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Research paper

Development of new reliability metrics for microgrids: Integrating renewable energy sources and battery energy storage system

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ABSTRACT

Microgrids (MGs) are gaining popularity due to their ability to provide reliable and resilient power supply, especially when integrated with renewable energy sources (RESs) and battery energy storage systems (BESS). Reliability is a critical factor for MG owners and policy makers. However, existing reliability indices such as loss of load expectation (LOLE) and expected energy not supplied (EENS) may not offer a comprehensive understanding of MG reliability and resiliency. To address this gap, this paper proposes three new indices for MGs to provide supplementary information on the performance of RESs: the Microgrid Resiliency Index (MRI), the Microgrid Renewable Energy Availability Index (MREAI), and the Microgrid Renewable Energy Energy Index (MREEI). The MRI assesses the MG's ability to recover from interruptions, providing insights into its resiliency. The MREAI and MREEI offer additional information beyond LOLE and EENS, specifically highlighting the contribution of RESs to the availability and energy losses in the MG. These indices enable a more comprehensive assessment of MG reliability. The formulation for calculation of the indices are provided and applied to a MG with integrated solar photovoltaic (PV), wind turbine (WT), and BESS components. To evaluate the effectiveness of the proposed indices in providing supplementary information on resiliency and the contribution of RESs, various scenarios are examined. These scenarios include the impact of using BESS, changes in RES availability, and variations in RES output. The results demonstrate that the proposed indices effectively capture the contribution of RES to MG reliability and offer valuable insights for decision-making related to RES installation. Also, by integrating BESS, the contribution of RESs to outage hours and lost energy is effectively decreased from 89.41% and 87.41% to 32.69% and 28.94% respectively. Additionally, results highlight the substantial enhancement in the resiliency of the MG, which witnessed an impressive 68.43% improvement.

1. Introduction

Microgrids (MGs) are increasingly being adopted as a means of providing a reliable and sustainable power supply to customers, particularly in remote or off-grid areas (D'Silva et al., 2020). A MG is a small-scale electricity distribution network that can operate independently as an islanded MG, or in parallel with the main grid as a grid-connected MG (Sharmila et al., 2019). It typically includes one or more distributed energy resources (DERs) such as solar photovoltaic (PV) panels, wind turbines (WTs), and energy storage systems (ESSs). MGs are considered an attractive solution for enhancing energy security and reliability, reducing carbon emissions, and promoting local energy generation. However, because of uncertainties in output power of RESs, one of the key challenges in MG operation and planning is ensuring reliable and resilient power supply to customers under various operating conditions and uncertainties (Impram et al., 2020).

One of the most promising technologies for improving the reliability and resilience of MGs is battery energy storage systems (BESSs) (Bahramirad et al., 2012). BESSs can provide a range of benefits to MGs, such as load shifting, peak shaving, frequency regulation, and voltage support (Shaker et al., 2021; Al-Mufti and Ghani, 2020). By storing excess energy during periods of low demand and releasing it during periods of high demand or when DERs are not available, BESSs can help MGs maintain a stable and reliable power supply to customers (Buchana and Ustun, 2015; IRENA, 2015). The widespread adoption of MGs has led to a growing interest in their reliability assessment, which is crucial for ensuring a stable and secure power supply to customers.

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Loss of load expectation (LOLE) and expected energy not supplied (EENS) has been widely used as reliability indices to quantitatively assess the reliability of MGs. In Akhtar et al. (2021), the impact of WT, PV, and changing the load on the reliability of system via different intelligent strategies is investigated. Their results show that the LOLE and EENS are changed from 0.9386 and 13.84 MWh/yr to 0.87 and 13.67 MWh/yr in cases of (30 MW WT+30 MW BESS) and (40 MW WT+40 MW BESS) respectively. The reliability of MG is enhanced up to 36 percent by adding 1 MWh to 5 MWh mobile BESS to the MG in Chen et al. (2016). They just calculated EENS as reliability index which is decreased from 31.45 kWh without BESS to 21.453 kWh with 5 MWh BESS. The study in Adefarati et al. (2017) has investigated the effect of combination of PV, WT, and BESS on reliability of MG. The EENS and LOLP for six different cases include 48 kW diesel generator (DE) and various PV, WT, and BESS capacity are calculated. As the first case they only utilized a 48 kW DE without RESs. In their second case a 3 kW PV, 1 kW WT, and 1 kW ESS is added to the MG. (ESS). Their results show that LOLE and EENS are improved significantly from case 1 to case 2 (from 0.004 and 48 kWh/yr to 0.0007 and 12 kWh/yr respectively). However, after the case 3 (6 kW PV, 2 kW WT, and 1 kW ESS) the improvements are not significant since the LOLE and EENS are close to zero after case 3. In Jiang et al. (2021), the EENS for different energy management strategies based on changes in forced outage rate of the grid, and BBES are calculated. Their results show that after increasing the forced outage rate of the grid (after 0.22), the EENS is increased significantly (up to 10 times for some participants) for all strategies. Another study has focused on MG reliability improvement considering the effect of BESS in Abdulgalil and Khalid (2019). Their results show significant improvement in reliability up to 99.61 percent. However, the authors used customer based reliability indices such as system average interruption duration index (SAIDI) and customer average interruption duration index (CAIDI), to assess the reliability and improvements in interruption hours and energy not supplied are not addressed.

There are many similar researches that using the RES without or with BESS to enhance the reliability of MG (Hirve and Deshmukh, 2013; Alsaidan et al., 2018; Wang et al., 2014; Aslani et al., 2021). The LOLE and EENS are improved which means that the expected hours of interruptions and the amount of energy lost are decreased, however, the contribution of RES and BESS in the reliability improvements, and the number of continue interruptions as the ability of MG as recover itself is not addressed. The traditional reliability indices may not fully capture the impact of RESs and BESSs on MG reliability and resiliency. LOLE and EENS do not distinguish between different sections or components of the MG. This can make it difficult to identify the causes of outages and prioritize investments in reliability improvement measures.

These limitations highlight the need for new reliability indices that can effectively evaluate the impact of RESs and BESS on MG reliability and provide more detailed and accurate information for decision-making. In this study, we propose three new reliability indices to provide supplementary information regarding performance of MG: the Microgrid Resiliency Index (MRI), the Microgrid Renewable Energy Availability Index (MREAI), and the Microgrid Renewable Energy Energy Index (MREEI).

MRI measures a MGs ability to recover from outages and disturbances. Unlike other reliability indices such as LOLE and EENS, which only consider the duration and energy not supplied during outages, MRI provides a more complete picture of a MGs resiliency by taking into account its ability to recover from disruptions. The calculation of MRI involves defining a threshold time for restoration and determining the time of disruptions that exceed this threshold. For instance, if the MG experiences an outage lasting more than one or two hours (the threshold time) during a 24-hour period, it is considered as not being recovered by the MG.

The MREAI considers the availability of the RESs in the MG. MREAI is defined as the ratio of the expected time the MG is not available due to failures in RESs to the total expected time the MG is not available. This index provides information on the ability of the MG to be available for use, including the contribution of RES and BESS. Unlike LOLE, which only considers the duration of outages, MREAI takes into account the availability of the MG. This index provides a more complete picture of the availability of the MG. The MREAI represents the percentage of total probable interruptions in the Microgrid (MG) that can be attributed to failures in its Renewable Energy Sources (RESs). A higher value of MREAI indicates a greater contribution of RES failures to the overall MG failures, leading to lower availability of the MG. Conversely, a lower MREAI value implies better availability of the MG, with fewer interruptions caused by RES failures.

The MREEI considers the expected energy supply capacity of the MG, including RESs and BESS. MREEI is defined as the ratio of the expected energy not supplied by the MG due to failures in RESs to the total energy demand. This index provides information on the ability of the MG to meet its energy demand during normal operation and thus helps to assess the energy reliability of the MG. Unlike EENS, which only considers the energy not supplied during outages, MREEI takes into account the contribution of RESs and BESS to the energy supply capacity of the MG. This index provides a more complete picture of the energy reliability of the MG.

The rest of the paper is organized as follows. In Section 2 the proposed indices are defined and formulated. Also, the BESS and other constraints of the problem are mathematically modeled in this section. Section 3 presents the simulation results and analysis of the proposed indices considering different scenarios. A comprehensive discussion is provided in Section 4. Finally, Section 5 provides the conclusion of the paper and possible future works.

2. Problem formulation

The formulation of LOLE, EENS, and new reliability metrics, and optimal sizing of BESS are provided in this section.

2.1. Reliability indices

Regarding the BESS and other network elements a two-state reliability model is used. For each component a failure rate, λ_i, and repair rate, μ_i, is considered. The availability, A_i, and unavailability, U_i, of each element are calculated using Eqs. (1) and (2) respectively.

$$A_i = \frac{\mu_i}{\lambda_i + \mu_i} \tag{1}$$

$$U_i = \frac{\lambda_i}{\lambda_i + \mu_i} \tag{2}$$

The following parameters are defined before formulating the reliability indices:

nf is the total number of overall system failure states in which the load demand is bigger than total generated capacity.

nf_MG is the total number of MG system failure states in which the failure in RES and BESS cause interruption in supplying demand and there is no failure in the main grid.

P_i is the probability of ith possible system state which is calculated based on the status of components in that state using Eq. (3).

$$P_i = \prod_{j=1}^{nc} pc_j \tag{3}$$

where, nc is the number of components in the system including RESs, BESS, and main grid. pc_j is the status probability of component j.

To calculate the MRI, as the resiliency index of the MG, first we define a binary variable that indicates whether state i results in an interruption at time t as shown in Eq. (4):

$$\alpha(i,t) = \left\{ \begin{matrix} 1 & if\ \ state\ \ i\ is\ failure\ state\ at\ time\ t \\ 0 & \end{matrix} \right\} \tag{4}$$

Also, a threshold value, th, for the maximum allowable interruption time and a set of all unaccepted interruption durations, U, are defined using Eq. (5):

$$U = \left\{ u : \sum_{t=1}^{u} \alpha(i,t) \geq th \right\} \tag{5}$$

The Eq. (5) calculates the set of all durations, U, where the sum of α (i,t) for time values t up to u exceeds the threshold value th. Finally, the MRI can be calculated as the probability that the MG does not recover within th hours, which is equal to the sum of the probabilities of all failure states that result in unaccepted interruption durations:

$$MRI = 1 - (\sum_{i=1}^{nf} \sum_{u \in U} p_i \times u) \tag{6}$$

The Eq. (6) is used to calculate the MRI. The MRI is calculated based on sums up the product of the probability of a failure state and the unaccepted interruption duration for that state, over all failure states and all unaccepted interruption durations.

The MRI will represent the capability of the MG to recover from disruptions and resist failure effectively. A higher value of the revised MRI will indicate a MG that demonstrates better resiliency by recovering quickly from interruptions and minimizing the impact of failures on overall performance.

The MREAI index is defined as the ratio of the expected time the MG is not available due to failures in RESs to the total expected time the MG is not available during the evaluation period. The expected time in which MG failures cause interruptions and total expected failures time are calculated using Eq. (7) and Eq. (8):

$$LOMP(L_i) = \sum_{i=1}^{n_{f\_MG}} p_i \tag{7}$$

$$LOLP(L_i) = \sum_{i=1}^{n_F} p_i \tag{8}$$

where $LOMP(L_i)$ is the loss of MG probability. Then $MREAI$ can be calculated using Eq. (9):

$$MREAI = \frac{\sum_{t=1}^{NT} LOMP(L_t)}{\sum_{t=1}^{NT} LOLP(L_t)} \tag{9}$$

where "NT" refers to the number of times that system failures or interruptions are observed in the MG during the entire study period.

The $MREEI$ represents the ratio of the expected energy not supplied by the MG due to failures in RESs to the total energy demand which is formulated in Eq. (10):

$$MREEI = \frac{\sum_{t=1}^{NT} LOMP(L_t) \times LC_t}{\sum_{t=1}^{NT} LOLP(L_t) \times LC_t} \tag{10}$$

where LC_i is the load curtailment value in each time.

In addition, the two well known $LOLE$ and $EENS$ reliability indices are calculated based on Eq. (11)-(12):

$$LOLE = \sum_{i=1}^{T} LOLP(L_i) \tag{11}$$

$$EENS = \sum_{i=1}^{T} LOLP(L_i) \times LC_i \tag{12}$$

$LOLE$ is equal to the sum of the loss of load probability, $LOLP(L_i)$, of each load in duration time (T). Also, $EENS$ is calculated based on $LOLP(L_i)$ and the amount of demand not supplied in each load LC_i.

2.2. BESS modeling

To model the BESS, the energy stored at time t, power and efficiencies of charging and discharging are considered as is formulated in Eq. (13) (Wongdet et al., 2023; Chen et al., 2012).

$$E_{ESS,T} = E_{ESS,T-1} + (P^c_{ESS}\eta_c - \frac{P^d_{ESS}}{\eta_d}) \times \Delta t \qquad \forall t \in NT \tag{13}$$

where, $E_{ESS,t}$ is the energy stored in the battery. P^c_{ESS} and P^d_{ESS} represent the charging and discharging power of the battery respectively. Also, the efficiency of charging and discharging of BESS are shown by η_c and η_d respectively.

In addition, the state of charge (SoC) of the battery energy storage system (BESS) plays a crucial role in its performance. The SoC represents the amount of charge stored in the battery at a specific time. It is a key parameter that significantly influences the performance of the BESS. Equations (14) and (15) are employed to model the SoC factor:

$$SoC_{\min} \leq SoC(t) \leq SoC_{\max} \tag{14}$$

$$SoC(t) = SoC(t-1) + \left\{ \begin{matrix} DC_b(t) & P(t) > 0 \\ CC_b(t) & P(t) > 0 \end{matrix} \right\} \tag{15}$$

where, the $SoC(t)$ represents the current charge level of the battery, $SoC_{\max}$ represents the maximum rate at which the battery can be charged, and $SoC_{\min}$ represents the minimum rate at which the battery can be charged. DC_b represents the amount of energy consumed by the battery during discharge, and CC_b represents the amount of energy consumed by the battery during charging. The variable represents the output power of the battery energy storage system at a given time, denoted by $P(t)$.

Furthermore, it is important to note that the energy stored in the battery is always positive. However, the power of the battery energy storage system (BESS) is considered negative when it is charging, indicating the flow of energy into the battery, and positive when it is discharging, indicating the release of stored energy from the battery. Equations (16) and (17) establish the limitations on the power and energy of the BESS, as they are bound by their rated values. These equations ensure that the power and energy flow within the predefined limits of the BESS's capacity.

$$-P^R_{ESS} \leq P_{ESS,t} \leq P^R_{ESS} \qquad \forall t \in NT \tag{16}$$

$$0 \leq E_{ESS,t} \leq E^R_{ESS} \qquad \forall t \in NT \tag{17}$$

Also, the main constraints of the problem are the load balance and limitations in imported power from the main grid. The load balance ensure that the load demand at each time is equal to the total generated power including output power of RESs, BESS output, and imported power from the grid. These constraints are formulated by Eq. (18) and Eq. (19).

$$\sum_{i=1}^{NI} RES_{i,t} + P_{ESS,t} + P_{Grid,t} = Load_t \qquad \forall t \in NT \tag{18}$$

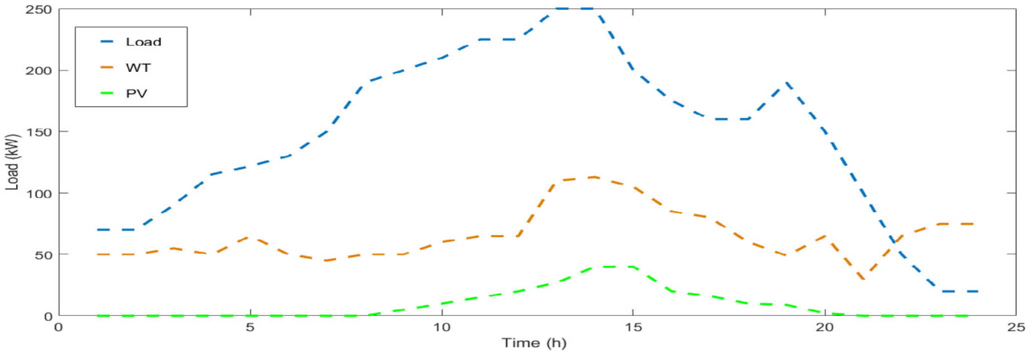


Fig. 1. Load profile of the MG and the output power of WT and PV.

Table 1
Reliability data of network elements [17].

Network Elements	Grid	PV	WT	DE	BESS
Failure Rate (Failure/year)	0.25	0.5	0.769	1.168	0.172
Repair Time (h)	48	40	279	100	7.8

$$P_{Grid,t} \leq P_{exchanged}^{\max} \qquad \forall t \in NT \tag{19}$$

3. Case study and results

In this section, the information of MG under study, renewable energies, BESS, and their reliability data are provided. Also, the LOLE, EENS and other proposed indices are calculated for different cases to evaluate their effectiveness in providing supplementary information regarding the MG reliability and resiliency. Fig. 1 shows the load profile of MG during the 24 h a day, and output power distribution of PV and WT installed as renewable energies which are provided from Nguyen-Duc et al. (2022). Also, the reliability data include failure rate and repair time of network elements are given in Table 1.

In this study, we have considered different scenarios and conducted several cases within each scenario to analyze the performance of the MG. The scenarios explored are as follows:

First Scenario: Various sizes of BESS are added to the PV and WT systems during peak hours.

Second Scenario: The output power of the PV system is varied, with increases and decreases of 10%, 30%, and 50% from its nominal value.

Third Scenario: The output power of the WT system is varied, with increases and decreases of 10%, 30%, and 50% from its nominal value.

Fourth Scenario: The availability of the WT system is modified by 10%, 30%, and 50%.

Fifth Scenario: The availability of the WT system integrated with a BESS is modified by 10%, 30%, and 50%. For each of these scenarios, the reliability indices are calculated to assess the performance of the MG and effectiveness of proposed indices. The results of these calculations are presented in Table 2 to Table 6, providing an overview of the performance of the MG under different scenarios and their corresponding indices.

Table 2 demonstrates the significant impact of installing a BESS on the reliability and resiliency of the MG. Without the BESS, the LOLE is 0.2721, indicating the expected interruption hours, and the EENS is 20.6505 kWh/day. However, with the addition of a 100 kW BESS, the LOLE decreases to 0.0488 and the EENS decreases to 2.6554 kWh/day. Furthermore, the MREAI and MREEI show notable improvements in performance of RES-BESS in MG. Without the BESS, the MREAI is 89.41% and the MREEI is 87.41%, indicating that more than 89% of the interruption hours and energy loss are attributed to failures in RESs. However, with the installation of the BESS, the MREAI decreases to 45.17% and the MREEI decreases to 40.51%. This indicates that the contribution of RESs to interruption hours and energy loss during outages is less than 50%. Additionally, the resiliency of the MG is significantly enhanced by the BESS. The capability of MG to recover itself for interruptions lasting continuously for more than one and two hours increases from 0.7792 and 0.8066 to 0.9791 and 0.9805, respectively. This improvement highlights the MG's ability to recover itself after disruptions, showcasing the positive impact of the BESS installation on resiliency.

The results presented in Tables 3 and 4 indicate that increasing the output power of the PV and WT sources does not lead to a significant improvement in the resiliency, reliability, and contribution of RESs in the MG. The LOLE and EENS values show a slight decrease when the PV output power is increased by 30% (from 0.2721 to 0.2245 for LOLE and from 20.6505 kWh/day to 15.1368 kWh/day for EENS). Similarly, in the case of a 30% increase in WT output power, the LOLE decreases to 0.2677 and the EENS decreases to 20.0312 kWh/day. The MREAI and MREEI indices reveal that more than 80% of interruptions and energy not supplied are still attributable to failures in RESs, with values of 87.16% and 83.40% respectively. Although there is a slight improvement in the resiliency of the MG (as indicated by the increase in capability of MG to recover itself for interruptions lasting more than one hour from 0.7792 to 0.8282 in the case of PV output increase), the overall impact on resiliency and reliability is not substantial.

Table 5 presents the reliability indices for the improvement in the availability of the WT source. Additionally, Table 6 shows the results when the availability of the WT source is enhanced and a BESS is employed. The findings demonstrate that increasing the availability of the WT source, along with the use of a BESS, can lead to significant improvements in the reliability indices. The LOLE and EENS values are reduced to 0.0367 and 2.0421 kWh/day, respectively, indicating a substantial decrease in the expected interruption hours and energy not supplied. Moreover, the contribution of RESs in these outages is also significantly reduced, with the MREAI and MREEI values decreasing by up to 32.69% and 28.94% respectively. These results highlight the positive impact of improving the availability of the WT source and integrating a BESS in enhancing the reliability of the MG. In the subsequent section, we further discuss the obtained results and explore into the significance of the findings.

Furthermore, the paper includes a sensitivity analysis of the proposed indices to changes in load demand, BESS capacity, and RES availability. Figs. 2 to 4 present the results of this analysis. The findings in Fig. 2 indicate that increasing the load demand leads to a significant impact on the reliability of the MG and the contribution of RES failures to interruptions. However, the resiliency index (MRI) remains relatively stable to a 20% increase in load, indicating the MG's ability to recover from these changes.

Table 2
Reliability indices for the first scenario – RES integrated with BESS.

BESS SIZE (kW)	LOLE	EENS	MREAI %	MREEI %	MRI (Th=1h)	MRI (Th=2h)
Without BESS	0.2721	20.6505	89.41	87.41	0.7792	0.8066
10	0.2200	14.2527	86.90	82.62	0.8304	0.8543
20	0.2200	12.4576	86.90	81.10	0.8304	0.8543
40	0.1961	8.6251	85.30	75.56	0.8544	0.8783
60	0.0755	4.2530	63.61	56.06	0.9763	0.9777
80	0.0503	2.8513	47.97	41.70	0.9777	0.9792
100	0.0488	2.6554	45.17	40.51	0.9791	0.9805

Table 3
Reliability indices for the second scenario – Changes in PV power output.

Changes	LOLE	EENS	MREAI %	MREEI %	MRI (Th=1h)	MRI (Th=2h)
−30%	0.2959	23.5679	90.26	88.59	0.7567	0.8066
−20%	0.2959	23.0718	90.26	88.48	0.7567	0.8066
−10%	0.2959	22.5758	90.26	88.35	0.7567	0.8066
0	0.2721	20.6505	89.41	87.41	0.7792	0.8066
10%	0.2721	20.1783	89.41	87.26	0.7805	0.8066
20%	0.2721	19.7060	89.41	87.10	0.7805	0.8066
30%	0.2245	15.1368	87.16	83.40	0.8282	0.8543

Table 4
Reliability indices for the third scenario – Changes in WT power output.

Changes	LOLE	EENS	MREAI %	MREEI %	MRI (Th=1h)	MRI (Th=2h)
−30%	5.1495	106.3853	99.41	97.04	−3.1221	−2.1234
−20%	4.1734	68.1228	99.31	95.65	−2.146	−1.1473
−10%	1.2513	27.3235	97.70	89.82	0.7739	0.8
0	0.2721	20.6505	89.41	87.41	0.7792	0.8066
10%	0.2721	20.4411	89.41	88.16	0.7805	0.8066
20%	0.2677	20.2117	89.23	88.92	0.7828	0.8066
30%	0.2677	20.0312	89.23	89.72	0.7828	0.8066

Table 5
Reliability indices for the forth scenario – Changes in WT availability.

Changes	LOLE	EENS	MREAI %	MREEI %	MRI (Th=1h)	MRI (Th=2h)
−50%	0.3915	29.6593	92.63	91.15	0.6849	0.7229
−30%	0.3438	26.0558	91.61	89.97	0.7232	0.7564
−10%	0.2960	22.4523	90.26	88.40	0.7614	0.7899
0	0.2721	20.6505	89.41	87.41	0.7792	0.8066
10%	0.2482	18.8488	88.39	86.23	0.7997	0.8234
30%	0.2005	15.2452	85.64	83.04	0.8379	0.8568
50%	0.1527	11.6417	81.15	77.86	0.8761	0.8903

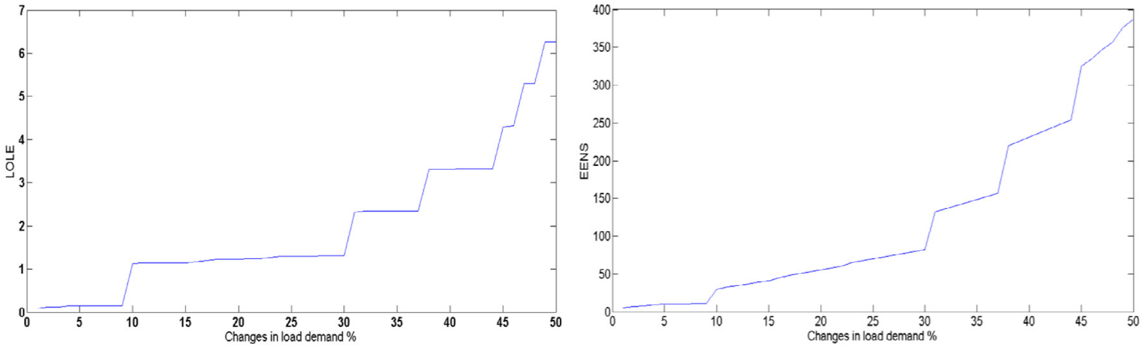
Table 6
Reliability indices for the fifth scenario – Changes in WT availability integrated with BESS.

Changes	LOLE	EENS	MREAI %	MREEI %	MRI (Th=1h)	MRI (Th=2h)
−50%	0.0609	3.2686	59.11	54.24	0.9789	0.9803
−30%	0.0561	3.0233	55.65	50.82	0.979	0.9804
−10%	0.0513	2.7780	51.54	46.80	0.9791	0.9805
0	0.0488	2.6554	49.17	44.51	0.9791	0.9805
10%	0.0464	2.5327	46.56	42.00	0.9791	0.9805
30%	0.0416	2.2874	40.44	36.17	0.9792	0.9806
50%	0.0367	2.0421	32.69	28.94	0.9793	0.9807

In Fig. 3, it is observed that improving the availability of RES, reflected by a decrease in forced outage rate, results in a linear improvement in all reliability and resiliency indices. As depicted in Fig. 3, increasing the availability of RESs results in a reduction in the contribution of RES failures to the total interruptions in the MG. This observation indicates that a significant proportion of the failures are attributed to issues with main grid sources rather than the RESs. As a result, the availability of the MG is enhanced, as fewer interruptions are caused by RES failures. This demonstrates the crucial role played by the improvement in RES availability in bolstering the overall reliability and resiliency of the MG. MREAI and MREEI decrease to below 30% when RES availability improves by up to 50%. Furthermore, Fig. 4 demonstrates the substantial influence of BESS capacity on all indices, with a more pronounced effect on energy-related indices (EENS/MREEI) compared to interruption-related indices (LOLE/MREAI). Notably, the resiliency of the MG, as indicated by the MRI index, improves from 0.1934 to 0.1457 with the installation of a 10 kW BESS. However, after reaching a BESS capacity of 55 kW, the MRI index stabilizes at 0.9777, suggesting an acceptable level of resiliency that is not significantly affected by further increases in BESS capacity.

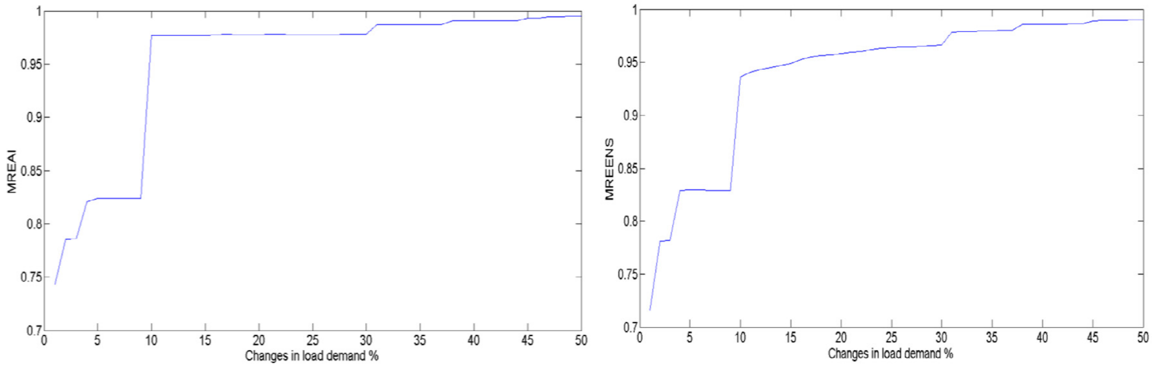
4. Discussion

The calculated reliability indices in this study serve as crucial quantitative measures for assessing the reliability and resiliency of MG, making them invaluable for decision-makers and MG owners. In recognition of the importance of these factors,



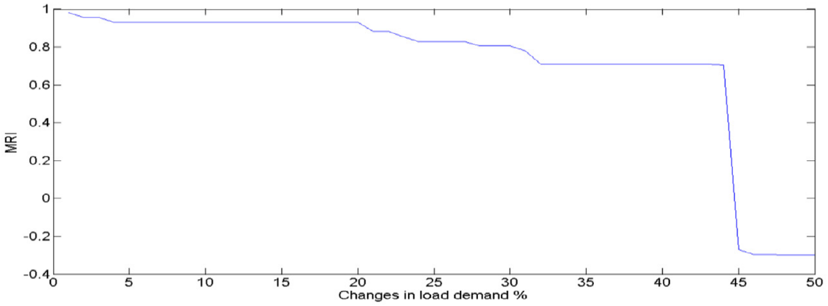
a: LOLE

b: EENS



c: MREAI

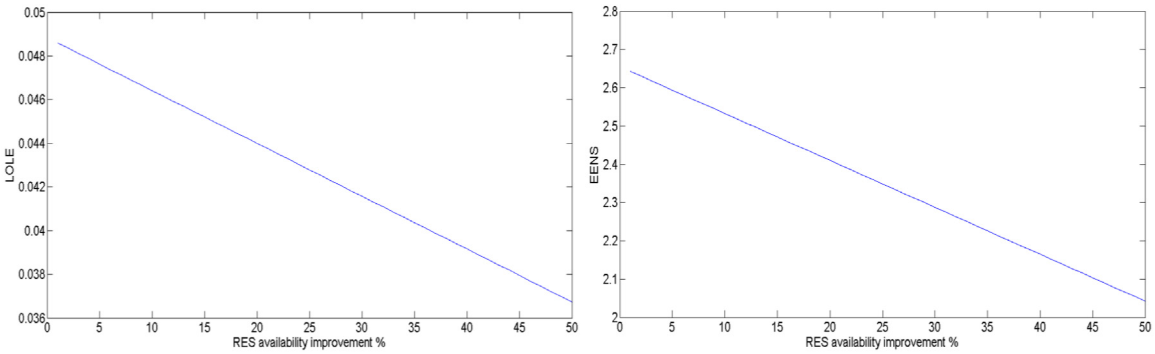
d: MREEI



e: MRI

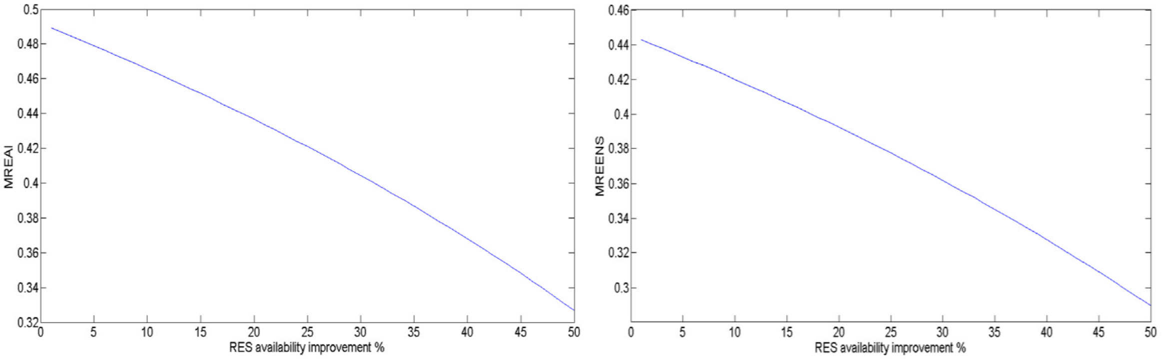
Fig. 2. Sensitivity of indices to changes in load demand.

new indices have been proposed to provide additional information regarding the reliability and resiliency of MG beyond the well-established LOLE and EENS indices. By utilizing the proposed indices, a deeper comprehension of the performance of MG sources can be attained, particularly in grid-connected MGs where a significant portion of the demand is still met by the main grid. The proposed indices enhance the understanding of MG reliability and resiliency, going beyond what is offered by traditional indices, from different points of view: First, regarding the resiliency assessment, while traditional indices might suggest an improvement in resiliency with an increase in REs, the MRI, as a proposed index, goes beyond just the occurrence of outages and their duration. It considers the MG's ability to recover from disruptions, thereby providing a more insightful assessment of the MG's overall resiliency. Also, the proposed indices are designed to aid MG owners and policymakers in making informed decisions related to RES integration and BESS implementation. They offer a more nuanced view of MG performance, enabling stakeholders to identify areas for improvement and optimize system design based on the specific goals and requirements of their MG. In addition, in term of contribution of RESs and BESS, the MREAI and MREEI provide valuable insights into the contribution of Renewable Energy Sources (RESs) and Battery Energy Storage Systems (BESS) to the overall MG performance. They highlight how the integration of RESs and BESS positively influences the availability of the MG for use and its ability to meet energy demand during normal operation. These aspects are not fully captured by traditional indices, making the proposed indices valuable tools in understanding the effectiveness of RES integration. For example, the results of Table 2 demonstrated that by adding 100 kWh BESS, the MREAI decreases from 89.41% to 45.17%, indicating that the contribution of RESs to interruption hours is reduced to less than 50%. Similarly, the MREEI decreases from 87.41% to 40.51%, demonstrating the reduced contribution of RESs to energy loss during outages. Moreover, Unlike traditional indices such as EENS and MRI, which focus on specific aspects of MG reliability (e.g., energy not supplied during outages or recovery time after disruptions), the proposed indices (MRI, MREAI, and MREEI) take into account multiple factors, including RES availability, energy supply capacity, and recovery from interruptions. By considering these diverse aspects, the proposed indices offer a more holistic and accurate evaluation of MG reliability and resiliency. Examining the basic status of the MG without the presence of BESS, it is observed that 54.28% of the load demand is



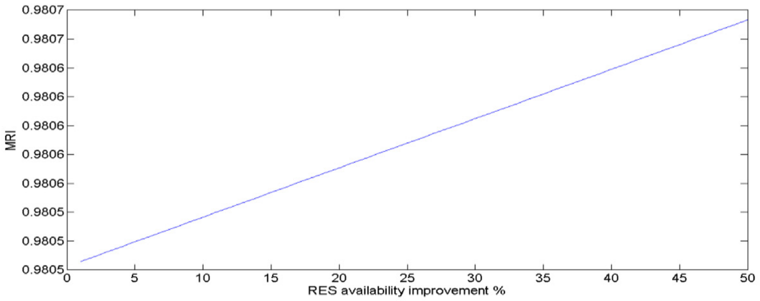
a: LOLE

b: EENS



c: MREAI

d: MREEI



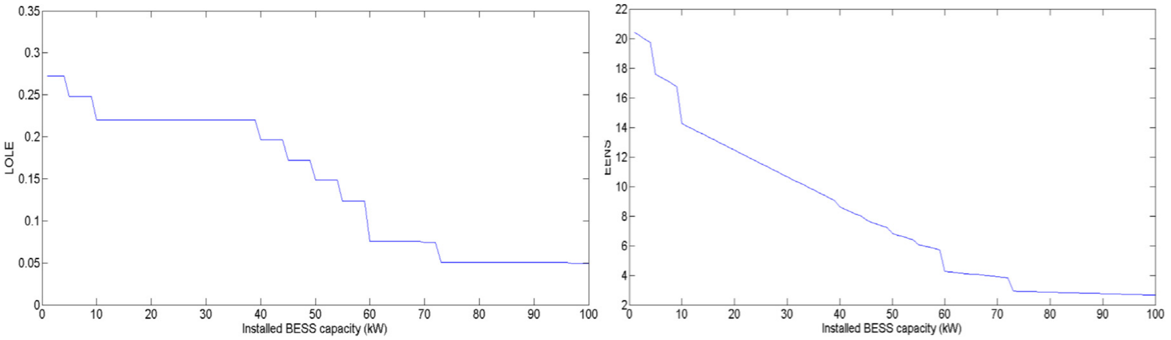
e: MRI

Fig. 3. Sensitivity of indices to RES availability improvement %.

fulfilled by the main grid. However, when evaluating the MREAI and the MREEI, it becomes evident that a substantial portion of interruption hours and energy not supplied, namely 89.41% and 87.41%, respectively, are attributed to failures in the RESs. These findings reveal the critical role played by PV and WT failures in MG performance and emphasize the need for further analysis and mitigation strategies to enhance the reliability and resiliency of these renewable energy sources within the MG context.

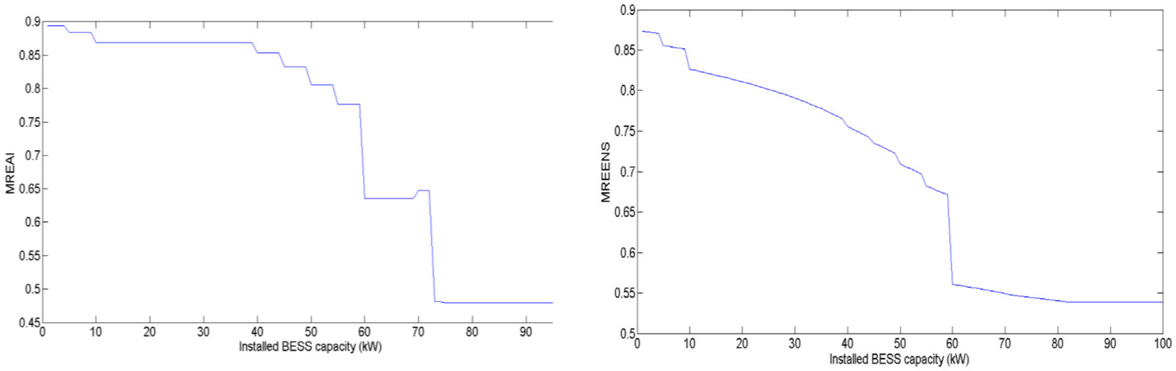
Also, the logic relation of BESS and the proposed indices are explained as follows: Regarding the MRI, The BESS plays a significant role in enhancing the resiliency of the MG by providing energy support during outages and disturbances. When the MG experiences an interruption, such as a prolonged outage lasting more than the defined threshold time, the BESS acts as an energy source to support the MG's critical loads. By supplying the stored energy during these disruptions, the BESS helps the MG recover from outages more effectively. Consequently, the BESS contributes to reducing the duration and frequency of disruptions that exceed the threshold time, leading to an improved MRI. Also, the integration of BESS with renewable energy sources (RESs) in the MG enhances its availability. During periods when RESs experience failures or reduced output due to weather conditions, the BESS can step in to supply energy, ensuring continuous power availability. As a result, the MREAI, which assesses the availability of the MG, benefits from the presence of BESS by reducing the expected time the MG is not available due to RES failures. The BESS helps maintain a higher level of energy availability, contributing to an improved MREAI, which provides insights into the contribution of RESs and BESS to the overall MG availability. In addition, regarding MREEI, by storing excess energy generated by RESs during periods of low demand and releasing it during peak demand, the BESS helps meet the MG's energy demand during normal operation. This reduces the expected energy not supplied by the MG due to RES failures, which in turn leads to an improved MREEI.

In addition, results suggest that solely increasing the output power of PV and WT sources may not be an effective strategy for enhancing the resiliency and reliability of the MG or reducing the dependency on RESs. In comparison to increasing the output of RESs, the utilization of BESS emerges as a superior approach for enhancing the reliability, performance, and resiliency of RESs within the MG. The installation of a BESS yields a remarkable reduction in the contribution of RESs to power outages, diminishing it from over 80% to less than 50%. This signifies the effectiveness



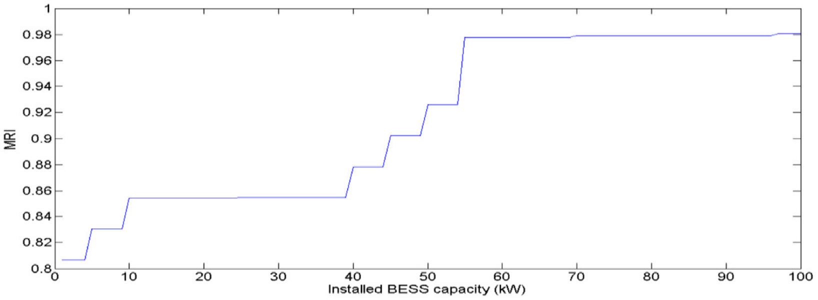
a: LOLE

b: EENS



c: MREAI

d: MREEI



e: MRI

Fig. 4. Sensitivity of indices to changes in installed BESS capacity (kW).

of BESS in mitigating the impact of RES failures and highlights its pivotal role in improving the overall reliability and resiliency of the MG.

Moreover, it is noteworthy that the WT exhibits the highest failure rate among all the components in the system, making it a critical factor in terms of reliability and the MREAI and MREEI indices. Remarkable performance improvements were observed when 50% enhancements were made to the availability of the WT, integrated with a 100 kW BESS. In this configuration, the LOLE and EENS were significantly reduced by 86.51% and 90.11%, respectively, compared to cases without a BESS and the basic WT availability value. Furthermore, the contribution of RESs to outage hours and lost energy was effectively decreased to 32.69% and 28.94%. These results highlight the substantial enhancement in the resiliency of the MG, which witnessed an impressive 68.43% improvement. By effectively managing the WT availability and utilizing energy storage, the MG can experience fewer interruptions and a reduced reliance on RESs for maintaining a reliable power supply.

Overall, the comparative analysis of the proposed indices with existing indices in the literature demonstrates the added value and usefulness of the proposed indices for reliability assessment of a MG. By providing supplementary information, the proposed indices offer a more comprehensive understanding of the performance and resiliency of the MG system. The results highlight the effectiveness of the proposed indices in capturing the contribution of RESs, BESS, and the ability of the MG to recover from interruptions. Through the application of these indices, valuable insights are gained for decision-making and operation of MGs.

5. Conclusion

In conclusion, this paper addresses the importance of reliability and resiliency assessment in MG systems and proposes three new indices to provide supplementary information for a more comprehensive evaluation. The proposed indices, including the MRI, MREAI, and MREEI, offer valuable insights into the performance, contribution of RESs, and recovery capabilities of the MG. Through a series of case studies, the effectiveness of the proposed indices is demonstrated. The results highlight the significant impact of BESS on MG reliability and resiliency, with reductions observed in both the expected interruption hours and energy not supplied. The introduction of BESS resulted in a decrease in the contribution of RESs to power outages, indicating improved system reliability. Furthermore, variations in the output power of PV and WT sources were investigated, revealing that changes in their output had minimal effects on overall MG reliability and resiliency. However, the availability of the WT had a influence, with improved availability leading to more improvements in LOLE, EENS, and the contribution of RESs to power outages. The best reliability and resiliency of the MG performance was achieved in case of utilizing BESS as well as enhancing the availability of WT. The proposed indices provide decision-makers and MG owners with valuable information for optimizing system performance and making informed choices regarding the integration of RESs and BESS. By considering these indices, a more comprehensive assessment of MG reliability and resiliency is achieved, enhancing the overall operation and management of MGs. For future work, further research can be conducted to explore additional factors that may impact MG reliability and resiliency. This could include studying the effects of different control strategies for BESS and RESs, investigating the optimal sizing and placement of BESS within the MG, and exploring the integration of other renewable energy sources and emerging technologies. Additionally, considering the dynamic nature of MGs, future work can focus on developing real-time monitoring and control systems that utilize the proposed indices to enhance the operational decision-making process.

CRediT authorship contribution statement

Mohammadreza Gholami: Idea generation or conceptualization, Methodology, First draft preparation, Data curation. **S.M. Muyeen:** Idea generation or conceptualization, First draft preparation, Data curation. **Soad Abokhamis Mousavi:** Idea generation or conceptualization, Part writing, Providing feedback, Review, Editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Prof. S M Muyeen reports financial support was provided by Open Access funding provided by the Qatar National Library.

Data availability

Data will be made available on request.

Acknowledgment

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