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Importance of Gas-Fired Power Plants Location in Integrated Operation of Power and Natural Gas systems: Peak Load Condition Analysis

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Abstract—**The increasing use of natural gas for power generation has caused a sudden improvement in interdependence between the two networks. These networks were analyzed traditionally as independent systems. In IRAN, Power Company is known as leader and Gas Company as a follower in the energy market. This situation imposes unfair charges on Gas Company. The aim of this paper is to determine the real operation cost of both systems. In this paper, an integrated operation of electricity and natural gas systems is used. Alternative fuel is considered as an effective peak shaving method in cold winters. The proposed model focused on the role of compressors in integrated optimization and obtain their fuel cost as an important decision variable. The applicability of the proposed approach has been demonstrated by analyzing a single branch gas pipeline network combined with the IEEE-9 test system. Simulations illustrate the importance of the location of power plants along the pipeline. The proposed model can be used to decide on the operation and planning of a coordinated electricity and natural gas systems.**

Keywords- integrated operation; energy market; compressor; gas pipeline; electricity system; natural gas infrastructure

I. INTRODUCTION

In the past two decades, the electricity and gas industries which previously operated separately, gradually converged. Gas-fired power plants are the point of connection between these two industries. The amount of natural gas used for power generation has increased since 1973, from 212 to 1167 Mtoe in 2012. The mentioned values are 21.8% and 41.5% of the world's total gas consumption. Today, natural gas is known as the cleanest fossil fuel. Natural gas is not only today's most important source of energy (where fossil fossils are still the world's leading source of energy) but also in the future (where renewable sources will supply the world's energy) can make a significant contribution to the primary energy basket [1].

The increasing of Shale oil and gas production in the United States has led to a sharp decline in oil and gas prices in the world in recent years. The natural gas price reduction has encouraged electricity producers to make more use of gas-fired power plants and replace conventional fuels, such as coal with natural gas [2]. In Iran, Natural gas accounts for about 70% of the energy basket of the country. In the last four years, the country has witnessed a doubling in gas consumption. Today natural gas is known as the main fuel of the country's power plants [3].

In [4] an ED model proposed considering constraints of natural gas and electric systems. Effects of compressors cost on gas-fired power plants in peak load condition on natural gas pipeline system has been considered. In [5], an integrated operation of tow systems whit consideration of alternative fuel is introduced. This paper focused on compressors role in natural gas transmission cost, especially during peak condition.

In [6], a comprehensive energy model has been introduced which used DC OPF with both steady-state and transient gas analyses. Dynamic and steady-state gas flow model in separate and combined operation condition are compared in [7]. Dynamic optimal energy flow transformed into a single stage linear programming whit assumptions and simplifications in [8]. Natural gas operating constraints impose limits on power plants output during cold winters. Today, in many parts of the world, natural gas is recognized as the most important fuel for power plants. Therefore, attention to gas supply infrastructure has become more important than before. The interruption of timely gas supply or the drop in gas pressure in the pipelines can cause loss of power plants and threaten the security of the system. The application of fuel diversity is known as an effective strategy for natural gas demand peak shaving that could reduce the upward price of electricity in peak condition [4],[5],[9]. Determine a secure region with distinct critical boundaries could be a valuable guidance for dispatching of gas-fired power plants [10].

In IRAN, Power Company is known as leader and Gas Company as a follower in the energy market. It means that power plants choose their best strategy without considering gas network constraints. Gas Company should provide power plants fuel and try to minimize its cost after that. This situation imposes unfair charges on Gas Company. Here an integrated

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optimization is suggested. The aim of using this method is to obtain an optimum strategy for both companies. This paper focuses on operating of gas-fired power plants in peak load condition on the natural gas pipeline system. Integrated and separated optimization solutions compared in term of cost. Electrical DC OPF and steady-state gas flow model are used here. Compressor's role has been considered. The main contribution of this paper is the comparison between the efficiency of the power plants and their proper location in the gas network.

The paper is organized as follows: Section II introduce natural gas modeling, different parts of the gas network and the related formulation. In section II the integrated power flow of electricity and natural gas is modeled. The application of the proposed approach to coupled systems is presented in Section IV. Finally, Section VI presents the conclusions of this study.

II. NATURAL GAS SYSTEM MODELING

Well, pipeline, compressor, and load are four main elements of the gas network in this study. The steady-state modeling of a natural gas network is formulated by the gas flow equations.

A. Well Gass

The gas supplier node can be either injection-known or pressure-known. The gas pressure is considered to be constant in the gas flow analysis. In real-time operation, the pressure or injection of gas does not remain constant by changing the load. Because the priority is the timely supply of the network [10].

B. Flow Equation In Pipeline

Several equations have been suggested to compute the gas flow through pipelines [11]. The main difference between them is the effect of the friction coefficient and gas characteristics on the formulas related to the gas flow through the pipelines [12]. In this paper, the Weymouth equations for gas flow in pipelines is employed to model steady-state gas flow between nodes i and j [11].

$$f_{ij} = \sqrt{pipecoeff}\left(\left|\Pi_i\right|^2 - \left|\Pi_j\right|^2\right)^{0.5} \tag{1}$$

$$\underline{f_{ij}} \le f_{ij} \le \overline{f_{ij}} \tag{2}$$

$$\underline{\Pi_i} \le \Pi_i \le \overline{\Pi_i} \tag{3}$$

f_{ij} = pipeline flow rate, MSCMH (Thousand Standard Cubic Meter Per Hour)

Π_i = pressure at node i, psia

$pipecoeff$ = pipeline coefficient (depending on pipeline structure), non-dimensional

This equation has been simplified because gas flow direction is known. In pipelines, gas flows from higher pressure node to lower pressure node. Therefore in single source gas flow studies, Π_i is considered greater than Π_j .

C. Compressor Station Model

Compression stations are installed in gas pipelines to compensate for the loss of pressure. The reasons for the drop in gas pressure through the pipelines are friction and the heat transfer between gas and the surrounding area in cold seasons. Actually, compressors provide the required pressure for gas to flow from one point to another [13]. Instead, they impose heavy charges on the network which should be considered in optimization equations.

$$BHP_{ij} = 4.063\left(\frac{Z_a f_{ij} T_i}{\eta_c}\right)\left(\frac{\Upsilon}{\Upsilon - 1}\right)\left(\left(\frac{\Pi_j}{\Pi_i}\right)^{\frac{\Upsilon-1}{\Upsilon}} - 1\right) \tag{4}$$

$$\tau_{ij}^c = \alpha_{ij}^c + \beta_{ij}^c.\left(BHP_{ij}\right) + \gamma_{ij}^c\left(BHP_{ij}\right)^2 \tag{5}$$

$$1 \le \frac{\Pi_j}{\Pi_i} \le \overline{ratio_{ij}^c} \tag{6}$$

BHP_{ij} = required energy for compressors, HP

Z_a = gas compressibility factor, non-dimensional

T_i =average gas temperature, K

η_c = compressor efficiency, decimal value

Υ =ratio of specific heats of gas, non-dimensional

τ_{ij}^c =amount of gas used by compressor, MSCM

α_{ij}^c = compressor coefficient, MSCM

β_{ij}^c = compressor coefficient, MSCM/hp

γ_{ij}^c = compressor coefficient, MSCM/hp^2

$\overline{ratio_{ij}^c}$ =maximum limit of compressor ratio, non-dimensional

D. Load modeling

Natural gas loads divided into electrical and nonelectrical loads. Nonelectrical loads consist of residential and commercial loads and it is considered constant in short-term operation. Electrical loads are variable and depend on power plants generation which varying according to following relationships.

$$H\left(Pg_m\right) = \alpha_m + \beta_m\left(Pg_m\right) + \gamma_m\left(Pg_m\right)^2 \tag{7}$$

$$Fuel\left(Pg_m\right) = \frac{H\left(Pg_m\right)}{GHV} \tag{8}$$

Pg_m = power generation, MW

$H\left(Pg_m\right)$ =power plant heat rate, MMBTU

α_m =power plant heat curve coefficient, MMBTU

β_m = power plant heat curve coefficient, MMBTU/MW

γ_m = power plant heat curve coefficient, MMBTU/MW^2

$Fuel\left(Pg_m\right)$ = amount of gas used by generators. MSCM

GHV =grossing heat value, MMBTU/MSCM

E. Gas Flow Balance

Nodal gas flow balance at all network nodes should be satisfied. It means that the sum of the gas is injected into the node should be equal to the sum of the gas flowing out of the node.

$$\sum_{(i,j)\in A} f_{ij} = S_i - D_i - \tau_{ij}^c - Fuel_{ij}^{gas} \tag{9}$$

D_i =NG nonelectrical load, MSCM

$Fuel_{ij}^{gas}$ =NG electrical load, MSCM

F. Alternative Fuel

The use of Second fuel is a common method for peak shaving of gas pipelines in cold winters. It can relax gas networks constraints and be helpful for network security improvement, but storage capacity of alternative fuel has limits as follows.

$$0 \le Fuel_i^{alt.} \le \overline{Fuel_i^{alt.}} \tag{10}$$

$Fuel_i^{alt.}$ =amount of alternative fuel used, SCMH

III. INTEGRATED OPTIMIZATION

A. DC OPF

DC OPF is used to provide a simple model for the electrical network which represents power system operation subject to static gas constraints to obtain a method for integrated optimization of gas and electricity systems.

$$T_{mn} = B_{mn}(\delta_m - \delta_n) \tag{11}$$

$$-\mathrm{T}_{mn}^{\max} \le \mathrm{T}_{mn} \le \mathrm{T}_{mn}^{\max} \tag{12}$$

$$\left(Pg_m^{\min}\right) \le \left(Pg_m\right) \le \left(Pg_m^{\max}\right) \tag{13}$$

$$\sum_{(m,n)\in T} T_{mn} = Pg_m - Pd_m \tag{14}$$

T_{mn} =power flow, MW

B_{mn} = susceptance of nodal admittance matrix (p.u.)

δ_m = voltage angle, rad

Pd_m = electrical demand, MW

B. Objective Function

The objective function consists of three parts. The first part is the total cost of consuming natural gas at power plants, the second part is alternative fuel cost and the third part is the total cost of natural gas consumed by compressors. Minimizing operation cost of a mixed integer nonlinear problem considering both network's constraints is article issue.

$$\sum_{nG} Fuel_{i,m}^{gas}.\mathrm{Price}^{gas} + \sum_{nG} Fuel_m^{alt.}.\mathrm{Price}^{alt.} + \sum_{nC} \tau_{ij}^c.\mathrm{Price}^{gas} \tag{15}$$

$Fuel_m^{alt.}$ = amount of alternative fuel used by power plants, SCM

Price^{gas} = 1(natural gas price)

$\mathrm{Price}^{alt.}$ = 1.625 (alternative fuel price)

C. State Variables

The state variables in our study are power plant's outputs, amount of used natural gas, generators alternative fuel, fuel burned in the compressors, the total cost of operation, the gas pressure in nodes and gas flow through pipelines.

IV. CASE STUDY

The proposed integrated approach is applied to a designed case study. The electricity network is a modified 9buses IEEE case study with 2 generators and 3 loads. The natural gas network has one source, 7 pipelines, 5 nonelectrical loads, 2 electrical loads and 2 compressor stations. Schematic diagram of this 8-node natural gas system integrated with the modified IEEE-9 test system is shown in FIGURE I. The maximum pressure in all nodes is 70Bar but minimum pressure for combined nodes is 35Bar and for nonelectrical nodes is 20Bar. Since the natural gas and electricity network may need to be expanded in the near future, minimum pressure for the last node is assumed about 42Bar [5].

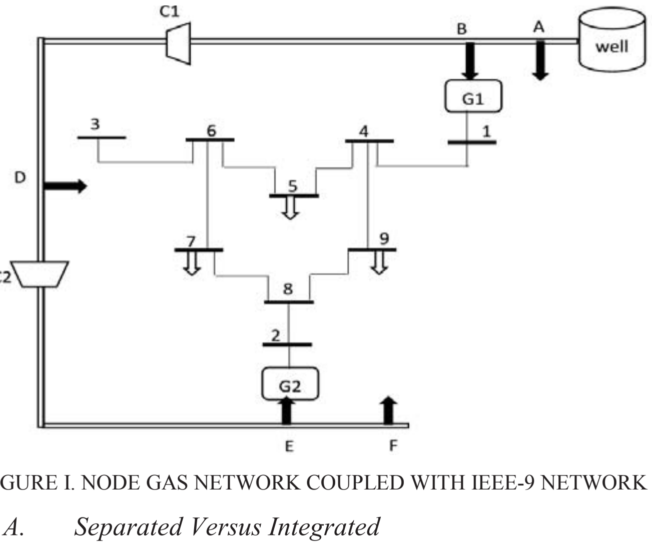

FIGURE I. NODE GAS NETWORK COUPLED WITH IEEE-9 NETWORK

A. Separated Versus Integrated

Three types of natural gas loads have been defined in TABLE I. The first type of loads are Constant loads. Actually, these loads are nonelectrical and include residential and commercial loads. The second type of loads are Combined ones. The Combined loads consist of electrical and nonelectrical loads. And finally, the third type are Compressor loads. The compressors use natural gas as their fuel to provide a proper pressure of natural gas, in the nodes of the network.

TABLE I. PIPELINES AND NATURAL GAS LOADS

Node Number	**Gas Network**				
	From	***To***	***Length (Km)***	***Load Node***	***Type***
1	W	A	140	A	Constant
2	A	B	9.6	B	Combined
3	B	C1	0.3	C1	Compressor
4	C1	D	115.2	D	Constant
5	D	C2	27.4	C2	Compressor
6	C2	E	34	E	Combined
7	E	F	58	F	Constant

In the first step, the separated and integrated optimizations are compared during peak condition. Results illustrate the integrated operation effectiveness. Integrated optimization saved 8.27% in operation cost. Power plants outputs have been changed extremely in the integrated operation state. In integrated optimization, the natural gas nonelectrical load variation can change the power plants output. The downstream power plant output decreases and consequently the output of upstream one increases. The compressors cost during peak load condition causes this changes in the optimization. Results are presented in TABLE III.

TABLE II. GENERATORS CHARACTERISTIC PARAMETERS

Number Of Generators	$P_m^{\min}$ ***(MW)***	$P_m^{\max}$ ***(MW)***	α_m *(Mbtu/h)*	β_m ***(Mbtu/Mw.h)***	γ_m ***(Mbtu/Mw^2.h)***
1	50	300	150	0.5	0.0001
2	50	300	150	0.5	0.0001

B. Second Fuel Role

Second fuel is more expensive than natural gas. In critical condition, when the pressure of natural gas in pipelines drops, this extra money will be paid for improving system security. In fact, using second fuel can reduce power system dependency on natural gas delivery. On the other hand, when nonelectrical gas load increases in cold winters and fuel consumption of compressors becomes remarkable, the use of second fuel can be economical too. Three scenarios of different load conditions are shown in TABLE IV.

TABLE III. SEPERATED VERSUS INTEGRATED

Variables	**State of Operation**	
	Separated	***Integrated***
P_{g1} (MW)	157.5	246.7
P_{g2} (MW)	157.5	68.3
NG_{comps} (MSCM)	1.148	0.855
NG_{g1} (MSCM)	0.853	1.144
NG_{g2} (MSCM)	0.853	0.631
$Cost$	2.854	2.613

Nonelectrical loads increase in "Peak2" state in TABLE IV and TABLE V.In this case, the security constraints are violated if alternative fuel is not used. Therefore the importance of using alternative fuel for improving system security is certain. In addition, using second fuel in "Peak1" state reduced cost by 11.23%. In TABLE V, power plants outputs are presented in three load states.

TABLE IV. PEAK AND OFFPEAK LOADS

Load Node	**Load Condition**		
	Off Peak (MSCM)	***Peak1 (MSCM)***	***Peak2 (MSCM)***
A	13.014	14.46	14.60
B	1.760	1.956	1.976
D	1.280	1.422	1.436
E	1.730	1.922	2.012
F	5.2425	5.825	5.883

TABLE V. SECOND FUEL EFFECT

Variables	**Load Condition**		
	Off Peak ***(MSCM)***	***Peak1*** ***(MSCM)***	***Peak2*** ***(MSCM)***
Pg1(MW)	157.5	215.6	204.85
Pg2(MW)	157.5	99.4	110.15
NG(G1) (MSCM)	0.853	1.030	0.995
NG(G2) (MSCM)	0.853	0	0
Alt(G1) (ML)	0	0	0
Alt(G2) (ML)	0	0.702	0.728
NG(Comps) (MSCM)	0	0.153	0.227
Cost	1.707	2.324	2.405

The heat value of one cubic meter of natural gas is almost equal to one litter of second fuel [14]. The price of second fuel is considered 1.625 times higher than natural gas.

C. Location Effects

Power plants location along pipeline has a great effect on units output during peak time. Especially in one source pipelines, it can be so important. Simulations show that the unit with more efficiency at the bottom of the pipeline is forced to produce less. TABLE VI illustrates outputs of tow power plants with different efficiency, which are installed at two different points of a gas pipeline. Insofar as, when the efficiency of upstream power plant is considered about 70% of downstream efficiency; this power plant plays a larger role in power generation due to the cost of compressors and network security constraints.

Impact of natural gas cost on integrated operation of electricity and natural gas has been neglected. So no attention has been paid to this in the planning sector. The results of simulations show that the location of the power plants in the gas network is even more important than their efficiency. The main reason for this difference is considering the cost of gas transport at the peak times of natural gas consumption in the network.

Therefore, taking into account the cost of gas transportation and the relative location of the power plants in the gas network compared to the gas well and in relation to each other is a key factor in reducing the cost of integrated operation of electricity and gas networks. Considering the cost of gas transmission in Planning of electricity and Natural gas can affect the location of the power plants in the network.

TABLE VI. LOCATION EFFECT

Efficiency ratio(η1/η2)	**Generators Production**	
	Pg1(MW)	***Pg2(MW)***
1	246.7	68.3
0.8	191.1	123.9
0.7	158.9	156.1
0.69	155.6	159.4

V CONCLUSION

This paper proposes an integrated operation of natural gas and electric power systems. Here, it is assumed that two gas-fired generators have variable consumed fuel as a function of their generation to better represent the interaction between both infrastructures. This integrated approach reduces the operation cost during peak time on pipelines. In our case study, integrated optimization saved 8.27% in operation cost. Use of second fuel has been known as an effective solution for operational cost reduction and security improvement during peak load, especially in cold winters. Using second fuel in “Peak1” state, reduced cost by 11.23%. In addition, with the sharp increase in gas load during the cold season, the importance of using alternative fuel to maintain system security was identified.

Simulations show the importance of gas-fired power plants location along the gas pipeline. In our case study, location is more effective than power plant efficiency in integrated operation cost during peak load time. Insofar as, when the efficiency of upstream power plant is considered about 70% of downstream efficiency; this power plant plays a larger role in power generation due to the cost of compressors and network security constraints.

The results of this study show the importance of the location of power plants in the gas network. Therefore, considering the efficiency of the power plants and the proper location to install them in the gas network to achieve the optimal point in integrated operation is an important factor that should be considered in the integrated planning of electricity and natural gas networks.

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