Adaptive Microgrid Integration and Distribution Generation Optimization for Enhancing Distribution Network Resilience and Minimizing Power Loss

Kishan Gadhavi, Shefali Talati, and Ajay Misra

Abstract The distribution network's incorporation of microgrids presents a viable route to sustainable energy solutions. The occurrence is high-risk and low-frequency event, and it has a significant impact on the distribution network. As a result, several nations have made the distribution network's resilience their main concern. Resilient distribution networks can withstand, adjust to, and quickly recover from interruptions. The distribution network's resilience is designed to withstand extreme events that are high-risk and low-probability, such as severe natural catastrophes and man-made assaults. The methodology for evaluating the robustness of an electrical distribution network with integrated microgrids under harsh circumstances will be presented in this study. This paper's goal is to show how islandable microgrids and distributed generation has increased the distribution network's resilience to harsh environments. The suggested mesh network technique is used to study the process by which severe events impact the operation of distribution networks. The resilience indices and the number of hours needed to reestablish the distribution network following the low-frequency, high-risk event are determined using the Monte Carlo approach. To improvement of system resilience, we fined the proper placement size of distribution generation in network using Particle swarm optimization also to calculate the most optimal power flow, the forward–backward sweep approach is employed. All this simulation will carry out using MATLAB. The IEEE 33 bus is used to illustrate the suggested distribution network resilience analysis approach.

Keywords Resilience · Distributed generation (DG) · Distribution networks resilience · Low-frequency high-risk event · Microgrid

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1 Introduction

Microgrids, which may operate alone or in conjunction with the main grid, offer a practical means of enhancing the reliability and resilience of electrical distribution networks as energy demands rise and environmental sustainability concerns intensify. However, high-risk, low-frequency catastrophic events like natural catastrophes and man-made cyber or physical attacks are posing a growing danger to the resilience of distribution networks. There are numerous, ambiguous, and contradictory definitions of resilience in power system literature, and as far as the authors are aware, there isn't yet a widely recognized definition. Here are a few definitions of grid resilience from reputable organizations:

DOE: "The capacity of a power system and its constituent parts to endure, adjust to, and quickly recover from disturbances" (Department of Energy (DOE)) [1]

FERC: "The capacity to anticipate, absorb, adapt to, and/or quickly recover from disruptive events, as well as the ability to withstand and lessen their magnitude and/or duration" (The Federal Energy Regulatory Commission (FERC)) [1].

As a result, research and development on resilient distribution networks has grown in importance, with a focus on developing systems that can withstand, respond to, and recover fast from such disruptions. The rapid integration of microgrids into distribution networks is a significant step toward more robust and sustainable electricity systems [1]. The study provides a complete review of power grid resilience, including existing definitions and indicators, as well as measures for ensuring and improving system resilience. The paper lists challenges such as increased demand, climatic unpredictability, and the integration of renewable energy supplies.

The resilience metrics (RMs), which are used to measure the resilience of distribution network, will be thoroughly introduced in [2]. In [3], the author presents a technique for assessing the resilience of an electric distribution network with integrated microgrids in severe conditions. He also demonstrates how regulated and islandable microgrids might improve distribution system resilience in challenging conditions. The link between the transmission grid, distribution grid, and microgrid under extreme conditions is also discussed. The Monte Carlo method is used to calculate the robustness indices. Reference [4] develops and describes metrics and analytical methods for grid resilience. A series of sample use cases are used to demonstrate the metrics and methodologies. The resilience triangle and the multiphase resilience trapezoid are presented differently by the author in [5]. According to Ref. [6], an integrated resilience response framework is put forth that offers effective and efficient responses in both emergency and preventative situations, in addition to connecting situational awareness with resilience enhancement. In paper [7], they discussed smart grid technologies and system hardening strategies as ways to make systems more resilient.

This study we provide the load restoration framework, which increases system resilience and lowers network load loss. We employed an IEEE 33 bus radial distribution network with tie switch in this paper. Using the Monte Carlo approach, we determine the likelihood of creating a microgrid in each scenario, as well as the resilience indices and the number of hours it will take to restore the distribution network following a low-frequency, high-risk event. We employed the forward backward sweep approach for optimum power flow in order to calculate the loss of load. MATLAB software will be used for all simulations.

2 Resilience Framework

For evaluating the resilience of a distribution network, first we have to identify the low-frequency, high-risk event that the distribution network may face, as resilience varies according to each of them. Distribution network resilience can be obtained in a single failure scenario or multiple failure scenarios.

2.1 Threat in Distribution Network

A factor of an event that has the potential to cause damage, destruction, or interruption to an electrical distribution network is considered a threat. That threat can be a natural disaster, a technological, or a man-made event.

2.2 Resilience Triangle

Figure 1 is a representation of the resilience triangle, which is used in this paper. This triangle is capable of conducting a resilience assessment in a single phase and multi failure scenarios.

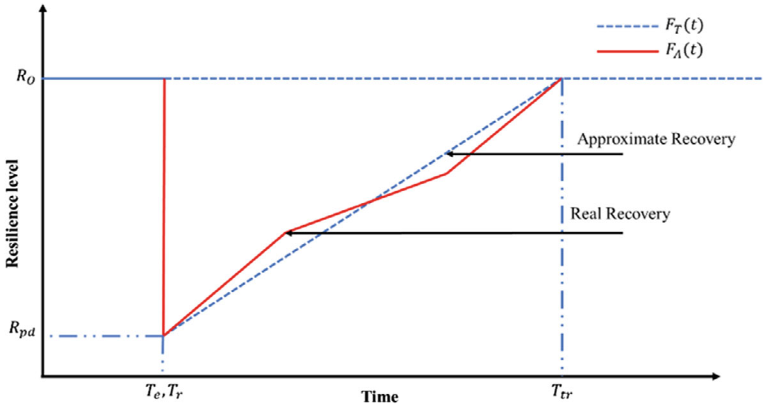

Fig. 1 Resilience triangle

In Fig. 1 $F_A(t)$ represents the level of real performance of the distribution network. $F_T(t)$ represents the level of target performance of the distribution network. T_e denotes the time of the low frequency high risk event ha accord in the distribution network. After that event accord the system has goes down new resilience matrix value is R_{pd}. Now the T_r is signifies the commencement of the restoration process. T_r is the where restoration process has to start. T_{pr} has the moment at which the recovery of the final or a targeted value of resilience has been achieved. The hypotenuse of the triangle can have different shapes it is not possible to always linear. This shape depends on the recovery strategy or function.

For measure the impact (L) between normal and abnormal condition during an event calculating the difference in functionality of the distribution network.

$$L = \int_{T_e}^{T_{\text{pr}}} [R_O - F_A(t)]\mathrm{d}t \tag{1}$$

where $F_A(t)$ is the distribution network functionality at time T_r. R_O is the total distribution network functionality in normal condition. T_e and T_{pr} are the time of the start of the event and restoration time respectively.

In this study we find the restoration period time or time to recover the original value of resilience of distribution network in all scenario mention in introduction.

$$T_F = T_e - T_{\text{pr}} \tag{2}$$

For infrastructure quality has been different during the both normal operating condition and during low frequency high risk event. For that we establish a resilience index as follow

$$\text{Resilience} = \frac{\int_{T_e}^{T_{\text{pr}}} Q(t)\mathrm{d}t}{100\left[T_e - T_{\text{pr}}\right]} \tag{3}$$

In this expressions $Q(t)$ represents the quality of the infrastructure in Fig. 1. So, we have to modified the R_O based on the quality of infrastructure.

3 Distribution Network Load Restoration Framework

Distribution network resilience for different perspectives, including survivability and recovery. Index K measures the expected number of line outages due to low-frequency, high-risk events. Index (POL) measures the probability of load not being fully supplied. Index (EDS) measures the expected demand supplied.

$$K = \int_{0}^{\infty} Kf(k)\mathrm{d}k \tag{4}$$

Index K represent the expected number of line on outage due to low frequency high risk event in distribution network. Two traditional resilience indices including the loss of load probability (POL) and expected demand supply (EDS) are given below.

$$\mathrm{POL} = \sum_{E_i \in S_e} P_e \tag{5}$$

$$\mathrm{EDS} = \sum_{E_i \in S_e} P_{e_i} * C_{e_i} \tag{6}$$

where P_{e_i} is the chance that the distribution network would experience E_i is the ith low frequency high risk event. The collection of high-risk, low-frequency events when the system demand is greater than the available generating capacity is known as S_e the load curtailment in E_i or C_{e_i}, may be computed using the forward backward sweep method and the optimum power flow (OPF) solution. In microgrids, incorporate selective load shedding as well. Depending on how severe the low frequency high risk incident is, the restoration of the distribution network may take several hours or perhaps a day.

Additionally, it depends on how much of the vital infrastructure such as the transportation, electricity generation, and cyber infrastructures has been damaged. In low-frequency, high-risk event scenarios, enhanced weather forecasting and situational awareness may be able to limit the extent of damage to vital infrastructures and deploy organizational human and material resources for a thorough distribution network recovery.

An overview of the distribution network's resilience-based structure is shown in Fig. 2.

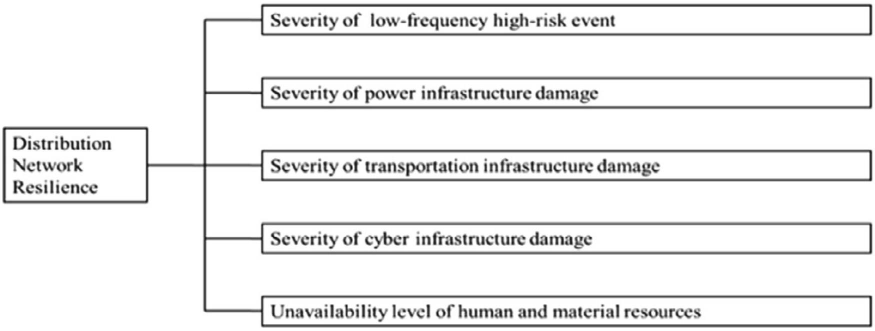

Fig. 2 Composition of distribution network resilience recovery

Figure 3 gives proposed framework analyses distribution network resilience under low-frequency, high-risk events, specifically for networks integrated with microgrids. It includes event modelling and statistical analysis of both the distribution network and microgrid performance during such conditions. Unlike cascading failures or $N - 1$ failures, these events impact multiple geographic areas and cause simultaneous outages in transmission lines or subsystems. A well-equipped microgrid with sufficient resources and fuel can sustain operations independently for an extended period. As a result, the suggested resilience indices heavily rely on the synchronization of microgrid runtimes and distribution network recovery procedures.

In this framework, we computed the distribution network robustness indices using the Monte Carlo technique. Network connection is checked to see if it is maintained with the distribution network. The network's optimal power flow is achieved if connection is maintained. A predetermined load reduction schedule is followed if OPF is not feasible. We upgrade the distribution network resiliency if OPF is

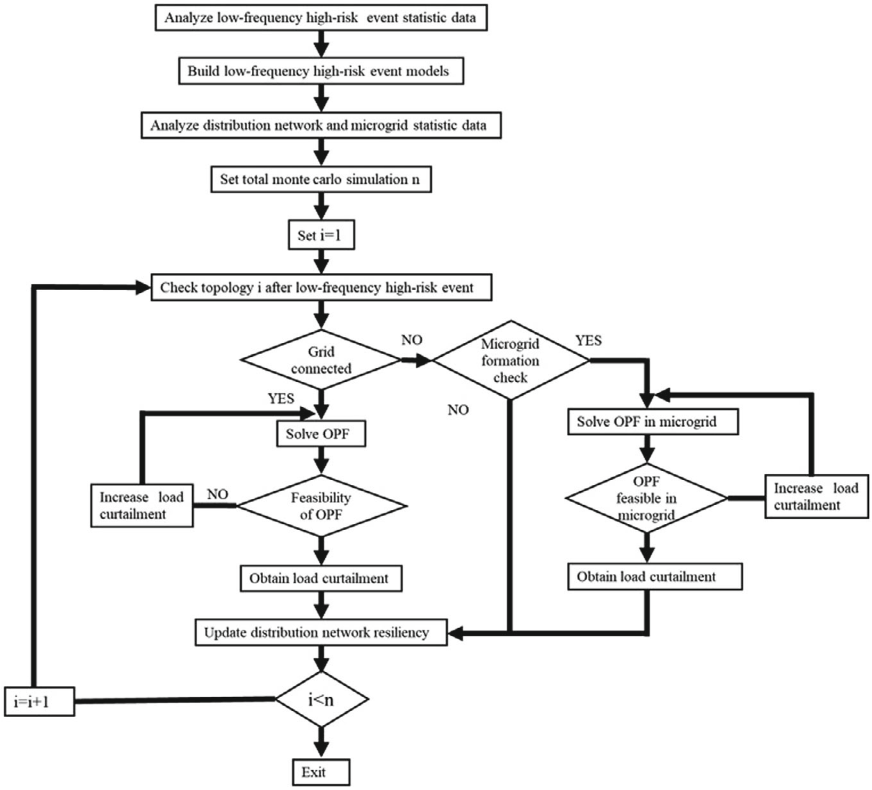

Fig. 3 Framework for resilience analyses of distribution network with microgrids

feasible. When the network is disconnected from the distribution network, we determine whether or not microgrids are possible to build and see what distribution generation capacity is available. If possible, we apply OPF to the microgrid and improve the distribution network's resiliency. Should it not be possible, we will upgrade the distribution network's resiliency.

4 Result and Analysis

We offer four distinct simulation cases for analytical purposes in order to validate over framework. The IEEE 33 bus distribution network technology was also utilized. The total load on the system is 3.7150 MW + 2.3 MVAR.

1. Case-1: distribution network has no tie switch and no distribution generation.
2. Case-2: distribution network has tie switch and no distribution generation.
3. Case-3: distribution network has tie switch and randomly selected distribution generation size and placement.
4. Case-4: distribution network has tie switch and optimized selected distribution generation size and placement.

To determine the ideal power flow, use the forward–backward sweep approach as well. In Case-4, we applied the particle swarm optimization approach to determine the ideal distribution generation size and location. MATLAB software is used for all of these simulations. We used the assumption for analytical purposes that the five lines had gone out of service as a result of accumulating low-frequency, high-risk events. Both distribution generation and a tie switch are absent in Case 1. As a result, that system is less resilient to low-frequency, high-risk events.

The resilience triangle for Case-1 is shown in Fig. 4. In this instance, no microgrid is formed, and it takes three to four days for the system to return to its initial configuration. This system will deliver 10% of the active power.

In Case-2, the system experiences a low-frequency, high-risk event with a tie switch and no distribution generation. The system is less resilient to that occurrence.

The resilience triangle for Case-2 is shown in Fig. 5. In this instance, the system is strengthened by the tie switch but no microgrid is formed. It takes two to three days for this system to return to its initial form. In this instance, we can see that the tie switch provided some assistance in enhancing system resilience. However, the system's power quality is a problem because it is a redial system and no longer has a meshed.

Figure 11 shows that this system has seen greater losses than the other system. In Case-3, Fig. 6 provides the system following a low-frequency, high-risk incident. Six distributions in all, with random placement and size, are generated in Case-3. The distribution generation information is shown in Table 1.

As a result, 3 microgrids are formed in this scenario, as seen in Fig. 6, with the first microgrid distribution generation operating parallel to the distribution network at buses 3, 10, and 20. There is only one distribution generation at bus 31 in the

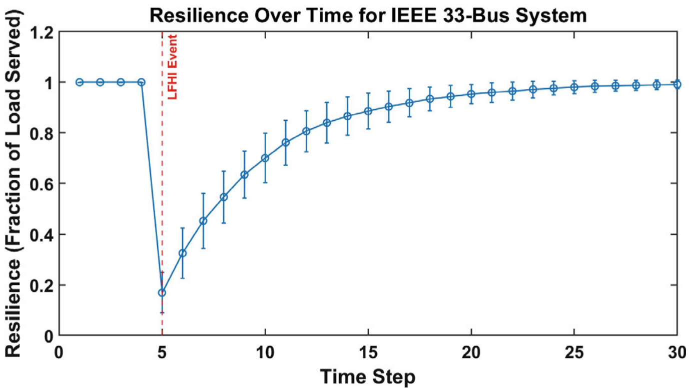

Fig. 4 Resilience triangle Case-1

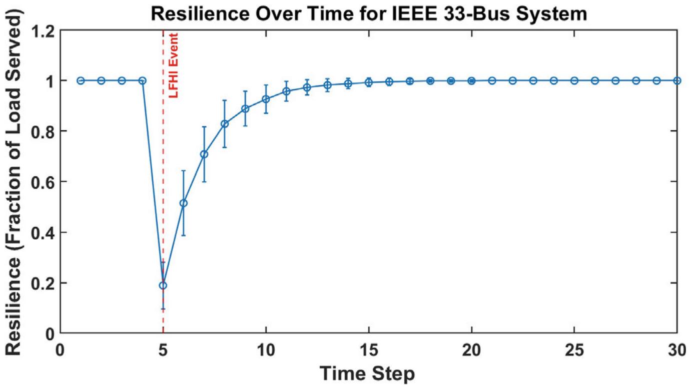

Fig. 5 Resilience triangle Case-2

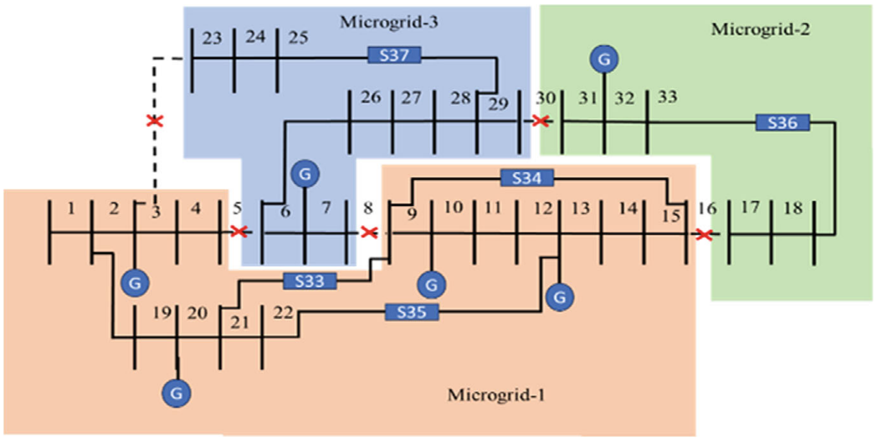

Fig. 6 System in Case-3 after low-frequency high-risk event

Table 1 Distribution generation in Case-3

Bus number	Distribution generation capacity in kVA
3	320
7	90
10	110
12	260
20	160
31	90

second microgrid, and there is only one distribution generation at bus 6 in the third. Load curtailment has occurred because the distribution generation is insufficient to supply electricity to the microgrid. There is only one distribution generation at bus 31 in the second microgrid, and there is only one distribution generation at bus 6 in the third. Load curtailment has occurred because the distribution generation is insufficient to supply electricity to the microgrid.

The resilience triangle for case three is shown in Fig. 7. This system is resilient to high-risk, low-frequency events. Restoring the system to its initial state takes one to one and a half days.

In Case-4, the system is shown in Fig. 8 following a low-frequency, high-risk occurrence. In this instance, six distributions are generated, and the particle swarm optimization method determines the ideal size and location. The distribution generation at the bus and its rating are shown in Table 2.

Loss reduction and distribution resilience function enhancement are used to determine this bus number and distribution generation rating.

The resilience triangle for Case-4 is shown in Fig. 9. This system is more resilient to high-risk, low-frequency events. Restoring the system to its initial state just takes a day. Distribution generation at buses 10 and 21 in this system runs in parallel with the distribution network, while distribution generation at buses 24 and 6 comes from

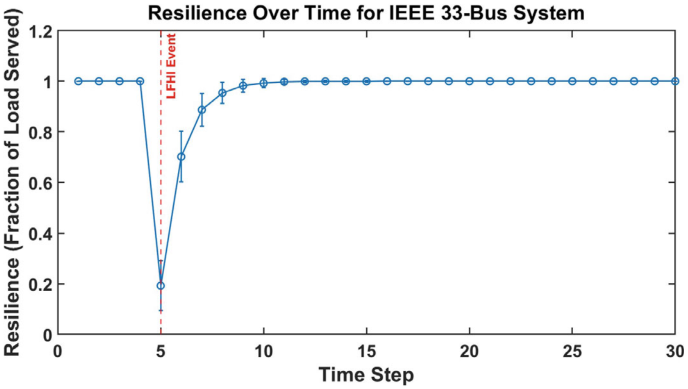

Fig. 7 Resilience triangle Case-3

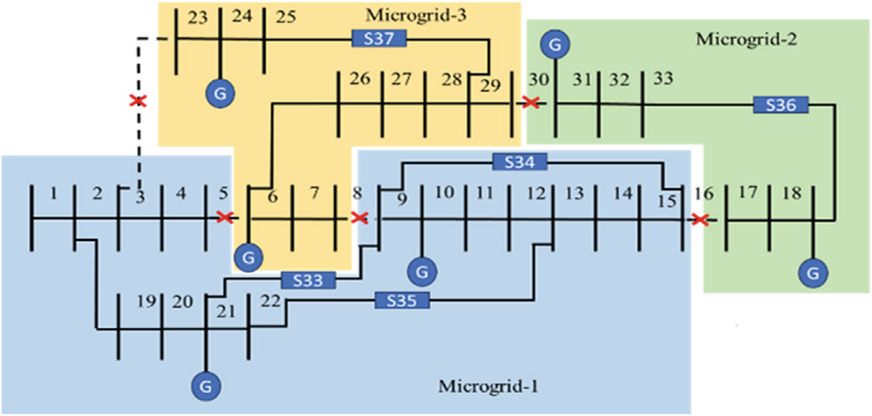

Fig. 8 System in Case-4 after low-frequency high-risk event

Table 2 Distribution generation in Case-4

Bus number	Distribution generation capacity in kVA
6	400
18	250
21	1100
24	900
29	280
30	600

the second microgrid. Additionally, the third microgrid provides the distribution generation at buses 30 and 18. There is no need for load curtailment in this setup because 100% of the load has been supplied following a low-frequency, high-risk incident.

The expected demand supply (EDS) is shown as a percentage in Fig. 10. It provides information on how much power the system will require afterwards a low-frequency, high-risk incident. Higher active power demand, such as 80.75% and 100%, will be supplied in Cases-3 and 4.

Figure 11 displays the power loss data for each situation. Figure 11 shows the active and reactive power losses in megawatts. In summary, the power loss is reduced if a microgrid is incorporated into the system. As we can see from the above chart, power loss is reduced in cases three and four due to the presence of distribution generation.

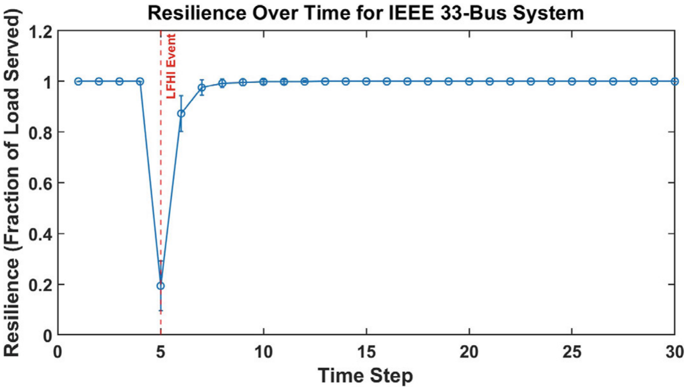

Fig. 9 Resilience triangle Case-4

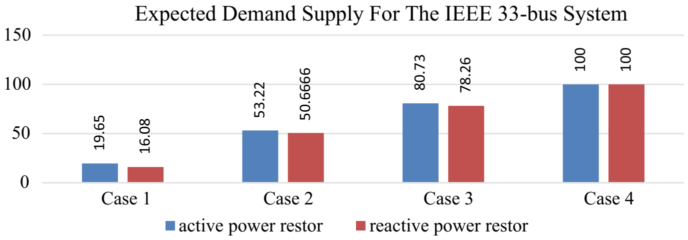

Fig. 10 Load restored for the IEEE 33-bus system

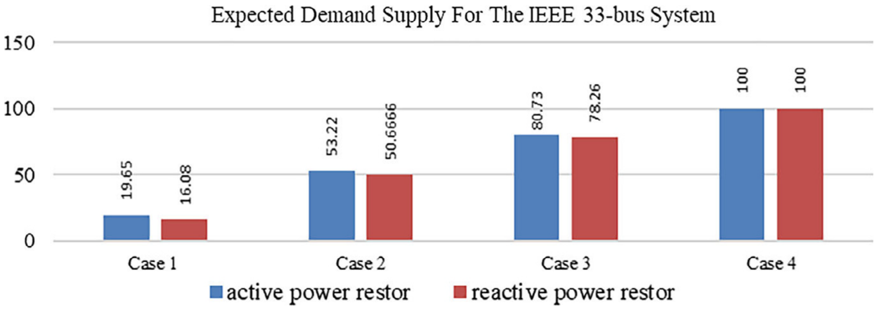

Fig. 11 Active and reactive power loss after restoration in system

5 Conclusion

Building a resilient distribution network has become essential for the network to withstand low-frequency, high-risk events. Low-frequency, high-risk events have increased in rate, which makes the distribution network's resilience more difficult to maintain. The approach for assessing the resilience of an electrical distribution network with an integrated microgrid in the case of a low-frequency, high-risk event is presented in this study. Additionally, we saw through simulation that we were able to optimize the distribution network's size and location. It offered 100% load restoration following the low-frequency, high-risk incident and the best microgrid island ability. Additionally, it demonstrates that distribution generation and islandable microgrids not only assist the distribution network but also boost its resilience.

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