,k} \le \zeta_{mn,k}\cdot gf_{mn,k}^{\max} \tag{37}$$

$$GF_{mn} = \sum_{k\in K} gf_{mn,k} \tag{38}$$

where $gf_{mn,k}$ represents the gas flow in linearization segment *k*. $c_{mn,k}$ and $b_{mn,k}$ denote the slope and intercept of segment k, respectively. $\zeta_{mn,k}$ is a binary variable and equals to 1 when the segment k is active.

5. CASE STUDY

The proposed model is tested on a 6-bus-6-node IEGS to demonstrate the effectiveness of the proposed probabilistic SCUC model. The topology of the 6-bus-6-node IEGS is taken from [1], which is given in Fig.2. The ramping rates, the minimum up and down time of generating units, generation cost coefficients, electricity load curve and gas demand are also taken from [1]. The electricity load shedding cost $VOLL_e$ is set to be 1000$/MWh. The gas load shedding cost $VOLL_g$ is set to be 240$/kcf [11]. The maximal charging rate and discharging rate for the gas storage system are set to be 600 kcf/h. The initial gas storage and the maximal gas storage in the natural gas system are 600 kcf and 1200 kcf, respectively. The conversion ratio from gas to electricity η_{g2e} is set to be 0.24MWh/kcf for all gas-fired generating units. The multi-state models of generating units, including their performance rates and corresponding probabilities are taken from [12].The multi-state models of gas well, including their performance rates and corresponding probabilities are taken from [2].The gas price is set to be 5$/kcf. The reserve price for generating unit is set to be 50$/MW. The operation cost of gas storage is set to be 0.5$/kcfh[1].

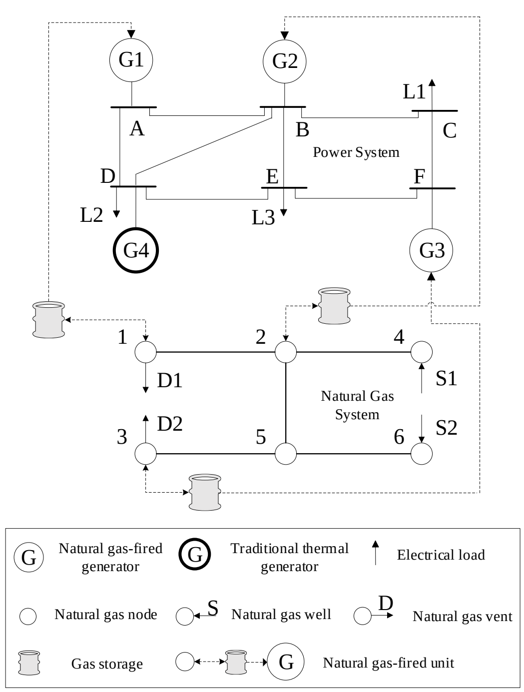

Fig 2 diagram of the 6-bus-6-node IEGS

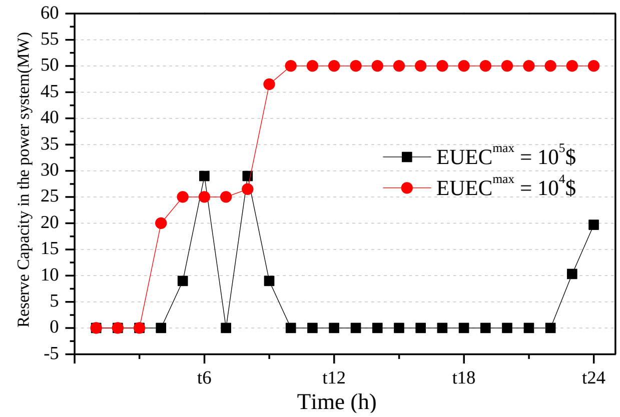

Fig 3 reserve capacity under different EUEC requirements

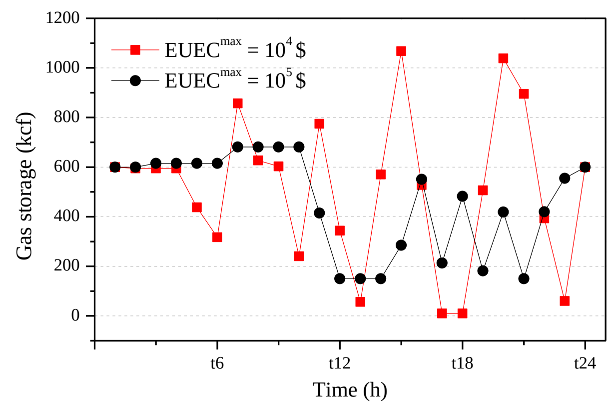

Fig 4 gas storage under different EUEC requirements

The simulation results are given in Fig.3 and Fig.4. A negative correlation is found between $EUEC^{\max}$ and system reserve capacity. A lower $EUEC^{\max}$ means a better operating reliability of the IEGS and requires needs more system reserve capacity to satisfy the possible unserved energy. When the need for reserve capacity in power system increases, the consumption of natural gas from NGU also increases to provide more operating reserve for the power system. The gas storage has to release more gas during the same time period. On the other hand, the gas storage needs to store quickly after releasing. The curve steepness of gas storing and releasing process has a positive correlation with $EUEC^{\max}$, as shown in Fig.4.

6. CONCLUSION

This paper proposes a probabilistic method to schedule operating reserve and natural gas storage simultaneously under operating reliability requirements considering random failures of gas wells and generating units. Simulation results show that the reserve increases and the gas storage changes more drastically, when the reliability requirements of IEGS increases.

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