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Two-stage Stochastic Scheduling of Transportable Energy Storage Systems for Resilient Distribution Systems

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Abstract— Transportable energy storage systems (TESSs) provide critical flexibility to enhance the distribution system (DS) resilience. In this paper, a two-stage stochastic restoration scheme is proposed to minimize the total cost. In this model, uncertainties of load consumption and PV power are considered to generate scenarios by using Monte Carlo simulation. A modified temporal-spatial network (TSN)-based scheduling model is proposed to schedule TESSs among MGs. The restoration problem is formulated as a mixed-integer linear programming, satisfying self-adequacy, operation and topology constraints. Case studies are implemented on a modified 33-bus test system to demonstrate the effectiveness of the proposed method.

Index Terms—Transportable energy storage systems, microgrids, resilience, temporal-spatial network.

I. INTRODUCTION

Extreme events such as natural disasters and cascading failures have catastrophic impacts on electricity infrastructures to cause prolonged blackouts, resulting in tremendous societal and economic disruptions. Severe weather has been the leading culprit of widespread and large-scale power outages in the U.S and costs economy billions of dollars a year [1]. Therefore, the emerging concept of power system resilience against major catastrophes, which refers to the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions [2] has been regarded as the critical characteristic of the smart grids. Effective restoration after major disruptions is becoming increasingly crucial and composes an essential prerequisite for resilient power systems.

Energy storage could provide various services to grid. Like stationary energy storage systems, mobile energy storage such as electric vehicles and transportable energy storage systems (TESSs) are of great interests. Some researches have been conducted to integrate TESSs into distribution systems (DSs) under various scenarios, including normal operation status for DSs and response to catastrophes. Firstly, in normal operation, TESSs are generally utilized to provide ancillary services such as load leveling and peak shaving [3], [4]. For resilient response to extreme events, TESSs have been deployed as uninterruptible power supplies [5]. In [6], electric buses and transportable batteries are deployed in pre-hurricane resource

allocation to respond to extreme events, which is mainly focused on proactive preparedness. In [7], a mobile hybrid energy generating stations are developed to acquire optimal generation portfolio for emergency response to power systems failures. Few studies investigated how to sequentially schedule TESS in coordination with MGs to facilitate DS restoration.

In this context, this work proposes a post-disaster restoration scheme to schedule TESSs in coordination with DS reconfiguration through microgrids (MGs), achieving resilient DS restoration after catastrophes. Specifically, MGs make the most of the available generating resources and act as root buses to dynamically form islands for loads pickup, while the temporal-spatial network (TSN) is adopted and customized in vehicle scheduling problem (VSP) [8] [9] to mathematically model the scheduling of TESSs. The optimization problem is formulated as a mixed-integer linear program (MILP).

The remainder of the paper consists of four sections. Section III provides the system architecture. Section IV describes the mathematical formulation of TESS scheduling model and DS reconfiguration with MGs. Section V presents the case studies results and the paper is concluded in Section VI.

II. PROBLEM STATEMENT

Fig. 1. System architecture

An integrated scheme to leverage TESSs and generating resources in MGs for service restoration is shown in Fig. 1. The idea behind it is to optimally coordinate scheduling of TESS and distribution network reconfiguration with MGs, enabling a

resilient service restoration after natural hazards.

A. Transportable Energy Storage System

TESSs provide opportunities for fast and effective restoration after major outages. TESSs are truck-mounted, mobile energy storage systems characterized by utility-scale capacity [7]. It has been widely deployed as back-up generation in kinds of major public activities in place to guarantee power supply security and reliability. Meanwhile, it can participate in ancillary services including load leveling, peak shaving and reactive power support, as with EVs [4], [10]. In 2011 Fukushima tsunami and earthquake, batteries in EVs played a significant part and were utilized to help people get through the worst situations [11]. In Hurricane Sandy, Federal Emergency Response Agency (FEMA) deployed a large number of emergency response generators to prepare for disaster relief efforts [12]. Also, IEEE initiated a mobile emergency relief program to engage volunteers in providing essential services through the IEEE USA-sponsored Mobile Outreach Vehicle (MOVE) [13].

B. Distribution Network Reconfiguration with multiple MGs

Fig. 2. A simplified MG model

A MG is modeled as a grid comprising a single bus, an equivalent dispatchable DG which aggregates the whole generating resources, an equivalent PV generation, an equivalent local load, and charging/discharging facilities, as depicted in Fig. 2.

In the aftermath of extreme events, the DS can no longer be supplied by transmission grids as a result of multiple faults across the power systems, including substation faults, broken feeders. Under this circumstance, MGs will be utilized to pick up critical loads by sectionalizing the DS into multiple islands. The objective is to minimize the total cost, considering customer interruption cost, MG generation cost, and TESS transportation cost and battery maintenance cost, subject to operation and topology constraints. Partial load restoration is adopted by introducing continuous variables for each load as in [14], [15].

C. Uncertainties and Scenario Reduction

In this work, uncertainties of PV generation and load consumption are considered. Monte Carlo simulation is used to generate scenarios for PV generation and load consumption. The beta function is adopted to characterize prediction errors of PV power [16]. For a predicted PV power generation, the beta function can be described by two associated parameters α and β .

$$f(x) = x^{\alpha-1} (1-x)^{\beta-1} \quad (1)$$

In this work, uncertainties of PV generation and load consumption are considered. Monte Carlo simulation is used to

generate scenarios for PV generation and load consumption. The beta function is adopted to characterize prediction errors of PV power and load consumption [16]. For a predicted PV power generation P_{pv} , the shape parameters of the corresponding beta function α and β can be calculated as.

$$\frac{P_{pv}}{S_{base}} = \frac{\alpha}{\alpha + \beta} \quad (2)$$

$$\sigma^2 = \alpha\beta(\alpha + \beta)^2(\alpha + \beta + 1) \quad (3)$$

The predicted power and its error variance can be represented as:

$$\sigma = \frac{0.2P_{pv}}{P_{pv}^{max} + 0.21} \quad (4)$$

The parameters of beta function can be obtained by the predicted power generation and (1)-(4). The load forecasting error is evaluated through normal distribution. For simplification of the computation efforts, the simultaneous backward reduction method [16] is utilized to reduce the number of scenarios while attaining a good approximation of uncertainties.

III. PROBLEM FORMULATION

A. Objective

$$\min \sum_{s \in S} \sum_{i \in T} \{ C_{tran} \sum_{\omega \in \Omega} \sum_{(m,u) \in Z, m \neq u} \zeta_{\omega, mu}^t + \sum_{s \in S} [\sum_{i \in N} W_i (PD_i^{t,s} - PD_{r,i}^{t,s}) + \sum_{m \in M} C_{gen} P_{DG,m}^{t,s} + C_{bat} \sum_{\omega \in \Omega} \sum_{m \in M} |P_{ch, \omega m}^{t,s} + P_{dch, \omega m}^{t,s}| \Delta T] \} \quad (5)$$

Where N is the set of DS buses, indexed by i, j, k . T is the set of time spans, indexed by $t, T=|T|$. M is the set of MGs, indexed by m, u . Ω is the set of TESSs, indexed by ω . Z is the set of arcs in TSN model, indexed by (m, u) . S is the set of scenarios. W_i is the unit customer interruption cost for load at bus i . C_{gen} is the unit generation cost for the DGs in MGs. C_{tran} is the unit transportation cost for the TESSs. C_{bat} is the unit battery maintenance cost for the TESSs. $\zeta_{\omega, mu}^t$ is binary variable, 1 if TESS ω stays at MG m in time span t . $PD_i^{t,s}$ stands for active/reactive load at bus i in time span t . $PD_{r,i}^{t,s}$ is the load restored at bus i in time span t . $P_{ch, \omega m}^{t,s}$, $P_{dch, \omega m}^{t,s}$ represent charging and discharging power of TESS ω from/to MG m in time span t . $P_{DG,m}^{t,s}$ is the active power generated in MG m in time span t .

The objective function is formulated as (5), which aims to minimize the total cost, considering the customer interruption cost, MG generation cost, and TESS transportation cost and battery maintenance cost. The term $C_{tran} \sum_{(m,u) \in Z, m \neq u} \zeta_{\omega, mu}^t$ is regarding transportation cost in time span t , where $\sum_{(m,u) \in Z, m \neq u} \zeta_{\omega, mu}^t$ describes whether transporting cost take effect. When it equals to 1, the TESS ω is in transit in time span t , resulting in transportation cost. Otherwise, the transportation cost would not be incurred. The expected cost account for load consumption and PV power forecasting errors in each scenario. The term $\sum_{i \in N} W_i (PD_i^t - PD_{r,i}^t) \Delta T$ calculates the customer interruption cost in time span t . The term $\sum_{m \in M} C_{gen} P_{DG,m}^t \Delta T$ indicates the MGs generation cost in time span t . The last term

$C_{\text{bat}} \sum_{\omega \in \Omega} \sum_{m \in \mathbf{M}} |P_{\text{ch},\omega m}^t + P_{\text{dch},\omega m}^t| \Delta T$ provides the TESS battery maintenance cost for charging/discharging.

B. Constraints for the first stage

$$\sum_{(m,u) \in \mathbf{Z}} \zeta_{\omega,mu}^t = 1, \forall \omega \in \Omega, t \in \mathbf{T} \quad (6)$$

$$\sum_{mu \in \mathbf{Z}_m^-} \zeta_{\omega,mu}^t = \sum_{mu \in \mathbf{Z}_m^+} \zeta_{\omega,mu}^{t+1}, \forall \omega \in \Omega, m \in \mathbf{M} \cup \mathbf{M}_v, t \in \mathbf{T} \setminus \{T\} \quad (7)$$

$$\sum_{mu \in \mathbf{Z}_m^+} \zeta_{\omega,mu}^t = \zeta_{\omega,m}^0, \forall \omega \in \Omega, m \in \mathbf{M} \cup \mathbf{M}_v \quad (8)$$

$$\zeta_{\omega,mu}^t + \zeta_{\omega,um}^{t+1} \leq 1, \forall \omega \in \Omega, (m,u) \in \mathbf{Z}, m \neq u, t \in \mathbf{T} \setminus \{T\} \quad (9)$$

$$0 \leq P_{\text{ch},\omega m}^t \leq \zeta_{\omega,mm}^t P_{\text{ch},\omega}^{\max}, \forall \omega \in \Omega, m \in \mathbf{M}, t \in \mathbf{T} \quad (10)$$

$$0 \leq P_{\text{dch},\omega m}^t \leq \zeta_{\omega,mm}^t P_{\text{dch},\omega}^{\max}, \forall \omega \in \Omega, m \in \mathbf{M}, t \in \mathbf{T} \quad (11)$$

$$0 \leq \sum_{m \in \mathbf{M}} P_{\text{ch},\omega m}^t \leq I_{\text{ch},\omega}^t P_{\text{ch},\omega}^{\max}, \forall \omega \in \Omega, t \in \mathbf{T} \quad (12)$$

$$0 \leq \sum_{m \in \mathbf{M}} P_{\text{dch},\omega m}^t \leq I_{\text{dch},\omega}^t P_{\text{dch},\omega}^{\max}, \forall \omega \in \Omega, t \in \mathbf{T} \quad (13)$$

$$I_{\text{dch},\omega}^t + I_{\text{ch},\omega}^t \leq \sum_{m \in \mathbf{M}} \zeta_{\omega,mm}^t, \forall \omega \in \Omega, t \in \mathbf{T} \quad (14)$$

$$SOC_{\omega}^{t+1} = SOC_{\omega}^t - \frac{\Delta T}{E_{\text{TESS}}^{\text{cap}}} \left(\sum_{n \in \mathbf{M}} \frac{P_{\text{dch},\omega n}^{t+1}}{\eta_{\text{dch},\omega}} - \eta_{\text{ch},\omega} \sum_{n \in \mathbf{M}} P_{\text{ch},\omega n}^{t+1} \right), \forall \omega \in \Omega, t \in \mathbf{T} \setminus \{T\} \quad (15)$$

$$SOC_{\min} \leq SOC_{\omega}^t \leq SOC_{\max}, \forall \omega \in \Omega, t \in \mathbf{T} \quad (16)$$

$$PG_m^t = P_{\text{DG},m}^t + P_{\text{PV},m}^t - \sum_{\omega \in \Omega} P_{\text{ch},\omega m}^t + \sum_{\omega \in \Omega} P_{\text{dch},\omega m}^t - P_{\text{D},m}^t, \forall m \in \mathbf{M}, t \in \mathbf{T} \quad (17)$$

$$QG_m^t = Q_{\text{DG},m}^t + Q_{\text{PV},m}^t - Q_{\text{D},m}^t, \forall m \in \mathbf{M}, t \in \mathbf{T} \quad (18)$$

$$0 \leq P_{\text{DG},m}^t \leq P_{\text{DG},m}^{\max}, \forall m \in \mathbf{M}, t \in \mathbf{T} \quad (19)$$

$$-Q_{\text{DG},m}^{\max} \leq Q_{\text{DG},m}^t \leq Q_{\text{DG},m}^{\max}, \forall m \in \mathbf{M}, t \in \mathbf{T} \quad (20)$$

$$E_{\text{DG},m}^{t+1} = E_{\text{DG},m}^t - P_{\text{DG},m}^{t+1} \Delta T, \forall m \in \mathbf{M}, t \in \mathbf{T} \setminus \{T\} \quad (21)$$

$$E_{\text{DG},m}^{\min} \leq E_{\text{DG},m}^t \leq E_{\text{DG},m}^{\max}, \forall m \in \mathbf{M}, t \in \mathbf{T} \quad (22)$$

$$\sum_{(i,j) \in \mathbf{E}} \alpha_{ij} = |\mathbf{N}| - |\mathbf{M}| \quad (23)$$

$$\beta_{ij} + \beta_{ji} = \alpha_{ij}, \forall (i,j) \in \mathbf{E} \quad (24)$$

$$\sum_{j \in \Psi(i)} \beta_{ij} = 1, \forall i \in \mathbf{N} \setminus \mathbf{M} \quad (25)$$

$$\beta_{ij} = 0, \forall i \in \mathbf{M}, j \in \Psi(i) \quad (26)$$

$$PG_i^t - PD_{r,i}^t = \sum_{(i,j) \in \mathbf{E}} P_{ij}^t - \sum_{(k,i) \in \mathbf{E}} P_{ki}^t, \forall i \in \mathbf{N}, t \in \mathbf{T} \quad (27)$$

$$QG_i^t - QD_{r,i}^t = \sum_{(i,j) \in \mathbf{E}} Q_{ij}^t - \sum_{(k,i) \in \mathbf{E}} Q_{ki}^t, \forall i \in \mathbf{N}, t \in \mathbf{T} \quad (28)$$

$$V_j^t - V_i^t \leq M(1 - \alpha_{ij}) + \frac{r_{ij} P_{ij}^t + x_{ij} Q_{ij}^t}{V_0}, \forall (i,j) \in \mathbf{E}, t \in \mathbf{T} \quad (29)$$

$$V_j^t - V_i^t \geq -M(1 - \alpha_{ij}) + \frac{r_{ij} P_{ij}^t + x_{ij} Q_{ij}^t}{V_0}, \forall (i,j) \in \mathbf{E}, t \in \mathbf{T} \quad (30)$$

$$-\alpha_{ij} S_{ij}^{\max} \leq P_{ij}^t \leq \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, t \in \mathbf{T} \quad (31)$$

$$-\alpha_{ij} S_{ij}^{\max} \leq Q_{ij}^t \leq \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, t \in \mathbf{T} \quad (32)$$

$$-\sqrt{2} \alpha_{ij} S_{ij}^{\max} \leq P_{ij}^t + Q_{ij}^t \leq \sqrt{2} \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, t \in \mathbf{T} \quad (33)$$

$$-\sqrt{2} \alpha_{ij} S_{ij}^{\max} \leq P_{ij}^t - Q_{ij}^t \leq \sqrt{2} \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, t \in \mathbf{T} \quad (34)$$

$$V_i^{\min} \leq V_i^t \leq V_i^{\max}, \forall i \in \mathbf{N} \setminus \mathbf{M}, t \in \mathbf{T} \quad (35)$$

$$V_i^t = V_0, \forall i \in \mathbf{M}, t \in \mathbf{T} \quad (36)$$

$$0 \leq PD_{r,i}^t \leq PD_i^t, \forall i \in \mathbf{N}, t \in \mathbf{T} \quad (37)$$

$$QD_{r,i}^t = PD_{r,i}^t \tan(\cos^{-1} \varphi), \forall i \in \mathbf{N}, t \in \mathbf{T} \quad (38)$$

Where $\mathbf{E}$ is the set of DS branches, indexed by (i,j) . $\Psi(i)$ is the set of buses connected to bus i in DS. $\mathbf{M}_v$ is the set of virtual nodes in TSN. $\mathbf{Z}_m^+$ is the set of arcs in TSN starting from MG m . $\mathbf{Z}_m^-$ is the set of arcs in TSN ending at MG m . ΔT is the time step. r_{ij} and x_{ij} are the resistance and reactance of line (i,j) . φ is Power factor of load at bus i . QD_i^t stands for active/reactive load at bus i in time span t . $S_{ij}^{\max}$ is the apparent power capacity of line (i,j) . $V_i^{\max}$ and $V_i^{\min}$ are the maximum/minimum voltage magnitude at bus i . $P_{\text{DG},m}^{\max}$ and $Q_{\text{DG},m}^{\max}$ are the maximum active and reactive power of equivalent dispatchable DG in MG m . $E_{\text{DG},m}^{\max}$ and $E_{\text{DG},m}^{\min}$ are the energy capacity and minimum reserve in MG m . $P_{\text{D},m}^t$ and $Q_{\text{D},m}^t$ represent local active and reactive load in MG m in time span t . η_{ch} and η_{dch} stand for charging and discharging efficiency of TESSs. $P_{\text{ch}}^{\max}$ and $P_{\text{dch}}^{\max}$ are the maximum charging and discharging power of TESSs. $SOC_{\max/\min}$ represent the maximum/minimum SOC level of TESSs. $E_{\text{TESS}}^{\text{cap}}$ is the energy capacity of TESSs. PG_i^t and QG_i^t are the active and reactive power generated at bus i in time span t . $P_{\text{PV},m}^t$ and $Q_{\text{PV},m}^t$ are the active and reactive PV power generation in MG m in time span t . $QD_{r,i}^t$ is the load restored at bus i in time span t . P_{ij}^t and Q_{ij}^t represent active and reactive power of line (i,j) in time span t . V_i^t is the voltage magnitude at bus i in time span t . α_{ij} is binary variable, 1 if the line (i,j) is connected. β_{ij} is binary variable, 1 if bus j is the parent of bus i . $Q_{\text{DG},m}^t$ is the reactive power generated in MG m in time span t . $E_{\text{DG},m}^t$ is the amount of energy of equivalent dispatchable DG in MG m in time span t . $I_{\text{ch},\omega}$ and $I_{\text{dch},\omega}$ are binary variables, charging/discharging state of TESS ω in time span t . SOC_{ω}^t stand for the SOC of TESS ω in time span t .

The optimization problem is formulated as a MILP and the constraints are classified into 5 categories as follows:

1) TESSs temporal-spatial constraints: (6)-(9). Equation (6) ensures that TESS ω can be either in transit arc or parking arc. Constraints (7) and (8) refer to the flow conservation for both MG nodes and virtual stations [17]. In (7), TESS ω which ends the trip in time span t at MG node m , is certain to keep staying on one of the arcs which start from node (t,m) in the next time span $t+1$. Constraint (8) declares the initial position. The constraint (9) guarantees that under no circumstances TESSs are able to make immediate round trip.

2) TESSs operation constraints: (10)-(16). Constraints (10) and (11) describe the feasible sets of charging/discharging power of TESS ω to MG m . Equations (12) and (13) define the TESS charging/discharging constraints associated with its operation mode. The operation mode constraint is described in (14), indicating that TESS can operate in charging/discharging mode for exchanging power with MGs only if it is on parking arcs to stay in a certain MG. Constraint (15) determines the state of charge (SOC) of TESS ω with respect to time span t . Finally, the SOC upper and lower bounds are denoted in (16),

in which the $SOC_{\min}$ and $SOC_{\max}$ are set to prevent batteries from deep discharging and overcharging.

3) MGs operation constraints: (17)-(22). Equations (17) and (18) stand for the active and reactive power support from MG to DS via PCC bus m , considering TESS charging from and discharging to MGS. Constraints (19) and (20) enforce the real and reactive power capacity constraints upon dispatchable DG in MGs. Equation (21) calculates the amount of energy in MGs. The energy constraints of MGs are given in(22).

4) Distribution network topology constraints: (23)-(26). The necessary condition for the spanning tree is denoted by (23). Equation (24) determines if a line is connected by checking that either $\beta_{ij}=1$ or $\beta_{ji}=1$ [18]. Equation (25) represents that every bus other than the MG buses has exactly one parent, while constraint (26) enforces that the MG buses, serving as the root buses, has no parent.

5) DS operation constraints: (27)-(38). Equations (27) and (28) are constraints regarding real and reactive power balance at each in time span t . Equations (29) and (30) enforce constraints on line voltage drop [15], [19]. Constraints (31)-(34) provides the branch capacity limit, which is a linearized approximation as given in [20]. Constraint (36) sets the voltage of MG buses to V_0 . Constraints (37) and (38) requires that power factor of each load should be maintained.

C. Constraints for the second stage

$$0 \leq P_{ch,om}^{t,s} \leq \zeta_{\omega,mm}^t P_{ch,\omega}^{\max}, \forall \omega \in \Omega, m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (39)$$

$$0 \leq P_{dch,om}^{t,s} \leq \zeta_{\omega,mm}^t P_{dch,\omega}^{\max}, \forall \omega \in \Omega, m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (40)$$

$$0 \leq \sum_{m \in \mathbf{M}} P_{ch,om}^{t,s} \leq I_{ch,\omega}^t P_{ch,\omega}^{\max}, \forall \omega \in \Omega, s \in \mathbf{S}, t \in \mathbf{T} \quad (41)$$

$$0 \leq \sum_{m \in \mathbf{M}} P_{dch,om}^{t,s} \leq I_{dch,\omega}^t P_{dch,\omega}^{\max}, \forall \omega \in \Omega, s \in \mathbf{S}, t \in \mathbf{T} \quad (42)$$

$$SOC_{\omega}^{t+1,s} = SOC_{\omega}^{t,s} - \frac{\Delta T}{E_{TESS}^{\text{cap}}} \left(\sum_{m \in \mathbf{M}} P_{dch,om}^{t+1,s} - \eta_{ch,\omega} \sum_{m \in \mathbf{M}} P_{ch,om}^{t+1,s} \right), \forall \omega \in \Omega, s \in \mathbf{S}, t \in \mathbf{T} \setminus \{T\} \quad (43)$$

$$SOC_{\min} \leq SOC_{\omega}^{t,s} \leq SOC_{\max}, \forall \omega \in \Omega, s \in \mathbf{S}, t \in \mathbf{T} \quad (44)$$

$$PG_m^{t,s} = P_{DG,m}^{t,s} + P_{PV,m}^{t,s} - \sum_{\omega \in \Omega} P_{ch,om}^{t,s} + \sum_{\omega \in \Omega} P_{dch,om}^{t,s} - P_{D,m}^{t,s}, \forall m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (45)$$

$$QG_m^{t,s} = Q_{DG,m}^{t,s} + Q_{PV,m}^{t,s} - Q_{D,m}^{t,s}, \forall m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (46)$$

$$0 \leq P_{DG,m}^{t,s} \leq P_{DG,m}^{\max}, \forall m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (47)$$

$$-Q_{DG,m}^{\max} \leq Q_{DG,m}^{t,s} \leq Q_{DG,m}^{\max}, \forall m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (48)$$

$$E_{DG,m}^{t+1,s} = E_{DG,m}^{t,s} - P_{DG,m}^{t+1,s} \Delta T, \forall m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \setminus \{T\} \quad (49)$$

$$E_{DG,m}^{\min} \leq E_{DG,m}^{t,s} \leq E_{DG,m}^{\max}, \forall m \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (50)$$

$$PG_i^{t,s} - PD_{r,i}^{t,s} = \sum_{(i,j) \in \mathbf{E}} P_{ij}^{t,s} - \sum_{(k,i) \in \mathbf{E}} P_{ki}^{t,s}, \forall i \in \mathbf{N}, s \in \mathbf{S}, t \in \mathbf{T} \quad (51)$$

$$QG_i^{t,s} - QD_{r,i}^{t,s} = \sum_{(i,j) \in \mathbf{E}} Q_{ij}^{t,s} - \sum_{(k,i) \in \mathbf{E}} Q_{ki}^{t,s}, \forall i \in \mathbf{N}, s \in \mathbf{S}, t \in \mathbf{T} \quad (52)$$

$$V_j^{t,s} - V_i^{t,s} \leq M(1 - \alpha_{ij}) + \frac{r_{ij} P_{ij}^{t,s} + x_{ij} Q_{ij}^{t,s}}{V_0}, \forall (i,j) \in \mathbf{E}, s \in \mathbf{S}, t \in \mathbf{T} \quad (53)$$

$$V_j^{t,s} - V_i^{t,s} \geq -M(1 - \alpha_{ij}) + \frac{r_{ij} P_{ij}^{t,s} + x_{ij} Q_{ij}^{t,s}}{V_0}, \forall (i,j) \in \mathbf{E}, s \in \mathbf{S}, t \in \mathbf{T} \quad (54)$$

$$-\alpha_{ij} S_{ij}^{\max} \leq P_{ij}^{t,s} \leq \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, s \in \mathbf{S}, t \in \mathbf{T} \quad (55)$$

$$-\alpha_{ij} S_{ij}^{\max} \leq Q_{ij}^{t,s} \leq \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, s \in \mathbf{S}, t \in \mathbf{T} \quad (56)$$

$$-\sqrt{2} \alpha_{ij} S_{ij}^{\max} \leq P_{ij}^{t,s} + Q_{ij}^{t,s} \leq \sqrt{2} \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, s \in \mathbf{S}, t \in \mathbf{T} \quad (57)$$

$$-\sqrt{2} \alpha_{ij} S_{ij}^{\max} \leq P_{ij}^{t,s} - Q_{ij}^{t,s} \leq \sqrt{2} \alpha_{ij} S_{ij}^{\max}, \forall (i,j) \in \mathbf{E}, s \in \mathbf{S}, t \in \mathbf{T} \quad (58)$$

$$V_i^{\min} \leq V_i^{t,s} \leq V_i^{\max}, \forall i \in \mathbf{N} \setminus \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (59)$$

$$V_i^{t,s} = V_0, \forall i \in \mathbf{M}, s \in \mathbf{S}, t \in \mathbf{T} \quad (60)$$

$$0 \leq PD_{r,i}^{t,s} \leq PD_i^{t,s}, \forall i \in \mathbf{N}, s \in \mathbf{S}, t \in \mathbf{T} \quad (61)$$

$$QD_{r,i}^{t,s} = PD_{r,i}^{t,s} \tan(\cos^{-1} \varphi_i), \forall i \in \mathbf{N}, s \in \mathbf{S}, t \in \mathbf{T} \quad (62)$$

In the second stage constraints, the uncertainty of PV power generation and load consumption is characterized under each scenario s .

D. Solution Algorithm

In the second stage constraints, the uncertainty of PV power generation and load consumption is characterized under each scenario s . The consideration of scenarios makes the problem difficult to solve directly. In this paper, a Benders decomposition algorithm is adopted to decompose the original problem into a master problem and multiple subproblems. The master problem determines the TESS trip chain and network topology, where the PV power and load consumption are adopted as forecasted value. The subproblems check the feasibilities for all scenarios and optimizes the generation output. If the feasibility check identifies any violations in scenarios, the feasibility Benders cuts will be generated and added into the master problem. The iteration process proceeds until it satisfies the terminate criteria.

IV. CASE STUDIES

In this section, the case studies are implemented on a modified 33-bus test system [21] to verify the proposed restoration method. The model is formulated using MATLAB 2016a and solved by Gurobi [22].

A. Test Systems

The modified 33-bus test feeder is shown in Fig. 3. The entire DS gets disconnected to the utility grid, the substation and three lines (1, 2), (6, 26) and (32, 33) are at fault as a result of disastrous events. Fig. 4 present the load profile [19] and two load priority levels with unit customer interruption cost [23], [24].

TABLE I provides the generation and load information for MGs. The local load in MGs also follow the load profile as given in Fig. 4. The PV power generation multipliers are shown in Fig. 5. The initial position of 4 TESSs are at MG14, MG21, MG21 and MG25, respectively. The charging/discharging power capacity are 0.2 MW. The energy capacity is 1.0 MWh. Initial SOC is set to 0.5, and $SOC_{\max}$ and $SOC_{\min}$ are 0.90 and 0.10, respectively. The charging/discharging efficiency are 0.95. The time horizon is set to 24 hours and time step is 1 hour. The unit generation cost for MG is \$0.5/kWh. The unit transportation cost for TESS is \$80 per transit. The unit battery

maintenance cost for TESS is 0.2\$/kWh. The V_0 is set to 1.0 p.u. The $V^{\max}$ and $V^{\min}$ are 1.05 p.u. and 0.95 p.u., respectively.

In the remaining section, three cases are investigated as follows.

Case 1) DS has MGs and TESSs, which serve as stationary energy storage systems;

Case 2) DS has MGs and TESSs, which serve as mobile energy storage systems.

Fig. 3. A modified 33-bus test system with 3 MGs and multiple faults

Fig. 4. Load type, profile and interruption cost

Fig. 5. Predicted PV power multipliers

MG bus #		14	21	25
DG Generation	Real power (MW)	1.60	1.60	1.80
	Reactive power (MVar)	1.28	1.28	1.44
PV Generation	Real power (MW)	0.2		
	Power factor	1.0		
Energy capacity (MWh)		23.04	23.04	25.92
Minimum fuel reserve (MWh)		2.30	2.30	2.59
Local load	Peak load (MW)	0.5	0.7	0.7
	Power factor	0.9	0.9	0.9
	Load type	C	R	I

Note: I = Industrial, C = Commercial, R = Residential

B. Simulation Results

Results		Case 1	Case 2
Interruption cost		77275	62108

Objective (\$)	MG generation cost	32400	32400
	Transportation cost	0	480
	Battery maintenance cost	487	1102
	Total cost	110163	96091
Load restoration (%)	Priority I	94.75	97.69
	Priority II	27.72	20.65
	Total	73.64	73.77

TABLE II compares the techno-economic results for two different cases.

Compared with case1, the total cost decreases by 12.77% to \$96091 in case 2, highlighting that the TESSs transportability can facilitate the service restoration. The load restored for priority I enhances to 97.69% and reduces to 20.65% for priority II, respectively. The opening line switches are (3, 4), (8, 21), (10, 11), (21, 22), and (24, 25). In addition, each one is energized by a corresponding MG to satisfy radial topology.

Fig. 6. TESS scheduling results in case 2

Fig. 7. Generation dispatch in case 2

In our simulations, it is observed that TESSs are charged where and when the power generation resource is relatively surplus for critical loads and discharged to the grid where and when the power or energy is insufficient. Energy imbalance posed by topology and operation constraints deters the effective utilization of MGs' generating resource. In this case, the TESS2 is charged from 00:00 to 02:00 and 08:00 to 09:00 in MG21 (see Fig. 6 and Fig. 7). Then TESS2 travels to MG25 in (14:00-15:00) and discharges to MG25 from 18:00 to 23:00. Here, energy is transferred from MG21 to MG25 through TESS1.

Similar phenomena can be observed from other TESSs.

Meanwhile, TESSs can also serve as stationary DERs to achieve load shifting within the same MGs. For instance, the TESS1 stays at MG14 in (00:00-17:00), it charges in 3 different periods and discharges to MG14 from 09:00 to 11:00. TESS1 would charge in energy sufficient hours and when it comes to the peak hour, the TESS1 can discharge to MG14 to achieve efficient utilization of energy resources within MG14.

V. CONCLUSIONS

The paper investigated a post-disaster restoration scheme to achieve the minimum total cost by scheduling TESSs in coordination with distribution network reconfiguration and MG operation. With charging/discharging facilities, MGs serve as root buses to dynamically form islands by controlling ON/OFF status of remote-controlled switches. A modified TSN-based TESS scheduling model is presented and integrated into distribution network reconfiguration to allocate TESSs among MGs. The TESSs transportability can efficiently transfer energy in DS in appropriate times and locations to facilitate critical loads service restoration without violating network topology and operation constraints. Meanwhile, TESSs can also serve as stationary DERs to implement load shifting within MGs.

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