Enhancing the Resilience of Urban Energy Systems in Multi-Energy Micro-grid Via Preventive and Corrective Intelligent Strategies

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***Abstract*—With the increase of occurrence frequency and severity of power outages, the urban micro-grid is gradually established to resist the impact of emergency events. The multi-energy micro-grid (MEMG) can further enhance resilience of urban energy systems, however, the cooperative operation of multi-energy sectors to enhance the resilience needs further optimization in the MEMG. In this paper, the normal operating mode of the multi-energy micro-grid and island operation mode under disaster conditions have been modeled, aiming to minimize costs through the coordinated optimization of operating equipment such as distributed generation (DG), combined heat and power (CHP), storage and so on. Furthermore, we have designed an intelligent overall operational strategy that includes preventive and corrective controls. This strategy optimizes the dispatch of local resources, reducing the curtailment of essential loads during disasters, thereby enhancing the resilience of urban energy systems.**

***Index Terms*—Multi-energy micro-grid, smart strategy, preventive, corrective, essential load.**

I. Introduction

With the increase of urban electrical demand, which is driven by the electrification of transportation, a variety of energy storage options, advancements in distributed generation, and demand-side management, etc. The operational framework of future urban energy systems will be changed. The resilience may be transformed from depending on national-level asset redundancy to using smart and novel holistic operation strategy in local MEMG [1] [2]. This smart approach will integrate local backup generation, energy storage, and demand-side response technologies, coupled with the strategic oversight of local energy infrastructure. Therefore, the establishment of smart MEMG will be critical for urban energy systems in the future, to achieve this purpose, a sophisticated and intelligent system, include preventive and corrective control measures, is indispensable.

In the past two decades, more than 140 significant power disruptions have taken place globally, influenced by factors such as climate change and escalating cyber threats [3]. Given the rising frequency and intensity of these outages in recent times, there is a growing focus on enhancing the resilience performance of power systems to withstand such challenges [4] [5]. Enhancing the resilience of power systems can be achieved by incorporating infrastructure redundancy. Besides, micro-grid has the capability to disconnect from the main grid and independently meet local energy demands by leveraging diverse distributed energy sources. The effectiveness of a resilient power system highly relies on the ability of prediction, adaptation, and quick recovery from potential disruptive events. In order to improve the survivability of islanding, resilience-oriented scheduling can be implemented prior to a potential disruptive event.

In the past, many studies have been dedicated to the enhancement of power system resilience. In [6], Chen et al. summarized and reviewed the tools and models related to natural disasters, highlighting the technologies such as smart grids and micro-grids can augment situational awareness and expedite power system restoration. In [7], Wei et al. formulated a planning problem for resilient distribution networks, aiming to minimize system losses by optimizing the allocation of distributed generation resources. Mansouri et al. introduced a three-stage hierarchical model, which optimized network outage management at various stages within the power system in [8]. In [9], a multi-level robust optimization dispatch method for regional power grids has been proposed by Qiu et al., offering significant guidance for resilient dispatch in power

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systems in face of disasters. In [10], an integrated post-disaster recovery strategy has been developed for the coordination of mobile energy storage systems and generation rescheduling within micro-grids, aiming to reduce overall costs.

When the micro-grid is disconnected from the main grid, due to dynamic restrictions of various components in micro-grid, the local resources fail to respond swiftly will generate substantial load reduction. This scenario underutilises the micro-grid's potential to maintain power supply, thereby causing additional, potentially avoidable load reductions. To enable a smooth islanding mode on demand, the micro-grid's energy management system (EMS) must optimise the allocation of local resources before the main grid's supply is disrupted, ensuring sufficient energy availability.

When the micro-grid separates from the main grid, the entire load must be supported by local energy sources. Nevertheless, the pre-existing energy reserves are depleted at an unsustainable rate, diminishing their advantages over time. Consequently, during the islanded operation of the micro-grid, there is an unavoidable reduction in power supply [11] [12], therefor, it is necessary to optimize the load reduction strategy based on the priority of different loads.

Resiliency in this stage of the disruptive event can be enhanced by prioritising the preservation of essential services (e.g., healthcare, water supply and public transport, etc.) through the compromise of non-essential services. The straightforward strategy is to follow the generation schedule and make decisions based on the real-time information of inevitable load shedding and curtail loads according to their priority. However, it cannot guarantee an overall minimisation of essential load curtailment during the whole contingency. For instance, the alteration of strategies of storage charging/discharging will lead to different curtailment pattern of loads (both essential and non-essential). Therefore, in this paper, after optimizing the load reduction strategy according to different priorities, we have proposed an intelligent control strategy, which include preventive strategy and corrective strategy, to realize the optimal control of resources. The preventive strategy involves, before the disaster coming, preemptively coordinating various local resource schedules according to the updated information in real-time, such as activating DG, CHP, and reducing the use of energy storage resources, in order to minimize the reduction of essential loads at the first moment after the disaster strikes and enhance the resilience of the power system. The corrective strategy, on the other hand, involves optimizing the dispatch of distributed resources such as energy storage devices after the disaster, reducing some non-essential loads to charge the energy storage devices, thereby minimizing the reduction of essential loads in the later stages of the disaster. The combination of these two strategies forms an intelligent regulation strategy that can enhance the resilience of the power system and reduce the losses caused by disasters.

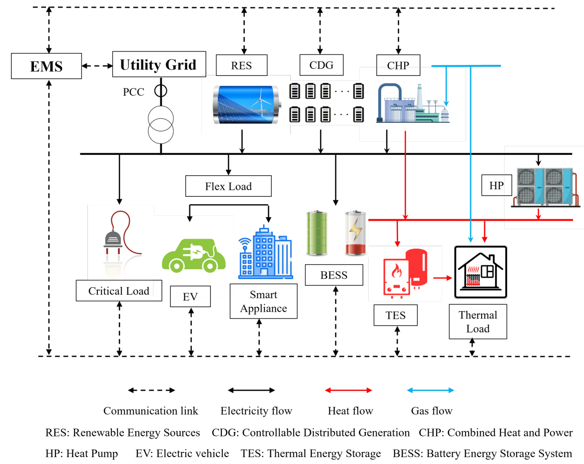

Fig. 1. The Schematic Structure of a multi-energy micro-grid.

II. Mathematical Model

MEMG will fundamentally enhance infrastructure utilisation and increase efficiency, security of supply and resilience of future urban energy systems through optimally mitigating disturbances by serving as a resource of smart timely response and recovery [13]. Figure 1 shows the schematic structure of the MEMG. The coordinated operation of different energy vectors can facilitate cost effective decarbonisation through improved flexibility needed to support the local network management and the national system operation. However, potential benefits of coordinated operation of multi-energy sectors to enhance the resilience of the urban energy system has not been adequately investigated.

In this context, this paper investigates novel holistic operation strategies, under both normal and extreme conditions, for the future urban energy system, taking into account the integration of multiple energy resources and rapid advancements in power system technologies and control, particularly through the application of storage, while would include application of local backup generation.

A. Normal operational mode

In normal operational mode, micro-grid is connected with the utility grid, enabling the electricity trade between both sides. Economic dispatch which optimises operational costs is initially considered in this operational mode.

Objective Function: The initial economic dispatch in our modelling is to minimize the operational costs incurred by the operation of dispatchable units (including generators and CHPs), degradation of storage and net cost of electricity purchase from the utility grid, as shown in (1), disregarding the consequences inflicted by potential disruptive events.

$$\begin{aligned} min\ Obj^{norm} = &\sum_{i\in G}\sum_{t\in T}\Big[\rho_i \cdot \Delta t \cdot P_{i,t} + C_i^{SU} \cdot SU_{i,t} + \\ &C_i^{SD} \cdot SD_{i,t}\Big] + \sum_{t\in T}\Big[\rho^{CHP} \cdot \Delta t \cdot P_t^{CHP} + \\ &C_{CHP}^{SU} \cdot SU_t^{CHP} + C_{CHP}^{SD} \cdot SD_t^{CHP}\Big] + \\ &\sum_{t\in T}\Big[\Delta t \cdot C^{stoD} \cdot (v_t + u_t)\Big] + \sum_{t\in T}\Delta t \cdot C_t^U \cdot P_t^U \end{aligned} \tag{1}$$

where Obj^{norm} denotes the minimization of the net cost of economic dispatch; Δt represents duration of the discretization time step ρ_n and $P_{n,t}$ denote operational cost and electricity power of n, $n \in \{i, CHP\}$; $P_{i,t}$ denotes electricity power from the generator i at time t; C_n^{SU} and C_n^{SD} denote the start-up/shut-down cost of n; $SU_{n,t}$ and $SD_{n,t}$ represent the generator start-up/shut-down indicator of n; C^{stoD} denotes the degradation cost of storage; v_t and u_t represent the binary storage charging/discharging indicator; C_t^U denotes the electricity price of the utility grid; P_t^U represents exchanged electricity power between MEMG and the utility.

A series of common operational constraints are considered as follows which apply to the the whole time horizon ($t \in T$) unless stated otherwise.

Electricity Balance: Equation (2) presents the electricity balance within the MEMG. On the supply side, electricity can be exchanged with the utility grid in normal operational mode, while dispatchable generators, CHP, distributed Photovoltaic (PV) and storage can also contribute to the local energy supply regardless of the connection state of the MEMG. On the demand side, heat-driven electricity demand is separated from the non-heat electricity demand.

$$\sum_{i\in G} P_{i,t} + P_t^{CHP} + P_t^{PV} + P_t^S + P_t^U = D_t \tag{2}$$

where P_t^{PV} denotes PV generation at time t; P_t^S represents charging/discharging power of the storage; D_t denotes power demand.

Power Exchange Limit: The power exchange between the MEMG and the utility grid is restricted by the capacity and state ($U_t = 1$: connected; $U_t = 0$: disconnected) of the point of common connection (PCC), as demonstrated in (3):

$$-U_t \cdot \overline{P}^U \leqslant P_t^U \leqslant U_t \cdot \overline{P}^U \tag{3}$$

where $\overline{P}^U$ denotes maximum power exchange from the utility grid. Similarly, in the following model, $\overline{P}^x$/ $\underline{P}^x$ represent the maximum/ minimum processing limits of the device, $x \in \{i, S\}$.

Generation Unit Constraints: The operation of dispatchable generators is described by a series of constraints incorporating the minimum stable generation and maximum output (4a); ramping (4b)-(4c); start-up and shut-down (4d)-(4e); minimum online/offline time (4f)-(4g).

$$\underline{P}_i \cdot I_{i,t} \leqslant P_{i,t} \leqslant \overline{P}_i \cdot I_{i,t} \tag{4a}$$

$$P_{i,t} - P_{i,t-1} \leqslant \Delta t \cdot RU_i \cdot I_{i,t} \tag{4b}$$

$$P_{i,t-1} - P_{i,t} \leqslant \Delta t \cdot RD_i \cdot I_{i,t-1} \tag{4c}$$

$$SU_{i,t} \geqslant I_{i,t} - I_{i,t-1} \tag{4d}$$

$$SD_{i,t} \geqslant I_{i,t-1} - I_{i,t} \tag{4e}$$

$$\sum_{k\in\left[t-\underline{T}_i^{on}/\Delta t+1,t\right]\cap T} SU_{i,k} \leqslant I_{i,t} \tag{4f}$$

$$\sum_{k\in\left[t-\underline{T}_i^{off}/\Delta t+1,t\right]\cap T} SD_{i,k} \leqslant 1 - I_{i,t} \tag{4g}$$

$$I_{i,t} \in \{0,1\} \tag{4h}$$

$$SU_{i,t} \in \{0,1\} \tag{4i}$$

$$SD_{i,t} \in \{0,1\} \tag{4j}$$

where $\underline{P}_i/\overline{P}_i$ denotes minimum/maximum output of generator i, $I_{i,t}$ represents binary generator ON/OFF indicator, RU_i/RD_i denotes generation ramp-up/ramp-down rate, The range of values for $I_{i,t}, SU_{i,t}, SD_{i,t}$ is {0,1}.

Storage Operating Constraints: The model of electrical storage is formulated as (5a)-(5e), where (5c) expresses the operational process and (5a) and (5b) limit the power and energy capacity, respectively.

$$\underline{P}^S \cdot u_t - \overline{P}^S \cdot v_t \leqslant P_t^S \leqslant \overline{P}^S \cdot u_t - \underline{P}^S \cdot v_t \tag{5a}$$

$$E_t^S \leqslant \overline{E}^S \tag{5b}$$

$$E_t^S = E_{t-1}^S - \Delta t \cdot P_t^S \tag{5c}$$

$$u_t + v_t \leqslant 1 \tag{5d}$$

$$u_t, v_t \in \{0,1\} \tag{5e}$$

where E_t^S denotes storage energy at time t; $\overline{E}^S$ represents energy capacity of storage.

CHP operating Constraints: The CHP operating constraint model is proposed based on [14].

B. Islanded operational mode

Before the occurrence of disruptive events, MEMG operates according to its original schedule

$$X' = \{P_{i,t}, P_t^{CHP}, P_t^S\}. \tag{6}$$

Once the MEMG is islanded from the utility grid due to the occurrence of a disruptive event, the local EMS has to re-schedule the dispatch of various local resources to minimise the load curtailment, as shown in objective function (7).

$$min\ Obj_s^{isld} = \alpha^P Cur_{t,s}^P \tag{7}$$

where α^P denotes weight factor on electricity load curtailment, $Cur_{t,s}^P$ denotes electricity power curtailment.

Weather-related disruptive events are predictable, although the occurrence time of disruptive events cannot be predicted accurately, it is possible to figure out the time interval in which these events with significantly probability. In order to give a robust dispatch strategy, it will be important to consider all the scenarios ($s \in S$) of disconnection time based on the forecast data of disruptive event occurrence.

$$\begin{aligned}&\sum_{i \in G} P_{i,t,s} + P_{t,s}^{CHP} + P_{t,s}^{PV} + P_{t,s}^{S} \\ &= D_{t,s} - Cur_{t,s}^{P}\end{aligned} \tag{8}$$

Considering scenario s in which the outage occurs at t_s^o. Before t_s^o, all components should operate as scheduled, as expressed in (9)-(10), where $P_{i,t,s}^{'}$ and $E_{t,s}^{S'}$ denote the scheduled output of generation units and energy in storage energy level, respectively, which have been determined by optimising the normal operational problem. Additionally, $\lambda_{i,t,s}$ and $\pi_{i,t,s}$ represent the dual variables of the corresponding constraints, subject to scenario s.

Based on the duality theory, dual variables can indicate the change in the optimal value of the objective function with the relaxation of the corresponding constraints. Therefore, $\lambda_{i,t,s}$ and $\pi_{i,t,s}$ provide an estimation of how much the objective can be further reduced in scenario s, with the adjustment of the schedule before t_s^o.

$$P_{i,t,s} = P_{i,t,s}^{'} : \lambda_{i,t,s}, \forall t \leqslant t_s^o \tag{9}$$

$$E_{t,s}^{S} = E_{t,s}^{S'} : \pi_{i,t,s}, \forall t \leqslant t_s^o \tag{10}$$

In order to better apply the duality theory, binary constraints (4h)-(4j) and (5d), (5e) are replaced by (11) and (12), (13) under the assumption that the unit commitments of local generators and storage are fixed as scheduled throughout the time horizon, where $I_{i,t,s}^{'}$ and $u_{t,s}^{S'}$, $v_{t,s}^{S'}$ are the optimal results determined in the normal operational problem. This assumption incurs no issues before t_s^o since all the components have to operate as scheduled anyway, as constrained in (9)-(13). However, after t_s^o the unit commitment should also be allowed to modulate during contingency if it can potentially reduce the load curtailment. Actually, the dual variables $\mu_{i,t,s}$, $\omega_{i,t,s}$ and $\sigma_{i,t,s}$ can inform the controller of an effective way to revise the unit commitment after t_s^o so that load curtailment can be alleviated. This revision can be achieved by re-scheduling the local resources in the normal operation problem with the feedback from the islanded problem. More details are presented in the next section.

$$I_{i,t,s} = I_{i,t,s}^{'} : \mu_{i,t,s} \tag{11}$$

$$u_{t,s}^{S} = u_{t,s}^{S'} : \omega_{i,t,s} \tag{12}$$

$$v_{t,s}^{S} = v_{t,s}^{S'} : \phi_{i,t,s} \tag{13}$$

C. Resilience Enhancement through Smart Control

1) Preventive control to alleviate load compromise

Under the scheme of economic dispatch, once a disruptive event strikes the system, consequence with increased severity is more likely to be inflicted due to a lack of preventive actions. Based on the dual variables obtained from solving the islanded problem, the normal dispatch can be adjusted in a resilience-oriented fashion to make sure that the objective of the islanded problem (7) is reduced conditioned on the revised dispatch strategy.

Constraint (14) demonstrates the mechanism of dispatch revision. As aforementioned, dual variables $\lambda_{i,t}$, $\pi_{i,t}$, $\mu_{i,t}$ and $\omega_{i,t}$ indicate the marginal reduction of objective (7) with the increase of $P_{i,t}$, E_t^S, $I_{i,t}$ and u_t^S, respectively, compared to the previous schedule $P_{i,t}^{'}$, $E_t^{S'}$, $I_{i,t}^{'}$ and $u_t^{S'}$. Therefore, (14) revises the dispatch of local resources, striving to cover the curtailment (the value of (7) in the last iteration) in the islanded problem.

$$\begin{aligned}&\sum_{i \in G} \lambda_{i,t}(P_{i,t} - P_{i,t}^{'}) + \sum_{i \in G} \mu_{i,t}(I_{i,t} - I_{i,t}^{'}) + \\ &\quad \pi_{i,t}(E_t^S - E_t^{S'}) + \omega_{i,t}(u_t^S - u_t^{S'}) + \\ &\quad SL_t \geqslant Obj^{isld'}\end{aligned} \tag{14}$$

A slack variable SL_t which is penalised in the objective function (15) is added to ensure the feasibility of the optimisation problem.

$$min\ Obj^{res} = Obj^{norm} + pnt \cdot SL_t \tag{15}$$

To this end, the resilience-oriented dispatch problem is constructed by adding constraint (14) to the initial economic dispatch problem while modifying the objective function as (15).

The proposed dispatch strategy minimise the curtailment for potential disruptive events at the lowest cost.

Step 1: Calculate the initial normal operation dispatch plan disregarding potential islanding scenarios.

Step 2: Based on the normal operation schedule, solve islanded problem in scenarios, in which the micro-grid is islanded at t_s^o. Before t_s^o, the operation is performed as scheduled. After t_s^o, unit commitments of local resources are fixed as scheduled but their output can be changed.

Step 3: If no load is curtailed or load shedding cannot be further alleviated, obtain resiliently optimal normal operation schedule for the current islanding scenario as in Step 2. Otherwise, adjust normal operation dispatch. Go to step 2, $s = s + 1$.

Step 4: Keep the optimal curtailment fixed as calculated in Step 2, and re-solve the islanded problem with the objective of minimising operational cost, obtain the economically optimal islanded operation dispatch plan for the current scenario.

Step 5: Repeat this process for all potential islanding scenarios while keeping the normal operation schedule for $t <= t_{s-1}^o$ unchanged as that in scenario $s - 1$. Obtain the final normal operation dispatch which is resiliently optimal for all potential islanding scenarios.

2) Corrective Control to preserve essential loads

In normal operation, the utility grid is supplying all demand and the electric battery can be used for power balancing and demand shifting to reduce the total operating cost. If the EMS simply applies the control strategy presented in (14) subject to objective (7), the pre-stored energy will keep supplying loads whenever there is energy imbalance regardless of the load priority, once the pre-stored energy is exhausted, the risk that essential load has to be curtailed will rise. The local EMS should be able to differentiate essential electricity loads $D_t^{P,E}$ and non-essential electricity loads $D_t^{P,NE}$. Once there is a shortage of energy supply, the electric storage devices have to re-schedule their operation accordingly, by means of shifting the non-essential load curtailment, to fulfill the supply of essential load and minimise the objective function (7). Loads characterised with different priorities or the priority of a single type of load will vary with time. Aiming at maintaining operations of key electricity systems during a power supply failure, we precisely classify the inflexible load into the following three types according to their operation characteristics:

- Type 1: *Constantly essential load*
  This type of load refers to those necessary for maintaining basic societal functions, e.g., hospital, data center, street lighting, etc.
- Type 2: *Non-essential load*
  This type load can be compromised to prioritize the supply of essential load, but its curtailment is not desired and should be minimized.
- Type 3: *Decreasingly/increasingly essential load*
  This type of load is only prioritized for a certain period after the outage, typically related to evacuation, e.g., underground trains, theatres, stadium, etc.

To model the amount of necessary demand after the occurrence of outage, given the demand profiles of these three types, we introduce the concept of *essential factor* $\gamma \in [0,1]$ to represent the essentiality for each type of loads presented above. Specifically, the essential factors are specified as

$$\gamma_{\ell,t}^{D} = \begin{cases} 1 & \ell = \ell_1, \text{ Type 1} \\ 0 & \ell = \ell_2, \text{ Type 2} \\ \bar{\gamma}_t & \ell = \ell_3, \text{ Type 3} \end{cases} \tag{16}$$

Then, based the essential factors, the aggregate demand, essential demand and non-essential demand are calculated as (17a), (17b), (17c), respectively, in which $L = \{\ell_1, \ell_2, \ell_3\}$. Accordingly, the amount of curtailment should satisfy constraints (17d), (17e) and (17f). Especially, the employment of corrective control through constraint (17f) ensures the priority of essential load.

$$D_t = \sum_{\ell \in L} D_{\ell,t} \tag{17a}$$

$$D_t^{EL} = \sum_{\ell \in L} \gamma_{\ell,t}^{D} \cdot D_{\ell,t} \tag{17b}$$

$$D_t = D_t^{NEL} + D_t^{EL} \tag{17c}$$

$$Cur_t^{EL} \leq D_t^{EL} \tag{17d}$$

$$Cur_t^{NEL} \leq D_t^{NEL} \tag{17e}$$

$$Cur_t^{EL} = \begin{cases} 0, & \text{if } Cur_t^P \leq D_t^{NE} \\ Cur_t^P - D_t^{NE}, & \text{otherwise} \end{cases} \tag{17f}$$

To the end, the local EMS should be able to coordinate all the local resources based on the information of different loads through corrective control to alleviate the consequences of disruptive events to the minimum level. The mechanism can be achieved through replacing objective (7) by the following:

$$Obj_t^{isld} = \min \alpha^P \left(\alpha^{P,NE} Cur_t^{P,NE} + \alpha^{P,E} Cur_t^{P,E} \right) \tag{18}$$

which minimizes the curtailed energy at time t. Due to the priority of essential load, the penalty coefficients satisfies $\alpha^{P,E} \gg \alpha^{P,NE}$.

It should be stressed that preventive control strategies highly depends on the accuracy of outage prediction since it is not economic to constantly take preventive actions disregarding the operational conditions. The application of preventive control is determined by the balance between costs and risks. However, corrective control strategy is not restricted by outage prediction, it can always provide effective means to alleviate the adverse consequences of disruptive events.

III. Case Studies

In this section, preventive and corrective control are investigated for their effectiveness in enhancing resilience in the urban MEMG depicted in Fig. 2.

As shown in Fig. 2, there was a power emergency at 4 a.m., the multi-energy micro-grid will swiftly switch to islanded operation mode to mitigate the adverse effects of an unexpected event.

Fig. 2(a) shows that without corrective or preventive control, there was substantial essential load curtailment during morning, midday, and evening peaks. Besides, CHP and DG need some time to ramp up when the power emergency strikes, this will lead to the inability of distributed power sources to start up immediately, resulting in further curtailment of essential loads. The significant reduction of essential loads can disrupt people's normal lives and cause tremendous harm to society.

Fig. 2(b) shows that inclusion of preventive control resulted in a moderate reduction in essential load curtailment at the start of islanding, because it reduced the use of storage equipment and prepare to turn on CHP and DG equipment in advance. The preventive strategy, based on real-time information, prepares in advance before the disaster strikes, ensuring that DG, CHP, and storage devices are operating at the first moment, thereby minimizing the curtailment of essential loads.

In fig. 2(c), it took a corrective control strategy by cutting off some non-essential loads to charge storage devices, in order to reduce the reduction of essential loads in midday, and evening peaks. After the disaster strikes, the corrective strategy can use storage devices flexibly, discharging during peak periods of essential load curtailment and charging the storage devices by curtailing non-essential loads at other times, this strategy can continuously exert its effect, reducing the curtailment of essential loads.

Fig. 2(d) shows that inclusion of preventive and corrective control resulted in moderate reductions in essential load curtailment for all essential load peak. Through the intelligent regulation strategy that combines preventive and corrective

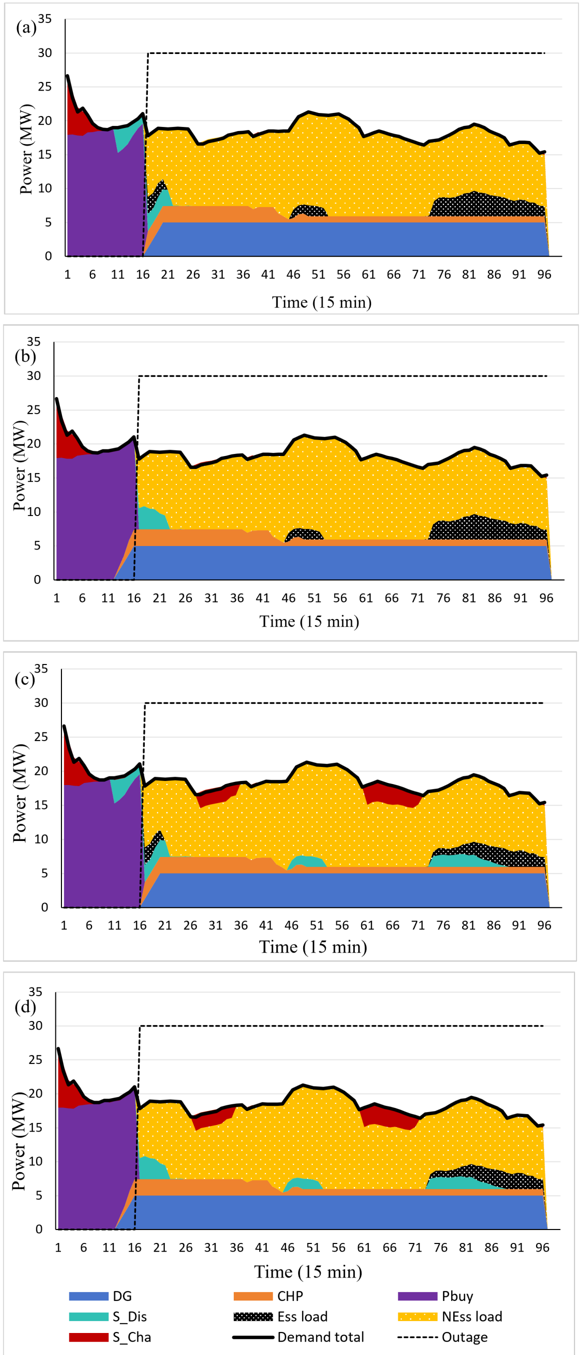

Fig. 2. (a) No preventive or corrective, (b) Preventive, (c) Corrective, (d) Preventive and corrective.

strategies, leveraging the advantages of both. The preventive measures are taken in advance before the disaster, and storage devices are flexibly adjusted during the disaster to reduce the curtailment of essential loads, further ensuring the normal operation of society and thereby enhancing the resilience of the power system.

IV. Conclusion

MEMG plays an important role in power emergency events. However, the straightforward strategy cannot guarantee an overall minimisation of essential load curtailment during the whole contingency. Therefor, in this paper, we optimized the load reduction strategy based on the priority of different loads, besides we designed a smart control strategy, which includes preventive and corrective control strategy, and used mixed-integer linear programming optimization approaches to optimise the dispatch of various local resources to maximise the total utility and enhance resilience of the micro-grid. Simulation results show that this intelligent control strategy can effectively reduce the curtailment of essential loads during high peak periods by starting CHP and DG devices in advance and controlling the orderly charging and discharging of energy storage device, thereby enhancing the resilience of the power system.

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