Coordinated Scheduling of District Integrated Energy System for Enhancing Resilience in Extreme Events

S X Qi¹, X L Wang¹, Q Peng² and C Z Zhu³

¹ School of Electrical Engineering, Xi’an Jiaotong University, No.28, Xianning West Road, Xi’an, Shaanxi, P.R. China
² School of Electrical Engineering, Dalian University of Technology, No.2 Linggong Road, Dalian, Liaoning, P.R. China
³ State Grid Zhejiang Electric Power Company. No. 8, Huanglong Road, Hangzhou, Zhejiang, P.R. China

Email: qishixiong@stu.xjtu.edu.cn

Abstract. In this paper, a coordinated scheduling model is proposed, which provides resilience enhancement for the district integrated energy system (DIES) against extreme events. The innovation of this model is to divide scheduling into three stages. In the normal scheduling, the objective is to minimize the operation costs until a disaster alert occurs. In the proactive scheduling, the objective is to maximize the stored energy for supplying post-disaster load demand. In the resilient scheduling, the objective is to minimize the amount of load shedding. Moreover, the time of disaster alert, disaster disruption and system recovery are uncertain. Hence, according to the intensity of disasters, the results of the proposed coordinated scheduling are analysed by three disaster scenarios. The scheduling is established by optimizing the model, which is transformed into a mixed integer linear programming. Finally, it is verified that the coordinated scheduling model proposed can effectively enhance resilience of DIES by case studies.

1. Introduction

Presently, most electricity distribution systems are designed and maintained for normal operation conditions, which cannot withstand disruptions caused by extreme events [1]. For example, in 2012, Hurricane Sandy hit the eastern shore of the United States and approximately 7.5 million customers suffered from power outages across 15 states and Washington D.C [2]. Moreover, the interaction between electricity distribution system, natural gas distribution system and district heating system is intensified based on energy hub (EH) [3]. Hence, energy industry has been more focusing on the district integrated energy system (DIES), which can maintain the loads across a small area in island mode by utilizing local distributed generators (DGs) and energy storages (ESs). The DIES is a viable solution to address the challenge of energy system resilience, when the extreme events break out. For example, the Great East Japan Earthquake caused great damage to power grid in March 2011, but the Sendai microgrid succeed to supply power to unserved loads by DGs and ESs [4]. From the above, the objective of this paper is to propose a coordinated scheduling, which can efficiently improve the energy resilience after extreme events.

The concept of resilience is different from that of reliability. The reliability evaluation focuses on high-probability and low-impact events, while the resilience analysis focuses on low-probability and
high-impact events. In the literature, at least dozens of definitions for resilience can be found in different references [5]. Although the definitions of resilience are different, the connotation is basically the same. The resilience can be described as the ability to anticipate, withstand, absorb and recover quickly from disruptions caused by extreme natural catastrophes such as earthquakes, hurricane and flooding [6]. As mentioned above, the DGs and ESs in the microgrids (MGs) are the efficient back-up resources. The study in [7] proposed a smart self-healing optimization strategy, which considers several factors, including the available power supply, system configuration and load management. What’s more, the MGs are managed by supporting and interchanging electricity with each other in the proposed infrastructure of the networked MGs [8]. The study in [9] presented mesh grid approach for analysing the resilience, and the result showed that MGs can improve the distribution system resilience.

The DIES is an extension of the MG, which is coupled with other energy types, such as natural gas, heat and cool. In terms of resilience, the transmission lines in power system are exposed to natural disasters, so they are quite vulnerable. However, the pipelines in natural gas system are generally underground, so they are unaffected by natural disasters, especially the surface natural disasters. Hence, it is necessary to study how to improve the resilience of the DIES. In [10], because the overhead power grid can be hardened by replacing segments of electric power grid with underground natural gas pipelines, the integrated planning is proposed for improving the power grid resilience. The study in [11] presented an approach to determine and reinforce the vulnerable components in the electricity and natural gas networks of island MG to enhance resilience against deliberate disruption. The objective of this paper is to propose a coordinated scheduling for enhancing DIES resilience in extreme events, which is divided into three operation modes.

The reminder of this paper is organized as follows: Section 2 describes the characteristics and problems of coordinated scheduling in DIES and formulates the optimization model of coordinated scheduling, which is a mixed integer linear programming (MILP). Section 3 provides numerical results to validate the effectiveness of improving resilience of the proposed coordinated scheduling. Section 4 concludes this paper.

2. Model Formulation

As noted earlier, a resilient DIES should be able to properly cope with low probability and high impact disturbances. It can be described from anticipation, absorption and restoration. Hence, the operation of DIES is divided into normal operation mode, proactive operation mode and resilient operation mode.

In the normal operation mode, the source is from purchased energy, which supplies the power loads, natural gas loads and heat loads. What’s more, ESs are charged or discharged to meet the needs of consumers. The normal operation model is formulated by:

Objective function:

\[
C^{\text{nor}} = \min \sum_{t=1}^{T} \left( C_{t}^{\text{nor}} + C_{t}^{\text{sto}} + C_{t}^{w} + C_{t}^{\text{shed}} \right)
\]  

Subject to:

\[
P_{t}^{i} + P_{t}^{w} + \sum_{i \in G^{\text{CHP}}} P_{t}^{\text{CHP}} = \sum_{i \in G^{\text{CHP}}} P_{t}^{\text{CHP}} + P_{t}^{\text{st}} + \sum_{i \in G^{\text{CHP}}} P_{t}^{\text{CHP}} - P_{t}^{\text{shed}} \quad \forall t
\]

\[
P_{t}^{f} + F_{t}^{\text{out}} + \sum_{i \in G^{\text{CHP}}} F_{t}^{\text{CHP}} = F_{t}^{\text{in}} + \sum_{i \in G^{\text{CHP}}} F_{t}^{\text{CHP}} + \sum_{i \in G^{\text{CHP}}} F_{t}^{\text{CHP}} - F_{t}^{\text{shed}} \quad \forall t
\]

\[
\sum_{i \in G^{\text{CHP}}} Q_{t}^{\text{CHP}} + \sum_{i \in G^{\text{CHP}}} Q_{t}^{\text{CHP}} + \sum_{i \in G^{\text{CHP}}} Q_{t}^{\text{CHP}} + \sum_{i \in G^{\text{CHP}}} Q_{t}^{\text{CHP}} = Q_{t}^{d} + \sum_{i \in G^{\text{CHP}}} Q_{t}^{\text{CHP}} - Q_{t}^{\text{shed}} \quad \forall t
\]
\[0 \leq P_i^t \leq \bar{P}_i^t \quad \forall t \]  
\[0 \leq F_i^t \leq \bar{F}_i^t \quad \forall t \]  
\[F_{\text{CHP}} = \psi_i \eta_i^\text{CHP} F_{\text{CHP}} \quad \forall i, \forall t \]  
\[Q_{\text{CHP}} = (1-\psi_i) \eta_i^\text{CHP} F_{\text{CHP}} \quad \forall i, \forall t \]  
\[0 \leq P_{\text{CHP}}^t \leq \bar{P}_{\text{CHP}} \quad \forall i, \forall t \]  
\[-\Delta L_{\text{CHP}} \leq P_{\text{CHP}}^t - P_{\text{CHP}}^t \leq \Delta \bar{P}_{\text{CHP}} \quad \forall i, \forall t \]  
\[Q_{\text{pump}}^t = \eta_{\text{pump}} P_{\text{pump}}^t \quad \forall i, \forall t \]  
\[0 \leq Q_{\text{pump}}^t \leq \bar{Q}_{\text{pump}}^t \quad \forall i, \forall t \]  
\[-\Delta L_{\text{pump}} \leq Q_{\text{pump}}^t - Q_{\text{pump}}^t \leq \Delta \bar{Q}_{\text{pump}} \quad \forall i, \forall t \]  
\[Q_{\text{boiler}}^t = \eta_{\text{boiler}} P_{\text{boiler}}^t \quad \forall i, \forall t \]  
\[0 \leq Q_{\text{boiler}}^t \leq \bar{Q}_{\text{boiler}} \quad \forall i, \forall t \]  
\[-\Delta L_{\text{boiler}} \leq Q_{\text{boiler}}^t - Q_{\text{boiler}}^t \leq \Delta \bar{Q}_{\text{boiler}} \quad \forall i, \forall t \]  
\[E_{x,1} = E_{x}^t + X_{\text{in}}^t \eta_{\text{in}}^t \Delta t - \frac{X_{\text{out}}^t - \Delta t}{\eta_{\text{out}}^t} \quad \forall i, \forall t \]  
\[0 \leq E_{x,1} \leq \bar{E}_{x}^t \quad \forall i, \forall t \]  
\[0 \leq X_{\text{in}}^t \leq \beta_i \bar{X}_{\text{in}}^t \quad \forall i, \forall t \]  
\[0 \leq X_{\text{out}}^t \leq (1-\beta_i) \bar{X}_{\text{out}}^t \quad \forall i, \forall t \]  
\[E_{x,0} = E_{x}^t \]  
\[0 \leq P_{w}^t \leq \bar{P}_{w}^t \quad \forall t \]  
\[P_{w,e} = \bar{P}_{w}^t - P_{w}^t \quad \forall t \]  
\[0 \leq P_{\text{shed}} \leq P_{r}^t \quad \forall t \]  
\[0 \leq F_{\text{shed}} \leq F_{r}^d \quad \forall t \]  
\[0 \leq Q_{\text{shed}} \leq Q_{r}^d \quad \forall t \]  

The objective of the scheduling is to minimize the operation costs $C^{\text{out}}$ including energy purchasing cost $C_{i}^t$, storage device operation cost $C_{i}^{\text{sto}}$, wind curtailment cost $C_{i}^{w}$ and load shedding cost $C_{i}^{\text{shed}}$. Where $P_{w}^t$ and $F_{w}^t$ are purchased electricity and gas; $\lambda_{i}^t$ and $\gamma_{i}^t$ are electricity price and gas price, respectively; $G^b$, $G^g$ and $G^s$ are sets of batteries, gas storages and heat storages; $P_{\text{in}}^t$, $P_{\text{out}}^t$, $F_{\text{in}}^t$, $F_{\text{out}}^t$, $Q_{\text{in}}^t$ and $Q_{\text{out}}^t$ are amount of charge and discharge of storage devices; $\lambda_{i}^{b,\text{in}}$, $\lambda_{i}^{b,\text{out}}$, $\lambda_{i}^{g,\text{in}}$, $\lambda_{i}^{g,\text{out}}$, $\lambda_{i}^{h,\text{in}}$ and $\lambda_{i}^{h,\text{out}}$ are operation cost of storage devices; $P_{w,c}$ is power of wind abandonment; $\pi_{w}$ is cost coefficient of wind abandonment; $P_{r}^t$, $F_{r}^d$ and $Q_{r}^d$ are load shedding of power, gas and heat, respectively; $\gamma_{i}^t$, $\gamma_{i}^t$ and $\gamma_{i}^t$ are cost coefficients of load shedding.

Where constraints (6)-(8) are energy balance constraints; constraints (9)-(10) restrict purchased energy; constraints (11)-(20) describes operation of CHP units, pumps and boilers; constraints (11)-(12), (15), (18) are energy conversion constraints, constraints (13), (16), (19) enforce the upper output limits of CHP units, pumps and boilers; constraints (14), (17), (20) limit ramp-up and ramp-down of CHP units, pumps and boilers; constraints (21) show the temporal continuity of ESs; constraints (22) refer to storage capacity limit; constraints (23)-(24) guarantee the states of charge and discharge are at a different time; constraints (25) guarantee balance of charge and discharge; constraints (26) limit output of wind power; constraints (27) show wind curtailment; constraints (28)-(29) limit the load shedding amount.
Where $P^d$, $F^d$ and $Q^d$ are power loads, gas loads and heat loads; $G^{\text{CHP}}$, $G^{\text{boiler}}$ and $G^{\text{pump}}$ are sets of combined heat and power (CHP) units, boilers and pumps; $P^\text{\text{CHP}}$, $Q^\text{\text{CHP}}$, $Q^\text{\text{boiler}}$ and $Q^\text{\text{pump}}$ are outputs of CHP units, boilers and pumps; $F^\text{\text{CHP}}$, $F^\text{\text{boiler}}$ and $F^\text{\text{pump}}$ are gas consumption of CHP units and boilers and power consumption of pumps, respectively; $\bar{P}^i$ and $\bar{F}^i$ are maximum purchased energy; $\delta_i$ is ratio coefficient of electricity and heat; $\eta^{\text{\text{CHP}}}$, $\eta^{\text{\text{boiler}}}$ and $\eta^{\text{\text{pump}}}$ are efficiency of energy conversion; $\bar{Q}^\text{\text{CHP}}$ and $\bar{Q}^\text{\text{boiler}}$ are maximum outputs of CHP units, pumps and boilers; $\Delta P^\text{\text{CHP}}$, $\Delta Q^\text{\text{boiler}}$, $\Delta P^\text{\text{pump}}$ and $\Delta Q^\text{\text{pump}}$ are maximum ramp-up and ramp-down of CHP units, pumps and boilers; $E_i^\text{in}$ is amount of ESs; $\eta^{\text{\text{in}}}$ and $\eta^{\text{\text{out}}}$ are efficiency of charge and discharge; $X_i^\text{in}$ and $X_i^\text{out}$ are charge and discharge power of ESs; $\bar{E}_i^\text{in}$ and $\bar{E}_i^\text{out}$ are maximum and discharge power; $\bar{E}_i^\text{a}$ is storage capacity; $\beta_i^a$ is a binary variable, which guarantees the states of charge and discharge are at a different time; $x$ represents type of energy, including electricity, gas and heat; $\bar{P}_i^a$ is maximum output of wind generator.

Assume that disaster alert is received at time $T_1$. After $T_1$, DIES will enter the proactive operation mode. In this mode, the source is from purchased energy, not only to supply the power loads, natural gas loads and heat loads, but also to charge ESs as much as possible. The proactive operation model is formulated by:

Objective function:

$$C^{\text{pro}} = \min \sum_{t=1}^{T} \left( C_i^e + C_i^{\text{sto}} + C_i^w + C_i^{\text{shed}} + C_i^{\text{emp}} \right)$$

(31)

$$C_i^{\text{emp}} = \pi^b (\bar{E}_i^\text{in} - E_i^\text{in}) + \pi^\delta (\bar{E}_i^\text{out} - E_i^\text{out}) + \pi^b (\bar{E}_i^\text{in} - E_i^\text{in})$$

(32)

Subject to:

Constraints (6)-(24), (26)-(30).

Where $\pi^b$, $\pi^\delta$ and $\pi^b$ are penalty coefficients of unused storage amount. In the case where purchased energy is allowed, whether ESs can be filled depends on the actual occurrence time $T_2$ of disaster. When disaster occurs at time $T_2$, the purchased energy will be limited. Hence, DIES has to optimize the stored energy in the proactive operation mode so that load shedding can be reduced as much as possible. The resilient operation model is formulated by:

Objective function:

$$C^{\text{res}} = \min \sum_{t=1}^{T} \left( C_i^{\text{sto}} + C_i^w + C_i^{\text{shed}} \right)$$

(33)

Subject to:

$$0 \leq P_i^\text{in} \leq \epsilon_i^e \bar{P}_i^a \quad \forall t$$

(34)

$$0 \leq F_i^\text{in} \leq \epsilon_i^e \bar{F}_i^a \quad \forall t$$

(35)

Constraints (6)-(8), (11)-(24), (26)-(30).

Where $\epsilon_i^e$ and $\epsilon_i^\delta$ are recovery coefficients of electrical power system and natural gas system. The recovery coefficients are between 0-1. It is worth mentioning that the cost coefficients of load shedding ($\pi^b$, $\pi^\delta$, $\pi^b$) will gradually decrease with the increase of scheduling period, which encourages to supply load in the first few periods after disaster, thus avoiding multiple solutions. The reason for setting cost coefficients of load shedding is that the failures of power distribution network and gas distribution network are being gradually repaired. According to the intensity of disasters, if the distribution network has been repaired and purchased energy has been allowed before the stored energy is exhausted, load shedding will be avoided.

The proposed coordinated scheduling model of DIES is a MILP, which can be solved by commercial optimization solver, such as Cplex and Gurobi.
3. Numerical Results

In this section, three scenarios in which integrated energy system is damaged by disaster are simulated. On this basis, the proposed coordinated scheduling model is examined on a DIES in mild, moderate, severe damage scenarios, respectively. Through different disaster scenarios, the enhancement effect on DIES resilience of the scheduling model proposed is analysed.

In case studies, the DIES includes two CHP units, two pumps, one boiler, two batteries, one gas storage and one heat storage. What’s more, the scheduling horizon is set to be 24 hours. It is assumed that the controller of DIES receives a disaster alert at the 5th hour, and the disaster attacks the DIES at 15th. Based on this assumption, normal operation, proactive operation and resilient operation cover 4 hours, 10 hours and 10 hours, respectively. The purchased energy in different scenarios is shown in figure 1.

As shown in figure 1, the 1 to 4 hours is during the normal operation and the purchased energy matches load demand. Next, the 5 to 14 hours is during the proactive operation, in which the purchased energy is extremely increased for load demand and ESs. And then, the 15 to 24 hours is the resilient operation. In the mild scenario and moderate scenario, the purchased energy is gradually allowed to a larger extent. However, it is totally limited in the severe scenario. Whether the purchased energy is allowed to be related to whether load is supplied. The load supply is shown in figure 2, figure 3 and figure 4.

![Figure 1. The purchased energy in different scenarios](image1)

![Figure 2. The load supply in mild scenario](image2)

![Figure 3. The load supply in moderate scenario](image3)
It is worth explaining that the power load curves and gas load curves are various in different scenarios, which is caused by electricity-gas-heat coupling equipment. For example, although matching the same heat load curve, it is possible that CHP units and boilers consume natural gas to generate heat, or pumps consumes electric power to generate heat.

As shown in figure 2, since the purchased energy is gradually allowed after 17th hour, the stored energy during the proactive operation is sufficient to support the load after disaster, achieving the goal of withstanding disaster without load shedding, and improving the resilience of DIES. However, as shown in figure 3, the purchased energy is not allowed until 20th hour, so part of gas loads and heat loads has to be out of supply in the 19th to 22nd hours. In this paper, when the stored energy is insufficient, the supply for gas load and heat load can be terminated, while power load needs to be supplied as much as possible. Furthermore, when the stored energy is exhausted in severe scenario, DIES has to lose load more seriously in figure 4. In conclusion, it can effectively avoid load shedding in mild disaster scenario. However, as the degree of natural disasters deepens, it will inevitably lose load.

In order to verify that coordinated scheduling model proposed can effectively enhance the resilience of DIES, this paper compares the operation without proactive stage. We choose the severe scenario, and the total power load shedding, gas load shedding and heat load shedding are 18.26MW, 74.17kcf/h and 20.20MBtu/h in the original DIES. However, in figure 4, the total load shedding is 4.26MW, 72.55kcf/h and 4.83MBtu/h, respectively, where we can see a significant decline both in power load and heat load with a gentle drop in gas load. This shows that coordinated scheduling model proposed can improve the resilience of DIES.

4. Conclusion
This paper studies the resilience of DIES. A coordinated scheduling model is proposed, which can enhance resilience of DIES against extreme events. This model is divided into three steps of scheduling, which can all be converted into mixed integer linear programming. They correspond to three operation modes of DIES: the normal operation, the proactive operation and the resilient operation. Actually, it is essentially a method of scheduling ESs in advance to prepare sufficient energy for avoiding load shedding as much as possible after disasters. The case studies show that coordinated scheduling model proposed can effectively alleviate load shedding in different intensity of disaster scenario and provide resilience enhancement for DIES greatly.

5. References
[1] S. S. Ma, L. Su, Z. Y. Wang, F. Qiu, and G. Guo, “Resilience Enhancement of Distribution Grids Against Extreme Weather Events,” IEEE Trans on Power Systems, vol. 33, no.5, pp. 4842-4853, Sep. 2018.
[2] L. Che, M. Khodayar, and M. Shahidehpour, “Only connect: Microgrids for distribution system restoration,” IEEE Power Energy Mag., vol. 12, no.1, pp. 70-81, Jan.-Feb. 2014.
[3] M. Geidl, G. Koeppel, P. Favre-Peerod, B. KLöckl, G. Andersson, and K. Fröhlich, “Energy hubs for the future,” IEEE Power Energy Mag., vol. 5, no. 1, pp. 2130, Jan.-Feb. 2007.
[4] C. Marnay, H. Aki, K. Hirose, A. Kwasinski, S. Ogura, and T. Shinji, “Japan’s pivot to resilience: how two microgrids fared after the 2011 Earthquake”, *IEEE Power Energy Mag.*, vol. 13, no. 3, pp. 44-57, May-Jun. 2015.

[5] M. Zare-Bahramabadi, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, “Resilience-based framework for switch placement problem in power distribution systems,” *IET Generation, Transmission & Distribution*, vol. 12, no. 5, pp. 1229230, Jan. 2018.

[6] A. Gholami, F. Aminifar, and M. Shahidehpour, “Front lines against the darkness enhancing the resilience of the electricity grid through microgrid facilities,” *IEEE Electrification Magazine*, vol. 4, no. 1, pp. 1274, Mar. 2016.

[7] M. A. Owaifeer, and M. Al-Muhaini, “MILP-based technique for smart self-healing grids,” *IET Generation, Transmission & Distribution*, vol. 12, no. 10, pp. 23022316, Apr. 2018.

[8] Z. Y. Wang, B. Chen, J. H. Wang, and C. Chen, “Networked microgrids for self-healing power systems,” *IEEE Trans. on Smart Grid*, vol. 7, no. 1, pp. 310-319, Jan. 2016.

[9] X. D. Liu, M. Shahidehpour, Z. Y. Li, X. Liu, Y. J. Cao, and Z. H. Bie, “Microgrids for enhancing the power grid resilience in extreme conditions,” *IEEE Trans. on Smart Grid*, vol. 8, no. 2, pp. 589-597, Mar. 2017.

[10] C. C. Shao, M. Shahidehpour, X. F. Wang, X. L. Wang, and B. Y. Wang, “Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience,” *IEEE Trans on Power Systems*, vol. 32, no. 6, pp. 4418-4429, Nov. 2017.

[11] S. MANSHAVDI, and M. KHODAYAR, “Preventive reinforcement under uncertainty for islanded microgrids with electricity and natural gas networks,” *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 6, pp. 1229233, Nov. 2018.

**Acknowledgments**

This work is supported in part by Science and Technology Foundation of SGCC (Research on Morphologies and Pathways of Future Power System)