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Gas Network's Impact on Power System Voltage Security

Abbas Rabiee, *Senior Member, IEEE*, Innocent Kamwa, *Fellow, IEEE*, Andrew Keane, *Senior Member, IEEE*, and Alireza Soroudi, *Senior Member, IEEE*

Abstract—Due to the energy linkage between electricity and gas networks, assessing the voltage security of the electricity system without considering the practical constraints of both systems, may lead to unrealistic values of loading margins (LM). This work proposes a model for investigating the impact of gas networks on the voltage security of electric transmission networks. The overall objective is to maximize the LM of the electricity network while satisfying all relevant constraints in both gas and electricity networks such as hourly line pack of gas pipelines, reactive power capability limits of generators, and complementarity constraints representing the generators active/reactive power limits based on the capability curves, power flow equations at both current operation, and security limit points. Three (small, medium, and large) case studies are presented as the applications of the proposed model for LM maximization in power systems that are highly coupled with gas networks. The obtained results corroborate the impact of both gas and electrical networks operation constraints such as voltage and reactive power limits, nodal gas pressure limits, gas network loading as well as the line pack phenomenon of gas pipelines on the LM of power systems.

Index Terms—Gas network, Voltage security, Loading margin, Line pack, Capability curve.

Abbreviations:

<i>IGES</i>	integrated gas and electricity system.
<i>PP</i>	Power plant.
<i>COP</i>	Current operation point.
<i>SLP</i>	Security limit point.
<i>LM</i>	Loading margin.
<i>GPP</i>	Gas-fired power plant.

Sets/Indices:

c	Index for operation point (c_0 denotes COP, c_1 denotes SLP).
b, k	Index for electrical network buses.
i, j	Index for gas network nodes.
t	Index for operation intervals.
Ω_B	Set of all buses of electrical network.
Ω_{B_G}	Set of electrical buses with PP
$\Omega_{B_{GPP}}$	Set of electrical buses with GPP.
Ω_{B_b}	Set of electrical buses connected to bus b .
Ω_T	Set of time intervals.
Ω_G	Set of all nodes of gas network.
Ω_{G_i}	Set of gas nodes connected to node i .
Ω_{G_S}	Set of gas nodes connected to gas sources.

NOMENCLATURE

The notations and symbols used throughout the paper are stated in this section.

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Ω_{GE}	Set of gas nodes connected to GPPs.
Variables:	
$(P/Q)_{b,t,c}^G$	Active/reactive power generation in node b at time t and operation point c , (pu).
$(P/Q)_{b,t,c}^D$	Active/reactive demand in bus b at time t and operation point c , (pu).
$Q_{b,t,c}^{G,L_1/L_2}$	Reactive power limit corresponding to stator/field current limit in bus b , time t and operation point c , (pu)
$(\bar{Q}/Q)_{b,t,c}^G$	Upper/lower limit of reactive power generation in bus b , time t and operation point c , (pu).
$(\alpha/\beta)_{b,t}$	Auxiliary variables for modeling active and reactive power limits of generators
$v_{b,t}^{up/dn}$	Auxiliary variables for modelling the voltage difference of COP and SLP as a result of reactive power limit activation.
λ	Loading parameter.
$S_{bk,t,c}$	Apparent power flowing through bk -th line at time t and operation point c , (pu).
$(V/\theta)_{b,t,c}$	Voltage magnitude/angle of bus b at time t and operation point c , (pu/rad).
$p_{i,t,c}$	Gas pressure of node i at time t and operation point c , (Bar).
$G_{i,t,c}^S$	Gas source injection from node i at time t and operation point c , (Mm^3/h)
$G_{i,t,c}^E$	Gas demand of GPP connected to node i at time t and operation point c , (Mm^3/h)
$f_{ij,t,c}$	Gas flow through ij -th pipeline at time t and operation point c , (Mm^3/h)
$f_{ij,t,c}^{+/-}$	Auxiliary positive variables for modelling of gas flow through ij -th pipeline at time t and operation point c , (Mm^3/h)
$\zeta_{ij,t,c}$	Line pack of ij -th pipeline at time t and operation point c , (Mm^3/h)
Parameters:	
$k_b^{P/Q}$	Active/reactive power demand increment factor at bus b .
k_b^G	Active power generation increment factor at bus b .
$E_{b,t,c}$	Internal voltage of the generator connected to bus b , time t and operation point c , (pu).
$(RU/RD)_b$	Ramp up/down rate of the generator connected to bus b , (pu/h).
X_{s_b}	Synchronous reactance of the generator connected to bus b .
$\bar{\delta}_b$	Upper limit on angular separation of stator and rotor fields of the generator connected to bus b , (rad).
$\bar{I}_b^G$	Upper limit on the stator current of the generator connected to bus b , (pu)
$M_{1/2,b}$	Big-M constants for reactive/active power generation limits modelling at bus b .

$\bar{X}/X$	Upper/lower bound of variable X
$\Lambda_{b,i}$	Gas to electricity power conversion ratio of GPP connected bus b and node i , (MWh/Mm^3).
$(D/L)_{ij}$	Internal diameter/length of ij -th gas pipe, (mm/km).
T_f	Gas temperature (K).
ϵ	Absolute pipe roughness, (mm).
Z	Gas compressibility factor.
δ	Specific gravity of gas.
F_{ij}	Friction factor of ij -th gas pipe.

I. INTRODUCTION

A. Background and Motivations

The market incentives, economic restrictions, and environmental concerns force the electric power systems to be operated closer to their security limits. Voltage security is an important factor that affects the power system's overall security and limits the available power transfer capacity of transmission networks. Voltage collapse typically occurs on power systems that are heavily loaded, weakened by element outages, or subjected to reactive power support deficiencies. To avoid voltage collapse, it is desirable to operate the system with a sufficient loading margin (LM). This level of LM ensures maintaining a margin in terms of bus voltages, reactive power requirements, available transfer capability, or system loading levels such that the system can survive the collapse under any single or multi-component outages.

In recent years, natural gas consumption has significantly increased such that a 4.6% growth in worldwide consumption was recorded in 2018 [1]. In line with the global increase in gas usage, its share in electricity production is also increased worldwide [2]. The gas-fired power plants (GPPs) are the main linkage between electricity and gas grids [3]. Compared to other fossil fuel power plants, GPPs have more competitive fuel costs, lower emissions, and faster response to energy fluctuations due to the volatility of renewable energy sources or sudden changes in electricity demands. A holistic approach called integrated gas and electricity system (IGES) seems to be suitable for modeling the strong interdependence between these networks.

B. Literature survey

Power system LM estimation and maximization is an important issue that gained the attention of various researches. As an example, in [4] the LM is estimated via adaptive neuro-fuzzy inference systems. Also, in [5] the LM is determined by a neuro-fuzzy methodology by considering the intermittent distributed generators. Back-propagation neural networks are trained for different contingencies in [6]. Also, [7] uses time-series data obtained from dynamic simulations subject to sequential load changes. In [8], the loadability of power systems is maximized including the complementarity constraints representing generator limits. In [9] a corrective voltage control scheme is proposed to maximize LM as well as minimising the control costs. In [10] the voltage security cost is minimized considering the LM constraints at the presence of demand response and voltage dependent load model.

TABLE I
SUMMARY OF THE EXISTING LITERATURE.

	IGES	LPK	CC	Security	RPC	Framework
[4], [5]	N	N	N	N	N	NFS
[6], [7]	N	N	N	N	N	ANN
[8]–[10]	N	N	Y	Y	N	OPF
[11]–[13]	Y	N	N	Y	N	SCOPF
[14]	Y	N	N	N	N	OPF
[15]	Y	Y	N	Y	N	SCUC
[16]	Y	Y	N	Y	N	OPF
[17]	Y	N	N	N	N	OPF
[18]	N	N	N	Y	N	SCOPF
[19]	Y	N	N	Y	N	SCOPF and UC
This work	Y	Y	Y	Y	Y	SCOPF

Neuro-Fuzzy System (NFS), Artificial Neural Network (ANN), Complementarity constraints (CC), Reactive Power Capability (RPC), Line Pack (LPK), Unit Commitment (UC), Security Constrained UC (SCUC), Optimal Power Flow (OPF), Security Constrained Optimal Power Flow (SCOPF)

Security constrained optimal power and gas flow model developed in [11] and [12] by considering N-1 security constraints. A robust scheduling model is developed in [13] for wind-integrated IGES with consideration of both gas pipeline and power transmission N-1 contingencies. In [14] a formulation is developed for steady-state analysis of IGES, by considering the temperature effect on gas flow and multi slack bus concept in the electricity network. But, the model is only suitable for uni-directional gas networks. In [15] a security-constrained unit commitment (SCUC) model is proposed for IGES by considering the line pack property of gas pipelines and the transmission contingencies both in power and gas networks, but the proposed model for line pack does not consider the nodal gas balance. In [16] a robust methodology is proposed to identify and protect vulnerable components of IGES from malicious attacks. The influence of the natural gas network on the electricity network is studied in [17], by representing an equivalent model for the feasible operation region of GPPs imposed by the operational constraints of the natural gas network.

In [18] a bi-level optimization model is developed aiming to determine the optimal placement of GPPs while improving the transmission network's static voltage stability. In its first stage, the GPPs' locations are optimized to improve the static voltage stability margin, via LM index. The optimal installed capacity of GPPs is determined to minimize the operation costs and power losses in the second stage. The authors in [19] studied the impacts of wind power forecast uncertainty on the operation of the GB integrated gas and electricity network. Three operational planning methods, namely deterministic, two-stage stochastic programming, and multistage stochastic programming are developed. In all the methods, thermal generators were controlled through an integrated UC and economic dispatch algorithm that used mixed-integer programming. The nonlinear characteristics of the gas network were also considered.

Also, [20]–[22] studied the impact of gas network's transient behavior using partial differential equations. It should be noted that the transient behavior of gas networks is much slower compared to the electricity network.

The main features of the aforementioned literature is summarized in Table I.

C. Contributions

It is inferred from the above literature survey that security evaluation and improvement of an IGES is a critical issue, especially due to the increasing penetration of gas as an efficient energy carrier in the emerging IGESs. The IGES security evaluation and enhancement are mainly characterized by OPF and SCUC models. While there are several ongoing discussions on the inter-dependency of gas and electricity networks in the existing literature, but the exact dynamic model of the gas network by including the impact of line pack phenomenon on the bi-directional gas flow-ability as well as nodal gas balance, is not quantified properly. Also, its potential implications on voltage security as well as the loadability of power systems has not been discussed. To fill this gap, this paper introduces a comprehensive AC-OPF model for determination of maximum loadability of power systems considering the detailed gas network model including the line pack. To characterize voltage security and the system loadability, the capability curve of generators are also included and the complementarity constraints that represent the generators active and reactive power limits are developed based on the limits defined through the capability curves.

Figure 1 shows two approaches to deal with voltage security assessment in IGESs. In Fig. 1-(a) the gas network is assumed to be an infinite source that can supply any quantity of gas to the GPPs. But, as it is shown in Fig. 1-(b), the gas network constraints are taken into account for calculating the LM on the power system side. Augmenting a new set of constraints (gas network model) to an optimization problem (here, maximization of power system LM) usually deteriorates the objective function. The impact of gas network constraints on the electricity network's LM can be illustrated conceptually by Fig. 1-(c). It is observed from this figure that by the inclusion of gas network's constraints, the GPPs operation point and consequently the LM of electricity network may be affected. There are some important questions in this regard:

- How to quantify the effects of the gas network on the power system side?
- Which constraints in the gas network affect the LM in the power system?

This work answers these questions, by proper modeling of line

Fig. 1. Voltage security assessment model : (a) without, and (b) with considering gas network constraints, c) P-V curve.

D. Paper organization

The remainder of this paper is organized as follows: Section II describes the proposed model for LM maximization. Section III shows the simulation results. Finally, the paper concludes in Section IV.

II. DESCRIPTION OF THE PROPOSED MODEL

A. Concept of voltage security

Voltage security is defined as the capability of a power system to maintain the acceptable voltage magnitudes at all buses, under normal and contingent operation conditions. The main factors causing voltage collapse are increasing the system demand beyond certain limits, as well as the inability of the power system to supply reactive power demand due to limitation in generation and transmission of reactive power. In this paper, LM is utilized for characterization of the voltage security margin. LM is the amount of load increase not arising voltage collapse or violation of operational constraints.

The power system is secure if there is a sufficient distance between the current operation point (COP) and the security limit point (SLP). The SLP itself is defined as the point where at least one operational constraint is going to be violated. The SLP usually happens earlier than the loadability limit point (LLP). Figure 2, shows a typical P-V curve of an arbitrary load bus. Point A corresponds to the COP, whereas the points B and C correspond to SLP and LLP, respectively. Also, P_0 is the demand at the COP. However, increasing the system demand at load buses moves the system operation point from the COP toward LLP. LM is the distance (in MW or MVA) between the COP and LLP, i.e. points A and B. If the SLP coincides LLP, then the LM will be the distance between A and C. The LM depends on transmission system strength, reactive power support, COP, and the settings of voltage control devices such as generators' terminal voltages and tap changers' tap positions [23].

Fig. 2. COP, SLP, LLP and LM characterization via a typical P-V curve.

B. Formulation of the proposed mode for LM maximization

1) *Objective function:* The aim is to maximize the LM of the electricity network in the entire operating horizon (e.g. 24 hours), as follows.

$$LM = \max_{DV} \lambda \quad (1)$$

Subject to :

(2) to (51)

2) *Problem constraints:* The electricity and gas network operational constraints and limits are presented in the following. It is worth to note that subscript c in all the following equations refers to both c_1 (COP) and c_2 (SLP), i.e., the corresponding constraints should be satisfied in both COP and SLP.

- Electricity network constraints:

Fig. 3. Capability curve of a typical synchronous generator.

The AC power flow equations are considered as follows for COP and SLP, simultaneously. Also, since the reactive power support by generators plays a crucial role in voltage security, in this paper, a detailed model of the capability curve of generators is considered. As shown in Fig. 3, the capability curve is defined by including the field current limit, stator current limit, and under excitation limit.

$$P_{b,t,c}^G - P_{b,t,c}^D = \quad (2)$$

$$\sum_{k \in \Omega_{B_b}} V_{b,t,c} V_{k,t,c} Y_{bk} \cos(\theta_{b,t,c} - \theta_{k,t,c} - \gamma_{bk}) \quad \forall b \in \Omega_B, \quad (3)$$

$$Q_{b,t,c}^G - Q_{b,t,c}^D = \quad (3)$$

$$\sum_{k \in \Omega_{B_b}} V_{b,t,c} V_{k,t,c} Y_{bk} \sin(\theta_{b,t,c} - \theta_{k,t,c} - \gamma_{bk}) \quad \forall b \in \Omega_B$$

$$\sum_{k \neq b \in \Omega_{B_G}} (\bar{P}_k^G - P_{k,t,c_1}^G) \geq P_{b,t,c_1}^G \quad b \in \Omega_{B_G} \quad (4)$$

$$-RD_b \leq P_{b,t,c}^G - P_{b,t-1,c}^G \leq RU_b \quad \forall b \in \Omega_{B_G} \quad (5)$$

$$(P_{b,t,c}^G)^2 + (Q_{b,t,c}^{G,L1})^2 = (V_{b,t,c} \bar{I}_b^G)^2 \quad (6)$$

$$(P_{b,t,c}^G)^2 + \left(Q_{b,t,c}^{G,L2} + \frac{V_{b,t,c}^2}{X_{sb}} \right)^2 = \left(\frac{V_{b,t,c} E_{b,t,c}}{X_{sb}} \right)^2 \quad (7)$$

$$\underline{Q}_{b,t,c}^G = P_{b,t,c}^G \cot(\bar{\delta}_b) - \frac{V_{b,t,c}^2}{X_{sb}} \quad (8)$$

$$\bar{Q}_{b,t,c}^G = \min \left(Q_{b,t,c}^{G,L1}, Q_{b,t,c}^{G,L2} \right) \quad (9)$$

$$\underline{P}_b^G \leq P_{b,t,c}^G \leq \bar{P}_b^G \quad \forall b \in \Omega_{B_G} \quad (10)$$

$$\underline{Q}_{b,t,c}^G \leq Q_{b,t,c}^G \leq \bar{Q}_{b,t,c}^G \quad \forall b \in \Omega_{B_G} \quad (11)$$

$$\underline{V}_b \leq V_{b,t,c} \leq \bar{V}_b \quad \forall b \in \Omega_B \quad (12)$$

$$\underline{S}_{bk} \leq S_{bk,t,c} \leq \bar{S}_{bk} \quad \forall b \in \Omega_B, \forall k \in \Omega_{B_b} \quad (13)$$

$$P_{b,t,c_2}^D = (1 + k_b^P \lambda) \times P_{b,t,c_1}^D \quad \forall b \in \Omega_B \quad (14)$$

$$Q_{b,t,c_2}^D = (1 + k_b^Q \lambda) \times Q_{b,t,c_1}^D \quad \forall b \in \Omega_B \quad (15)$$

$$P_{b,t,c_2}^G = \min \left((1 + k_b^G \lambda) \times P_{b,t,c_1}^G, \bar{P}_b^G \right) \quad \forall b \in \Omega_{B_G} \quad (16)$$

where (2) and (3) are hourly nodal active and reactive power balances in COP and SLP. Also (4) is the hourly reserve constraint. The hourly ramp rate constraints are given by (5). The capability curve of generators is modeled via (6)-(9), which

express respectively the field current, stator current and under excitation limits. Also, (10)-(13) are the upper/lower limits of active/reactive power generations, voltages and apparent power flowing through lines, respectively. The relationship between COP and SLP is expressed by (14)-(16), by considering the loading parameter, λ .

- Voltage security constraints:

As it is aforementioned, the voltage magnitude of generator buses at COP and SLP are related together. While a generator's reactive power limit is not activated, its terminal voltage will be fixed. With the increase in load, generators may reach their upper limits. When a generator reaches its upper limit, its terminal voltage decreases. This means that voltage magnitude of generator buses is not necessarily the same in the COP and SLP. The mathematical expression of this issue is described as follows ($\forall b \in \Omega_{BG}, \forall t \in \Omega_T$):

$$V_{b,t,c_2} = V_{b,t,c_1} + v_{b,t}^{dn} - v_{b,t}^{up} \quad (17)$$

$$(\bar{Q}_{b,t,c_2}^G - Q_{b,t,c_2}^G) \times v_{b,t}^{up} \leq 0 \quad (18)$$

$$(Q_{b,t,c_2}^G - \underline{Q}_{b,t,c_2}^G) \times v_{b,t}^{dn} \leq 0 \quad (19)$$

$$v_{b,t}^{dn}, v_{b,t}^{up} \geq 0 \quad (20)$$

where (17)-(20) indicate that for generators that reach their reactive power limits, voltage magnitude at the corresponding bus is not equal in COP and SLP. It is worth to note that $\bar{Q}_{b,t,c_2}^G$ and $\underline{Q}_{b,t,c_2}^G$ in (18) and (19) are defined in (8) and (9), respectively. It is worth to note that (17)-(20) are the complementarity constraints of the generators reactive power limits. These limits are defined based on the capability curves, as denoted by (8) and (9).

- Gas network constraints:

The steady-state hourly gas flow model is considered here by including the impact of line pack phenomenon. As gas flows through a pipeline, the pressures varies along the pipeline length. The volume of gas contained in a given length of pipeline is refereed as the line pack [24]. The General Flow equation, for the steady-state iso-thermal flow in a gas pipeline is the basic equation for relating the pressure drop with gas flow rate, which can be expressed as follows [24] ($\forall i \in \Omega_G, \forall j \in \Omega_{Gi}, \forall t \in \Omega_T$).

$$\text{sign}(f_{ij,t,c}) f_{ij,t,c}^2 = C_{ij}^2 (p_{i,t,c}^2 - p_{j,t,c}^2) \quad (21)$$

$$\text{sign}(f_{ij,t,c}) = \begin{cases} +1, & p_{i,t,c} \geq p_{j,t,c} \\ -1, & p_{i,t,c} < p_{j,t,c} \end{cases} \quad (22)$$

where (21) is the general flow equation of gas in a pipeline, which describe the gas flow in terms of the pipe diameter, gas properties, nodal pressures and temperature [24]. Based on the above flow constraint, the gas network nodal balance equation can be expressed as follows.

$$G_{i,t,c}^S - G_{i,t,c}^D - G_{i,t,c}^E = \sum_{j|(i,j) \in \Omega_{Gi}} (\zeta_{ij,t,c} - \zeta_{ij,t-1,c}) + \sum_{j|(i,j) \in \Omega_{Gi}} f_{ij,t,c} - \sum_{j|(j,i) \in \Omega_{Gi}} f_{ji,t,c} \quad (23)$$

And, the line pack, which is the volume of gas contained in the length of a pipeline, can be calculated by the following equation

[24], $\forall i \in \Omega_G, \forall j \in \Omega_{Gi}$:

$$\zeta_{ij,t,c} = \frac{2}{3} \kappa_{ij} \left(\frac{(p_{i,t,c} + p_{j,t,c})^2 - p_{i,t,c} p_{j,t,c}}{p_{i,t,c} + p_{j,t,c}} \right) \quad (24)$$

The operational limits of the gas sources and GPPs gas demand are expressed as follows.

$$\underline{G}_i^S \leq G_{i,t,c}^S \leq \bar{G}_i^S \quad \forall i \in \Omega_{GS}, \forall t \in \Omega_T \quad (25)$$

$$\underline{G}_i^E \leq G_{i,t,c}^E \leq \bar{G}_i^E \quad \forall i \in \Omega_{GE}, \forall t \in \Omega_T \quad (26)$$

Also, the hourly nodal gas pressure limits are as follows.

$$\underline{p}_i \leq p_{i,t,c} \leq \bar{p}_i \quad \forall i \in \Omega_G, \forall t \in \Omega_T \quad (27)$$

The gas flow limits of pipelines can be stated as follows.

$$\underline{f}_{ij} \leq f_{ij,t,c} \leq \bar{f}_{ij} \quad \forall i \in \Omega_G, \forall j \in \Omega_{Gi}, \forall t \in \Omega_T \quad (28)$$

The hourly limits on the line pack of gas pipelines is expressed as follows.

$$\underline{\zeta}_{ij} \leq \zeta_{ij,t,c} \leq \bar{\zeta}_{ij} \quad \forall i \in \Omega_G, \forall j \in \Omega_{Gi}, \forall t \in \Omega_T \quad (29)$$

where, (25) is the gas sources capacity limits, (26) is GPPs gas demand capacity limits, (27) is the nodal pressure limits, (28) is gas flow limits of ij -th pipelines and (29) is its line pack limits. Also, the parameters C_{ij}^2 and κ_{ij} in (21) and (24) are defined as follows [24] ($\forall i \in \Omega_G, \forall j \in \Omega_{Gi}, \forall t \in \Omega_T$).

$$C_{ij}^2 = 1.8649 \times 10^{-16} \left(\frac{D_{ij}^5}{F_{ij} Z T_f L_{ij} \delta} \right) \quad (30)$$

$$\kappa_{ij} = 2.4887 \times 10^{-7} \left(\frac{L_{ij} D_{ij}^2}{T_f} \right) \quad (31)$$

where F_{ij} in (30) is the ij -th gas pipeline's friction factor. This factor is calculated as follows.

$$\frac{1}{F_{ij}} = \left(2 \log_{10} \left(\frac{3.7 D_{ij}}{\epsilon} \right) \right)^2 \quad (32)$$

- Gas and electrical networks interfaces:

The gas and electricity networks are linked via GPPs as the energy conversion path, in which the gas is absorbed from the gas network by GPPs and is converted to electricity. The following equation describes the output electric power of GPPs as a function of input gas volume:

$$P_{b,t,c}^G = \Lambda_{b,i} G_{i,t,c}^E, \quad \forall b \in \Omega_{BGPP}, \forall i \in \Omega_{GE}, \forall t \in \Omega_T \quad (33)$$

3) *Reformulation of complicated constraints:* It is evident from (9) and (16) that the min operator is a non-differentiable function resulting an MINLP optimization model. In order to avoid dealing with such an MINLP model, (34)-(39) is used instead of (9), as follows.

$$Q_{b,t,c_2}^G \leq Q_{b,t,c_1}^{G,L_1} \quad (34)$$

$$Q_{b,t,c_2}^G \leq Q_{b,t,c_1}^{G,L_2} \quad (35)$$

$$Q_{b,t,c_2}^G \geq Q_{b,t,c_1}^{G,L_1} - M_{1,b} \times \alpha_{b,t} \quad (36)$$

$$Q_{b,t,c_2}^G \geq Q_{b,t,c_1}^{G,L_2} - M_{1,b} \times (1 - \alpha_{b,t}) \quad (37)$$

$$\alpha_{b,t} = (\alpha_{b,t})^2 \quad (38)$$

$$0 \leq \alpha_{b,t} \leq 1 \quad (39)$$

Similarly, (16) is substituted by (40)-(45) as follows.

$$P_{b,t,c_2}^G \leq (1 + k_b^G \lambda) \times P_{b,t,c_1}^G \quad (40)$$

$$P_{b,t,c_2}^G \leq \bar{P}_b^G \quad (41)$$

$$P_{b,t,c_2}^G \geq (1 + k_b^G \lambda) \times P_{b,t,c_1}^G - M_{2,b} \times \beta_{b,t} \quad (42)$$

$$P_{b,t,c_2}^G \geq \bar{P}_b^G - M_{2,b} \times (1 - \beta_{b,t}) \quad (43)$$

$$\beta_{b,t} = (\beta_{b,t})^2 \quad (44)$$

$$0 \leq \beta_{b,t} \leq 1 \quad (45)$$

Also, it is evident that (21) is highly non-differentiable. The left hand side of this equation can be expressed as follows.

$$\text{sign}(f_{ij,t,c}) f_{ij,t,c}^2 = |f_{ij,t,c}| \times f_{ij,t,c} \quad (46)$$

In order to make (21) differentiable, the following constraints can be used to calculate $|f_{ij,t,c}|$ ($\forall i \in \Omega_G, \forall j \in \Omega_{G_i}, \forall t \in \Omega_T$).

$$f_{ij,t,c} = f_{ij,t,c}^+ - f_{ij,t,c}^- \quad (47)$$

$$|f_{ij,t,c}| = f_{ij,t,c}^+ + f_{ij,t,c}^- \quad (48)$$

$$f_{ij,t,c}^+ \times f_{ij,t,c}^- = 0 \quad (49)$$

$$f_{ij,t,c}^+, f_{ij,t,c}^- \geq 0 \quad (50)$$

Now, (21) can be expressed in terms of $f_{ij,t,c}^+$ and $f_{ij,t,c}^-$ as:

$$(f_{ij,t,c}^+)^2 - (f_{ij,t,c}^-)^2 = C_{ij}^2 (p_{i,t,c}^2 - p_{j,t,c}^2) \quad (51)$$

4) *Decision variables*: The sets of decision variables (DV), are as follows.

$$DV = \left\{ \begin{array}{l} V_{b,t,c}, (P/Q)_{b,t,c}^G, (P/Q)_{b,t,c}^G, Q_{b,t,c}^{G,L_1/L_2} \\ \lambda, \alpha_{b,t}, \beta_{b,t}, \zeta_{ij,t,c}, \phi_{t,c} \\ G_{i,t,c}^S, G_{i,t,c}^E, p_{i,t,c}, f_{ij,t,c}, f_{ij,t,c}^{+/-} \end{array} \right\} \quad (52)$$

In this paper, the generators' voltage set-points are considered as the control variables to enhance the LM, but other control measures such as cap banks, tap changers, load shed, etc can be incorporated in the proposed optimization problem. The focus of this work is to find the impact of gas network on power system voltage security issue.

III. NUMERICAL STUDIES

The proposed NLP optimization model is implemented in GAMS [25] and solved by the IPOPT [26] solver that implements an interior point line search method [27], **running on an Intel(R) Core(TM)-i5 6200U CPU @ 2.3 GHz PC with 8 GB RAM**. In order to show the features of the proposed model for LM maximization in IGESSs, first, an illustrative IGES network is presented consisting of 3 electrical buses and 2 gas nodes (i.e. *test system-1*). Then, the model is implemented on two larger IGESSs, namely integrated IEEE 39-bus and modified Belgian 20-node gas network (i.e. *test system-2*), and integrated IEEE 118-bus and modified Belgian 20-node gas network (i.e. *test system-3*). In order to investigate the impact of gas network on the LM of electricity network, two cases are considered, namely:

- *Case I*: Without modeling the gas network. In *Case I* the λ in (1) is maximized subject to just the electrical network hourly operation constraints, i.e. (2)-(20). As it is aforementioned, one may substitute (9) and (16) by (34)-(39) and (40)-(45), respectively to maintain NLP structure of the optimization model.

TABLE II
ELECTRICAL LINES DATA FOR *test system-1*.

	R (pu)	X (pu)	B (pu)	$\bar{S}$ (MVA)
L_1	0.01625	0.05313	0.01375	225
L_2	0.02500	0.12500	0.03125	175
L_3	0.03750	0.18750	0.03125	150

- *Case II*: With modeling the gas network. In *Case II* the λ in (1) is maximized subject to the both networks hourly operation constraints, namely (2)-(33). Similarly, (9), (16) and (21) can be replaced by (34)-(39), (40)-(45) and (49)-(51), respectively.

A. Test system-1: A simple IGES

1) *Data*: The single-line diagram of this IGES is depicted in Fig. 4. It comprises of a 3-bus electricity network connected to a 2-node gas network. The lines data is given in Table II. Also, the hourly demand of electricity and gas are given in Fig. 5.

Fig. 4. Single-line diagram of *test system-1*.

Fig. 5. Gas and electricity demand profile of *test system-1*

The electrical load is located at bus B_3 , whereas the gas demand fed at node N_2 . The generator located at bus B_2 is a GPP that absorb gas via node N_2 . The electric bus voltages upper and lower limits are 1.10 pu and 0.90 pu, respectively. Besides, a constant power demand increment pattern is assumed for this test system, i.e. $k_b^P = k_b^Q = 1$ in (14) and (15). The remaining data, including the parameters in (30)-(32), are same with the data of test systems 2 and 3, that will be given in the next sections. **Besides, for this system, the number of variables in optimization problem is 2041 and the CPU-time is 2.5 sec.**

Fig. 6. Binding constraints of *test system-1* in *Case I*: (a) Voltage at bus B_3 ; (b) Loading of line L_2 .

Fig. 7. Gas network nodal pressure in *test system-1*, *Case II*

2) *Results*: In *Case I*, the maximum LM is obtained to be 49.57% (i.e. $\lambda = 0.4957$). As it is depicted in Fig. 6, the binding constraints that restrict the LM in this case, are the voltage magnitude of bus B_3 (Fig. 6-(a)) and power flow of line L_2 (Fig. 6-(b)), both at hour t_{22} where the electric system experiencing peak loading condition. In the case of considering the gas network constraints (i.e. *Case II*) the maximum LM is 30.36%. In this case the binding constraints limiting the LM are the nodal gas pressure limits (i.e. (27)). It is inferred from Fig. 7 that at the peak hour of gas network, i.e. t_{19} , the gas pressure falls to its lower limit at node N_2 (i.e. 25 Bar). At the same time, the pressure at node N_1 hits the upper limit (i.e. 45 Bar), in order to facilitate gas delivery to node N_2 .

In order to investigate the impact of the aforementioned limits on the LM, a sensitivity analysis is performed by varying the lower limit of nodal gas pressure. Figure 8-(a) shows the LM variation versus minimum limit of nodal pressure. By increasing p from 20 Bar to 23 Bar, the LM is constant and equals to that

Fig. 8. Sensitivity analysis of LM in *test system-1*: (a) Variation of minimum pressure limit; (b) Variation of gas demand peak value.

Fig. 9. Single-line diagram of the integrated IEEE 39-bus and modified Belgian 20-node gas systems (*test system-2*).

obtained in *Case I*, i.e. 49.57%. This means that for this interval of pressure, gas network does not imply any binding constraints on LM. By further increase of pressure, the LM decreases such that for the limit of 29 Bar, it vanishes.

B. Test system-2: Integrated IEEE 39-bus and modified Belgian 20-node gas systems

1) *Data*: In this section, the proposed model for maximization of LM is implemented on the hybrid IEEE 39-bus and modified Belgian 20-node gas systems. The single-line diagram of the studied integrated energy system is depicted in Fig. 9. Also, a 24 hours operation horizon is considered and the hourly gas and electricity demand data are provided in Table III. Besides, again a constant power increment pattern is assumed for all demands in this test system, i.e. $k_b^P = k_b^Q = 1$ in (14) and (15).

The data of IEEE 39-bus system is adopted from [28]. The hourly electricity demand given in Table III is distributed among load buses based on the initial load share given in [28]. As it is shown in Fig. 9, it is assumed that generators located at buses 33 to 38 (i.e. $G4-G9$), are GPP units which

TABLE III
HOURLY GAS AND ELECTRICITY DEMANDS OF *test system-2*.

Time (h)	Gas demand (Mm^3)	Electricity demand (MW)	Time (h)	Gas demand (Mm^3)	Electricity demand (MW)
t_1	0.942	4109	t_{13}	1.336	5179
t_2	0.886	3828	t_{14}	1.336	4672
t_3	0.844	3659	t_{15}	1.307	4503
t_4	0.83	3287	t_{16}	1.321	4616
t_5	0.83	3085	t_{17}	1.392	4784
t_6	0.844	3344	t_{18}	1.406	5066
t_7	1.04	3715	t_{19}	1.406	5291
t_8	1.209	4165	t_{20}	1.35	5359
t_9	1.336	4222	t_{21}	1.28	5460
t_{10}	1.35	4841	t_{22}	1.166	5629
t_{11}	1.35	5122	t_{23}	1.026	5122
t_{12}	1.336	5404	t_{24}	1.026	4672

Fig. 11. Hourly total active power generation of GPPs in *test system-2* at COP and SLP.

gas inflow limitations, the total active power injected by GPPs is almost the same at the entire horizon since the generators $G4$ - $G9$ are almost generating their maximum active capacity. However, the dispatch of GPPs in *Case II* strongly depends on the hourly gas flow constraints and inherent limitations in gas inflow to the GPPs, such that injected active power in both COP and SLP varies considerably during the entire horizon.

The voltage magnitude of generator buses in COP and SLP are also shown in Fig. 12 for both cases. It is observed that in each case the voltages at SLP are lower than COP due to the activation of reactive power limits of generators that modifies the voltages according to (17)-(20). As an example, one can observe the voltage profile of generator $G1$, where at hours t_3 - t_6 the voltages at COP and SLP are the same, which means the reactive limits are not activated in this interval.

are directly fed through gas network. The remaining units do not use gas as the input fuel. The generation units data is given in Table V at the Appendix. Also, the constants $M_{1,b}$ and $M_{2,b}$ are assumed to be 2 times of $\bar{P}_b^G$. The gas network data is based on Belgian gas network. The nodal gas network and pipelines data are given respectively in Tables VI and VII at Appendix. Also the hourly gas demand is distributed based on the load participation factors given in Table VI. Also, the conversion ratio of gas to electricity by the gas-fired power plants (i.e. $\Lambda_{b,i}$ in (33)) is assumed to be the same for all units and equals to $5 \times 10^3 MWh/Mm^3$, which means a 45% efficiency for the power plants. The parameters in (30), (32) and (31) are as follows: $T_f = 279K$, $\epsilon = 0.05mm$, $Z = 0.8$ and $\delta = 0.6106$. Besides, for this system, the number of variables in optimization problem is 21,241 and the CPU-time is 212.8 sec.

2) *Results*: In *Case I* the maximum value of LM is obtained to be 25.71% (i.e. $\lambda = 0.2571$), whereas the maximum LM in *Case II* is 15.02%.

Active power generation dispatches at COP and SLP for both cases are shown in Fig. 10. Since it is assumed that generators

Fig. 10. Hourly active power output of different generators of *test system-2*, at COP and SLP in both cases.

$G4$ - $G9$ are GPPs, the gas network constraints have the highest impact on the active power generation of these units. The total active power generations of GPPs in both cases are compared in Fig. 11. It can be observed that in *Case I* where there are no

Fig. 12. Hourly generator bus voltages (in pu) of *test system-2* at COP and SLP for cases I and II

The optimal hourly reactive power supplied by generators in both cases are also depicted in Fig. 13. It is observed that most of GPPs can provide less reactive power at SLP in *Case II*,

Fig. 13. Hourly reactive power output (in MVar) of different generators of *test system-2*, at COP and SLP in both cases.

Fig. 14. Hourly gas supply in *test system-2*: (a) line pack; (b) total injection of gas sources.

especially at peak loading, i.e. t_{22} . This limited reactive power support in the case of considering gas network constraints (i.e. *Case II*), is the main reason for lower LM in this case, in comparison with *Case I*.

The optimal hourly line pack and gas source injections are given in Fig. 14. It is inferred from Fig. 14-(a) that the stored gas in pipelines through their line pack property increases during off-peak demand interval in COP and it is used to supply the extra demand of GPPs in SLP. Besides, from Fig. 14-(b) one can observe that during the first valley of the interval, i.e. t_1 - t_4 , the gas injection by the sources decreases in COP, as the demands of both networks are in the corresponding lowest level. But, since the electric network is subjected to demand increase in SLP, the gas injection is almost increasing during the interval t_4 - t_{20} , as the line pack reduced as a result of gas pressure drop.

3) Sensitivity analyses:

- Sensitivity analysis-1 (impact of line pack and gas demand on LM): In this section, to evaluate the impact of initial line pack (i.e. $\zeta_{ij,0}$) on LM, a sensitivity analysis is conducted by varying $\zeta_{ij,0}$ from 70% to 130% of its given values in

Fig. 15. The LM of *test system-2* in *Case II* vs the variation of: (a) initial line pack; (b) gas network loading.

Table VII. As it is shown in Fig. 15-(a), the LM increases from 12.87% to 17.14% as a result of $\zeta_{ij,0}$ increment from 70% to 130%. Hence, it is inferred that by increasing the initial line pack, the electric power system's LM increases. The proposed optimization model is solved with/without considering the line pack capability, by varying the gas demand from 70% to 130% of the value given in Table III. It is evident from Fig. 15-(b) that in the case of neglecting the line pack of gas pipelines (by neglecting $\zeta_{ij,c,t}$ in (23), (24) and (29)), more optimistic LM values are obtained, in contrary to the line pack consideration. Also, in the stressed gas network, in some hours the gas pressure hits its minimum limit at some nodes as shown in Fig. 16-(a). Besides, to deliver the gas demand at different nodes, the required pressure difference is obtained not only by reduction of nodal pressures, but also by increase of the pressure of some nodes, especially the source nodes. One can see from 16-(b) that the maximum nodal pressure is increased in some hours for higher loading percentages. These pressure limits influences the ability of GPPs in tuning the power supply, such that for higher levels of gas demand scale factors, less power can be generated by GPPs, as shown in Fig. 16-(c).

It is worth noting that the inclusion of gas network constraints (with/without line pack capability), reduces the LM of the power system. But, as shown in Fig. 15-(a), even for 30% increase of line pack, the LM is about 17.14%, which is less than that obtained in *Case I*, i.e., 25.71%. Besides, one can observe from Fig. 15-(b) that the line pack can enhance the LM in the power system side of the IGES compared to the case of neglecting line pack capability. But, the inclusion of gas network constraints (with or without line pack capability), results in a lower value of the system's LM, as for this test system the LM without gas network (i.e., in *Case I*) is 25.71%, which is higher than those shown in Fig. 15-(a) and (b).

- Sensitivity analysis-2 (impact of the GPPs location on LM):

Fig. 16. The impact of gas network loading on: (a) minimum hourly pressure; (b) maximum hourly pressure; (c) total hourly generation of GPPs.

Here, a scenario is studied in which the GPPs are located only in a limited region instead of evenly distributed in the whole power system. Accordingly, the GPPs set changed, and based on Fig. 9, the generators at buses 31-36 (i.e., $G_2 - G_7$) are assumed to be the new set of GPPs. By considering this set of GPPs, the LM equals 0.1123, which is smaller than the initial LM (i.e., 0.1502). It can be observed that for this new set of GPPs, the bottleneck transmission lines that connect them to the rest of the network are those connected between buses 4 – 14, 5 – 6, 14 – 15, 16 – 19 and 16 – 21. The capacity of these lines is changed in the range of $\pm 25\%$ of the initial values given in [28], to investigate the impact of transmission lines congestion. Hence, the proposed optimization model is solved considering 75%, 100%, and 125% of the initial capacities of the aforementioned critical lines. The obtained values for LM in these three cases are given in Fig. 17-(a). It is inferred from this figure that the LM depends on the imposed limits on transmission lines between the areas where GPPs are located and the rest of the network, such that the more transfer capacity is limited, the smaller values are obtained for LM. The hourly total power generation of GPPs at COP for these three limits of line capacities are shown in Fig. 17-(b). It is observed that the power dispatch of GPPs is almost the same for all three line capacities. The power generated by GPPs at the corresponding SLP is also shown in 17-(c). It can be observed from this figure that imposing a limit on the critical lines connecting the GPPs to the rest of the network, influences the electricity network's LM.

Fig. 17. Impacts of critical lines capacity variations on: (a) the LM of electricity network; (b) the total hourly dispatch of GPPs at COP; (c) the total hourly generation of GPPs at SLP.

- Sensitivity analysis-3 (impact of gas pipelines length on LM): The length of gas pipelines is another factor that influences the LM of electricity network, as the pressure drop as well as the line pack capability directly depend to this parameter. Here, the length of pipelines is varied from 50% to 150% of the values given in Table VII in the Appendix. Then, the impact of this variation on the electricity network's LM is studied. The obtained results are shown in Fig. 18. It is observed from Fig. 18-(a) that by reducing of pipelines length, the LM increases, such that for a 50% reduction, the LM increases from the initial value of 0.1502 (for the initial length), to 0.1619. Contrarily, when the length increases by 50%, i.e., with 150% of the initial lengths, the LM reduces to 0.1055. Besides, the total hourly power generation by GPPs, for different lengths of pipelines, is depicted in Fig. 18-(b). It is observed from this figure that, when the pipelines got shorter, more power could be injected by GPPs.

C. Test system-3: Integrated IEEE 118-bus and modified Belgian 20-node gas systems

1) Data: In this section, the proposed model for maximization of LM is implemented on the hybrid IEEE 118-bus and the Belgian 20-node gas systems. The single-line diagram of this system is depicted in Fig. 19. The data of the IEEE 118-bus network is available in [28]. Also, the demand profile for this

Fig. 18. Impacts of different gas pipelines' lengths on: (a) the LM of electricity network; (b) the hourly dispatch of GPPs.

system is the same as those given in Table III, except that the hourly electricity demands are scaled based on peak demand of 4242 MW at time t_{22} . The remaining data are the same with *test system-2*. Since the LM highly depends on load increment pattern from COP to SLP, in this test system, three different load increment patterns are considered to determine the maximum LM of the network. More specifically, the following patterns are considered in (14) and (15).

- Pattern-1: $k_b^P = 1$, $k_b^Q = 1$.
- Pattern-2: $k_b^P = 1$, $k_b^Q = 0.5$.
- Pattern-3: $k_b^P = 1$, $k_b^Q = 0$.

It is worth noting that *Pattern-1* is the constant power factor demand increment pattern from COP to SLP that is the most common pattern for evaluating the grid's LM. Besides, in *Pattern-2* the active power is increased more than the reactive power, and *Pattern-3* substantiates the constant reactive power pattern, as only the active power increases to attain SLP.

Besides, for this system, the number of variables in optimization problem is 46,561 and the average CPU-time of the above cases is 780.3 sec.

2) *Results*: The obtained results for both cases (i.e. cases I and II) in all aforementioned demand increment directions are given in Table IV. It is observed that for all patterns, the LM in *Case II* is less than *Case I*, that shows the impact of gas network's constraints on the LM. Besides, one can observe the impact of demand increment pattern on the LM, such that in *Pattern-1*, where both active and reactive powers are increased with a constant power factor, the LM is the lowest among all patterns and in both cases.

IV. CONCLUSIONS

This paper proposed an optimization model for maximization of electrical network LM in an IGES. The developed model

Fig. 19. Single-line diagram of the integrated IEEE 118-bus and modified Belgian 20-node gas systems (*test system-3*).

TABLE IV
LM VALUES FOR DIFFERENT LOAD INCREMENT PATTERNS IN IEEE 118-BUS NETWORK.

Pattern#	Case I: without Gas network	Case II: with Gas network
Pattern-1	0.4521	0.4078
Pattern-2	0.5844	0.4777
Pattern-3	0.6522	0.5625

consists of multi-period gas and electricity flow equations for both COP and SLP, including various realistic operational constraints such as reactive power capability curve of generators and line pack of gas pipelines. The model is implemented on an illustrative IGES and two larger systems, namely the IGES comprising the Belgian 20-node gas systems in conjugation with IEEE 39-bus and 118-bus electric power networks. The concluding remarks can be summarized as follows.

- In addition to electrical network operational limits such as voltage magnitudes, line flow limits, and reactive power generation limits, another important operational limit, namely the gas network nodal pressure limit may be a binding constraint for maximization of LM in the electrical network.
- Power system's LM reduces when the gas network oper-

TABLE V
ELECTRICITY NETWORK GENERATOR DATA.

Bus #	Gen. #	$\bar{P}^G$ (MW)	$\underline{P}^G$ (MW)	V_{rated} (kV)	$\bar{T}^G$ (kA)	RU (MW/h)	RD (MW/h)	δ (deg.)
30	G1	1004	0	15	39	150	150	70
31	G2	646	0	15	25	97	97	70
32	G3	725	0	15	28	109	109	70
33	G4	652	0	15	25	98	98	70
34	G5	508	0	15	20	76	76	70
35	G6	687	0	15	26	103	103	70
36	G7	580	0	15	22	87	87	70
37	G8	564	0	15	22	85	85	70
38	G9	865	0	15	33	130	130	70
39	G10	1100	0	15	42	165	165	70

ational constraints (with and without line pack capability) are included in the IGES model. If the power to gas is also considered in IGES, then the gas network can improve the security margin of the power system by increasing the line pack stored in the gas pipelines.

- Inclusion of line pack phenomenon for characterizing the hourly behavior of gas networks leads to a more realistic estimate of security margin. It is observed that the hourly available line pack, influences the security margin of IGESs.
- The ability of the gas network in supporting the voltage security of the electricity network, depends on gas pipelines' length; such that the longer the pipelines are, the smaller LM would be.
- The proposed model can be used to determine the maximum loadability of both gas and electricity networks. It means that the generalized concept of security limit point can be further extended for IGESs in terms of both gas and electricity networks' operational constraints.
- Demand increment pattern is another factor influencing the LM. The analysis showed that the patterns with an increment of both active and reactive powers will result in smaller LM values.

V. APPENDIX

The generators' data of IEEE 39-bus system is given in Table V. Also, the nodal gas network data is provided in Table VI and the gas pipelines data is given in Table VII.

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REFERENCES

- [1] IEA, Paris, "Iea (2019), world energy outlook 2019," <https://www.iea.org/reports/world-energy-outlook-2019>, Online; accessed 22 May 2020.
- [2] Sustainable Energy Authority of Ireland (SEAI), "Energy in Ireland, 2019 report," <https://www.seai.ie/publications/Energy-in-Ireland-2019-.pdf>, Online; accessed 22 May 2020.
- [3] H. Ameli, M. Qadrdan, G. Strbac, and M. T. Ameli, "Investing in flexibility in an integrated planning of natural gas and power systems," *IET Energy Systems Integration*, vol. 2, no. 2, pp. 101–111, 2020.
- [4] S. P. Torres, W. H. Peralta, and C. A. Castro, "Power system loading margin estimation using a neuro-fuzzy approach," *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 1955–1964, 2007.
- [5] M. F. Zambroni de Souza, Y. Reis, A. B. Almeida, I. Lima, and A. C. Zambroni de Souza, "Load margin assessment of systems with distributed generation with the help of a neuro-fuzzy method," *IET Renewable Power Generation*, vol. 9, no. 4, pp. 331–339, 2015.
- [6] X. Gu and C. A. Canizares, "Fast prediction of loadability margins using neural networks to approximate security boundaries of power systems," *IET Generation, Transmission Distribution*, vol. 1, no. 3, pp. 466–475, 2007.
- [7] V. S. N. Arava and L. Vanfretti, "A method to estimate power system voltage stability margins using time-series from dynamic simulations with sequential load perturbations," *IEEE Access*, vol. 6, pp. 622–632, 2018.
- [8] M. E. Karystianos, N. G. Maratos, and C. D. Vournas, "Maximizing power-system loadability in the presence of multiple binding complementarity constraints," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 54, no. 8, pp. 1775–1787, 2007.
- [9] A. Rabiee, A. Soroudi, B. Mohammadi-ivatloo, and M. Parniani, "Corrective voltage control scheme considering demand response and stochastic wind power," *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 2965–2973, 2014.
- [10] A. Rabiee, S. M. Mohseni-Bonab, M. Parniani, and I. Kamwa, "Optimal cost of voltage security control using voltage dependent load models in presence of demand response," *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2383–2395, 2019.

TABLE VI
NODAL GAS NETWORK DATA.

Node	$\underline{G}^S$ (Mm ³)	$\bar{G}^S$ (Mm ³)	$\underline{p}$ (Bar)	$\bar{p}$ (Bar)	Load participation
Zeebrugge	0.1	2	15	77	0
Dudzele	0	0.35	15	77	0
Brugge	0	0	15	80	0.063
Zomergem	0	0	15	80	0
Loenhout	0	0.2	15	77	0
Antwerpen	0	0	15	80	0.057
Gent	0	0	15	80	0.109
Peronnes	0	0.04	15	66.2	0
Voeren	0.1	1	25	66.2	0
Berneau	0	0	25	66.2	0
Liege	0	0	15	66.2	0.117
Warnand	0	0	15	66.2	0
Namur	0	0	15	66.2	0.046
Anderlues	0	0.05	15	66.2	0
Mons	0	0	15	66.2	0.198
Blaregnies	0	0	25	66.2	0.4
Wanze	0	0	15	66.2	0
Sinsin	0	0	15	63	0
Arlon	0	0	15	66.2	0.005
Petange	0	0	15	66.2	0.005

TABLE VII
GAS PIPELINES DATA.

line no.	from (i)	to (j)	D_{ij} (mm)	L_{ij} (km)	$\zeta_{ij,0}$ (Mm ³ /h)
1	Zeebrugge	Dudzele	890	4	0.124
2	Zeebrugge	Dudzele	890	4	0.124
3	Dudzele	Brugge	890	6	0.189
4	Dudzele	Brugge	890	6	0.189
5	Brugge	Zomergem	890	26	0.831
6	Loenhout	Antwerpen	590.1	43	0.595
7	Antwerpen	Gent	590.1	29	0.407
8	Gent	Zomergem	590.1	19	0.267
9	Zomergem	Peronnes	890	55	1.630
10	Voeren	Berneau	890	20	0.614
11	Voeren	Berneau	890	20	0.614
12	Berneau	Liege	890	20	0.580
13	Berneau	Liege	890	20	0.580
14	Liege	Warnand	890	25	0.683
15	Liege	Warnand	890	25	0.683
16	Warnand	Namur	890	42	1.147
17	Namur	Anderlues	890	40	1.093
18	Anderlues	Peronnes	890	5	0.137
19	Peronnes	Mons	890	10	0.273
20	Mons	Blaregnies	890	25	0.725
21	Warnand	Wanze	395.5	10.5	0.057
22	Wanze	Sinsin	395.5	10.5	0.056
23	Sinsin	Arlon	315.5	80	0.269
24	Arlon	Petange	315.5	6	0.021

- [11] L. Bai, F. Li, T. Jiang, and H. Jia, "Robust scheduling for wind integrated energy systems considering gas pipeline and power transmission n-1 contingencies," *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 1582–1584, 2017.
- [12] G. Sun, S. Chen, Z. Wei, K. W. Cheung, and H. Zang, "Corrective security-constrained optimal power and gas flow with binding contingency identification," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 2, pp. 1033–1042, 2020.
- [13] F. Fallahi and P. Maghouli, "Integrated unit commitment and natural gas network operational planning under renewable generation uncertainty," *International Journal of Electrical Power & Energy Systems*, vol. 117, p. 105647, 2020.
- [14] A. Martinez-Mares and C. R. Fuerte-Esquivel, "A unified gas and power flow analysis in natural gas and electricity coupled networks," *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2156–2166, 2012.
- [15] C. M. Correa-Posada, P. Sanchez-Martin, and S. Lumbreras, "Security-constrained model for integrated power and natural-gas system," *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 3, pp. 326–336, 2017.
- [16] C. Wang, W. Wei, J. Wang, F. Liu, F. Qiu, C. M. Correa-Posada, and S. Mei, "Robust defense strategy for gas-electric systems against malicious attacks," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 2953–2965, 2016.
- [17] W. Dai, J. Yu, Z. Yang, H. Huang, W. Lin, and W. Li, "A static equivalent model of natural gas network for electricity-gas co-optimization," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 3, pp. 1473–1482, 2020.
- [18] J. Fan and X. Tong, "Optimal location allocation strategy of gas-fired unit in transmission network," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 2, pp. 229–237, 2020.
- [19] M. Qadrdan, J. Wu, N. Jenkins, and J. Ekanayake, "Operating strategies for a gb integrated gas and electricity network considering the uncertainty in wind power forecasts," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 1, pp. 128–138, 2013.
- [20] A. Zlotnik, M. Chertkov, and S. Backhaus, "Optimal control of transient flow in natural gas networks," in *2015 54th IEEE Conference on Decision and Control (CDC)*, 2015, pp. 4563–4570.
- [21] A. Zlotnik, L. Roald, S. Backhaus, M. Chertkov, and G. Andersson, "Coordinated scheduling for interdependent electric power and natural gas infrastructures," *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 600–610, 2017.
- [22] S. Misra, M. W. Fisher, S. Backhaus, R. Bent, M. Chertkov, and F. Pan, "Optimal compression in natural gas networks: A geometric programming approach," *IEEE Transactions on Control of Network Systems*, vol. 2, no. 1, pp. 47–56, 2015.
- [23] A. Rabiee and M. Parniani, "Voltage security constrained multi-period optimal reactive power flow using benders and optimality condition decompositions," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 696–708, 2013.
- [24] E. S. Menon, *Gas pipeline hydraulics*. Crc Press, 2005.
- [25] A. Soroudi, *Power system optimization modeling in GAMS*. Springer, 2017.
- [26] A. Wächter, "Short tutorial: getting started with ipopt in 90 minutes," in *Dagstuhl Seminar Proceedings*. Schloss Dagstuhl-Leibniz-Zentrum für Informatik, 2009.
- [27] A. Wächter and L. T. Biegler, "On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming," *Mathematical programming*, vol. 106, no. 1, pp. 25–57, 2006.
- [28] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Transactions on power systems*, vol. 26, no. 1, pp. 12–19, 2010.

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