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### Abstract

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# Resilient Restoration of Power Distribution System Based on Minimum Spanning Forest

Shiva Poudel<sup>1</sup>, Hongbo Sun<sup>2</sup>, Daniel Nikovski<sup>2</sup>, and Jinyun Zhang<sup>2</sup>

<sup>1</sup>Washington State University, Pullman, WA 99164,

<sup>2</sup>Mitsubishi Electric Research Laboratories, Cambridge, MA, 02139,

<sup>1</sup>shiva.poudel@wsu.edu, <sup>2</sup>{hongbosun, nikovski, jzhang}@merl.com}

**Abstract**—In this paper, the concept of minimum spanning forest (MSF) is utilized to formulate the restoration problem where each spanning tree in a forest is a self-sustained islanded grid (SSIG). Specifically, a weight is assigned to each edge in a distribution system based on several factors such as their exposure to vegetation, span length, location and structures supporting them. Then, a MSF is obtained for the given network by switching off the edges with higher weights to form several SSIGs each energized by a master unit (micro-turbine) in coordination with several intermittent DGs (wind, solar) and energy storage system (ESS) while achieving the resilience objectives. Numerical results based on modified IEEE 123-node test case validates the effectiveness of the proposed approach.

## I. INTRODUCTION

The electric power grid is one of the most critical infrastructures of a nation; virtually every aspect of a modern society (transportation, water supply, school, city halls, airports and so on) relies on the supply of electricity. Unfortunately, the increased frequency, duration, and intensity of extreme weather events pose severe threats to the power grid causing wide-area power outages primarily affecting in low- and mid-voltage power distribution grid that contributes to an estimated of 90% of the outages [1]. Although weather-related power outages in the power grid are not frequent, their consequences are staggering. For example, when hurricanes Harvey, Irma and Maria hit the United States on August and September of 2017, a total of around 7.5 million customers in Texas, Florida and Puerto Rico were left without electricity [2].

Although the smart and optimal designs for a resilient power grid outlined in [3], [4] help to maintain the standard of service, the outage in distribution networks is inevitable. Thus, it is always an open and interesting topic to study how well to utilize the available resources during the disaster period to achieve a certain level of resilience. Several restoration strategies proposed in [5]–[7] are not applicable for disaster scenarios because they only consider typical outages and assume distribution and transmission network are intact. The distributed generation (DG) units managed by microgrids are considered an effective and reliable way to continue supplying critical loads in such a scenario [8]. Several articles in past have sought to improve the grid resilience with distributed generators by circuit reconfiguration using remote-controlled switches [9]–[12].

Although a vast body of literature exists in the resilient restoration domain, there remain few gaps in the state-of-the-art. First, the methods based on search or other heuristics, although model a detail three-phase distribution system, do not provide mathematical insights and can be time-consuming [5], [13]. Second, the existing methods using linear programming based on per-phase analysis are not applicable for practical distribution feeder [9], [11], [12]. Third, most of the literature fails to prove the physical survivability of the islanded grid in the post-restorative state until the infrastructures are fully recovered. Motivated by such observations, we propose a novel method of resilient restoration of disaster-impacted distribution network using the concept of MSF for bridging the aforementioned gaps in the literature.

The specific contributions of the paper are

- 1) A novel restoration approach is proposed to meet the resilience criteria during the disaster period based on the concept of MSF.
- 2) The uncertain behavior of load consumption and power output from intermittent DGs are modeled for providing the solution in a given optimization horizon.
- 3) A mixed-integer linear program (MILP) is developed by transforming the combinatorial problem of path search which can be efficiently and quickly solved by off-the-shelf solvers.

## II. RESILIENT RESTORATION PROBLEM DESCRIPTION

In this section, the scope of this work is clearly defined and the graphical representation of the proposed framework is presented. Several variables are introduced and defined for a better understanding of the problem formulation in Section III.

### A. Problem Definition and Scope

It is well known from a conceptual resilience curve that the response of the power grid in case of an extreme event is divided into different time frames. The system undergoes through the degraded and restorative state before the utility comes back and infrastructure recovery has been completed. We specifically focus on time frame where some restorative actions are implemented by utility and crew members such that system gradually moves from degraded to restorative state. The restorative actions are completed and the system reaches a higher level of performance called as post-restoration state.

The system remains on the post-restoration state where several islands or isolated system are formed as per the restoration algorithm until the normal power from the utility comes back. Usually, during an outage caused by extreme events, it takes several days and sometimes even weeks and months to access normal power from the utility. A recent example is an outage in Puerto Rico where strong winds and tree branches damaged power lines, transmission towers and substations that were already weakened by hurricane Irma less than two weeks before the strike of hurricane Maria and the result was complete blackout [14]. Thus, it is very important to ensure that the restoration solutions do not fail physically in the aftermath of the disaster before the main grid comes back. One key approach to restoring the loads after a natural disaster is to use the local DGs by suitable islanding scheme. With this in mind, we propose a resilient restoration strategy to restore the maximum possible critical loads by forming a MSF from the available DGs in the network.

### B. Graphical Representation

The distribution network can be modeled as a graph  $\mathcal{G}(\mathcal{V}, \mathcal{E})$  with set of buses or nodes  $\mathcal{V}=\{1,2,3,\dots,n\}$  and set of edges  $\mathcal{E}$ . The restoration of distribution system can be viewed as splitting the graph into self-adequate sub-areas which are referred as ‘Self-Sustained Islanded Grid’. Each SSIG is energized by a single MT and other non-dispatchable DGs and no MTs are networked in the restoration process. Several binary variables associated with the problem are defined below:

- A binary variable  $v_i = \{0,1\}$  is assigned to each node, where  $v_i = 1$  implies that node  $i$  belongs to one of the SSIGs while  $v_i = 0$  implies node  $i$  is not energized during the restoration process.
- A binary variable  $s_i = \{0,1\}$  is assigned to each of node, where  $s_i = 1$  implies that load connected to node  $i$  is picked up and vice-versa. Note that for a load to be picked up both  $v_i$  and  $s_i$  should pick a value of 1.
- A binary variable  $\delta_{ij} = \{0,1\}$  is assigned to each of the sectionalizing and tie switches, where  $\delta_{ij} = 1$  implies that switch joining nodes  $i$  and  $j$  is closed and vice-versa. Fig. 1 shows the graphical representation of the distribution system restoration problem and illustrates the operation of several switches to restore the loads. Similarly, a dispatchable DG i.e., a MT is modeled as a virtual switch in the proposed framework and a binary variable  $\delta_{ij} = \{0,1\}$  is assigned to each MT switch where  $\delta_{ij} = 1$  implies that MT is connected to node  $j$  and virtual switch between substation node ( $i$ ) and MT-node ( $j$ ) is closed. Now, the MT is ready to inject power  $P_{MT}$  and  $Q_{MT}$  to node  $j$ .

### III. PROBLEM FORMULATION

In this study, the resilient restoration of distribution system with DGs is formulated as a constrained multi-objective problem. The objective function and associated problem constraints are explained in following sub-sections.

#### A. Resilient Restoration Objective

Several articles in past describe a resilient design tool to determine an optimal design of distribution system upgrades

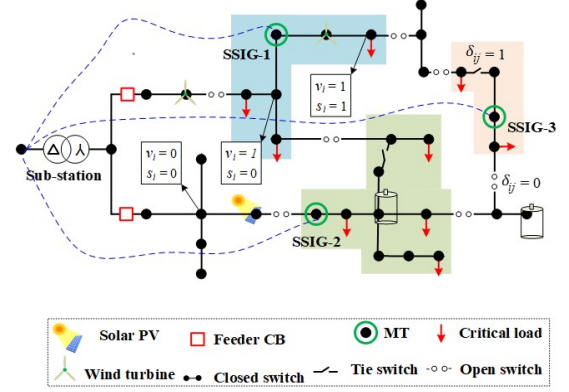


Fig. 1: Example feeder and graphical representation of SSIGs.

$(i, j, c)$	Node indices
$\mathcal{V}/\mathcal{E}$	Set of nodes/edges in graph $\mathcal{G}$
$\mathcal{E}^f$	Set of faulted or disconnected lines
$\mathcal{E}_v$	Set of virtual edges for a DG
$\mathcal{E}^c$	Set of edges in a particular cycle $c$
$\mathcal{V}_c$	Set of nodes with critical loads
$\mathcal{Y}_i$	Set of children nodes of node $i$
$\mathcal{M}$	A big number
$v_i$	Node energizing variable
$s_i$	Load pick-up Variable
$\delta_{ij}$	Line or switch decision variable
$w_{ij}^v$	Weight assigned to an edge ( $i \rightarrow j$ )
$L_{ij}$	Length of line joining nodes $i$ and $j$
$\mathbf{r}_{ij}/\mathbf{x}_{ij}$	Resistance/reactance matrix of line $i \rightarrow j$
$P_{Li}^\phi + jQ_{Li}^\phi$	Apparent power demand at node $i$ for each phase
$P_{Li} + jQ_{Li}$	Three-phase load demand at node $i$
$P_{ij} + jQ_{ij}$	Three-phase apparent power flowing from $i \rightarrow j$
$P_{ij}^\phi + jQ_{ij}^\phi$	Per-phase apparent power flow from bus $i$ to $j$
$P_{DG} + jQ_{DG}$	Three-phase apparent power output from a DG
$P_{DG}^{max} + jQ_{DG}^{max}$	Real and reactive power capacity of a DG
$\mathbf{U}_i$	Vector of square value of nodal voltage magnitude
$\mathbf{U}^{min}, \mathbf{U}^{max}$	Permissible values for square of node voltage

to meet the resilience performance targets during extreme events (for example, [3]). Suppose, the predetermined load satisfaction level for which the resilient planning is done be  $\lambda = \lambda_{min}$  and  $\beta = \beta_{min}$ . Note that  $\lambda$  and  $\beta$  are the resilience criteria in the percentage of critical loads and non-critical loads. With this consideration, the primary objective function is to restore maximum possible critical and few non-critical loads using DGs.

$$\text{Max: } \lambda + \beta \quad (1)$$

where,  $\lambda$  and  $\beta$  are the fractions of critical and non-critical loads picked up during the restoration. For each time interval, these resilience parameters can be expressed as,

$$\lambda_t = \frac{\sum_{i \in \mathcal{V}_c} \sum_{\phi \in \{a,b,c\}} s_{i,t} P_{Li,t}^\phi}{\sum_{i \in \mathcal{V}_c} P_{Li,t}^\phi} \quad (2a)$$

$$\beta_t = \frac{\sum_{i \in (\mathcal{V} \setminus \mathcal{V}_c)} \sum_{\phi \in \{a,b,c\}} s_{i,t} P_{Li,t}^\phi}{\sum_{i \in (\mathcal{V} \setminus \mathcal{V}_c)} P_{Li,t}^\phi} \quad (2b)$$

$$\lambda_t \geq 0.8 \quad \text{and} \quad \beta_t \geq 0.1 \quad (2c)$$

Different isolated areas (SSIGs) are formed using DGs to restore the loads after an extreme event where each area

is energized by a single MT in coordination with several intermittent DGs. Specifically, several sub-trees are formed and each sub-tree is operating in a radial topology. In graph theory, such a process is referred to as forming a spanning forest where each spanning trees are a connected network. It is also well understood that the restoration scheme should be able to withstand any further shock or second strike of a disaster. In addition, the distribution network is stressed after experiencing an extreme event. Thus, it is desired that the restoration solution obtained from the proposed approach doesn't fail physically before the utility power comes back. The main reason of fault in the distribution system is because of trees falling on lines, wind loading or snow storm causing lines to be tripped. Thus, a new metric is defined such that distribution lines with longer spans, having right-of-way across a dense vegetation (trees) or those which are prone to failures are avoided. Specifically, a weight is assigned to each edge based on above-mentioned factors and we try to minimize the weighted sum of edges in a restored network. This is in accordance with the formation of MSF in a distribution network. Different SSIGs are formed by switching the edges with higher weights to get MSF which is our secondary objective function.

$$\text{Min: } \sum_{(ij) \in \mathcal{E}} \delta_{ij} (w_{ij}^v \times L_{ij}) \quad (3)$$

The overall objective function for resilient restoration (4) is a combination of the primary and secondary objectives provided in (1) and (3). A proper value of  $w_s$  should be selected to ensure that the secondary objective is considered only when the primary objective values are the same.

$$\text{Min: } - \sum_t^t (\lambda_t + \beta_t) + w_s \sum_{(ij) \in \mathcal{E}} \delta_{ij} (w_{ij}^v \times L_{ij}) \quad (4)$$

### B. Problem Constraints

The several constraints associated with the proposed restoration problem are described in equations (5)-(12).

#### 1) Connectivity constraints:

$$v_i \leq 1, \quad \forall i \in \mathcal{V} \quad (5a)$$

$$s_{i,t} \leq v_i, \quad \forall i \in \mathcal{V} \quad (5b)$$

- Constraint (5a) implies that a node can be picked up by one of the SSIGs in a restoration process and at max, it can take a value of 1. Equation (5b) requires that a load with the switch can only be energized if it is connected to an energized node.

$$\delta_{ij} \leq v_i v_j, \quad \forall (ij) \in \mathcal{E} \setminus \mathcal{E}^f \quad (6a)$$

$$\delta_{ij} = 0, \quad \forall (ij) \in \mathcal{E}^f \quad (6b)$$

- Decision variables for line ( $\delta_{ij}$ ) is obtained from (6). This implies that during normal operating conditions, the decision variables for a line to be used in the restoration depends upon the nodes that are energized. Equation (6a) ensures

that if a line with remote controlled switch is energized, nodes connecting that line must be energized. The fault or open switches in a distribution network is modeled using constraint (6b).

$$\sum_{(ij) \in \mathcal{E}^c} \delta_{ij} \leq |\mathcal{E}^c| - 1, \quad \forall (i, j) \in \mathcal{V} \quad (7)$$

- A new radial configuration of the faulted PDS is achieved by closing and opening appropriate tie switches, sectionalizing switches and MT virtual switches. This radiality is ensured by constraint (7) which enforces at least one of the switches in a cycle to be open. The number of cycles and the edges within a cycle are enumerated using iterative loop counting algorithm which is a "brute force" technique.

2) *Power balance and voltage constraints:* A linear power flow model for the three-phase unbalanced distribution system is proposed in [15] and is directly incorporated into our power balance and voltage constraints by coupling with line variables and linearizing it with the big-M method.

$$\begin{aligned} U_{i,t} - U_{j,t} &\leq 2(\tilde{\mathbf{r}}_{ij} \mathbf{P}_{ij,t} + \tilde{\mathbf{x}}_{ij} \mathbf{Q}_{ij,t}) + M(1 - \delta_{ij}), \\ U_{i,t} - U_{j,t} &\geq 2(\tilde{\mathbf{r}}_{ij} \mathbf{P}_{ij,t} + \tilde{\mathbf{x}}_{ij} \mathbf{Q}_{ij,t}) - M(1 - \delta_{ij}), \end{aligned} \quad (8)$$

$$\forall (i, j) \in \mathcal{V}, \forall (ij) \in \mathcal{E}$$

where,  $\tilde{\mathbf{r}}_{ij} = \text{Real}\{\alpha\alpha^H\} \otimes \mathbf{r}_{ij} + \text{Im}\{\alpha\alpha^H\} \otimes \mathbf{x}_{ij}$ ,  $\tilde{\mathbf{x}}_{ij} = \text{Real}\{\alpha\alpha^H\} \otimes \mathbf{x}_{ij} + \text{Im}\{\alpha\alpha^H\} \otimes \mathbf{r}_{ij}$  and  $\alpha = [1 \ e^{-j2\pi/3} \ e^{j2\pi/3}]^T$

$$\begin{aligned} \sum_{(ij) \in \mathcal{E}} \delta_{ij} \mathbf{P}_{ij,t} + \mathbf{P}_{j,t}^R + \mathbf{P}_{j,t}^E &= s_{j,t} \mathbf{P}_{L,j,t} + \sum_{c \in \mathcal{Y}_i} \delta_{jc} \mathbf{P}_{j,c,t}, \\ \sum_{(ij) \in \mathcal{E}} \delta_{ij} \mathbf{Q}_{ij,t} + \mathbf{Q}_{j,t}^R &= s_{j,t} \mathbf{Q}_{L,j,t} + \sum_{c \in \mathcal{Y}_i} \delta_{jc} \mathbf{Q}_{j,c,t}, \end{aligned} \quad (9)$$

$$\forall (i, j) \in \mathcal{V}$$

$$v_i U^{min} \leq U_{i,t} \leq v_i U^{max}, \quad \forall (i, j) \in \mathcal{V} \quad (10)$$

- Constraints (8) is written for the voltage constraints by coupling with a line or switch variable  $\delta_{ij}$ . If two nodes  $i$  and  $j$  are connected without a remotely switchable line or if the line is energized, the voltage difference of the branch is then constrained by power flow; otherwise, the voltage difference is arbitrary. This is represented by equation (8) which ensures the equality constraints are applied for energized lines only. The voltage of each node should be within the limit and is ensured by equation (10).  $U^{min}$  and  $U^{max}$  are set to  $0.95^2$  p.u. and  $1.05^2$  p.u. respectively for each phase present in the line.
- Power flow equations, ignoring the losses, are represented using (9). Three-phase linear power flow model is used in this formulation where power flow equations are written along each line.
- Energy storage constraints are given in (11). Constraint (11a) represents the charging and discharging limits of an energy storage system (ESS) depending on its operating mode. Charging action and discharging action are mutually exclusive; that is, an ESS works in only one mode at a certain time. This is ensured by (11b) which requires

that an ESS can only start to charge or discharge when the connected node is energized. Constraint (11c) evaluates the state of charge (residual energy) of an ESS. Similarly, Constraint (11d) represents the limit of SOC.

$$-\lambda_{i,t}^c \mathbf{P}_{i,t}^{ch,max} \leq \mathbf{P}_{i,t}^E \leq \lambda_{i,t}^d \mathbf{P}_{i,t}^{dch,max} \quad (11a)$$

$$\lambda_{i,t}^c + \lambda_{i,t}^d \leq v_i \quad (11b)$$

$$SOC_{i,t} = SOC_{i,t-1} - \frac{T}{EC_i} (\lambda_{i,t}^d \mathbf{P}_{i,t}^E \eta_d^{-1} + \lambda_{i,t}^c \mathbf{P}_{i,t}^E \eta_c) \quad (11c)$$

$$SOC_i^{min} \leq SOC_{i,t} \leq SOC_i^{max} \quad (11d)$$

3) *MT capacity constraints:*

$$\delta_{ij} P_{MT}^{min} \leq \sum_{\phi \in \{a,b,c\}} P_{ij,t}^\phi \leq \delta_{ij} P_{MT}^{max}, \forall (ij) \in \mathcal{E}_V \quad (12)$$

$$\delta_{ij} Q_{MT}^{min} \leq \sum_{\phi \in \{a,b,c\}} Q_{ij,t}^\phi \leq \delta_{ij} Q_{MT}^{max}, \forall (ij) \in \mathcal{E}_V$$

- Constraint (12) ensures that the in-flow power of each MT-node from substation node should be less than or equal to the MT capacity.

#### IV. RESULTS

The proposed resilient restoration algorithm is tested on the modified IEEE 123-node test feeder [16]. Regulators and capacitors are not modeled in the restoration problem. In addition, to fully utilize the performance of tie switch 54-94, line configuration of 93-94 is changed from 9 to 2, i.e., the line is made three phase.

##### A. Parameters and Environment Setup

The proposed MILP formulation is solved using CPLEX 12.6. We have used MATLAB R2018a to formulate the desired model which is then linked with the CPLEX solver. The simulation is carried out on a PC with Intel Core i7-7700K CPU @ 4.20 GHz processor and 64 GB RAM.

It is assumed that the test-case has experienced a major disaster and hence the main substation is at fault. Thus, the feeder has no access to the normal supply of electricity. In addition, several distribution lines are at fault as shown in Fig. 2. In such case, it is desired to utilize the locally available DGs to pick up maximum possible critical loads. Components participating in the restoration of different categories have different operational attributes. For example, the output power of intermittent DGs (solar and wind) and load demand vary with the weather condition, human activities, and many other factors, causing uncertainties. Continuous operation of dispatchable DGs and ESS depends on the available generation resources (i.e., fuel reserve or state of charge).

Fig. 3 shows the load profile and predicted DG (solar and wind) outputs with assumed multipliers where the multipliers are used to make the load and generation profile change with time. For simplicity, it is assumed that all loads have the same multiplier. The key point is to obtain the adjustable output of dispatchable DGs and perform necessary load-shedding while utilizing the given loading, renewable generation, and storage

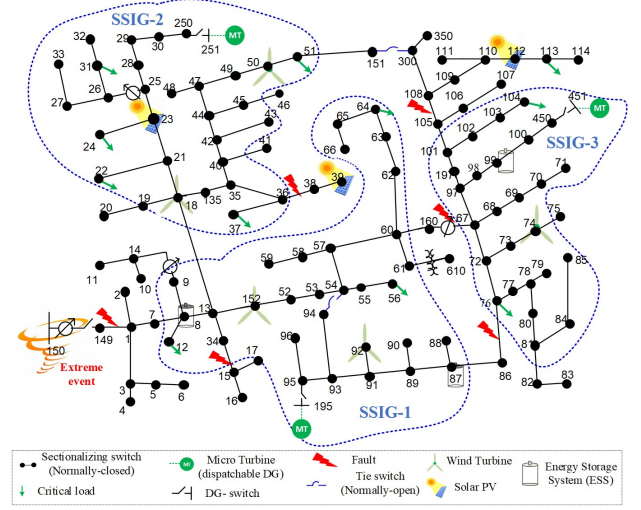


Fig. 2: Three SSIGs formed from three MTs and coordination of several intermittent DGs and ESS.

TABLE I: Parameters of DGs and ESS

Resources	$P^{max}$ (kW)	
MT	202.35, 220.65, 210.21	
WT	60, 30, 45, 60, 36	
PV	30, 30, 60	
	60, 72, 120	
ESS	Attribute	Value
	$E_{SS}^{rated}$	200 kWh
	$\eta_c$ and $\eta_d$	95%
	$SOC_{max}/SOC_{min}$	0.9/0
	$p_{ch,max}/p_{dch,max}$	0.5 $p^{max}$
$SOC_{initial}$	0.3, 0.55, 0.42	

system. Each SSIG will have one master control unit located at a dispatchable DG where the control strategy is a single master operation mode (SMO). Three storage devices are connected to nodes 8, 99, and 87 through a bidirectional AC/DC converter. Their parameters are summarized in Table I.

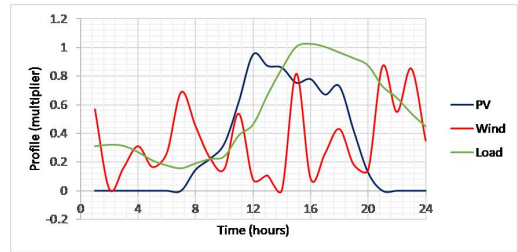


Fig. 3: Daily profile of load and intermittent DGs modeling uncertainties

##### B. Simulation Results

The aforementioned environment of natural disaster (Fig. 2) is simulated to test how the proposed approach coordinates several dispatchable and non-dispatchable generations for the chosen optimization horizon. The three MTs located at distribution network forms three different SSIGs by picking maximum critical and few non-critical loads in coordination with other non-dispatchable DGs and ESS. So, the first task is to form three SSIGs where each of them is energized by a

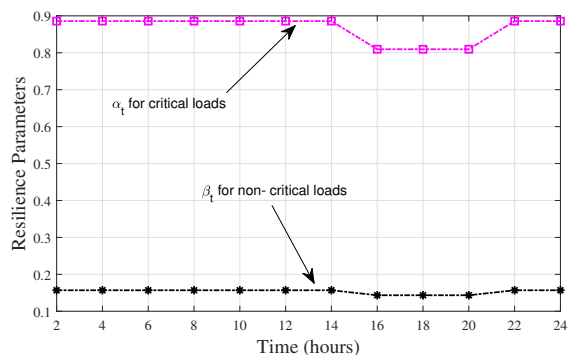


Fig. 4: Resilience parameters ( $\alpha$ ,  $\beta$ ) for different time period.

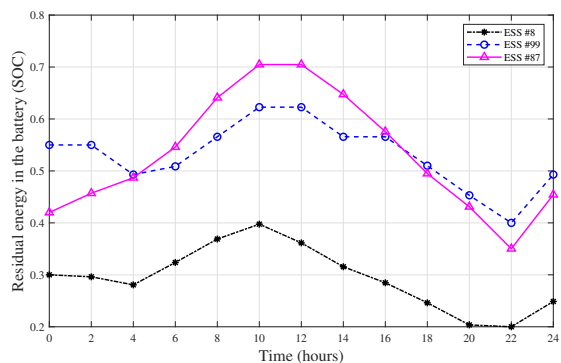


Fig. 5: SOC of three batteries.

single MT. After three isolated areas are formed, each isolated area works independently managing their own critical loads and generation. Fig. 2 shows three SSIGs formed by switching off the corresponding edges to form a minimum spanning forest. Each SSIG is a connected graph having different generation sources and are independent spanning trees of the forest. Note that islanding scheme is done only once before picking up the loads. After forming islands, once each of them are energized and start restoring the service to critical loads, only load switches and dispatchable DGs are controlled within each isolated areas.

Finally, each isolated areas have their own generation sources and loads to pick up. Based on renewable generation and load profile for a particular day, optimization is done for given time interval. It is assumed that the renewable generation and load profiles follow the similar trend as shown in Fig. 3 for the number of days a disaster is lasting. This simply means the optimization solution for a particular day ( $T^H$ ) is repeated for next successive days until damaged infrastructures are fully recovered and utility comes back. Fig. 4 shows the resilience parameters for a particular day. It is observed that pre-specified resilience criteria are met and during peak load period, parameters  $\alpha$  and  $\beta$  reduces slightly implying few loads are switched off to meet the available generation. The ESS response is illustrated graphically in Fig. 5 where each ESS goes into charging and discharging mode. It is clearly observed that ESS charges itself during the early period (less loading) and discharge itself during the peak load period.

## V. CONCLUSION

In this paper, a resilient restoration of the distribution network is proposed using the concept of minimum spanning forest. A weight is assigned to each edge in a distribution system based on several factors such as their exposure to vegetation, span length, location and structures supporting them. The concept of MSP is realized by switching off the edges with higher weight during the restoration process such that the probability of link failure is reduced. The modeling of tie switches helps to achieve the same objective of restoring the critical loads with different forest configuration thus making the SSIG less susceptible for link failures in the post-restorative state before the system enters the infrastructure recovery stage. Our results validate that the optimally placed tie switches and locally available DGs with ESS enhance the network performance in the post-disaster period.

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