Stochastic Scheduling of Mobile Energy Storage Systems for Transmission System Resilience Enhancement

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***Abstract*—Mobile energy storage systems (MESSs) have significant potential to enhance the resilience of the power transmission system against extreme weather. A novel two-stage model is proposed to schedule the MESSs and recover the transmission networks (PTNs). The first stage determines the on-off state of the generation unit, and MESSs are dispatched in real-time for load recovery at the second stage. The proposed model is formulated as a two-stage mixed integer programming problem, which is solved by a modified Benders decomposition algorithm. Case studies are conducted on the IEEE-RTS 79 test system to show the effectiveness of the proposed method in the resilience enhancement of the transmission systems.**

***Index Terms*—Mobile energy storage, resilience enhancement, power transmission network, Benders decomposition**

I. Introduction

Driven by electrification and decarbonization, the power transmission networks (PTNs) have been recognized as the backbone of modern power and energy systems. Unfortunately, PTNs suffer from damage caused by extreme natural disasters that have become more and more frequent. The damage will lead to large-scale power outages and result in enormous economic loss. Therefore, the resilience of PTNs is highlighted, and the resilience enhancement against extreme natural conditions is urgent.

The power system is composed of multiple components. Many strategies have been proposed to improve the resilience of the power system. Considering the fault probability of high-risk components, a three-layer optimization model is formulated to plan the optimal pre-event actions for resilience enhancement, and the model is solved by a greedy searching algorithm [1]. A framework to assess tower fragility to hurricanes under the impact of climate change is proposed and it is found that climate change has a significant impact on tower structural failure probability. It is suggested that effective methods should be explored to determine when the towers should be replaced to withstand extreme weather [2]. A reinforcement strategy framework is designed to evaluate the effectiveness of targeted hardening measures for the key elements to improve the system's resilience against typhoon disasters [3]. The mentioned researches focus on the replacement or reinforcement strategy of high-risk components based on the prediction of disaster impact range to enhance the power system resilience.

Further, mobile energy storage systems (MESSs) are a promising solution for the resilience enhancement of distribution systems. A pre-hurricane resource allocation model is proposed to decrease operating costs and improve recovery ability [4]. The framework not only considers the generation but also pre-allocates the electric buses in distribution systems. Besides, electric buses are also scheduled to recover the distribution systems in [5], where the public transport capacity is taken into account. The co-optimized scheduling of mobile power source and repair crew is proposed after the disaster occurs. The case results show that the co-optimize method effectively improves the load recovery of the system [6]. Another two-stage stochastic programming model is established where different disaster scenarios are considered to optimize mobile energy supply equipment investment at the first stage [7]. The mentioned models schedule the electric buses or electric vehicles and focus on the resilience enhancement for the distribution system. Moreover, few studies consider the routing of MESSs in railway transportation systems and improve PTNs' ability to respond to natural disasters. The contributions of this work can be summarized as follows:

- A novel transmission system model with MESSs is proposed to improve the resilience of PTN.
- A modified Benders decomposition algorithm is introduced to solve the formulated two-stage mixed-integer programming model.

The rest of this paper is organized as follows. Resilient management of PTNs with MESSs is presented in Section II and the routing of the MESSs is discussed in Section III, respectively. The proposed management is formulated as a two-stage optimization problem in Section IV. In Section V, the modified Benders decomposition algorithm is introduced.

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Case studies are conducted in Section VI and the conclusions are summarized in Section VII.

II. Resilient Management of Transmission Systems with Mobile Energy Storage Systems

In this section, the integrated PTNs with MESSs are presented by the graph at first. Then stochastic impacts of extreme weather events on the transmission systems are depicted as a scenarios set. Finally, the resilient management of PTNs with MESSs is introduced to respond to these impacts.

A. Integrated Power Transmission Systems with Mobile Energy Storage Systems

An integrated PTN with MESSs is shown in Fig. 1. The PTN is an AC transmission network, denoted by $(\mathcal{D}, \mathcal{E}_\mathrm{P})$ where $\mathcal{D}$ is the bus set, indexed by i, j. $\mathcal{E}_\mathrm{P} \subseteq \mathcal{D} \times \mathcal{D}$ is the line set, indexed by ij. $\mathcal{G}$ is the set of generator units.

A railway transportation system that MESSs travel in is denoted by $(\mathcal{N}_\mathrm{E}, \mathcal{R})$ where $\mathcal{N}_\mathrm{E}$ is the station set and $\mathcal{R} \subseteq \mathcal{N}_\mathrm{E} \times \mathcal{N}_\mathrm{E}$ is the railroad set. The variable w_{mn} is the travel time of the trip on railroad $mn \in \mathcal{R}$. Stations are integrated to PTNs by the charging equipment.

$\mathcal{T}$ is the set of hours, indexed by t. $\mathcal{T}_\omega$ is the set of time slots in layer ω, indexed by t_ω. Γ_{t_ω} is the set of hours in the time slot t_ω.

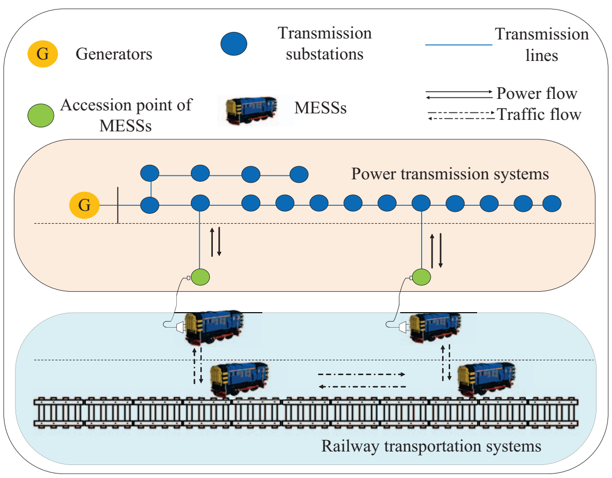

Fig. 1. Illustrative figure for integrated power transmission and railway transportation Systems.

B. Impacts of Hurricanes on the Transmission Systems and Uncertain Set with Finite Scenarios

Hurricanes will damage the key equipment in the PTNs, especially the overhead lines and towers. The failure probability of transmission lines and towers under the influence of hurricane track and intensity is discussed in [8].

Due to the influence of random disturbances such as terrain, there will be some deviation between the actual generation and prediction of hurricanes. A data-driven method is used in [8] to develop an uncertain scene of hurricane generation. $\mathcal{S}$ is the set of scenarios.

C. Resilient Operation of Power Systems with Mobile Energy Storage Networks

PTNs should be well prepared for possible hazards caused by hurricanes. The resilient operation is a two-stage decision-making problem. Before the advent of hurricanes, the first stage is to schedule the Unit on/off state and the initial position of MESSs in the day-ahead operation. In the second stage, transmission lines and towers may be damaged caused by the hurricane, resulting in load shedding. To supply the power load and minimize the operating cost, the generator output is adjusted. Besides, MESSs carry out load recovery resources and move in the railway network to supply power. The process of the resilient operation is shown in fig.2.

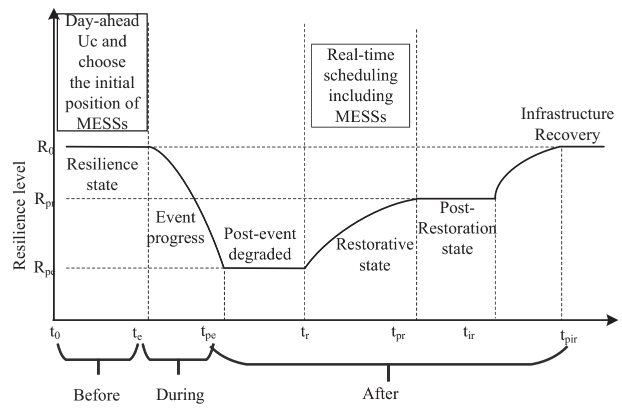

Fig. 2. Resilient operation of PTNs with MESSs towards hurricanes.

III. Vehicle Routing Problem for Mobile Energy Storage Systems

The set of MESSs is denoted by Ω.To schedule the MESSs, the time-space network (TSN) technology [9] is adapted. A layer of TSN is denoted by $(\mathcal{N}_\mathrm{TS}^\omega, \mathcal{A}^\omega)$, where $\mathcal{N}_\mathrm{TS}^\omega$ is a set of time-space nodes in the ω-th layer of TSN. $\mathcal{A}^\omega$ is divided into two types: $\mathcal{A}_\mathrm{T}^\omega$ and $\mathcal{A}_\mathrm{P}^\omega$, representing the set of moving/holding arcs in layer ω, respectively.

To explain the behavior of MESSs in more detail, time-space cuts in each time slot t_ω are introduced, which divide $\mathcal{N}_\mathrm{TS}^\omega$ into two disjoint subsets $(\mathcal{N}_{\mathrm{L},\omega}^{t_\omega}, \mathcal{N}_{\mathrm{R},\omega}^{t_\omega})$ where $\mathcal{N}_{\mathrm{L},\omega}^{t_\omega}$ represents the set of time-space nodes on the left-hand side of the cut while $\mathcal{N}_{\mathrm{R},\omega}^{t_\omega}$ denotes those on the right-hand side. The set of time-space cuts denoted by $\Phi_\omega^{t_\omega,s} = \{(\hat{n}, \check{n}) \in \mathcal{A}_\mathrm{T}^\omega \cup \mathcal{A}_\mathrm{P}^\omega | \hat{n} \in \mathcal{N}_{\mathrm{L},\omega}^{t_\omega}, \check{n} \in \mathcal{N}_{\mathrm{R},\omega}^{t_\omega}\}$, is introduced to describe all the feasible arcs that intersect time slot t_ω.

The following constraints should be held in the scheduling of MESSs.

$$\sum_{(\hat{n},\check{n})\in\Phi_{\omega}^{t_\omega,s}} \zeta_{\hat{n}\check{n}}^{\omega,s}=1, \forall\omega, t_\omega, s \tag{1}$$

$$\sum_{(\hat{n},\check{n})\in\acute{\mathcal{A}}_n^{\omega,s}} \zeta_{\hat{n}\check{n}}^{\omega,s}= \sum_{(\hat{n},\check{n})\in\grave{\mathcal{A}}_n^{\omega,s}} \zeta_{\hat{n}\check{n}}^{\omega,s}, \forall n\in\mathcal{N}_{\omega}^{s}, \omega, s \tag{2}$$

$$\sum_{(\hat{n},\check{n})\in\acute{\mathcal{A}}_n^{\omega,s}} \zeta_{\hat{n}\check{n}}^{\omega,s}=\zeta_{\text{init}}^{\omega,s,n}, \forall n\in\widetilde{\mathcal{N}}_{\omega}^{s}, \omega, s \tag{3}$$

Eq.(1) indicates that MESS ω can only choose one arc at each time slot. Eqs. (2)-(3) indicates that the number of MESSs entering the node equals the number of MESSs exiting the node. $\mathcal{N}_{\omega}^{s}$ represent the location of MESSs at a specific time point. $\widetilde{\mathcal{N}}_{\omega}^{s}$ represent the initial and end depot position of MESSs. $\zeta_{\hat{n}\check{n}}^{\omega,s}$ is a binary variable,which is 1 if the MESS ω selects this arc, and 0 if it does not.$(\hat{n},\check{n})\in\mathcal{A}_{\text{T}}^{\omega}\cup\mathcal{A}_{\text{P}}^{\omega}$. $\grave{\mathcal{A}}_n^{\omega,s}$,$\acute{\mathcal{A}}_n^{\omega,s}$ are the sets of arcs that start and end at time-space node n in scenario s. $\zeta_{\text{init}}^{\omega,s}$ indicates the initial position of MESS ω.

$$0\leq P_{\text{ME,c},m}^{\omega,t,s}\leq\zeta_{\hat{n}\check{n}}^{\omega,s}\overline{P}_{\text{ME,c}}^{\omega}, \forall t\in\Gamma_{t_\omega}, (\hat{n},\check{n})\in\mathcal{A}_{\text{P},m}^{\omega,t_\omega,s}, \omega, m, s \tag{4}$$

$$0\leq P_{\text{ME,d},m}^{\omega,t,s}\leq\zeta_{\hat{n}\check{n}}^{\omega,s}\overline{P}_{\text{ME,d}}^{\omega}, \forall t\in\Gamma_{t_\omega}, (\hat{n},\check{n})\in\mathcal{A}_{\text{P},m}^{\omega,t_\omega,s}, \omega, m, s \tag{5}$$

$$\begin{aligned}0\leq R_{\text{ME},m}^{\omega,t,s}\leq&\zeta_{\hat{n}\check{n}}^{\omega,s}\max(\overline{P}_{\text{ME,d}}^{\omega},\overline{P}_{\text{ME,c}}^{\omega}),\\ &\forall t\in\Gamma_{t_\omega}, (\hat{n},\check{n})\in\mathcal{A}_{\text{P},m}^{\omega,t_\omega,s}, \omega, m, s\end{aligned} \tag{6}$$

$$0\leq\sum_{m\in\mathcal{M}} P_{\text{ME,c},m}^{\omega,t,s}\leq I_{\text{ME,c}}^{\omega,t,s}\overline{P}_{\text{ME,c}}^{\omega}, \forall\omega, t, s \tag{7}$$

$$0\leq\sum_{m\in\mathcal{M}} P_{\text{ME,d},m}^{\omega,t,s}\leq I_{\text{ME,d}}^{\omega,t,s}\overline{P}_{\text{ME,d}}^{\omega}, \forall\omega, t, s \tag{8}$$

$$I_{\text{ME,d}}^{\omega,t,s}+I_{\text{ME,c}}^{\omega,t,s}\leq\zeta_{\hat{n}\check{n}}^{\omega,s}, \forall t\in\Gamma_{t_\omega}, (\hat{n},\check{n})\in\mathcal{A}_{\text{P},m}^{\omega,t_\omega,s}, \omega, s \tag{9}$$

$$\begin{aligned}E_{\text{ME}}^{\omega,t,s}=E_{\text{ME}}^{\omega,t-1,s}+&\eta_{\text{ME,c}}^{\omega}\sum_{m\in\mathcal{M}} P_{\text{ME,c},m}^{\omega,t,s}\\ &-\sum_{m\in\mathcal{M}} P_{\text{ME,d},m}^{\omega,t,s}/\eta_{\text{ME,d}}^{\omega}, \forall\omega, t, s\end{aligned} \tag{10}$$

$$E_{\text{ME,cap}}^{\omega}\underline{E}_{\text{ME}}^{\omega}\leq E_{\text{ME}}^{\omega,t,s}\leq E_{\text{ME,cap}}^{\omega}\overline{E}_{\text{ME}}^{\omega}, \forall\omega, t, s \tag{11}$$

Eqs. (4)-(6) determine whether the station can charge, discharge,and output of MESS ω at charge and discharge station m during time slot t in time slot t_ω, respectively. where $\mathcal{A}_{\text{P},m}^{\omega,t_\omega,s}$ denotes the holding arcs of Charge and discharge station m in time slot t_ω in scenario s. Eqs. (7)-(9) determine that MESS ω only charging or discharging can be performed at hour t. Eq.(10) illustrates the remaining battery energy and Eq.(11) ensures the state-of-charge (SOC) of MESS ω is within the desired range. A detailed explanation of the above variables is introduced in [10].

IV. Two-stage Stochastic Optimization method for Resilient Operation

In this section, the problem is formulated as the following two-stage stochastic optimization problem, considering the stochastic impacts of hurricanes on transmission lines and towers.

$$\min_{\mathbf{x}\in X} f(\mathbf{x})+\mathbb{E}_s\{v(\mathbf{x})\} \tag{12}$$

A. First Stage Problem Formulation

$$f(\mathbf{x})=\mathrm{c}^{\mathrm{T}}\mathbf{x}=\sum_{t\in\mathcal{T}}\sum_{g\in\mathcal{G}}\{c_{\text{start},g}\alpha_g^t+c_{\text{shut},g}\beta_g^t+b_g u_g^t\} \tag{13}$$

$$\alpha_g^t-\beta_g^t=u_g^t-u_g^{t-1}, \forall t, g \tag{14}$$

$$\sum_{q=t-\mathrm{UT}_g+1}^{t}\alpha_g^q\leq u_g^t, \forall t\in\{\mathrm{UT}_g,...,T\}, g \tag{15}$$

$$\sum_{q=t-\mathrm{DT}_g+1}^{t}\beta_g^q\leq 1-u_g^t, \forall t\in\{\mathrm{DT}_g,...,T\}, g \tag{16}$$

$$\sum_{n\in\mathcal{N}_E}\zeta_{\text{init}}^{\omega,s,n}=1, \forall\omega, s \tag{17}$$

where $\mathbf{x}$ refers to the first-stage variables in Eqs. (13)-(17). The goal of the first stage is to minimize the scheduling cost of generators, represented by Eq.(13). Besides, the constraints for generators, including start-up, and shut-down are given in Eqs. (14)-(16). The initial position of MESSs is limited by Eq.(17). Variables are explained in detail in the literature [8].

B. Second Stage Problem Formulation

For the scheduled plan in the first stage, the second stage problem is formulated under given ambiguity set to assess the system resilience.

$$\begin{aligned}v(\mathbf{x})&=\min_{\mathbf{y}\in\mathcal{Y}}\mathrm{d}^{\mathrm{T}}\mathbf{y}\\ &=c_{\text{VOLL}}\sum_{t\in\mathcal{T}}\sum_{d\in\mathcal{D}}p_{\text{ls},d}^t+\\ &c_{\text{VOGC}}\sum_{t\in\mathcal{T}}\sum_{g\in\mathcal{G}}p_{\text{gc},g}^t+\sum_{t\in\mathcal{T}}\sum_{g\in\mathcal{G}}c_g*p_{\text{g},g}^t\end{aligned} \tag{18}$$

$$P_g^t-R_g^t\leq p_g^{s,t}\leq P_g^t+R_g^t, \forall t, g \tag{19}$$

$$0\leq p_{gc}^{s,t}\leq P_{g,max}, \forall t, g \tag{20}$$

$$-\mathrm{R}_g^{60-}\Delta t\leq p_g^{s,t}-p_g^{s,t-1}\leq\mathrm{R}_g^{60+}\Delta t, \forall t, g \tag{21}$$

$$\left(I_{ij}^t-1\right)M\leq p_{ij}^{s,t}-B_{ij}\left(\gamma_i^{s,t}-\gamma_j^{s,t}\right)\leq\left(1-I_{ij}^t\right)M, \forall t, ij \tag{22}$$

$$-I_{ij}^t P_{ij}^{\max}\leq p_{ij}^{s,t}\leq I_{ij}^t P_{ij,k}^{\max}, \forall t, ij \tag{23}$$

$$P_d^t+\Delta p_d^t\geq p_{\text{ls},d}^{s,t}\geq 0, \forall t, d \tag{24}$$

$$\begin{aligned}&\sum_{g\in\mathcal{G}_j}p_g^{s,t}-\sum_{g\in\mathcal{G}_j}p_{gc}^{s,t}+\sum_{ij}p_{ij}^{s,t}-\sum_{ji}p_{ji}^{s,t}=\\ &\sum_{d\in\mathcal{D}_j}(p_d^{s,t}-p_{\text{ls},d}^{s,t})+\sum_{m\in\mathcal{M}_j}(p_{\text{ch},m}^{s,t}-p_{\text{dc},m}^{s,t}), \forall t, j\end{aligned} \tag{25}$$

$$Eq(1)-Eq(11) \tag{26}$$

where **y** refers to the second-stage variables in Eqs. (18)-(26). The objective of the second stage is real-time operating costs of PTNs and MESSs, represented by Eq.(18). Eqs. (19)-(21) limit generators' output. Due to hurricanes affecting line status, Eqs. (22)-(23) limit the power transmission of each line. The load shedding is limited by Eq.(24). The generation curtailment is limited by Eq.(20). Eq.(25) is the power balancing at each bus. Eq.(26) is the constraint of MESSs. A detailed explanation of variables is introduced in [8].

V. Solutions Methods

The proposed model is reformulated as the following master-slave problem and solved by a modified Benders decomposition algorithm based on [11] in this section.

A. Problem Reformulation

The master problem is Eq. (27) and the slave problem is Eq. (28).

$$\begin{aligned} &\min_{\mathbf{x}\in\mathbf{X}} \quad \mathrm{c}^{\mathrm{T}}\mathbf{x} \\ &\text{s.t.} \quad \mathrm{A}\mathbf{x} \le \mathrm{b} \end{aligned} \tag{27}$$

$$\begin{aligned} &\min_{\mathbf{y}\in\mathbf{Y}} \quad \mathrm{d}^{\mathrm{T}}\mathbf{y} \\ &\text{s.t. } \mathrm{W}\mathbf{y} + \mathrm{G}\mathbf{x} \le \mathrm{h} - \mathrm{M}\cdot\xi \end{aligned} \tag{28}$$

The inequalities in Eq. (27) refer to Eqs. (14)-(17) and the inequalities in Eq. (28) refer to Eqs. (1)-(11) and Eqs. (19)-(26).

Then the slave problem is expanded as follows.

$$\begin{aligned} &\min_{\mathbf{y}\in\mathbf{Y},\mathbf{x}\in\mathbf{X}} \mathrm{d}^{\mathrm{T}}\mathbf{y} + 0 * \mathbf{x} \\ &\text{s.t. } \mathrm{W}\mathbf{y} + \mathrm{G}\mathbf{x} \le \mathrm{h} - \mathrm{M}\cdot\xi \\ &\mathbf{x} = \mathrm{x_a}, \mathbf{x} \in (0,1) \end{aligned} \tag{29}$$

Where x_{a} is the solution of the Eq.(27).

Finally the Lagrange model can be constructed in Eq.(30).

$$\begin{aligned} &\min_{\mathbf{y}\in\mathbf{Y},\mathbf{x}\in\mathbf{X}} \mathrm{d}^{\mathrm{T}}\mathbf{y} + 0 * \mathbf{x} \\ &\text{s.t. } \mathrm{W}\mathbf{y} + \mathrm{G}\mathbf{x} \le \mathrm{h} - \mathrm{M}\cdot\xi \\ &\mathbf{x} \in (0,1) \end{aligned} \tag{30}$$

The strengthen benders cut Eq. (31) is generated.

$$\theta \ge \left(v_s^m + \left(\pi_s^m\right)^T \mathbf{x}\right) \tag{31}$$

Where π_s is the Lagrange multiplier of the constraint $x = \mathrm{x_a}$ in Eq.(29), v_s is the objective of Eq.(30).

To accelerate the solving speed, add the primal cut to the master problem.

$$\mathrm{W}\mathbf{y} + \mathrm{G}\mathbf{x} \le \mathrm{h} - \mathrm{M}\cdot\xi_\rho \tag{32}$$

Where the ρ is the number of scenario with the largest objective function value and the largest weight in the second stage.

Algorithm 1: Modified Benders Decomposition with Strengthen Benders Cut and Primal Cut

Input: the model of first stage and second stage
Output: output result
Initialize: LB = -inf, UB = inf, m=1 solve the master problem Eq. (27) **if** *problem Eq. (27) is infeasible* **then**
    Terminate
else
    while $(m < m_{\max}) \wedge ((\mathrm{UB^m} - \mathrm{LB^m}) / \max(\mathrm{UB^m}, \mathrm{LB^m}) > \epsilon)$ **do**
        Derive an optimal solution x^m
        Solve Eq. (29) with x^m derive π_m
        Solve Eq. (30) with π_m derive $\mathrm{v_m}$
        Derive the strengthen benders cut Eq. (31)
        Add the strengthen benders cut Eq. (31) to the master problem
        if $m > 1$ **then**
            Add the primal cut to the master problem
            Solve the master problem
        else
            Solve the master problem
        end
        if *master problem is infeasible* **then**
            Terminate
        else
            Derive an optimal solution x^m
            Update $\mathrm{LB^m} = \max\{\mathrm{LB^{m-1}}$, objective of master problem$\}$
            Solve the problem Eq. (28) with x^m, update $\mathrm{UB^m} = \max\{\mathrm{UB^{m-1}}, \mathrm{c^T}x^m + \mathrm{d^T}y^m\}$
            $\mathrm{m} = \mathrm{m} + 1$
        end
    end
end

VI. Case Study

In this section, numerical simulation is conducted to verify the performance of the proposed approach on a modified IEEE RTS 79 test system. The parameters are listed as follows. VOLL = 4000$/MWh, VOGC = 1000$/MWh,$\Delta t = 1$ h, $\mathrm{T} = 24$ h, $\epsilon = 0.01$. The maximum iteration is $m_{max} = 400$. The charging and discharging power of a MESS is limited to 10 MW and the efficiency is 0.95. The maximum, minimum and initial SOC is 40 MWh, 10 MWh, and 20 MWh, respectively. There are five MESSs. The specific parameters of the railway network are shown in Tables I and II. The simulation is implemented on Matlab and solved by commercial solver CPLEX and GUROBI.

To show the effectiveness of the proposed method, three cases are conducted. Case 1 is used to analyze the impact of hurricane weather on the system without energy storage. Case 2 is the case with fixed energy storage. Five MESSs were held

TABLE I
COUPLING BETWEEN RAILWAY NETWORKS AND POWER TRANSMISSION NETWORKS

Station of RNs #	Bus of PTNs #
1	1
2	9
3	10
4	16
5	23
6	24

TABLE II
PARAMETERS FOR RAILROAD NETWORK

Railroad #	Departure station #	Arrival station #	Travel time (h)
1	1	2	1
2	1	3	4
3	1	4	2
4	2	4	3
5	2	5	2
6	3	4	5
7	4	5	3
8	5	6	3
9	3	6	2

in five charging and discharging stations and fixed to analyze the impact of fixed energy storage on the system. In Case 3, five MESSs are scheduled to move on the railroad to analyze the improvement of MESSs on the system resilience. Besides, 100 scenarios are generated by the method in [8] for cases 1-3.

The results of three cases are listed in Table III. Compared with Case 1, the first-stage cost is increased by 0.03% while the second-stage cost is decreased by 1.39% in Case 2, and the total cost in Case 2 reduce 16287.38$ due to the fixed energy storage. Compared with Case 2, the first-stage cost is decreased by 1.32% and the second-stage cost decreased by 0.79% in Case 3, and the total cost in Case 3 reduce 10744.94$, which indicates that MESSs can further decrease the operating costs of PTN.

The reason for the reduction of operating costs is that the fixed energy storage and MESSs can reduce the load shedding in those scenarios with the hurricane, e.g. Scenario 42. For Scenario 42, as listed in Table IV, the total operating cost of Case 1 is increased by 1.74% compared to Case 2 and increased by 3.18% compared to Case 3. On the one hand, the load shedding of Case 1 is increased by 1.51% compared with Case 2 and increased by 3.01% compared with Case 3. Results indicate that the energy storage can improve the recovery ability of PTN, which is further enhanced by MESSs in the proposed resilient operation method.

TABLE III
RESULTS UNDER CASES 1-3

Case	First-stage cost ($)	Second-stage cost ($)	Total cost ($)
1	115500.21	1177767.67	1293267.89
2	115542.48	1161438.02	1276980.51
3	114015.57	1152220.0	1266235.57

TABLE IV
RESULTS UNDER CASES 1-3 FOR SCENARIO 42

Case	total operating cost ($)	Generating cost ($)	Load shedding cost ($)	Generation curtailment cost($)
1	26046940	620233.53	25216334.34	210371.13
2	25601420.58	615200.59	24842266.14	143953.85
3	25243555.42	616516.51	24458829.97	168208.95

VII. CONCLUSION

MESSs are introduced into the PTN against the hurricane. Resilience management is formulated as a two-stage model, including the on-off command model of generation units and pre-location of the MESSs for preparation at the first stage and the model of the real-time operation of PTN and MESSs at the second stage. To solve the formulated two-stage mixed integer programming problem, a novel algorithm is introduced to obtain the optimal solution. The simulation results indicate that the resilience of PTNs can be improved to face extreme weather by introducing MESSs into PTNs.

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