Reliability-Based Optimal Integrated Microgrid Scheduling in Distribution Systems

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ABSTRACT

This paper proposes a reliability-based optimal scheduling model of integrated microgrids. The proposed model is capable of delivering optimal scheduling of each individual microgrid and aggregated system. In addition, it is compatible with both grid-connected and islanded operation modes. The developed problem formulation of the proposed model takes into account the reliability indices SAIDI, SAIFI, and CAIDI to evaluate the reliability of the integrated system. Numerical simulations on a modified IEEE-33 bus test system, involving four integrated microgrids, were performed to investigate the advantages and the robustness of the developed model. Furthermore, the impact of merging Battery Energy Storage Systems (BESSs) on the optimization outcome is examined, which demonstrates its significant effectiveness in improving the power systems' reliability.

Keywords-distributed energy resource; grid-connected operation; integrated microgrids; islanded operation; optimal scheduling; reliability indices

I. INTRODUCTION

Continuously optimizing and developing distribution systems' reliability is significant in the power systems optimization segment. Power outages may cause serious and massive difficulties for the end-users, such as the disruption of industrial, commercial, educational, and health systems [1-4]. The reliability of the distribution systems can be assessed and evaluated by reliability indices, including but not limited to, System Average Interruption Duration Index (SAIDI) to measure the aggregated duration of an interruption, Customer Average Interruption Duration Index (CAIDI) to measure the average time of restoration, and System Average Interruption Frequency Index (SAIFI) to measure the average number of times customers experience outages during the study period [5-6]. Consequently, several studies have been conducted toward improving and assessing distribution systems' reliability. Authors in [7] investigated the impact of the integration of a large-scale solar photovoltaic (PV) system with wind turbines on the system reliability. An IEEE-40 bus test system was utilized in the proposed study, and the zone branch methodology was performed to evaluate the system reliability. Authors in [8] investigated the potential capability of the vehicle-to-grid with the grid-connected battery swapping station in improving the reliability of distribution networks by proposing a comprehensive methodological framework based on quantitative and Latin Hypercube Sampling (LHS) methods. Authors in [9] proposed an Electric Vehicle (EV) charging station placement strategy based on a Voltage stability, Reliability, and Power loss (VRP) index for distribution networks considering the impact of the resulting fast EV charging station loads. In [10], a new approach based on a general probability formulation was developed to capture the availability of generation and transmission capacities and the randomness related to the load level. In addition, it was developed to calculate various quality measures and reliability indices. Authors in [11] solved the reconfiguration problem of distribution systems to improve the reliability indices and minimize the total active power losses based on a proposed Mixed Integer Second-Order Conic Programming (MISOCP) model.

Microgrids, as an intelligent technique to integrate Distributed Energy Resources (DERs), can significantly improve the range-specific reliability of the system within the microgrid's served area [12-15]. DERs could include renewable units, dispatchable Distributed Generators (DGs), and Battery Energy Storage Systems (BESSs) [16-18]. Microgrids support the islanding operation capability [19-21]. Nevertheless, in some conditions, microgrids can provide ancillary services to other parts of the distribution network by supplying their excess generation back to the utility grid. The impact of the microgrids on the distribution networks' reliability is discussed in [22-24]. In [22], the impact of the microgrid control strategies during the islanded operation mode on distribution network reliability was investigated based on a probabilistic methodology and the use of the sequential Monte Carlo simulation. Authors in [23] developed a probabilistic approach for the optimal operation of active distribution networks based on the multi-microgrid framework considering technical indices of the system such as the system reliability and efficiency, and solved the problem by the non-dominated genetic algorithm-II. Authors in [24] proposed an improved binary genetic algorithm approach to determine the optimal control and scheduling of DERs in hybrid microgrids to reduce the negative impact of outages on customers and improve system reliability.

Nonetheless, the integrated operation of the microgrids opens the horizon to further advantages. Enabling the local power exchange among the integrated system can significantly impact the microgrids' total operation costs by permitting their excess generation to be sold during the islanded operation. In addition, it will positively impact the distribution networks' reliability by supplying power to other parts with power deficiency. In this paper, the impact of the integrated microgrids on the power distribution networks' reliability is investigated based on the developed model. The contributions of the developed model are summarized as follows: (i) it significantly minimizes, individual- and integrated-base, microgrids' total operation cost, (ii) it distinctly improves the overall reliability of the distribution network, (iii) it explicitly supports the optimal operation of BESS in the integrated system, and (iv) it efficiently enables optimization during the islanded operation.

II. MODEL OUTLINE

The proposed reliability-based optimal integrated microgrid scheduling model ensures minimizing each individual microgrid's operation cost and the aggregated total operation cost of the integrated system. In addition, it significantly expands the reliability of the distribution network including the integrated microgrids. In the grid-connected mode, each microgrid in the system optimally schedules the local dispatchable DGs and BESS, and exchanges the power conventionally with the utility grid, i.e. imports power when needed and exports its excess generation, to increase its economic benefits from this process. On the other side, in the islanded mode, i.e. when the upstream grid faces interruptions or disturbances, all microgrids would be switched into the islanded operation mode. However, during the islanded mode, the integrated microgrids would exchange the power locally to support each other and to supply the other parts of the distribution network that are electrically connected to the microgrids. It is worth mentioning that the microgrids are typically connected to the other parts of the distribution network by the Points of Common Coupling (PCC), as depicted in Figure 1. The primary aim of this process is to minimize the amount of the load curtailments in the distribution network, i.e. to maximize the entire distribution system reliability, which will be evaluated by calculating the formulated reliability indices. Nevertheless, the impact of exchanging the power locally calls attention to the total operation cost, which is predicted to be further minimized due to the export of further excess generation. One-hour time periods are considered over a 24-hour scheduling horizon when solving the given problem. In addition, 25 different operation scenarios were applied to investigate the robustness of the proposed model. Shorter time periods could be deployed for more accurate results in order to follow fast changes in the proposed model without loss of generality.

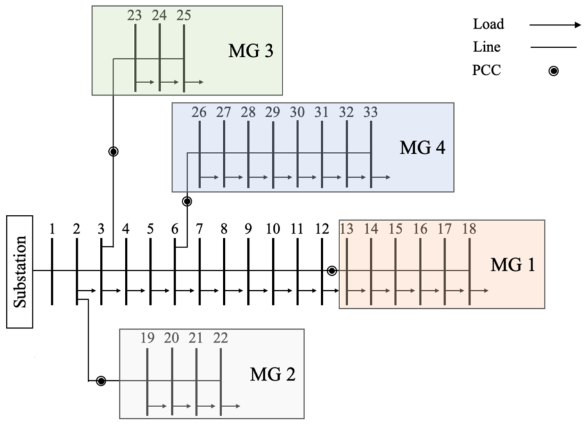

Fig. 1. IEEE-33 bus distribution test system involving four integrated microgrids.

III. PROBLEM FORMULATION

The objective of the reliability-based optimal integrated microgrid scheduling problem is to minimize the microgrids' total operation cost and to improve the integrated system reliability, as in (1):

$$\min \sum_{m}^{M} \sum_{t}^{T} \sum_{s}^{K} \Big(\sum_{i}^{DG} F_{mi}(P_{mits}) I_{mit} + \rho_{mt} P_{mts}^{M} + \sum_{n,n\neq m}^{M} \lambda_{mnt} P_{mnts}^{G} + \upsilon_{mt} LS_{mts} + \gamma_{mt} \kappa_{mts}\Big) \quad (1)$$

The first term in the objective function refers to the microgrids' dispatchable DGs, which includes the generation cost and the commitment status throughout the specified horizon. The second term refers to the cost of the power exchange with the utility, which could be a revenue once the power flow direction is from the microgrids to the utility, i.e. as it would be considered a negative cost. The third term represents the local power exchange among the integrated microgrids, i.e. it will be a cost for the buyer microgrid and a revenue for the seller microgrid. The fourth term represents the load curtailments, where it is multiplied by the Value Of Lost Load (VOLL). The last term is included as an auxiliary value of the reliability indices in the proposed model.

These cost expressions are calculated based on investigated operation scenarios that define the operation mode, i.e. grid-connected or islanded. The operation modes are recognized in the objective and in the developed constraints by the scenario index s, where s = 0 refers to the grid-connected mode and other values of s refer to the islanded operation mode over the selected horizon. The proposed objective is subjected to a set of linearized power flow constraints [25], and the following operation constraints: the power balance constraint, dispatchable DGs constraints, BESS constraints, and reliability indices constraints.

$$\sum_{i}^{DG} P_{mits} + \sum_{i}^{S} P_{mits} + P_{mts}^{M} + P_{mts}^{G} + LS_{mts} = D_{mts} \quad \forall m, \forall t, \forall s \quad (2)$$

$$-P^{M,\max} U_{ts} \leq P_{mts}^{M} \leq P^{M,\max} U_{ts} \quad \forall m, \forall t, \forall s \quad (3)$$

$$-P^{G,\max}(1-U_{ts}) \le P^{G}_{mts} \le P^{G,\max}(1-U_{ts})$$
$$\forall m, \forall t, \forall s \quad (4)$$

Constraint (2) represents the integrated system power balance equation to guarantee that the total power generated and imported matches the local demand. However, it is worth mentioning that the non-dispatchable generations, such as PVs and wind turbines, have predicted values based on the units' characteristics and the historical data, hence, they are handled as constant negative loads in the problem formulation. In addition, it is noted that the load curtailment variable is included to the power balance constraint to achieve a feasible solution during the islanded operation. The power exchange of the integrated system with the utility grid is subjected to a maximum power exchange limitation, as in constraint (3), and is further imposed to zero (using a binary islanding indicator) once the system operates in the islanded mode. The local power exchange among the integrated microgrids is subjected to the line flow limits of (4). Nevertheless, the binary islanding indicator is added to the constraint to impose the local power exchange to zero during the grid-connected mode due to the fact that each microgrid in the system prefers to export or import power with the utility when it would be more economically beneficial. For example, when the local hourly bid price is higher than the hourly market price, the microgrids with power deficiency would prefer to import power from the utility. On the other side, when the local hourly price is lower than the hourly market price, the microgrids with excess generation would prefer to export power to the utility.

$$P_i^{\min} I_{mit} \le P_{mits} \le P_i^{\max} I_{mit} \quad \forall m, \forall i \in \mathrm{G}, \forall t, \forall s \quad (5)$$

$$P_{mits} - P_{mi(t-1)s} \le UR_{mi} \quad \forall m, \forall i \in \mathrm{G}, \forall t, \forall s \quad (6)$$

$$P_{mi(t-1)s} - P_{mits} \le DR_{mi} \quad \forall m, \forall i \in \mathrm{G}, \forall t, \forall s \quad (7)$$

$$T_{mi}^{\text{on}} \le UT_{mi}(I_{mit} - I_{mi(t-1)}) \quad \forall m, \forall i \in \mathrm{G}, \forall t, s=0 \quad (8)$$

$$T_{mi}^{\text{off}} \ge DT_{mi}(I_{mi(t-1)} - I_{mit}) \quad \forall m, \forall i \in \mathrm{G}, \forall t, s=0 \quad (9)$$

Dispatchable DGs' optimal operation is subjected to the following constraints. The capacity limit of each dispatchable DG is subjected to minimum and maximum limitations, as in (5), and is further subjected to the commitment status using the binary variable. Generated power by dispatchable DGs is also subjected to the ramp up and down rate limits, as in constraints (6) and (7). In addition, they are subjected to the minimum up and down time limits once they are switched ON/OFF, as in constraints (8) and (9). Dispatchable DGs could be also restricted by fuel and emission constraints, which are however neglected in this paper.

$$P_{mits} \le P_{mit}^{dch,\max} u_{mit} - P_{mit}^{ch,\min} v_{mit}$$
$$\forall m, \forall i \in \mathrm{S}, \forall t, \forall s \quad (10)$$

$$P_{mits} \ge P_{mit}^{dch,\min} u_{mit} - P_{mit}^{ch,\max} v_{mit}$$
$$\forall m, \forall i \in \mathrm{S}, \forall t, \forall s \quad (11)$$

$$C_{mits} = C_{mi(t-1)s} - P_{mits} u_{mits}\, {}^{\tau}/_{\eta_i} - P_{mits} v_{mits} \tau$$
$$\forall m, \forall i \in \mathrm{S}, \forall t, \forall s \quad (12)$$

$$C_{mi}^{\min} \le C_{mits} \le C_{mi}^{\max} \quad \forall m, \forall i \in \mathrm{S}, \forall t, \forall s \quad (13)$$

$$T_{mi}^{ch} \le MC_{mi}\left(u_{mits} - u_{mi(t-1)s}\right)$$
$$\forall m, \forall i \in \mathrm{S}, \forall t, s=0 \quad (14)$$

$$T_{mi}^{dch} \ge MD_{mi}\left(v_{mits} - v_{mi(t-1)s}\right)$$
$$\forall m, \forall i \in \mathrm{S}, \forall t, s=0 \quad (15)$$

$$u_{mits} + v_{mits} \le 1 \quad \forall m, \forall i \in \mathrm{S}, \forall t, s=0 \quad (16)$$

BESS is subjected to maximum and minimum charging and discharging limits, as in constraints (10) and (11). The stored energy in the BESS is computed based on the charging and discharging processes over the specified horizon, considering the BESS efficiency, as in constraint (12). The BESS is further restricted by the minimum and maximum capacity limits, as in constraint (13). In addition, BESSs are restricted by minimum charging and discharging time limits, as in constraints (14) and (15). Moreover, they are regulated by adding the binary variables u and v to ensure that they operate only in one mode (i.e. either charging or discharging), at each time-period, as in constraint (16).

$$0 \le Ni_m \le LS_{mts}/w_m \quad \forall m, \forall t, \forall s \quad (17)$$

$$0 \le ri_m \le 60(1-U_{ts}) \quad \forall m, \forall t, \forall s \quad (18)$$

$$\text{SAIDI} = \sum (ri_m Ni_m)\kappa_{mts}/NT_m \quad \forall m, \forall t, \forall s \quad (19)$$

$$\text{SAIFI} = \sum Ni_m \kappa_{mts}/NT_m \quad \forall m, \forall t, \forall s \quad (20)$$

$$\text{CAIDI} = \sum (ri_m Ni_m)\kappa_{mts}/\sum Ni_m \quad \forall m, \forall t, \forall s \quad (21)$$

Reliability indices are formulated in (17)-(21). The number of interrupted customers who have suffered from power outages for each sustained interruption event is computed by (17). The restoration time for each interruption event, once the outage occurs, is formulated by (18). The reliability indices SAIDI, SAIFI, and CAIDI are computed by (19), (20), and (21), respectively. The auxiliary binary variable κ is added to provide value and significance of minimizing the reliability indices in the objective.

IV. NUMERICAL SIMULATIONS

A modified IEEE-33 bus test system was utilized to investigate the proposed reliability-based optimal integrated microgrid scheduling problem. The investigated test system involves four integrated microgrids, named MG 1 to 4, as demonstrated in Figure 1. In addition, the test system involves 33 buses, 32 distribution lines, and 11 fixed loads [26]. The total number of served customers, in the proposed study is assumed to be 50,000. Furthermore, based on the declared average annual electricity consumption per customer by the U.S. Energy Information Administration for residential sector, i.e. 10,715kWh [27], the parameter w for the hourly average power consumption per customer is assumed to be 1.223kW. The microgrids' hourly fixed load and the forecasted hourly market price for the 24-hour period can be found in [26]. In addition, it is assumed that the price of the power exchange among the integrated microgrids λ is higher than the forecasted market price by 10% in ($/kWh).

The aggregated hourly forecasted fixed load for buses beyond the area covered by the microgrids is shown in Table I. The characteristics of the microgrids' dispatchable units are illustrated in Table II, which includes the cost coefficient ($/kWh) of all dispatchable DGs, the ramping rates (kW/h), the up/down time limits (h), and the minimum and maximum capacity limits of the DGs (kW). The impact of installing BESSs is considered, and the BESS characteristics are shown in Table III. The BESS efficiency η is assumed to be 90% [16]. It is worth mentioning that the proposed problem is solved for one complete operational day over a 24-hour horizon considering 25 islanded operation scenarios (i.e. one scenario presents the grid-connected operation, while the other scenarios present a power outage for every hour). Moreover, a relatively small VOLL of $10/kWh is assumed [28], to specify the value of the undesired load curtailment. The proposed problem is programmed and solved in CPLEX 11.0 [29]. The following case studies are investigated:

Case 0: Optimal individual scheduling without BESS: In this case, the microgrids are optimally scheduled independently, i.e. there is no power exchange at all among the microgrids in the system, based on the islanded operation scenarios horizon and without installing BESSs. The optimal scheduling results of the microgrids ensure minimum operation cost and maximum reliability "locally", i.e. within the microgrids' served area. However, the other parts of the distribution network would not gain any advantages from this process. The microgrids' total operation costs are computed as $176.72, $191.25, $543.96, and $641.86 for MG 1, MG 2, MG 3, and MG 4, respectively (Table IV). Three islanded operation scenarios are arbitrarily nominated to investigate the reliability of the entire distribution network, i.e. islanded hours 9, 16, and 17, by calculating the reliability indices. Table V illustrates and summarizes the results of the reliability indices calculations in this case. The reliability indices SAIDI, SAIFI, and CAIDI are calculated as 3.78min, 0.03776, and 100.23min, respectively.

Case 1: Optimal integrated microgrid scheduling without BESSs: In this case, the local power exchange among the integrated microgrids is activated by utilizing the distribution network's lines. This case study investigates the impact of exploiting the unused capacity of the microgrids on the distribution system. Enabling local power exchange could significantly impact the microgrids' total operation costs and the overall reliability of the system. Comparing the microgrids' total operation costs in this case study with the obtained results in the base case, the microgrids' total operation costs are computed as $71.56 (–59.51%), $133.76 (–30.06%), $499.04 (–8.26%), and $587.36 (–8.49%) for MG 1, MG 2, MG 3, and MG 4, respectively, as shown in Table IV. Furthermore, this pointedly influences the reliability of the distribution network by supplying the fixed load on buses beyond the microgrids' covered area in case of outages. The reliability indices SAIDI, SAIFI, and CAIDI in this case are calculated as 3.02 (–20.11%), 0.02992min (–20.76%), and 99.95min (–0.28%), respectively, as illustrated in Table V.

TABLE I. FIXED LOAD ON BUSES BEYOND THE MICROGRIDS COVERED AREA

	Fixed load over 24h							
Time (h)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Load (kW)	744	741	738	738	738	738	781	763
Time (h)	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Load (kW)	761	763	773	773	775	773	773	773
Time (h)	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Load (kW)	775	758	744	741	741	741	738	733

TABLE II. CHARACTERISTICS OF MICROGRIDS' DISPATCHABLE UNITS

DG	MG 1	MG 2	MG 3	MG 4
	Price ($/kWh)			
DG 1	0.065	0.072	0.085	0.089
DG 2	0.039	0.064	0.065	0.069
DG 3	0.017	0.019	0.025	0.029
	Minimum – maximum capacity (kW)			
DG 1	20 – 100	14 – 70	20 – 100	30 – 150
DG 2	20 – 100	16 – 80	40 – 200	50 – 250
DG 3	40 – 200	30 – 150	80 – 400	60 – 300
	Minimum up/down time (h)			
DG 1	3	4	5	3
DG 2	3	4	4	3
DG 3	1	2	2	1
–	Ramp up/down rate (kW/h)			
DG 1	50	35	50	75
DG 2	50	40	100	125
DG 3	100	75	200	150

TABLE III. MICROGRIDS' BESS CHARACTERISTICS

Microgrid	BESS characteristics			
	Storage	Capacity (kWh)	Min.Max. ch/dch Power (kW)	Min. ch/dch Time (h)
MG 1	BESS	100	4 – 20	5
MG 2	BESS	50	2 – 10	4
MG 3	BESS	60	8 – 20	4
MG 4	BESS	120	16 – 40	5

TABLE IV. SUMMARY OF TOTAL OPERATION COST

Microgrid	Total operation cost		
	Case 0	Case 1	Case 2
MG 1	$176.72	$71.56 (–59.51%)	$41.39 (–76.58%)
MG 2	$191.25	$133.76 (–30.06%)	$118.75 (–37.91%)
MG 3	$543.96	$499.04 (–8.26%)	$489.77 (–9.96%)
MG 4	$641.86	$587.36 (–8.49%)	$561.45 (–12.53%)

TABLE V. SUMMARY OF RELIABILITY INDICES CALCULATIONS

Index	Reliability Indices		
	Case 0	Case 1	Case 2
SAIDI (min)	3.78	3.02	2.66
SAIFI	0.03776	0.02992	0.02641
CAIDI (min)	100.23	99.95	99.31

Case 2: Optimal integrated scheduling considering the impact of BESSs: In this case, the impact of installing the BESSs on the optimization outcome is investigated. The microgrids' total operation cost is computed as $41.39 (–76.58%), $118.75 (–37.91%), $489.77 (–9.96%), and $561.45 (–12.53%) for MG 1, MG 2, MG 3, and MG 4, respectively, as shown in Table IV. The achieved results show further minimization in the microgrids' total operation costs due to the exploitation of BESSs in storing energy during lower hourly market prices and exporting it back to the utility grid

during higher price periods. The optimal scheduling of the power exchange between the microgrids and the upstream grid is illustrated in Figure 2, while Figure 3 demonstrates the BESS optimal scheduling results. Moreover, the examined distribution network's reliability is obviously improved. The reliability indices SAIDI, SAIFI, and CAIDI are calculated as 2.66min (–29.63%), 0.02641 (–30.06%), and 99.31min (–0.92%), respectively, as illustrated in Table V. Accordingly, the integration of BESSs in power systems significantly expands the anticipated outcome and enhances the optimization results.

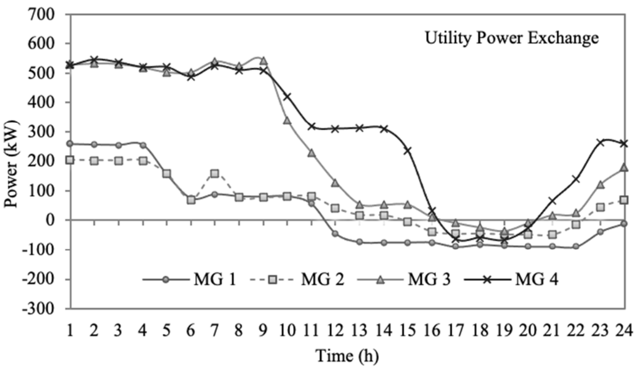

Fig. 2. Optimal power exchange with the utility grid in Case 2.

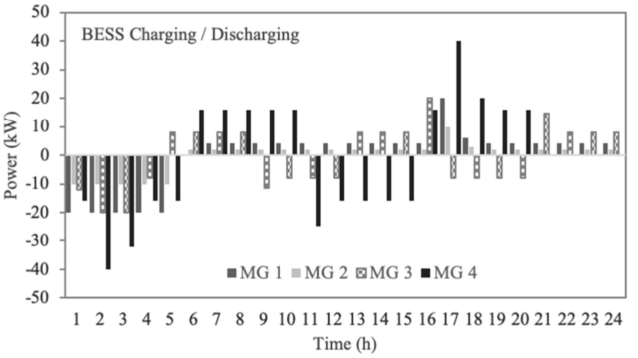

Fig. 3. Optimal BESS scheduling in Case 2.

V. DISCUSSION

Microgrids can promote the anticipated minimization of the total operation cost and maximize the local points of reliability. However, further benefits can be achieved once the microgrids are integrated with each other. This paper investigates the potential impact of the integrated system on the microgrids and on the entire distribution system by the proposed optimization model. In addition, it examines the optimal operation of BESSs and investigates their impact on the optimization results. Moreover, the probability of the islanded operation of the integrated system is efficiently inspected in the proposed optimization model using the developed islanded operation scenarios. The proposed model is mathematically formulated as a Mixed-Integer Linear Programming (MILP) problem and is solved using CPLEX.

The key features of the proposed optimization model can be outlined as follows:

- It significantly minimizes the total operation cost of each microgrid and of the whole integrated system.
- It explicitly enhances and improves the integrated system's reliability.
- It supports the optimal operation of BESSs.
- It considers optimal islanded operation.

Nonetheless, the proposed model is generic, and larger test systems and additional reliability indices can be carried out without loss of generality.

VI. CONCLUSION

An efficient reliability-based optimal scheduling model of integrated microgrids was developed in this paper. The proposed model was capable of optimally minimizing the microgrids' total operation costs and significantly boosting the overall reliability of the integrated system including the microgrids and the other parts of the power distribution grid. In addition, it was capable of identifying the optimal scheduling of the integrated system during the islanded operation. Numerical simulations on a modified IEEE-33 bus test system were performed to investigate the merits and the effectiveness of the proposed model in improving the system's power distribution reliability. The reliability indices SAIDI, SAIFI, and CAIDI were calculated by the formulated problem in all the considered case studies. Furthermore, the impact of installing Battery Energy Storage Systems (BESSs) was also studied and examined, and their significant weight, in minimizing the microgrids' total operation costs and enhancing the overall reliability of the power distribution system, was emphasized.

NOMENCLATURE

Indices:

ch	Superscript for BESS charging mode.
dch	Superscript for BESS discharging mode.
i	Index for DERs.
m,n	Index for microgrids.
s	Index for scenarios.
t	Index for time.

Sets:

DG	Set of dispatchable units.
M	Set of microgrids.
K	Set of islanded operation scenarios.
S	Set of energy storage systems.
T	Set of time periods.

Parameters:

DR	Ramp down rate.
DT	Minimum down time.
F(.)	Generation cost of dispatchable units.
MC	Minimum BESS charging time.
MD	Minimum BESS discharging time.
NT	Total number of customers served for the area.
ri	Restoration time for each interruption event.
U	Islanding state (0 when islanded, 1 otherwise).
UR	Ramp up rate.
UT	Minimum up time.
w	Average power consumption per customer.
ρ	Forecasted market price.
λ	Price of local power exchange.
γ	Auxiliary value of reliability indices.
η	Battery energy storage efficiency.
υ	Value of lost load.

Variables:

C	Stored energy in battery energy storage systems.

D Forecasted load demand.
I Commitment state of dispatchable units.
LS Load curtailment during islanded operation.
Ni Number of interrupted customers for each sustained interruption event.
P DER generated power.
P^G Local power exchange among the microgrids.
P^M Power exchange with utility grid.
T^{ch} Number of BESS successive charging hours.
T^{dch} Number of BESS successive discharging hours.
T^{on} Number of successive ON hours.
T^{off} Number of successive OFF hours.
κ Auxiliary binary variable for reliability indices (1 during outage, 0 otherwise).
τ Time period.
u BESS discharging state.
v BESS charging state.

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