| کد نشست | سالن | زمان | تاریخ |
|---|---|---|---|
| A4 | A | ۱۰:۳۰ تا ۱۲:۱۰ | ۱۳۹۴/۱۰/۳۰ |
| عنوان جلسه : مدیریت بازار تولید و فروش برق | | | |
| کد مقاله : 09117 | | | |

# Effects of Natural Gas Network on Optimal Operation of Gas-Fired Power Plants

A. Hejazi, H. Rajabi Mashhadi
Ferdowsi University of Mashhad
aminhejazifum@yahoo.com, h_mashhadi@um.ac.ir

Keywords: Natural gas network, Optimal integrated operation, Optimization, Power system operation, 2nd-fuel

Due to economic, environmental and technological changes, consumption of Natural Gas (NG) for generation of electricity has burgeoned over the last two decades. This has led to strong interdependency between NG and electricity systems. Studies indicate a great reduction in total operating cost after considering NG transmission in power system operation. As Fuel consumption of compressor stations plays a major role in the NG transmission cost which constitutes of up to 75% of the overall expenses. In this paper a novel approach to integrated operation of two systems with consideration of 2nd-fuel is introduced. Static load flow equation of NG and electricity system is modeled as an optimization problem with focusing on compressor station roles. The aim is to Minimized total operating cost of both systems. Simulation result of Khorasan Province NG and electricity Network show success in power plant fuel management and great reduction in total cost of two systems especially in peak condition.

# Effects of Natural Gas Network on Optimal Operation of Gas-Fired Power Plants

Amin Hejazi
Faculty of Engineering,
Department of Electrical Engineering
Ferdowsi University of Mashhad
Mashhad, Iran
aminhejazifum@yahoo.com

Habib Rajabi Mashhadi
Center of Excellence on Soft Computing
and Intelligent Information Processing
Ferdowsi University of Mashhad
Mashhad, Iran
h_mashhadi@um.ac.ir

***Abstract*—Due to economic, environmental and technological changes, consumption of Natural Gas (NG) for electricity generation has burgeoned over the last two decades. This has led to strong interdependency between NG and electricity systems. Studies indicate a great reduction in total operating cost after considering NG transmission in power system operation. As Fuel consumption of compressor stations plays a major role in the NG transmission cost which constitutes of up to 75% of the overall expenses. In this paper a novel approach to integrated operation of two systems with consideration of 2nd-fuel is introduced. Static load flow equation of NG and electricity system is modeled as an optimization problem with focusing on compressor station roles. The aim is to Minimized total operating cost of both systems. Simulation result of Khorasan Province NG and electricity Network show success in power plant fuel management and great reduction in total cost of two systems especially in peak condition.**

***Keywords-* *Natural Gas Network, Optimal Integrated Operation, Optimization, Power System Operation, 2nd-fuel***

## I. INTRODUCTION

Fuel consumption of compressor stations plays a major role in the Natural Gas (NG) transmission cost which constitutes of up to 75% of the overall expenses. As a result of this huge share, NG consumed by compressor stations referred to as an NG transporting loss. Many studies focus on modeling and optimizing the operation of NG transporting network. In [1] the problem of distributing NG through a network of pipelines operation solved by an extension of the Simplex Method without considering the effects of compressor stations. [2] a mixed integer nonlinear programming (MINLP) formulation is proposed to model NG operation. The model provides the main design parameters of the pipelines and the characteristics of compressor stations.

Due to economic, environmental and technological changes, consumption of NG for generation of electricity has burgeoned over the last two decades. This has led to strong interdependency between NG and electricity systems. [3] presents fundamental modeling of the natural gas network to be used in electricity network optimal load flow (OPF). The objective function is to maximize social welfare of both networks. Although the effect of compressor station is considered in the modeling of the problem, but without comprehensive detailed of pipelines and compressor stations. A new methodology to calculate the amount of energy needed to transport NG from wellhead to power plants via pipelines is introduced in [4]. Then, the evaluated energy cost is used as the NG transportation cost along with the production cost in the electricity network economic dispatch problem. [5] presents integrated formulation for the steady-state analysis of NG and electricity coupled systems, Where the effect of temperature in the natural gas system operation and a distributed slack node technique in the electricity network is considered. The method proposed in [3], [4], and [5] is only valid for NG network with single source node. On the contrary actual NG networks may have different source nodes. [6] presents a model to compute the maximum amount of power that can be supplied by the combined-cycle power plants. The NG network with role compressor station effect is included. Proposed optimization process will be inserted into a higher level model that analyzes the electrical system supply reliability taking into account natural gas system features. A maintenance coordination algorithm is proposed in [7] in which, NG network constraints and uncertainties are taken into account. Moreover, the importance of 2nd- fuel was examined. It was shown that units with ability to switch their fuel will result more flexible maintenance schedules and more improvement in the reliability index could be achieved.

In this paper novel approach to integrated operation of NG and electricity network with consideration of 2nd-fuel is introduced. Static load flow equation of NG and electricity system is modeled as an optimization problem with focusing on compressor station roles to Minimized total operating cost of both systems.

The paper is organized as follows. NG network elements and equation for modeling is discussed in Section 2. The integrated optimal operation of NG & electricity network is formulated in Section 3 as a MINLP optimization problem. Numerical results on Khorasan Province NG and electricity Network are demonstrated in section 4. Some concluding remarks are provided in Section 5.

## II. NATURAL GAS NETWORK

Source nodes, pipelines, compressor stations and load nodes are the four main parts of NG network. This section introduced these elements and how they related to each other's based on the equations in [8]. Fig. 1 shows a simplified NG network [9] containing these four elements. Actual network configurations may vary.

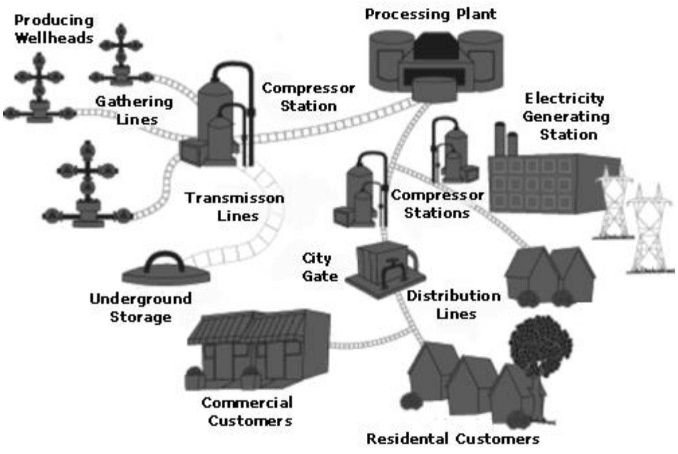


Figure 1. Simplified NG network[9]

*A. Source Nodes*

NG wellhead, Import pipelines, NG storage and LNG [1] regasification terminal are common example of source nodes.

*B. Pipelines*

Pipelines transport NG from source nodes to consumers. To model this part of NG several equations proposed. In this paper Weymouth equation is employed to model steady state flow between node k and m.

$$Q^{km} = \sqrt{Pipecoeff^{km}}.(2Dir - 1).(\left|\Pi^{k^2} - \Pi^{m^2}\right|)^{0.5} \quad (1)$$

Where $Q^{km}$ is NG flow through the pipeline km in MSCMH [2]. $\Pi^k$ and $\Pi^m$ are node k and m pressures. $Pipecoeff^{km}$ is pipeline coefficient depending on Pipeline's structures[8]. In pipelines NG flows from higher pressure node to lower pressure nodes. Therefore, in (2) the binary variable $Dir$ is introduced to define the NG flow directions.

$$\begin{cases} Dir = 0 & if\ \Pi^m \succ \Pi^k \\ Dir = 1 & if\ \Pi^k \succ \Pi^m \end{cases} \quad (2)$$

Unlike [3], [4] and [5] modelling which is only practical for single source NG networks. Using $Dir$ enable us to model NG network with multiple source nodes as the flow direction define during optimization.

*C. Compressor Stations*

NG Internal energy decreases due friction of pipelines and heat transfer between NG and its surrounding environments. This cause drops in NG pressure. Similar to step-up transformers in electricity networks compressor stations are installed to compensate this pressure loss as well as to provide the pressure needed to transport gas from one location to another. With Horsepower equation (3) energy consumption for the compression station connecting *km* nodes is computed.

$$BHP_C^{km} = 4.063(\frac{RK.Z_a.Q_C^{km}.T^k}{\eta_C}).((\frac{\Pi^m}{\Pi^k})^{RK^{-1}} - 1) \quad (3)$$

In (3) $BHP_C^{km}$ is compressor station required energy in HP. $\eta_C$ is compression process efficiency. $Q_C^{km}$ is Compressor NG flow in MSCMH. $Z_a$ and RK constant related to the super-compressibility factor of the compressor and the NG specific heat ratio. $(\Pi^m/\Pi^k)$ is the ratio between compressor output and input pressure. Equation (4) sets minimum and maximum $(\overline{ratio_C^{km}})$ limits of compression ratio.

$$1 \le (\frac{\Pi^m}{\Pi^k}) \le \overline{ratio_C^{km}} \quad (4)$$

The compressor stations can use steam, electricity and NG as the energy source. In high pressure pipelines NG is the most economical source. The amount of gas extracted from the NG network is given by (5).

$$\tau_C^{km} = \alpha_C^{km} + \beta_C^{km}.BHP_C^{km} + \gamma_C^{km}.BHP_C^{km^2} \quad (5)$$

Where $\tau_C^{km}$ is the amount of gas used by compressor in MSCMH. $\alpha_C^{km}$, $\beta_C^{km}$ and $\gamma_C^{km}$ are the compressors NG consumption coefficients.

*D. Load Nodes*

To study the effects of NG and electricity networks on each other Load node is divided into electric and nonelectric load nodes. In short term perspective the value of nonelectric load nodes is constant. Electric nodes, place where the NG fired power plants established, is the main reason of two networks interdependency. Power plants i heat rate $(HR_G^i)$ is computed using (6) in MMBTU[3].

$$HR_G^i = \alpha_G^i + \beta_G^i.P_G^i + \gamma_G^i.P_G^{i^2} \quad (6)$$

[1] Liquefied Natural Gas

[2] Thousand Standard Cubic Meter Per Hour (M here stands for the Roman numeral 1000, sometimes used in symbols to indicate a thousand, as in Mcf, a traditional symbol for 1000 cubic feet.)

[3] Million British Thermal Unit

Where $\alpha_G^i$ , $\beta_G^i$ and $\gamma_G^i$ are the power plant i Heat curve coefficients. $P_G^i$ is the power generated in MW, which is computed from the DC load flow. Equation (7) determines power plant i NG consumption flow rate $(Fuel_{gas}^{k,i})$ in kth node of NG network. Where $GHV_{NG}$ is gross heating value of NG.

$$Fuel_{NG}^{k,i} = HR_G^i / GHV_{NG} \tag{7}$$

A similar way is applied to determine the 2nd-fuel consumption flow rate of power plants i.

## III. Integrated Optimal Operation of Natural Gas & Electricity Network

In this section the mathematical formulation of the NG and electricity network integrated operation is expressed as a mixed-integer nonlinear programming (MINLP). Minimizing total system operating cost is the objective function of this optimization, see (8).

$$Min \left\{ \text{cost} = \sum_{nC} \tau_C^{km}.Price_{gas} + \sum_{nG} Fuel_{gas}^{k,i}.Price_{gas} + \sum_{nG} Fuel_{2nd-fuel}^{i}.Price_{2nd-fuel} \right\} \tag{8}$$

Equation (8) contains:

1. NG Transporting Loss $(\sum_{nC}\tau_C^{km}.Price_{gas})$ in other words, total NG cost consumed by compressor stations.
2. Total electricity generation cost using NG $(\sum_{nG}Fuel_{gas}^{k,i}.Price_{gas})$
3. Total electricity generation cost using 2nd-fuel $(\sum_{nG}Fuel_{2nd\text{-}fuel}^{i}.Price_{2nd\text{-}fuel})$. In this paper NO.6 Fuel Oil, mazut, is used as 2nd-fuel.

- NG network constraints:

$$\sum_{m|(k,m)\in A} Q^{km} = S^k - D^k - \tau_C^{km} - Fuel_{gas}^{k,i} \tag{9}$$

$$-\overline{Q^{km}} \le Q^{km} \le \overline{Q^{km}} \tag{10}$$

$$\underline{\Pi^k} \le \Pi^k \le \overline{\Pi^k} \tag{11}$$

$$1 \le \left(\frac{\Pi^m}{\Pi^k}\right) \le \overline{ratio_C^{km}} \tag{12}$$

Equation (9) is nodal-flow balance of the NG network where $S^k$ is NG injection in node k and $D^k$ is a nonelectric load of node k. (10), (11) and (12) represent the lower and upper limits of NG flow, pressure and compression ratio.

- Electricity network constraints:

$$T^{ij} = B^{ij}(\delta^i - \delta^j) \tag{13}$$

$$\sum_{j|(i,j)\in T} T^{ij} = P_G^i - P_L^i \tag{14}$$

$$\underline{P_G^i} \le P_G^i \le \overline{P_G^i} \tag{15}$$

$$-\overline{T^{ij}} \le T^{ij} \le \overline{T^{ij}} \tag{16}$$

(13) - (16) represents a DC load flow equation which is used to model electricity network.

- 2nd-fuel constraints:

$$0 \le Fuel_{2nd-fuel}^{i} \le \overline{Fuel_{2nd-fuel}^{i}} \tag{17}$$

Optimization variables are Pressure of NG nodes, flow and direction of pipelines, compression ratio, power generated in power plants, power transmitted in transmission lines, NG and 2nd-fuel consumed by power plants, voltage magnitude and phase. MINLP problem is solved by using the SCIP [1] solver of GAMS [2] package. SCIP requires bounded variables and expressions to guarantee global optimality. As all the variables of proposed integrated operation approach is bounded so global optimality is guaranteed.

## IV. Case Study

### A. *Khorasan Province Network*

The proposed integrated operation approach is applied to Khorasan province NG [10] and electricity network, shown in Fig. 2 and Fig .3. The 26-nodes NG network is composed of 12 nonelectric load nodes, 1 source node, 3 Junction nodes, 25 pipelines and two compressor stations, Razavi with 3+1 compressor units and Faroj with 2+1 compressor units, driven by NG. The maximum pressure is 70 Bar in all nodes. Minimum pressure is 20 Bar for nonelectric load, 35 Bar for combined nodes and 50 Bar for Bojnord because this node

1 Solving Constraint Integer Programs
[2] General Algebraic Modeling System

place in the middle of Khangiran-Neka pipeline. Detailed information about the NG network can be found in [10].

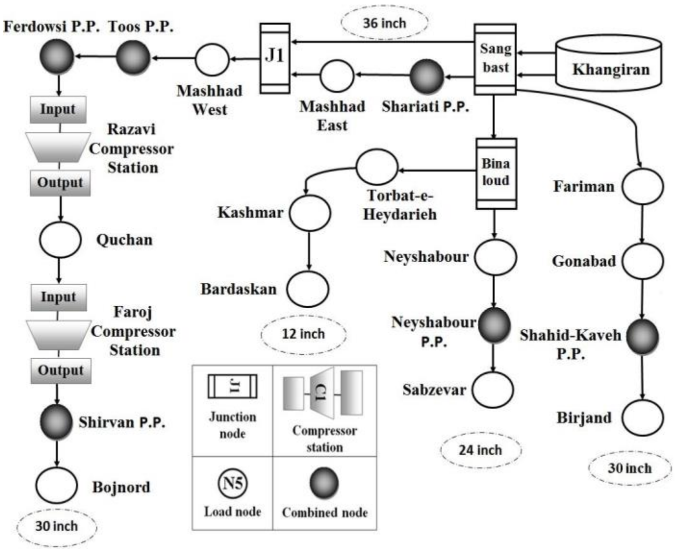


Figure 2. Khorasan province NG network[10]

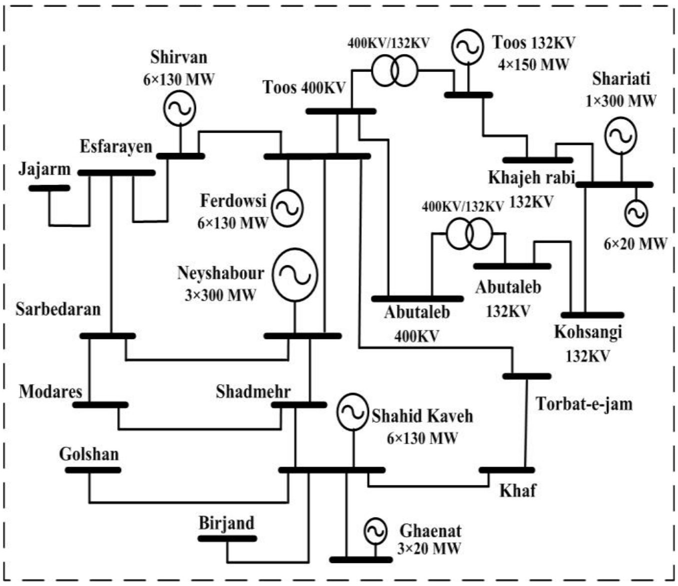


Figure 3. Khorasan province electricity network

NG consumption coefficients of Razavi and Faroj compressors, compressor efficiency, maximum allowable flow and maximum compression ratio are given in Table I.

TABLE I. RAZAVI AND FAROJ COMPRESSOR UNITS DATA [10]

| $\alpha_C^{km}$ | $\beta_C^{km}$ | $\gamma_C^{km}$ | $\overline{Q}_C^{km}$ | $E_C$ | $ratio_C^{km}$ |
|---|---|---|---|---|---|
| 0 | 7.3e-3 | 3.408e-8 | 312.5 | 0.84 | 1.6 |

Heat curve coefficients of Khorasan province Power plants as affected by NG are shown in Table 2.

TABLE II. POWER PLANTS INFORMATION OF KHORASAN PROVINCE ELECTRICITY NETWORK

| **Power plants** | $\alpha_G^i$ | $\beta_G^i$ | $\gamma_G^i$ | $\overline{P}_G^i$ | **No of plants** | **Type** |
|---|---|---|---|---|---|---|
| ***Shariati*** | 13.44 | 0.1636 | 4e-5 | 300 | 1 | CCGT |
| ***Toos*** | 6.33 | 0.17 | 4.77e-4 | 150 | 4 | Steam |
| ***Ferdowsi*** | 10.813 | 0.2 | 9.68e-5 | 130 | 6 | Gas T. |
| ***Shirvan*** | 10.813 | 0.2 | 9.68e-5 | 130 | 6 | Gas T. |
| ***Neyshabour*** | 13.44 | 0.1636 | 4e-5 | 300 | 3 | CCGT |
| ***Shahid-Kaveh*** | 10.813 | 0.2 | 9.68e-5 | 130 | 4 | Gas T. |

Due to the lack of information the heat rate coefficients of power plants as affected by NO.6 Fuel Oil (mazut) was estimated by use of data in Table 2 and statistical analysis in [11]. Depend on data taken from more than 65 boiler tests, although NO.6 Fuel Oil combustion is about 2.5% more efficient compared with NG, but in overall using NG between 2% and 5% are more efficient. The summary of [11] and the losses associated with each fuel are given in Table 3. In this paper, we modified Heat curve coefficients in Table 2 by 3% to compute heat curve coefficients as affected by NO.6 Fuel Oil.

TABLE III. A COMPARISON OF BOILER THERMAL LOSSES AS AFFECTED BY NO.6 FUEL OIL VERSUS NG IN EACH PROSES[11]

| **Process** | **Losses %** | **Process** | **Losses %** |
|---|---|---|---|
| ***Stack*** | 0.6 % | ***Makeup Water*** | 0.22 % |
| ***Preheating*** | 0.78 % | ***Soot Blowing*** | 0.43 % |
| ***Atomization*** | 1.88 % | ***Preventing Corrosion*** | 0.8 % |
| ***Pumping*** | 0.8 % | ***Combustion*** | -2.3 % |

Based on the IMF report [12], price and energy content of NG and NO.6 Fuel Oil are shown in Table4.

TABLE IV. PRICE & ENERGY CONTENT OF NG AND NO.6 FUEL OIL[12]

| **Fuel** | **unit** | **Energy content per unit (MMBTU)** | **Price per unit (USD)** | **Price per MMBTU (USD)** |
|---|---|---|---|---|
| ***NG*** | MSCM | 40.62 | 407.0124 | 10.02 |
| ***NO.6 Fuel Oil(Mazut)*** | Barrel | 6.4 | 124.352 | 19.43 |

## *B. Optimization Results*

To see the impact of the NG network on power system operation two cases were studied.

- Both NG and electricity operation optimize independently.
- Using proposed integrated operation approach for both networks.

The result of independent and integrated Optimization is reported respectively in Table 5&6. Note that the winter peak time NG and electricity demand data are used where the total electricity demand is 2254 MW. Proposed optimization model has 469 equations, 38 discrete variables and 215 continuous variables. The total execution time is 11.53 min.

TABLE V. INDEPENDENT OPTIMAL OPERATION RESULTS

| Power plants | NG (MSCM) | NO.6 Fuel Oil (Barrel) | Power Generation (MW) |
|---|---|---|---|
| *Shariati* | 1×66.125 | 0 | 1×300 |
| | 66.125 | 0 | 300 |
| *Toos* | 3×39.958 | 1×200.72 | 3×141+1×111 |
| | 119.875 | 200.72 | 534 |
| *Ferdowsi* | 2×38.458 | 0 | 1×130 |
| | 76.916 | 0 | 260 |
| *Shirvan* | 1×38.458 | 0 | 1×130 |
| | 38.458 | 0 | 130 |
| *Neyshabour* | 1×66.125 | 2×432.116 | 1×300+2×300 |
| | 66.125 | 864.233 | 900 |
| *Shahid-Kaveh* | 1×38.458 | 0 | 1×130 |
| | 38.458 | 0 | 130 |
| *Total* | 405.958 | 1064.953 | 2254 |
| **NG Transporting Loss** | | | 160.5 MSCM |
| **Total Cost** | | | 362984.46 USD |

TABLE VI. INTEGRATED OPTIMAL OPERATION RESULTS

| Power plants | NG (MSCM) | NO.6 Fuel Oil (Barrel) | Power Generation (MW) |
|---|---|---|---|
| *Shariati* | 1×66.125 | 0 | 1×300 |
| | 66.125 | 0 | 300 |
| *Toos* | 3×37.08 | 1×254.4 | 3×131.9+1×139 |
| | 111.25 | 254.4 | 534 |
| *Ferdowsi* | 1×38.458 | 0 | 1×130 |
| | 38.458 | 0 | 130 |
| *Shirvan* | 0 | 2×251.495 | 2×130 |
| | 0 | 502.1 | 260 |
| *Neyshabour* | 2×66.125 | 1×432.116 | 2×300+1×300 |
| | 132.25 | 432.116 | 900 |
| *Shahid-Kaveh* | 1×38.458 | 0 | 1×130 |
| | 38.458 | 0 | 130 |
| *Total* | 386.541 | 1188.616 | 2254 |
| **NG Transporting Loss** | | | 19 MSCM |
| **Total Cost** | | | 312867 USD |

Power plants generation and their associated fuel in both independent and integrated operation is depicted Fig.4

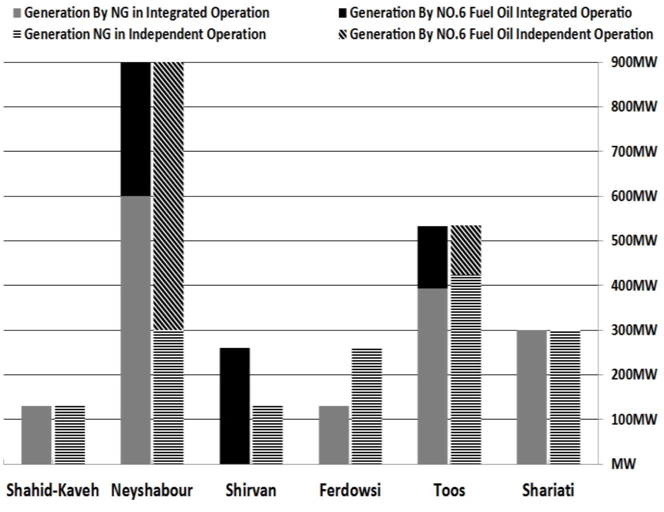


Figure 4. Power plants generation and their associated fuel in both independent and integrated operations

Regarding Fig.4 and Table 5&6 the power generations of power plants are considerably different in two optimization cases. The power generated by NG decrease in Toos, Ferdowsi and Shirvan power plants in the integrated operation case compare with the independent operation case. Due to this the NG flow through the Sangbast-bojnord path reduced, which led to the lower pressure drop and consequently the lower NG consumption rate of Razavi and Faroj compressor stations compare with the independent operation case. To compensate this reduction in power generation, Neyshabour power generation associated with NG and Toos, Ferdowsi and Shirvan power plants generation associated with NO.6 Fuel Oil increase. The generation schemes of Shariati and Shahid-Kaveh power plants remain same in both cases.

NG and electricity operation cost composed of NG, NO.6 Fuel Oil and NG transporting cost in both independent and integrated operations is illustrated in Fig.5.

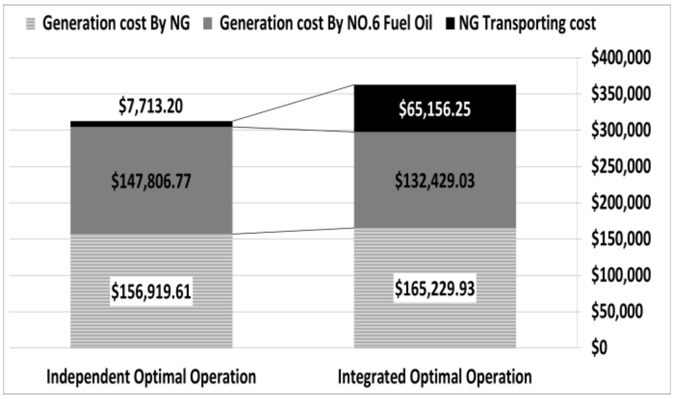


Figure 5. NG and electricity operation cost composed of NG, NO.6 Fuel Oil and NG transporting cost in both independent and integrated operations

Although the overall generation cost increase in integrated operation, but considering NG network transporting cost cause 13.8%, 50117 USD[1], reduction in total cost in peak hour. Approximately applying this approach between December and March when NG is at peak demands could save 13.08 Million of USD.

## V. CONCLUSION

The interdependency of NG and electricity network strongly demands novel approach for network operation. This paper proposed integrated optimal operation of both systems with consideration of 2nd-fuel. Static load flow equation of NG and electricity system is modeled as an optimization problem with focusing on compressor station roles to Minimized total operating cost. Simulation results on Khorasan province NG and electricity networks indicate success in power plant fuel management and great reduction in total cost of two systems especially in peak condition.

## REFERENCES


[1] De Wolf D, Y. Smeers, "The Gas Transmission Problem Solved By An Extension Of The Simplex Algorithm", Management Science, vol. 46, no. 11, pp. 1454-1465, 2000.


[1] United States Dollar

[2] Tabkhi, Firooz, et al. "Improving The Performance Of Natural Gas Pipeline Networks Fuel Consumption Minimization Problems." AIChE journal 56.4, pp. 946-964, 2010.

[3] A. Seungwon, L. Qing, and T. W. Gedra, "Natural gas and electricity optimal power flow," in Transmission and Distribution Conference and Exposition, 2003 IEEE PES, pp. 138-143 2003.

[4] H. Rajabi Mashhadi and S. Mohtashami, "Economic Dispatch Problem Considering Natural Gas Transportation Cost," in World Academy of Science, Engineering and Technology, pp.1482-1487, 2009.

[5] A. Martinez-Mares and C. R. Fuerte-Esquivel, "A Unified Gas and Power Flow Analysis in Natural Gas and Electricity Coupled Networks," Power Systems, IEEE Transactions on, vol. 27, pp. 2156-2166, 2012.

[6] J. Munoz, N. Jimenez-Redondo, J. Perez-Ruiz, and J. Barquin, "Natural Gas Network Modeling for Power Systems Reliability Studies," in Power Tech Conference Proceedings, 2003 IEEE Bologna, 2003, p. 8 pp. Vol.4.

[7] M. A. Latify, H. Seifi, and H. Rajabi Mashhadi, "An Integrated Model for Generation Maintenance Coordination in A Restructured Power System Involving Gas Network Constraints and Uncertainties," International Journal of Electrical Power & Energy Systems, vol. 46, pp. 425-440, 2013.

[8] E. Shashi Menon, "Gas Pipeline Hydraulics". CRC PressMay 24, 2005.

[9] C. A. Luongo , B. J. Gilmour, and D.W. Schroeder. Optimization in natural gas transmission networks: A tool to improve operational efficiency. Technical report, Stoner Associates, Inc., Houston, April 2009.

[10] M.A.Fanaei Shykholeslami, "Dynamic Simulation of Iranian Fourth Region Gas Transmission Pipelines", Funded Research Project of Fourth Region Gas Transmission Corporation.

[11] H. M. Eckerlin, "Results From the Nationwide Oil-Versus-Gas Boiler Test Program," Energy Engineering; (USA), vol. 91, 1994.

[12] The IMF Primary Commodity Prices, Dec 3, 2014. From: http://ycharts.com/indicators/sources/international_monetary_fund