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Coordinated operation of the electricity and natural gas systems with bi-directional energy conversion

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Abstract

A coordinated operation of the natural gas and electricity network with bi-directional energy conversion is expected to accommodate high penetration levels of renewables. This work focuses on the unified optimal operation of the integrated natural gas and electricity system considering the network constraints in both systems. An iterative method is proposed to deal with the nonlinearity in the proposed model. The models of the natural gas and power system are linearized in every iterative step. Simulation results demonstrate the effectiveness of the approach. Applicability of the proposed method is tested in the sample case. Finally, the effect of Power to Gas (P2G) on the daily economic dispatch is also investigated.

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Keywords: Integrated electricity and gas network, coordinated operation, successive linearization, Power to Gas, economic dispatch

1. Introduction

The rapid development of the renewable energy brings sustainability of the energy supply [1], while challenging the power system operators with the intermittent and unpredictable features at the same time. In recent years, research investigations have demonstrated that the integration of energy systems can balance the energy production and consumption in a broader scope, thereby improve the overall efficiency and sustainability of the energy utilization [2].

Among different energy systems such as power, gas, heating, transportation, etc., the natural gas and electrical power systems are the most common options for bulk energy transmission over thousands of kilometers. Moreover, the emerging power-to-gas technology enabling the bi-directional energy conversion further enhances the interaction

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between the gas and power systems [3]. More recent researches are carried out from the market perspective, illustrating that neglecting the gas supply limitations may lead to the energy cost distortion [4] and coordination can help to reduce energy supply cost [5].

The optimal operation of integrated gas and power systems can be formulated as an optimization problem. However, network constraints for both gas and electricity systems are usually presented in nonlinear forms which challenge the tractability of the global optimality. Existing work [6] decouples the optimization into two subproblems representing gas and electricity. However, it may not work for the loop-locked system with bi-directional energy conversion.

To achieve the optimal operation of the integrated gas and electricity system synchronously, this work focuses on the coordinated operation of the integrated gas and power system with bi-directional energy conversion. The objective is to minimize the operation cost for both electricity and gas systems while maximizing the renewable energy accommodation. It is mathematically formulated as a scaled nonlinear optimization problem. An iterative method is proposed to handle its scale and nonlinearity.

2. Integration of the electricity and natural gas systems

The integrated natural gas and power system is composed of a natural gas network and an electricity network as shown Fig. 1. It is a test system which has been used in the steady-state analysis of the combined gas and power system, and the details can be found in [7].

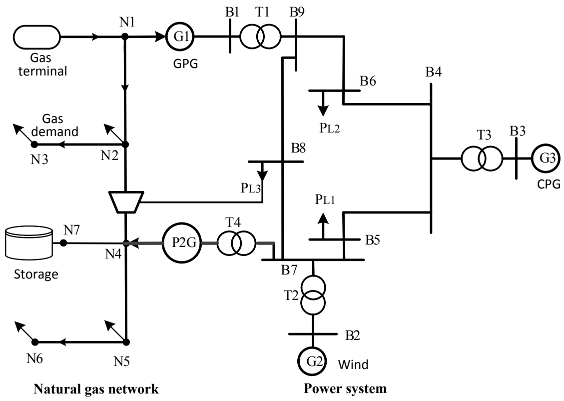

Fig. 1. The test system of a 7-node gas network coupled with IEEE-9 system

The bi-direction energy conversion between the natural gas and electric power systems primarily takes place in the GPG units and P2G. So the integrated natural gas and power system is a loop-locked system. The production and consumption in both networks need to be balanced simultaneously.

To simplify the analysis, the unit of the gas flow rate is converted to power unit as MW and then the per-unit system is used in this paper. The base value of voltage is set as 110kV. The base value of gas pressure is 1MPa. The base value of power is 100MW. Finally, all the related coefficients are adjusted to meet the per-unit system accordingly.

3. Mathematical formulations of the optimization problem

3.1. Objective function

The aim of the optimal operation is to minimize the total operational cost of the integrated electricity and gas systems.

$$F = \sum_{h=1}^{H} C_{\text{gas production}}(h) + C_{\text{power production}}(h) + C_{\text{compressor}}(h) + C_{\text{wind curtailment}}(h) \tag{1}$$

The first term is the cost of gas production. The second term represents the cost of power supply. The third term represents the operational cost of the gas compressor. The fourth term is the penalty cost of a wind farm which is proportional to the square of wind power curtailment.

3.2. Constraints

The steady-state load flow in the electrical system is well-documented as shown in (2) and (3). For the natural gas system, the natural gas flow formulated by the pipeline flow equation (4), nodal balance equation (5), gas compressor equation (6), linepack constraints (7) and (8). The energy conversions between the gas and power system primarily take place in the GPG units and P2G are shown in (9) and (10).

$$\Delta P_i = P_{\text{g},i} - P_{\text{d},i} - |V_i| \sum_{j=1}^{N} |V_j| \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0 \tag{2}$$

$$\Delta Q_i = Q_{\text{g},i} - Q_{\text{d},i} - |V_i| \sum_{j=1}^{N} |V_j| \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) = 0 \tag{3}$$

$$\Pi_i - \Pi_j = Z_{ij} S_{ij}^2 \tag{4}$$

$$S_{\text{sup},i} - S_{\text{load},i} = \sum_{j \in i} S_{ij}, (\forall i, j \in N) \tag{5}$$

$$P_{\text{GC},ij} = K_{\text{GC}} S_{\text{GC},ij} \left[\frac{c_k}{c_k - 1} \right] \left[\left(\Pi_j / \Pi_i \right)^{\frac{c_k - 1}{c_k}} - 1 \right] \tag{6}$$

$$LP(t) = LP_0 + \int_0^t \left[S_{\text{sup}}(t) - S_{\text{con}}(t) \right] dt \tag{7}$$

$$LP_{\text{end}} = LP_0 \tag{8}$$

$$P_{\text{GPG}} = \eta_{\text{GPG}} S_{\text{GPG}} \tag{9}$$

$$S_{\text{P2G}} = \eta_{\text{P2G}} P_{\text{P2G}} \tag{10}$$

Those mentioned above are the equality constraints. Besides, there are various inequality constraints related to the transmission capacities of the gas pipeline and power line, the available capacities of the gas storage, gas linepack, gas terminal and electricity generator. Moreover, nodal pressures and bus voltages are also required to meet the operation limits.

4. Optimization algorithm for solving the problem

Since the objective function and most of the equality constraints are nonlinear equations, it is a large-scale nonlinear programming. Finding a globally optimal solution is difficult. To achieve the global optimal solution efficiently, this work proposes an iterative method to handle its scale and nonlinearity. The models of the natural gas and power system are linearized in every iterative step.

The nonlinear objective function can be approximated by piecewise linear curves. Then by using DC power flow, nonlinear model of the AC system is simplified to a linear form.

$$P_{ij} = B_{ij}(\theta_i - \theta_j) \tag{11}$$

$$\Delta P_i = P_{g,i} - P_{d,i} - \sum_{j \in i} P_{ij} = 0 \tag{12}$$

The nonlinear equations of the natural gas model can be linearized based on the following simplifications. Given the initial values of gas flow rate in pipelines, (4) can be linearized as (13). The compressor works with a constant compression ratio of *CR* that the compressor calculation can be rewritten as (14) and (15).

$$\Pi_k - \Pi_m = Z_{km} S_{0,km} \cdot S_{\text{gas},km} \tag{13}$$

$$P_{\text{GC},km} = K' \cdot S_{\text{gas},km} \tag{14}$$

$$K' = K_{\text{GC}} \left[\frac{T_s}{E_c \eta_c} \right] \left[\frac{c_k}{c_k - 1} \right] \left[(CR)^{\frac{c_k - 1}{2c_k}} - 1 \right] Z_a \tag{15}$$

Now this problem is a linear convex optimization, which can easily be solved using commercial software such as CPLEX. As the calculated value depends on the given value $S_{0,km}$, it is an iterative process: at the beginning, given the initial value of $\text{x}(0)=[S_{0,km}(0)]$; then solve the linearized optimization problem; update the value of x(t+1) by $\text{x(t+1)} = \lambda_1 \text{x(t}-1) + \lambda_2 \text{x(t)}$, $\lambda_1 + \lambda_2 = 1$; solve the linearized optimization problem based on the updated value. Calculate $\Delta\text{x}=\text{x(t+1)}-\text{x(t)}$, if $\Delta\text{x} \cdot (\Delta\text{x})^{\text{T}} \le \varepsilon$, end. Otherwise, proceed to the next iteration.

5. Case studies

The test case is shown in Fig. 1 which is used to verify the feasibility of the proposed approach. The iteration process of the calculation is shown in Fig. 2 that the value of $\Delta\text{x} \cdot (\Delta\text{x})^{\text{T}}$ is under the pre-set tolerance of 10^{-4} after 7 iterations.

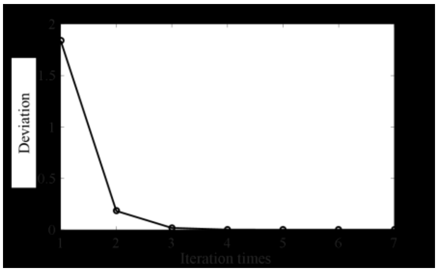

Fig. 2. The iteration of the linearized program

Fig. 3 shows the optimal output of electricity network throughout the 24 time periods. The power outputs from both of the GPG and CPG in the integrated system with P2G agree well with that in the integrated system without P2G. During the peak load periods (1:00 PM~7:00 PM), all the available wind power is used to supply the electrical load, and both the GPG and CPG increase their unit outputs to balance the power demand. However, due to the limitation of the available capacities of the generators, load curtailment happens at 6:00 PM. When the valley load occurs in the midnight (12:00 PM~6:00 AM), the excess wind power is converted into gas fuel by P2G, which decreases the wind power curtailment compared to the case without P2G. It should be mentioned that the total power load includes both the nodal power demand and electricity consumed by P2G. So the total power demand in the case with P2G is higher than that without P2G in the midnight.

Fig. 4 shows the optimal output of gas network throughout the 24 time periods. Due to the gas production from P2G, the daily gas supply from the gas terminal in the integrated energy system with P2G is lower than that without P2G. It should be noted that the gas supply from the gas terminal is assumed to be flat. Linepack plays a major role in providing flexibility to meet the load fluctuation. In Fig. 4, the linepack is consumed when the value is positive, and the linepack is replenished when the value is negative. It can be seen that the linepack is consumed in the day and restored in the midnight. In the peak-demand hour, the increased gas demand from GPG will lead to a rapid linepack consumption, which brings challenges to the reliability of gas supply. Therefore, it is important to maintain a sufficient linepack and the linepack at the end of the day should be equal to the beginning of the day.

Fig. 5 shows the linepack variation. The linepack reaches its trough at around 9:00 PM and then starts to replenish. The linepack is growing faster in the case with P2G after 9:00 PM. The reason is that the surplus wind power can be converted to gas fuel by using P2G, which helps to replenish the linepack faster.

Compared to the case without P2G, the case with P2G can reduce the wind curtailment and natural gas consumption. Thereby, its daily operational cost can be reduced. In this case study, the daily operational costs are 355.5 thousand Euro and 368.8 thousand Euro for the integrated energy system with and without P2G, respectively. 3.6% operational cost is reduced by introducing the P2G.

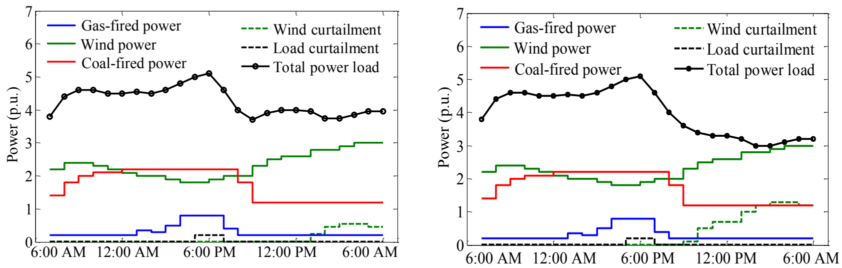

Fig. 3. (a) Daily economic dispatch of power units with P2G (b) Daily economic dispatch of power units without P2G

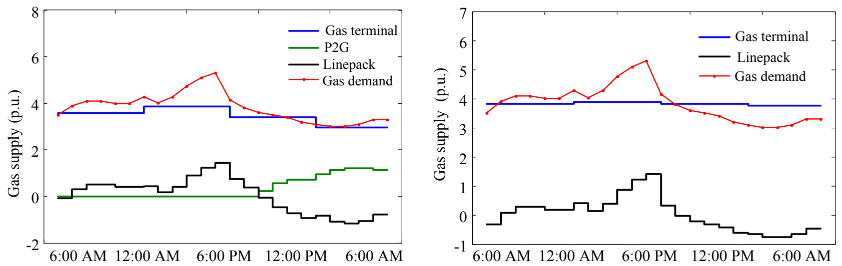

Fig. 4. (a) Daily economic dispatch of gas supply with P2G (b) Daily economic dispatch of gas supply without P2G

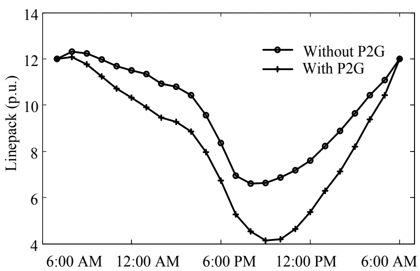

Fig. 5. The simulation results of daily linepack variation

6. Conclusion

This paper investigates the unified optimal operation of the electricity and natural gas systems with bi-directional energy conversion. It is mathematically formulated as a large-scale nonlinear program considering the network constraints in both systems. This work proposes an iterative method to handle its scale and nonlinearity. The models of the natural gas and power system are linearized in every iterative step. Simulation result demonstrates the effectiveness of the proposed method. The effect of P2G on the daily economic dispatch of the integrated energy system is also investigated. It can help to reduce the wind curtailment and natural gas consumption, thereby cut the operational cost. This model and method can provide the system operators with decision support in the integrated energy systems.

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