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# Multi-time combined gas and electric system optimal power flow incorporating wind power

Shuang Chen[a]*, Guoqiang Sun[a], Zhinong Wei[a], Sheng Chen[a], Yichi Li[b,] *

[a]Hohai University, Focheng West Road, Jiangning District, Nanjing, 211100, China
[b]State Grid Suzhou Power Supply Company, Suzhou, 215004,China

**Abstract**

To alleviate environment pollution, it has become a tendency for energy adjustment that natural gas is taking the place of fossil fuels. The coupling between natural gas system and electric system is being strengthened by gas-fired power plants. A multi-time combined gas and electric system optimal power flow (M-GEOPF) model is proposed aiming at minimizing the overall cost. To address available wind power uncertainty, underestimation and overestimation of wind power are considered in the model. A test case on the combined IEEE 39-bus system and Belgium 20-node natural gas system is performed to verify the effectiveness of the proposed method.

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*Keyword:* combined electric and natural gas system; multi-time optimal power flow; wind power uncertainty

## 1. Introduction

Over the last few decades, energy depletion and environment pollution has accelerated the pace of natural gas industry. Natural gas is a promising energy source in three folds, relatively low capital cost, low greenhouse gas emission and fast response to renewable energy. With the large-scale exploitation of natural gas, it is competitive among other energy sources in power sector in the foreseeable future. According to the U.S. Energy Information Administration (EIA) [1], 60% of new electric generation capacity built by 2035 is expected to be natural gas combined-cycle or combustion turbine generation.

* Corresponding author. Tel.: +86-159-5193-4924
*E-mail address*: hhuchenshuang@163.com.


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A natural gas-fired power plant couples two networks, known as electric network and natural gas network [2]. The strong interdependency between gas and electricity networks appeals for a combined viewpoint of the integrated system. Thus, to maximize social welfare, or minimize overall cost, it is pregnant to integrate the gas and electric networks and employ the combined gas and electric optimal power flow (GEOPF) for the best system operation, planning and control. However, in conventional power system-oriented optimal power flow (OPF), little attention has been paid to the operation status of gas system [3], [4].

Recently, a relevant number of works propose the combined modeling of natural gas and electric infrastructure for a unified analysis and coordinated optimization. In [5], the steady-state model of gas system is formulated. Then, a natural gas system flow model is proposed based on nodes and arcs, in resemble with the electric power flow. On that basis, the flow model is improved to the optimal flow model [2], [6]-[7], called GEOPF. Later, it is extended to a multi-time framework. Dynamic models are proposed to further demonstrate the physical process of gas flow in response to a sudden change of gas demand [8]-[11].

Furthermore, the commitment of gas-fired generators has provoked the widely deployment of renewable energies (i.e. wind power). The volatility and uncertainty of wind power is hopeful to be mitigated by gas-fired generators due to its fast response. Power system operators are now facing a problem of scheduling not only conventional power plants but also wind power. Overestimation of wind power means taking the risk of power supply shortage in case of a sudden decrease in wind speed. In this case, additional power must be procured from electric market or load curtailment should be encountered. If the available wind power is underestimated, the surplus power is dropped or wasted by dummy loads. Thus, it is reasonable to impose a reserve cost for overestimating wind power and a penalty cost for underestimating wind power [12].

In this context, the remainder paper is organized as follows. In Section 2, the steady-state model of natural gas system is introduced and a detailed M-GEOPF model incorporating wind power is established. Section 3 develops case studies to validate the proposed method and Section 4 draws a conclusion.

## 2. M-GEOPF based on steady-state model

### 2.1. Natural gas system steady-state modelling

The natural gas system consists of wells, pipelines, compressors, storages and valves. Natural gas flows into the network from a distant gas well or a remote storage tank, and transported to end users via pipelines in distribution network.

For an adiabatic pipeline, *m* and *n* being its first and terminal nodes, the steady-state gas flow $f_{mnt}$ is written as [2]:

$$f_{mnt} = \mathrm{sgn}_{mnt}\, c_{mn} \sqrt{\mathrm{sgn}_{mnt}(\pi_{mt}^2 - \pi_{nt}^2)} \tag{1}$$

$$\mathrm{sgn}_{mnt} = \begin{cases} +1 & \pi_{mt} \ge \pi_{nt} \\ -1 & \pi_{mt} < \pi_{nt} \end{cases} \tag{2}$$

where $c_{mn}$ is pipeline efficiency constant; $\pi_{mt}$, $\pi_{nt}$ are the pressures of node *m* and *n* at time *t*.

Compressors are deployed as a compensation for energy loss. Adjusting the pressure consumes extra energy, which is proportional to its flow rate and compression ratio. For a compressor station *k*, *p* and *q* being its inlet and outlet node, its energy consumption is [2]:

$$H_{kt} = B_k f_{kt} \left[ \left( \frac{\pi_{qt}}{\pi_{pt}} \right)^{Z_k} - 1 \right] \tag{3}$$

$$\tau_{kt} = \alpha + \beta H_{kt} + \gamma H_{kt}^2 \tag{4}$$

where $H_{kt}$ is the horsepower consumption by compressor *k*; $B_k$ is a compressor constant and $Z_k$ is compression factor; $\pi_{kt}$ is the equivalent gas flow consumption; and $\alpha$, $\beta$, $\gamma$ are energy conversion constants.

Each node in the gas system must satisfy the conservation of flow rate, which follows:

$$w_{g,mt} - w_{d,mt} - \sum_{n\in m} f_{mnt} - \sum_{k\in m} f_{kt} - \sum_{k\in m} \tau_{kt} - \sum_{i\in m} \varphi(P_{g,it}) = 0 \tag{5}$$

where $w_{\mathrm{g},mt}$ is gas source injection at node $m$; $w_{\mathrm{d},mt}$ is gas load at node $m$; $P_{\mathrm{g},it}$ is the active output of $i$th gas-fired generator; $\varphi(P_{\mathrm{g},it})$ denotes the gas consumption by gas-fired turbines. Note that it is the term $\varphi(P_{\mathrm{g},it})$ couples the two networks.

### *2.2. M-GEOPF formulation incorporating wind power*

The objective of M-GEOPF is to minimize the overall cost of the combined system over a dispatch horizon while satisfying the constraints of both systems. Nevertheless, because of the uncertain factors related to wind power, additional terms should be included as payment [2], [12].

1) Objective function

The objective of the M-GEOPF model incorporating wind power is formulated as:

$$\min \sum_{t\in T}[\sum_{i\in N_t} C_i(P_{\mathrm{g},it}) + \sum_{i\in N_\mathrm{w}} C_{\mathrm{w},i}(P_{\mathrm{w},it}) + \sum_{m\in \Omega_s} C_\mathrm{g}(w_{\mathrm{g},mt}) + \sum_{i\in N_\mathrm{w}} C_\mathrm{uw}(P_{\mathrm{av},it} - P_{\mathrm{w},it}) + \sum_{i\in N_\mathrm{w}} C_\mathrm{ow}(P_{\mathrm{w},it} - P_{\mathrm{av},it})] \tag{6}$$

where $T$, $N_t$, $N_\mathrm{w}$ , $\Omega_s$ are the sets for time periods, thermal power plants, wind farms, gas sources, respectively. $P_{\mathrm{w},it}$ is scheduled wind power; $P_{\mathrm{av},it}$ is available wind power, which is a random variable with predetermined distribution.

In (6), the first term is the generation cost of thermal plants. Conventionally, it is assumed as a quadratic function of power generation, written as:

$$C_i(P_{\mathrm{g},it}) = c_i + b_i P_{\mathrm{g},it} + c_i P_{\mathrm{g},it}^2 \tag{7}$$

where $a_i$, $b_i$, $c_i$ are cost coefficients of $i$th thermal power plant.

The second term in (6) represents wind power generation cost, and it depends on the wind farm owner. The third term is the natural gas fuel cost, and is assumed to be a linear function:

$$C_\mathrm{g}(w_{\mathrm{g},mt}) = g_m w_{\mathrm{g},mt} \tag{8}$$

where $g_m$ is natural gas cost coefficient.

Extra payment accounting for wind power uncertainty is added in (6). It is assumed that the penalty cost for not using all the available wind power, or underestimating wind power, is linearly related to the difference between the available wind and dispatched wind power. The penalty cost function is given as:

$$C_\mathrm{uw}(P_{\mathrm{av},it}, P_{\mathrm{w},it}) = k_\mathrm{uw}(P_{\mathrm{av},it} - P_{\mathrm{w},it}) = k_\mathrm{uw}\int_{P_{\mathrm{w},it}}^{P_\mathrm{r}} (P - P_{\mathrm{w},it}) f_\mathrm{W}(P)dP \tag{9}$$

where $k_\mathrm{uw}$ is penalty cost (underestimation) coefficient; $P_\mathrm{r}$ is the rated wind power.

The last term in (6) is similar to underestimate penalty cost, it stands for reserve requirement cost, or overestimate cost. It also takes the form of an integral over the pdf of wind power random variable.

$$C_\mathrm{ow}(P_{\mathrm{av},it}, P_{\mathrm{w},it}) = k_\mathrm{ow}(P_{\mathrm{w},it} - P_{\mathrm{av},it}) = k_\mathrm{ow}\int_0^{P_{\mathrm{w},it}} (P_{\mathrm{w},it} - P) f_\mathrm{W}(P)dP \tag{10}$$

where $k_\mathrm{ow}$ is reserve cost (overestimation) coefficient.

2) Electric system operation constraints

In resemble with conventional OPF model, electric system multi-time operation constraints includes power balance, thermal plant generation capability, wind power availability, ramp rate limit, voltage limit and line flow limit, written as:

$$\begin{cases} P_{\mathrm{g},it} + P_{\mathrm{w},it} - P_{\mathrm{d},it} - V_{it}\sum_{j\in i} V_{jt}(G_{ij}\cos\theta_{ijt} + B_{ij}\sin\theta_{ijt}) = 0 \\ Q_{\mathrm{g},it} - Q_{\mathrm{d},it} - V_{it}\sum_{j\in i} V_{jt}(G_{ij}\sin\theta_{ijt} - B_{ij}\cos\theta_{ijt}) = 0 \\ P_{\mathrm{g},i}^{\min} \le P_{\mathrm{g},it} \le P_{\mathrm{g},i}^{\max} \\ Q_{\mathrm{g},i}^{\min} \le Q_{\mathrm{g},it} \le Q_{\mathrm{g},i}^{\max} \\ 0 \le P_{\mathrm{w},it} \le P_\mathrm{r} \\ \mathrm{RD}_i \le P_{\mathrm{g},it} - P_{\mathrm{g},i(t-1)} \le \mathrm{RU}_i \\ V_i^{\min} \le V_{it} \le V_i^{\max} \\ P_l^{\min} \le P_{l,t} \le P_l^{\max} \end{cases} \tag{11}$$

where $Q_{g,it}$ is reactive output of $i$th generator; $P_{d,it}$, $Q_{d,it}$ are active and reactive electric load; $V_{it}$, $\theta_{it}$ are the voltage magnitude and phase of bus $i$, $\theta_{ijt}=\theta_{it}-\theta_{jt}$; $G_{ij}$, $B_{ij}$ are the conductance and susceptance between bus $i$ and $j$; $RU_i$, $RD_i$ are the ramp up and ramp down rate of unit $i$; $P_{l,t}$ is the power flow in electric line $l$; and the superscript 'min' and 'max' denote minimum and maximize value.

3) Natural gas system operation constraints

Natural gas system constraints include equivalent gas consumed by gas-fired generators, gas supply capability, pressure limit and compression ratio limit, following:

$$\begin{cases} \phi(P_{g,it}) = K_{2i}P_{g,it}^2 + K_{1i}P_{g,it} + K_{0i} \\ w_{g,m}^{\min} \le w_{g,mt} \le w_{g,m}^{\max} \\ \pi_m^{\min} \le \pi_{mt} \le \pi_m^{\max} \\ R_c^{\min} \le \pi_{qt} / \pi_{pt} \le R_c^{\max} \end{cases} \tag{12}$$

where $K_{2i}$, $K_{1i}$, $K_{0i}$ are power to gas conversion constants; $w_g^{\min}$, $w_g^{\max}$ are minimum and maximum gas supply; $\pi_m^{\min}$, $\pi_m^{\max}$ are minimum and maximum node pressure; $R_c^{\min}$, $R_c^{\max}$ are minimum and maximum compression ratio.

Our established M-GEOPF model incorporating wind power is a nonlinear programming model with discontinuous derivatives (DNLP) due to (6). In this paper, CONOPT solver in GAMS platform is adopted to solve this DNLP model. Also, numerical methods are employed to address integral.

## 3. Case study

### 3.1. M-GEOPF analysis

The modified combined IEEE 39-bus system and Belgium 20-node natural gas system is used for case study. Here we assume four generators are gas-fired that are integrated into the gas system and the others are conventional thermal plants. A 600-MW wind farm is integrated into the electric system at bus 9. Wind speed is obtained from [13] and converted to wind power. Assuming cut-in, rated and cut-out speed are 3.5m/s, 15m/s and 25m/s, respectively. The Belgium 20-node system consists of 20 nodes, 6 gas sources, 21 pipelines and 2 electric-driven compressors. The total gas demand is 46.298Mm3/d, and daily electric load is in [11].

**Case 1) $k_{uw}=k_{ow}$=2000$/MW**

In this case, the underestimation or overestimation of wind power penalty is assumed equal. The overall cost of the combined gas and electric system is 6465.403k$. The optimal generation scheduling curve over the 24-h period is in Figure 1. Unit 31 and unit 34 are both gas-fired generators. Unit 31 is expected to generate at its full capacity due to low marginal cost of natural gas. However, it is a different thing for unit 34, which is making quite little contribution.

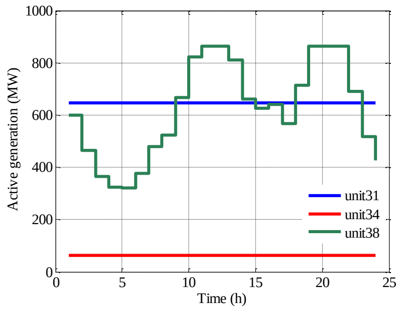


Fig. 1. Optimal generation scheduling of a day.

In this case, 19:00 is the electric load peak hour. The scheduled power generation of each unit at 19:00 is listed in Table 1. Three of four gas-fired units are expected to generate at their full capacity. However, it is noted the gas-fired unit，unit 34, connected to node 20 at natural gas system, is contributing fair little compared with its full capacity. It is because that the pressure of node 20 in gas system is quite sensitive to gas flow. When connected with a gas load at this node, the pressure drops rapidly.

Table 1. Optimal power generation at 19:00

| Unit bus | $P_g$ (MW) | $Q_g$ (MVar) |
|---|---|---|
| 30 | 305.32 | 140.00 |
| 31 | 646.00 | 300.00 |
| 32 | 725.00 | 300.00 |
| 33 | 652.00 | 161.19 |
| 34 | **62.36** | 113.78 |
| 35 | 488.21 | 171.49 |
| 36 | 459.38 | 41.13 |
| 37 | 564.00 | 0 |
| 38 | 865.00 | 37.32 |
| 39 | 1100.00 | -39.96 |
| Total | 5867.27 | 1224.96 |

The pressure of node 20 is 25 bar, the lower bound. This also indicates the reason for not making full use of unit 34. This case study has demonstrated the significance of optimizing the combined system.

**Case 2) variable $k_{uw}$ and $k_{ow}$**

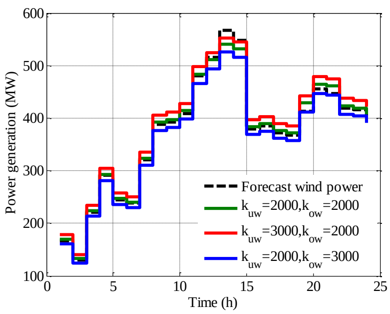


Fig. 2. Scheduled wind power generation under different penalty coefficients

We set the penalty coefficient variable to further investigate the impact of wind power availability. Figure 2 shows the scheduled wind power under different penalty coefficients. It is as expected in Figure 2, when kuw=kow, the scheduled wind power is almost the same as forecasted. This is because the mean value of forecasted wind power is the scenario with the largest probability to happen. The system operator had better make full use of forecasted energy to avoid either a penalty for underestimation or a reserve cost for overestimation. However, when kuw>kow, it means the system suffers a more severe penalty for underestimating wind power. Thus, it is rational to make optimistic decisions to avoid large penalty for wasting wind power.

Table 2. Power generation (GW) with different $k_{uw}$

| $k_{ow}=2000, k_{uw}$ | Unit bus | | |
|---|---|---|---|
| | 31 | 34 | 38 |
| 2000 | 15.50 | 1.497 | 14.93 |
| 2500 | 15.50 | 1.497 | 14.89 |
| 3000 | 15.50 | 1.497 | 14.86 |
| 3500 | 15.50 | 1.497 | 14.84 |
| 4000 | 15.50 | 1.497 | 14.82 |

Table 3. Power generation (GW) with different $k_{ow}$

| $k_{uw}=2000, k_{ow}$ | Unit bus | | |
|---|---|---|---|
| | 31 | 34 | 38 |
| 2000 | 15.50 | 1.497 | 14.93 |
| 2500 | 15.50 | 1.497 | 14.96 |
| 3000 | 15.50 | 1.497 | 14.99 |
| 3500 | 15.50 | 1.497 | 15.01 |
| 4000 | 15.50 | 1.497 | 15.03 |

Also, a statistic analysis is conducted on thermal and gas-fired power plants. Table 2 lists total scheduled power generation over a day with different penalty coefficient and Table 3 with different reserve cost according to optimization. It can be observed that unit 31 and unit 34 are gas-fired plants, and no matter how wind penalty or reserve cost changes, their scheduled generation keeps the same. But for unit 38, its scheduled power generation decreases as wind penalty increases, and increases as reserve cost increases.

## 4. Conclusion

This paper proposes a multi-time combined gas and electric system optimal power flow model considering variable wind power. The stochastic nature of wind power is characterized by its probability density function. By establishing an M-GEOPF model, the overall optimal schedule is achieved. Both electric and natural gas system security constraints are guaranteed. To address the uncertainty induced by wind power, penalty and reserve cost are included to account for underestimation and overestimation of wind power by utilizing the obtained wind power distribution. The results show that the coupled two systems are restricted to each other and the proposed M-GEOPF model is helpful for system optimal operation.

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