Research on sensitivity analysis of wind power consumption capability of integrated energy system based on unified optimal power flow model

Yongqiang Mu1, Chunsheng Wang1, Guangyou Kang1, Zheng Wang1, Tao Jiang1, Jianfeng Li1, Wenlei Dou1

1Economic Technology Research Institute, State Grid LiaoNing Electric Power Supply Co., Ltd., Shenyang, People’s Republic of China
E-mail: myq2211@sina.com

Abstract: A sensitivity analysis method for the wind power capacity of integrated energy systems based on unified optimal power flow is proposed, aiming at the large-scale grid-connected wind power problem of integrated energy systems with multiple energy sources and strong coupling characteristics. Based on the unified optimal power flow model of integrated energy system with power system, heat system and gas system, this study establishes the sensitivity analysis method of integrated energy system operation state. Based on the sensitivity matrix, the influence of wind power consumption capability by capacity of energy coupling unit on wind power consumption is analysed. The results of the example show that the proposed method can provide auxiliary information for the safe and stable operation of the integrated energy system, and effectively improve the wind power acceptance level.

1 Introduction

The integrated energy system is a multi-energy comprehensive utilisation system with multi-energy integration and integrated complementary features. It is an effective way to solve the problems of integrated energy supply, energy efficient utilisation, and large-scale development of renewable energy [1–4]. The optimisation of the integrated energy system operation is the basis for the stable operation of integrated energy systems [5–8]. However, the existing energy-supply systems are separately planned and operated independently [9, 10], which is not conducive to the coordinated development of integrated energy systems. Therefore, to solve the multi-objective and multi-constrained non-linear optimisation operation problem, it is necessary to establish a unified optimal power flow model for the power systems, the heat systems, and the gas systems.

At present, the literature on the optimisation of integrated energy systems has involved the study of power flow models for multiple energy networks. The steady-state analysis model of the integrated energy system considering the interaction of the two systems from the perspective of energy flow is established in [11]. Considering the network operation constraints, the optimal energy flow model of the integrated energy system is proposed in [12], which provides decision-making assistance for the optimal scheduling of the system. The idea that constantly changes in natural gas loads can have a significant impact on gas network pressures of integrated energy systems which is presented in report. Based on the energy hub model, the hybrid power flow algorithm is used to analyse the interaction characteristics of each electrical-gas energy-supply network under steady state in [13].

Wind power has strong volatility and high intermittent [14]. In the case of limited power grid regulation, the wind will be dissipated and resources will be wasted [15]. Therefore, increasing the proportion of wind power access is an effective way to reduce power generation costs and solves wind power consumption in the integrated energy system [16–18]. However, in an integrated energy system, how changes in state variables affect wind power output. This problem is difficult to analyse through a system optimisation power flow model that does not fully consider the interaction of different energy-supply network states.

Relevant research has been carried out to improve wind power consumption by using the power generation side, transmission side, and usage side interaction. The load following control strategy was studied, and the relationship function between the controllable load growth rate and wind power utilisation was proposed [19]. Ai and Liu [20] researched the perspective of demand response, and studied the use of electrical equipment to improve the level of large-scale wind power consumption. Allan and Al-Shakarchi [21] proposed the evaluation method of wind power consumption capacity based on the method of random production simulation, and obtained the probability distribution of wind power consumption. The above studies can provide a theoretical basis for the wind power consumption of computing systems. However, in the face of the increasingly complex process of energy system evolution, how can an integrated energy system with a high proportion of renewable energy resources be coordinated and rationally planned to achieve large-scale grid connection of renewable energy represented by wind power, providing wind power consumption capacity. The quantitative calculation method has become an urgent problem to be solved in the field of electric energy.

A sensitivity analysis method for wind power consumption capability of integrated energy system based on unified optimal power flow is proposed in this paper, and the unified optimal power flow model is used to analyse the interaction mechanism between the power systems, the heat systems, and the gas systems. Firstly, the unified optimal power flow model of the integrated energy system is established. Based on this, the sensitivity matrix of the energy coupling unit capacity change for the wind power consumption capacity is defined. Then, the wind energy consumption capacity of the integrated energy system is analysed combined with the sensitivity index of the integrated energy system and the wind energy consumption capability in the typical energy coupling unit ratio scenario. Finally, the effectiveness of the proposed method is verified by simulation examples.
Fig. 1 Integrated energy system structure

2 Optimal power flow model for integrated energy systems

2.1 Overview of integrated energy system

The integrated energy system is a multi-form energy integrated management system that uses power system, heat system, and the gas system as energy transmission networks. Electrical energy, heat energy, and gas energy can be flexibly exchanged as energy carriers. The electric-gas-thermal integrated energy system is composed of energy management equipment, renewable energy devices, energy storage devices, energy conversion devices, and energy loads. The process of energy flow can be divided into energy input, conversion, storage, transportation, and distribution. As an energy coupling in the integrated energy system, the gas turbines convert natural gas into heat and electricity, the P2Gs convert electricity into natural gas, and the electric boiler converts electricity into heat. Therefore, the integrated energy system is a combined system of multi-energy complementary operation, and the system structure is shown in Fig. 1.

In this section, we compare the optimal power flow model of the power system and establish the optimal power flow model of heat system and gas system, including heat source, heating pipe network, heat load, gas source, gas pipeline, and gas load. The unified optimal power flow model of the integrated energy system is established using the energy flow characteristics of energy. On the one hand, it can realise multi-energy complementary synergy analysis between the power systems, the heat systems, and the gas systems. On the other hand, it lays a foundation for the subsequent safe and stable operation of the system and the analysis of renewable energy consumption capacity.

2.2 Optimum power flow model of power system

The optimal power flow model of power system reflects the relationship between node power, node voltage, and phase angle

\[
\min \Omega_e(U_e, X_e) = \sum_{i=1}^{N_e} \left[ \alpha_e(PG_i) \right]^2 + \beta_e(PG_i) + \gamma_e \]  
\]

\[
s.t. \quad g_e(U_e, X_e) = 0 \]  
\]

\[
h_e(U_e, X_e) \leq 0 \]  

where \( \Omega_e \) represents the objective function, i.e. the total cost of grid operation. \( P_{G,i} \) represents the active output of the \( i \)th thermal power unit. \( P_{RE,j} \) represents the active output of the \( j \)th wind turbine. \( \alpha_{e,i} \), \( \beta_{e,i} \), and \( \gamma_{e,i} \) represent the fuel cost factor of unit \( i \). \( \xi_{RE,j} \) represents the cost coefficient of the wind turbine \( j \). \( U_e \) and \( X_e \) represent control variables and state variables of the power system, respectively. State variables include balanced node active output, load node voltage, unit reactive output, and apparent power. The control variables include the active output of all units except the balance node, the generator node voltage, the transformer tap, and the reactive power compensation device power output.

g_e \text{ and } h_e \text{ represent the equality and inequality constraints of the power system, respectively. And the equation constraints refer to the power flow balance, such as (4) and (5). The inequality constraints refer to the generator active output (6) and (8), and the generator reactive output (7) and (9), reactive power compensation equipment output (10), transformer ratio (11), node voltage (12), and upper and lower limits of apparent power (13) constraints:}

\[
P_{G,i} + P_{RE,j} - P_{CL,i} - V_i \sum_{j=1}^{N_e} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \leq 0 \]  

\[
Q_{G,i} + Q_{RE,j} - Q_{CL,i} - V_i \sum_{j=1}^{N_e} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \leq 0 \]  

\[
P_{G,i}^\text{max} \leq P_{G,i} \leq P_{G,i}^\text{min} \quad i = 1, \ldots, N_G \]  

\[
Q_{G,i}^\text{max} \leq Q_{G,i} \leq Q_{G,i}^\text{min} \quad i = 1, \ldots, N_G \]  

\[
P_{RE,j}^\text{max} \leq P_{RE,j} \leq P_{RE,j}^\text{min} \quad j = 1, \ldots, N_{RE} \]  

\[
Q_{RE,j}^\text{max} \leq Q_{RE,j} \leq Q_{RE,j}^\text{min} \quad j = 1, \ldots, N_{RE} \]  

\[
T_i^\text{min} \leq T_i \leq T_i^\text{max} \quad i = 1, \ldots, N_T \]  

\[
V_i^\text{min} \leq V_i \leq V_i^\text{max} \quad i = 1, \ldots, N_E \]  

\[
h_i(U_b, X_b) \leq 0 \]  

2.3 Optimum power flow model of heat system

The heat network optimal power flow model reflects the relationship between flow rate and node temperature. The heat network consists of heat sources, heating pipe networks, and heat loads

\[
\min \Omega_h(U_h, X_h) = \sum_{i=1}^{N_h} \left[ \alpha_h(Q_{hi}) \right]^2 + \beta_h Q_{hi} + \gamma_h \]  

\[
s.t. \quad g_h(U_h, X_h) = 0 \]  

\[
h_h(U_h, X_h) \leq 0 \]  

where \( \Omega_h \) represents the objective function, \( i \) represents the total cost of the heating network operation, \( Q_{hi} \) represents the heat injected into the heating pipe network by the \( i \) node, and \( \alpha_h \), \( \beta_h \), \( \gamma_h \) represent the heat source cost coefficient of the \( i \) node. \( U_h \) and \( X_h \) represent the control variables and state variables of the thermal system, respectively. The state variables are the injected heat of the balance node, the heat pipe network flow, and the node heat other than the balance node. Control variables include node flow and pump head.
$g_b$ and $h_b$ represent the equations and inequality constraints of the heat network, respectively. The equation constraint refers to the simultaneous (17) of the hydraulic model, the node temperature, and the heat equation. The inequality constraint refers to the heat source injection heat constraint (18)

$$\begin{align*}
H_{c,i} + A_{H,i} &= 0 \\
Q_{h,i} &\leq - (Q_{h,i} - \Delta Q_{h,i}) \\
\Delta Q_{h,i} &= \delta T_{h,n} - T_{h,n} L_{h,i} \\
Q_{h,i}^{\text{min}} &\leq Q_{h,i} \leq Q_{h,i}^{\text{max}}
\end{align*}$$

(17)

2.4 Optimum power flow model of gas system

The gas network includes gas pipelines, gas sources, compressors, and loads, and the optimum power flow model is

$$\begin{align*}
\min \Omega_k(U_g, X_g) &= \sum_{i=1}^{N} \left[ \alpha_k(F_{g,i})^2 + \beta_k F_{g,i} + \gamma_k \right] \\
s.t. \quad g_k(U_g, X_g) &= 0 \\
&\quad h_k(U_g, X_g) \leq 0
\end{align*}$$

(19)

where $\Omega_k$ represents the objective function, i.e. the total cost of operation of the natural gas network, $F_{g,i}$ represents the amount of natural gas injected into the gas pipeline by the $i$ node, $\alpha_k$, $\beta_k$, and $\gamma_k$ represent the air cost coefficient of the $i$ node. $U_g$ and $X_g$ represent the control variables and state variables of the natural gas network, respectively. The state variables are the amount of natural gas injected by the equilibrium node, the flow of the gas pipeline, and the pressure of the node other than the equilibrium node. The control variables include the amount of natural gas injected from the gas source other than the equilibrium node and the compressor pressure ratio of the compressor.

$g_k$ and $h_k$ represent the equality and inequality constraints of the natural gas network, respectively, the equation constraint refers to the natural gas flow balance constraint (22), the inequality constraint refers to the equipment constraint (23), the gas source injection quantity constraint (24), and the compression ratio constraint (25). And node air pressure constraints (26)

$$B_{C} F_k - B_{C} v - B_{C} e - B_{l} L_k = 0$$

(22)

$$F_{k,n} \leq F_k \leq F_{k,n}$$

(23)

$$R_{n,n} \leq \max (\pi_n, \pi_i) \leq R_{n,n}$$

(24)

$$\pi_n, \pi_i \leq \pi_n, \pi_i \leq \pi_n, \pi_i$$

(25)

2.5 Unified optimal power flow model of integrated energy system

The energy coupling unit acts both as an energy supply unit and as an energy consumption unit in the integrated energy system, which can have a large impact on the system power flow distribution. The energy coupling unit is the hub for energy transfer between various systems. The capacity and spatial variation characteristics of the energy coupling unit are the key basis for the operation of the integrated energy system. Therefore, to simplify the dimension of the computational variables, when the operation process of the integrated energy system is studied, the spatial variation effect of the energy coupling unit appears as a constraint in the unified optimal power flow. The effect of the spatial variation effect is to effectively guarantee the safe and stable operating margin of the integrated energy system. Therefore, the energy coupling unit uses gas turbines, electric boilers, and electrical gas-transfer equipment as the main components, and does not consider other interactions between the energy-supply networks, and its static model is

$$\begin{align*}
P_{MT,c} + Q_{MT,h} &= c_{MT} F_{MT,g} \\
Q_{EB,h} + c_{EB} P_{EB,e} \\
F_{P,G,e} &= c_{P,G} P_{P,G,e}
\end{align*}$$

(26)

where the gas turbine intake air amount is $F_{MT,g}$, the output electric power is $P_{MT,c}$, the output heat is $Q_{MT,h}$, and the conversion efficiency is $c_{MT}$. The electric boiler consumes $P_{EB,e}$, the output heat is $Q_{EB,h}$, and the conversion efficiency is $c_{EB}$. The electric power consumption of the electric-gas conversion equipment is $P_{P,G,e}$, the output natural gas power is $F_{P,G,e}$, and the conversion efficiency is $c_{P,G}$.

The integrated energy system power flow calculation is defined as the process of obtaining the system operating point under a given set of conditions. The unified optimal power flow model is described as

$$\begin{align*}
P^r &= \text{Re}[V(V^*)] = 0 \\
Q^r &= \text{Im}[V(V^*)] = 0 \\
\Omega(U, X) &= 0 \\
\frac{P^r}{P} &= 0 \\
\frac{Q^r}{Q} &= 0 \\
\frac{L^r}{L} &= 0 \\
\frac{A^r}{A} &= 0 \\
\frac{P_{MT,c} + Q_{MT,h} c_{MT} F_{MT,g}}{P_{EB,e} + c_{EB} P_{EB,e}} \\
\frac{F_{P,G,e}}{c_{P,G} P_{P,G,e}} &= 0
\end{align*}$$

(27)

where $X$ is the state variable of the integrated energy system and $U$ is the control variable of the integrated energy system, as described above.

The unified optimal power flow model is solved by the Newton–Raphson method. The iterative form is

$$\begin{align*}
\Delta x^{(k+1)} &= x^{(k)} - \Delta x^{(k)} \\
\Delta F^{(k+1)} &= F^{(k)} - \Delta F^{(k)}
\end{align*}$$

(28)

where $\Delta F$ is the deviation of the power flow equations, $J$ is the Jacobian matrix, and $x^{(k)}$ and $\Delta x^{(k)}$ are the state variables and state variable deviations in the $k$th iteration.

3 Sensitivity analysis method for wind power consumption capacity

The operation of the integrated energy system is better for wind power consumption. Since the integrated energy system containing electric boiler, the power to gas, and gas turbine was established, the mechanism of wind power consumption is shown in Fig. 2. The electric load is subtracted from the predicted power of the wind.

Fig. 2 Mechanism of wind power consumption

Electric load of integrated energy system

Initial electrical load

Improved wind power

Wind power forecasting power

P2G

M1

t1

t2

Power/MW

Mechanism of wind power consumption

as the main components, and does not consider other interactions between the energy-supply networks, and its static model is

$$\begin{align*}
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Q_{EB,h} + c_{EB} P_{EB,e} \\
F_{P,G,e} &= c_{P,G} P_{P,G,e}
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The integrated energy system power flow calculation is defined as the process of obtaining the system operating point under a given set of conditions. The unified optimal power flow model is described as

$$\begin{align*}
P^r = \text{Re}[V(V^*)] = 0 \\
Q^r = \text{Im}[V(V^*)] = 0 \\
\Omega(U, X) = 0 \\
P^r = P \\
Q^r = Q \\
L^r = L \\
A^r = A \\
P_{MT,c} + Q_{MT,h} c_{MT} F_{MT,g} \\
Q_{EB,h} + c_{EB} P_{EB,e} \\
F_{P,G,e} = c_{P,G} P_{P,G,e}
\end{align*}$$

(27)

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power to obtain the equivalent electric load. The equivalent electric load is an important variable for power flow calculation in power system, which directly affects the safe operation margin of the power system and even the integrated energy system. Therefore, to increase the electrical load by electric boiler and power to gas equipment, and the increased capacity is shown in the shaded part of Fig. 2. At the same time, the unified optimal power flow of the integrated energy system can reflect the safe operation margin of the system, and improve the coupling degree of the power grid, the heat network, and the natural gas network. When the uncertain factors in the system increase, the stability of the system is enhanced by increasing the power of the gas turbine, which provides a basis for the calculation of the grid-connected capacity of the wind power in the integrated energy system.

The influencing factors of wind power consumption capacity in the integrated energy system are equivalent to the analysis of the changes of wind power in the energy-supply network under the optimal power flow of the integrated energy system. Therefore, the sensitivity analysis model of the integrated energy system wind power capacity is

\[
\frac{dx_{\text{RE}}}{dt} = - \left( \frac{\partial \Omega}{\partial x_{\text{RE}}} \right) \left( \frac{\partial \Omega}{\partial u} \right) \tag{29}
\]

where \(x_{\text{RE}}\) is the wind power. According to the changes of different physical quantities in different energy networks, different forms of sensitivity models for wind power consumption can be constructed.

This paper considers the ratio of the energy coupling unit capacity of the integrated energy system, which varies according to the location and investment situation. At the same time, due to the conversion of various energy forms, the electrical load, heat load, and natural gas load are changed. This situation will have an impact on the energy network trends of different energy forms. Therefore, the energy coupling unit is the main factor for the wind energy consumption capacity of the integrated energy system. The wind power is used as the state variable, and the energy coupling unit-wind power absorption sensitivity matrix \(S\) is defined as

\[
S = \frac{\partial P_{\text{RE}}}{\partial (P_{EB,e} + P_{P2G,e} + F_{MT,g})} \tag{30}
\]

where \(P_{EB,e}\) is the electric boiler capacity, \(P_{P2G,e}\) is the power to gas capacity, and \(F_{MT,g}\) is the gas turbine capacity.

The sensitivity analysis method of wind energy consumption capacity of integrated energy system is shown in Fig. 3. According to the transmission relationship of Jacobian matrix in the unified energy model of the integrated energy system, the sensitivity matrix can be solved.

### 4 Results

To verify the effectiveness of the proposed method, the modified IEEE39 node power system, 11-node natural gas system, and Bali 32-node thermal system [22, 23] are taken as examples to analyse the energy of the gas turbine, electric boiler, and P2G equipment. The system structure is shown in Fig. 4. Among them, the 5 nodes of the power system increase the 500 MW wind power capacity, and the initial wind rejection rate is set to 50%.
The technical parameters of the energy coupling unit are shown in Table 1.

The capacity selection of the energy coupling unit should be selected according to the actual situation of the project. The change can take a continuous function from the theoretical analysis point of view, but the continuous function will increase the calculation time of the algorithm and increase the abnormal point. At the same time, discrete values can improve the accuracy of a quantitative assessment of wind power consumption. Therefore, the capacity of the electric boiler and P2G is increased by 10%, respectively, and the capacity of the gas turbine is increased by 5%.

Assume that the wind power prediction curve of the system is shown in Fig. 5.

Taking the capacity increase of energy coupling unit as an example, set up a three-fold scheme: electric boiler capacity increases by 10%, P2G device and gas turbine capacity remain unchanged, P2G device capacity increases by 10%, electric boiler and gas turbine capacity remain unchanged, gas turbine capacity increased by 5%, and the electric boiler and P2G device capacity remained unchanged. The results are shown in Figs. 6–8. In the figure, the abscissa is the percentage of the energy coupling unit capacity with respect to the initial capacity increase, and the ordinate is the wind power grid-connected capacity. It can be seen from the figure that the increase of electric boiler and P2G device capacity plays a positive role in wind power consumption, and the increase of gas turbine capacity will lead to an increase in wind abandonment.

The size of the histogram in Fig. 9 indicates the sensitivity of the change of the capacity ratio of the energy coupling unit to the change of the wind power consumption capacity. The ratio of the sensitivity is arranged according to the three schemes. There are 64 cases. The sensitivity definition shows that when the electric boiler capacity increases by 50%, when the P2G device capacity increases by 30% and the gas turbine capacity increases by 10%, the integrated energy system can accept the wind power most, and the system maintains the optimal power flow state.

5 Conclusion

The sensitivity of wind energy capacity in integrated energy systems can be analysed based on the unified optimal power flow model. Owing to the unified power flow model of the power system, heat system, and gas system, the effects of different capacity ratios of energy coupling units on wind power consumption in integrated energy systems are studied. Also the
optimal operating state and capacity configuration of energy coupling units are determined. The capacity has increased relative to the initial set capacity, such as the electric boiler capacity increased by 50%, the electrical-gas transfer capacity increased by 30%, and the gas turbine capacity increased by 10%. The integrated energy system can accept the wind power most, and the system maintains the optimal power flow state under such a result. The method proposed in the paper has a certain guiding role for the operation planning of integrated energy systems.

6 References

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