IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 27 October 2023, accepted 16 November 2023, date of publication 24 November 2023, date of current version 30 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3336858

RESEARCH ARTICLE

Enhancing Indian Practical Distribution System Resilience Through Microgrid Formation and Integration of Distributed Energy Resources Considering Battery Electric Vehicle

T. YUVARAJ[1], K. R. DEVABALAJI[2], T. D. SURESH[3], NATARAJAN PRABAHARAN[4], (Senior Member, IEEE), SOICHIRO UEDA[5], (Student Member, IEEE), AND TOMONOBU SENJYU[5], (Fellow, IEEE)

[1]Centre for Computational Modeling, Chennai Institute of Technology, Chennai 600069, India
[2]Department of Electrical and Electronics Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Missions Research Foundation, Chennai 603104, India
[3]Department of Electrical and Electronics Engineering, Saveetha Engineering College, Chennai 602105, India
[4]School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur 613401, India
[5]Faculty of Engineering, University of the Ryukyus, Nakagami, Okinawa 903-0213, Japan

Corresponding authors: Tomonobu Senjyu (a985542@yahoo.co.jp) and Natarajan Prabaharan (prabaharan@eee.sastra.edu; prabaharan.nataraj@gmail.com)

ABSTRACT Electrical microgrids (EMGs) are positioned to play an important role in the future distribution grid as technology advances and distributed energy resources (DERs) emerge. In the event of major natural disasters, the functioning capabilities of active distribution systems (DS) face ongoing problems. To assess the resilience of a distribution system, a thorough methodology must be established. This study proposes a methodology that demonstrates how the use of EMGs and DERs, in conjunction with line hardening, can improve resilience in extreme operating situations. The framework examines four separate scenarios, each with its own set of restoration procedures and critical loads. A combination of battery electric vehicles (BEVs), solar photovoltaic distributed generation (SPV-DG), battery energy storage systems (BESS), and distribution static compensators (DSTATCOMs) is being integrated into practical Indian distribution systems consisting of 28 and 52 buses to improve resilience. The goal is to improve the newly specified resilience indices and restore all of the loads that have been affected by the faults. The bald eagle search algorithm (BESA) is used to identify the appropriate allocation of SPV-DG and solve the objective function within the system. The results of our tests show that our proposed technique has the capacity to enhancement the resilience and successfully restore all damaged loads in a distribution system.

INDEX TERMS Electrical microgrid (EMG), resilience indices (RI), distributed energy resources (DERs), solar photovoltaic distributed generation (SPV-DG), battery energy storage systems (BESSs), distribution static compensator (DSTATCOM), bald eagle search algorithm (BESA), Indian distribution systems.

I. INTRODUCTION

In an era marked by rapid urbanization, technological progress, and a burgeoning population, the interconnectedness of critical infrastructures assumes paramount significance within the Indian environment. Energy, health, banking, transportation, and telecommunications collectively serve as the cornerstone of a nation's functionality, ensuring the welfare of its citizens and the seamless operation of its economy. Central to this intricate network is the uninterrupted provision of electric power, supporting vital services ranging from emergency response and healthcare delivery to financial transactions and communication systems [1].

However, sustaining a seamless and reliable power supply in India presents a formidable challenge. The nation's energy grid, characterized by its scale and complexity, is vulnerable

The associate editor coordinating the review of this manuscript and approving it for publication was Alexander Micallef.

to an array of external threats, including cyber-attacks, vandalism, natural calamities, and geomagnetic disturbances. India's susceptibility to severe weather conditions, exemplified by monsoons and cyclones, underscores the imperative for robust infrastructures capable of withstanding climatic extremes. Given that a substantial portion of the grid infrastructure is situated above ground, disruptions stemming from adverse weather conditions persist as a primary source of power outages, necessitating comprehensive strategies for reinforcement and recovery [2].

Within this context, the concept of resilience emerges as a pivotal focal point. Resilience, defined as a system's capacity to absorb and recover from disturbances while minimizing downtime and adverse consequences, assumes paramount importance in the Indian scenario. As disruptions increase both in frequency and severity, a thorough exploration of strategies and technologies to enhance the resilience of distribution systems becomes imperative [3].

This research article embarks on a multi-sectoral exploration, delving into the intricate interplay between energy, health, banking, transportation, and telecommunications infrastructures in India. Through a comprehensive analysis, our aim is to pinpoint key areas for intervention and propose innovative solutions to fortify these critical systems. In doing so, we endeavor to contribute to the body of knowledge crucial for safeguarding India's vital infrastructures amidst an ever-evolving landscape of challenges.

On the other hand, electric vehicles (EVs) are revolutionizing transportation with cleaner, efficient technology. India, a thriving automotive market, is steering towards eco-friendly options. The sector, contributing 7.1% to GDP and jobs, anticipates significant growth. The Economic Survey 2023 forecasts a 49% CAGR in India's EV market, targeting 10 million annual sales by 2030. Government initiatives, including the FY24 Union Budget, with INR 35,000 crore for energy transition, demonstrate a strong push. Reductions in custom duties and excise on key components further incentivize the EV industry. Leading Indian automakers and international players, like Volvo, are entering the EV market. Charging infrastructure is expanding rapidly, with Delhi's EV Policy yielding substantial growth. By December 2022, EVs comprised 16.8% of vehicle sales, up 86% YoY. This growth presents a pivotal opportunity for India's EV ecosystem [4].

EVs contribute significantly to the resilience of India's distribution system. By diversifying energy sources and integrating with renewable energy, EVs reduce dependency on traditional fuels. Vehicle-to-Grid (V2G) technology enables EVs to act as mobile energy storage units, stabilizing the grid during peak demand. During emergencies, EVs serve as mobile power sources, vital for essential services. The government's focus on EVs aligns with efforts to build a more robust and sustainable energy infrastructure. Overall, the growth of EVs in India presents a transformative opportunity for a greener, more resilient energy landscape.

Enhancing the resilience of Indian power distribution networks to disasters through planning strategies has been a major topic for power network operations. Increased investment in distribution network resilience can reduce additional operational costs associated with extreme occurrences. In this regard, the development of electrical microgrids (EMGs), which are localized distribution networks comprised of distributed energy resources (DERs) such as renewable distributed generators (RDGs), battery electric vehicles (BEV), battery energy storage system (BESS), and other devices, can help to harden vulnerable distribution lines and improve distribution system resilience. EMGs have attracted significant attention in recent years, since several studies and pilot projects have demonstrated their potential to make distribution networks more sustainable [5], [6]. Hardening distribution lines with stronger materials can lessen their vulnerability to natural disasters, allowing them to serve important loads [7], [8]. Furthermore, because of the possibility of losing the main grid during extreme weather events such as a hurricane, controllable generators can supply electricity for important loads and construct self-supplied microgrids (MGs) to boost load restoration capabilities after an extreme weather event. As a result, developing a resilient distribution system planning model to optimize the design of planning strategies can significantly reduce the negative impacts of natural disasters [9].

BESS and BEV have the potential to significantly improve distribution system resilience. The integration of these BESS and BEV into the system can improve resilience by offering load control, grid stability, backup power supply, demand response capabilities, and enhanced power quality. These technologies contribute to a more robust and dependable distribution system that can resist disturbances and provide uninterrupted power supply during emergencies [10]. BEVs provide substantial advantages over regular vehicles in terms of alleviating the energy crisis, increasing energy efficiency, and safeguarding the environment [11]. BEVs have been used in the literature for a variety of goals, including increasing the economic value of system operation, providing voltage and frequency management, and delivering peak load to lessen the likelihood of a system outage [12].

DSTATCOM is crucial in assuring the reliable operation of key loads during the faults. It adjusts voltage, improves fault ride-through capability, boosts power quality, responds quickly, and minimizes fault currents. These features assist in mitigating the impact of faults, minimizing downtime, and protecting essential loads from voltage changes and other fault-related disruptions [13]. According to statistics, distribution system incidents account for around 80% to 90% of power system blackouts. With the advancement of DERs, distribution systems have increasingly evolved into the focal point of energy utilization, and current distribution systems are evolving into vast and complex cyber physical systems. As a result, the resilience of distribution systems becomes increasingly essential and critical. Figure 1 depicts the main

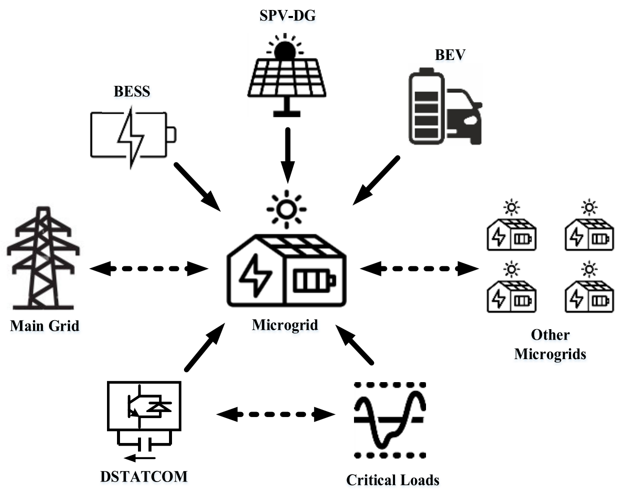

FIGURE 1. General layout of the proposed framework.

layout of the proposed framework with several DERs for resilience improvement.

II. LITERATURE REVIEW

Several research, including DERs, have been done in recent decades to improve power system resilience. Various resilience metrics have been developed to quantify system performance. Section II contains an extensive explanation in which the researchers explain each aspect and its significance. The authors suggested a hierarchical control technique that optimizes MG economic performance while improving their resilience to shocks and grid breakdowns. To improve the economic efficiency of DC MGs, the study emphasized the combination of renewable energy sources with energy storage systems [14]. The study's major goal was to develop a method for assessing the resilience of distribution networks in the event of diverse disturbances and providing ideas for increasing their resilience. To assess the durability of the distribution network, the authors presented a paradigm that integrates network theory and modularity analysis [15]. The researchers looked into many elements of MGs with energy storage systems, such as their effects on power quality, energy management, and cost-effectiveness. According to the outcomes of the literature study, adding energy storage devices into MGs can greatly improve power resilience in office buildings [16]. The study proposed a design framework for distribution feeders that include networked MGs, which are localized power generating and distribution systems. The incorporation of MGs into distribution feeders sought to improve overall power system resilience by enabling local generation and energy sharing capabilities [17].

The presented approach provided a systematic method to decision-making in load restoration scenarios, taking both technical and economic factors into account. It laid the groundwork for future research and development in the field of resilient distribution systems, assisting utilities and operators in restoring power efficiently during outages and improving overall system dependability [18]. The article's key finding was that incorporating DS technology into networked MGs allows for better coordination and management of power distribution among various MG units. DS provides a centralized management solution for the MG network, allowing for real-time monitoring, intelligent decision-making, and dynamic reconfiguration [19]. The essay intensive on the employment of an islanded DC microgrid that generates power using renewable energy sources. The researchers presented an improved resilient control system for the MG, with the goal of increasing its stability, dependability, and overall performance [20]. To improve microgrid resilience, the authors examined the possible benefits of adding renewable energy sources, energy storage systems, and improved monitoring tools. They also stressed the significance of good coordination and collaboration across MGs, utilities, and other stakeholders in order to improve overall system resilience [21].

The research offered a mathematical methodology for evaluating appropriate DER location and sizing while taking into account numerous parameters such as load demand, reliability indices, and investment costs. The authors demonstrated the efficiency of their proposed approach in improving system robustness in a case study based on a genuine distribution system [22]. Using a case study, the authors proved that optimizing the sizing and placement of DGs can considerably improve the resilience of MG networks [23]. In prior research, a framework was developed to demonstrate the enhancement of resilience in extreme operating conditions through the utilization of multi-microgrids (MMGs) and mobile energy storage considering critical loads. Within this framework, four critical resilience indices, namely withstand, recover, adapt, and prevent were introduced [24]. The research emphasized the importance of creating adequate approaches and models to analyses distribution network resilience and identify vulnerabilities that may cause to outages during extreme weather events [25].

Amirioun et al. developed a complete set of criteria for evaluating MG performance during windstorms, including reliability indices, restoration time, economic losses, and customer satisfaction [26]. The author offered a review of the literature, which provides an overview of current research and developments in this field. The study emphasizes the significance of robust electricity distribution systems in the face of growing threats such as natural catastrophes, cyber-attacks, and other disturbances [27]. The study investigated the substantial influence of renewable energy resources, loads, and their associated uncertainty on the resilience of the distribution system. Furthermore, the research determined the necessary emergency budgets for operational restoration following extreme events [28]. This paper delved into the complexities and benefits associated with incorporating networked MGs into segments of a power distribution system. This integration served as an efficient means to oversee DERs, with a special focus on rooftop solar photovoltaic and battery energy storage systems. The ultimate aim was to bolster the resilience of the power distribution system, particularly in the face of natural disasters [29].

Although various research on the resilience of power distribution systems have been undertaken, there are still gaps in the literature, particularly in producing realistic case studies and utilizing relevant resilience indicators. Furthermore, determining the actual impacts on energy customers caused by outages due to natural disasters or other disruptive events requires extensive research. Furthermore, failing to quantify the potential impacts of such events' blackouts using the appropriate resilience metrics can limit decision makers' ability to identify the best approach for infrastructure investments and additions to improve the overall resilience of the power distribution system. Unlike previous papers, this paper addresses the aforementioned challenge of quantifying the impact of natural disasters on electricity consumers by analyzing and evaluating potential improvements in power distribution system resilience to natural disasters using appropriate resilience metrics.

In general, the novelty of this paper lies in the aspects described as (i) Evaluating the impact of outages on system loads in practical two Indian bus systems using an emerging and promising networked EMGs mechanism with an effective utilization of solar PV-DG, BESS, and DSTATCOM along with BEV as DERs and (ii) Assessing the impacts the utility or system operator and customers will experience due to natural disasters using new resilience indices. In light of prior work, this study contributes to the state-of-the-art in power distribution grid resilience to improve its capabilities under four different natural disaster-caused scenarios. This paper's significant contributions are as follows:

- Development of a complete resilience study offering accurate case studies with Indian practical distribution systems that demonstrate the potential benefits that DERs may provide to power distribution grids when appropriately controlled in networked EMGs.
- A novel integration of BEV in V2G mode to EMGs in the distribution system is presented to offer real power and improve resilience.
- A new resilience indices is framed to measure and analysis the system's resiliency under various cases.
- The suggested framework's main feature is tested using two real-world Indian distribution systems (28 and 52 DS buses) with diverse situations.
- Optimal planning of DERs into the distribution system is proposed to form microgrid operation to improve the system resilience.
- Hardening the distribution poles to avoid damage during severe natural calamities.
- Allocated DSTATCOM and BESS for improving the power quality, resilience and reliability of the EMGs. They also help to protect sensitive equipment and ensures uninterrupted operation of critical loads.
- The solar PV-DG allotted in the EMGs in two ways (i) Optimal generation (70%) and, (ii) Highest generation (100%).
- The SPV-DG's optimal position and size are found utilizing the recently developed nature-inspired Bald Eagle Search Algorithm (BESA).

III. PRESENTED APPROACH FOR ASSESSING RESILIENCE

Figure 2 shows the overall planning of the presented approach for assessing resilience as follows:

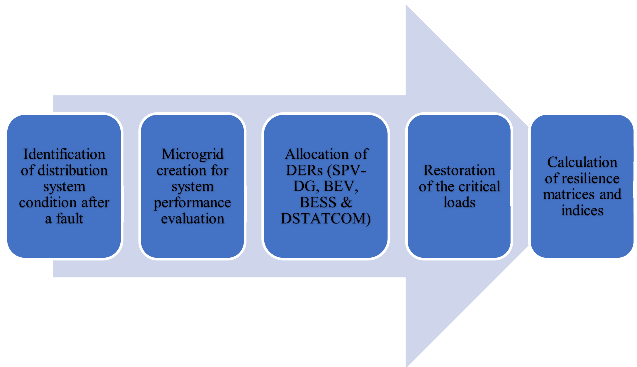

FIGURE 2. Flow chart of proposed resilience evaluation framework.

(i) Identification of distribution system condition after a fault: Analyze the distribution system and determine its status following a fault event. This entails determining how the fault will affect various components such as electricity lines, transformers, and loads.

(ii) Microgrid creation for system performance evaluation: Build a microgrid model of the distribution system under consideration. The required components, such as DERs, loads, and control systems, should be included in this model.

(iii) Allocation of DERs (SPV-DG, BEV, BESS & DSTATCOM): Define the allocation and characteristics of various DERs within the microgrid. SPV-DG, BEV, BESS, and DSTATCOMs may be included.

(iv) Restoration of the critical loads: Define and priorities key loads that must be restored during or immediately following a fault event. Create a load restoration plan that takes into account the available DERs and their capabilities. DSTATCOM contributes significantly to essential load restoration by providing voltage support, improved power quality, load balancing, fault current limiting, and voltage regulation. Its reactive power compensation and control capabilities make it an invaluable tool for guaranteeing the reliable and robust functioning of important loads within an EMG or DS.

(v) Calculation of resilience matrices and indices: Define resilience matrices and indicators to assess the MGs performance and resilience. Metrics such as system dependability, power quality, economic impact, environmental impact, and social impact can be included in these matrices and indexes. Data from the microgrid model, including as fault events, restoration times, load profiles, DERs capabilities, and other pertinent factors, should be collected. Using preset methods or techniques, compute the resilience matrices and indices from the collected data. Analyze the derived resilience matrices and indices to assess the MGs overall resilience and identify areas for improvement.

IV. SYSTEM MODELLING FOR RESILIENCE METRICS CALCULATION

This section places emphasis on the problem formulation, encompassing the delineation of objective functions, and resilience metrics. The principal aim is to enhance resilience metrics while concurrently reducing operational costs and augmenting the restoration of critical loads. Achieving this necessitates strict adherence to ensuring radial operation within the distribution grid, covering both the EMGs and DERs. The Resilience analysis process constitutes the evaluative framework employed to gauge the resilience of this grid configuration. Figure 3 showcases a sample EMG integrated within a distribution system, employing the proposed approach.

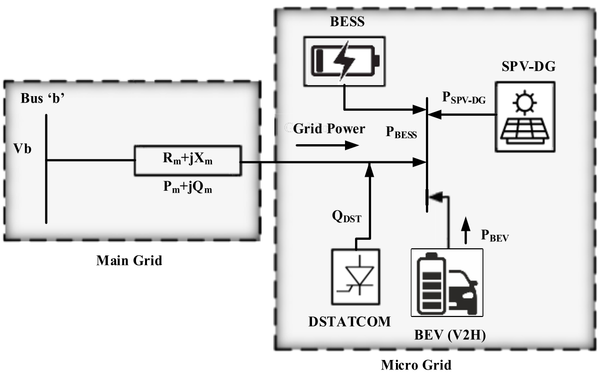

FIGURE 3. Sample EMG in distribution system with proposed approach.

The microgrid system embodies a resilient energy framework, integrating a spectrum of components to guarantee ceaseless power provision and steadfast stability. It introduces a BEV functioning in V2G mode, allowing for bidirectional energy exchange between the vehicle and the grid. A BESS is in place to accumulate surplus energy, while a SPV-DG ensemble harmonizes renewable solar power. Critical loads, comprising pivotal infrastructure, remain supplied with uninterrupted power. Strengthening measures fortify the grid infrastructure, complemented by a DSTATCOM ensuring steadfast voltage and premium power delivery. This comprehensive integration substantially elevates the resilience and dependability of the microgrid across diverse scenarios, positioning it as a robust energy solution catering to a spectrum of needs. Below, detailed mathematical models for each DERs in the EMG are expounded.

A. POWER BALANCE EQUATIONS

The power balance equation for the microgrid is given by:

$$P_{SPV-DG} + P_{BEV}^{V2G} + P_{BESS} - P_{Load} = 0 \tag{1}$$

where, P_{SPV-DG} is the power generated by the SPV-DG system; P_{BEV}^{V2G} is the power contributed by the BEV in V2G mode; P_{BESS} is the power supplied by the BESS; P_{Load} is the total power demand, including critical loads.

B. SOLAR PV-BASED DG MODEL

Incorporating solar photovoltaic (PV) systems as a distributed generation source is crucial for enhancing the resilience of MGs. The power output (P_{SPV-DG}) of the solar PV system is determined by the incident solar irradiance (G) and the efficiency of the PV modules (η_{SPV}). The modeling equations for a solar PV-based DG unit are given below.

$$P_{SPV-DG} = A_{SPV} * G * \eta_{SPV} \tag{2}$$

where, A_{SPV} is the area of the PV panels.

C. BEV AND BESS MODEL

1) STATE OF CHARGE (SOC) BEV AND BESS

The SOC of the BEV and BESS can be modeled as follows:

(i) For BEV:

$$SOC_{BEV}(t) = SOC_{BEV}(t-1) - \left({P_{BEV}(t)}/{E_{BEV}(t)} \right) \tag{3}$$

(ii) For BESS:

$$SOC_{BESS}(t) = SOC_{BESS}(t-1) - \left({P_{BESS}(t)}/{E_{BESS}(t)} \right) \tag{4}$$

where, E_{BEV} and E_{BESS} represent the energy capacities of the BEV and BESS, respectively.

2) CHARGING AND DISCHARGING RATES

For the BEV, the charging and discharging rates are determined as follows:

(i) Charge rate:

$$P_{BEV}^{Charge}(t) = \min(P_{BEV}^{V2G}(t), P_{EV}^{Max}) \tag{5}$$

Discharge rate:

$$P_{BEV}^{Discharge}(t) = \min(P_{BEV}^{G2V}(t), SOC_{BEV}(t).E_{BEV}) \tag{6}$$

For the BESS, the charging and discharging rates are determined as follows:

Charge rate:

$$P_{BESS}^{Charge}(t) = \min(P_{BESS}^{Max}(t) - P_{BESS}(t), CR) \tag{7}$$

Discharge rate:

$$P_{BESS}^{Discharge}(t) = \min(P_{BESS}(t), DR) \tag{8}$$

where, $P_{BEV}^{V2G}(t)$ and $P_{BEV}^{G2V}(t)$ are the power flows for V2G and G2V modes; P_{BESS}^{Max} is the maximum charge/discharge power capacity of the BESS and CR and DR are the charge and discharge rate limits for the BESS.

D. DSTATCOM MODEL TO SUPPORT FOR CRITICAL LOADS

The DSTATCOM plays a pivotal role in ensuring the stability and reliability of the microgrid, particularly during contingencies. It provides compensating reactive power to support critical loads. The injected reactive power by DSTATCOM at bus b can be expressed as:

$$Q_{DST}(b) = Q_{CL}(b) - Q_b \tag{9}$$

where, $Q_{DST}(b)$ is the reactive power injected by the DSTATCOM at bus b; $Q_{CL}(b)$ is the reactive power demand of critical loads at bus b; Q_b is the available reactive power at bus b.

E. LINE HARDENING MEASURES

In microgrid systems, line hardening is essential to fortify the distribution network's physical infrastructure. This involves strengthening power lines to withstand various environmental and operational challenges. The equations representing line hardening measures can be expressed as:

$$F_h = F_O * (1 + H_p) \tag{10}$$

where, F_h is the strengthened line tensile strength; F_O is the initial tensile strength of the power line; and H_p is the hardening factor representing the degree of line reinforcement.

Hardening measures, such as increasing line pole density (N_p) to ensure consistent physical support along the distribution path, can be defined as:

$$N_p = {}^{L}/{}_{D_p} \tag{11}$$

where, N_p is the Number of line poles/buses; L is the length of the power line; and D_p is the desired pole spacing to maintain line integrity.

By incorporating these line hardening measures, microgrids can effectively bolster their distribution infrastructure, ensuring the reliability and resilience of power lines under adverse conditions.

F. FORMULATION OF RESILIENCE METRICS

The calculation of resilience metrics (RM) for enhancing the resilience of the EMG is carried out as follows.

1) TOTAL NO OF HOUSEHOLDS- HOURS DURING OUTAGE (RM_1)

$$\mathrm{RM}_1 = \sum_{\mathrm{j}=1}^{\mathrm{b}} (\mathrm{A_j} * t) \tag{12}$$

where $(A_j * t)$ is the no of household's hours during outage and 'b' is the no of buses in the distribution system.

2) TOTAL NO OF HOUSEHOLDS-ENERGY NOT SUPPLIED (RM_2)

$$\mathrm{RM}_2 = \sum_{\mathrm{j}=1}^{\mathrm{b}} (\mathrm{E_j} * t) \tag{13}$$

where $(E_j * t)$ is the no of household energy not supplied (ENS) during outage.

3) TOTAL NO OF HOUSEHOLDS AFFECTED DURING OUTAGE (RM_3)

$$RM_3 = \sum_{c=1}^{T_c} \sum_{j=1}^{b} A_{j,c} \tag{14}$$

where RM_3 is total no of households affected during case 'c' outage and T_c is the total no of cases.

4) AVERAGE NO OF HOUSEHOLDS AFFECTED DURING OUTAGE (RM_4)

$$RM4 = \frac{\sum_{c=1}^{T_c} \sum_{j=1}^{b} A_{j,c}}{T_c} \tag{15}$$

where RM_4 is average no of households affected during case 'c' outage.

5) TOTAL REVENUE LOSS FROM THE UTILITIES DURING OUTAGE (RM_5)

$$\mathrm{RM5} = \mathrm{CE} * (\sum_{\mathrm{j}=1}^{\mathrm{b}} \mathrm{E_j} * t) \tag{16}$$

where RM_5 is total revenue loss from the utilities (₹) and, CE is the cost of energy (₹/kWh).

6) RESTORATION TIME (RM_6)

After a disaster, the time required for equipment repair is influenced by several factors. These include the nature and severity of the disaster, the availability of repair crews, the presence of spare equipment, and the operator's capacity to swiftly identify the issue and determine the best course of action. Nevertheless, based on empirical cases, it is approximated that the restoration time for each failed bus (T_r) follows a random distribution ranging from 3 to 8 hours.

$$T_r(h) = \{r\ (3, 8)\ \ for\ bus \tag{17}$$

Certainly, if 'N' represents the number of faulted buses in each section of the EMG, the restoration time for entire section (RM_6) can be computed as the sum of the restoration times for each individual faulted bus within that section. Therefore, the restoration time for each section (RM_6) will be equal to the total time needed to repair all 'N' faulted buses within that particular section.

$$RM_6 = \sum_{j=1}^{b} N_j * T_r \tag{18}$$

7) NEW RESILIENCE INDICES (RI)

The system's resilience Indices (RI) after a catastrophic event can be approximated as the reciprocal of the system's loss performance, which is defined as (19);

$$RI = \frac{1}{\Delta P_L} \tag{19}$$

In the preceding equation, ΔP_L denotes the amount of generated real power that is not available to the test system. As a result, the ΔP_L can be calculated as (20);

$$\Delta \mathrm{P_L} = \frac{\mathrm{P_{TL}} - \mathrm{P_{AL}}}{\mathrm{P_{AL}}} \tag{20}$$

where P_{TL} and P_{AL} represent the total and active loads in the system following the occurrence, respectively. As a result, the degree of resilience, which potentially goes from 0 to ∞, may be quantified. In this scenario, ∞ represents complete resilience (no performance deterioration caused by the extreme event) and 0 represents no resilience (failure to survive or even immediate collapse once the extreme event happens).

G. OBJECTIVE FUNCTION FORMULATION

The major goal of this study is to assess the resilience of distribution networks in the face of natural disasters. As shown in equation (21), the proposed technique proposes that the main target function be maximizing the overall power of restored loads. Load recovery is prioritized in this function based on its importance.

$$Objective\ Function(F) = Maximize\left(\sum_{c=1}^{T_c}\left(\frac{1}{\Delta P_{L,c}}\right)\right) \tag{21}$$

V. BALD EAGLE SEARCH ALGORITHM

This section provides a detailed explanation of the BESA and its application in determining the optimal placement and sizing of SPV-DG to solve the objective function within real-world distribution systems.

A. INTRODUCTION

Bald eagles are known for their foraging behavior, with fish, including both live and deceased specimens, serving as their primary food source, notably salmon. In 2020, Alsattar et al. [30] introduced an innovative meta-heuristic approach called the BESA. This algorithm is inspired by the hunting behavior of bald eagles, which face the challenge of capturing fish in water. While they often hunt from perches, they are also adept at aerial tracking and can detect fish from significant distances. When embarking on a foraging mission over a body of water, bald eagles exhibit specific flight patterns and select precise positions. Due to their position at the apex of the food chain, bald eagles are considered predatory creatures. Moreover, they are characterized as spirits that thrive on crucial, protein-rich sustenance. Consequently, the BESA algorithm is structured into three distinct steps, which are detailed below.

B. ALGORITHM STEPS

1) STAGE I: SELECTION

During this stage, the eagle identifies a promising food source using the following mathematical expression (22):

$$Q_{new,j} = Q_{best} + \mu * x * (Q_{mean} - Q_j) \tag{22}$$

where, μ is a parameter controlling position changes within the range of 1.5 to 2; x is a random value between [0, 1]; Q_{best} represents the previously identified best location; Q_{mean} denotes the aggregate information from prior points; Q_j is the current position, and $Q_{new,j}$ is the updated position.

2) STAGE II: SEARCH

In this stage, the eagles navigate within a defined search zone while executing spirals to intensify their search. The optimal swoop position is computed as follows (23):

$$Q_{new,\mathrm{j}} = Q_j + \beta\,(j) * \left(Q_j - Q_{j+1}\right) + \alpha\,(j) * (Q_j - Q_{mean}) \tag{23}$$

$$\alpha(j) = \frac{\alpha x(j)}{(max\,|\alpha x|)} \tag{24}$$

$$\beta(j) = \frac{\beta x(j)}{(max\,|\beta x|)} \tag{25}$$

$$\alpha \mathrm{x}\ (\mathrm{j}) = \mathrm{x}\ (\mathrm{j}) * \sin\phi(j) \tag{26}$$

$$\beta \mathrm{x}\ (\mathrm{j}) = \mathrm{x}\ (\mathrm{j}) * \cos\phi(j) \tag{27}$$

$$\phi\ (j) = \mu * \pi * rand \tag{28}$$

$$x\ (j) = \phi\ (j) + D * rand \tag{29}$$

In the search stage, equations (24)-(29) are utilized. Within this stage, the parameter μ, falling within a range of 5 to 10, is employed to determine the angle between the point being searched and the central point. Additionally, the value D, which ranges from 0.5 to 2, dictates the quantity of search cycles. Lastly, the variable rand, taking values from the interval [0, 1], is used as a random number generator.

3) STAGE III: SWOOPING

In this final stage, all points converge towards the best point as the eagles execute a swooping motion towards their target fish from the most promising location. An example of this behavior is represented by equation (30):

$$Q_{new,j} = rand * Q_{best} + \alpha 1\,(j) * (Q_j - (B_1 * Q_{mean})) + \beta 1\,(j) * (Q_j - (B_2 * Q_{best})) \tag{30}$$

$$\alpha 1(j) = \frac{\alpha x(j)}{(max\,|\alpha x|)} \tag{31}$$

$$\beta 1(j) = \frac{\beta x(j)}{(max\,|\beta x|)} \tag{32}$$

$$\alpha x\ (\mathrm{j}) = x\ (\mathrm{j}) * \sinh\phi(j) \tag{33}$$

$$\beta x\ (\mathrm{j}) = x\ (\mathrm{j}) * \cosh\phi(j) \tag{34}$$

$$\phi\ (j) = \mu * \pi * rand \tag{35}$$

$$x\ (j) = \phi\ (j) \tag{36}$$

Equations (31) to (36) are also employed in this swooping stage. The parameters B_1 and B_2 take values within the range of [1, 2]. Additionally, rand represents a random number between [0, 1]. Figure 4 illustrates the comprehensive flowchart outlining the proposed optimization process employing the BESA algorithm to find SPV-DG optimal size.

C. OPTIMIZATION PROCEDURE

The elaborated optimization procedure to find the optimal size of SPV-DGs using the BESA:

(i) Initialization

- ***Define the number of populations:*** Determine how many eagles (population size) will be used for the optimization process.

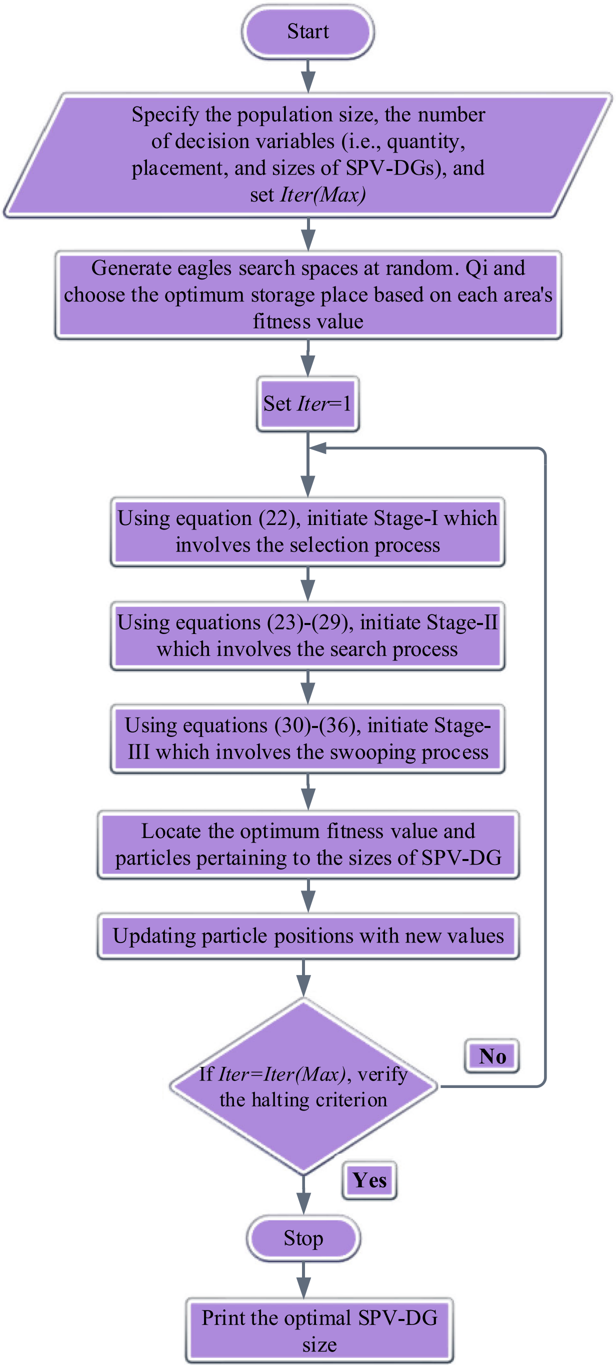

FIGURE 4. Implementation process of the BESA.

- ***Specify the number of decision variables:*** Identify the decision variables, which in this case are the number, locations, and sizes of SPV-DGs.
- ***Set the maximum number of iterations:*** Determine the termination condition for the algorithm.

(ii) Initial Population

- Randomly initialize the search spaces (positions) for the eagles. Each eagle's position represents a potential configuration of SPV-DGs.
- Calculate the fitness value for each location according to the optimization objective using the equation (21). This fitness value indicates how well a particular configuration performs.

(iii) Initialization of Best Location

- Keep track of the best location found among the initial positions.
- This best location represents the configuration of SPV-DGs with the best fitness value at the beginning.

(iv) Iteration Setup

- Set the iteration count (*iter*) to 1 to start the optimization process.

(v) Select Stage (Stage-I)

- Update the locations of eagles using Equation (22) from BESA.
- This equation guides eagles to explore the search space by adjusting their positions based on the best position found so far and the overall mean position of all eagles.

(vi) Evaluation of Fitness

- Evaluate the fitness value for the new locations using the optimization objective function (21).
- Update the best location found if any eagle's new position results in a better fitness value than the previous best.

(vii) Search Stage (Stage-II)

- Update the locations of eagles again, this time using Equation (23) from BESA.
- Equation (23) simulates the spiraling behavior of eagles as they search for better positions within a designated search zone.

(viii) Evaluation of Fitness

- Evaluate the fitness value for the locations obtained in the previous step.
- Update the best location found if any eagle's new position results in a better fitness value.

(ix) Swooping Stage (Stage-III)

- Update the locations of eagles one more time using Equation (30) from BESA.
- Equation (30) simulates the swooping behavior of eagles towards the best location in the search space.

(x) Evaluation of Fitness

- Evaluate the fitness value for the locations obtained in the swooping stage.
- Update the best location found if any eagle's new position results in a better fitness value.

(xi) Iteration Control

- Check if the current iteration count (*iter*) has reached the maximum number of iterations specified earlier.
- If not, increment *iter* by 1 and go back to step 5. This continues the iterative process.

(xii) Termination

- If the maximum number of iterations is reached, stop the optimization process.

- The best location found at the end of the iterations represents the optimal configuration of SPV-DGs, including their sizes, locations, and the number of units.

This process delineates the iterative application of the BESA algorithm in the quest for the optimal configuration of SPV-DG, accounting for numerous decision variables to obtain the optimized resilience values of distribution networks. It entails a balanced approach of exploration and exploitation, aiming to uncover the most favorable solution through multiple iterations.

VI. CASE STUDY AND NUMERICAL RESULTS

This research investigates the efficiency of a suggested microgrid formation technique using modified versions of real-time Indian 28-bus and 52-bus distribution networks in this section. The proposed study is conducted using Indian practical test systems, and consequently, all costs are denoted in Indian rupees (₹). It is assumed that all DERs will stay functioning even after a severe occurrence. Several case studies are carried out to test the resilience measures stated previously. The simulations are run for each scenario, and the statistics of each case are compared to a base situation in which no DERs are present. The simulations last a day (24 hours) and include outages that occur five hours after a natural disaster. Furthermore, outage costs are considered for this investigation is ₹424.54 per hour. This study also takes into account the hardening of distribution system poles using historical data from prior disasters [24]. A substantially damaged system is one in which the distribution system poles and lines have been seriously damaged, causing more than 70% of the loads to be unserved. Otherwise, it is categorized as a moderate disaster.

It is vital to highlight that all lines are repaired concurrently within the same time period in order to analyses the impact of different scenarios under identical conditions. The case studies take into account a total of 284 households for the 28-bus distribution system and 2786 households for the 52-bus distribution system, which are distributed across three different EMGs. For the purposes of the simulation study, each household is considered to require a 4kW SPV-DG installation.

The Indian electric vehicle market is currently undergoing dynamic growth, providing an exciting array of options for environmentally conscious consumers. It's worth noting that this market is still in its early stages and continuously evolving. New entrants, alongside established manufacturers, are consistently introducing improved variants of EVs. Expect to see the launch of enhanced models across different categories including hatchbacks, sedans, saloons, SUVs, MPVs, and more. Many of the latest BEV models in India now boast driving ranges exceeding 400 miles, equipped with batteries ranging from 17.3kWh to 77.4 kWh [31]. Moreover, five out of the top nine best-selling EVs in India feature battery capacities of 40kWh or higher, reflecting a growing industry trend. This suggests that future EV models will likely adopt larger battery capacities as the standard in most distribution systems. For this study, the MG ZS EV model with a 50 kWh battery is chosen for BEV modeling, with the BEV's state of charge (SOC) ranging from a minimum of 0% to a maximum of 100% [32]. Regarding the BESS used in simulations, a Tesla Powerwall India battery model is employed [33]. The Powerwall battery has a capacity of 13.5kWh, and a charging/discharging power rating of 4kW. It also maintains a minimum and maximum SOC of 0% and 100%, respectively.

The outcomes presented in this study were simulated and executed using MATLAB R2019a on a personal computer equipped with a 2.8 GHz CPU and 8 GB of RAM.

Following assumptions are made for the case studies:

- The projected duration for line repairs is 5 hours, specifically from 3p.m. to 8p.m.
- All lines are repaired simultaneously, ensuring equal attention to each.
- The case study focuses solely on Hardening, DSTATCOM, and critical loads for Case-IV.
- Each critical load within the EMG has one BESS and DSTATCOM unit installed.
- A single BEV is allocated to each EMGs.
- In order to maintain consistency for comparison, the fault locations and EMG formation remain the same for all cases.
- The BEV operates in the vehicle-to-grid (V2G) mode, allowing it to transfer power to and from the grid.
- An ample number of repair crews are available to address all damaged lines.
- The repair crews are capable of restoring each bus within a span of 5 minutes.

The following four distinct scenarios are frequently examined in relation to modified real-time distribution networks in India, specifically the 28-bus and 52-bus systems. A summary of the various case studies is also provided in Table 1.

i. Base Case
ii. Considering BEV (V2G Mode) and EMG
iii. Considering BEV (V2G Mode), BESS, SPV-DG (Optimal generation, 70%) and EMG
iv. Considering BEV (V2G Mode), BESS, SPV-DG (Highest generation, 100%), DSTATCOM, Hardening and EMG with critical loads.

TABLE 1. Case study characteristics.

Cases	EMG	BEV	SPV-DG	BESS	DSTATCOM	Hardening
Case-I	×	×	×	×	×	×
Case-II	✓	✓	×	×	×	×
Case-III	✓	✓	✓	✓	×	×
Case-IV	✓	✓	✓	✓	✓	✓

A. CASE STUDY-I (INDIAN 28-BUS DN)

The simulations take into account three EMGs in a 28-bus Indian distribution system, as shown in Fig. 5. The data for the test system was gathered and adapted from a source referred to as [34]. The adjustments included installing three EMGs along the test system's feeders and modifying the load values. The goal is to evaluate the impact of EMGs and DERs on enhancing distribution system resilience in the case of natural disasters. A storm occurred in this case, causing moderate damage to branches 11-15, 17-21, and 22-26, as indicated in Fig. 5. The event is presumed to have occurred at 3 p.m., and the outage is scheduled to last 5 hours, from 3 p.m. to 8 p.m. BESA is used to assess the size of the SPV-DG for installation in the EMGs.

To improve system resilience, the SPV-DG unit's capacity must be increased to optimize load recovery during emergencies or network disturbances. The BESS size is defined by the expected surplus energy generated by each EMG. The case studies take into account a total of 284 households spread among three EMGs. The total active load of the test system is 761.04 kW. Figure 11 depicts five buses within the 28-bus system that are recognized as critical load (CL) connected buses. The next section describes the various cases examined for the 28-bus system. Table 2 summarizes the data used in the case study, including households (HHs), peak load, and EMGs. The EMG includes SPV-DG, BESS, BEV, and DSTATCOM units, and the load values are listed in Table 3.

TABLE 2. Load and household data of EMG for the simulation of 28-bus.

EMG	Bus	Households (HHs)	Load (kW)
EMG-1	11	37	56
	12	24	35.28
	13	24	35.28
	14	9	14
	15	24	35.28
EMG-2	17	6	8.96
	18	6	8.96
	19	24	35.28
	20	24	35.28
	21	9	14
EMG-3	22	24	35.28
	23	6	8.96
	24	37	56
	25	6	8.96
	26	24	35.28

1) CASE-I

The base case in this case covers normal grid functioning in the Indian 28-bus test system, without the inclusion of EMG/DERs/Hardening. Three faults occur at 3 p.m. in the basic case simulation, resulting in a 5-hour outage on buses 11-15, 17-21, and 22-26 (as illustrated in Fig. 5). Following these problems, roughly 422.8kW of the total load of 761.04kW is affected. According to Fig. 6, the ENS value is high (2114kWh) and the resilience indices value is low (0.8), owing to the lack of a backup unit. In this scenario, the percentage of load restoration is determined by calculating the difference between the total number of available households and the affected households in the EMGs. The load restoration rate is approximately 44.54%, with a restoration time of 1.25 hours (Table 6). As a result, if a fault occurs, the entire load may be cut off from grid power. In order to solve this issue, the introduction of EMG/DERs/Hardening into the system attempts to improve system reliability and robustness.

TABLE 3. DERs data for the simulation of 28-bus.

Cases	DERs	Electrical Microgrid (EMG)		
		EMG-1	EMG-2	EMG-3
Case-II	SPV-DG Size in kW (Bus No)	-	-	-
	BESS Size in kW (Bus No)	-	-	-
	BEV Size in kW (Bus No)	50 (12)	50 (18)	50 (23)
	DSTATCOM Size in kVAr (Bus No)	-	-	-
Case-III	SPV-DG Size (Optimal) in kW (Bus No)	70 (12)	20 (18)	20 (23)
	BESS Size in kW (Bus No)	70 (12)	20 (18)	20 (23)
	BEV Size in kW (Bus No)	50 (13)	50 (21)	50 (26)
	DSTATCOM Size in kVAr (Bus No)	-	-	-
Case-IV	SPV-DG Size (Maximum) in kW (Bus No)	Hardening	100 (19)	100 (22)
	BESS Size in kW (Bus No)		100 (19)	100 (22)
	BEV Size in kW (Bus No)		50 (21)	50 (26)
	DSTATCOM Size in kVAr (Bus No)		100 (21)	100 (26)

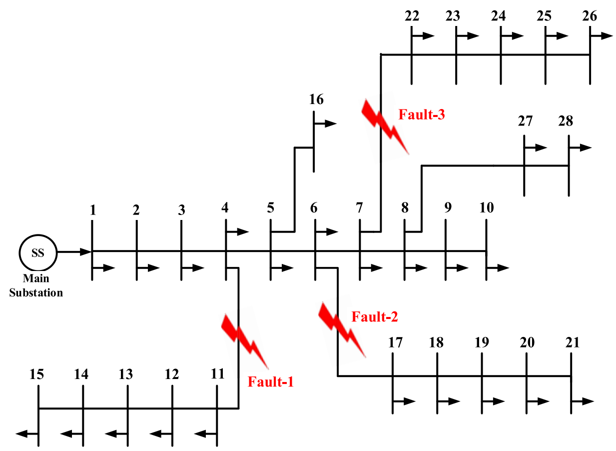

FIGURE 5. 28-bus system (Case-I).

2) CASE-II

Three EMGs are supposed to exist in a practical Indian 28-bus distribution system. On the system diagram (Figure 7), each EMG is represented by a dotted line.

This distribution network includes the use of BEVs in V2G mode. BEVs can serve as mobile energy storage devices, giving electricity back to the grid during the power outage.

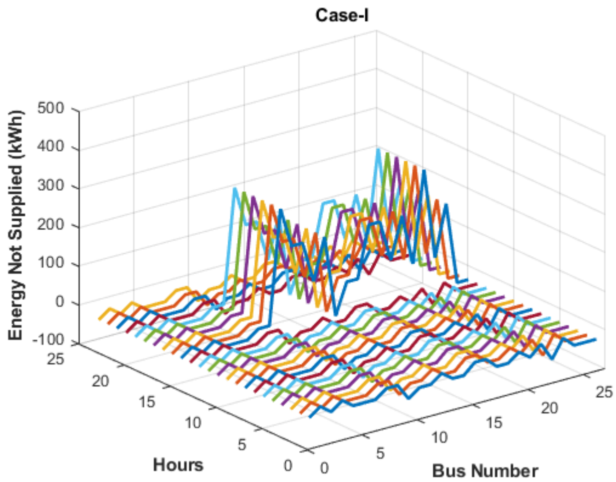

FIGURE 6. ENS profile for 28-bus system (Case-I).

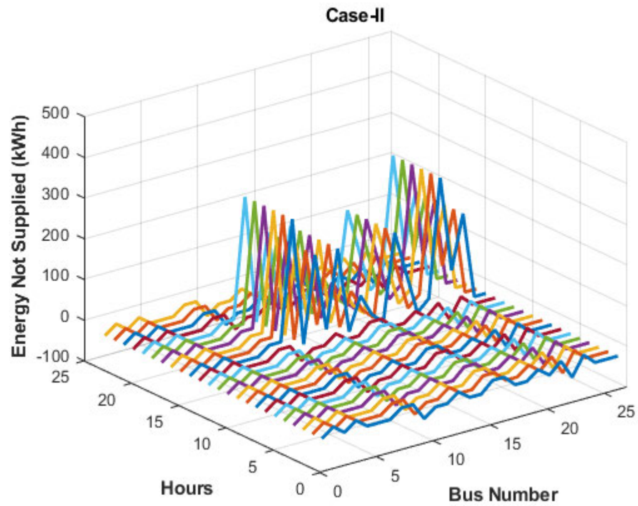

FIGURE 8. ENS profile for 28-bus system (Case-II).

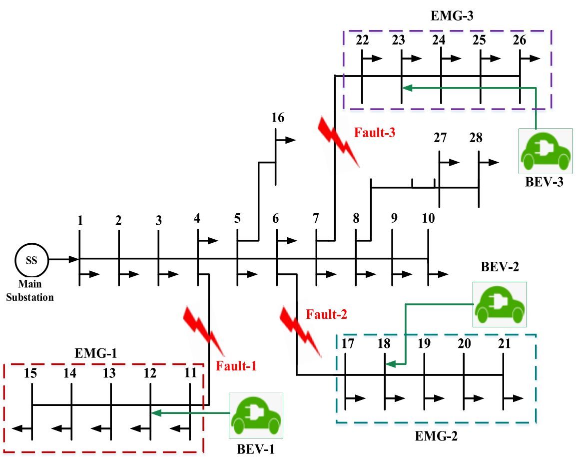

FIGURE 7. 28-bus system (Case-II).

The strategic positioning of BEVs with 50 kW ratings at the 12th, 18th, and 23rd buses in the EMGs intends to minimize the requirement for load curtailment under diverse scenarios. Multiple benefits are realized by integrating BEVs into the DS, including energy storage, load shifting, demand response, grid ancillary services, renewable energy integration, resilience enhancement, and environmental benefits. These advantages add up to a more dependable, efficient, and sustainable distribution system. The installation of BEVs at EMGs aids in recovering some of the power lost during outages. After the installation of BEVs in the 28-bus system, the ENS profile, as shown in Fig. 8, shows a reduction in comparison to the conventional network (Case-I). Simultaneously, the resilience indices values improve, showing that the distribution of BEVs to the EMGs improves system resilience.

3) CASE-III

BESA is used to efficiently equip the network, with three solar PV-based DGs and BESS units built at buses 12, 18, and 23 (Figure 9). The BESS units have capabilities of 70kW, 20kW, and 20kW, respectively. When SPV-DG electricity is unavailable, the BESS units discharge power and distribute it to the microgrids. In addition, three BEVs with 50kW ratings are positioned in the same locations as in the prior scenario. This restoration plan goes into effect at 3 p.m. and lasts 5 hours, from 3 p.m. to 8 p.m. The inclusion of DERs in the EMG reduces the ENS value from 2114kWh to 814kWh, as well as the percentages of impacted homes (109 or 21.29%) and average percentages (27 or 5.27%) as shown in Table 6.

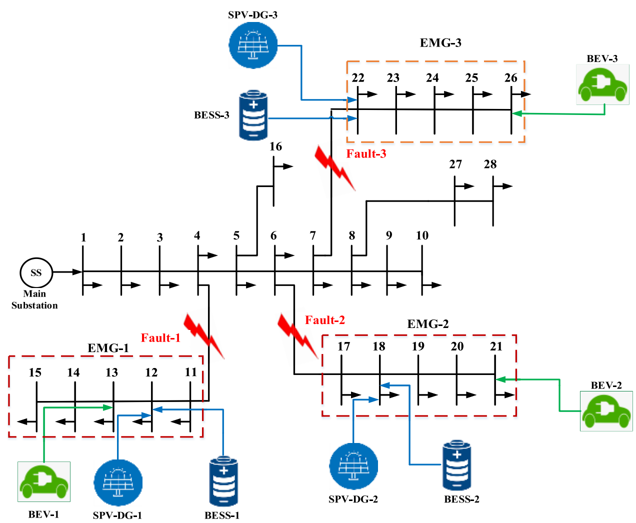

FIGURE 9. 28-bus system (Case-III).

Figure 10 depicts the ENS profile for Case III's 28-bus system. The system's robustness indices have been increased from 0.8 to 3.67. While optimizing the location of SPV-DGs in EMGs for cost-effectiveness and minimizing power loss, keep in mind that this strategy may have limits in fully restoring loads after an event. To obtain the highest level of

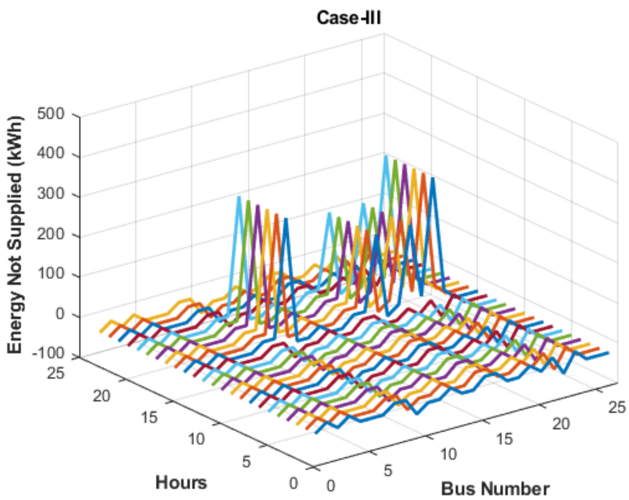

FIGURE 10. ENS profile for 28-bus system (Case-III).

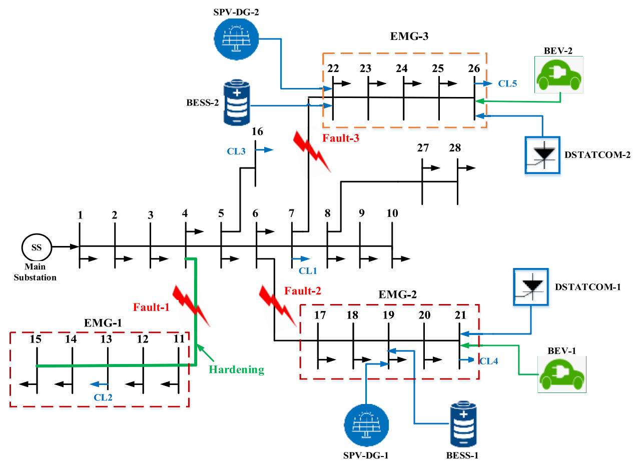

FIGURE 11. 28-bus system (Case-IV).

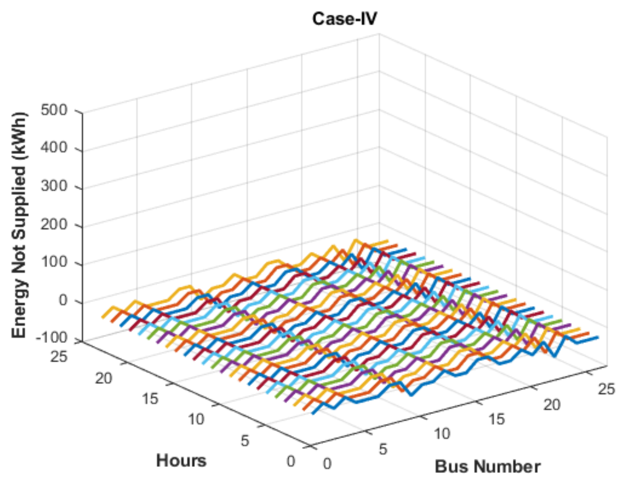

FIGURE 12. ENS profile for 28-bus system (Case-IV).

distribution system resilience, it is necessary to prepare for a greater generating capacity of SPV-DGs, which exceeds the capacity required for the ideal placement strategy. This ensures complete load restoration and excellent disruption control, maximizing distribution system resilience.

4) CASE-IV

The major goal of this case is to obtain a zero ENS while considering critical loads, which entails maximizing the distribution system's resilience. The technology accomplishes this through a mix of line hardening and DERs placement. Table 3 details the specific distribution of DERs and line hardening, and Fig. 11 depicts the entire system configuration. In EMG-1, line hardening is applied to poles along lines 4-15 to ensure that these power distribution lines remain intact even if a fault occurs. As a result, no DER installation is required to restore these lines in the event of an outage. DERs such as SPV-DG, BEV, BESS, and DSTATCOMs, on the other hand, are strategically placed in the remaining EMGs (EMG-2 and EMG-3). These DERs are used to establish restoration paths made up of system devices in order to effectively restore load in the event of problems in these areas. Figure 12 depicts the results of an evaluation of the system's fault response. The statistics show that implementing line hardening and DERs dramatically lowered the ENS when compared to other cases, showing a considerable increase in system dependability and resiliency. The ENS value approaches zero, while the resilience value looks to be infinite, indicating that all loads were successfully restored following the fault event.

In this case, the implementation of hardening measures alongside DERs in the EMGs has led to a remarkable improvement. The load restoration rate has reached an impressive 100%, with the restoration time significantly reduced to 0.83 hours. This outcome highlights the effectiveness of the combined approach in enhancing the resilience of the system (Table 6).

TABLE 4. Critical load data for the simulation (case-iv) of 28-bus.

EMG	Bus Number	Load (kW)
--	7	35.28
EMG-1	13	35.28
--	16	35.28
EMG-2	21	14
EMG-3	26	35.28
Total Load (kW)		155.12

This research investigated critical loads such as laboratory equipment, emergency and operating rooms, and information systems and computers to illustrate the efficiency of the proposed approach. Table 4 shows that five of the 28 buses are designated as critical load buses. The analysis does not take into account load uncertainty because the essential loads vary very little during the restoration procedure. In addition, the operator may choose to install a DSTATCOM near the important load buses to improve power quality. The restoration of essential loads demands a 155.12 kW power supply. Table 5 depicts the integration of DERs as well as the restoration method for restoring critical loads. Notably, all of the aforementioned key loads have been effectively restored with the help of DERs. The results show a lower ENS value and better DSTATCOM unit management for critical loads.

TABLE 5. DERs and restoration path for CLS recovery (case-iv) of 28-bus.

CL	Bus	SS	EMG	SPV-DG	BEV	BESS	DSTATCOM	Recovery Path
1	7	✓	--					B1-B7
2	13		EMG-1	Hardening				B4-B13
3	16	✓	--					B1-B5-B16
4	21		EMG-2	✓	✓	✓	✓	B6-B17-B21
5	26		EMG-3	✓	✓	✓	✓	B22-B26

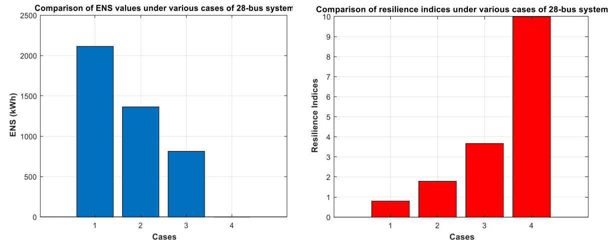

FIGURE 13. Comparison of (a) ENS values (b) Resilience indices under various cases of 28-bus system.

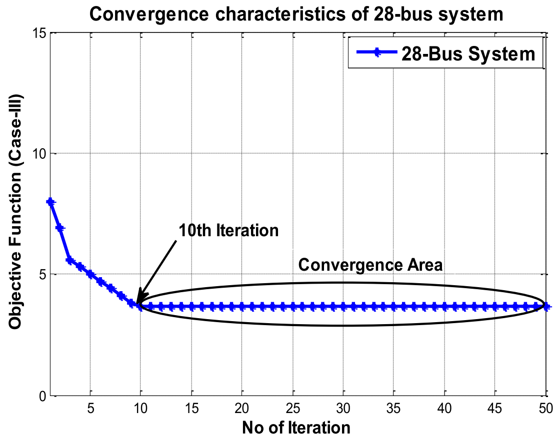

FIGURE 14. Convergence characteristics of 28-bus system using BESA.

Figure 13 compares (a) ENS values and (b) Resilience indices for several cases of the Indian 28-bus system. In comparison to the other three examples described before, the data show that in Case-IV, ENS is at its lowest while resilience indicators are at their highest. As a result, the suggested methodology, which includes the allocation of DERs as well as line hardening, leads to significant increases in resilience for practical distribution systems in India.

The algorithm's effectiveness in approaching the global optimum solution hinges on the reliability of its convergence. In Fig. 14, we present the convergence profile of the 28-bus test system using BESA. The resilience indices (Objective function) value for the most optimal Case-III is selected for this convergence graph. Notably, it is evident that BESA starts to converge from iteration number 10, signifying the attainment of the most optimal solution. This graphical representation forms the basis for assessing the performance of the BESA algorithm.

B. STUDY-II (INDIAN 52-BUS DN)

In the second case study, three EMGs have been formatted in a 52-bus distribution system in India, as shown in Fig. 15. The data for the test system was collected from Reference [35] and adjusted by installing three EMGs on the system's feeders and altering the load levels. The goal is to evaluate how EMGs and DERs can improve distribution system resilience to natural disasters. A storm occurred in this case study, inflicting moderate damage to branches 10-19, 20-31, and 41-52, as shown in Fig. 15. In case study II, the event is similarly supposed to have occurred at 3 p.m., resulting in a 5-hour outage from 3 p.m. to 8 p.m. BESA is used to calculate the best size of SPV-DG for installation in EMGs. Three EMGs are assumed for this case study, with a total of 2786 households. The total active load of the test system is 4184kW.

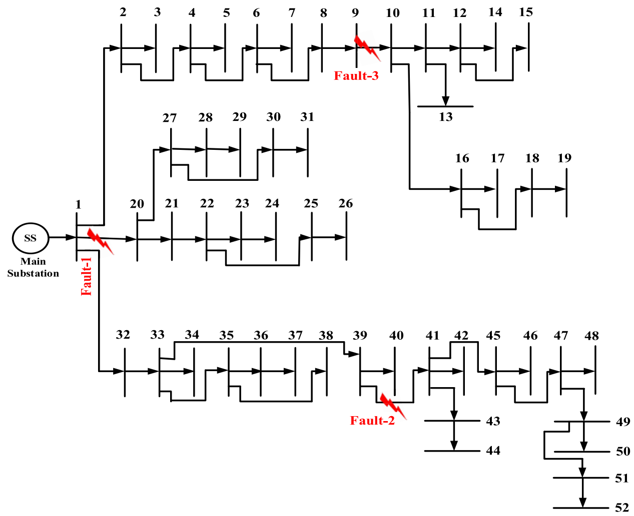

FIGURE 15. 52-bus system (Case-I).

1) CASE-I

The baseline case for the Indian 52-bus test system in this example assumes no incorporation of EMG/ DERs/ Hardening, representing ordinary grid operation. In this baseline instance, three faults occur at 3 p.m., resulting in a 5-hour outage on buses 10-19, 20-31, and 41-52. These failures in various regions of the system affect about 2724kW of the overall load of 4184kW. The results, as shown in Fig. 16, show a high ENS value (13620kWh) and a poor resilience index value (0.54) due to the lack of backup units. In this scenario, the load restoration stands at approximately 34.89%, with a restoration time of 2.83 hours (Table 11). As a result, if grid power is unavailable during breakdowns, the complete load may not be handled. To overcome this issue and improve

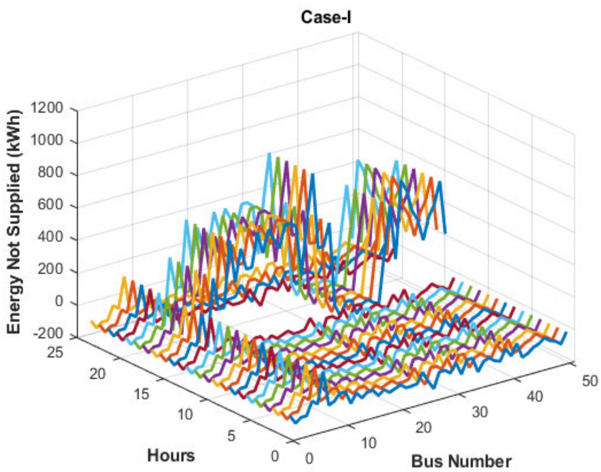

FIGURE 16. ENS profile for 52-bus system (Case-I).

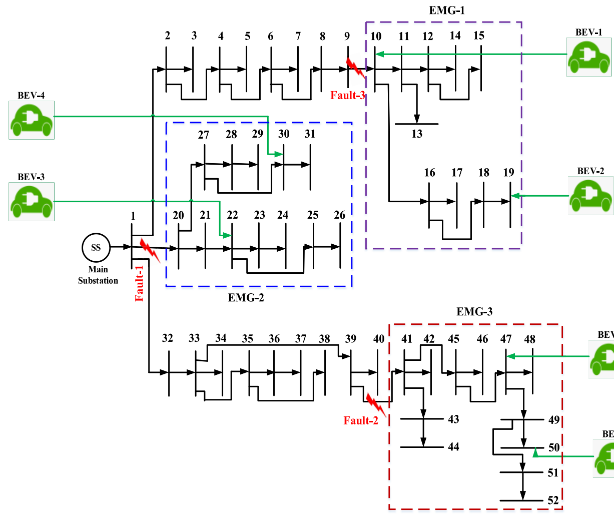

FIGURE 17. 52-bus system (Case-II).

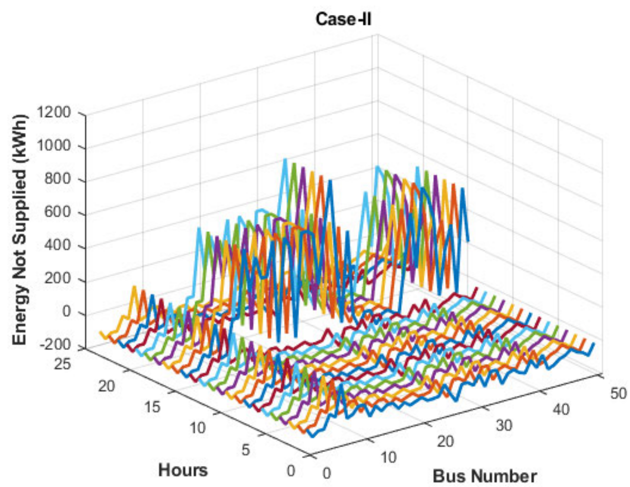

FIGURE 18. ENS profile for 52-bus system (Case-II).

system dependability and robustness, EMG/DERs/Hardening measures must be implemented.

As shown in Fig. 21, ten of the 52 buses in the system are deemed CLs connected buses. The next section describes the various scenarios examined for the 52-bus systems. Table 7 summarizes the data utilized for the case study, where households are abbreviated as HHs, Load indicates peak load, and EMGs reflect the inclusion of SPV-DG, BESS, BEV, and DSTATCOM units, as well as their associated load values, as shown in Table 8.

2) CASE-II

Three EMGs are strategically positioned at specific points in a practical Indian 52-bus distribution system, as shown by the dotted lines in Fig. 17. The system employs a total of six BEVs in V2G mode, in which BEVs can act as mobile energy storage units, giving power back to the grid during outages. This BEV integration allows for load shifting and demand response capabilities, which contribute to increased system performance. BEVs with power ratings ranging from 70kW (minimum) to 80kW (maximum) are optimally located at the various buses in the EMGs to minimize load curtailment in various cases. Using BEVs during power outages has several benefits, including energy storage, load shifting, demand response, ancillary grid services, renewable energy integration, resilience enhancement, and environmental benefits. These advantages add up to a more dependable, efficient, and sustainable distribution system. The installation of BEVs helps to mitigate power interruptions in EMGs caused by faults. After the installation of BEVs in the 52-bus system, the ENS profile, as shown in Fig. 18, indicates a reduction in comparison to the conventional network (Case-I). Concurrently, the resilience indices values improve in this scenario, showing improved system resilience following the allocation of BEVs in the EMGs.

3) CASE-III

BESA was used to optimize the network to make the best use of the power generated by three SPV-DGs and BESS placed at three EMGs. Table 8 shows the capabilities of the SPV-DGs and BESSs on the ideal buses. In the event that the SPV-DG fails to provide electricity, the BESS will discharge and power the microgrids. Furthermore, three BEVs are installed in the same positions as before (Case-II). It should be noted that the hardening process and critical loads are not taken into account in this case.

The network restoration strategy has been developed and is set to be implemented at 3 p.m. Figure 19 depicts the formation of three microgrid networks, which include the main network and the DERs. These loads are currently disconnected from these networks. The restoration plan is anticipated to last 5 hours, from 3 p.m. to 8 p.m. It is possible to reduce the ENS value from 13620kWh to 6120kWh by distributing DERs in the EMGs. This allocation also reduces the total and average proportion of impacted households to 816 (29.28%) and 204 (7.32%), respectively. The ENS profile for the 52-bus system (Case-III) is depicted in Fig. 20. Furthermore, the system's resilience indicators have increased dramatically, rising from 0.54 to 2.41 as mentioned in (Table 11).

TABLE 6. Simulation results of various resilience metrics of 28-bus.

Cases	Total no of households-hours during outage (h)	Total no of households-ENS (kWh)	Total no & percentage of households affected	Average no & percentage of households affected	Total revenue loss from the utilities (₹/kWh)	Load Restoration (%)	Restoration time (h)	Resilience Indices
Case-1	1420	2114	284 (55.46%)	71 (13.86%)	6856479	44.54	1.25	0.8
Case-2	910	1364	182 (35.54%)	46 (8.98%)	7174872	64.46	1.25	1.79
Case-3	545	814	109 (21.29%)	27 (5.27%)	7408360	78.71	1.25	3.67
Case-4	0	0	0 (0%)	0 (0%)	7753889	100	0.83	∞

TABLE 7. Load and household data of EMG for the simulation of 52-bus.

EMG	Bus	Households (HHs)	Load (kW)
EMG-1	10	45	67
	11	18	27
	12	18	27
	13	72	108
	14	36	54
	15	63	94
	16	45	67
	17	45	67
	18	72	108
	19	54	81
EMG-2	20	72	108
	21	63	94
	22	54	81
	23	72	108
	24	72	108
	25	68	102
	26	27	41
	27	72	108
	28	108	162
	29	45	68
	30	45	68
	31	63	95
EMG-3	41	27	41
	42	63	95
	43	18	27
	44	81	122
	45	72	108
	46	54	81
	47	45	68
	48	27	41
	49	45	68
	50	54	81
	51	72	108
	52	27	41

TABLE 8. DERs data for the simulation of 52-bus.

Cases	DERs	Electrical Microgrid (EMG)		
		EMG-1	EMG-2	EMG-3
Case-II	SPV-DG Size in kW (Bus No)	-	-	-
	BESS Size in kW (Bus No)	-	-	-
	BEV Size in kW (Bus No)	70 (10) 80 (19)	80 (22) 70 (30)	70 (47) 80 (50)
	DSTATCOM Size in kVAr (Bus No)	-	-	-
Case-III	SPV-DG Size (Optimal) in kW (Bus No)	180 (15) 200 (18)	190 (25) 180 (31)	225 (44) 75 (48)
	BESS Size in kW (Bus No)	180 (15) 200 (18)	190 (25) 180 (31)	225 (44) 75 (48)
	BEV Size in kW (Bus No)	70 (10) 80 (19)	80 (22) 70 (30)	70 (47) 80 (50)
	DSTATCOM Size in kVAr (Bus No)	-	-	-
Case-IV	SPV-DG Size (Maximum) in kW (Bus No)	Hardening	700 (20) 530 (28)	450 (45) 450 (51)
	BESS Size in kW (Bus No)		700 (20) 530 (28)	450 (45) 450 (51)
	BEV Size in kW (Bus No)		80 (26) 70 (31)	70 (44) 80 (48)
	DSTATCOM Size in kVAr (Bus No)		100 (26) 140 (31)	200 (44) 100 (48)

The ideal placement of SPV-DGs in the EMGs can be optimized to ensure cost-effectiveness and minimize power loss. It should be noted, however, that this optimization strategy may have limits in entirely restoring the loads following an event. To achieve the highest level of distribution system resilience, it is necessary to prepare for a greater generation capacity of SPV-DGs, beyond the capacity required for the ideal placement strategy. This ensures optimum distribution system resilience by allowing for thorough load restoration and excellent disruption control.

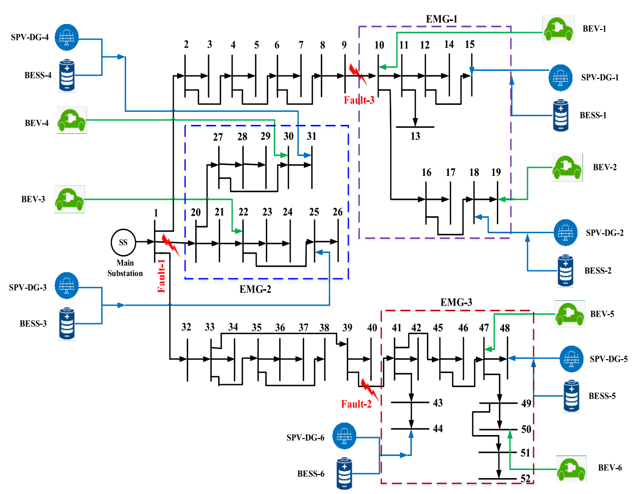

FIGURE 19. 52-bus system (Case-III).

4) CASE-IV

The primary purpose of this case is to obtain an ENS value of zero while taking into account the essential loads. We estimated the optimal generation capacity of the SPV-DG units and applied line hardening techniques to accomplish this. The decisions about line hardening (EMG-1) and DER

TABLE 9. Critical load data for the simulation (case-iv) of 52-bus.

EMG	Bus Number	Load (kW)
--	4	108
--	8	135
EMG-1	12	27
EMG-1	18	108
EMG-2	26	41
EMG-2	31	95
--	34	41
--	37	81
EMG-3	44	122
EMG-3	48	41
	Total Load (kW)	799

TABLE 10. DERs and restoration path for CLS recovery (case-iv) of 52-bus.

CL	Bus	SS	EMG	SPV-DG	BEV	BESS	DSTATCOM	Recovery Path
1	4	✓	--					B1-B2-B4
2	8	✓	--					B1-B2-B4-B6-B8
3	12		EMG-1	Hardening				B1-B2-B9-B12
4	18		EMG-1					B1-B2-B9-B10-B16-B18
5	26		EMG-2	✓	✓	✓	✓	B1-B20-B22-B25-B26
6	31		EMG-2	✓	✓	✓	✓	B1-B20-B27-B30-B31
7	34	✓	--					B1-B32-B34
8	37	✓	--					B1-B32-B33-B35-B37
9	44		EMG-3	✓	✓	✓	✓	B1-B32-B33-B39-B41-B43-B44
10	48		EMG-3	✓	✓	✓	✓	B1-B32-B33-B39-B41-B45-B47-B48

TABLE 11. Simulation results of various resilience metrics of 52-bus.

Cases	Total no of households-hours during outage (h)	Total no of households-ENS (kWh)	Total no & percentage of households affected	Average no & percentage of households affected	Total revenue loss from the utilities (₹/kWh)	Load Restoration (%)	Restoration time (h)	Resilience Indices
Case-1	9070	13620	1814 (65.11%)	454 (16.27%)	22603323	34.89	2.83	0.54
Case-2	7580	11370	1516 (54.41%)	379 (13.60%)	23558502	45.59	2.83	0.84
Case-3	4080	6120	816 (29.28%)	204 (7.32%)	25785588	70.72	2.83	2.41
Case-4	0	0	0 (0%)	0 (0%)	28385339	100	2	∞

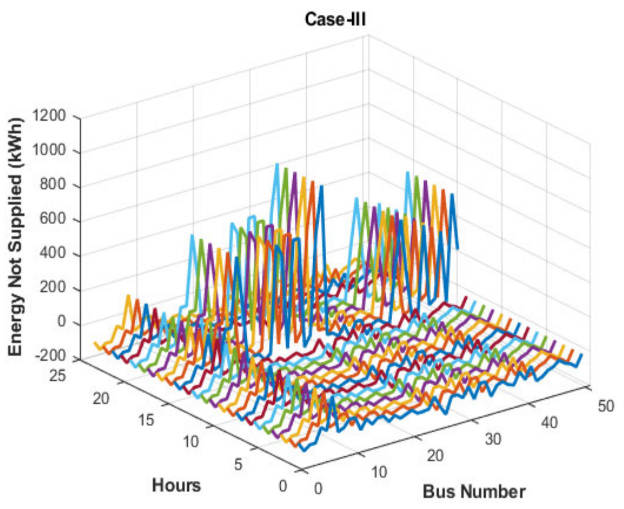

FIGURE 20. ENS profile for 52-bus system (Case-III).

placement (EMG-2 & EMG-3) were taken with the goal of increasing the distribution system's resilience.

Table 8 shows how DERs and line hardening are allocated in the EMGs. Figure 21 depicts the full setup of this case, including the generation of EMGs, line hardening, and DERs allocation. To improve system resilience, techniques such as pole hardening and the deployment of DERs are used to restore electricity supply in the event of distribution system disruptions. Pole hardening has been implemented along lines 10-19 in the EMG-1, assuring the power distribution lines' sustained health even during faults.

To restore power in this area of the distribution system, no further DERs are required. However, in the remaining two EMGs (EMGs 2 and 3), DERs such as SPV-DG, BEV, BESS, and DSTATCOMs are required. These DERs are used to create restoration routes, which are made up of system devices that allow load to be restored. Figure 22 shows that when the test system is subjected to faults and the performance is analyzed using the ENS metric, the ENS is dramatically reduced when compared to other circumstances. This decrease indicates an improvement in system dependability and resilience. The ENS value approaches 0, whereas the resilience value approaches infinity, suggesting that the system

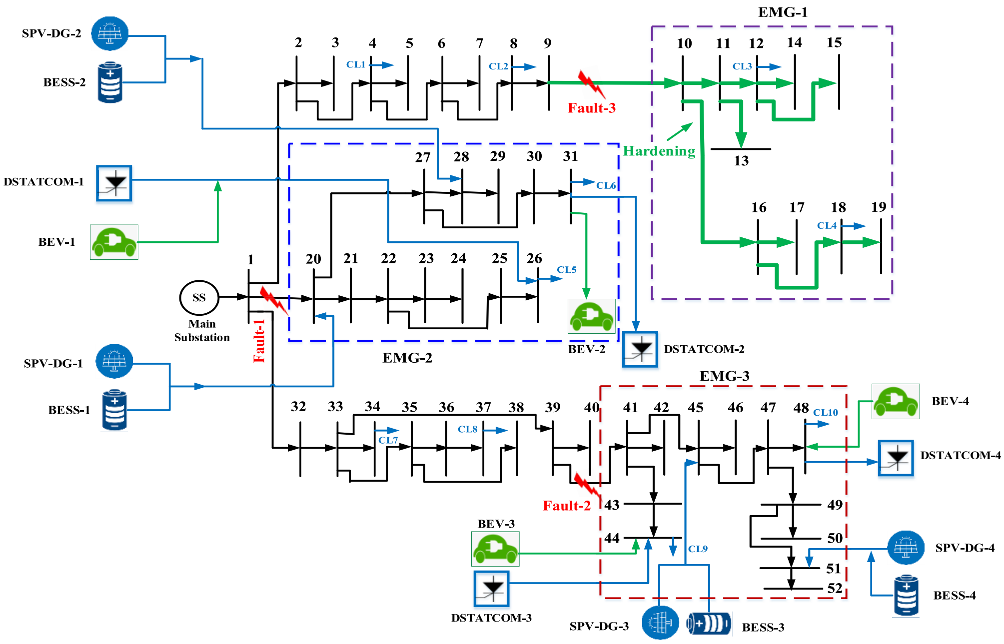

FIGURE 21. 52-bus system (Case-IV).

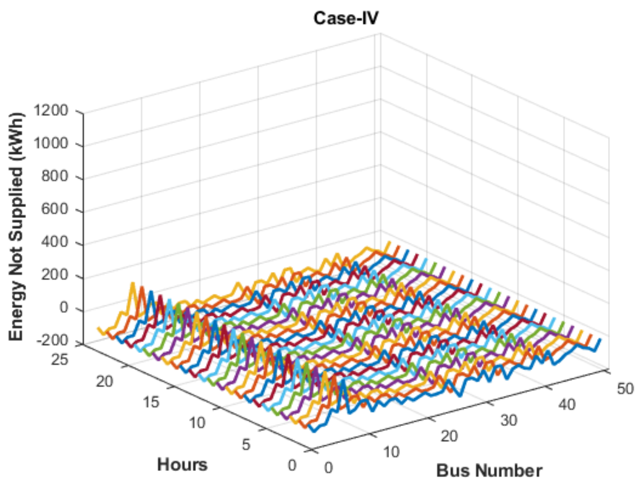

FIGURE 22. ENS profile for 52-bus system (Case-IV).

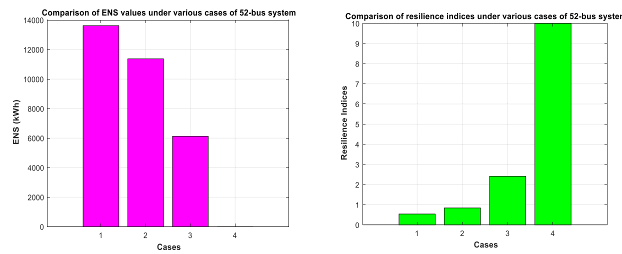

FIGURE 23. Comparison of (a) ENS values (b) Resilience indices under various cases of 52-bus system.

successfully recovers all loads after an event or malfunction occurs.

In this case, with the implementation of hardening measures along with DERs in the EMGs, the load restoration has reached 100%, and the restoration time has been significantly reduced to 2 hours. This demonstrates the enhanced resilience of the system, ensuring that all households have their power restored quickly even under adverse conditions (Table 11).

This research concentrated on critical loads such as laboratory equipment, emergency and operation rooms, and information systems and computers to illustrate the efficacy of the proposed strategy. Table 9 shows that 10 buses were classified as essential load buses out of a total of 52 buses. In addition, the operator has the option of installing a DSTATCOM near the important load buses to improve power quality. The electricity required to restore the critical loads is 799kW.

Table 9 depicts the deployment of DERs as well as the restoration method for critical load recovery. With the assistance of DERs, all of the aforementioned important loads were effectively restored. The results show a reduction in ENS and enhanced management of the DSTATCOM unit for critical loads.

Figure 23 depicts a comparison of (a) ENS values and (b) resilience indices for the Indian 52-bus system. The graph clearly shows that Case-IV has the lowest ENS value and the highest resilience index among the four examples analysed. This suggests that the framework's suggested mix of DER allocation and line hardening provides significant increases in resilience for practical distribution networks in India.

In Fig. 24, the convergence profile of the 52-bus test system using BESA is depicted. This graph provides valuable insights into the performance of BESA. Remarkably, the BESA algorithm achieves convergence to the optimal objective value in a mere 12 iterations, surpassing its counterparts in terms of speed. What sets BESA apart is its exceptional convergence rate, characterized by a harmonious blend of stability and swiftness, along with an impressive capacity for near-global exploration. Consistently, the algorithm maintains a rapid convergence pace, particularly excelling in both

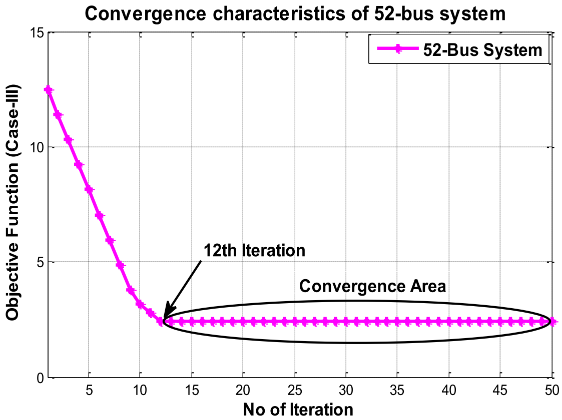

FIGURE 24. Convergence characteristics of 52-bus system using BESA.

the speed and precision of its convergence when compared to the other algorithms subjected to testing.

VII. CONCLUSION

This research proposes a novel methodology for measuring distribution system resilience in the aftermath of major events. The researchers conducted a resilience analysis on two real-world Indian distribution networks, a 28-bus system and a 52-bus system. Damage levels of varying severity were applied to the systems and tested under various situations, with resilience metrics used for evaluation. This paper's findings shed light on the benefits that DERs can provide to power distribution grids when managed successfully within networked EMGs. The test findings revealed that DERs, such as BEVs and BESS, can contribute to power generation support and improve distribution system resilience by efficiently scheduling energy discharge during outages. Furthermore, the DSTATCOM was vital in recovering critical loads. The suggested framework provides an enhanced planning and operation scheme that can be applied to conventional test systems, allowing for the quantification of resilience features and comparison with previous research. With the use of this strategy, a large number of users could potentially be subjected to power interruptions for an extended period of time. It is crucial to highlight, however, that this study concentrated primarily on a particular renewable source, specifically SPV-DG systems. Future study should look towards including more renewable sources, supplementary devices, and network reconfiguration plans to improve the system's stability and speed of recovery. Furthermore, it would be interesting to investigate DERs' ability to maintain the distribution system over extended time periods by integrating random duration faults and utilizing other resilience metrics.

REFERENCES

[1] R. K. Mall, S. D. Attri, and S. Kumar, "Extreme weather events and climate change policy in India," *J. South Asia Disaster Studies*, vol. 4, no.2, pp. 37–56, 2011.

[2] L. Xu, Q. Guo, Y. Sheng, S. M. Muyeen, and H. Sun, "On the resilience of modern power systems: A comprehensive review from the cyber-physical perspective," *Renew. Sustain. Energy Rev.*, vol. 152, Dec. 2021, Art. no. 111642.

[3] L. Das, S. Munikoti, B. Natarajan, and B. Srinivasan, "Measuring smart grid resilience: Methods, challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 130, Sep. 2020, Art. no. 109918.

[4] Invest India. (Feb. 7, 2023). *India's EV Economy: The Future of Automotive Transportation*. [Online]. Available: https://www.investindia.gov.in/team-india-blogs/indias-ev-economy-future-automotive-transportation

[5] N. M. Tabatabaei, S. N. Ravadanegh, and N. Bizon, *Power Systems Resilience*. Cham, Switzerland: Springer, 2018.

[6] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Enhancing power system resilience through hierarchical outage management in multi-microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2869–2879, Nov. 2016.

[7] Q. Shi, W. Liu, B. Zeng, H. Hui, and F. Li, "Enhancing distribution system resilience against extreme weather events: Concept review, algorithm summary, and future vision," *Int. J. Electr. Power Energy Syst.*, vol. 138, Jun. 2022, Art. no. 107860.

[8] X. Wang, Z. Li, M. Shahidehpour, and C. Jiang, "Robust line hardening strategies for improving the resilience of distribution systems with variable renewable resources," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 386–395, Jan. 2019.

[9] Y. Lin and Z. Bie, "Tri-level optimal hardening plan for a resilient distribution system considering reconguration and DG islanding," *Appl. Energy*, vol. 210, Jan. 2018, Art. no. 12661279.

[10] E. Galvan, P. Mandal, S. Chakraborty, and T. Senjyu, "Efficient energy-management system using a hybrid transactive-model predictive control mechanism for prosumer-centric networked microgrids," *Sustainability*, vol. 11, no. 19, p. 5436, Sep. 2019.

[11] L. P. Fernández, T. G. S. Roman, R. Cossent, C. M. Domingo, and P. Frías, "Assessment of the impact of plug-in electric vehicles on distribution networks," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 206–213, Feb. 2011.

[12] Y. Guo, J. Xiong, S. Xu, and W. Su, "Two-stage economic operation of microgrid-like electric vehicle parking deck," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1703–1712, May 2016.

[13] G. Kumar and P. S. Raju, "Study of DSTATCOM in improved custom power park for power quality improvement," *Int. J. Elect. Eng. Technol.*, vol. 2, no. 2, pp. 12–20, 2011.

[14] L. Che and M. Shahidehpour, "DC microgrids: Economic operation and enhancement of resilience by hierarchical control," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2517–2526, Sep. 2014.

[15] S. Mousavizadeh, T. G. Bolandi, M.-R. Haghifam, M. Moghimi, and J. Lu, "Resiliency analysis of electric distribution networks: A new approach based on modularity concept," *Int. J. Electr. Power Energy Syst.*, vol. 117, May 2020, Art. no. 105669.

[16] E. Rosales-Asensio, M. de Simón-Martín, D. Borge-Diez, J. J. Blanes-Peiró, and A. Colmenar-Santos, "Microgrids with energy storage systems as a means to increase power resilience: An application to office buildings," *Energy*, vol. 172, pp. 1005–1015, Apr. 2019.

[17] A. Barnes, H. Nagarajan, E. Yamangil, R. Bent, and S. Backhaus, "Resilient design of large-scale distribution feeders with networked microgrids," *Electr. Power Syst. Res.*, vol. 171, pp. 150–157, Jun. 2019.

[18] J. Zhu, Y. Yuan, and W. Wang, "An exact microgrid formation model for load restoration in resilient distribution system," *Int. J. Electr. Power Energy Syst.*, vol. 116, Mar. 2020, Art. no. 105568.

[19] L. Ren, Y. Qin, Y. Li, P. Zhang, B. Wang, P. B. Luh, S. Han, T. Orekan, and T. Gong, "Enabling resilient distributed power sharing in networked microgrids through software defined networking," *Appl. Energy*, vol. 210, pp. 1251–1265, Jan. 2018.

[20] M. U. Shahid, M. Mansoor Khan, K. Hashmi, R. Boudina, A. Khan, J. Yuning, and H. Tang, "Renewable energy source (RES) based islanded DC microgrid with enhanced resilient control," *Int. J. Electr. Power Energy Syst.*, vol. 113, pp. 461–471, Dec. 2019.

[21] A. Hussain, V.-H. Bui, and H.-M. Kim, "Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience," *Appl. Energy*, vol. 240, pp. 56–72, Apr. 2019.

[22] Y. Gilasi, S. H. Hosseini, and H. Ranjbar, "Resiliency-oriented optimal siting and sizing of distributed energy resources in distribution systems," *Electr. Power Syst. Res.*, vol. 208, Jul. 2022, Art. no. 107875.

[23] A. Hussain, S. D. A. Shah, and S. M. Arif, "Heuristic optimisation-based sizing and siting of DGs for enhancing resiliency of autonomous microgrid networks," *IET Smart Grid*, vol. 2, no. 2, pp. 269–282, Jun. 2019.

[24] D. K. Mishra, M. J. Ghadi, L. Li, J. Zhang, and M. J. Hossain, "Active distribution system resilience quantification and enhancement through multi-microgrid and mobile energy storage," *Appl. Energy*, vol. 311, Apr. 2022, Art. no. 118665.

[25] A. N. Tari, M. S. Sepasian, and M. T. Kenari, ‘‘Resilience assessment and improvement of distribution networks against extreme weather events,’’ *Int. J. Electr. Power Energy Syst.*, vol. 125, Feb. 2021, Art. no. 106414.

[26] M. H. Amirioun, F. Aminifar, H. Lesani, and M. Shahidehpour, ‘‘Metrics and quantitative framework for assessing microgrid resilience against windstorms,’’ *Int. J. Electr. Power Energy Syst.*, vol. 104, pp. 716–723, Jan. 2019.

[27] D. K. Mishra, M. J. Ghadi, A. Azizivahed, L. Li, and J. Zhang, ‘‘A review on resilience studies in active distribution systems,’’ *Renew. Sustain. Energy Rev.*, vol. 135, Jan. 2021, Art. no. 110201.

[28] M. A. Gilani, A. Kazemi, and M. Ghasemi, ‘‘Distribution system resilience enhancement by microgrid formation considering distributed energy resources,’’ *Energy*, vol. 191, Jan. 2020, Art. no. 116442.

[29] E. Galvan, P. Mandal, and Y. Sang, ‘‘Networked microgrids with roof-top solar PV and battery energy storage to improve distribution grids resilience to natural disasters,’’ *Int. J. Electr. Power Energy Syst.*, vol. 123, Dec. 2020, Art. no. 106239.

[30] H. A. Alsattar, A. A. Zaidan, and B. B. Zaidan, ‘‘Novel meta-heuristic bald eagle search optimisation algorithm,’’ *Artif. Intell. Rev.*, vol. 53, no. 3, pp. 2237–2264, Mar. 2020.

[31] Servotech Power Systems Ltd. (Aug. 31, 2023). *Top Electric Cars in India 2023*. [Online]. Available: https://www.servotech.in/blog/top-electric-cars-in-india/

[32] MG Motor India. *MG ZS EV | Specification | MG Motor India*. Accessed: Oct. 27, 2023. [Online]. Available: https://www.mgmotor.co.in/vehicles/mgzsev-electric-car-in-india/specifications

[33] *Open a Tesla Power Shop, Tesla Power Distributorship, Tesla Power Shop*. Accessed: Oct. 27, 2023. [Online]. Available: https://teslapowerusa.in/teslapowershop.php

[34] D. Das, ‘‘Novel method for solving radial distribution networks,’’ *IEE Proc.-Gener., Transmiss. Distrib.*, vol. 141, no. 4, p. 291, 1994.

[35] D. Thukaram, H. P. Khincha, and H. P. Vijaynarasimha, ‘‘Artificial neural network and support vector machine approach for locating faults in radial distribution systems,’’ *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 710–721, Apr. 2005.

T. YUVARAJ received the B.E. degree in electrical and electronics engineering and the M.E. degree in power electronics and drives from Anna University, Chennai, India, in 2011 and 2013, respectively, and the Ph.D. degree from VIT University, Vellore, India, in 2017. He is currently an Associate Professor with the Department of EEE and a Research Member of the Centre for Computational Modeling, Chennai Institute of Technology, Chennai. He has published more than 70 articles in Web of Science/Scopus-indexed journals. His current research interests include power system optimization, allocation of distributed energy resources, electric vehicle technology, power system resilience, and renewable energy. He is a member of IET and IAENG. He has also served as a reviewer for various reputed journals, such as IEEE, Elsevier, Springer, Taylor & Francis, and Inderscience journals.

K. R. DEVABALAJI received the bachelor’s degree in electrical and electronics engineering and the master’s degree in power electronics drives from Anna University, Chennai, India, in 2011 and 2013, respectively, and the Ph.D. degree from the Vellore Institute of Technology, Vellore, India, in 2016. He is currently an Associate Professor with the Department of Electrical and Electronics Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Missions Research Foundation, Chennai. He has published several research articles in reputed journals. He has over ten years of teaching and research experience. He has visited Thailand, Singapore, Indonesia, and the U.K., for presenting research papers, funded proposals, and collaborative research activities. His current research interests include renewable energy systems, power systems, and power electronics and drives.

T. D. SURESH received the B.E. degree in electrical and electronics engineering and the M.E. degree in power systems engineering from Anna University, Chennai, India, in 2007 and 2015, respectively, where he is currently pursuing the Ph.D. degree (part-time). He is currently an Assistant Professor of electrical and electronics engineering with the Saveetha Engineering College, Chennai. He has published articles in Scopus-indexed journals. His current research interests include the optimal allocation of DFACTS and BESS in distribution networks using optimization algorithms.

NATARAJAN PRABAHARAN (Senior Member, IEEE) received the B.E. degree in electrical and electronics engineering and the M.E. degree in power electronics and drives from the Affiliated College, Anna University, Chennai, India, in 2012 and 2014, respectively, and the Ph.D. degree in energy and power electronics from the Vellore Institute of Technology (VIT) University, Vellore, India, in 2017. He is currently an Assistant Professor with the Department of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur, India. His current research interests include power electronics, new topologies for inverters and converters, energy trading, electric vehicles, demand side management, grid integration of renewable energy sources and its controllers, photovoltaic systems, and microgrids. He is a technical program committee member of many reputed international conferences. He was a recipient of the University Merit Ranker Award, in 2014. He was a recipient of two prestigious travel grants under the category of the Young Scientist from the Science and Engineering Research Board and the Asian Development Bank, in 2015 and 2016, respectively. He received the Outstanding Editorial Board Member Award from *International Transactions on Electrical Energy Systems* (Wiley), in 2020 and 2021. He serves as an Associate Editor for the *IET Renewable Power Generation*, *International Transactions on Electrical Energy Systems*, IEEE Access, *Journal of Power Electronics*, and *International Journal of Renewable Energy Research*.

SOICHIRO UEDA (Student Member, IEEE) received the B.Eng. degree in electrical systems engineering from the University of the Ryukyus, Japan, in 2022, where he is currently pursuing the M.Eng. degree. His current research interests include renewable energy, energy management, microgrids, and model predictive control.

TOMONOBU SENJYU (Fellow, IEEE) received the B.S. and M.S. degrees in electrical engineering from the University of the Ryukyus, in 1986 and 1988, respectively, and the Ph.D. degree in electrical engineering from Nagoya University, in 1994. Since 1988, he has been with the Department of Electrical and Electronics Engineering, Faculty of Engineering, University of the Ryukyus, where he is currently a Professor. His current research interests include power system optimization and operation, advanced control, renewable energy, the IoT for energy management, ZEH/ZEB, smart city, and power electronics. He is an IEEJ Fellow and an AAIA Fellow.