Economic Dispatch Problem Considering Natural Gas Transportation Cost

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Abstract:

The increase of electricity generation using natural gas has linked the gas and electric generation systems in many technical and economical aspects. Considering electric power network and NG network as a single energy system, we can determine the economic distribution of electric load between different gas-fired units to minimize the total generation cost and related gas transportation cost. The aim of this paper is to analyze both technical and economical effects of NG networks on power systems operation in countries where both industries are government owned. It introduces a new methodology to calculate the amount of energy needed to transport gas from wellhead to power plants via pipelines. Then, the evaluated energy cost is used as gas transportation cost along with the production cost in ED problem. The proposed generalized ED problem is solved through the application of genetic algorithm. Then, to discus the application of the proposed ED method a numerical example is presented.

Keywords: Economic dispatch, loadflow; natural gas transportation, genetic algorithm,

I. INTRODUCTION

Since the early 1970's crude oil crisis the consumption of natural gas as economic energy source has increased roughly. The development of combined cycle power plant also caused the rise of natural gas portion among other primary source of energy in electricity generation. Natural gas–fired combined cycle units are an attractive choice for expanding generation capacity due to their fuel efficiency, operation flexibility, reliability, short construction times and lower investment cost. According to International Energy Outlook 2006 (IEO2006), natural gas-fired generation capacity increases by approximately 2.7% per year within the period of 2003 to 2030 [1] and its portion of installed capacity in the world rises from 27% in 2003 to 33% in 2030.

The increase of electricity generation by natural gas has promoted the power system and natural gas network to merge into a single energy system. The operation of the combined NG network and electric power system naturally requires simultaneous optimization due to the interdependence of these two systems. Thus, synergies between natural gas and electricity systems have to be identified and economically quantified so that integrated decision could improve the social benefits especially in countries where the two networks are still under the same authority.

Each of the gas and electric networks has been well studied individually but there have been few studies on the combined networks. In [2], Seungwon An, Qing Li and Gedra propose a method to solve natural gas load flow problems using the electric loadflow techniques. They also present a combined natural gas and electricity optimal power flow. In [3], Mello and Ohishi introduce an integrated dispatch model of a natural gas supply system and a gas power plants system. The model considers a set of NG power plants supplied by a gas pipelines network. The objective is to minimize the cost of power generation and NG production subject to system requirements, such as electric load demand, power generation limits, NG flow pressure limits at pipeline network, and take-or-pay contracts. In [4], Shahidepour, Fu and Wiedman discuss the essence of the natural gas infrastructure for supplying the ever-increasing number of gas-fired units and use security constrained unit commitment to analyze the short-time impacts of natural gas prices on power generation scheduling.

To study electricity and natural gas networks as an integrated system in the generation decision process, fuel supply condition as well as generation and transmission capacity constraints have to be simultaneously taken into account [6]. In this paper the ED problem is generalized to minimize both the production cost and the transportation cost with respect to the technical constraints of both networks.

Transmission and distribution pipelines deliver natural gas from gas wellhead to costumers. By modeling pipeline system in ED problem, the best economical solution for serving the plants and supplying the electric demand is obtained among the feasible solutions.

The aim of this paper is to analyze both technical and economical effects of NG networks on power systems operation in countries where both industries are government

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owned, like Iran. It introduces a new methodology to calculate the amount of energy needed to transport gas from wellhead to power plants via pipelines. Then, the evaluated energy cost is used as gas transportation cost along with the production cost in ED problem. The proposed generalized ED problem is solved through the application of genetic algorithm as the ED problem is a non-linear optimization with several nonlinear constraints in both gas and electricity networks.

The paper is organized as follows. The interactions of the natural gas and power system are discussed in section 2. In section 3 the natural gas network modeling is presented. Formulation of the generalized economic dispatch problem is discussed in section 4 and 5 and the simulation results are presented in section 6. Finally, section 7 is a summery of the important results.

II. Natural Gas and Electricity Networks Interactions

The continual and rapid growth of NG-fueled electricity generating plants has increased the interdependency of natural gas and electricity industries. As the electric power plants are major NG consumers, there is a close interaction between the gas-fired power plants operation and the gas supply system operation. The dispatch of the NG fueled power plants affects the gas flow in the pipeline system and, on the other hand; the pipeline operating constraints can impose limits on power plants generation.

For a secure operation of gas and electricity system, it is necessary to impose some extra constraints on electricity system operation in case of some particular operating conditions. For instance in severe weather situations (e.g., hot summer and cold winter days) when demands for gas and electricity peak together, the pressure drop in pipelines is very likely. In these cases, it is unavoidable to limit the amount of gas used by some power plants to prevent the loss of multiple gas consumers.

Beside the technical issues, when two networks are under the same authority, there are economic advantages in optimization of the combined gas and electric power networks operation compared to the optimization of operation of each of the two networks separately. In natural gas plants, the fuel cost can be split into two parts: the production cost and the transportation cost. The gas transportation is performed via gas pipeline systems which have similar characteristics to that of the electricity transmission network. Gas transportation cost depends on the location of consumer (e.g. power plant) in the gas network and the pipeline network topology. Like electric power transmission networks, gas loses a part of its initial energy due to the frictional resistance when flows in the pipelines. Therefore, while gas is delivered from gas wellhead to costumers, its pressure drops through the pipeline. The farther the distance gas flows in the pipeline, the more pressure it loses. To maintain the desired pressure level in the gas pipelines, compressor stations are installed in the network. The fuel cost used in the compressor stations, forms a considerable part of the pipeline operation cost. Usually, in large gas networks, natural gas is used to drive the major compressor. The amount of gas used in the compressor stations, which can be considered as pipelines loss, depends on the operating point of each compressor. As the power plants are major gas consumers, the amount of their generating power affects the gas flow equations in the pipelines and consequently, the operating conditions of the compressor stations. So the gas network losses i.e., the energy usage in the compressors, will change when dispatch of power plants in power system changes. Therefore, it is reasonable to add the fuel cost of the compressor stations to the economic dispatch cost function. By solving this new optimization problem, the optimal generation schedule is obtained in an approach that minimizes both electricity production cost and the related gas transportation cost.

III. Gas Network Modelling

Natural gas is transported from gas wellheads to different customers by gas transmission network. The NG transportation network model consists of four basic components namely, gas wellheads, pipelines, compressor stations and interconnection nodes. Figure 1 shows a simplified NG transportation network which is utilized in this study for analyzing the impacts of natural gas system operation on the economic dispatch.

The transportation pipelines connect the gas wellhead, usually far from load centers, to distribution system or large industrial users. The compressors act like step-up transformers in electric networks [4]. As gas flows through the pipelines, its pressure will drop. Thus the compressors are an essential component in the natural gas system to maintain the desired pressure level in the transportation pipelines.

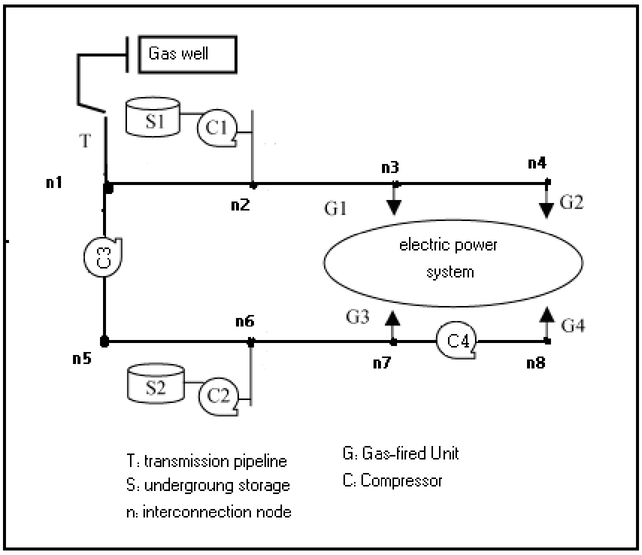

Figure 1:Gas pipeline system[4]

A. Flow Equation in Pipeline

The flow equations in gas transportation network describe the relation between gas flow rate, the pressures at the two ends of pipelines. For isothermal gas flow in long horizontal pipeline, which begins at node i and ends at node j , the general steady state flow rate (in mmSCF[3]/hr) is often expressed by the following formula[8]:

$$f_{ij} = S_{ij} \times 0.08531 \frac{T_0}{\pi_0} \sqrt{S_{ij} \frac{(\pi_i^2 - \pi_j^2) D^5}{FGLT_a Z_a}} \qquad (1)$$

where:

f_{ij} = pipeline flow rate, mmSCF/hr

S_{ij} = +1 if $\pi_i - \pi_j > 0$

= -1 if $\pi_i - \pi_j < 0$

F = pipeline friction factor

D = internal diameter of pipeline (inches)

G = gas specific gravity

L = pipeline length between nodes (miles)

π_i = pressure at node *i*, psia

π_j = pressure at node *j*, psia

π_0 = standard pressure, psia

T_0 = standard temperature, ^0R

T_a = average gas temperature, ^0R

Z_a = average gas compressibility factor

(1) is a nonlinear equation that defines the relation between the flow rate through a pipeline and its terminal nodes pressures.

B. Compressor Model:

Gas flow loses a part of its energy during transportation along the pipelines due to its frictional resistance which results in a loss of pressure. To maintain the gas pressure at a desirable level, compressor stations are installed in the network. The amount of energy consumed by compressor stations, can be computed based on "the horsepower equation" as follows: [9]

$$H = B.f[(\pi_i / \pi_j)^{Z(\alpha-1)/\alpha} - 1] \qquad (2)$$

Where:

H: compressor rate of work (horsepower)

$B = 0.08531T / \eta * (\alpha / \alpha - 1)$

f : flow rate through compressor, mmSCF/hr

π_i : compressor suction pressure, psia

π_j : compressor discharge pressure, psia

Z : gas compressibility factor at compressor inlet,

T : compressor suction temperature, R°

α : specific heat ratio (*cp=cv*)

´η : compressor efficiency

[3] -million standard cubic feet

The above equation shows the rate of work of each compressor as a function of the gas flow rate through the compressor and the pressure ratio between the inlet and outlet gas.

The compressor stations can use steam, electricity and natural gas as the energy source. Usually, in large pipeline systems, the most economic source is the natural gas, which is available and flowing through the compressors. The amount of gas withdrawn to power a gas turbine to operate the compressor can be approximated as:

$$\tau = \alpha + \beta.H + \gamma.H^2 \qquad (3)$$

Where τ is the amount of gas used by compressor, H is horsepower required for gas compressor in equation (2) and α, β, γ are the compressor coefficients.

C. Gas-fired Power Plants Modeling

Gas and electric networks interconnect at gas-fired power generation station. The input-output characteristic of the power plants expresses the relation between the two networks. It determines the gas consumption flow rate in the power plant (q_i , mmscf/hr) as a function of the generated electric power. This is obtained by dividing the plant's heat energy function (H_i , MBtu/hr)) by the gas gross heating value (GHV, MBtu/ mmscf).

$$q_i = H_i \cdot \frac{1}{GHV} \qquad (4)$$

Also, we have:

$$F_i = C.H_i \qquad (5)$$

where:

F_i : the cost function of the i^{th} plant

H_i : the heat energy function of the i^{th} plant

C: the gas energy cost($/MBtu)

Replacing H_i in equation 11 with $\frac{F_i}{C}$ we have:

$$q_i = F_i \cdot \frac{1}{GHV} \cdot \frac{1}{C} \qquad (6)$$

Equation 13 expresses the gas consumption flow rate of the i^{th} power plant as a linear function of the plant cost function.

D. Gas load flow problem:

The problem of simulation of gas network with N nodes in steady state, known as loadflow, is usually that of commuting the values of node pressure and flow rates in individual pipes for known values of source pressures and gas injection in all other nodes. For more studies you can see loadflow statement and solution in [4].

IV. Economic Dispatch Considering Gas Transportation Cost

In this section the economic dispatch problem, considering both the electricity generation cost and the gas transportation cost is formulated. Therefore, the hourly operation cost of pipelines in different gas flow conditions will be added to the hourly operation cost of power plants in the ED cost function.
Suppose there are *m* compressor stations in the study system, the objective function of the generalized economic dispatch will be:

$$\text{Min} \sum_{i=1}^{n} F_i(p_i) + \sum_{j=1}^{m} c.\tau_j \tag{7}$$

Subjected to:

$$P_D + P_{loss} - \sum_{i=1}^{n} P_i = 0 \tag{8}$$

$$P_{i\min} \le p_i \le P_{i\max} \qquad i = 1,...,n \tag{9}$$

Where:

τ_i : the amount of gas used by each compressor obtainable from equation (3)
c: gas price (Rs/mmSCF)
m: numbers of compressors
n: numbers of gas-fired power plant
N_n : number of gas nodes in the pipeline system

V. SOLOUTION PROCEDURE

Since the ED problem in equation (7) is a non-linear optimization and several nonlinear equations in both gas and electricity networks should be solved to find the optimum solution, genetic algorithm is employed to solve the problem.

A. Chromosome coding

In this optimization problem the parameters are the output power plants (P_i). Each parameter P_i has upper bound $P_{i\max}$, and lower bound $P_{i\min}$. Here the binary method is used for chromosome coding. The bit length m_i and the corresponding resolution R_i is related by:

$$R_i = \frac{P_{i\max} - P_{i\min}}{2^{m_i} - 1} \tag{10}$$

As the results, the P_i set can be transformed into a binary string with length $\sum m_i$. Each chromosome presents one possible solution to the ED problem.

B. Fitness Function:

The fitness function is defined as follows:

$$fitness(\overline{P}) = \sum_{i=1}^{n}(a_i + b_i P_i + c_i P_i^2) + \sum_{j=1}^{n} C.\tau_j + r\left(\sum_{i=1}^{n} P_i - P_D - P_{loss}\right)^2 \tag{11}$$

Where r is coefficient of penalty.
To return the fitness value for each chromosome, the compressors gas consumption in the relative operating condition is needed.
Therefore, for each possible solution that a chromosome refers to, the gas network condition should be simulated. From equation (6) the amount of gas used in each power plant is calculated. Then the standard Newton-Raphson method is employed to solve the gas loadflow problem to determine gas pressure at all system nodes. Once all the pressures are known, all other variable such as gas flow rate in pipelines and gas consumption in compressor units can be determined. Now the fitness value for the particular chromosome can be computed through equation (11).

VI. Case Study

The proposed economic dispatch method was applied to a test network similar to NG transmission network and thermo electric generation plants in Khorasan Province in north east of Iran. (Figure 2)
The electric network has five gas-fired power plants, fed via gas pipeline system. The pipeline system has a single gas wellhead node, five loads at the combined nodes and three non-electrical loads. Three transmission pipelines transport natural gas from wellhead to power plants in three different directions. Five compressor stations are installed along the pipelines to maintain the desired pressure level. The compressors are driven by gas turbines.
The number of generator units in each power plants station, the generators characteristics parameters and the *B* matrices of the loss formula for the system are found in appendix. The compressor efficiencies and gas turbine fuel rate coefficients in equation (3) and compressor pressure ratios are listed in appendix. The non-electrical loads in direction 1 (D1) are mainly industrial loads. D2 and D3 are mostly representing the commercial and household sector in gas network.
To study the ED problem, the winter gas peak demand condition is simulated. In cold winter days the gas demand roughly increases in commercial and household

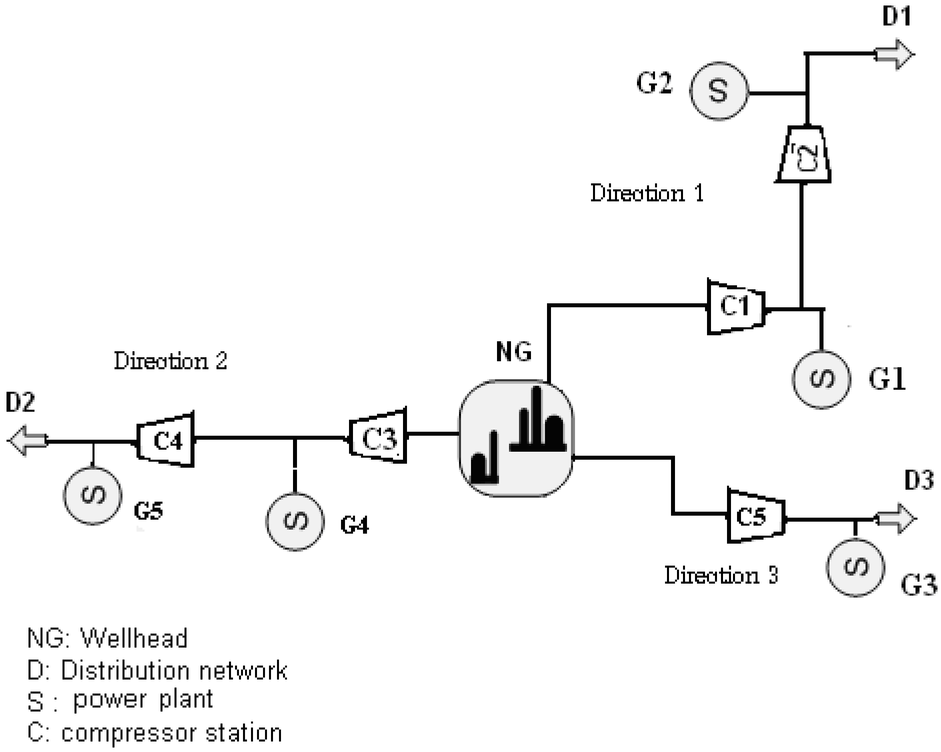

Figure 2: Natural gas network and power plants schematic

sectors for heating purpose. There for the gas flow rate through pipelines in directions 2 and 3 are more intense than direction 1. To see the impacts of gas transporting cost on the ED problem results, two cases are considered. In case I only electricity production cost was considered in ED cost function, while in case II the gas transporting cost was also included in the cost function. Table 1 shows the optimum generation schedule in the two cases.

Table 1 – Economic dispatch results in two cases

Plant No.	MW (case I)	MW (case II)
1	120	175
2	180	250
3	151	100
4	200	200
5	183	105
Gas transporting cost	23848	21105
Total cost	69360	65710

The power generations of power plants are considerably different in two cases. As was expected, the generation of G1 and G2 at the direction 1, increase to their maximum generation bounds in case II due to lower gas flow rate through this direction and consequently lower transporting cost compared to the other three. On the other hand, the generation of G3 and G5 decrease by about 51 Mw and 78 Mw in each of their units in case II because of their high gas transporting cost. Since unit #4 is the cheapest unit in the network and also it is close to the gas source, in both cases it operates at its maximum capacity and including the gas transporting cost in the cost function can not change its portion of total generation.

As shown in the table 1 the total generation cost is reduced by 5.1% in case II as the gas transporting cost is reduced by 12%.

VII. Conclusion

The interdependence of natural gas and electricity requires simultaneous optimization of the combined natural gas and electric power networks, especially with the increased use of natural gas in the generation of electricity. There are competitive advantages in optimization the combined gas and electric power networks compared with the optimization of the two networks independently for system operation and economic analysis.

This paper presented a methodology to evaluate the gas transportation cost for each gas-fried unit in the pipeline system. The evaluated fuel transportation cost and electricity production cost were used in ED problem to find the best economic generating schedule that minimizes the total electricity generation cost considering both electric power and natural gas networks. By solving this new economic dispatch problem, the optimum generation schedule in thermal system is obtained in such a way that minimizes both the electricity production cost and the related gas transportation cost.

VIII. APPENDIX:

Table 1- Generators characteristics parameters

No	Number of plants	P_i^{min} (MW)	P_i^{max} (MW)	a_i	b_i	c_i
1	4	50	175	213.1	15.7	0.008
2	2	30	250	230	11.85	0.008
3	4	50	250	369	14.9	0.009
4	4	15	200	203	11.9	0.008
5	3	37.5	300	280	12.3	0.009

Table 2- compressors and gas turbine data

No	Efficiency	π_i / π_j	Turbine Fuel Rate Coefficients		
			α	β	γ
1	0.84	1.4	0	0.2 e-3	0.02 e-3
2	0.83	1.3	0	0.2e-3	0.025e-3
3	0.84	1.5	0	0.2e-3	0.03e-3
4	0.83	1.4	0	0.2e-3	0.03e-3
5	0.83	1.5	0	0.2e-3	0.03e-3

B matrices of the loss formula

$$B = \begin{bmatrix} 0.0676 & 0.00953 & -0.00507 & 0 & 0 \\ 0.00953 & 0.0521 & 0.00901 & 0 & 0 \\ -0.00507 & 0.00901 & 0.0294 & 0 & 0 \\ 0 & 0 & 0 & 0.003 & 0 \\ 0 & 0 & 0 & 0 & 0.009 \end{bmatrix}$$

$$B_0 = \begin{bmatrix} -0.0766 & -0.00342 & 0.0189 & 0 & 0 \end{bmatrix}$$

$$B_{00} = 0.0403057$$

$$P_{loss} = P^T BP + P^T B_0 + B_{00}$$

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