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Cost-effective and Resilient Operation of Distribution Grids and 5G Telecommunication

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***Abstract*—5G base stations have growing importance in an integrated electric power and telecommunication system, for mobile user equipment mobile data supply and demand response in distribution grids. However, demand response through base station's flexibility can have a growing impact on the power flow of the grid. Additionally, in extreme events, if a power outage occurs at the physical base station, data loads need to be first reconnected to the 5G network, which is essential for the grid to further recover the electricity loads. In this paper, a cost-effective and resilient operation method is proposed to optimally utilize the flexibility of renewable-based 5G base stations and the data load shedding to recover the data transmission. The flexibility from batteries equipped in the base stations and the flexible associations between user equipments and base stations are considered. The simulation results verify the proposed method can achieve lower energy costs and power losses of the grid in normal operation and a resilient operation in an extreme event.**

***Index Terms*—distribution grids, fifth-generation (5G) mobile technology, flexibility, resilience**

I. Introduction

With the evolution of fully duplex digital technology and it's potential in power systems from consumers to sources along with high-speed information and communication technology (ICT), electric power and telecommunication systems are becoming more strongly integrated. This is especially in area of power system protection, control and information sharing which require mobile networks. Flexibility from demand response, adjusting the power consumption applied via ICT has been studied to provide frequency regulation service [1], to minimize EV charging costs [2], to support congestion management in distribution grids [3] and to enhance the grid resilience [4].

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5G (5th generation) mobile technology is developing rapidly and is characterized by its simultaneous, multiple vertical applications, low latency, high data rates, high traffic capacity and improved quality of service (QoS) [5]. Due to the increasing need for data transmission, 5G base stations (BSs) have high power consumption, which have a large potential of providing flexibility to distribution grids. For example, renewable-supported and based 5G BSs equipped with photovoltaic (PV) panels and batteries have been investigated to reduce their operational costs considering variable electricity prices in [6]. The optimal sharing of renewable energy and batteries among grid-connected BSs is studied in [7] to save energy costs. The network topology is optimized by changing the cell size of BSs to reduce the energy consumption [8]. In addition, the flexible mobile user equipment (UE) associations with BSs are modeled in [9] to adapt power consumption to minimize the energy cost. However, the impact of the BSs' operation on distribution grids has not been investigated in [6]–[9]. Such impact on existing distribution grids can lead to power flow congestion, large voltage drops, and high operational cost issues of the distribution grids. Therefore, the power flow study considering the electricity load of BSs is essential for the grid.

Furthermore, the data load of mobile UEs and the electricity load of 5G BSs are interconnected. The 5G massive MIMO (multiple-input multiple-output) technology can adapt the number of antennas to optimize the energy efficiency and data rates when serving UEs with large variations of data load [10], [11]. However, system operation in an extreme event where the power supply to the BSs suffers an outage leading to the loss of existing telecommunication link, has not yet been studied. In such a situation, the remaining BSs have to increase their data coverage areas, and the data load shedding becomes essential to maintain a secure operation of the distribution grid. A resilient system operation strategy is important to recover the data transmission for control signals

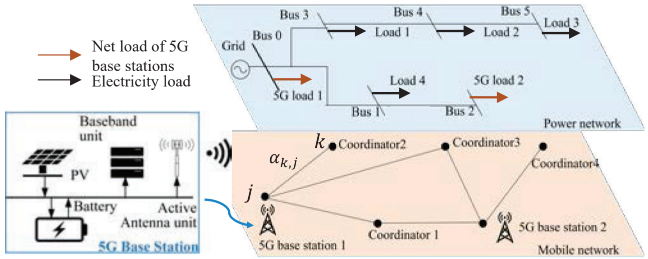

Fig. 1: Integrated distribution grid and mobile network

in the grid and to recover the electricity load. Such a strategy should minimize the operational cost of the BSs considering the penalty cost of data load shedding, by optimizing the associations between UEs and the BSs. The contributions of the study can be summarized as follows:

1) A cost-effective operation approach of an integrated power and telecommunication system is proposed to optimize the operational cost. Demand response from 5G BSs as flexibility is modeled in the proposed approach.
2) A resilient operation approach of the system is proposed to minimize the penalty from the loss of load under extreme events. The lost telecommunication link is recovered by expanding the coverage area of BSs and optimal data load shedding.

The rest of this paper is organized as follows. In Section II, the operation framework of an integrated power and telecommunication system is introduced. In Section III, the mathematical formulation is described. In Section IV, the case study is simulated to validate the proposed method. The conclusion and future work are presented in Section V.

II. Cost-effective and Resilient Operation of Integrated Power and Telecommunication System

An integrated power and telecommunication system is shown in Fig. 1, where the distribution grid and mobile network are coupled by 5G BSs. The 5G BSs consume electricity to operate the 5G radio access network (RAN). The renewable-based 5G BSs are equipped with PVs, batteries, baseband units (BBUs) for baseband digital signal processing, and active antenna units (AAUs) to convert the digital signal to analog signal and to modulate it to be transmitted by antennas. The BSs are integrated into distribution electricity grids and seen as the net load of the grid.

Furthermore, the 5G RAN provides data and control plane to UEs such as mobile phones, energy smart meters, potentially to UEs and distribution system operators. We assume the coordinator as a collection of UEs served under the same BS and consumes data from the same BS. Moreover, the 5G BSs coverage areas are designed to be overlapped for secure data transmission. Thus, the coordinators in the overlapped area can be associated with one of those BSs, such as coordinators 1 and 3 that are covered by both BSs 1 and 2 in Fig. 1. Such flexible associations are allocated by the BSs. The BSs have to provide adequate data transmission rates to ensure the expected QoS for UEs and ensure the cost-effective and secure operation of the distribution grid.

The flexible association $\alpha_{k,j}$ between the coordinator k and BS j enables the power consumption adaptation of the BSs. In addition, the batteries equipped in renewable-based BSs can provide extra flexibility to the distribution grid, contributing to the more cost-effective operation of the distribution grid. In an extreme event where the power supply of BSs suffers short or longer term outages, the data links to coordinators may be lost. Those links can be recovered by the remaining BSs expanding their coverage areas to provide data links to coordinators' lost associations with BSs. However, the increased power consumption of the remaining BSs imposes an additional electricity load on the distribution grid. Limited by the impact on the grid and the power consumption of BSs, the data load shedding is essential to satisfy the QoS of data loads partly. Therefore, the flexibility of the telecommunication system should also contribute to the resilient operation of the distribution grid.

III. Mathematical Formulation

The mathematical model of the proposed flexible and resilient operation method of the integrated power and telecommunication system is formulated here. The physical constraints of BBUs and AAUs are neglected for simplicity. The sleep mode of BSs is ignored to save the computational time.

A. Normal operation

In the normal operation mode without contingencies, the proposed cost-effective operation method is expressed in the optimization problem (1). $\boldsymbol{X} = \{\boldsymbol{K}, \boldsymbol{M}, \boldsymbol{P}, \boldsymbol{E}, \boldsymbol{v}, \boldsymbol{l}, \boldsymbol{R}, \boldsymbol{\alpha}\}$ is the set of decision variables in the normal operation problem, where $\boldsymbol{P}$ represents the vector of power consumption/generation/flow in the distribution grid; $\boldsymbol{E}$ is the vector of energy storage status of the batteries; $\boldsymbol{K}$ is the vector of the number of coordinators associated with BSs; $\boldsymbol{M}$ is the vector of the number of antennas of BSs; $\boldsymbol{v}$ and $\boldsymbol{l}$ are vectors of squared voltage and current magnitudes; $\boldsymbol{R}$ is the vector of data downlink rates of the coordinators; $\boldsymbol{\alpha}$ is the vector of associations between coordinators and BSs.

$$\min_{\boldsymbol{X}} \sum_{t\in\mathcal{T}} \lambda_t P_{\text{ref},t} \tag{1a}$$

$$\text{s.t. } P_{\text{BS},j,t} = \frac{P_{\text{tran},j,t}}{\eta} + \text{C}_{\text{N}} M_{j,t} + \text{C}_{\text{K}} K_{j,t} + \text{C}_0 \tag{1b}$$

$$0 \le P_{\text{BS},j,t} \le \overline{P}_{\text{BS},j} \tag{1c}$$

$$E_{j,t} = E_{j,t-1} + \eta_c P_{\text{ch},j,t} - \frac{P_{\text{dis},j,t}}{\eta_d} \tag{1d}$$

$$E_{j,\text{T}} = E_{j,t_0} \tag{1e}$$

$$0 \le E_{j,t} \le \overline{E} \tag{1f}$$

$$0 \le P_{\text{ch},j,t} \le \overline{P}_{\text{ch}} \beta_{\text{ch},j,t} \tag{1g}$$

$$0 \le P_{\text{dis},j,t} \le \overline{P}_{\text{dis}} \beta_{\text{dis},j,t} \tag{1h}$$

$$\beta_{\text{ch},j,t} + \beta_{\text{dis},j,t} = 1, \qquad \beta_{\text{ch},j,t}, \beta_{\text{dis},j,t} \in \{0,1\} \tag{1i}$$

$$r_{k,j,t} = \text{B}(1 - \frac{K}{T_c}) \log_2(1 + SNR_{k,j,t}) \tag{1j}$$

$$R_{k,t} = \sum_{j\in\mathcal{J}} r_{k,j,t} \cdot \alpha_{k,j,t} \tag{1k}$$

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$$\mathrm{R}_{\mathrm{req},k,t} \leq R_{k,t} \quad (1l)$$

$$\sum_{j\in\mathcal{J}} \alpha_{k,j,t} = 1, \quad \alpha_{k,j,t} \in \{0,1\} \quad (1m)$$

$$SNR_{k,j,t} = \frac{P_{\text{tran},j,t}G_{k,j}}{\sigma_k^2} \quad (1n)$$

$$G_{k,j} = \mathrm{A}(\frac{d_{k,j}}{d_0})^{-\mu} \quad (1o)$$

$$a + bK_{j,t} \leq M_{j,t} \quad (1p)$$

$$K_{j,t} = \sum_{k\in\mathcal{K}} \alpha_{k,j,t} \quad (1q)$$

$$0 \leq K_{j,t} \leq \overline{K}, \quad 0 \leq M_{j,t} \leq \overline{M}, \quad 0 \leq P_{\text{tran},j,t} \quad (1r)$$

$$\sum_{m:n\to m} P_{m,t} = p_{n,t} + P_{n,t} - r_n l_{n,t} \quad (1s)$$

$$p_{n,t} = P_{\text{PV},n,t} - P_{\text{ch},n,t} - P_{\text{ld},n,t} + P_{\text{dis},n,t} - P_{\text{BS},n,t} \quad (1t)$$

$$\sum_{m:n\to m} Q_{m,t} = q_{n,t} + Q_{n,t} - x_n l_{n,t} \quad (1u)$$

$$q_{n,t} = -Q_{\text{ld},n,t} \quad (1v)$$

$$v_{n,t} = v_{\pi_n,t} - 2r_n P_{n,t} - 2x_n Q_{n,t} + (r_{n,t}^2 + x_{n,t}^2) l_{n,t} \quad (1w)$$

$$\frac{P_{n,t}^2 + Q_{n,t}^2}{v_{\pi_n,t}} \leq l_{n,t} \quad (1x)$$

$$\underline{v}_n \leq v_{n,t} \leq \overline{v}_n, \quad l_{n,t} \leq \bar{l}_n \quad (1y)$$

$$|V_{\text{ref},t}| = 1 \quad (1z)$$

$$v_{n,t} = |V_{n,t}|^2, \quad l_{n,t} = |I_{n,t}|^2 \quad (1aa)$$

The objective function in (1a) aims to minimize the operational costs of the local distribution grid in the day-ahead electricity market over time T. The net load of the distribution grid is denoted by P_{ref}, which is the reference bus connected to the main grid. The power consumption of each BS j at time t in (1b) includes the transmit power of antennas, hardware power consumption by transmit antennas and coordinators, and the static hardware power [12]. The dynamic of battery energy storage is formulated in (1d)-(1e) and the battery can only charge or discharge at time t (1i). The capacity limits of the power/energy consumption of the batteries are expressed in (1c), (1f)-(1h).

In the 5G RAN, there are 5G BSs represented by the set $\mathcal{J} = \{1, 2, ..., j, ..., \mathrm{J}\}$, the coordinators represented by the set $\mathcal{K} = \{1, 2, ..., k, ..., \mathrm{K}\}$, and the associations between them are represented by the association matrix $\boldsymbol{\alpha} \in \{0, 1\}^{\mathrm{J}\times\mathrm{K}\times\mathrm{T}}$. One coordinator is only associated with one BS but one station can cover many coordinators as formulated in (1m) and (1q). The downlink data rate of the link connecting (j, k) is represented as $\boldsymbol{r} \in \mathbb{R}^{\mathrm{J}\times\mathrm{K}\times\mathrm{T}}$ in (1j), where B is the bandwidth for data transmission between j and k. The prelog-factor $1 - \frac{\overline{K}}{T_c}$ represents the overhead for the link acquisition. The signal-to-noise ratio (SNR) of the link between k and j in (1n) is a measure of signal quality, and the interference of other signal channels is marginal and thus ignored to simplify the model. The transmit power from BS j is represented by $P_{\text{tran},j}$, which is attenuated by the channel gain $G_{k,j}$ plus the white noise σ_k^2 at the receiver of the coordinator k. The channel gain is modelled as the simplified space path loss model in (1o). The number of antennas of the 5G BS, M, is linear to K, the number of coordinators associated with j in (1p). Such formulation follows the optimal design of BSs suggested in [13]. The data downlink rate of coordinator k is obtained from one BS (1k) and should satisfy the QoS constraint in (1l). The limits of the number of associated coordinators, antennas, and transmit power of BS j are expressed in (1r). The power flow of the distribution grid is formulated as a branch flow model in (1s)-(1aa), where the nonconvex relaxation through second-order cone is utilized [14].

B. *Resilient operation*

In the resilient operation mode, where power outages of BSs are considered, the optimization problem is formulated as (2). $\boldsymbol{\Omega} = \{\boldsymbol{K}, \boldsymbol{M}, \boldsymbol{P}, \boldsymbol{E}, \boldsymbol{v}, \boldsymbol{l}, \boldsymbol{R}, \boldsymbol{\alpha}, \boldsymbol{R}_{\text{shed}}\}$ is the set of decision variables in the resilient operation problem. $\boldsymbol{R}_{\text{shed}}$ is the vector of data load shedding.

$$\min_{\boldsymbol{\Omega}} \quad \sum_{t\in\mathcal{T}} (\lambda_t P_{\text{ref},t} + C_{\text{shed}} \sum_{\forall k} R_{\text{shed},k,t}) \quad (2a)$$

$$\text{s.t.} \quad (1\text{b}) - (1\text{k}), \quad (1\text{m}) - (1\text{aa}) \quad (2b)$$

$$R_{\text{req},k,t} - R_{\text{shed},k,t} \leq R_{k,t} \quad (2c)$$

$$0 \leq R_{\text{shed},k,t} \leq R_{\text{req},k,t} \quad (2d)$$

The objective function in (2a) aims to maximize the integrated system resilience, which is to minimize the sum of operational costs and the penalty costs of coordinators' downlink rate shedding in the mobile network during the contingency. The QoS of coordinator k can be compromised by shedding the received downlink rate with the amount of $R_{\text{shed},k,t}$ in (2c), (2d).

C. *Linearization method*

The bilinear term in (1k) is linearized by the following Glovers linearization method, where $z_{k,j,t} = r_{k,j,t}\alpha_{k,j,t}$,

$$R_{k,t} = \sum_{j\in\mathcal{J}} z_{k,j,t} \quad (3)$$

$$\underline{r}_{k,j}\alpha_{k,j,t} \leq z_{k,j,t} \leq \overline{r}_{k,j}\alpha_{k,j,t} \quad (4)$$

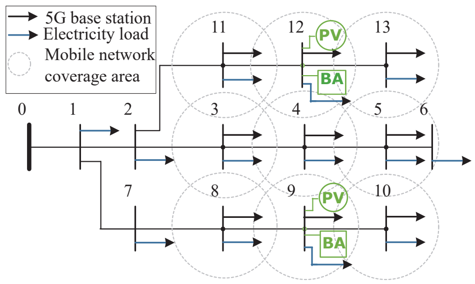
$$r_{k,j,t} - \overline{r}_{k,j}(1 - \alpha_{k,j,t}) \leq z_{k,j,t} \leq r_{k,j,t} - \underline{r}_{k,j}(1 - \alpha_{k,j,t}) \quad (5)$$

The concave log term in (1j) is linearized by the piecewise-linear approximation method [15].

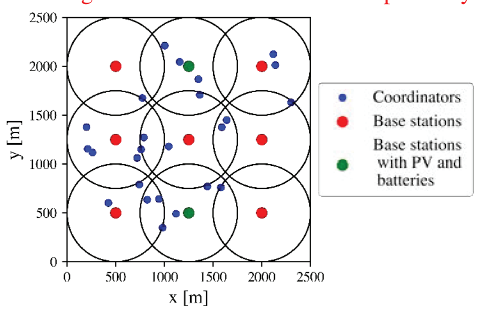
IV. Case Study

The test system configuration is shown in Fig. 2. The 14-bus distribution grid is part of the IEEE 33-bus network [16] and the mobile network parameters are from [13]. Two BSs marked with green at buses 9 and 12 are renewable-based BSs. The system parameters utilized in the case study can be found in [17]. The 25 coordinators are geographically normally distributed in the 2.5 km^2 coverage area. It is assumed each coordinator represents the aggregated data and control requirement of 150 UEs, which are assigned to the same BS that the coordinator is associated with.

This simulation is conducted on a 64-bit PC with an Intel i7 CPU and 32 GB RAM using PyCharm and solved by GUROBI solver [15]. The hourly electricity prices of the 24-hour operation are shown in Fig. 3a. The peak hours are 9-11h and 16-19h, while the off-peak hours are in the night 3-5h, 21-23h and noon 12-15h.



(a) An integrated telecommunication and power system

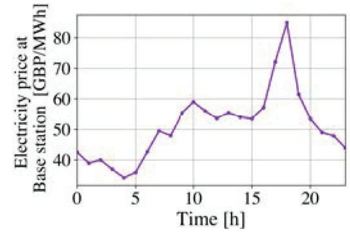


(b) Geographical locations of 5G BSs and coordinators

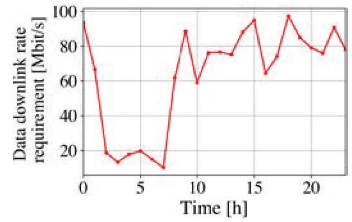
Fig. 2: Test system configuration

In normal operation, the stack plots of power consumption of BSs at buses 9 and 12 are shown in Fig. 4. The power generation from PV and battery discharging is negative value represented by areas with stripes. At hours with low electricity prices, e.g. 3-5h, 12-14h, 21-23h, the net load of the BSs is increased compared to the neighboring hours. Meanwhile, the net load is lower in peak hours, e.g. 9-11h, 16-19h. This is achieved by utilizing the flexibility of the BSs in terms of battery storage and flexible association allocations between BSs and coordinators. Furthermore, to demonstrate the flexibility of the associations, the changed association compared to the reference association allocated by shortest distance at hour 13 is shown in Fig. 5. The dashed lines show the adapted associations in Scenario 2 compared to the fixed ones in Scenario 1. Table I further shows the results comparison between the reference scenario with fixed associations between coordinators and BSs (shortest distance), and the scenario with optimized association allocation (Scenario 1 and Scenario 2). The flexibility of the association allocation contributes to 1.2% lower energy cost, and 8.6% lower power loss, though the energy cost per power consumption and the energy efficiency of the BSs (defined as the power consumption of BSs over the total downlink rates) are slightly compromised.

In Scenario 3, a power outage occurs in the second distribution line where buses 3, 4, 5 and 6 lose their power supply. The BSs at those buses also lose their power supply for data transmission to the coordinators. Those coordinators are associated with other BSs instead, i.e. at buses 8, 9,

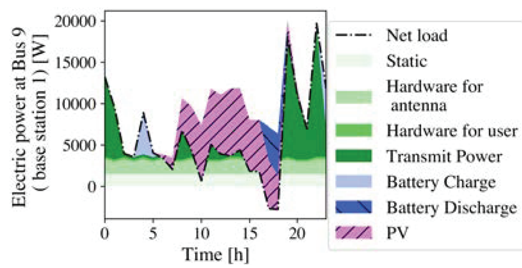


(a) Hourly day-ahead electricity prices

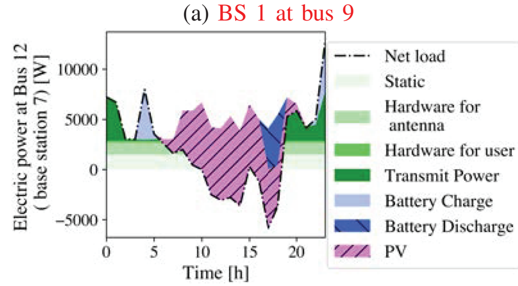


(b) Hourly mobile data requirement of one single UE (UE1)

Fig. 3: Electricity prices and data downlink rate requirement



(a) BS 1 at bus 9



(b) BS 7 at bus 12

Fig. 4: Stack plots of power consumption of BSs with flexible association allocations

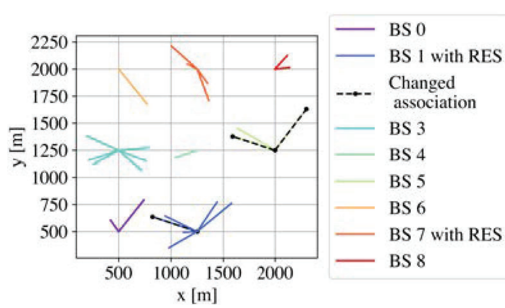


Fig. 5: Flexible association between coordinators and BSs at hour 13 in Scenario 2

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TABLE I: Results of the test system in Scenarios 1, 2 and 3

	Total Energy Cost of Micro-grid [GBP]	Total Net Load of Micro-grid [MWh]	Energy cost per power consumption [GBP/MWh]	Electric Power loss [MWh]	Minimum Voltage [p.u.]	Energy Efficiency of Base Stations [Mbit/joule]
Scenario 1 (Ref.)	1056.99	9.958	106.145	0.00524	0.997	6.512
Scenario 2	1044.20	9.837	106.150	0.00479	0.997	6.502
Scenario 3	27860709.19	11.347	2455337.02	0.000241	0.996	1.975

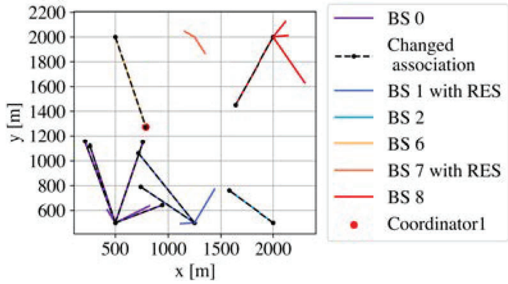

Fig. 6: Flexible association between coordinators and BSs at hour 13 in Scenario 3

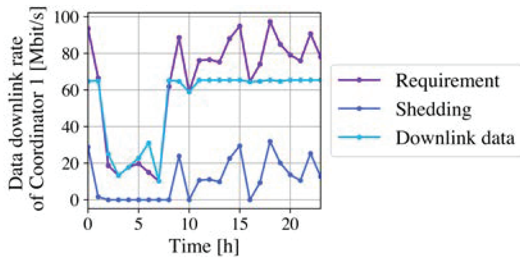

Fig. 7: Flexible association between coordinators and BSs in Scenario 3

10, 11, 12 and 13, which double their coverage radius as expected. Fig. 6 shows that coordinator 1 marked by a red spot that should have been covered by the BS at bus 3 is instead associated with the BS at bus 11. However, due to the limit of the power consumption of BSs, only part of the data requirement can be satisfied. Fig. 7 shows the required and shedding data downlink rate of coordinator 1, where the highest data load shedding occurs at hour 18 with the highest electricity price and data downlink requirement. Therefore, the data load shedding can also contribute to the resilient operation of the integrated system. In Table I scenario 3, the penalty costs of unsatisfied QoS lead to much higher energy costs and lower energy efficiency. The power losses are however decreased, due to the outage of power supply and low power consumption of base stations.

V. Conclusion and Future Work

In this paper, a cost-effective and resilient operation method of an integrated electric power and telecommunication system is proposed. The proposed method is verified on a test-integrated system. Compared to the fixed association allocation, the proposed method can lead to lower operational costs of the system. In addition, the results verify the effectiveness of the data load shedding for a resilient operation of the system. Such a method can be applied by the distribution system operator to achieve the cost-effective and resilient operation. At the same time, the requirement of ICT infrastructure for grid operation can be satisfied.

In future works, the uncertainty of UEs' data requirements, and the recovery strategy of electricity loads during contingency will be considered in the operation approach. Artificial intelligence can be applied to achieve the optimal decision-making of larger-scale cyber-physical energy systems faster.

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