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QUANTIFYING THE IMPACTS OF WINDSTORMS ON RESILIENCE OF URBAN ENERGY SYSTEMS

Minglei Bao[1], Yang Yang[1], Kexin Wang[2], Yi Ding [1*], Xiaoming Zhou[1]

1 College of Electrical Engineering, Zhejiang University, Hangzhou, China

2 Economic & Technology Research Institute of State Grid Shandong Electric Power Company, Jinan, China

ABSTRACT

Faced with ever-increasing environmental pollution and public concerns about energy security, urban energy systems (UESs) need to be constructed to improve the efficiency and reliability of energy utilization. However, due to significant impacts of extreme weather on the operation of UESs, it is important to develop a model to evaluate the resilience of UESs. In this paper, a synthetic model is proposed to quantify the impacts of windstorms on the resilience of UESs. Firstly, the optimization model of UESs under contingency states is developed to determine the generation re-dispatch and load shedding. Moreover, considering the effects of high winds, the line fragility model is utilized to calculate the unavailability of power lines according to the surrounding wind speeds. On the basis, the simulation framework for the resilience evaluation of UESs is developed utilizing Monte Carlo Simulation (MCS) technique to quantify the impacts of high winds on the UESs. Finally, the proposed methods are validated using the urban energy test systems.

Keywords: resilience; urban energy systems, High Winds, line fragility, Monte Carlo Simulation

NONMENCLATURE

Abbreviations

UESs	urban energy systems
MCS	Monte Carlo Simulation
CHP	combined heat and power plants

Symbols

i, j	subscript of nodes in electric system
m, n	subscript of nodes in gas system
l	superscript of contingency state
C_{ig}	generation cost of generator g at node i
P_{ig}^{l}	generation output of generator g at node i
C_{iL}	compensation cost of load curtailments
$\Delta P_{iL}^{l}, \Delta Q_{iL}^{l}$	active and reactive load curtailments at node
C_{ms}	production cost of gas source at node m
W_{ms}^{l}	gas production of gas source s at node m
P_{iL}^{0}, Q_{iL}^{0}	active and reactive load demand at normal state 0
θ_{i}^{l}	phase angle of voltage at node i
Y_{ij}^{l}	element of admittance matrix
V_{i}^{l}	voltage of electric node i
$V_{i}^{\min}, V_{i}^{\max}$	min/max voltage at node i
$P_{ig}^{\min}, P_{ig}^{\max}$	min/max generator output at node i
$\Delta P_{iL}^{\max}, \Delta Q_{iL}^{\max}$	max active/reactive load shedding
S_{ij}^{l}	power flow on line ij
$S_{ij}^{\max}$	limits of power flow on line ij
π_{m}^{l}	gas pressure at node m
f_{mn}^{l}	gas flow on pipeline mn
M_{mn}	constant pipeline flow coefficient
$\pi_{m}^{\min}, \pi_{m}^{\max}$	min/max gas pressure at node m
$f_{mn}^{\min}, f_{mn}^{\max}$	min/max gas flow on pipeline mn
$W_{m\mathrm{L}}^{l}$	gas load at node m
$W_{ms}^{\min}, W_{ms}^{\max}$	min/max gas production of gas source

M	number of nodes in gas system
N	number of nodes in electricity system

1. INTRODUCTION

The increasing environmental pollution and energy crisis entail the need for the construction of future low-carbon cities. As important "life floods" to low-carbon cities, urban energy systems (UESs) could provide clean, efficient and sustainable energy to guarantee the rapid development of society [1]. Through operational optimization of UESs, different energy vectors (heat, gas and electricity) could be converted efficiently to supply multi-energy to consumers.

Recently, affected by climate change (high temperatures, frequent windstorms and heavy rains), the resilient operation of UESs under severe weather can be threatened [2]. It is reported that the total annual economic loss of distribution electricity systems caused by severe weather ranges from 20 to 50 billion dollars [3]. Due to the dramatic consequences of severe weather, it is urgent to evaluate the resilience of UESs under extreme weather to guarantee the reliable provision of energy to consumers.

Resilience is defined as the ability of systems to resist the possible disturbances and recover to normal operation, which has been widely investigated in ecological, social and engineering systems [4]. In terms of power systems, numerous efforts have been paid to quantifying and modelling the impacts of severe weather on the system operation. Reference [2] proposes a conceptual framework to analyze the resilience of power systems caused by windstorms. In reference [3], the operational resilience and infrastructure resilience of power systems are investigated using time-dependent resilience metrics. In reference [4], a three-stage analysis framework is developed to investigate the change of system performance during resistive, absorptive and restorative stages. The previous researches mainly focus on the resilience evaluation of power systems, without considering the integration between different energy systems [5]. Faced with the rapid development of UESs, additional efforts need to be devoted to the resilience evaluation of UESs.

In this paper, a synthetic model is developed to evaluate the resilience of UESs induced by extreme weather. Firstly, the energy hub is modelled to describe the coupling relationship between its input energy and output energy. On the basis, the operation model of UESs under contingency states caused by component failures is proposed to determine the generation re-dispatch and load curtailments. Moreover, the fragility model of power lines under high winds is developed to characterize the relationship between line unavailability and wind speeds. Based on the fragility model of power lines, the simulation framework for resilience analysis of UESs is developed using Monte Carlo Simulation (MCS) technique. Case studies illustrate the validity of the proposed model.

2. MODEL OF URBAN ENERGY SYSTEMS

The traditional UESs consist of distribution electric system, natural gas system and energy hub, as shown in Fig.1 [1]. The UESs obtain electricity and gas from common-utilities to satisfy the multi-energy demands of consumers. The energy conversion between different energy vectors could be realized through the energy hub.

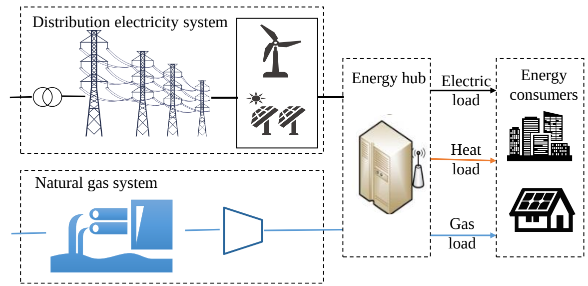

Fig 1. Description of urban energy systems.

2.1 Energy hub model

In this paper, the energy hub depicted in Fig.2 consists of a power transformer, a heat pump and combined heat and power plants (CHP) [1]. The input energy consists of electricity and gas, while the output energy consists of electricity heat. The energy hub could optimize the energy conversion between heat pump and CHP to improve system efficiency.

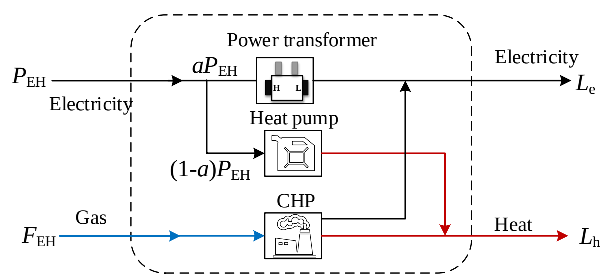

Fig 2. Structure of energy hub.

The coupling relationship between input energy and output energy could be expressed as:

$$\begin{bmatrix} L_e \\ L_h \end{bmatrix} = \begin{bmatrix} \alpha & \eta_e \\ (1-\alpha)\cdot\varphi & \eta_h \end{bmatrix} \cdot \begin{bmatrix} P_{EH} \\ F_{EH} \end{bmatrix} \quad (1)$$

where α represents the dispatch factor of electricity flow; η_e and η_h represent the electrical efficiency and thermal efficiency of CHP, respectively; φ represents heat pump efficiency; L_e and L_h represent the electricity demand and heat demand of energy hub, respectively; P_{EH} and F_{EH} represent the input electricity flow and gas flow of energy hub.

2.2 UES model under contingency states

Considering the impacts of high winds, the component failures can make the UESs deviate from its normal operation state. In order to maintain the reliable operation of UESs, measures such as load shedding or generation re-dispatch will be adopted [6, 9]. For contingency state l, the load shed and generation re-dispatched could be determined with optimization model which is described in (2)-(16). The objective function is to minimize total system cost including energy cost and load shedding cost.

$$\min \sum_{i=1}^{N}\left[C_{ig}\left(P_{ig}^{l}\right)+C_{iL}\left(\Delta P_{iL}^{l}\right)\right]+\sum_{m=1}^{M}C_{ms}(W_{ms}^{l}) \quad (2)$$

The objective function (2) is subject to the following constraints:

$$P_{ig}^{l}-\left(P_{iL}^{0}-\Delta P_{iL}^{l}\right)-P_{EH,i}^{l}=\sum_{j=1}^{N}\left|V_i^l\right|\left|V_j^l\right|\left|Y_{ij}^l\right|\cos(\theta_i^l-\theta_j^l) \quad (3)$$

$$Q_{ig}^{l}-\left(Q_{iL}^{0}-\Delta Q_{iL}^{l}\right)=\sum_{j=1}^{N}\left|V_i^l\right|\left|V_j^l\right|\left|Y_{ij}^l\right|\sin(\theta_i^l-\theta_j^l) \quad (4)$$

$$V_i^{\min}\le V_i^l\le V_i^{\max} \quad (5)$$

$$P_{ig}^{\min}\le P_{ig}^l\le P_{ig}^{\max} \quad (6)$$

$$Q_{ig}^{\min}\le Q_{ig}^l\le Q_{ig}^{\max} \quad (7)$$

$$0\le \Delta P_{iL}^l\le \Delta P_{iL}^{\max} \quad (8)$$

$$0\le \Delta Q_{iL}^l\le \Delta Q_{iL}^{\max} \quad (9)$$

$$0\le \left|S_{ij}^l\right|\le S_{ij}^{\max} \quad (10)$$

$$\begin{bmatrix} L_e \\ L_h \end{bmatrix} = \begin{bmatrix} \alpha & \eta_e \\ (1-\alpha)\cdot\varphi & \eta_h \end{bmatrix} \cdot \begin{bmatrix} P_{EH,i}^l \\ F_{EH,i}^l \end{bmatrix} \quad (11)$$

$$\operatorname{sgn}(\pi_m^l,\pi_n^l)\left(f_{mn}^l\right)^2=M_{mn}\left[\left(\pi_m^l\right)^2-\left(\pi_n^l\right)^2\right] \quad (12)$$

$$\pi_m^{\min}\le \pi_m^l\le \pi_m^{\max} \quad (13)$$

$$f_{mn}^{\min}\le f_{mn}^l\le f_{mn}^{\max} \quad (14)$$

$$W_{ms}^l-W_{m\mathrm{L}}^l-\sum_{m=1}^{M}f_{mn}^l=0 \quad (15)$$

$$W_{ms}^{\min}\le W_{ms}^l\le W_{ms}^{\max} \quad (16)$$

where Eq.(3) is active power balance equation; Eq.(4) is reactive power balance equation; Eq.(5) is bus voltage constraint of electric distribution system; Eq.(6) is active power output constraints of generators; Eq.(7) is reactive power output constraints of generators; Eq.(8) and Eq.(9) are electric load curtailment limits; Eq.(10) is power flow constraints of power lines; Eq.(11) is coupling relationship between input and output energy of energy hub; Eq.(12) is pipeline flow equation. Eq.(13) is nodal pressure constraints. Eq.(14) is gas pipeline flow constraints. Eq.(15) is nodal gas flow balance equation. Eq.(16) is gas source production constraints.

3. RESILIENCE EVALUATION OF UESS

A synthetic model can be developed to evaluate the impacts of high winds on the resilience of UESs. Considering gas pipelines are usually buried underground, only the impacts of high winds on distribution electricity system are modelled in this paper. Due to the integration between electricity distribution system and natural gas system, the failures in electricity system due to high winds can also have high impacts on the gas system. If the line failures lead to the power imbalance in the electricity system, the production of gas will be re-dispatched to adjust the power output of CHP. Therefore, although there are no component failures in natural gas system, the operation condition of gas system can also be adjusted considering the integration between different energy vectors. In this section, the modelling of line fragility and resilience evaluation of UESs to windstorms are illustrated.

3.1 Line fragility model

Considering the impacts of high winds, the fragility of power lines is closely related to their surrounding wind speeds. According to [2], the unavailability of a line is a piecewise function of wind speeds, which can be expressed as:

$$p_{ij}(v)=\begin{cases} p_{ij}^0, & \text{if } v\le v_{critical} \\ p_{ij\_v}(v), & \text{if } v_{critical}<v\le v_{collasape} \\ 1, & \text{if } v>v_{critical} \end{cases} \quad (17)$$

where $p_{ij}(v)$ denotes the unavailability of power line ij as the function of wind speed of v; p_{ij}^0 denotes the unavailability of line for good weather state; $p_{ij\_v}(v)$

denotes the linear relation between unavailability and wind speeds between $v_{critical}$ and $v_{collasape}$.

3.2 Simulation framework for resilience analysis of UESs

As illustrated in Fig.3, the process for the resilience evaluation of UESs can be divided into three steps. The first step is to initialize system parameters, including the data of distribution electricity system, gas system and energy hub.

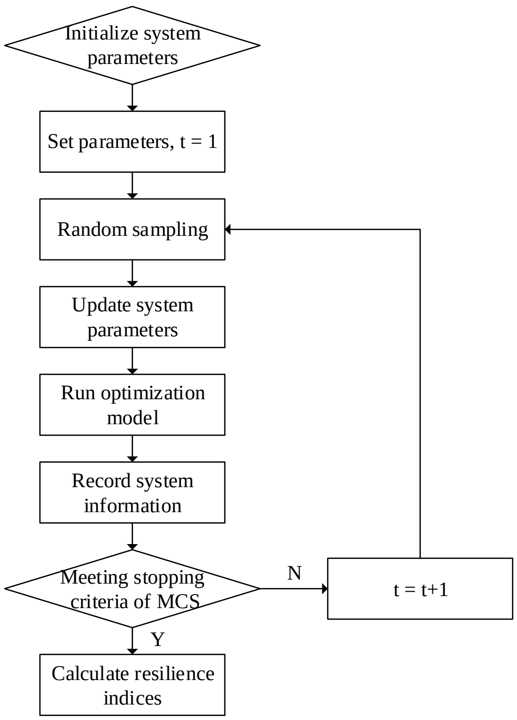

Fig 3. Simulation framework for resilience evaluation of urban energy systems

The second step is the resilience analysis of UESs using MCS technique [10, 11]. Firstly, the parameters about wind speeds in different regions are set, based on which the unavailability of power lines can be determined. According to the unavailability induced by high winds, the failure lines could be determined through random sampling. For certain failures, the optimization model in (2)-(15) can be applied to determine the load shedding and re-dispatch of generation. Repeat the previous procedures until the stopping criteria of MCS technique are satisfied.

Based on the load curtailments for each simulation time, the resilience indices of UESs can be calculated. The resilience indices of UESs are defined as the amount of electric load demand which are still connected after high winds, which can be expressed as:

$$W_{ms}^{\min} \leq W_{ms}^{l} \leq W_{ms}^{\max} \quad (18)$$

where t and T represent the simulation time and the total sampling number of MCS technique.

4. CASE STUDIES AND DISCUSSIONS

The test system in this paper is composed of IEEE 33-node distribution system and the modified 7-node gas system. The network topology and the parameters of test system can be found in [1]. The distribution energy resources in electricity system are assumed to be storage devices. The electrical efficiency and thermal efficiency of CHP are assumed to be 0.4 and 0.45 [7]. The heat pump efficiency is assumed to be 3 [8]. The line fragility curve is determined according to [3], which is shown in Fig.4. In order to evaluate the impacts of windstorms on the resilience of UESs, three cases with different winds speeds are analyzed, including 31m/s, 33m/s, 36m/s and 40m/s wind speeds. Moreover, the resilience of UESs under different wind speeds are compared with that of IEEE 33-node distribution system. The simulation results are given in Fig.5.

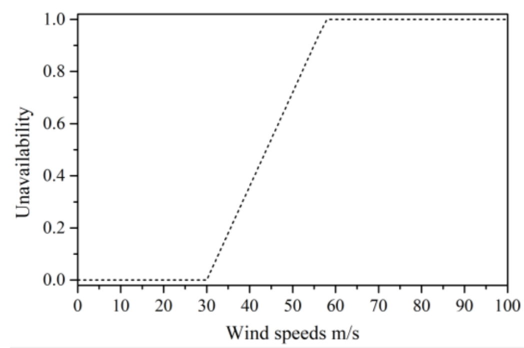

Fig 4. Relationship between unavailability of lines and winds speeds

It can be noted from Fig.5 that the increase of wind speeds can reduce the resilience of UESs. This is mainly because that the more power lines will be attacked with the increase of wind speeds and more electric load will be cut for the reliable operation of UESs. The resilience of UESs is for 31m/s, 33m/s, 36m/s and 40m/s wind speeds, respectively. Besides, it can be noted that UESs are more resilient than distribution electricity system for the same wind speeds. This is mainly because that the gas system can provide electricity to distribution electricity system through CHP for contingency states.

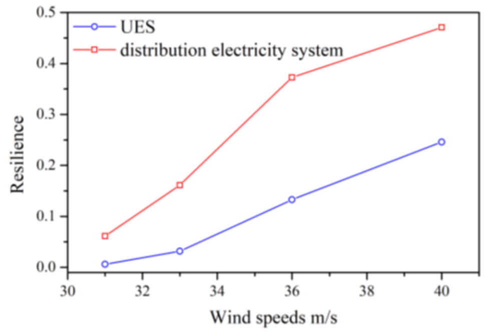

Fig 5. Simulation results of UESs and distribution electricity system for different wind speeds

5. CONCLUSIONS

This paper proposes a synthetic model to quantify the impacts of windstorms on the resilience of UESs. Firstly, the operation model of UESs under contingency states is proposed to determine the generation re-dispatch and load curtailments. Moreover, the simulation framework for resilience analysis of UESs is developed using MCS technique. The simulation results show that the increase of wind speeds can reduce the resilience of UESs. Besides, the UESs can be more resilient to windstorms than distribution electricity system due to the support of gas system for contingency states.

The studies in this paper mainly focus on the impacts of windstorms on the resilience of UESs composed of power, gas and heat systems. In the future work, the resilience of different energy systems (e.g. water system) under different extreme weather (e.g. earthquake) can be evaluated.

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