Information-Gap Decision Theory for Robust Operation of Integrated Electricity and Natural Gas Transmission Networks

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***Abstract*—Natural gas consumption and the share of renewable energy in meeting global energy demand has grown dramatically in the recent years. On the other hand, the rapid growth of gas-fired generating units (GFU) (i.e., producing lower carbon dioxide emissions compared to coal-fired generating units), could play a key role in more integration of renewable energy sources (RESs) into the system due to their high flexibility. Therefore, the interaction between the electricity and natural gas networks (ENGN) becomes more challenging. This paper proposes a robust multi objective integrated mixed integer nonlinear optimization model, utilizing information-gap decision theory (IGDT), for secure and optimal operation of ENGN considering security constraints as well as gas and electricity load demand uncertainties. This bi-objective optimization problem is modified using normalization in the weighted sum method in order to ensuring the consistency of the optimal solutions. The proposed framework is validated on the modified IEEE 24-bus power system with a 15-node natural gas system.**

Keywords— Integrated electricity and natural gas networks, information-gap decision theory, load demand uncertainty, linepack, weighted sum method.

NOMANCLATURE

Indices & Subscripts:

u	Index of generating units
gu	Index of gas-fired generating units
ou	Index of generating units except gas-fired units
ot, ot'	Index of operating hours
tl	Index of transmission lines
eb, eb'	Index of buses
k	Index of compressors
pl, pl'	Index of pipelines
ter	Index of gas terminals
s	Index of segments of generators piecewise linear cost function
n, n', n''	Index of natural gas network nodes
N	Index of sets

Superscripts:

min, max	Minimum/maximum
up,down	Up, down
su,sd	startup and shutdown
ini	Initial status
elec	electricity
gas	Natural gas
fe,se	First-end/second-end
sp,dp	Suction/discharge pressure
ud	Up and down for terminal ramp rates
avg	average
int	integrate
emm	Greenhouse emission
req	Required gas flow rate for gas-fired units

Parameters & variables:

M	Slope of each segments of piecewise linear cost function of units
C	Cost
P	Electrical power generation
R	Ramp rate
T	Time of up/down status of units
CA	Capacity
X	Reactance
DE	Electrical demand
DG	Gas demand
SRE	Spinning reserve
EF	CO_2 emission factor
η	Efficiency
EMM	Produced greenhouse gas
Q	Pressure
I	0/1 commitment status
Y, Z	0/1 startup/shutdown status
FP	Real power flow
θ	Phase angle
FG	Natural gas flow
LP	Linepack
ΔLP	Linepack changes
CP	Consumption power

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G	Amount of tapped gas
ω	Weighted sum coefficient
OBJ	Objective function
GT	Gas turbine fuel rate coefficient

I. INTRODUCTION

A. Motivation and Background

The International Energy Agency (IEA) announces a 4% increase in power generation by GFUs which are accounting for 23% of total power generation in 2019. According to the report, this trend is expected to continue by 2030 [1], which increases the interaction of gas and electricity systems. GFUs are more flexible than other generation technologies, which make these units as the main back-up to complement renewable energy generation. Furthermore, gas compressors driven by electricity as well as the emergence of power to gas (Pegs) technology, increases the interdependency of gas and electricity systems [2]. Therefore, as this interaction between the electricity and natural gas infrastructures increases, operation of each network will impact the other energy vector, which emphasizes the importance of coordinated operation of ENGN from operation [3]-[5] and planning perspectives [6].

B. Relevant Literature

There are various ways for coordinated operation of ENGN, including the most commonly used iterative and integrated methods [2, 7]. In [8], stochastic coordinated programming of ENGN is provided where in the gas network, compressors are not considered. The stochastic model considers the random outage of transmission lines and generators along with hourly load prediction errors. It is shown that the coordinated stochastic model is an effective way to show the uncertainties (hourly) of electricity and natural gas dependent systems.

In [5], the iterative and integrated operation models are compared, and it is shown that under completely identical conditions, the integrated method results in about 7% cost savings. It is also shown that the cost difference could be reduced by using flexible elements such as multi-directional compressors or flexible GFUs. In [9], the role of reserves in managing the uncertainties RESs and N-1 contingencies through a day-ahead robust economic dispatch using the second-order cone (SOC) relaxation method is investigated. One of the most important aspects that should be considered in the coordinated modeling of ENGN is the uncertainty of the loads. Various methods have been used to model the uncertainties in the electricity network, including the IGDT technique [10].

Stochastic optimization has been used widely to model uncertainties in the previous studies, such as in [8, 11, 12]. Authors in [12], used stochastic programming in an energy and reserve market problem and addressed the role of GFUs. The accuracy of stochastic modeling depends on the number of scenarios, and the use of an exact distribution curve, which makes usually these methods ineffective in many real problems [13]. Therefore, since the IGDT is a non-probabilistic technique in solving optimization problems with regard to uncertainties, decisions are made without considering the probability of uncertainties [14]. In [15], the IGDT technique is used to model the electric load demand uncertainty in security-constrained unit commitment problem. To the best of our knowledge, this technique has not been employed in the coordinated operation problem of ENGN to model the demand uncertainty in the gas network.

C. Contributions and Organization

In this paper, in order to achieve a robust solution against the loads uncertainties, a bi-objective integrated ENGN operational model is modeled utilizing IGDT technique. To assess the uncertainty in the gas network, in addition to the load uncertainty in the power system, natural gas load demands are also considered with IGDT method for the first time. To determine the necessity of coordinated operation of the ENGN, the effect of load uncertainty on gas and electricity networks are compared and investigated in both separated and proposed integrated operational strategies. The multi objective optimization problem obtained from the IGDT modelling is solved with normalized weighted sum method to ensuring the consistency of the optimal solutions. Finally, to validate the effectiveness of the proposed framework, the model is implemented on the modified IEEE 24-bus power system with 15-node natural gas system.

The reminder of the paper is organized as follows: section II presents the proposed integrated operational model as well as IGDT technique modeling. In section III, case study and simulation results are presented. Finally, section IV concludes the paper.

II. PROPOSED OPERATIONAL MODEL

A. Integrated ENGN Operation model

To model a coordinated operation for integrated ENGN, the operation of both networks needs to be optimized in one single objective function. To achieve this, the operation costs of ENGN is demonstrated through equation (1).

$$\begin{aligned} OBJ^{\text{int}} &= \min\left[\text{Cost}^{\text{gas}} + \text{Cost}^{\text{elec}}\right] \\ &= \min \\ &\left\{\sum_{N_{ot}}\left[\begin{array}{c} \sum_{N_{ter}} FG_{ter,ot}.C^{\text{gas}} + \sum_{N_{pl}} \Delta LP_{pl,ot}.C^{\text{gas}} \\ +\sum_{N_u}\left[\begin{array}{c} C_{ou}^{\min}.I_{ou,ot} + Y_{u,ot}(C_u^{\text{su}}) + Z_{u,ot}(C_u^{\text{sd}}) \\ +C_u^{\text{emm}}.EMM_{u,ot} + \sum_{s=1}^{N_s} M_{s,ou}.P_{s,ou,ot} \end{array}\right] \end{array}\right]\right. \end{aligned} \quad (1)$$

This objective function (1) takes into account the cost of power generation, startup and shutdown of power plants, greenhouse gas emissions, linepack changes and natural gas withdrawal from terminals.

Equation (1) is subjected to the operation constraints of gas and electricity networks. Important non-linear and non-convex constraints associated with natural gas compressors and linepack are also considered in natural gas network.

Electricity network modeling is in the form of network-constraint unit commitment (NCUC), which includes binary and continuous variables.

$$P_{u,ot} = P_u^{\min} I_{u,ot} + \sum_{s=1}^{N_{s,u}} P_{s,u,ot} \quad \forall \mathrm{N}_u, N_{ot} \tag{2}$$

$$0 \le P_{s,u,ot} \le P_{s,u}^{\max} I_{u,ot} \quad \forall \mathrm{N}_u, N_{ot}, N_{s,u} \tag{3}$$

$$P_u^{\min} I_{u,ot} \le P_{u,ot} \le P_u^{\max} I_{u,ot} \quad \forall \mathrm{N}_u, N_{ot} \tag{4}$$

$$\begin{cases} Y_{u,ot} + Z_{u,ot} \le 1 \\ Y_{u,ot} - Z_{u,ot} = I_{u,ot} - I_{u,ot-1} \end{cases} \forall \mathrm{N}_u, N_{ot} \tag{5}$$

$$\begin{cases} \sum_{ot=1}^{\tau-1} I_{u,ot} + \min\left(T_u^{\mathrm{up}} - ot + 1, T_u^{\mathrm{ini}}\right) I_u^{\mathrm{up}} \\ \qquad \ge T_u^{\mathrm{up}} Z_{u,ot} \\ \sum_{ot=\tau-\tau}^{\tau-1} I_{u,ot} \ge T_u^{\mathrm{up}} Z_{u,ot} \end{cases} \tag{6}$$

$$\begin{cases} \sum_{ot=1}^{\tau-1} (1 - I_{u,ot}) + \min\left(T_u^{\mathrm{down}} - ot + 1, T_u^{\mathrm{ini}}\right) \\ .(1 - I_u^{\mathrm{up}}) \ge T_u^{\mathrm{down}} Y_{u,ot} \\ \sum_{ot=\tau-\tau}^{\tau-1} (1 - I_{u,ot}) \ge T_u^{down} Y_{u,ot} \end{cases} \tag{7}$$

$$\begin{cases} P_{u,ot}^{\max} \le P_{u,ot-1} + R_u^{\mathrm{up}} I_{u,ot-1} + R_u^{\mathrm{su}} \left[I_{u,ot} - I_{u,ot-1}\right] \\ \qquad + P_u^{\max} \left[1 - I_{u,ot}\right] \quad \forall \mathrm{N}_u, N_{ot} \end{cases} \tag{8}$$

$$P_{u,ot}^{\max} \le P_u^{\max} I_{u,ot+1} + R_u^{\mathrm{sd}} \left[I_{u,ot} - I_{u,ot+1}\right] \quad \forall \mathrm{N}_u, N_o \tag{9}$$

$$\begin{cases} P_{u,ot-1} - P_{u,ot} \le R_u^{\mathrm{down}} I_{u,ot} + R_u^{\mathrm{sd}} \left[I_{u,ot-1} - I_{u,ot}\right] \\ \qquad + P_u^{\max} \left[1 - I_{u,ot-1}\right] \quad \forall \mathrm{N}_u, N_{ot} \end{cases} \tag{10}$$

$$FP_{tl,ot} = \left(\frac{1}{X_{tl}}\right)(\theta_{eb,ot} - \theta_{eb',ot}) \quad \forall \mathrm{N}_{tl}, N_{ot} \tag{11}$$

$$-CA_{tl}^{\max} \le FP_{tl,ot} \le CA_{tl}^{\max} \quad \forall \mathrm{N}_{tl}, N_{ot} \tag{12}$$

$$DE_{eb,ot} + \sum_{N_{u,eb}} P_{u,ot} = \sum_{N_{tl,eb}} FP_{tl,ot} \forall \mathrm{N}_{tl}, N_{ot} \tag{13}$$

$$\sum_{N_u} P_u^{\max} I_{u,ot} \ge SRE_{ot} + \sum_{N_{eb}} DE_{eb,ot} \quad \forall \mathrm{N}_{ot} \tag{14}$$

$$EMM_{u,ot} = (EF_u . P_{u,ot}) / \eta_u \quad \forall \mathrm{N}_u, \forall N_{ot} \tag{15}$$

In summary, constraints (2)-(10) are related to the thermal unit and (11)-(15) relate to transmission network constraints [16]. Equation (2) is presenting the linearized cost functions of the units (i.e. The output power of the units is equal to the sum of the power generated in each segment of the linearized cost function) and (3) limits the generated power of each segments. The inequality (4) limits the output power of the generating units to a minimum and maximum allowable output power per hour. Equation (5) presents the relationship between binary variables related to the On/Off (0/1) status of the unit commitment approach, and start-up and shut-down status of generating units. The constraints on the minimum up and down time are given in (6) and (7), respectively. Limits on ramp rates are also given in (8)-(10). The DC power flow [20] equation that determines the flow of the transmission lines is given in (11) and the resulting flow is limited to the capacity of the lines in (12). Equation (13) shows the energy balance and inequality (14) determines the generating power by considering the required spinning reserve and the amount of demand. Finally, in (15), the produced greenhouse gas emissions by the generating units is obtained.

The constraints of natural gas network are nonlinear which makes the operation of the gas network nonlinear programming (NLP).

$$\begin{aligned} &\sum_{N_{ter,n}} FG_{ter,ot} + \sum_{N_{k,n}} \mathrm{IM}_{k,n} FG_{k,ot} + \sum_{N_{pl,n}} \mathrm{IM}_{pl,n} FG_{pl,ot} \\ &\quad = DG_{n,ot} + \sum_{N_{gu,n}} FG_{n,ot}^{req} + \sum_{N_{k,n}} G_{k,n,ot} \forall N_n, N_{ot} \end{aligned} \tag{16}$$

$$Linepack = \left(\frac{L_{pl} A_{pl}}{\rho^{\mathrm{std}} \mathrm{Z.R.T}^{\mathrm{std}}}\right) Q_{pl}^{\mathrm{avg}} \tag{17}$$

$$\begin{cases} \Delta LP_{pl,ot} = LP_{pl,ot} - LP_{pl,ot-1} \\ = (Q_{pl,ot}^{\mathrm{avg}} - Q_{pl,ot-1}^{\mathrm{avg}}) \left(\frac{L_{pl} A_{pl}}{\rho^{\mathrm{std}} \mathrm{Z.R.T}^{\mathrm{std}}}\right) \forall \mathrm{N}_{pl}, N_{ot} \end{cases} \tag{18}$$

$$\begin{cases} \left(FG_{pl,ot}\right)^{1.485} = \left[\frac{\left(D_{pl}\right)^{4.854} (Eff_{pl})^2}{18.43 L_{pl}}\right] \\ \left[\left(Q_{n,ot}^{\mathrm{se}}\right)^2 - \left(Q_{n,ot}^{\mathrm{fe}}\right)^2\right] \forall \mathrm{N}_{pl}, N_{ot} \end{cases} \tag{19}$$

$$CP_{k,ot} = \left(\frac{FG_{k,ot}}{Eff_k \left(\frac{\varsigma - 1}{\varsigma}\right)}\right) \left[\left(\frac{Q_{k,ot}^{\mathrm{dp}}}{Q_{k,ot}^{\mathrm{sp}}}\right)^{\left(\frac{\varsigma - 1}{\varsigma}\right)} - 1\right] \forall \mathrm{N}_k, N_{ot} \tag{20}$$

$$1 \le \left(\frac{Q_{k,ot}^{\mathrm{dp}}}{Q_{k,ot}^{\mathrm{sp}}}\right) \le Q_k^{\max} \quad \forall \mathrm{N}_k, N_{ot} \tag{21}$$

$$\begin{cases} FG_{k,ot} \le CA_k^{\max} \\ CP_{k,ot} \le CP_k^{\max} \end{cases} \forall N_{k,ot}, N_{ot} \tag{22}$$

$$\begin{cases} Q_{k,ot}^{\mathrm{dp}} \le Q_k^{\mathrm{dp,max}} \\ Q_{k,ot}^{\mathrm{sp}} \ge Q_k^{\mathrm{sp,min}} \end{cases} \forall N_{k,ot}, N_{ot} \tag{23}$$

$$G_{k,n,ot} = GT_k CP_{k,ot} \tag{24}$$

$$FG_{ter,ot} \le CA_{ter}^{\max} \quad \forall \mathrm{N}_{ter}, N_{ot} \tag{25}$$

$$\left|FG_{ter,ot} - FG_{ter,ot-1}\right| \le R_{ter}^{\mathrm{ud}} CA_{ter}^{\max} \quad \forall \mathrm{N}_{ter}, N_{ot} \tag{26}$$

$$Q_n^{\min} \le Q_{n,ot} \le Q_n^{\max} \quad \forall \mathrm{N}_n, N_{ot} \tag{27}$$

$$CA_{pl}^{\min} \le FG_{pl,ot} \le CA_{pl}^{\max} \quad \forall \mathrm{N}_{pl}, N_{ot} \tag{28}$$

The gas flow balance that should be maintained at each node (16) where the $IM_{k,n}$ and $IM_{pl,n}$ are node-compressor and node-pipeline incident matrix, respectively. Unlike the electricity transmission, due to the slower transport speed of gas, supplying gas to the demand centers takes more time. For this reason, a minimum amount of gas in the pipelines is maintained in the short time to deal with these conditions (called linepack) by the system operator [17]. Equations (17) and (18), show the amount and variations of linepack in the gas pipelines, respectively, where ρ^{std}, Z, R and T^{std} are gas density at standard condition, compressibility factor, gas constant for natural gas, and gas temperature at standard condition [17]. L_{pl} and A_{pl} are the length and cross-sectional area of pipelines. The Panhandle A approach [18] is used to calculate the gas flow through the high pressure network pipelines, which is illustrated in (19). In this equation Eff_{pl} is the efficiency factor of the pipe and the following assumptions are taken into account [18]: a) The gas pipelines are horizontal, b) velocity and temperature are constant throughout the pipeline, c) the diameter of the pipelines is smaller than the radius of curvature, and d) change of cross-sectional area along the path of gas stream is negligible.

Equations (20)-(24) are related to the compressor operation. The power consumption equation of the compressor is presented in (20), where Eff_k and ς are the efficiency and the power consumption constant, respectively. The ratio of the discharge pressure to suction pressure of the compressor is limited by inequality (21). Limitations related to the maximum compressor flow rate, maximum power consumption, maximum and minimum compressor pressure and finally the amount of gas tapped by the compressor are given in (22)-(24), respectively. The maximum capacity of the terminals is determined by (25), and produced gas flow ramp rate by the terminals is also limited by the inequality (26). The constraints on the pressure limit of the nodes and the flow capacity of the gas passing through the pipelines are also given in (27) and (28), respectively.

GFUs are the coupling link of ENGN, which the required gas for these units is calculated in (29).

$$FG_{n,ot}^{req} = \mathrm{E}_{\mathrm{conv}} \sum_{N_{gu,n}} \left(\frac{P_{gu,ot}}{Eff_{gu}} \right) \forall \mathrm{N}_n, \forall N_{ot} \tag{29}$$

Where E_{Conv} and Eff_{gu} are the energy conversion coefficient and the efficiency of the GFU, respectively.

B. Information-Gap Decision Theory

In this section the IGDT method is introduced in order to be applied into the deterministic model presented in section A. Power and natural gas demand uncertainties could be modeled through the IGDT technique. Due to the fact that real probability density function of uncertain parameters, especially for the gas network is not available, IGDT method is adopted to model the uncertainty. An advantage of this method is in cases that the uncertainty of the planning is not determined initially [10].

Each decision made of IGDT-based technique requires system model (30) (which is ENGN total related operation costs in this paper), performance necessities (31) (which is conventional to robustness function), and uncertainty modeling (32)-(33) [13].

$$OBJ = Total\ \mathrm{Cost} = f(X, DE^{\mathrm{elec}}, DG^{\mathrm{gas}}) \tag{30}$$

$$\begin{cases} OBJ^{\mathrm{IGDT}}(k, DE^{\mathrm{elec}}, DG^{\mathrm{gas}}) = \\ \max\limits_{\alpha,\beta} \begin{cases} (\alpha,\beta): \\ \text{Maximum operation cost which is} \\ \text{not higher than pre-defined biggest cost} \end{cases} \end{cases} \tag{31}$$

$$\begin{cases} DE^{\mathrm{elec}} \in U(\alpha, \overline{DE}^{\mathrm{elec}}) \\ U(\alpha, \overline{DE}^{\mathrm{elec}}) = \left| \dfrac{DE^{\mathrm{elec}} - \overline{DE}^{\mathrm{elec}}}{\overline{DE}^{\mathrm{elec}}} \right| \le \alpha \end{cases} \tag{32}$$

$$\begin{cases} DG^{\mathrm{gas}} \in U(\beta, \overline{DG}^{\mathrm{gas}}) \\ U(\beta, \overline{DG}^{\mathrm{gas}}) = \left| \dfrac{DG^{\mathrm{gas}} - \overline{DG}^{\mathrm{gas}}}{\overline{DG}^{\mathrm{gas}}} \right| \le \beta \end{cases} \tag{33}$$

Where α and β are uncertainty horizons of DE^{elec} and DG^{gas} respectively. The $\bar{}$ denotes the expected value.

According to the above explanations, in the IGDT technique α and β should be maximized to achieve its required performance. Therefore, the objective function of IGDT-based model is derived in (34) (subjected to (2)-(12), (14), (15) and (17)-(28)):

$$OBJ^{\mathrm{IGDT}}(k, DE^{\mathrm{elec}}, DG^{\mathrm{gas}}) = \max(\omega_1.\alpha + \omega_2.\beta) \tag{34}$$

subject to:

$$\begin{cases} \sum\limits_{N_{ot}} \left[\begin{array}{l} \sum\limits_{N_{ter}} FG_{ter,ot}.C^{\mathrm{gas}} + \sum\limits_{N_{pl}} \Delta LP_{pl,ot}.C^{\mathrm{gas}} \\ + \sum\limits_{N_u} \left[\begin{array}{l} C_{ou}^{\min}.I_{ou,t} + Y_{u,ot}(C_u^{\mathrm{su}}) + Z_{u,ot}(C_u^{\mathrm{sd}}) \\ + C_u^{\mathrm{emm}}.EMM_{u,t} + \sum\limits_{s=1}^{N_s} M_{s,ou}.P_{s,ou,t} \end{array} \right] \end{array} \right] \\ \le (1+\sigma).OBJ^{\mathrm{int}} \end{cases} \tag{35}$$

$$\begin{cases} DE_{eb,ot}^{\mathrm{elec}} \le (1+\alpha)\overline{DE}^{\mathrm{elec}} \\ DE_{eb,ot}^{\mathrm{elec}} \ge (1-\alpha)\overline{DE}^{\mathrm{elec}} \end{cases} \tag{36}$$

$$\begin{cases} DG_{n,ot}^{\mathrm{gas}} \le (1+\beta)\overline{DG}^{\mathrm{gas}} \\ DG_{n,ot}^{\mathrm{gas}} \ge (1-\beta)\overline{DG}^{\mathrm{gas}} \end{cases} \tag{37}$$

$$(1+\alpha).DE_{eb,ot} + \sum_{N_{u,eb}} P_{u,ot} = \sum_{N_{tl,eb}} FP_{tl,ot} \quad \forall \mathrm{N}_{tl}, N_{ot} \tag{38}$$

$$\begin{aligned} &\sum_{N_{ter,n}} FG_{ter,ot} + \sum_{N_{k,n}} \mathrm{IM}_{k,n} FG_{k,ot} + \sum_{N_{pl,n}} \mathrm{IM}_{pl,n} FG_{pl,ot} \\ &= (1+\beta).DG_{n,ot} + \sum_{N_{gu,n}} FG_{n,ot}^{req} + \sum_{N_{k,n}} G_{k,n,ot} \quad \forall N_n, N_{ot} \end{aligned} \tag{39}$$

Equation (35) demonstrates the robustness of the cost function to the cost deviation determined by the system

operator. Electric and gas demands are limited to their uncertainty horizons in equations (36) and (37), respectively.

III. CASE STUDY AND SIMULATION RESULTS

A. Case Study

The proposed models are implemented on the IEEE RTS 24-bus electricity system and a 15-node gas system. The optimization is performed with CPLEX and DICOPT solvers of GAMS optimization software version 25.1.2 on a system with Intel (R) Core (TM) i5 CPU (2.13 GHz) processor and 8 GB of memory. The performance of the proposed framework is examined with different cost deviations and different operational strategies.

1) Updated version of IEEE RTS 24-bus

The modified of updated IEEE reliability test system (RTS) [15] is used to model the electricity network where in the modified version there are 13 generating units, 17 loads and 34 transmission lines.

2) 15-node natural gas network test system

To model the gas network, a 15 nodes test system with one terminal is used. The network has 16 pipelines, with loads on all nodes and one compressor at node 15. The diagram of the ENGN is shown in Fig. 1.

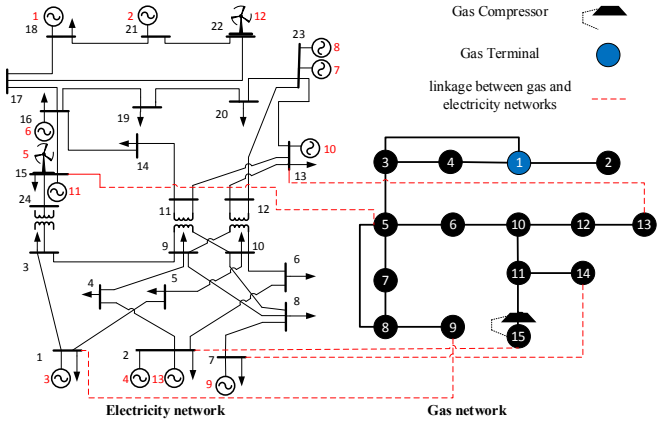


Figure 1. Network diagram

B. Simulation Results

The optimization problem is solved in three different scenarios. In the first scenario, a deterministic base scenario is employed without considering the uncertainty, which leads to $4.442m operating cost (solution time 80.95 seconds). In the second scenario, uncertainty of the load is taken into account through different cost deviations in the proposed integrated operation model. This scenario is named “robust scenario”. In the third scenario, each network is operated separately and uncertainty is addressed. By changing the coefficient of cost deviation, σ, with steps of 0.1, the uncertainty horizons, α and β, are obtained. For σ, ω_1 and ω_2 values equal to 0.3, 0.8 and 0.2, respectively, the problem solving time for α and β values is equal to 114.37 seconds in the second scenario. As shown in Fig. 2, the uncertainty of the load on the electricity network has a greater impact on the deviation of the resulting cost. Therefore, it can be concluded that the network is more secure in case of load changes of the gas network and by increasing the ω_2, obtained values for α will become more close to zero.

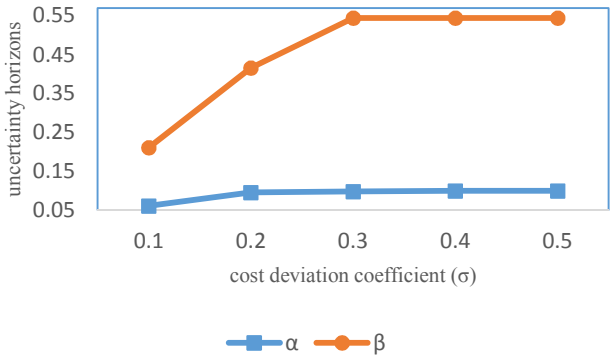


Fig.2 Cost deviation coefficient σ versus uncertainty horizons α and β in integrated model for natural gas and electricity networks

It can also be concluded that the network is robust up to 0.2 for the uncertainty of the electrical load and 0.3 for the uncertainty of the gas load, and then the curve is saturated. This indicates that from these values onwards, the network will not be able to cope with the uncertainties of the loads and will lead to load shedding.

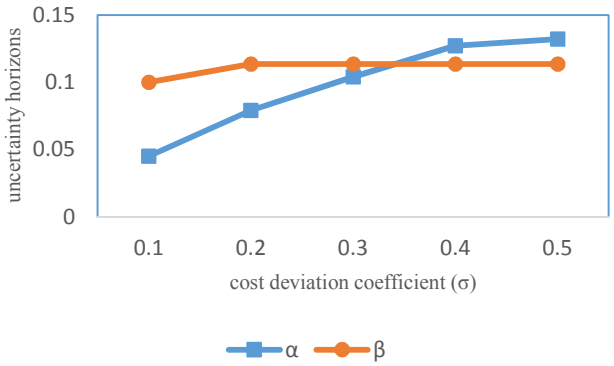


Fig. 3. Cost deviation coefficient σ versus uncertainty horizons α and β in separated model for electricity and gas networks

As shown in Fig 3, if each network is operated separately, the situation is completely different and the obtained values for α and β are changed. The electricity network has the ability to deal with more uncertainties, and the curve is not saturated for higher deviations (i.e., σ=1.5). On the other side, in the natural gas network, the saturated area is obtained in σ=1.2. This difference indicates that the operating status of the ENGN in form of separated and integrated operation mode is different and in the integrated model, for lower level of electrical uncertainty, the load needs to be shed and the network is experiencing contingencies.

Table I, ilustrates the commitment scheduling of separated and integrated operation. As it can be seen, the units are 17 hours less committed in integrated method compared to the separated method.

It should be noted that the total amount of power generated by units in integrated model is 55968 MWh/day is lower

compared to the separated model with 58267 MWh/day power generation. Since the power generated by gas-fired units is also lower in integrated model, consequently less gas is injected to natural gas network from the terminal and therfore the total operational cost of gas and electricity networks is lower in the integrated model compared to the separated model.

Table I. Commitment status of units in separated and integrated method where the σ = 0.3

unit	separated	integrated
	Operation period (1-24)	*Operation period (1-24)*
G1	111111111111111111111111	111111111111111111111111
G2	111111111111111111111111	111111111111111111111111
G3	111111111111111111111111	111111111111111111111111
G4	111111111111111111111111	111111111111111111111111
G5	111100111111111111111111	111110111111111111111100
G6	111111111111111111111111	000000111111111111111111
G7	000011111111111111111100	111111111111111111111111
G8	000000111111111111111111	001111111111111111111111
G9	111111111111111111111111	000000111111111111100000
G10	111111111111111111111111	111111111111111111111111
G11	111111111111111111111110	111100111111111111111111
G12	111110011111111111111110	110000011111111111111110
G13	000001111111111111111111	000000111111001111111000

IV. CONCLUSION

The exact distribution curve of the network loads (mainly gas demand) was not available. Therefore, in this paper in order to evaluate appropriately the uncertainty in operation of natural gas and electricity networks, the IGDT technique is employed to model the robust operation of ENGN. The IGDT technique is applied in an integrated approach with considering uncertainties in electricity and gas demands. The results were evaluated in different scenarios including two scenarios with considering uncertainty in integrated and separated modeling and one without uncertainty (base case). Afterwards, according to different values of the cost deviation coefficient σ, uncertainty horizons (α and β) were obtained. It turned out that the network operation was different in separated and integrated approaches and lower operational costs was achieved in integrated modeling. This indicated the importance of the coordinated operation of ENGN from security perspectives. The electricity network in separated approach was more able to deal with the uncertainty of the electricity demand, while in the integrated approach, the gas network was more able to deal with the uncertainty.

REFERENCES

[1] IEA. Tracking Power. Available: https://www.iea.org/reports/tracking-power-2019/natural-gas-fired-power, 2019.

[2] H. Ameli, M. Qadrdan, G. Strbac, "Coordinated Operation of Gas and Electricity Systems for Flexibility Study", *Frontiers in Energy Research*, 8, 120, 2020.

[3] X. Zhang, M. Shahidehpour, A. Alabdulwahab, A. Abusorrah, "Hourly electricity demand response in the stochastic day-ahead scheduling of coordinated electricity and natural gas networks", *IEEE Transactions on Power Systems*, 31(1), 592-601, 2015.

[4] I.G. Sardou, M. Khodayar, M.T. Ameli, "Coordinated operation of natural gas and electricity networks with microgrid aggregators", *IEEE Transactions on Smart Grid*, 9(1), 199-210, 2016.

[5] H. Ameli, M. Qadrdan, G. Strbac, "Coordinated operation strategies for natural gas and power systems in presence of gas-related flexibilities" *IET Energy Systems Integration*, 1(1), 3-13, 2019.

[6] H. Ameli, M. Qadrdan, G. Strbac, M.T., Ameli, "Investing in Flexibility in an Integrated Planning of Natural Gas and Power Systems", *IET Energy Systems Integration*, 2(2), 101-111, 2020.

[7] H. Ameli, M. Qadrdan, G. Strbac, "Value of gas network infrastructure flexibility in supporting cost effective operation of power systems" *Applied Energy*, 202, 571-580, 2017.

[8] A. Alabdulwahab, A. Abusorrah, X. Zhang, M. Shahidehpour, "Stochastic security-constrained scheduling of coordinated electricity and natural gas infrastructures", *IEEE Systems Journal*, 11(3), 1674-1683, 2015.

[9] 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*, 10(2), 646-658, 2018.

[10] Y. Ben-Haim, "Info-gap decision theory: decisions under severe uncertainty", *Elsevier,* 2016.

[11] X. Zhang, M. Shahidehpour, A. Alabdulwahab, A. Abusorrah, "Hourly electricity demand response in the stochastic day-ahead scheduling of coordinated electricity and natural gas networks", *IEEE Transactions on Power Systems*, 31(1), 592-601, 2016.

[12] M.A., Mirzaei, A.S. Yazdankhah, B. Mohammadi-Ivatloo, M. Marzband, M. Shafie-khah, J.P. Catalão, "Stochastic network-constrained co-optimization of energy and reserve products in renewable energy integrated power and gas networks with energy storage system", *Journal of Cleaner Production*, 223, 747-758, 2019.

[13] A. Ahmadi, A.E. Nezhad, P. Siano, B. Hredzak, S. Saha, "Information-gap decision theory for robust security-constrained unit commitment of joint renewable energy and gridable vehicles" *IEEE Transactions on Industrial Informatics,* 16(5), 3064-3075, 2019.

[14] A. Najafi, M. Marzband, B. Mohamadi-Ivatloo, J. Contreras, M. Pourakbari-Kasmaei, M. Lehtonen, R. Godina, "Uncertainty-based models for optimal management of energy hubs considering demand response" *Energies*, 12(8), 1413, 2019.

[15] A. Ahmadi, A.E. Nezhad, B. Hredzak, "Security-constrained unit commitment in presence of lithium-ion battery storage units using information-gap decision theory", *IEEE Transactions on Industrial Informatics,* 15(1), 148-157, 2018.

[16] M. Parvania, M. Fotuhi-Firuzabad, M. Shahidehpour, "Comparative hourly scheduling of centralized and distributed storage in day-ahead markets", *IEEE Transactions on Sustainable Energy*, 5(3), 729-737, 2016.

[17] M. Chaudry, N. Jenkins, N., G. Strbac, " Multi-time period combined gas and electricity network optimization", *Electric power systems Research,* 78(7), 1265-1279, 2008.

[18] A. Osiadacz, Simulation and Analysis of Gas Networks, (Gulf Publishing Company, 1987).

[19] C. Ordoudis, P. Pinson, J.M.M. González, M. Zugno, "An Updated Version of the IEEE RTS 24-Bus System for Electricity Market and Power System Operation Studies", 2016.

[20] K. Purchala, L. Meeus, D. Van Dommelen, R. Belmans, "Usefulness of DC power flow for active power flow analysis", *In IEEE Power Engineering Society General Meeting,* (pp. 454-459). 2005.