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Abstract— The main purpose of this paper is to develop a method for sequential gas and electricity networks expansion planning problem. A leader-follower approach performs the expansion planning of the joint gas and electricity networks. Electric system operator under adequacy incentive decides about investment in capacity addition to the generation and transmission levels while considers the limitations on fuel consumption. On the other hand gas operator decides about investment in gas pipelines expansions considering the demanded gas by the electricity network. In this planning model for a joint gas-electricity network, supply and demand are matched together while adequacy of fuel for gas consuming units is also guaranteed. To illustrate the effectiveness of the proposed method Khorasan province of Iran is considered as a case study which has a high penetration level of gas-fired power plants (GFPP). Also results are compared with the integrated gas-electricity networks expansion planning method.

Keywords—Gas; Electricity; Expansion Planning; Leader-Follower; Optimization; MINLP.

NOMENCLATURE

Indices and Sets

i,j	Indices of gas nodes
m,n	Indices of electricity nodes
t	index for load period (off-peak, mid load, and peak)
d	Index of days
y	Index of years
g	Index of generation units
T	Planning period
N^{Gas}, N^{Elec}	Sets of nodes in gas and electricity networks
$\mathcal{TL}$	Set of transmission lines
$\mathcal{PL}, \mathcal{PL}^{Active},$ $\mathcal{PL}^{passive}$	Sets of pipelines, active pipelines and passive pipelines
GU, GU^{gas}	Sets of power plants and GFPPs

Variables

S_{iyd}^{Gas}	Gas production in node i on day d of year y
OC_{ydt}	Operation cost of electricity network
f_{ijyd}^{Gas}	Gas flow through pipeline ij on day d of year y
θ_{mydp}	
s_{iyd}^{l}	Gas load at node i on day d of year y
pr_{iyd}^{g}	Gas pressure at node i on day d of year y
PF_{mnyd}	Power flow through line $m\text{-}n$ on day d of year y
X_{mgyd}^{Elec}	Gas consumption of power plants on day d of year y in electricity network
X_{iyd}^{gas}	Gas consumption of power plants on day d of year y in gas network
p_{mgydt}^{Gen}	Power generation of unit g of bus m at period t of day d of year y
θ_{mydt}	Voltage angle at period t of day day d of year y
bin_{ij}^{Pipe} / bin_{mn}^{Trans} / bin_{mg}^{Gen}	Binary variable indicating existence of pipeline/transmission line/generation

Parameters

K_{ij}^{pipe}	Weymouth constant
λ_{iyd}^{Gas}	Gas price in gas network
L_{ij}^{Pipe}	Length of pipeline
A_{ij}^{Pipe}	Diameter of pipeline
P_{mg}^{rated}	Power plant rated power
$p_{mydp}^{load} p_b$	Load in electricity network
λ_{m}^{X}	Fuel price
y_{mn}	Per unit admittance
p_b	Base MW
GHV_h	Gross heating value of fuel
$cost_{ij}^{Pipe}$ / $cost_{mn}^{trans}$ / $cost_{mg}^{Gen}$	Construction cost of pipeline/ transmission line/generation unit
r	Interest rate

I. Introduction

Gas-fired power plants (GFPPs) are key players in an integrated energy system, which connect gas and electricity networks tightly together. GFPPs are environmentally friendly because of their high efficiency rates and low CO_2 emissions, which is a crucial factor in future of green energy [1]. Renewables do not generate a reliable output. Hence GFPPs in combination with new electricity storage systems are ideally suited to this purpose as they can easily be fired up in just a few minutes, far more quickly than coal-fired power plants [2].

In the literature, there are some studies on gas-electricity expansion planning problem. A model that integrates electricity distribution and natural gas networks is presented in [3]. This model is proper for utilities that own both electricity and natural gas networks and could reduce their investment costs via electricity or gas tariffs. Proposed model in [4] simultaneously minimizes the total operational and expansion costs of gas and electricity networks. Additionally it determines the optimal location of the planned power generating units. In [5] a robust model proposes an integrated electricity and natural gas planning with the grid resilience considered as a set of constraints. An iterative process between gas and electricity networks in a combined market is illustrated in [6]. Obtained model minimizes the total investment and operational cost of a gas-electricity expansion problem.

On the other hand multi-level game theoretic approaches are a well thought-out procedure in optimization problems. A review on multilevel decision-making techniques is provided in [7]. Authors of [8] models grid reinforcement investment as a two-stage strategic game between the line investor and local. The proposed methodology in [9] is a bi-level programming model whose upper-level represents the problem of investment in transmission and the lower-level problems represent market outcomes obtained from clearing the market and their investment in generation capacity. Work presented in [10] proposes a sequential coordination of transmission expansion planning with strategic generation investments. Generation companies (GenCos) move first and expand their future generation capacities and then transmission company (TransCo) makes investment decisions.

In this paper a sequential approach to co-expansion of gas-electricity planning problem is introduced. A leader-follower approach performs the coordinated expansion planning of gas and electricity networks. Electricity network, as a leader in the proposed leader-follower approach, makes decisions and gas network expansion plan will be obtained according to the received data of gas consuming generation units. In electricity network level both transmission and generation expansion opportunities are optimized in a centralized manner. Generation expansion determines the size and location of new units and transmission expansion ensures a feasible power delivery. On the other hand, gas network operator tracks the electricity network gas consumption needs to make appropriate decision regarding the pipeline expansions.

In the following sections, firstly gas and electricity networks expansion planning are modeled. Then, the proposed leader-follower approach is described and its effectiveness is demonstrated within a case study on Khorasan province of Iran which has a high penetration level of gas consuming units. Finally, a brief discussion is presented over the results and the future work will be outlined.

II. Expansion Planning Problem Formulation

A. Gas network expansion model

The main objective of the gas network expansion planning is to supply the loads with minimum total cost which includes both operation and investment costs. In this way supplying new load could be achieved by adding new pipes if needed. New pipelines should be located in the gas network in a way to guarantee the feasible performance and operating point. Hence the objective function of gas network is to minimize the cost of expansion and the net present value (NPV) of operation cost during the planning period. This optimization process is subjected to the Weymouth equations [11] and some other technical constraints of gas network. So expansion planning model of the gas network could be written as:

$$Min \; C^{Gas} = \left\{ \begin{array}{l} \sum_{i,j} bin_{ij}^{Pipe} L_{ij}^{Pipe} A_{ij}^{Pipe} cost_{ij}^{Pipe} \\ + \sum_{y=1}^{T} (1+r)^{-(y-1)} \sum_{d,i} S_{iyd}^{Gas} \lambda_{iyd}^{Gas} \end{array} \right\} \tag{1}$$

$s.t.$

$$\underline{f_{ij}^{Gas}} \leq f_{ijyd}^{Gas} \leq \overline{f_{ij}^{Gas}} \qquad \forall \, ij \in \mathcal{PL}^{passive} \tag{2}$$

$$\begin{array}{l} sign(f_{ijyd}^{Gas}) f_{ijyd}^{Gas\,2} \\ = K_{ij}^{Pipe\,2}(pr_{iyd}^{g\,2} - pr_{jyd}^{g\,2}) \end{array} \qquad \forall \, ij \in \mathcal{PL}^{passive} \tag{3}$$

$$\begin{array}{l} sign(f_{ijyd}^{Gas}) f_{ijyd}^{Gas\,2} \\ \geq K_{ij}^{Pipe\,2}(pr_{iyd}^{g\,2} - pr_{jyd}^{g\,2}) \end{array} \qquad \forall \, ij \in \mathcal{PL}^{Active} \tag{4}$$

$$0 \leq f_{ijyd}^{Gas} \leq \overline{f_{ij}^{Gas}} \qquad \forall \, ij \in \mathcal{PL}^{Active} \tag{5}$$

$$\underline{S_i^{Gas}} \leq S_{iyd}^{Gas} \leq \overline{S_i^{Gas}} \qquad \forall \, i \in N^{Gas} \tag{6}$$

$$\underline{pr_i^g} \leq pr_{iyd}^g \leq \overline{pr_i^{Gas}} \qquad \forall \, i \in N^{Gas} \tag{7}$$

$$S_{iyd}^{Gas} = \sum_j bin_{ij}^{Pipe} f_{ijyd}^{Gas} + (X_{iyd}^{Gas} + s_{iyd}^l) \qquad \forall \, i \in N^{Gas} \tag{8}$$

$$X_{iyd}^{Gas} \geq \sum_g X_{mgyd}^{Elec} \qquad \forall \, g \in GU^{Gas} \tag{9}$$

In which constraint (2) is limitations of gas flow in passive – pipelines without a compressor- pipelines. Constraints (3)-(4) are Weymouth equations of gas network which relates the gas flow to the pressure difference in passive and active –pipelines with compressor- pipelines respectively [11]. Gas flow in active pipelines is limited by (5). Constraint (6) indicates supply bounds in different nodes. Constraint (7) determines gas pressure limits at each node. Node balance is defined by (8). Constraint (9) is the coupling factor which relates gas and electricity networks through fuel consumption of gas fired power plants.

B. Electricity network expansion model

Electricity network operator also aims at keeping a feasible and economic operation profile while making an expansion planning for the electricity network. To simplify the load flow studies while checking the feasibility of solutions in terms of meeting the technical constraints, DC power-flow is incorporated in the planning loop [12]. Proposed formulation performs both generation and transmission expansion planning in which location and size of new generation units is determined and on the other hand new transmission lines are located to have a reliable network. The objective function of this optimization problem comprises of three terms. Two terms are considering the cost of generation and transmission expansion plan and the third is targeting the NPV of electricity network operation cost.

$$Min\, C^{Elec} = \left\{ \begin{matrix} \sum_{m,n} bin_{mn}^{Trans} cost_{mn}^{trans} + \sum_{m,g} bin_{mg}^{Gen} P_{mg}^{rated} cost_{mg}^{Gen} \\ + \sum_{y=1}^{T} (1+r)^{-(y-1)} \sum_{d,t} OC_{ydt} \end{matrix} \right\} \qquad (10)$$

$s.t.$

$$OC_{yd} = \sum_{mg} \lambda_m^X X_{mgyd}^{Elec} bin_{mg}^{Gen} \qquad \forall m \in N^{Elec}, g \in GU \qquad (11)$$

$$\sum_g bin_{mg}^{Gen} \times p_{mgydt}^{Gen} = \sum_n \frac{bin_{mn}^{Trans} \times PF_{mnydt}}{+ p_{mydt}^{load}} \qquad \begin{matrix} \forall m \in N^{Elec}, p \in P \\ N^{Elec}, \forall p \in P \end{matrix} \qquad (12)$$

$$\begin{matrix} PF_{mnydt} = \\ p_b \times \sum_n y_{mn} (\theta_{mydt} - \theta_{nydt}) \end{matrix} \qquad \forall m \in N^{Elec}, p \in P \qquad (13)$$

$$\theta_{ref} = 0 \qquad (14)$$

$$\underline{p_{mg}^{Gen}} \le p_{mgydt}^{Gen} \le \overline{p_{mg}^{Gen}} \qquad \begin{matrix} \forall m \in N^{Elec}, g \in GU, \forall p \in P \\ \forall m \in N^{Elec}, \\ p \in P, g \in GU \end{matrix} \qquad (15)$$

$$-\overline{PF_{mn}} \le PF_{mnydt} \le \overline{PF_{mn}} \qquad \begin{matrix} \forall m \in N^{Elec}, mn \in TL \\ \forall mn \in TL, \forall p \in P \end{matrix} \qquad (16)$$

$$\begin{matrix} X_{mgyd}^{Elec} = \\ \sum_t T_t \frac{\alpha_{mg} + \beta_{mg} p_{mgydt}^{Gen} + \gamma_{mg} p_{mgydt}^{Gen\,2}}{GHV_g} \end{matrix} \qquad \forall m \in N^{Elec}, g \in GU \qquad (17)$$

Constraint (11) defines operation cost of generation units in each day of a year. Node balance is indicated by (12). Power flow in transmission lines is obtained using (13). Based on DC load flow reference bus angle is fixed to zero by (14). Generation units' bounds are defined by (15). Constraint (16) determines the limitations in transmission lines. Fuel consumption of generating units is obtained by their Gross heating value using (17).

C. Leader-follower approach

To coordinate the expansion planning of gas and electricity networks, a leader-follower approach is used where electricity network is supposed to be the leader and gas network is the follower who tracks the decisions. By initializing the problem with an upper-limit for gas consumption of GFPPs, electricity network operator makes decisions about generation and transmission network planning. Updated gas fuel consumption of GFPPs is sent to the gas network operator which checks the feasibility according to the gas network expansion decisions.

Electricity network expansion planning is known as leader and it is performed by electricity network operator using (10)-(17). This problem aims to deal with both generation and transmission expansion decisions. Gas network operator is supposed to be follower and makes his decisions on pipeline expansion by (1)-(9) based on electricity network fuel request.

III. SIMULATION RESULTS

The test system used to apply the proposed methodology is the Khorasan province of Iran gas and electricity networks. The 400 KV electricity system includes 18 transmission lines and 15 buses in which 33 gas consuming units are dispatched among 7 buses. In gas network, there are 14 nodes that are connected together through 13 pipelines. Supplementary data of the proposed electricity and gas networks are given in [13] and [14], respectively. We suppose a planning period of 15 years with annual load grows of 3% in both gas and electricity networks.

The current demand in electricity network is 3129 MW while a maximum generation of 3880 MW is available. In gas network there is a consumption rate of 39.133 million standard cubic meters per day (MSCMD) demanded by other parties than GFPPs such as residential sector. Existing pipelines, transmission lines, and generating units and their candidates for expansion planning are depicted in Fig. 1. Expansion candidates of both gas and electricity networks and their investment cost are given in TABLE I.

a- Khorasan Electricity network
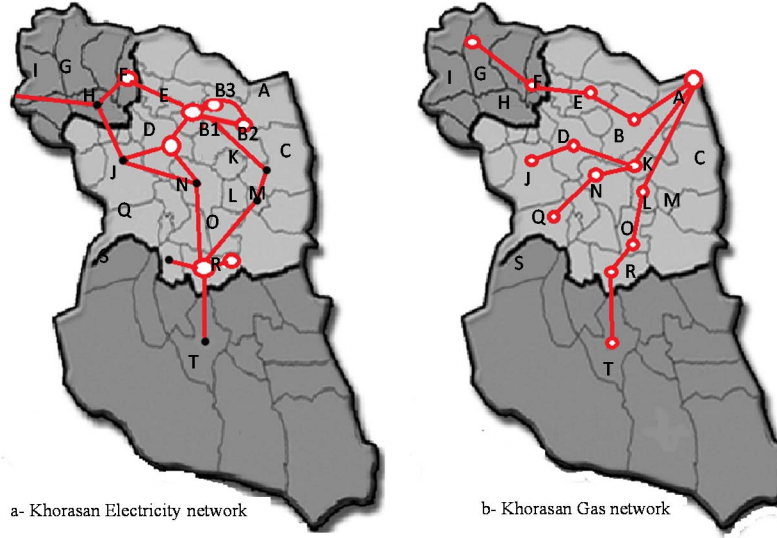
b- Khorasan Gas network

Fig. 1. Khorasan Electricity (A) And Gas (B) Networks

Numerical results show that electricity network intends to add almost 1000 MW more capacity in regions Q, R and B2 while there is no need to setup a new transmission line. Additionally in gas network a capacity increment in pipelines A-B and A-K is needed. Results are summarized in TABLE 2. Obtained results shows a total cost of 37.28 billion dollars for gas network.

TABLE I: EXPANSION CANDIDATES AND THEIR INVESTMENT COSTS

Pipe.	Cost (k\$/inch-km)	Trans.	Cost (k\$/km)	Gen.	Cost (k\$/MW)
A-B3	40	S-Q	240	C	900
A-L	40	K-C	240	S	900
A-K	60	B-C	360	Q	900
F-D	60	K-D	480	L	900
G-J	60	R-Q	480	F	900
		R-T	480	I	900
		R-S	480	T	1170
				B	1440
				R	1080

Results of the proposed methodology are also compared to those of an integrated method. In integrated method a single entity is responsible for expansion of both gas and electricity networks [4]. By this method, total expansion cost of gas network is 37.19 billion dollars which is relatively lower than the cost estimated by the proposed leader-follower approach. Results also demonstrate that to ensure maximum profit of both agents there is a need to develop a model which makes decisions with consensus of both gas and electricity networks.
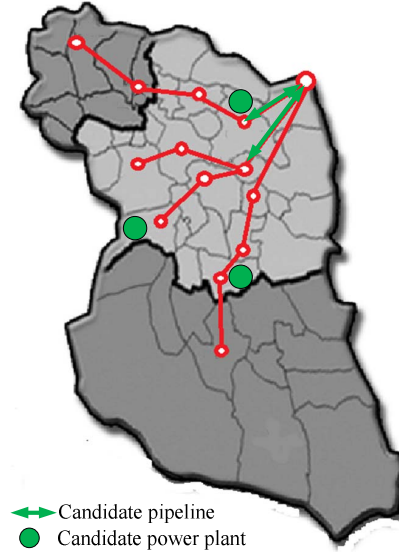

Candidate pipeline
Candidate power plant

Fig. 2. Expansion planning results of leader-follower approach for generation and pipelines

TABLE II: RESULTS OF GAS-ELECTRICITY EXPANSION

Case	Leader-follower (Proposed Method)		Integrated	
	Electricity	Gas	Electricity	Gas
Expansion cost(10^9\$)	0.35	0.1	0.37	0.019
Total cost(10^9\$)	7.75	37.28	7.76	37.19
New lines	-	A-B, A-K	F-H	A-B
New generation units	Q,R,B2	-	F,R,B2	-

Obtained results show that the total cost of investment and operation in gas network is 37.28 billion dollar which is more than the results of integrated method. The reason is that the electricity network wants to install a new power plant in Q region as shown in Fig. 2. In gas network, Q is supplied mainly by A-K pipeline. So to supply the new demand in Q, the capacity of A-K pipeline must be increased whereas it is not an efficient option for gas operator. However gas network is forced to supply sufficient gas demand for Q region. If there wasn't such an infliction, the costs and final plans would be the same in both leader-follower and integrated methods.

IV. CONCLUSION

In this paper a leader-follower approach for expansion planning problem of gas-electricity system was presented. Electricity network operator was considered as leader making decisions on both generation and transmission expansion planning. On the other hand, Gas network operator was assigned as a follower to make decisions on pipeline expansion planning based on electricity network fuel request. Results of leader-follower approach were compared with those of an integrated method. It was shown that with leader-follower approach extra cost is forced to gas network while electricity network chooses the minimum cost plan. Hence other decomposition approaches must be provided to coordinated expansion planning of gas and electricity networks. A real case study in Iran was used to demonstrate the effectiveness of the model. Adequacy of gas-electricity network was satisfied in a period of 15 years with a minimum cost of operational planning.

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